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STRUCTURE OF THE HEADWATER VALLEY SEGMENT IN THE WESTERN TATRAS

Abstract. The aim of this paper is to determine the detailed structure of the headwater valley segment in the Western Tatra Mountains. Seven sub-catchments were chosen in Chochołowski Stream catchment for a detailed geomorphological analysis of the headwater valley segments. Selected sub-catchments represent both the crystalline and the sedimentary environment of the study area. Geomorphological mapping was used to study the structure of headwater valleys which strictly depends on the conditions of the natural environment and can be varied even in such a small area as the catchment of Chochołowski Stream. Statistical analysis showed that headwater valleys in the crystalline part differ in terms of morphometric parameters from these in the sedimentary part and are characterized by greater gradients but smaller channel widths and roughness. However, the structure of headwater valley segment in the longitudinal profile shows a similar pattern in both parts of the study area and follows a sequence of valley types: unchanneled valley – colluvial channel (channel without steps) – cascade channel.

Keywords: headwater valley, channel morphometry, geomorphological mapping, Western Tatras

INTRODUCTION

Headwater valley is a longitudinal hollow formed by linear erosion of rainwater or snowmelt, together with denudation processes (Klimaszewski 1978, p. 408–410; Goudie 2006, p. 220, 237, 371; Migoń 2006, p. 158, 213). Despite their relatively small size, these features are abundant and are thus of high morphogenetic importance (Klatka 1955; Twardy 1995). Many researchers emphasize the crucial role of headwater channels in the development of mountain relief (Davis 1899; Horton 1945; Schumm 1956; Morisawa 1957; Strahler 1957; Goudie 2006, p. 81) because they are an important source of water, mineral and organic matter delivered to the fluvial system (Dietrich, Dunne 1978; Sidle et al. 2000; Tsuboyama et al. 2000; Gomi et al. 2002; Mazurek 2010). Accounting for more than half of the total channel length (Schumm 1956; Goudie 2006, p. 371), these channels dominate drainage networks in all morphoclimatic zones. Frequency of surface runoff in the headwater valley segments depends on climate conditions (Dietrich, Dunne 1993). In temperate climate, if there is no permanent spring, the upper part of a headwater valley segment remains dry for most of the year but permanent flow may occur in its downstream part (Dylik 1953). These segments are common for the headwater areas (Gomi et al. 2002; Mazurek 2010; Wrońska-Wałach et al. 2013) and usually occur above stream heads (Klimaszewski 1978). Shallow water flow may occur periodically in headwater segments which function as *colluvial channels* (Montgomery, Buffington 1997).

According to geomorphologists, the most important slope processes transforming headwater valley segments include slope wash (Jahn 1956; Mazurek 2010; Tylman 2011), solifluction (Dylik 1953; Mazurek 2010), corrosive action of debris flows (Klatkowa 1965), landslides (Starkel 1960; Goudie 2006, p. 486; Tylman 2011), piping (Poesen 2011; Starkel 2011) and seepage erosion (Mazurek 2010). Observations by these authors were carried out in upland and lowland areas where such forms are usually cut in unconsolidated sediments (loess covers or moraine). In the high-mountain environment of the Tatra Mountains, the array of active processes also involves periglacial processes such as solifluction, frost creep and nivation, which may intensively transform a headwater valley segment (Rączkowska 2006, 2007). L. Starkel (1957, 1960) distinguished similar forms in the Carpathians and classified them as erosive forms, and, similarly to other authors, considered them to have been "created by the erosion of water, flowing continuously or periodically, in cooperation with the denudation processes" (Starkel 1957, p. 71). The common features of headwater valley segments are gullies and V-shaped valleys that can cut the bedrock (Starkel 1960; Kaszowski 1965; Froehlich 1975; Krzemień 1984). L. Kaszowski and K. Krzemień (1977) distinguished two morphodynamic segments in the longitudinal profile of the valley: headwater and fluvial. In the headwater valley segment an initial channel is transformed mainly by rock weathering and denudation processes acting on the streambed and the surrounding slopes (Kaszowski 1975; Krzemień 1984; Kaszowski, Krzemień 1977). Fluvial processes may occur in the headwater segment, however, in contrast to the fluvial segment, they do not cause significant channel transformation (Kaszowski 1975). Thus headwater valley segments are common in the lowlands, uplands and as well as in mountain areas. However, headwater valley segment in mountain areas was merely recognized and, despite its importance for the development of the entire drainage network, detailed information on its structure is lacking. Therefore, the aim of this paper is to determine the detailed structure of headwater valley segment in the Western Tatras. The objectives are: 1) to distinguish headwater channel reaches that are characterized by significantly different morphometric parameters and 2) to determine the differences between headwater valley segments located in various mountain environments.

STUDY AREA

The catchment of Chochołowski Stream in the Tatra National Park was selected as a study area as it represents the natural environment of the Western Tatras. Seven sub-catchments (0.10–1.14 km^2) were chosen for a detailed geomorphological analysis of the headwater valley segments. These sub-catchments can be further divided into two groups based on geological structure, topography and climate conditions.

The first group consists of three sub-catchments located above the upper timberline (>1500 m a.s.l) (Piękoś-Mirkowa, Mirek 1996) in the southern part of the study area (Fig. 1A), and underlain by crystalline rocks – granitoids and metamorphic schists (Fig. 1B; Bac-Moszaszwili et al. 1979). The mean annual temperature in this part of the study area ranges from 0 to 2°C (Hess 1996), total annual precipitation reaches 2000 mm (Chomicz, Šamaj 1974) and the average thickness of snow cover exceeds 1 m (Briedoň et al. 1974). The slopes of the sub-catchments are transformed mainly by snow avalanches, nivation, solifluction, gelideflation and debris flows (Kotarba et al. 1987; Kaszowski et al. 1988; Krzemień 1988; Krzemień et al. 1995; Rączkowska

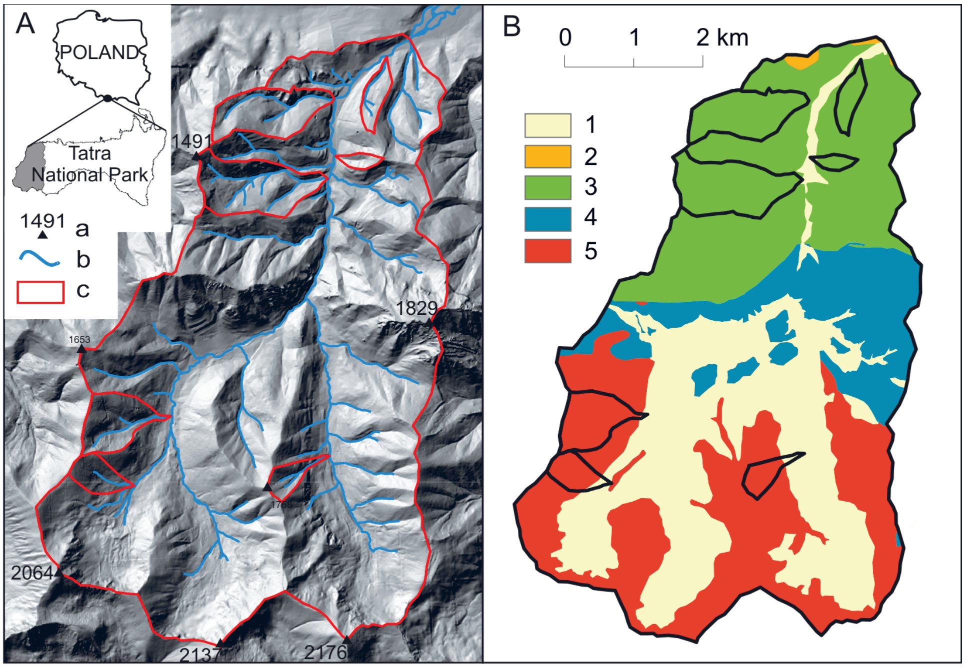

Fig. 1. Study area. A) The Chochołowski Stream catchment (www.geoportaltatry.pl): a – summit, b – streams, 3 – catchment border; B) Geological map of the study area (Bac-Moszaszwili et al. 1979): 1 – fluvial, glaciofluvial, moraine and colluvial sediments, 2 – conglomerates and limestones, 3 – limestones, dolomites and marls, 4 – quartzitic sandstones and limestones, 5 – metamorphic schists and granitoids

2006, 2007). Debris flows are relatively rare in the study area as they only occur once in over ten years (K a s z o w s k i et al. 1988; K r z e m i e ń 1988) but their role in the transformation of the relief is essential (K o t a r b a et al. 1987; K a s z o w s k i et al. 1988).

The second group consists of four sub-catchments located in the northern part of the study area, in the forest zone (<1500 m a.s.l.; Fig. 1A; P i ę k o ś-M i r k o w a, M i r e k 1996) and underlain by sedimentary rocks - limestones, dolomites and marls (Fig. 1B; B a c-M o s z a s z w i l i et al. 1979). Mean annual temperature in this part of study area ranges from 2 to 4°C (H e s s 1996), total annual precipitation is about 1400 mm (C h o m i c z, Š a m a j 1974) and average thickness of snow cover is 60 cm (B r i e d o ň et al. 1974). The slopes of the sub-catchments are transformed mainly by mass movement (landslides, creep) and slope wash, while valley floors are transformed by bedload transport during torrential flows that occur more frequently than debris flows above the upper timberline (G o r c z y c a, K r z e m i e ń 2008; F i d e l u s, P ł a c z k o w s k a 2013; G o r c z y c a et al. 2014).

METHODS

Geomorphological mapping was carried out on the basis of topographic map in the scale of 1:10,000 (www.geoportal.gov.pl) in order to recognize the detailed structure of the headwater valley segments and their catchments. Morphometric parameters (gradient of the valley bottom, channel width and depth) were measured in the field using hand clinometer and measure tape. Channel roughness, including log steps in forested catchments, was estimated using the metal chain method. This method involves the arrangement of a chain in the channel so as to reflect the irregularities in the channel bed and then measur-

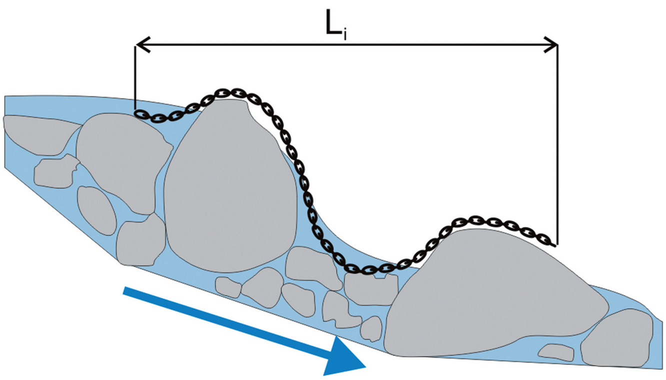

Fig. 2. Measurement of a channel roughness using the metal chain method. L_i – a length of the chain placed in the channel bed. An arrow indicates a direction of water flow

ing the “short” length of the chain (Fig. 2; Oostwoud Wijdenes et al. 2000). Channel roughness was next calculated as a ratio:

$$R= L_i/ L_t,$$

where L_i is the length of the chain placed in the channel bed and L_t is the total chain length (2 m). Therefore, the lower the ratio, the greater the channel roughness.

The statistical distribution of the data was examined using Shapiro-Wilk’s and Lilliefors’ tests at the significance level of $p \leq 0.05$. All of the dataset followed normal distribution. The analysis of the significance of differences in morphometric parameters values were calculated using the *t*-test (to compare the means of two groups) and ANOVA (to compare the means of more than two groups) at the significance level of $p \leq 0.05$, using STATISTICA 12 software.

GEOMORPHOLOGICAL CONDITIONS OF SELECTED SUB-CATCHMENTS

Sub-catchments located in the southern part of the study area are relatively small (0.22–0.66 km^2). Greater part of these catchments is located above the upper timberline. The valleys are not deeply incised. This part of the study area is typified by the presence of avalanche source areas without turf in the upper parts of the slopes (Fig. 3). Depending on the season and weather conditions they are exposed to the morphogenetic processes such as nivation, needle ice action and slope wash. Soil creep is common on steep slopes in the subalpine zone. The slopes are dissected by unchanneled valleys that are shaped mainly by creep and slope wash (Fidelus, Płaczkowska 2013). Rockfalls may occur from relatively few rock outcrops. The valleys are cut mainly in schists which generally break into small particles. Thus, the availability of rock material for debris flows is limited and this process does not play a significant role in the transformation of the studied valleys. The channel bed material consists mostly of cobbles and boulders (>64 mm). The lower parts of the slopes were transformed by glacial processes during the Pleistocene (Zasadni, Kłapyta 2014). Material transported by snow avalanches is accumulated in the downstream valley reaches. K. Krzemień et al. (1995) reported that the geomorphic role of snow avalanches in the study area is rather small and mostly results in the removal of turf from the slopes, thereby exposing the surface to other morphogenetic processes (Fig. 4). Avalanches also contribute to the accumulation of organic material in the channel, which then acts as traps for bedload. There are alluvial fans of different sizes at the mouth of the valleys but, as evidenced by the presence of vegetation cover, their recent transformation is limited. The only exceptions are areas of avalanche accumulation.

In the northern part of the study area the sub-catchments have more varied sizes that range from 0.10 to 1.14 km^2. The valleys are deeply incised with rocky

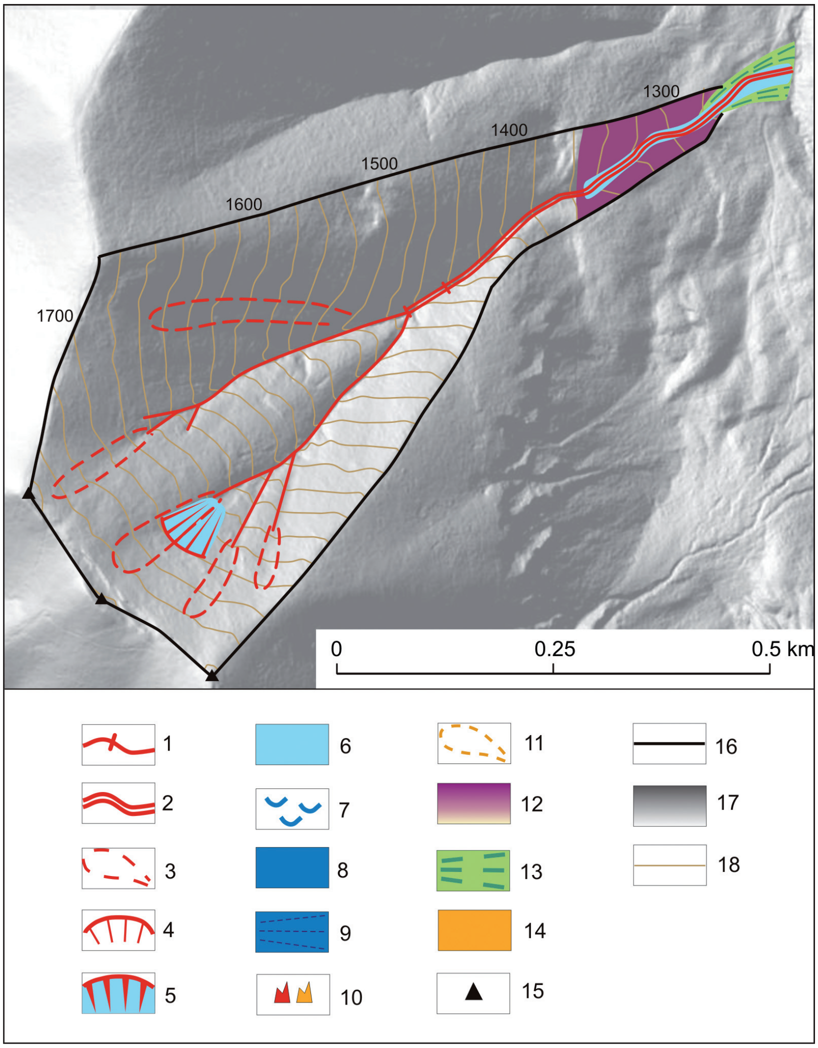

Fig. 3. Geomorphological map of a sub-catchment in the crystalline part of the Chochołowski Stream catchment. 1 – bottom of a headwater valley segment/rock step, 2 – bottom of a fluvial valley segment, 3 – unchanneled valley, 4 – landslide niche, 5 – avalanche source area, 6 – avalanche accumulation area, 7 – colluvial area, 8 – alluvial valley bottom, 9 – holocene alluvial fan, 10 – rock outcrop (holocene/pleistocene), 11 – pleistocene hollow, 12 – slope with moraine cover, 13 – Pleistocene alluvial fan, 14 – rocky walls, 15 – summit, 16 – ridge line or watershed, 17 – mountain slope, 18 – contour line

slopes and floors (Fig. 5). Steep slopes are transformed by landslides and creep (Fig. 6). In this part of the catchment the slopes are more dissected than in the southern part and creep hollows are common. The outlets of small piping channels can be observed at springs in the channel heads. Valley floors in the lower sections of the larger valley systems (Fig. 6) are covered with alluvium. Large

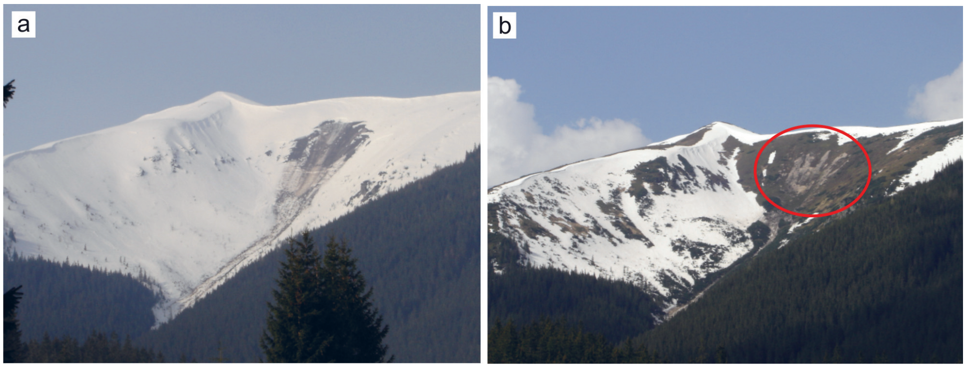

Fig. 4. Avalanche source area (a) with removed turf (b)

areas of limestone and dolomite outcrops with active rockfalls supply coarse debris and enable bedload transport during torrential flows or even debris flows. These processes occur quite rarely, but they cause fundamental transformation of the valleys in this part of the study area. Bed material consists mostly of cobbles and boulders (>64 mm), and the grain-size of the material transported in

Fig. 5. Rocky bottom and slopes of valley

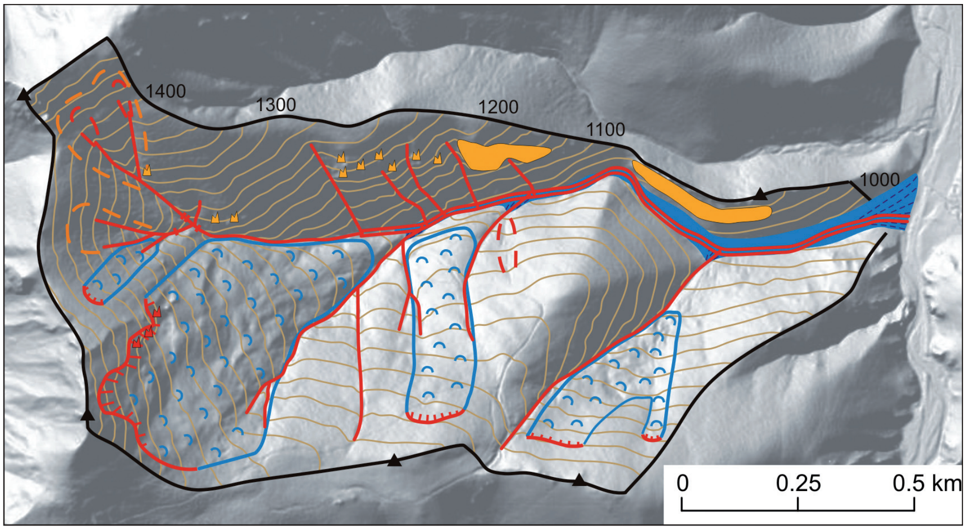

Fig. 6. Geomorphological map of a sub-catchment in the sedimentary part of the Chochołowski Stream catchment (description see Fig. 3)

the channel reaches 200 mm. Most of the bedload transferred downstream is directly supplied to the channel of Chochołowski Stream because the outlet parts of the valleys are very narrow and the alluvial fans are small in size. Bedload transported during torrential flows effectively transforms alluvial fans once every few years (Krzemień et al. 1995) and provides fresh debris which is not covered with vegetation (Fidelus, Płaczkowska 2013).

STRUCTURE OF THE HEADWATER VALLEY SEGMENT

Headwater valley segment begins mostly with unchanneled valley without well-defined banks (Fig. 7). The mean gradient of an unchanneled valley is 0.68 m m^{-1} in the crystalline part of the study area and 0.53 m m^{-1} in the sedimentary part, and it is significantly ($p \leq 0.05$) larger than the mean gradient of valley reaches located downstream (Fig. 8). At the end of the unchanneled valley there is usually a channel head, which is also a place where a spring is present and which is shaped by seepage erosion, piping and landslides. It is the beginning of a channel reach (colluvial channel) filled with coarse bed material without a clear sequence of *rock-woody debris steps* (Fig. 7). The mean channel gradient is relatively large, and it is 0.62 m m^{-1} in the crystalline part and 0.49 m m^{-1} in the sedimentary part. Such channel reaches have episodic or intermittent water flow, and in the case of a permanent drainage, the discharge is small. Colluvial channels are shaped by linear erosion, creep, needle ice action and slope wash. Such a channel reach can also be transformed by snow avalanches and debris

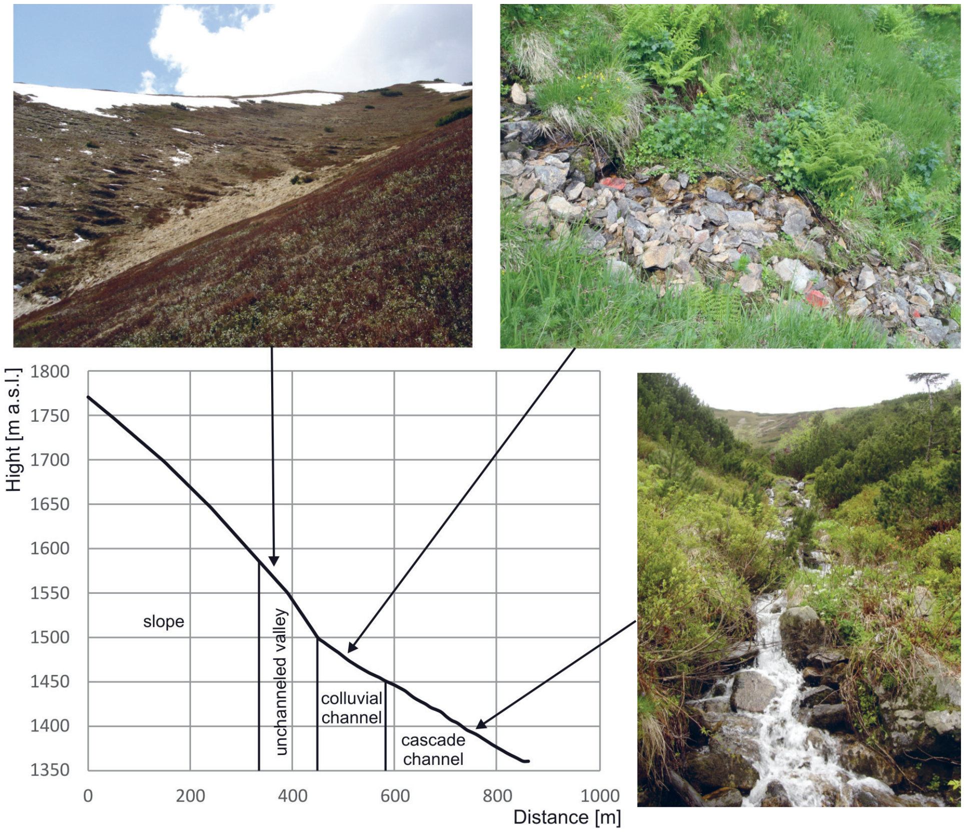

Fig. 7. Model of a longitudinal profile of the headwater valley segment in the Western Tatras

flows or beadload transport during torrential flows. Small single steps appear downstream where discharge increases.

The channel reach with the sequence of rock-woody debris steps, called *cascade channel* (Montgomery, Buffington 1997), is characterized by an uneven longitudinal profile which results from a greater discharge than in the upstream channel reach. The cascade channel generally lacks scour pools (Fig. 7). Between steps there are channel sections with finer bed material (<64 mm). Heights of rock-woody debris steps are 0.30–1.50 m in the crystalline part of the study area and 0.15–1.00 m in the sedimentary part and the average distance between the steps is 5 m and 15 m, respectively. Water flow might be discontinuous along the longitudinal profile of a channel and depends on the amount of water and bed material in the channel. The cascade channel is transformed by morphogenetic processes similar to those in the upstream channel reach, but the role of fluvial processes is more important. Above the upper timberline the channel may be transformed by nival processes and debris flows, while in the forest zone bedload transport during torrential flows is more active

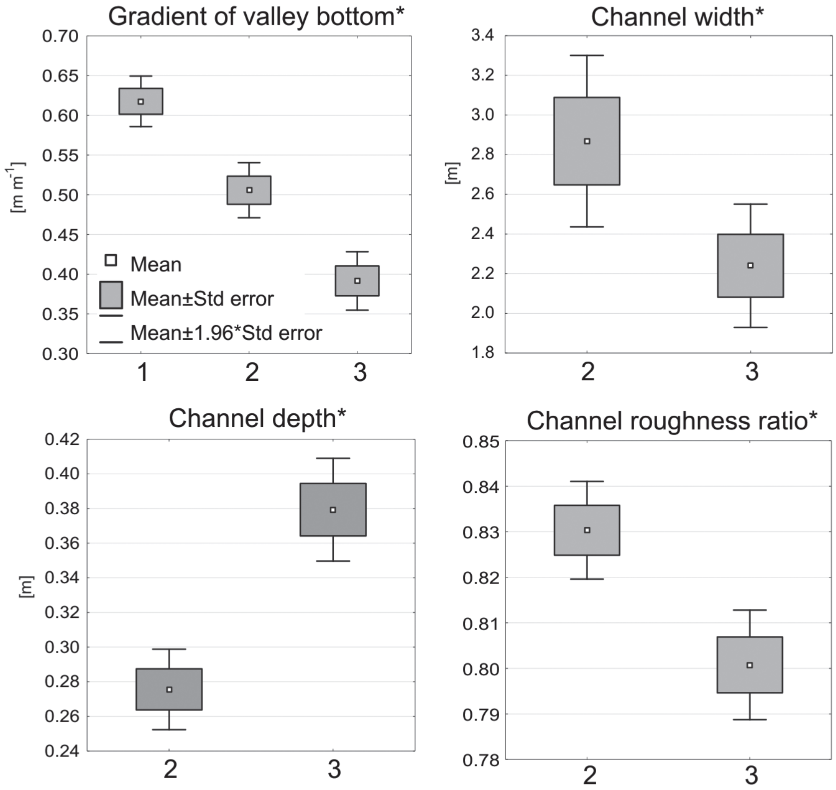

Fig. 8. Differences of morphometric parameters of valley reaches between unchanneled valleys (1), colluvial channels (2) and cascade channels (3) in the Western Tatras (*significant differences at level of $p \leq 0.05$)

because of the availability of coarse bed material. In the season without much rainfall the channel reach remains dry, and then it can be also shaped by creep, needle ice action or slope wash. The average gradient of a cascade channel is 0.44 m m^{-1} in the crystalline part and 0.38 m m^{-1} in the sedimentary part and it is the smallest among all headwater reaches of the valley. Furthermore, this channel reach has smaller width and greater depth and roughness than the colluvial channel (Fig. 8). With the increase in discharge and energy gradient in the downstream direction, scour pools appear between the steps and the cascade channel changes to a step-pool channel that is transformed mainly by fluvial processes.

Although the structure of the headwater valley segments in both parts of Chochołowski Stream catchment is similar, they differ in terms of morphometric parameters. The headwater valley segments in the crystalline part, above the upper timberline, are characterized by greater gradients, but smaller widths and roughness than the headwater valley segments in the sedimentary part of the study area (Fig. 9).

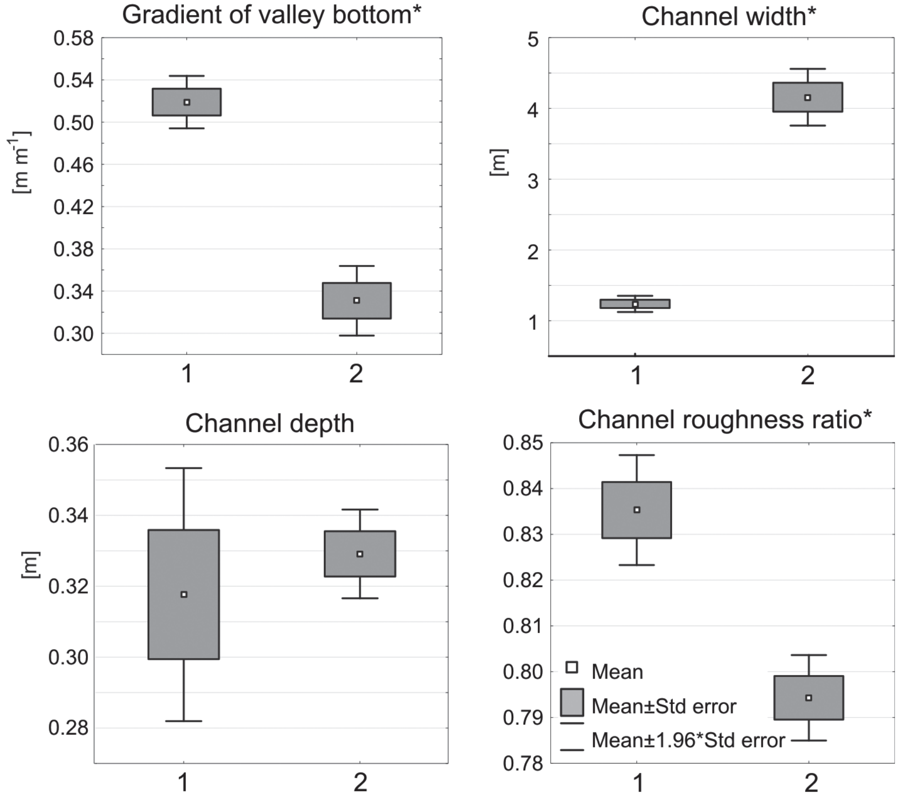

Fig. 9. Differences of morphometric parameters of headwater valley segments between crystalline (1) and sedimentary (2) part of the Chochołowski Stream catchment (*significant differences at level of $p \leq 0.05$)

THE HEADWATER VALLEY SEGMENT IN MOUNTAIN AREA

Headwater valley segments are polygenetic forms regardless of large-scale topography (mountains, uplands, lowlands). However, the type of morphogenetic processes that are decisive in the development of the headwater valley segment depends on the properties of bedrock, slope gradient and land use. Linear erosion and slope wash supported by needle ice action are important in the development of these forms, both in the study area and in other mountain areas in Poland (Starkel 1960; Parzóch 2001; Kasprzak 2005; Fidelus, Płaczkowska 2013). Mass movements further contribute to the transformation of the existing headwater valley segments and the formation of new landforms (Kotarba 1986; Wrońska-Wałach et al. 2013). Especially large landslides contribute to greater fragmentation of headwater areas. A similar relation was observed by D.R. Montgomery and W.E. Dietrich (1988, 1989) who reported that headwater areas transformed by mass movements are characterized by larger surface area and smaller gradients than those without active landslides. Thus, this is a typical result of the mass movement impact in the denudation system.

Piping, which is considered one of the main processes for the development of headwater valley segments in loess areas (Rodzik, Zgłobicki 2000; Jary, Kida 2002; Verachtert et al. 2010), plays a minor role in the study area. In contrast, in the eastern part of the Carpathians (Bieszczady Mts.) this process plays an important role in the development of the headwater valley network as it leads directly to the formation of new valleys and extending and deepening of the existing ones (Czeppe 1960; Galarowski 1976; Bernatek 2015). The headwater valley segments which are generated mostly by piping are often discontinuous in the longitudinal profile (Bernatek, Sobucki 2012), in contrast to the headwater valleys in the Tatras where they are usually connected to the fluvial system. Incision of headwater valley segments in the mountain areas is limited by bedrock and coarse weathered cover (Parzóch 2001; Fidelus, Płaczkowska 2013).

Similar to the majority of headwater valleys in mountain areas, the studied valleys are characterized by a V-shaped cross section, with a narrow floor and steep slopes, and uneven or convex longitudinal profile resulting from the activity of slope processes (Starkel 1960; Kaszowski 1965; Krzemień 1984). The structure of these valley segments depends mainly on the local geology and the location above or below the upper timberline which determines the type and intensity of morphogenetic processes (Gorczyca et al. 2014). Therefore, there are differences between morphometric parameters of headwater valley segments located in different parts of Chochołowski Stream catchment. Crystalline bedrock is more resistant to erosion and this is the reason for greater valley gradients in this part of the study area. More frequent bedload transport during torrential flows in forested catchments contributes to the increase in the rate of erosion and thus to the reduction in valley gradients and the increase in channel widths in the sedimentary part. Smaller channel roughness in the crystalline part of the catchment possibly results from the fact that metamorphic schists produce finer regolith than limestones and dolomites and from the lack of in-channel woody debris above the upper timberline.

CONCLUSIONS

The structure of a headwater valley segment in the longitudinal profile shows a pattern and follows a sequence of valley types: unchanneled valley → colluvial channel (channel without steps) → cascade channel. These valley types differ significantly ($p \leq 0.05$) in terms of morphometric parameters. In the downstream direction both valley floor gradient and channel width decrease but channel depth and roughness increase.

The structure of a headwater valley segment strictly depends on the environmental conditions in a mountain region, and may differ even in an area as small as the catchment of Chochołowski Stream. The headwater valley segments located in the crystalline part, above upper timberline and with more severe climate conditions are characterized by greater gradients but smaller widths and channel roughness than these located in the sedimentary part in forest zone.

As local environmental conditions may strongly affect the structure of headwater valley segments, especially in mountain areas, understanding the slope-to-valley transition still requires further research into headwater valley segments, particularly in areas with different geological and climate background.

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