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Slope–fluvial system structure in the Western Tatra Mountains (Poland): slope–to–channel transition

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A B S T R A C T

The slope–fluvial system comprises two subsystems: (a) the slope subsystem, with the dominance of mass movements, and (b) the fluvial (channel) subsystem, with fluvial processes dominating. The most interesting element of this system, and the most difficult to identify and explore, is the slope–to–channel transition zone between the dominance of slope processes and the dominance of fluvial processes. This article aims at exploring the detailed structure of the slope–fluvial system, with a particular focus on the transition zone between the slope and fluvial subsystems in the alpine and montane environments of the Western Tatra Mountains. This purpose is pursued through: (1) identifying the morphometry of headwaters, and (2) delimiting a theoretical border between the slope subsystem and the fluvial subsystem. To this end, a statistical analysis of morphometric parameters of 50 first- to third-order subcatchments was conducted. Particular attention was paid to analyzing the catchments' gradient–to–area relationship. On the basis of gradient–to–area relationship, seven catchment types were defined, characterized by various sequences of slope–fluvial system sections, as well as a border between the slope subsystem and the fluvial subsystem. Based on the morphometric parameters and the slope–fluvial system structure, the catchments under research may be divided into two groups, representing areas with different natural environmental conditions. Alpine zone comprises mostly catchment systems in their initial development stage, with little-developed drainage networks, classified entirely to the slope subsystem. These catchments have very high gradients, elongated shapes, and low bifurcation ratios. Montane zone is composed mainly of catchments at a similar development stage, with relatively large surface areas (~1 km²) and well-developed drainage networks, which include fluvial reaches. Such catchments are usually wide-shaped and have low gradients and high bifurcation ratios. The transition from slope process dominance to fluvial process dominance may be either smooth or abrupt.

INTRODUCTION

According to the Process Domain Concept by Montgomery (1999), two subsystems may be distinguished in the slope–fluvial system: (a) the slope subsystem, with the dominance of slope processes, and (b) the fluvial (channel) subsystem, with fluvial processes dominating. Slope–fluvial systems in mountain areas have been explored to various extents. The respective subsystems have been explored separately in vari-

ous scales in research undertaken in different regions worldwide. However, the element of the slope–fluvial system that is the most difficult to identify and explore is the slope–to–channel transition zone between the dominance of slope processes and the dominance of fluvial processes.

The channel head is the upper limit of fluvial processes' operation. According to Montgomery and Dietrich (1988), the channel head is the uppermost location on the slope where concentrated water flow and transport of

sediments may occur between clearly developed channel edges. The channel head does not constitute the border between the dominance of slope processes and that of fluvial processes because channel reaches with intermittent or ephemeral flow as well as channel reaches with permanent flow may occur downstream from the channel head (Dietrich and Dunne, 1993; Henkle et al., 2011; Williams, 2012; Płaczowska et al., 2015). Headwaters or transitional channels, also known as colluvial channels, despite showing signs of intermittent or weak permanent fluvial transport, are filled with mostly slope material (Hack and Goodlett, 1960; Montgomery and Buffington, 1997). According to Swanson et al. (1998), only 20% of the total bedload in first-order channels is subject to fluvial transport. The majority of mineral material in headwater valley reaches is transported through debris flows, provided that there are favorable conditions for the occurrence of this process on the steep mountain slopes. If the channel head is not always the starting point of the dominance of fluvial processes, the question is, Where should the border between the slope subsystem and the fluvial subsystem be located?

The morphometric parameters of catchments and stream channels reflect long-lasting operation of morphogenetic processes, their type, and intensity (Zuchiewicz, 1984, 1995). The parameters used for identifying the transition between the dominance of slope processes and that of fluvial processes are: the contributing area, the slope gradient and the channel gradient, the flow path length, and the unit stream power (Shreve, 1974; Montgomery and Dietrich, 1988, 1989, 1992, 1994; Tarboton et al., 1991; Montgomery and Fouloula-Georgiou, 1993; Church, 2002; Gomi et al., 2002; Stock and Dietrich, 2003; May and Gresswell, 2004; Williams, 2012). The values of these parameters are not universal, though, being dependent on climate conditions and geological structure; consequently, they assume different values in different regions (Shreve, 1974; Tarboton et al., 1991; Tarboton and Ames, 2001; Wrońska-Walach et al., 2013).

In headwater channel reaches, there is a problem of scale: data generalization on topographical maps means that not all first-order channels are depicted (Horton, 1945; Morisawa, 1957; Leopold et al., 1964; Mark, 1983; Montgomery and Fouloula-Georgiou, 1993; Heine et al., 2004). For this reason, high-resolution digital elevation models are increasingly used for locating the drainage network starting points (Montgomery and Dietrich, 1992; Ijjasz-Vasquez and Bras, 1995; Hancock and Evans, 2006; Imaizumi et al., 2010; Henkle et al., 2011; Julian et al., 2012). Importantly, while using digital methods, the impact of the precision and resolution of digital elevation data on the results must be taken into consideration (Tarboton et al., 1991; Orlandini et al., 2011).

Although there is a growing body of research in the subject (Montgomery and Dietrich, 1988, 1992; Gomi et al., 2002; Benda et al., 2005; Williams, 2012), much remains unknown, because the development of slopes and channel networks is determined by the local geological structure, climate, and land use (Shreve, 1974; Dietrich and Dunne, 1993; Benda et al., 2005; Marchi et al., 2008) and consequently is different in various mountain areas worldwide. Exploration of headwater systems is therefore necessary in a broad spatial scale (Benda et al., 2005). Exploration of the transition zone between the dominance of slope processes and that of fluvial processes is important as the stream channels in this zone (first-order channels) contribute crucially to the development of mountain relief (Davis, 1899; Horton, 1945; Schumm, 1956; Morisawa, 1957; Strahler, 1957; Benda et al., 2005). They are an important source of the supply of water and mineral and organic matter to the fluvial system; consequently, they determine the intensity of hydrogeomorphological processes in downstream river channel reaches (Dietrich and Dunne, 1978; Sidle et al., 2000; Tsuboyama et al., 2000; Gomi et al., 2002). However, the dynamics of hydromorphological processes in headwater catchments in mountain environment is different in each altitudinal zone. In the Western Tatra Mountains, the most evident differences in structure of the slope-fluvial system are expected to be between alpine and montane zones. Alpine and montane areas in the Western Tatra Mountains differ not only in climatic and vegetation conditions related to altitudinal zonation, but also in geological structure and history of mountain relief development (Kotarba et al., 1987). This is a limitation of this hypothesis because of the inability to identify a specific factor influencing the differentiation of the slope-fluvial system structure. However, it points to the complexity of the environment of such a small area, where the valley network development occurs in two ways. Therefore, this paper aims at exploring the detailed structure of the slope-fluvial system, with a particular focus on the transition zone between the slope and fluvial subsystems, in different altitudinal zones. This purpose is pursued through: (1) identifying the morphometry of headwaters (subcatchments) in the alpine and montane zones, and (2) delimiting a theoretical border between the slope subsystem and the fluvial subsystem, based on morphometric parameters of subcatchments.

STUDY AREA AND METHODS

Study Area

The catchment of the Chochołowski Potok stream was chosen for the research, representing the natural environment of the Western Tatra Mountains. The

Chochołowski Potok stream valley (or the Chochołowska Valley) is the largest (35.4 km²) and westernmost valley in the Polish part of the Tatras. Given its large surface area and its dendritic stream and valley pattern, it is ideally suited for studying headwater valley reaches, which are ubiquitous in the area. It is also characterized by a diverse environment.

Within the Chochołowski Potok stream catchment, closing at the boundary of the Tatra National Park, I determined 50 subcatchments (Fig. 1, part A). They are first- to third-order catchments (according to the Horton-Strahler classification; Strahler, 1957). Although the Horton-Strahler classification relates chiefly to permanent streams, it is also used in this study for intermittent streams in headwater valley reaches, which are part of a drainage network (Siwek et al., 2009). The subcatchments have been selected so as to include all tributaries of the Chochołowski Potok stream with their outlets as junctions of the tributary and the main channel. The sector of the catchment upstream of glacial cirques has been omitted in all analyses within this study, and only subcatchments that were not significantly transformed by glacial processes in the Pleistocene (according to Zasadni and Kłapyta, 2014) were

analyzed. This is important regarding the method chosen for the analysis of the morphometric parameters; this method has to date only been used for catchments untransformed by glacial processes (Montgomery and Dietrich, 1988, 1992; McNamara et al., 2006; Jaeger et al., 2007).

The study area comprises two types of areas with entirely different natural environmental characteristics according to altitudinal zonation (Fig. 1, part A). The alpine environment, according to the criteria defined by Troll (1973), is represented by 22 subcatchments. A significant part thereof is located above the upper timberline (>1500 m a.s.l.; Piękoś-Mirkowa and Mirek, 1996). The slopes of catchments in this altitudinal zone are transformed by processes including snow avalanches, nivation, solifluction, gelidiflation, and debris flows (Kotarba et al., 1987; Rączkowska, 1995). Debris flows are relatively rare in the study area, occurring less than once every 10 years (Krzemień, 1988), but their role in relief transformation is meaningful (Kotarba et al., 1987). As far as the geological structure of the study area is concerned, it consists mostly of erosion-resistant crystalline rocks, namely granitoids and metamorphic rocks (Fig. 1, part B; Bac-Moszaszwili et al., 1979). The mean annual

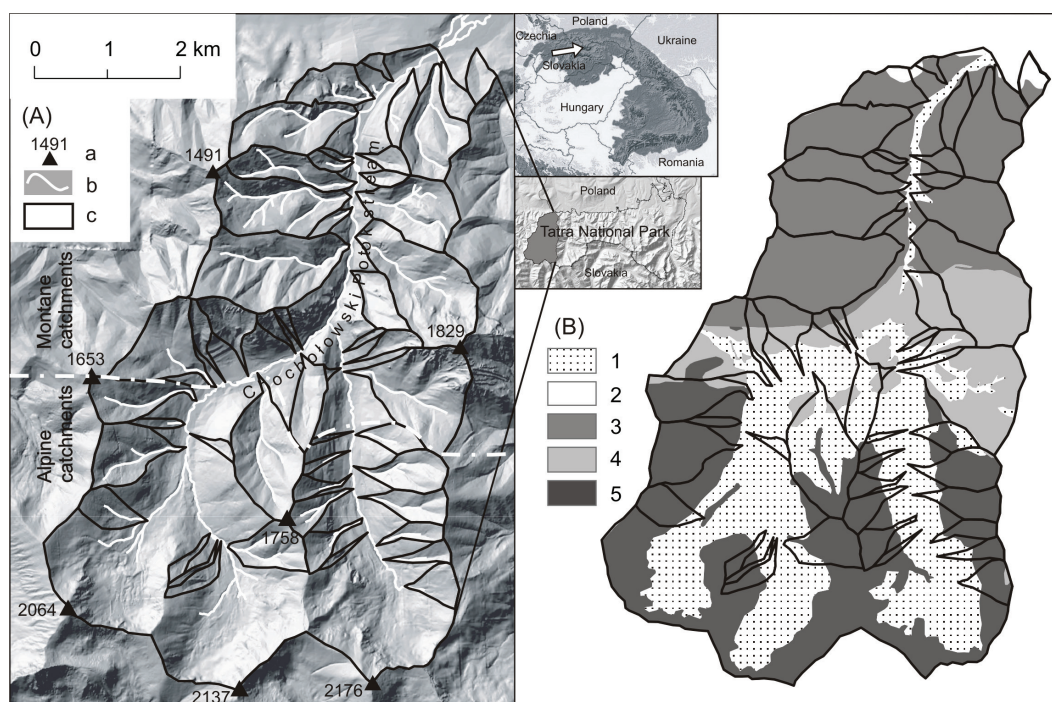


FIGURE 1. Location of the study area: (A) topography of the Chochołowski Potok stream catchment: a—summit and its elevation in meters (a.s.l.), b—stream, c—catchment boundary. (B) Geological structure of the Chochołowski Potok stream catchment (Bac-Moszaszwili et al., 1979): 1—Quaternary fluvial, fluvio-glacial, moraine, and colluvial deposits; 2—Eocene conglomerates and limestones; 3—Subatric successions (limestones, dolomites, marls); 4—Hightatric succession (sedimentary cover: quartzitic sandstones, limestones); 5—Hightatric succession (crystalline core: schists, granitoids).

air temperature in the alpine zone is between 0 and 2 °C (Hess, 1965), the total annual rainfall is up to 2000 mm (Chomicz and Šamaj, 1974), and the average snow-pack thickness is more than 1 m (Briedoň et al., 1974). The montane zone is represented by 28 catchments, mostly located within the forest zone (<1500 m a.s.l.; Piękoś-Mirkowa and Mirek, 1996). The slopes of these catchments are mostly transformed by mass movements (landsliding, creep) and slope wash, whereas the valley bottoms are transformed by bedload movement during torrential flows, which are more frequent than debris flows in the high mountain zone (Gorczyca et al., 2014). Geologically, most of the area consists of sedimentary rocks, namely limestones, dolomites, and marls (Fig. 1, part B; Bac-Moszaszwili et al., 1979). The mean annual air temperature in the montane zone is between 2 and 4 °C (Hess, 1965), the total annual rainfall is approx. 1400 mm (Chomicz and Šamaj, 1974), and the average snow-pack thickness is 0.6 m (Briedoň et al., 1974).

Material and Methods

The morphometric analysis of subcatchments within the Chochołowska Valley was based mostly on a 10-m-resolution digital elevation model (DEM) of 2009 and a topographic map scaled 1:10,000 (INSPIRE Geoportal, 2016). Based on the DEM, I delimited 50 catchments

and for each I calculated the values of 17 morphometric parameters (Table 1) normally used to characterize the catchment shape and hydrogeomorphological conditions (Marchi and Dalla Fontana, 2005; McNamara et al., 2006; Mesa, 2006; Ozdemir and Bird, 2009). I defined the valley network based on a topographic map scaled 1:10,000 (INSPIRE Geoportal, 2016) and a DEM from 1-m-resolution aerial laser scanning of 2012–2013. The catchments, the valley network, and the parameter values were established using ArcGIS 10.1 software.

The catchment parameters were normalized using log-transformation and standardized. Statistical distributions of the data were verified using Shapiro-Wilk and Lilliefors tests, at significance level $p \leq 0.05$. The correlation coefficients were calculated using STATISTICA 12 software; only correlations at the significance level of $p \leq 0.05$ were considered significant. For catchment parameters divided into two groups, the significance of differences between their values was calculated using a two-sampled t -test with a significance level of $p \leq 0.05$.

To identify the theoretical border between the slope subsystem and the fluvial subsystem, additional subcatchments were delimited within each of the 50 catchments, with the subcatchment closings located at 50-m intervals along the main axis. The 50-m interval was found to be appropriate considering the resolution of the topographical data and very small total catchment area that starts

TABLE 1
Formulas of morphometric parameters of catchments.

Catchment parameter	Symbol	Formula
Area (km ²)	A	—
Maximum height (m a.s.l.)	H_{max}	—
Minimum height (m a.s.l.)	H_{min}	—
Height differences (m)	ΔH	$= H_{max} - H_{min}$
Width (m)	W	—
Length (m)	L	—
Circularity index (-)	C_k	$= 4\pi(A/P^2)$
Axis gradient (m m ⁻¹)	S_p	$= \Delta H/1000L$
Drainage density (km km ⁻²)	D	$= \sum L/A$
Valley frequency (km ⁻²)	F_s	$= \sum N/A$
Texture ratio (km ⁻¹)	T	$= N I/P$
Melton ruggedness number (-)	MRN	$= (\Delta H/1000)/A^{0.5}$
Number of 1st-order valleys	$N I$	—
Total length of 1st-order valleys (m)	$L I$	—
Bifurcation ratio (1st- and 2nd-order valleys) (-)	$Rb I/II$	$= N I/N II$
Mean bifurcation ratio (-)	Rb	$= (Rb I/II + Rb II/III)/2$

P – catchment perimeter; $N II$ – number of 2nd-order valleys; $Rb II/III$ – bifurcation ratio (2nd- and 3rd-order valleys).

TABLE 2
Morphometric parameters of catchments (N = 50).

Parameter	Unit	Minimum	Mean	Maximum	Standard deviation
<i>A</i>	km ²	0.01	0.37	1.67	0.42
<i>Hmax</i>	m a.s.l.	1119	1568	1855	232.08
<i>Hmin</i>	m a.s.l.	927	1146	1471	156.34
ΔH	m	100	422	828	143.65
<i>W</i>	km	0.06	0.28	0.88	0.20
<i>L</i>	km	0.14	1.05	2.18	0.51
<i>Ck</i>	—	0.26	0.56	0.79	0.12
<i>Sp</i>	m m ⁻¹	0.15	0.45	0.72	0.14
<i>D</i>	km km ⁻²	2.97	5.92	11.76	2.11
<i>Fs</i>	km ⁻²	4.67	25.80	89.55	16.68
<i>T</i>	km ⁻¹	0.46	2.52	6.17	1.55
<i>MRN</i>	—	0.30	0.96	1.83	0.40
<i>NI</i>	—	1.00	5.52	29.00	5.66
<i>LI</i>	km	0.09	1.05	6.07	1.14
<i>Rb I/II</i>	—	2.00	3.47	6.00	1.15
<i>Rb</i>	—	2.50	3.29	5.40	0.75

from 0.01 km². In this way, a total of 1283 subcatchments were delimited. The surface area of each of them was calculated using ArcGIS 10.1. The subcatchment's axis gradient was measured along the thalweg as a ratio of height differences and thalweg length (ΔH -to-*L*). These data were then compiled in logarithmic charts, followed by an analysis of the slant direction and angle of the trend line expressing the gradient-to-area relationship (*Sp*-to-*A*) for respective catchments, expressed as:

$$\log Sp = m \log A + b, \quad (1)$$

where *Sp* is the catchment axis gradient, *A* is the catchment area, *m* is the constant and is equal to the trend line slant, and *b* is the trend line intercept. The chart has been divided into sections for which the trend is growing (*m* > 0), almost constant (*m* ≈ 0), decreasing (0 > *m* > -0.1), and decreasing with a relatively steep trend line slant (*m* ≤ -0.1). These sections relate to respective landforms (see Fig. 4; Montgomery and Foufoula-Georgiou, 1993; Ijjasz-Vasquez and Bras, 1995; Stock and Dietrich, 2003; Šilhán and Pánek, 2010). Statistical distributions of the constant *m* of the *Sp*-to-*A* relationships for respective slope-fluvial system sections were verified using Shapiro-Wilk and Lilliefors tests with the significance level of *p* ≤ 0.05. The data distributions were close to normal and therefore analysis of variance (ANOVA) and two-sam-

pled *t*-test were used to determine the significance of differences between the slope-fluvial system sections for the significance level of *p* ≤ 0.05.

Statistical distributions of the data relating to the catchment areas and gradients were verified with Shapiro-Wilk and Lilliefors tests, at significance level *p* ≤ 0.05. The data did not show normal distributions and consequently non-parametric tests (Pettitt test, Standard normal homogeneity test [SNHT], and Buishand test) were used to identify the data homogeneity. They were then used to verify the analyses of constant *m*.

RESULTS

Morphometric Characteristics of the Subcatchments

Catchments of the tributaries of the Chochołowski Potok stream were analyzed. These catchments have small surface areas (up to 1.67 km²) and relatively high axis gradients (up to 0.72 m m⁻¹, mean 0.45 m m⁻¹). Height differences within respective catchments range from 100 m to 828 m. The catchments have various shapes, from elongated to rounded, as demonstrated by the wide range of values of parameters describing their shapes, such as length, width, and circularity index (Table 2). The slopes of catchments are dissected by valleys to a varying extent: the drainage

density ranges from 2.97 to 11.77 km km⁻². The bifurcation ratio, reflecting the extent of valley branching, assumes values up to 6.0. The valley frequency index is also relatively high (mean 25.80 km⁻²). The Melton ruggedness number (MRN) is an index of catchment steepness, related to the relative processes dynamics, and catchment response time (McNamara et al., 2006; Ozdemir and Bird, 2009; Slaymaker, 2010) and assumes values between 0.30 and 1.83 in the studied catchments. The number of first-order valleys within individual subcatchments is up to 29 and the number of second-order valleys is up to 5. Their lengths range from 0.09 to 6.07 km and from 0 to 1.86 km, respectively. The total number of valley reaches of all orders within a subcatchment ranges from 1 to 35, and their length ranges from 0.09 to 9.62 km.

There are significant correlations between some morphometric parameters of the studied catchments (Table 3). Larger-area catchments have greater height differences, and greater numbers and lengths of first-order valley reaches. Smaller-area catchments have higher drainage density values. There is an average inverse correlation ($r = -0.50$) between the catchment area and its axis gradient. There is a very high positive correlation ($r = 0.89$) between the catchment length and its surface area and a high negative correlation ($r = -0.68$) between the catchment length and its axis gradient. Catchments with higher gradients have greater Melton ruggedness number, which indicates faster flow concentrations. Catchments with greater numbers of first-order valley reaches have greater height differences, lower gradients, and Melton ruggedness numbers, which indicates slower flow concentrations.

The above characteristics of catchments reveal a high diversity of relief in the small study area, which is a result of the natural environmental diversity. Statistical analysis has revealed significant differences in morphometric param-

eters between catchments lying mostly in the alpine zone (above upper timberline) and those entirely in the montane zone. These differences concern the catchment axis gradient, the drainage density, the Melton ruggedness number, and the bifurcation ratio (Fig. 2). Catchments within the montane zone have lower gradients, lower drainage densities, and lower Melton ruggedness numbers but higher bifurcation ratios than catchments within the alpine zone. The values of other parameters do not show significant differences but are more heterogeneous in catchments within the montane zone (Fig. 2). Statistical analysis has revealed no significant differences in morphometric parameter values between catchments of different aspects.

Border Between Slope Subsystem and Fluvial Subsystem

Based on the ratio of the catchment axis gradient to its surface area (Sp -to- A) and the results of the analysis of data homogeneity using the Pettitt test, Standard normal homogeneity test (SNHT), and Buishand test, I determined a border between the slope subsystem and the fluvial subsystem and calculated the limit values of morphometric parameters of catchments in the slope subsystem. Within the study area, the mean catchment axis gradient value above which slope processes dominate is 0.49 [m m⁻¹], with 50% of the cases falling within the interval between 0.41 and 0.58 [m m⁻¹]. The mean surface area contributing to the fluvial system lying below is ~0.21 km², with 50% of the cases falling between 0.07 and 0.33 km². The length of the contributing area, which is also the distance of the fluvial system starting point from the watershed, is 761 m on average, with 50% of the cases falling between 550 and 950 m.

With the slope/fluvial subsystem border being defined thus, the valley reaches classified in the slope subsystem are significantly more numerous than fluvial sub-

TABLE 3
Correlation matrix between catchments parameters ($N = 50$).

	<i>A</i>	ΔH	<i>L</i>	<i>Sp</i>	<i>D</i>	<i>MRN</i>	<i>NI</i>	<i>LI</i>
<i>A</i>		0.58	0.89	-0.50	-0.46	-0.62	0.90	0.91
ΔH	0.58		0.63	0.03	-0.36	-0.05	0.44	0.50
<i>L</i>	0.89	0.63		-0.68	-0.51	-0.65	0.82	0.82
<i>Sp</i>	-0.50	0.03	-0.68		0.39	0.81	-0.55	-0.48
<i>D</i>	-0.46	-0.36	-0.51	0.39		0.64	-0.26	-0.28
<i>MRN</i>	-0.62	-0.05	-0.65	0.81	0.64		-0.62	-0.53
<i>NI</i>	0.90	0.44	0.82	-0.55	-0.26	-0.62		0.95
<i>LI</i>	0.91	0.50	0.82	-0.48	-0.28	-0.53	0.95	

Bold font—significant correlation with $p \leq 0.05$; regular font—not significant.

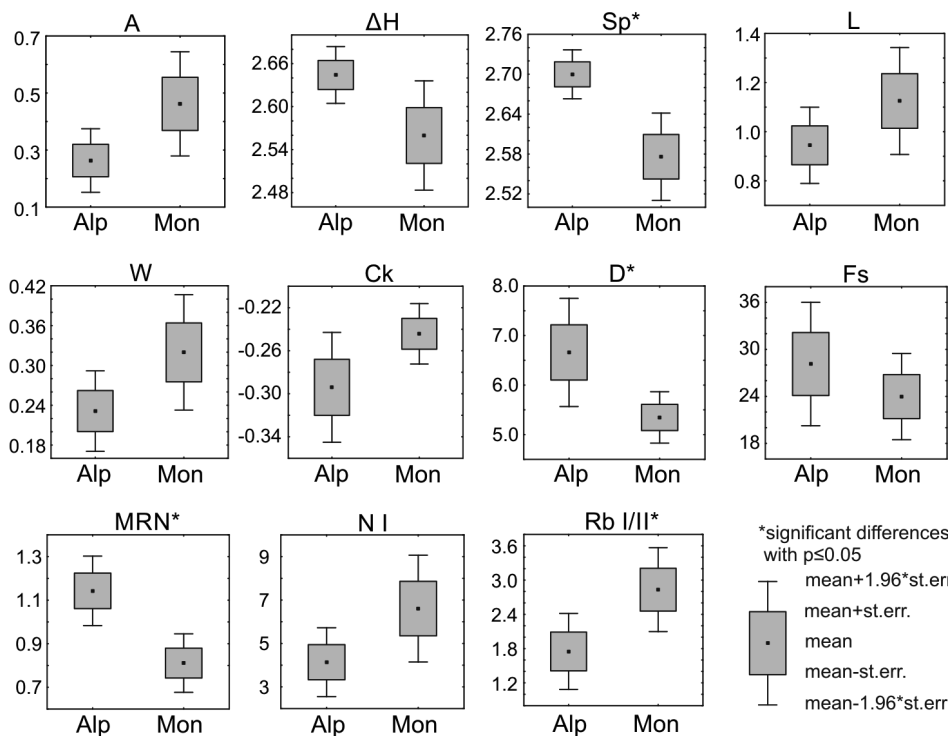


FIGURE 2. Differences in catchment parameters between alpine catchments (Alp) and montane catchments (Mon) (values of parameters are normalized and standardized). See Table 1 for explanation of parameter symbols.

system reaches and account for 94% of all valley reaches. Their total length is 77.3 km, representing 84% of the total length of all valley reaches defined. All first-order valley reaches (according to the Horton-Strahler classification) except for one are within the slope subsystem. At each subsequent order number, the number of slope subsystem valley reaches and their proportion in the total length of the valley network is lower. However, most second-order valley reaches have also been classified in the slope subsystem. Of third-order valley reaches, half are within the slope subsystem but their length is far smaller, at ~30% of all third-order valley reaches (Fig. 3).

The method of analyzing the catchment gradient-to-area relationship (Sp -to- A), which I used, is based on the method developed and used by Montgomery and Foufoula-Georgiou (1993) and Stock and Dietrich (2003). With the use of this method, these authors defined several sections of slope-fluvial system within the longitudinal cross section of the catchment (Montgomery and Foufoula-Georgiou, 1993), which may be different depending on the study area and the natural environmental conditions. Within the studied catchments in the Western Tatras, the following sections of the slope-fluvial system may be distinguished based on the Sp -to- A relationship (Fig. 4): (a) hillslope, where material is transported in a scattered manner; (b) unchannelled valley or colluvial channel (with intermittent or ephemeral flow), shaped mostly by slope processes; (c) transitional channel, where slope and fluvial processes overlap and the role of each de-

pends on hydrometeorological conditions; and (d) semi-alluvial channel, with fluvial processes dominating. Given the very small surface areas of the studied catchments, they lack the typical alluvial channel section as defined by Montgomery and Foufoula-Georgiou (1993). Within the montane zone, a fluvial subsystem includes sections of a bedrock channel and sections of a channel filled with coarse, sharp-edged debris that is usually transported at short distances as a result of fluvial processes (Krzemień, 1992). For channels within the alpine zone, their lower reaches are not typical alluvial channels either, as, besides material transported as a result of fluvial processes, they also include moraine covers and sharp-edged material deposited through avalanches and debris flows. However, they are not semi-alluvial channels, which are defined by Galia and Hradecký (2014) as the steepest headwater channel reaches (bedrocks and bedrock-cascades) in the Outer Western Carpathians (the Czech Republic). Unlike the channels in the Czech Republic, semi-alluvial channel reaches in the Western Tatras lie lower within the river continuum and consequently have lower gradients, and fluvial processes contribute significantly to their transformation.

The constants m of the Sp -to- A relationships decrease for subsequent sections of the slope-fluvial system from the hillslope to the semi-alluvial channel; only for the hillslope do they assume positive values (Fig. 5, part A). The analysis of variance (ANOVA) revealed significant differences between the constants m of the Sp -to- A

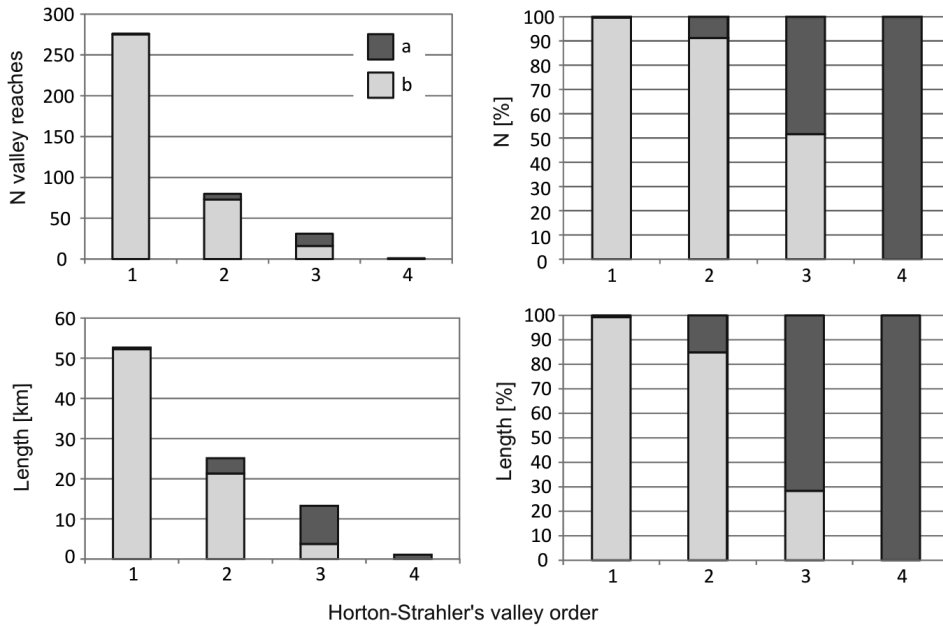


FIGURE 3. Number and percentage of fluvial (a) and slope (b) sections of the slope-fluvial system of the Chochołowski Potok stream catchment.

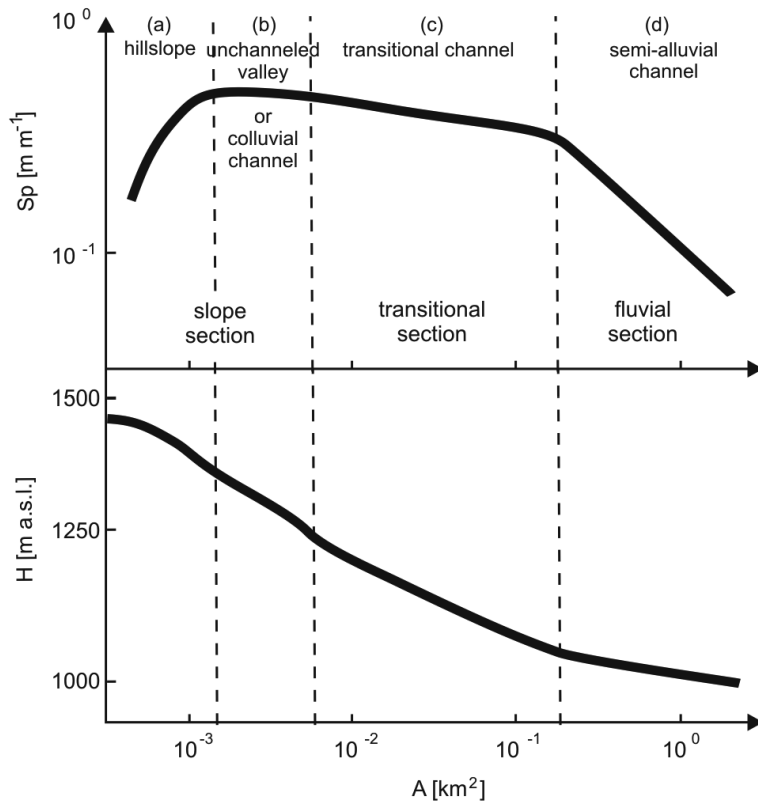


FIGURE 4. Slope-fluvial system sections within the longitudinal profile of the catchment (Montgomery and Foufoula-Georgiou, 1993; modified).

relationships for respective sections of the slope-fluvial system, except for the transitional channel and the semi-alluvial channel (Fig. 5, part B). This is because of fluvial processes occurring in both these channel types. For larger catchments (>1 km²), the differences between the constants m for transitional channels and semi-alluvial channels are more pronounced (Fig. 5, part B). However, when the slope section is taken in its entirety (a, b,

and c reaches), its constants m of the Sp -to- A relationship are significantly different from those for the fluvial reaches (Fig. 5, part C); furthermore, they assume positive or near-zero values and are generally higher than the constants m for the fluvial reaches, irrespective of the catchment size (Fig. 5, part C). This results from different process-type domination regardless of the geological structure and altitudinal zonation.

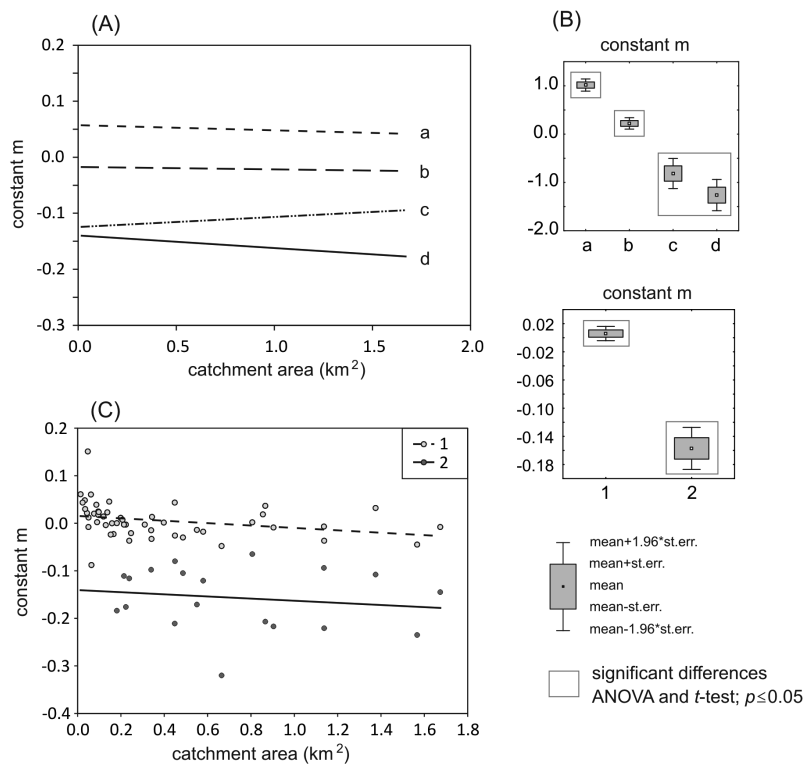


FIGURE 5. Trend line slant (constants m) of the catchment gradient-to-area relationship (Sp/A) for slope-fluvial system sections: (A) dependence between constants m and the catchment area for the respective slope-fluvial system sections: a—non-dissected hillslope; b—unchanneled valley or colluvial channel; c—transitional channel reach; d—semi-alluvial channel, $N = 134$; (B) top chart: differences between constants m for respective slope-fluvial system sections, $N = 134$; bottom chart: differences between constants m for slope (1) and fluvial (2) sections, $N = 69$; and (C) relationship between constants m and catchment area for slope (1) and fluvial (2) sections, $N = 69$.

In the study area there are simple catchments, comprising one or two sections of the slope-fluvial system, as well as catchments where three or four sections are represented (Fig. 6). However, most catchments are classified entirely into the slope subsystem (31 catchments); catchments with sequences of type II and type IV sections of the slope-fluvial system being the most numerous. Most catchments ($N = 36$) begin (looking downslope from the watershed) as a non-dissected slope, turning into valley forms (from denudational to fluvial). However, catchments with sequences of type I, III, and IV slope-fluvial system sections (Fig. 6) start as a concave form, that is, as a highly convergent slope, which directs the material transport starting already from the watershed. In part of the catchments ($N = 21$) the transitional section is not represented, that is, there is a clear border between the slope subsystem and the fluvial subsystem.

DISCUSSION

The development of a valley network in a given region, expressed by morphometric parameters, depends largely on the local geological structure and climate conditions. However, despite the differences in natural environments, there is a noticeable pattern in mountain areas: first-order stream or valley reaches have a large share in all-order stream or valley reaches in a catchment. The percentages of first-order valley reaches in

the total numbers and lengths of valley reaches in the studied catchments is, respectively, 63.8% to 83.3% and 28.4% to 79.7% (excluding catchments with only one first-order valley reach) and are similar to the percentages in mountain catchments in other mountain regions worldwide: 75.5% and 61.0% in the Kazdagi Mountains (Turkey; Ozdemir and Bird, 2009), 75.8 to 82.7% and 42.8 to 60.5% in the Andes (Argentina; Mesa, 2006), 77.3% and 51.0% in the Western Ghats (India; Kaliraj et al., 2014), 71.8% and 54.2% in the Satpura Range (India; Yadav et al., 2014), and 75.4 to 81.8% and 38.5 to 49.5% in the Bieszczady Mountains (Poland; Siwek et al., 2009). The high bifurcation ratio values (>5) suggest structural determinants of the development of the first-order valley reaches network and are typical (as is the high drainage density) for mountain areas characterized by high gradients, low infiltration, and high degree of slope dissection (Horton, 1945; Strahler, 1957; Dar et al., 2014; Kaliraj et al., 2014). Bifurcation ratio values between 3 and 5 are typical for natural valley systems with uniform natural environmental conditions and at similar developmental stages. Such values are typical for montane catchments. On the other hand, most alpine catchments have bifurcation ratios below 3, which suggest that they are in the initial stage of valley network development. Very high valley frequencies in the entire study area confirm the high gradients, the low bedrock permeability and infiltration, and the high height differ-

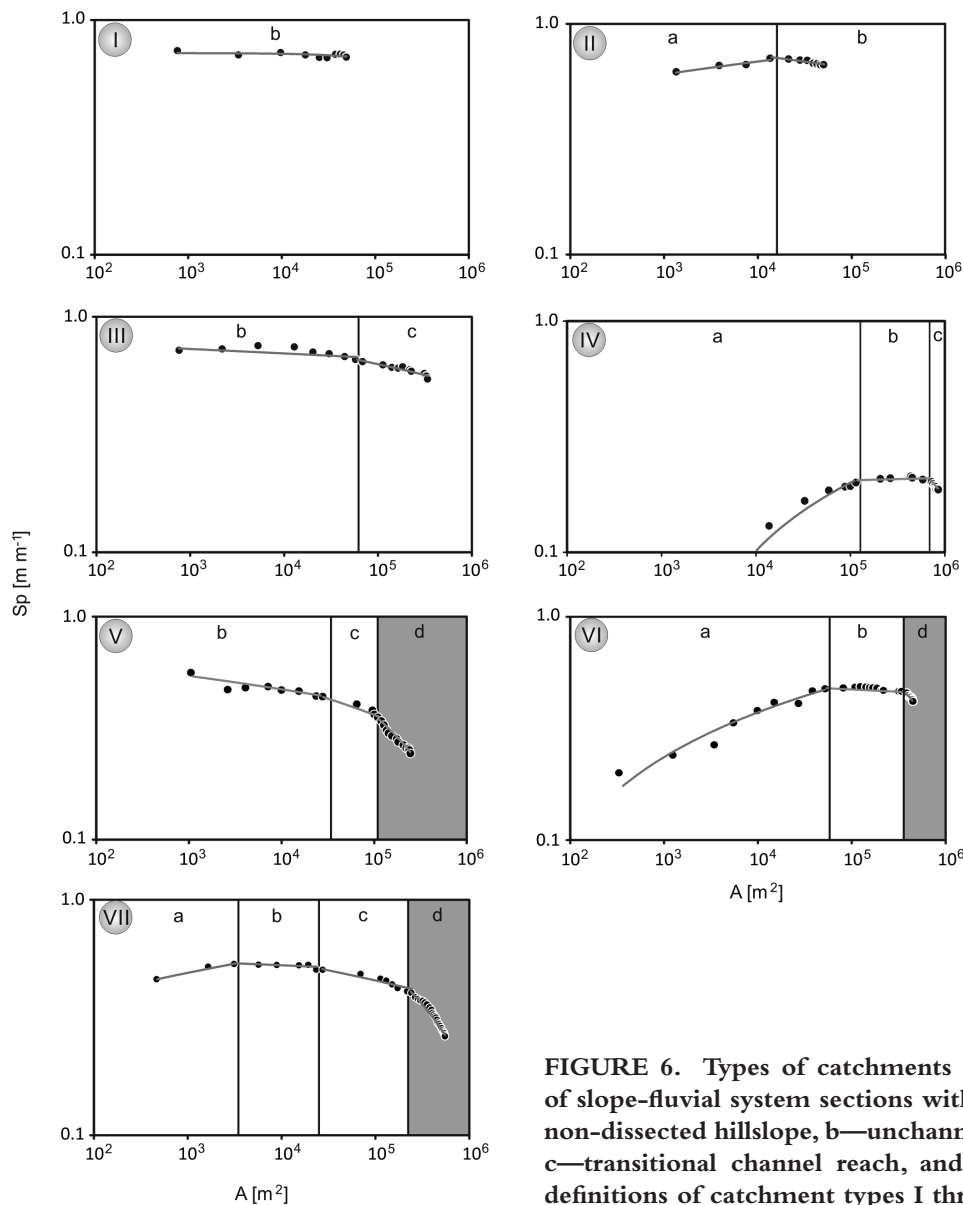


FIGURE 6. Types of catchments (I–VII) with defined sequences of slope–fluvial system sections within the longitudinal profile: a—non-dissected hillslope, b—unchanneled valley or colluvial channel, c—transitional channel reach, and d—semi-alluvial channel. For definitions of catchment types I through VII, see text.

ences, which favor higher water runoff (Horton, 1945; Strahler, 1957; Yadav et al., 2014). Great height differences within catchments are typical for high mountain areas. They reflect the water stream gradient and result in a quick runoff formation and a high potential of water runoff from the catchment (Schumm, 1956; Strahler, 1957; Mesa, 2006).

Different environmental conditions within altitudinal zones, which are determined by various climate conditions and result in differences in the type and intensity of morphogenetic processes, but also lithological differences, substantially affect valley network development patterns in the study area. This is reflected by significant differences of morphometric parameter values of catchments within different altitudinal zones (Fig. 2). Values of *MRN* reflect differences in relative process dynamics

in the catchment in the study area. Catchments within the slope subsystem are characterized by higher *MRN* (mean *MRN* = 1.15) than catchments in the fluvial subsystem (mean *MRN* = 0.65), and this is consistent with previous findings by Slaymaker (2010) and Bertrand et al. (2013). However, the values of *MRN*, especially for fluvial subsystem, are higher in the Western Tatra Mountains than in other mountain areas (Bertrand et al., 2013), and this is related to the lack of typical alluvial channels in the study area. Differences of *MRN* values also occur between alpine and montane catchments (Fig. 7). Alpine catchments exhibit a greater potential intensity of geomorphic hazards than montane ones, and thus the possibility of occurrence of debris flows going down to fluvial subsystem. However, in the post–Little Ice Age period, the activity of debris flows in the Tatra

Mountains became much lower, especially in the western part of the mountains (Rączkowska, 2006; Długosz, 2015). At the present, the stabilized coarse-grained slope covers do not favor the occurrence of debris flows, although they were active in the past (Krzemień, 1988; Rączkowska, 2006).

Relationships between different parameters also carry information on the functioning of catchments. The relationship between the catchment area and its length for the study area is:

$$L = 1.79A^{0.41} \quad (2)$$

and is very close to that identified by Montgomery and Dietrich (1992) for small catchments with different geological structure and different climate conditions:

$$L = 1.78A^{0.49} \quad (3)$$

Although some irregularities may occur in short valley reaches (Hack, 1957), in general the relationship of length to catchment area occurs for small non-dissected zero-order catchments as well as for large river systems, which suggests that catchment geometry is highly similar irrespective of the catchment size, climate conditions, or geological conditions (Montgomery and Dietrich, 1992).

In areas of different geological structure, climate conditions, and vegetation, the axis gradient of zero-order

catchments has been found to decrease with the growth of the catchment area, and consequently, the drainage density should also decrease (Montgomery and Dietrich, 1988, 1989). Within the study area, this pattern is observable for first-order to third-order catchments: the higher the catchment axis gradient is, the smaller its surface area ($r = -0.53$) and the greater the drainage density ($r = 0.51$). The catchment axis gradient explains 28% of the variation in catchment area and 26% of the variation in drainage density.

The relationship between the local gradient and the catchment area (Sp -to- A) in the longitudinal profile reflects the downslope sequence of the slope-fluvial system sections (Montgomery and Foufoula-Georgiou, 1993; Ijjasz-Vasquez and Bras, 1995; Stock and Dietrich, 2003; Šilhán and Pánek, 2010). Based on the direction of the Sp -to- A relationship, it is possible to delimit a border between the slope subsystem and the fluvial subsystem. Montgomery and Foufoula-Georgiou (1993) observed that a positive correlation is typical for the slope, whereas a negative correlation is typical for the valley. The limit value of the size of the valley head contributing area is 10^{-4} – 10^{-3} km², whereas the limit value of the size of the alluvial channel head contributing area is 10^{-1} – 10^0 km² (Montgomery and Foufoula-Georgiou, 1993; Ijjasz-Vasquez and Bras, 1995). The results of the Sp -to- A relationship analysis for the valley network in the Western Tatras confirm the occurrence of a sequence of slope-fluvial system sections within the studied subcatchments. The limit values, calculated for the Western Tatra Mountains, of the contributing areas of the valley head and the semi-alluvial channel head are close to those calculated by previous researchers and equal 10^{-3} – 10^{-2} km² and 10^{-2} – 10^0 km², respectively (Fig. 8, part A). The sequences, thus defined, of slope-fluvial system sections correspond very well with headwater area elements (Hack and Goodlet, 1960; Gomi et al., 2002; Wrońska-Wałach et al., 2013). However, the complete sequence of sections is not present in all the studied catchments (Figs. 6 and 8, part B); this is related to the development stage of the given valley system, as expressed by respective morphometric parameters of the catchment. Larger-area catchments (~ 1 km²), with many first-order valley sections (>10), include a semi-alluvial channel (a type of reach classified to the fluvial subsystem). This is typical for most catchments in the montane zone where, although mostly intermittent streams flow (Ziemońska, 1973), fluvial processes are predominant in valley transformations. Small catchments with few valleys have been classified entirely to the slope subsystem, and this is typical for the alpine zone where, although mostly permanent streams flow (Ziemońska, 1973), moraine covers on the slopes reduce the effects of

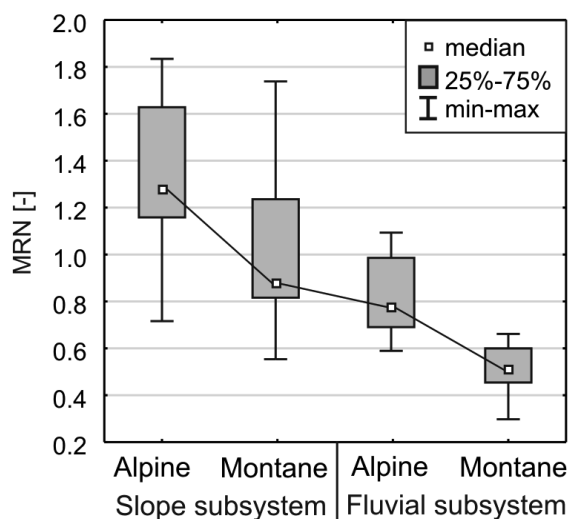


FIGURE 7. Melton ruggedness number for alpine and montane catchments within slope and fluvial subsystem.

fluvial processes, and processes such as debris flows and avalanches are most important for the long-term valley transformations. This is also confirmed by the values of other catchment parameters. High height differences (>400 m) and high bifurcation ratios (>3) also favor the occurrence of a semi-alluvial channel. Particularly interesting are three catchments located in the SE part of the study area, which (despite their small surface areas) include semi-alluvial channels but not transitional reaches (Fig. 8, part B). These catchments are characterized by very high gradients compared to other catchments with semi-alluvial channels; they also have high bifurcation ratios. Hence, it can be inferred that larger catchments with smaller gradients are characterized by a smooth transition between the slope subsystem and the fluvial subsystem, by means of a transitional reach. On the other hand, in high-gradient catchments the rapid transition means that the transitional reaches did not develop or are too short to be revealed in the S_p -to- A relationship analyses.

The S_p -to- A relationship analyses in various mountain ranges have shown that the trend line illustrating this relationship may have different shapes depending

on climate conditions and geological structures (Ijjasz-Vasquez and Bras, 1995; Stock and Dietrich, 2003; Marchi et al., 2008; Šilhán and Pánek, 2010). This method does not always enable the channel head location to be identified, as in some cases the S_p -to- A ratio may be the same for an unchannelled valley and a colluvial channel (Ijjasz-Vasquez and Bras, 1995). Still, this method makes it possible to specify fairly precisely the location of the theoretical border between the part of valley where slope process dominate and the part predisposed for fluvial processes (Stock and Dietrich, 2003).

CONCLUSIONS

The development of headwater reaches of valley networks in the studied subcatchments is determined by a number of factors including the geological structure and climate conditions, which affect the type and intensity of morphogenetic processes. Within the Chochołowski Potok stream catchment, two types of areas may be distinguished, with differences in the above environment elements, in which subcatchments differ significantly

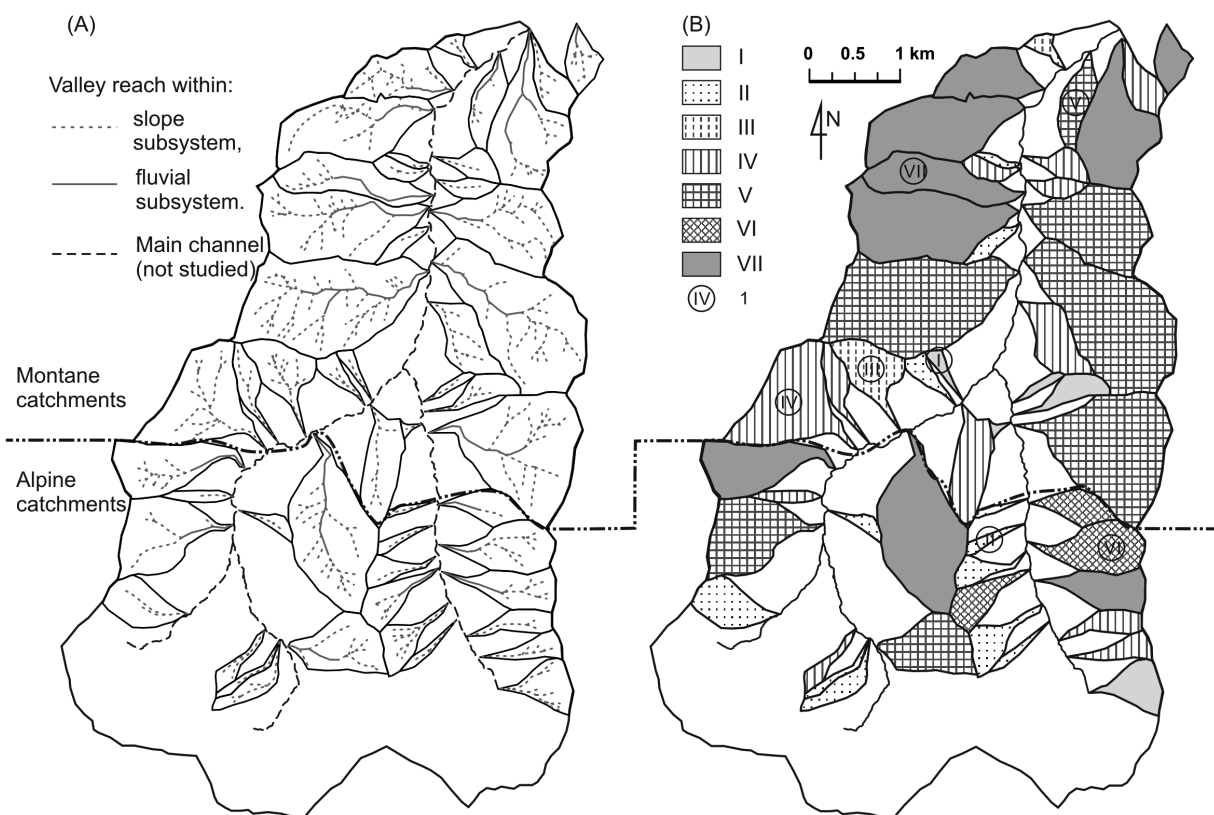


FIGURE 8. Valley network in the studied catchments (A) and location of catchments with the respective sections of the slope-fluvial system (B) within the longitudinal profile (I–VII): 1—examples of catchments shown in Figure 6.

in terms of their morphometric parameters. The alpine catchments are mostly systems in their initial development stage, with little-developed drainage networks, mostly including one or two first-order reaches (according to the Horton–Strahler classification). These catchments have very high gradients, elongated shapes, and low bifurcation ratios. The montane catchments are mainly at a more advanced development stage, with relatively large surface areas (~1 km²) and well-developed drainage networks, which include several (up to 29) first-order reaches. Such catchments are usually wide-shaped and have low gradients and high bifurcation ratios.

Within the small first- to third-order catchments, one can distinguish several sections of the slope–fluvial system, important for the catchment development and functioning. These sections have thus far been little analyzed. A detailed relief analysis in the studied catchments resulted in two basic morphodynamic sections being distinguished: the slope section and the fluvial section, characterized by different hydrogeomorphological process dynamics. Small-area catchments, with little-developed valley networks, have been entirely classified to the slope subsystem, while larger catchments (~1 km²), with multi-reach valley systems, usually include a fluvial reach. In the latter type, the transition from slope process dominance to fluvial process dominance may be either (1) smooth, over a longer distance (>50 m), with a transitional reach, or (2) abrupt, over a shorter distance (<50 m), without a transitional reach.

The analyses of catchment morphometric parameters in this article are a good introduction to field observation and measurements of morphogenetic processes in headwater valleys in difficult to access alpine environment. Such analysis is a useful tool for identifying the effects of natural processes in a slope–fluvial system in the long term.

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