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Original Article

Influence of tributaries on downstream bed sediment grain sizes under flysch conditions

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Abstract: Tributaries are one of the most important factors contributing to variability in the downstream evolution of bed sediment grain size. The primary aim of this work is to evaluate the response of the bed sediment texture in the recipient channel induced by ten tributaries of the Černá Ostravice stream and find reach-scale and catchment-scale parameters that would be able to predict this response. The research was based on collecting information on the grain size distributions at sites adjacent to confluence zones. A significant change in sediment texture occurred in the vicinity of five confluences. Considering the other factors contributing to grain size variability (e.g., local channel geometry, lithology, and lateral sediment sources), it was assumed that only four of them were associated with a sufficient bedload influx to alter the sediment calibre below the junction. Moreover, a significant morphological effect in the form of a large confluence bar was observed in one case. These tributaries had several common features: (i) they had a larger relative catchment area than that of non-significant tributaries; (ii) they were characterized by different bed grain sizes, with some exceptions; and (iii) they had a higher unit stream power close to the confluence in relation to that of the mainstream. These characteristics were represented by the proposed relative parameters, including the relative unit stream power and bed material texture, which allowed the best classification of significant and non-significant tributaries. In their simplified form, the parameters described the transport capacity and grain size distribution, which were generally considered to be primary factors responsible for a redefinition of the sediment texture in the recipient channel. However, it should be noted that these results are subject to some degree of uncertainty due to the relatively small sample size of only 10 tributaries.

Keywords: Tributary; Bed sediments; Headwater streams; Flysch Carpathians

1 Introduction

Bed sediments play a substantial role in the fluvial system. Bed sediments represent a roughness element involved in the dissipation of flow energy and thus significantly affect the hydraulics and riverbed morphology (Benda et al. 2005). One of the most important characteristics of the bed material is the grain size, which has significant implications for sediment transport or river ecology. The river continuum is characterized by a gradual downstream fining of bed sediments, which is generally attributed

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to the processes of abrasion and selective transport (Surian 2002). However, downstream fining is a general trend rather than a smooth function of distance. Especially in mountain streams, the trend is repeatedly interrupted by inputs of new material from lateral sources along the channel. This trend is supported by strong hillslope-channel coupling encouraged, in many cases, by the absence of floodplain segments acting as buffers sensu Fryirs et al. (2007). Sediment delivery in mountain catchments is often dominated by slope movements associated with the development of small rotational landslides and riverbank failures. Gullies or river bedrock may also deliver a substantial amount of material, particularly in the presence of geomorphologically less-resistant rocks, such as claystones (Borja et al. 2018). Thus, the intensive sediment supply contributes to considerable grain size variation in mountain streams and often leads to the trend of downstream coarsening (Brummer and Montgomery 2003; Vianello and D'Agostino 2007; Wohl and Wilcox 2005).

In addition to the abovementioned nonalluvial sources, tributaries can produce a significant proportion of this variability (e.g., Knighton 1980; Dawson 1988; Ichim and Radoane 1990; Rice 1998; Swanson and Meyer 2014). The supply of sufficiently voluminous and/or sedimentologically different material (relative to the mainstream) generally causes an abrupt change in the grain sediment texture in the recipient channel (Rice et al. 2001), which in many cases, results in disruption of the downstream fining (Rice and Church 1998). Rice (1998) considered the sediment sources responsible for grain-size steps as significant lateral sources, and in most cases, he identified them with tributaries. In accordance with previous research, the most significant sources are related to an increase in grain size (e.g., Church and Kellerhals 1978; Rice and Church 1998; Swanson and Meyer 2014), but if a sufficient volume of relatively fine material is introduced, a sudden decrease in sediment calibre may occur (Ferguson et al. 2006). Nevertheless, the relatively high transport capacity of the mainstream channel is responsible for the removal of potentially fine sediment supply from a tributary, which leads to the rare presence of downstream fining below the confluence. The channel reaches between significant lateral sources are relatively isolated from sediment inputs. Therefore, the downstream fining can more easily develop, largely due to sorting processes (Swanson and Meyer 2014). Rice and Church (1998) refer to these sub-reaches as sedimentary links, which are analogous to hydrological network links but reflect the supply and transfer of sediment rather than water.

Rice (1998) noted that only a relatively small portion of tributaries have a significant effect on the mainstream channel. He found that approximately 20% of tributaries along the Pine and Sukunka Rivers in British Columbia had an impact on the mainstream grain size. The key question is, what factors affect the ability of a given tributary to redefine the bed texture in the recipient channel? Knighton (1980) stated that the impact of a tributary on its mainstream channel depends mainly on their relative differences in discharge, sediment size, and sediment load. Generally, it can be assumed that the probability of a significant impact on sediment size increases with a larger volume of supplied material and with an increasing grain size disparity between the supplied material and mainstream bed sediment. Concerning tributaries, an additional water inflow also plays an important role because it modifies the transport capacity of the river below the confluence, which directly affects the grain size distribution (Rice 1998).

In particular, the potential volume of inflowing water and sediment yield from tributaries scale with the size of their catchments. Benda et al. (2004) reviewed case studies at a total of 167 sites in western North America and found that the frequency of the significant impact increased with the tributary size relative to the mainstream. The amount of introduced material depends not only on the production of sediment within the catchment but also on the ability of the tributary to transport it downstream. In this regard, the important factor is primarily the riverbed gradient, which directly affects the flow energy and hence the flow transport capacity (Rice 1998). Rice (1998) confirmed that the relative catchment area and tributary slope helped to predict tributaries with a significant effect on downstream fining.

The primary aim of this study is to describe how tributaries influence the downstream evolution of the bed sediment grain size in a torrential stream based in flysch rocks (Western Carpathians, Czech Republic). A further objective is to identify the controlling factors influencing the tributary impacts on the mainstream bed sediment and to propose parameters indicating the ability of the tributary to influence the grain size distribution in the recipient channel.

2 Study Area

The study area is the catchment of the Černá Ostravice stream located in the southern part of the Moravian-Silesian Beskids Mts., Western Carpathians, Czech Republic. It is a torrential gravel-bed stream with a length of 10.8 km and a drainage area of 28.9 km². The approximately 6-km-long lower part of the stream was investigated, which flows through a relatively wide valley that contains the 10 most important tributaries examined in this study (Fig. 1). The catchment altitude varies from 521 m to 957 m asl., with an average of 691 m asl. The average hillslope gradient is 12.5°. The selected characteristics of the tributary catchments are listed in Table 1.

The Moravian-Silesian Beskids Mts. are located in the regions that are the most exposed to precipitation in the Czech Republic. The annual mean precipitation in the case study catchment is approximately 1260 mm. The rainfall in this area reaches a peak in the summer period with a maximum in the month of July (156 mm), when there is a frequent occurrence of intensive convective storm events. During extreme floods, specific discharges

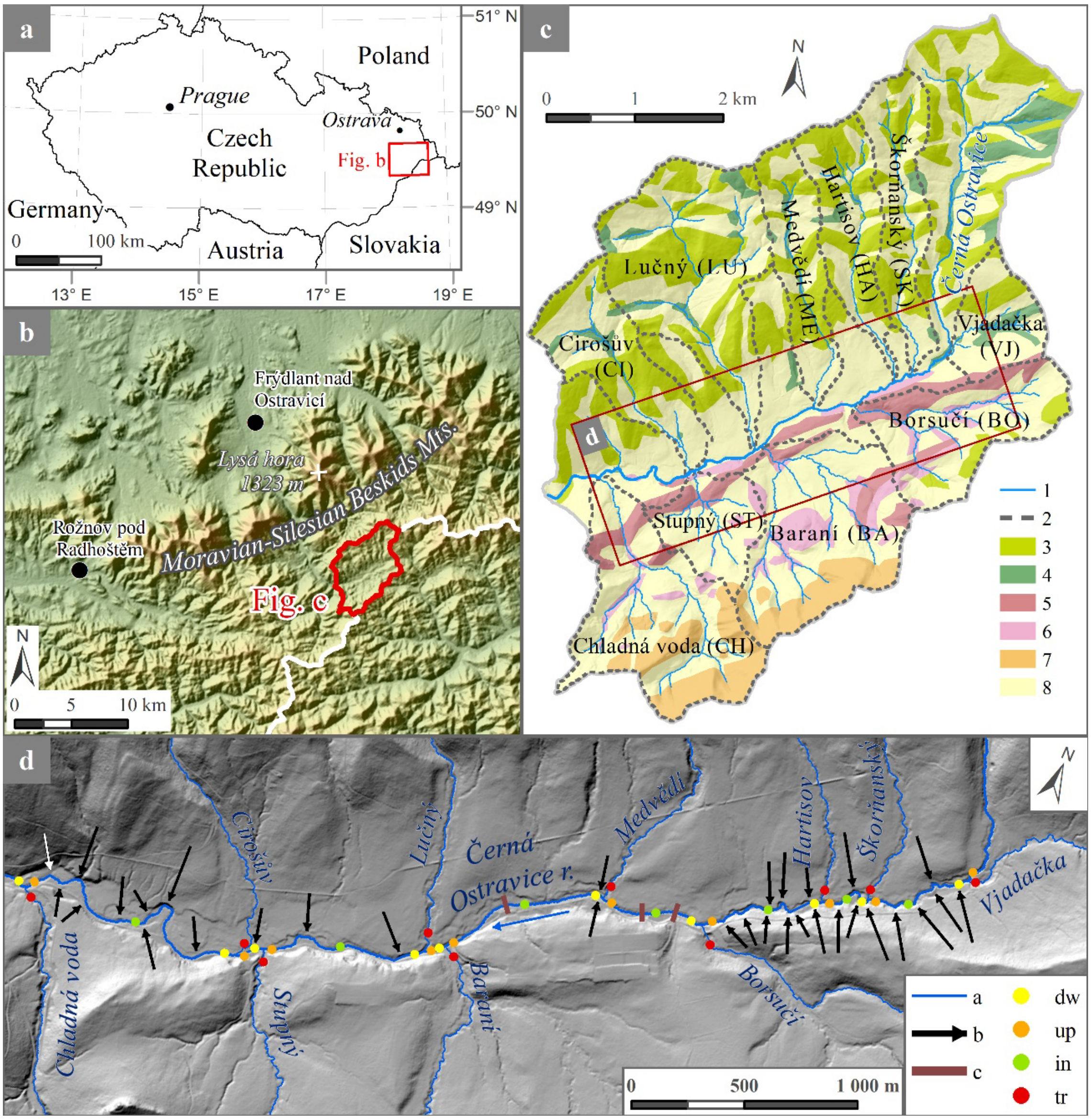

Fig. 1 (a, b) – Location of the study area; (c) – geological conditions: 1 – stream, 2 – tributary catchment, 3 – Istebna Formation, thick-bedded flysch, 4 – Istebna Formation, thin-bedded flysch, 5 – Submenilitic Formation, thick-bedded flysch, 6 – Submenilitic Formation, thin-bedded flysch, 7 – Soláň Formation, thick-bedded flysch, 8 – Quaternary deposits; (d) – geomorphological context of the study reach: a – stream, b – sediment input (bank failure), c – check dam; sample sites downstream (dw), upstream (up), intermediate (in) and in a tributary (tr).

Table 1 Characteristics of evaluated tributaries and the Černá Ostravice stream.

Tributary	Tributary code	*L* (km)	*A* (km^2)	*St* (m/m)	*SC* (m/m)	*Dd* (km/km^2)	*H* (m asl.)	*Cf* (%)
Chladná v.	CH	4.0	3.3	0.059	0.306	3.18	689	96
Cirošův	CI	3.2	1.8	0.075	0.249	3.41	688	79
Stupný	ST	1.6	1.1	0.059	0.162	3.35	608	93
Lučný	LU	4.3	3.6	0.053	0.240	3.31	720	86
Baraní	BA	2.7	3.2	0.076	0.236	3.99	673	93
Medvědí	ME	3.4	1.4	0.067	0.216	3.28	713	85
Borsučí	BO	2.9	2.2	0.048	0.191	3.52	670	86
Hartisov	HA	3.5	1.6	0.068	0.235	3.72	742	82
Škorňanský	SK	4.0	1.7	0.054	0.246	3.16	734	93
Vjadačka	VJ	1.4	1.1	0.045	0.196	2.85	680	86
Č. Ostravice		10.8	28.9	0.033	0.222	3.31	691	89

Notes: *L* – stream length, *A* – catchment area, *St* – average channel gradient, *SC* – average catchment slope, Dd – drainage density, *H* – average catchment height above sea level, *Cf* – a cover of the forest.

may reach up to 2000 - 3000 L/s/km^2 (Bíba et al. 2006). Forest covers approximately 90% of the area in the catchments of individual tributaries, especially because it is a mountain region with a minimal population. However, many slopes were deforested during the so-called Wallachian colonization in the 16th and 17th centuries, and this trend continued until the 19th century, when significant reforestation began. In the past, deforestation led to accelerated sediment delivery to the mountain rivers of the Moravian-Silesian Beskids Mts. (Galia and Hradecký 2014).

The study catchment was selected due to the presence of different geomorphological resistances of rocks, which have the potential to significantly influence the texture of fluvial sediments, and consequently, the sediments supplied by individual tributaries can impact the parameters of the mainstream bed sediments (Golden and Springer 2006). From a geological point of view, the Černá Ostravice catchment is part of the flysch zone of the Outer Western Carpathians and has a typical allochthonous nappe structure, which was transported to the present position during the Miocene period of Alpine orogeny movements (Menčík et al. 1983). Generally, local Cretaceous-Oligocene flysch consists of alternating sequences of more-resistant sandstone layers with varying proportions of less-resistant claystone (Galia et al. 2015). Most of the stream catchment is formed by the Istebna and Submenilitic Formations, which are components of the Silesian unit of the Outer Carpathian Group of Nappes. The southern part of the catchment is formed by the Soláň Formation of the Magura Group of Nappes (Menčík et al. 1983). The studied reach of the stream, practically throughout its total length, follows the front of the Magura Nappe (Fig. 1c).

The right-side tributaries evaluated in this work drain the area formed by the Istebna Formation, which consists of thick-bedded flysch (sandstone and conglomerates) and similarly thick sequences of claystones. In the wide valley bottom of the Černá Ostravice stream, less geomorphic-resistant claystones predominate (Menčík et al. 1983), followed by the Submenilitic Formation, which forms most of the area drained by the left-side tributaries (Fig. 1c). The dominating lithology of the Submenilitic Formation is low-resistant, friable claystone into which, in the base of the formation sequence, are deposited several metres-thick lenticular zones of massive sandstones and conglomerates called the Ciężkowice Member. The mountain ridge in the southernmost part of the study catchment represents the eroded front of the Magura Nappe, and it is formed by the Soláň Formation, which consists of sandstone and claystone layers of variable thickness (Menčík et al. 1983).

A considerable part of the Černá Ostravice catchment is covered by unconsolidated deluvial sediments. In a relatively wide valley bottom, fluvial sediments dominate river terraces as well as floodplain deposits with different proportions of clay, sand, and gravel fractions (Wistuba et al. 2018). Flysch structures strictly predispose sediment delivery into local channel segments. The grain-size character of the sediment supply in the study area is very rarely represented by sandstone boulders; cobbles and finer-grained fractions prevail. The lack of boulder obstructions directly affects the total flow resistance and leads to a higher potential transport capacity of the streams (Galia et al. 2015). Flysch lithology, characterized by an alternation of layers with different water permeabilities, is prone to both shallow and deep slope deformations (Hradecký and Pánek 2008), which are generally an important source of sediments for the fluvial systems of mountain streams (Benda et al. 2005). Six active landslides are found in the surveyed catchment (CGS 2019), but the direct input of material from landslides into the channel of the Černá Ostravice was not observed. Frequent bank failures are the most important sediment inputs. Many of bank failures occur in unconsolidated alluvial sediments, especially in the lower part of the surveyed stream, where the river flows through a relatively wide mountain floodplain. In this way, a considerable amount of material with various granular compositions can enter the channel. The upper part of the stream profile is relatively deeply incised into the soft claystone bedrock. Therefore, most of the bank failures are characterized by the input of fine-grained claystone sediments (Fig. 2c). Three check dams are located in the middle part of the investigated stream, which can also have an effect on the resulting grain size of the bed material because they often represent disconnectivity in sediment transport (Bombino et al. 2009) (Fig. 1d).

3 Methods

3.1 Grain-size parameters

The downstream development of sediment sizes was analysed to assess the tributary impact on the mainstream bed sediment texture, and it was evaluated mainly at the scale of individual confluences by a possible change in particle size between upstream and downstream of confluences. Pebble count was used as the primary tool to obtain information about the grain size distribution of the bed sediments based on the measure of 100 clasts extracted from the active layer (Wolman 1954). The length of the b-axis of individual clasts was then measured using a ruler; the *D16*, *D50*, and *D84* percentiles of the grain size distribution were assessed. The random heel-to-toe sampling was performed along transects perpendicular to the streamline. This method is popular for its simplicity and efficiency but is prone to sampling errors which can either be introduced by the operator or can be associated with a statistical error. Operators introduce errors into pebble counts, for example, by favouring mid-sized and handy particles and avoiding very small or large

Fig. 2 (a) – Confluence bar associated with the Lučný stream (LU), (b) – damaged check dam immediately downstream of the confluence with the Medvědí stream (ME), (c) – one of several bank failures in the upper part of the study stream reach based in claystone lithology, (d) – confluence with the Hartisov stream (HA).

clasts. However, all measurements in the present study were made by the same person; thus, it can be assumed that eventual errors introduced to pebble counts by the operator has at least the similar rate through the sampling sites (Bunte and Abt 2001). Wohl (2010) stated that pebble count by random walk produces almost identical values of *D50* and *D84* when performed by a single operator. Unlike operator errors, the statistical errors can be improved by increasing sample size. The surface sample size of 100 clasts used in this study is generally the most commonly used. It represents a reasonable compromise between the achievement of desirable precision and practical reasons such as time-consuming (Bunte and Abt 2001).

This method also does not consider the fine particle-size fraction, since it is a manual sampling and, especially in flowing water, the handling of fine sediment is very problematic. Therefore, the minimum size of measured clasts was set at 8 mm (Bunte and Abt 2001). Although, the largest volume of bedload in gravel-bed rivers is generally considered to be in fine fraction (<8 mm), the coarse fraction (gravel and boulder) determines and comprises the major features of the channel morphology (Leopold 1992) and therefore, the grain sizes below 8 mm may be omitted in our case. In addition, the lithology of each measured clast was determined (sandstone or claystone). Within the mainstream, the transects, where the grain size was measured, were always located upstream and downstream of the confluence at a distance of three times the channel width measured near the confluence point. This distance was determined on the basis of the morphologically most-affected locality (confluence with the Lučný stream (LU)) and corresponded to a place where no morphological effect of the tributary (i.e., the presence of confluence bar) was observed (Fig. 2a). In the mainstream, the grain size was also collected in transects located half the distance between individual tributary inlets but only in cases that the distance between subsequent confluences exceeded 200 m. Similarly, as in the mainstream, sediments were also collected from tributaries to obtain information about their bed sediment grain size distribution immediately upstream of a confluence (namely, at three-channel widths measured near the confluence point) (Fig. 1d).

Since we did not perform a detailed sampling of mainstream reaches between the individual confluences, we decided to choose the proportion of sediment calibre between the sites upstream and downstream of the confluence as the main indicator of the tributary effect on the mainstream bed sediment texture. The study thus primarily focuses on the influence of tributaries on the mainstream bed sediment calibre in the immediate vicinity of individual confluences and does not investigate other possible downstream variations in grain-sizes produced by other sedimentary inputs. The resulting grain size distributions of locations upstream and downstream had non-normal distribution (Fig. 3), and therefore, the samples were tested by the non-parametric Mann-Whitney U test at a significance level $\alpha = 0.05$. In the case of a significant result of the test, the tributary was evaluated as a significant source of sediments.

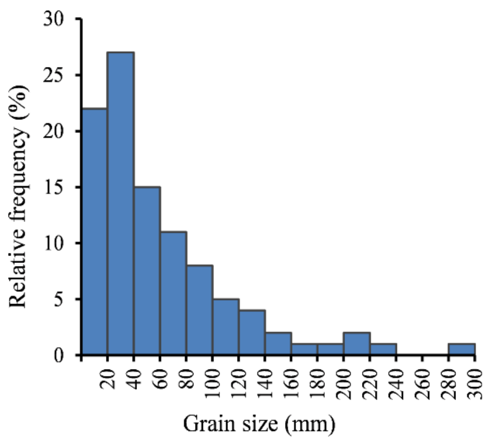

Fig. 3 Relative frequency histogram of the grain size distribution of a typical sample (sampling point between VJ and SK).

A detailed fluvial-geomorphologic mapping was carried out to evaluate the effect of the tributaries on the bed morphology within the confluence. This mapping was focused primarily on the identification of sediment accumulations in the form of confluence bars, which can indicate that a tributary is associated with a substantial supply of sediment. The fluvial-geomorphologic mapping also focused on the identification of potential lateral sources of material to evaluate their influence on downstream grain-size trends.

3.2 Reach-scale parameters

Many factors influence the bed material grain size at a given site, and they can completely overlap the response caused by the tributaries. To evaluate their importance concerning the bed sediment texture, the parameters of the channel geometry (bankfull width, local channel gradient) were determined at each sediment sampling site in the mainstream and tributaries. The statistical significance of the relationship between the grain size and selected parameters was evaluated by linear regression analysis, including the coefficient of determination and *p* significance. The local channel gradient was derived from the detailed digital terrain model based on laser scanning (DMR 5G with a 2-m resolution) and provided by the State Administration of Land and Cadastre, which represents the mean gradient of 100 m reach centred on each sampling site. The second evaluated parameter of the channel geometry was the bankfull width, which was conducted using a tape (0.1 m accuracy). The criteria of the demarcation of riparian vegetation as well as inflexion points in the cross-section profile were helpful to determine the bankfull width (Wohl and Wilcox 2005).

3.3 Catchment analysis

Together with the basic field-measured parameters (channel gradient of the downstream part of tributary – *St*, bankfull width – *Wt*, and median of grain size distribution – *D50t*), the other four derived parameters were proposed to evaluate the factors influencing the ability of the tributary to alter the grain size texture of the bed substrate in the mainstream channel. These parameters assume that the impact of the tributary primarily scales with water discharge, the bedload flux, and the calibre of added material (Ferguson et al. 2006). However, the exact quantification of sediment and water fluxes is considerably difficult, especially in small catchments without gauging records. Therefore, the use of surrogate parameters that subsume the complexity of these factors is required (Rice 1998). The first parameter is the catchment area (A), which primarily determines the amount of water and, to some extent, the potential volume of sediments supplied by a tributary. The second parameter is the approximated form of the stream power (Ω), which indicates the ability of the stream to transport sediment into the main channel: $\Omega = \gamma QS$, where γ is the specific weight of water [9810 N/m3], Q is the discharge [m3/s], and S is the local bed gradient [m/m]. This formula can be simplified because Q is, to some extent, a function of the stream catchment area. Gauging records for five headwater streams located in the Moravian-Silesian Beskids Mts. were used to obtain the relationship between the catchment area and two-year discharge, which is assumed close to bankfull and is considered to be responsible for shaping the channel geometry and river bed morphology (Galia and Škarpich 2016): $Q_2 = Q_{bf} = 0.55A^{0.88}$ ($R^2 = 0.87$). This discharge is also capable to move grain-sizes up to 100 mm (i.e., >*D50* in the studied basin) in the headwater flysch-based streams (Galia and Hradecký 2012). The resulting surrogate for sediment delivery is then as follows: $\Omega = 0.55A^{0.88}S_t$, where S_t is the gradient of the downstream part of the tributary, which represents 10% of the total stream length measured from the confluence point; this parameter was obtained from the DMR 5G. The reason for using S_t is that tributaries, which are characterized by low-gradient downstream parts, have a limited ability to transport material up to the mainstream channel and significantly affect its bed sediment texture (Rice 1998). Unit stream power (ω) is the next evaluated parameter reflecting the transport capacity of the flow. ω is similar to Ω but also considers the bankfull channel width (W_{bf}): $\omega = (0.55A^{0.88}S_t)/W_{bf}$. Knighton (1980) suggests the importance of the calibre of sediment supplied by tributaries in the resulting confluence effect. Therefore, the fourth parameter includes the median of the bed sediment grain size distribution (D50) in the final form: *ωD50* which is referred to as the product of unit stream power and riverbed sediment texture.

It is expected that tributaries with small sediment and water yields have a negligible effect on texture because their inputs are easily accommodated by the mainstream. However, as this relative input increases, a significant response becomes more likely (Rice 1998), which implies the importance of relative tributary parameters with regard to the mainstream in addition to the absolute values of the tributary parameters. These relative parameters were calculated as the ratio of the tributary value (denoted by the index *t*) to that for the mainstream catchment upstream of the confluence (denoted by the index *m*) in the following forms: *At/Am, Ωt/Ωm, ωt/ωm,* and *ωD50t/ωD50m* for derived parameters. Similarly, the basic field parameters were expressed as: *St/Sm, Wt/Wm* and *D50t/D50m*. The channel gradient of 200 m long reach (centred on the confluence) was used for the mainstream reaches to express the

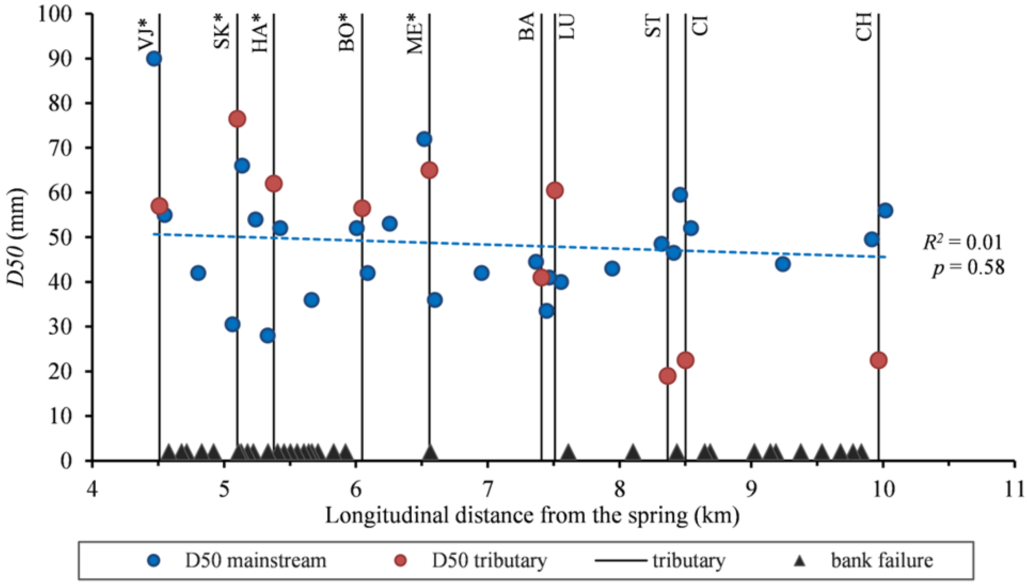

Fig. 4 Downstream evolution of *D*50 in the mainstream together with *D*50 in the tributaries. The locations of individual tributaries and bank failures are included. The tributaries associated with a significant change of sediment texture between upstream and downstream of confluence are marked with an asterisk.

transport capacity of the mainstream in the confluence zone.

4 Results

4.1 Influence of tributaries on the mainstream bed sediment grain size

We observed no clear downstream trend in the evaluated grain-size percentiles within the whole examined part of the Černá Ostravice stream. At this scale, the tributaries appear to be a source of the relatively high variability in grain size percentiles in the vicinity of confluences, mainly in the upper part of the studied reach. No detectable trend ($R^2 = 0.01$ for *D*50) of particle size with downstream distance was found (Fig. 4). We observed a significant difference between upstream and downstream of confluences in the case of five tributaries (Table 2). In three cases, there was a relative decrease in sediment size, which occurred in the confluences with the Vjadačka (VJ), Borsučí (BO) and Medvědí (ME), while relative coarsening was characteristic of the confluences with the Hartisov (HA) and Škorňanský (SK). The remaining 5 tributaries located in the lower part of the studied stream were associated with a non-significant change in the confluence zones (all tributaries are listed in Table 1).

All five tributaries associated with significant grain size differences were located in the upper half of the studied stream reach, and it is apparent that the

Table 2 Grain size percentiles with statistical significance (*p*) of the difference between localities downstream (DW) and upstream (UP) of confluence based on non-parametric tests.

Tributary code	Site	Particle size (mm)			*p* (α = 0.05)
		*D*16	*D*50	*D*84	
CH	DW	22	56	136	0.44
	UP	23	50	117	
CI	DW	20	52	86	0.19
	UP	24	60	97	
ST	DW	20	47	100	0.46
	UP	21	49	110	
LU	DW	20	40	67	0.44
	UP	19	41	93	
BA	DW	17	34	87	0.17
	UP	19	45	90	
ME*	DW	16	36	87	< 0.01
	UP	27	72	138	
BO	DW	22	42	76	0.03
	UP	25	52	87	
HA	DW	27	52	108	< 0.01
	UP	15	28	55	
SK	DW	31	66	116	< 0.01
	UP	14	31	80	
VJ	DW	32	55	137	< 0.01
	UP	50	90	149	

Note: *Significant change within the confluence with Medvědí stream (ME) was attributed to the influence of bank failures and therefore was not considered a significant tributary.

size of this difference gradually decreased with downstream distance (Fig. 4). However, an exception was the confluence with the ME, which was characterized by the presence of a strong fining. Based on the fluvial-geomorphological mapping, this confluence can be described as unique because the sampling site below the junction was located in the former retention area of a destroyed check dam. After the destruction, the Černá Ostravice stream incised into accumulated material, which initiated the formation of bank failures, supplying the channel with mostly fine-grained sediment (Fig. 2b). Thus, we expect that the significant fining within the confluence was not the result of the tributary effect but was conditioned by the supply of the relatively fine material trapped by the check dam. For this reason, the ME was no longer considered a significant tributary.

To evaluate the other sources of variability influencing the bed sediment composition, the grain size percentiles were related to the channel geometry and sediment lithology. A relationship between channel slope and grain size percentiles was not detected (Fig. 5a). Moreover, no dependence existed between sediment size and channel width (Fig. 5b). The next evaluated factor with an expected impact on grain size was the sediment lithology. Generally, a decrease in sediment size can be expected with an increasing proportion of claystone clasts in the sample due to the lower geomorphological resistance of the claystone. This relationship was confirmed for all the evaluated percentiles, with the highest dependence for *D50* (Fig. 5c).

4.2 Controls on tributary-associated discontinuities

The objective of this analysis was to investigate the relationships between the tributary catchment characteristics and their impacts on the mainstream, and it was focused on distinguishing the significant and non-significant tributaries. In other words, the main aim was to find any parameter or combination of parameters that would predict the impact of the tributary on the mainstream bed sediment texture. Based on changes in the grain size distribution, the HA (Fig. 2d) and the SK can be considered tributaries causing significant coarsening, while significant fining occurred within the confluence with the BO and the VJ. The LU, which caused the most significant

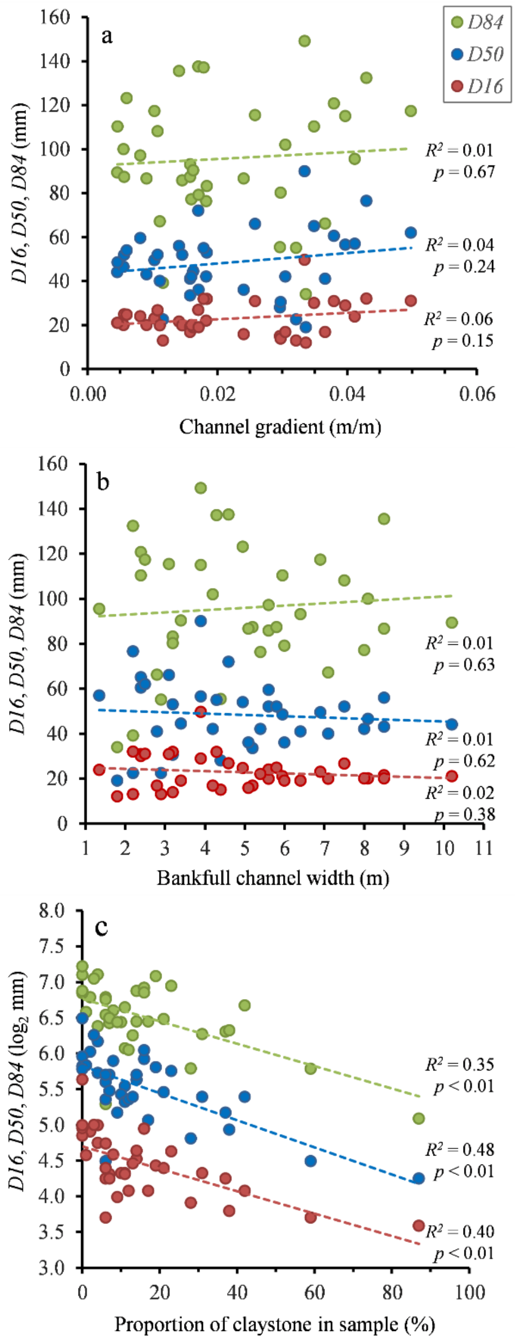

Fig. 5 Relationship between sediment grain size percentiles and local channel slope (a), bankfull width (b), and proportion of claystone clasts in the sample (c). The grain sizes in Fig. c were $\log_2$-transformed to the ψ-scale.

morphological changes in the mainstream riverbed in the form of a notable confluence bar associated with a significant influx of sediments (Fig. 2a) was a unique tributary. However, there was no significant difference in sediment calibre between upstream and downstream sampling sites. Of the ten tributaries considered in the analysis, four were associated with a significant change in the mainstream grain size (Table 2), and the LU was assigned to a separate category as the tributary with the most morphological mainstream impact.

We firstly tested pairwise relationships between the basic field-measured parameters, namely the absolute values of channel gradient (*St*), bankfull width (*Wt*), the median of the grain size distribution (*D50t*) and the derived parameter of catchment area (*At*) for individual tributaries (Fig. 6) together with their relative counterparts (*At/Am*, *St/Sm*, *Wt/Wm* and *D50t/D50m*) (Fig. 7). Based on the bivariate analysis of absolute parameters, it was not possible to

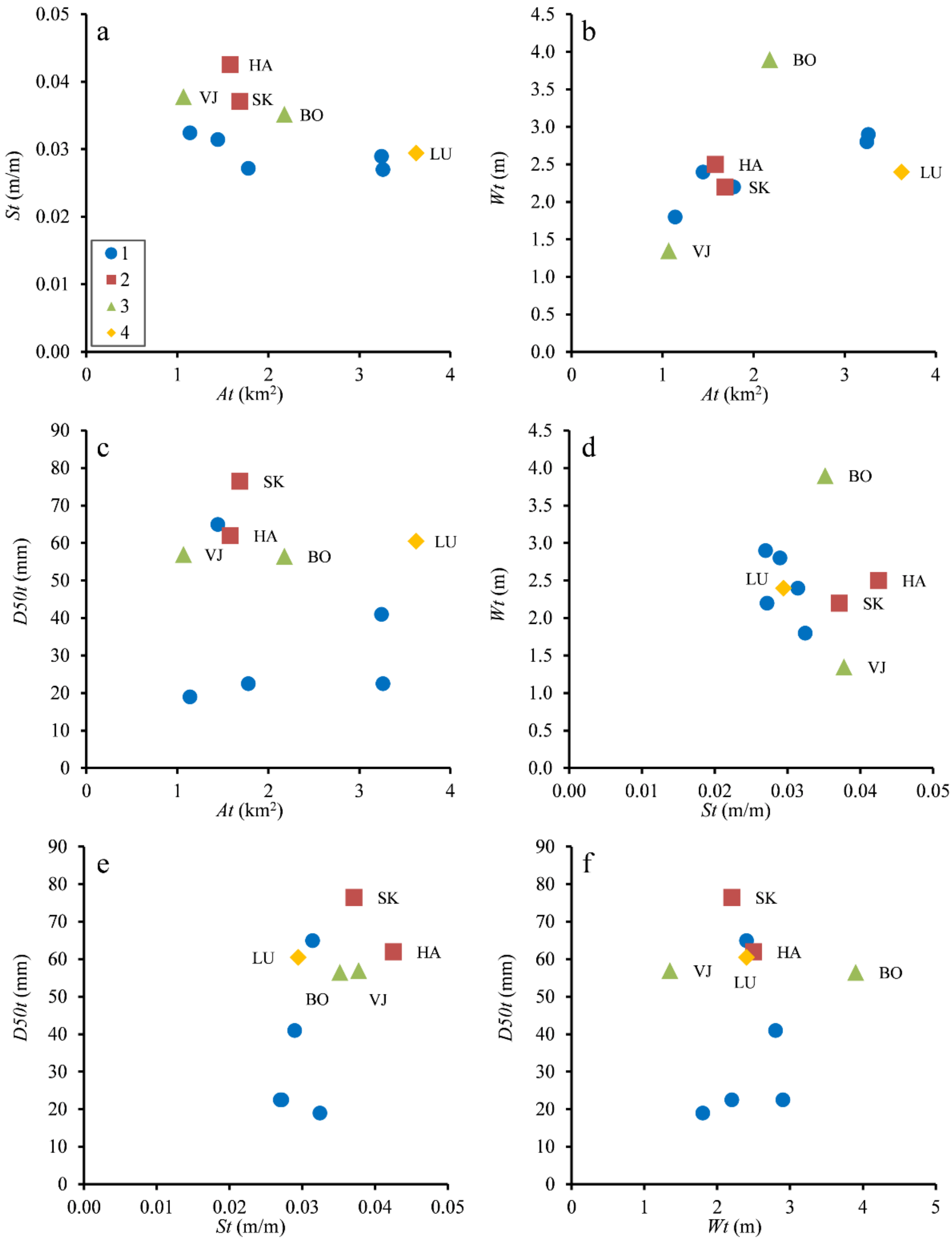

Fig. 6 Bivariate plots for absolute values of basic field-measured parameters (channel gradient (*St*), bankfull width (*Wt*), the median of the grain size distribution (*D50t*) and the derived parameter of catchment area (*At*)) for individual tributaries: non-significant tributaries (1), significant tributaries causing relative coarsening (2), relative fining (3), and tributary associated with the most significant morphological changes (4).

clearly distinguish significant tributaries from those without significant impact on the mainstream. However, some indication of the cluster was formed in the case of the *St-D50t* plot, where especially, the tributaries associated with significant coarsening were characterised by a higher channel gradient and at the same time, by larger grain sizes. When relative parameters were considered, the significant tributaries were well distinguished when the *At/Am* was plotted against the *D50t/D50m* (Fig. 7c). Based on the other combinations of the relative parameters, it was not possible to unequivocally separate significant tributaries into a clearly defined cluster.

When considering the derived parameters, the LU was associated with the highest observed values of all of them (*A, Ω, ω, ωD*50), probably due to its

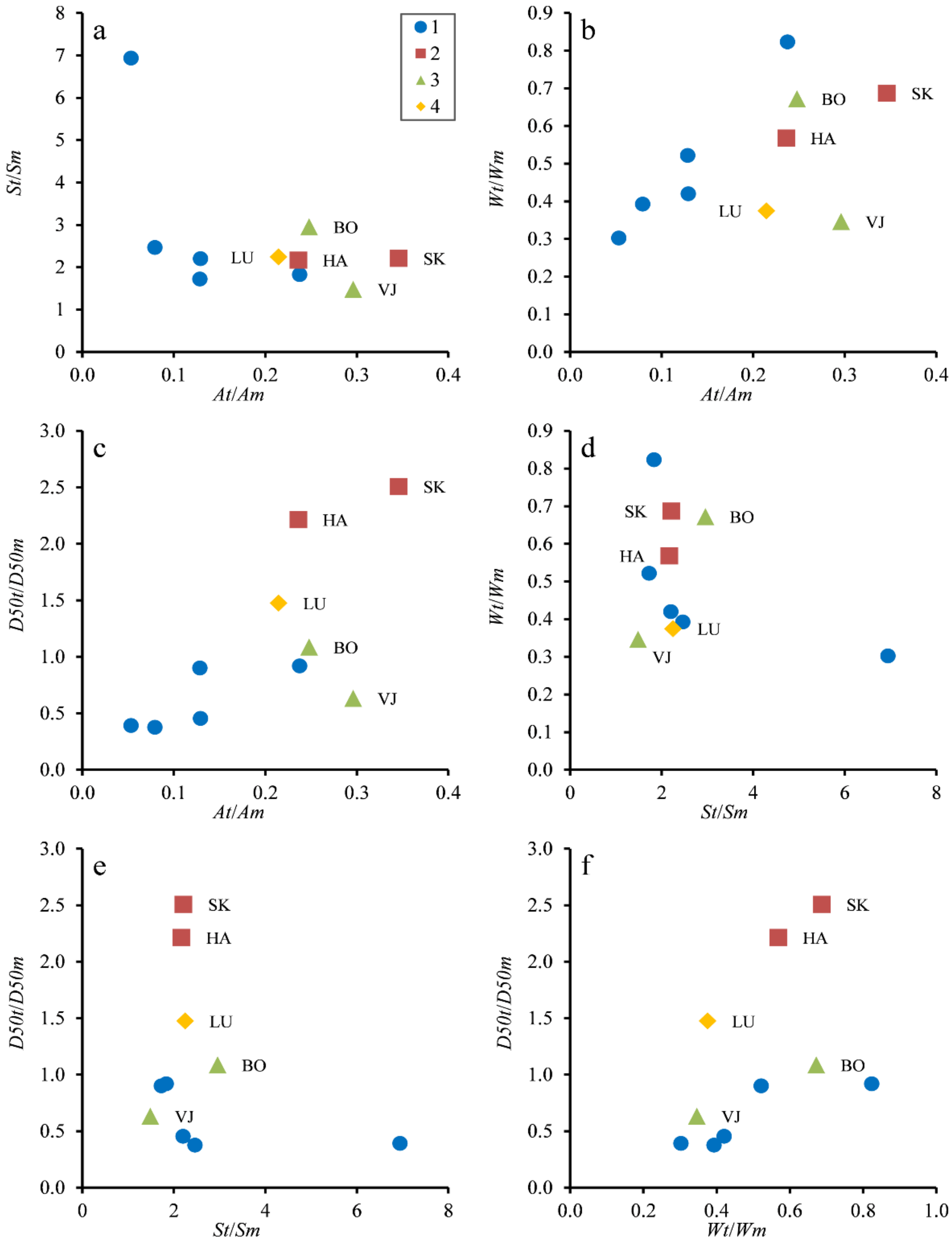

Fig. 7 Bivariate plots for relative values of basic field-measured parameters computed as the ratio between tributary (*t*) to mainstream (*m*) value: non-significant tributaries (1), significant tributaries causing relative coarsening (2), relative fining (3), and tributary associated with the most significant morphological changes (4).

catchment area, which was the largest of all the tributaries. In addition to the LU, the product of unit stream power and grain size ($\omega D50$) also showed high values in the HA, SK, and VJ, probably in connection with the occurrence of relatively coarse-grained bed material in these tributaries. In summary, on the basis of the absolute values of the abovementioned parameters, it was impossible to distinguish significant and non-significant tributaries. A different situation occurred if these parameters were related to the mainstream. It was clear that the ratio of the tributary-to-mainstream catchment area (At/Am) generally increased with the distance from the mouth, reaching the highest value at the SK (0.35). Relatively high values (ranging from 0.24 to 0.30) were also found in all the significant tributaries and in the LU (0.21). The non-significant tributaries did not exceed the value of 0.13, with the exception of the BA (0.24). In the case of the relative stream power ($\Omega t/\Omega m$), the highest values were again calculated for the significant tributaries (0.51–0.87), and the situation was similar for the relative unit stream power ($\omega t/\omega m$). However, the significant tributaries were best distinguished on the basis of the relative product of the unit stream power and sediment texture ($\omega D50t/\omega D50m$). Together with the LU, they were associated with substantially higher values compared to tributaries without marked impact on the mainstream.

The plotting of individual relative parameters ($\Omega t/\Omega m$, $\omega t/\omega m$, $\omega D50t/\omega D50m$) against the relative catchment area (At/Am) showed a clear differentiation of significant tributaries. In the case of the relationship At/Am and relative stream power ($\Omega t/\Omega m$) (Fig. 8a), it can be noted that the significant tributaries were characterized by relatively high values of both parameters, and together with the LU and BA, they developed an isolated cluster in the upper right corner of the plot. Even better, a group of significant tributaries can be distinguished on the basis of the relationship between the relative catchment area (At/Am) and the relative unit stream power ($\omega t/\omega m$) (Fig. 8b). The additional information about channel width (included in ω) thus apparently helped to better classify the significant tributaries. Based on the last evaluated relationship (At/Am and $\omega D50t/\omega D50m$), the significant tributaries could be successfully classified as well (Fig. 8c). The highest values of both parameters were characteristic of the two tributaries that caused significant coarsening together with the LU. The tributaries that produced a significant decrease in sediment size were accompanied by slightly lower values of both parameters, while the tributaries with a negligible

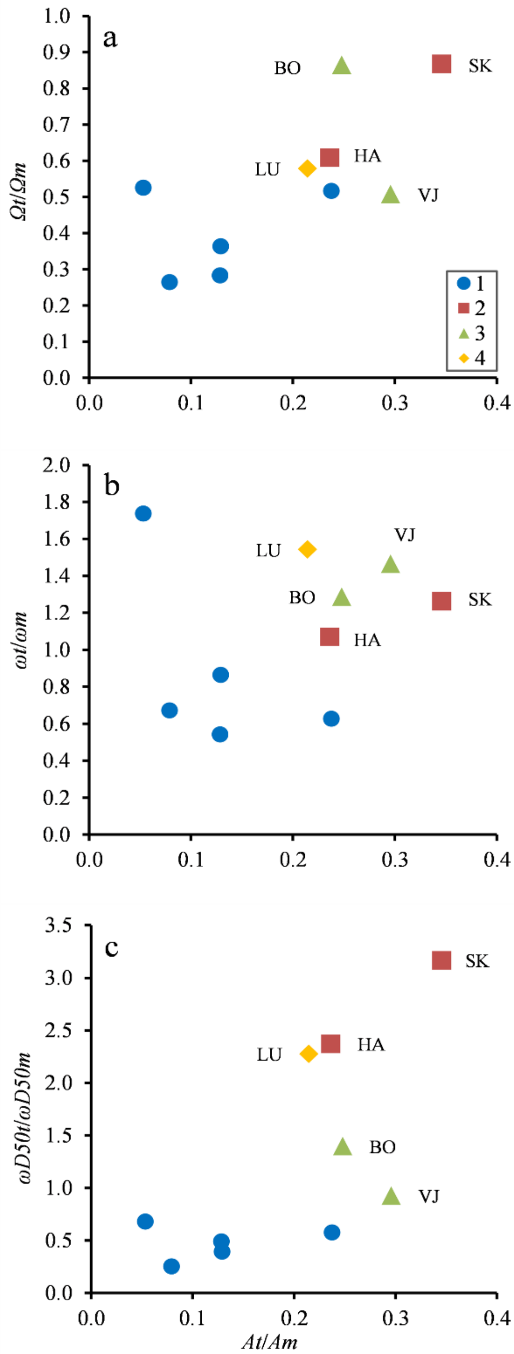

Fig. 8 Bivariate plot for relative catchment area (At/Am) and relative stream power (a), unit stream power (b) and product of unit stream power and bed sediment texture (c): non-significant tributaries (1), significant tributaries causing relative coarsening (2), relative fining (3) and tributary associated with the most significant morphological changes (4).

mainstream impact occupied the lowest part of the bivariate plot.

5 Discussion

5.1 Tributary impact on the downstream sediment calibre

The sediment texture was quite variable along the study reach, especially in the upper part, where the stream intensively interacted with adjacent hillslopes mainly through numerous bank failures. However, a considerable part of this variability appeared to be associated with the effect of tributaries, at least in the vicinity of the individual confluences (Fig. 4). Conversely, the lower variability in the lower part of the stream might be related to the gradual development of a relatively wide floodplain which buffers a material coming from hillslopes by creating at least temporary storage zones (Fryirs et al. 2007).

In the case of the five uppermost confluences, there were significant differences in sediment size immediately upstream and downstream of the junctions (Table 2). However, the significant fining within the confluence with the ME was attributed to the impact of the riverbank failures located in the former check dam-induced accumulations. Therefore, only four tributaries were considered to be significant sediment sources – two of them were associated with fining and the other two with significant sediment coarsening within the confluence area. These tributaries represented 40% of the total number of evaluated tributaries, which was in contrast to the findings of other studies that have revealed that only a small portion of tributaries produce a significant response in mainstream grain size (e.g., Rice 1998; Surian 2002; Lambert 1997). The higher proportion of significant tributaries in our case may be related to the much smaller size of our study catchment and to the flysch lithology, which directly affects stream transport capacity due to its lower rock resistance and lack of boulders in the channels. Flysch is specific in this sense because the bed material is relatively fine-grained and can be transported more often compared to transport-limited conditions, where the material is relatively immobile (Galia et al. 2015). Therefore, it can be assumed that a higher proportion of significant tributaries is characteristic not only of flysch catchments but also for rivers with similar transport-capacity conditions regardless of the underlying bedrock. However, this assumption requires further research.

Previous studies revealed that significant tributaries generally lead to a step increase in sediment size due to the influx of coarse material, which is more likely than the input of fine-grained sediment to persist (Rice and Church 1998; Knighton 1980; Ichim a Radoane 1990; Swanson and Meyer 2014). This increase corresponds to the occurrence of the relative coarsening detected in the case of the SK and HA. However, the decrease in sediment size observed within the confluences with the VJ and BO is much less frequent in the context of previous studies (Heitmuller and Hudson 2009). According to Rice and Church (1998), significant fining of bed particles may occur if the volume of the fine-grained material input is sufficiently large. In our case, it is probably not only the effect of volume; the flysch lithology conditions also played an important role mostly due to the presence of fine-grained claystones. The significant decrease in the mainstream grain size associated with the VJ and BO may be related to the fact that a substantial part of their catchment areas are underlain by formations with a dominant claystone lithology characterized by the delivery of relatively fine grain-size fractions into the channel. In contrast, the tributaries responsible for significant coarsening drain the area built by the Istebna Formation, which is characterized by a predominance of relatively resistant sandstone layers (Fig. 1c) (Menčík et al. 1983).

As mentioned before, it was difficult to clearly separate the influence of significant tributaries from the other factors that contribute to the resulting downstream variability in mainstream bed sediment sizes. More detailed knowledge of the conditions in the confluence area is required, e.g., the lithology and channel characteristics or the location of other sediment sources and barriers to its transport. The regressions between grain size percentiles and the channel geometry parameters showed that the local channel slope and bankfull width explained only a minor proportion of the variability detected in the grain size distributions within the sampling sites. Thus, the significant changes in grain sizes observed in confluences with significant tributaries do not seem to be the result of the varying channel geometry characteristics. A greater impact on grain sizes can be expected in relation to the sediment lithology, which was supported by the statistically significant negative correlation between the sediment calibre and the proportion of claystone clasts in a sample (Fig. 5c).

5.2 Factors determining the tributary impact on mainstream sediments

The bivariate analysis of the basic field-measured parameters showed that significant tributaries (especially those associated with significant coarsening) are characterized by a certain combination of relatively larger catchments together with relatively coarser bed sediment compared to the mainstream. However, on the basis of the other combination of these parameters (whether absolute or relative), we were unable to clearly differentiate significant tributaries.

As the next step, we performed the analysis of derived parameters. The proposition of these parameters is partially based on previous research by Rice (1998), from which the parameters of the relative catchment area (*At/Am*) and the relative stream power (*Ωt/Ωm*) between the tributary (t) and mainstream (m) were used. However, we added the relative parameters of unit stream power (*ωt/ωm*) and the product of unit stream power and grain size (*ωD50t/ωD50m*).

On the basis of the absolute values of these parameters for individual tributaries (i.e., *At, Ωt*, *ωt*, and *ωD50t*), it was not possible to clearly separate the group of significant tributaries from those without remarkable influence. However, this finding contrasts with the findings of Rice (1998), who was able to differentiate significant tributaries using both the absolute and relative values of parameters with relatively high success. His observations may be conditioned by the substantially larger catchment areas and relatively uniform lithology compared to those of the Černá Ostravice catchment. The LU, which was accompanied by the most morphological impact in the form of the large confluence bar, had the highest values of all the absolute parameters, but a significant grain size alteration was not observed. This case pointed to the complex nature of tributary-mainstream interaction since a substantial influx of material does not necessarily produce grain-size discontinuity below the junction.

The four suggested relative parameters have the potential to indicate the ability of the tributary to influence the bed sediment texture (or morphology) of the mainstream river (Fig. 9). In the case of relative parameters, the significant tributaries, compared to the non-significant ones, were associated with noticeably higher values for all parameters. In particular, the relative catchment area (*At/Am*), which Benda et al. (2004) consider to be the main factor determining the mainstream response, was higher for the significant tributaries together with the LU, which supports the general trend assuming an increasing probability of alteration of the receiving channel with the increasing relative catchment area of the tributary. Compared to the non-significant tributaries, the significant tributaries were also characterized by a higher relative stream power (*Ωt/Ωm*), unit stream power (*ωt/ωm*), and product of unit stream power and bed sediment grain size (*ωD50t/ωD50m*). The bed sediment grain size had the highest values for the tributaries, indicating significant coarsening. This finding clearly supported the general assumption, which expects that the likelihood of tributary impact increases with an increasing ratio between the tributary and mainstream bed load calibre (Rice et al. 2006).

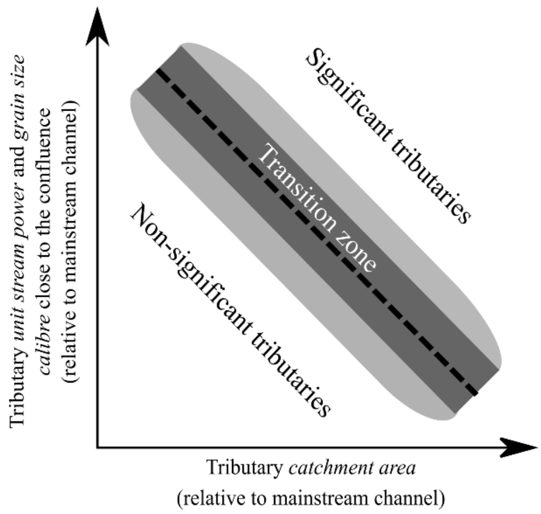

Fig. 9 Conceptual model showing the influence of the relative parameters of a catchment area, unit stream power, and grain size calibre of the tributaries on mainstream sediment texture.

The bivariate analysis compared (*At/Am*) with other relative parameters, (*Ωt/Ωm*), (*ωt/ωm*), and (*ωD50t/ωD50m*), allowing the relatively good differentiation of significant tributaries, especially in the case of *ωD50t/ωD50m*. This parameter includes surrogates for water and sediment production (relative catchment area), tributary bedload flux and calibre (relative tributary unit stream power and sediment size close to the confluence), which are generally key controls affecting whether the bed sediment texture in the receiving channel will be altered (Knighton 1980; Rice 1998; Rice et al. 2006).

Many tributary impact controls, based on the findings of previous research, likely also operate in the case of the Černá Ostravice stream. However, it is necessary to note the relatively small sample of observations with only ten tributaries, which substantially limits the possibility of inferring general conclusions. The low number of samples also limited the possibility of using statistical tests to distinguish between significant and non-significant tributaries. Therefore, the differentiation of these two groups was evaluated visually on bivariate plots. The methodology of this work was set up to emphasize the eventual tributary response in mainstream bed sediments. However, it is still challenging to distinguish this response from other sources of variability, which again contributes to the uncertainty of the results.

6 Conclusion

The downstream bed sediment grain sizes of the Černá Ostravice stream were analysed to determine the impact of the tributaries on the mainstream sediment calibre. There was a relatively high variation in sediment size without any overall trend of fining or coarsening of bed particles in the scale of the whole study reach. The tributaries strongly affected the bed material composition in the vicinity of 40% of all the evaluated confluences, confirming the general assumption that not all tributaries have a significant impact on the mainstream sediment texture, but this proportion is relatively higher than that in previous studies. It was possible to distinguish significant tributaries on the basis of the relative catchment area and relative product of unit stream power and bed material texture. To some extent, these parameters subsumed three key controls: relative catchment discharge, sediment yield, and calibre of sediment debris, which are generally expected to be controlling factors of the tributary impact. However, on the basis of absolute parameters, we were unable to differentiate significant tributaries, which indicates that in the case of flysch lithology, only the relative parameters seem to be important for distinguishing significant tributaries. The specific nature of the flysch conditions in our case (i.e., supply of relatively fine sediments implying long-term transport capacity of local streams to move all presented grain-sizes) may also give rise to a relatively higher proportion of significant tributaries and to the most frequent occurrence of fining below tributary confluences, in contrast to previous research on this topic. Although flysch-based conditions may mimic well nature of many mountainous environments characterised by sufficient transport capacity of both mainstreams and tributaries in their confluence zones, we recommend to further verify our derived relations in regions with different lithologies and hydrological regimes. Since confluences can be considered biological hot spots, the identification of significant tributaries can find an application in river management and could guide river restoration efforts.

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