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Contrasting patterns of wood storage in mountain watercourses narrower and wider than the height of riparian trees

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ABSTRACT

Large wood exerts a beneficial influence on the functioning of riverine and riparian ecosystems but can be also the source of flood risk. Several studies have recognised a trend of decreasing amounts of large wood on unit channel area with increasing width of mountain streams. This study verifies whether this trend can also be generalised for wide mountain rivers. Longitudinal wood distribution was compared for two watercourses in the Polish Carpathians: second- to fourth-order Kamienica Stream, 14 m wide on average, and the fifth-order Czarny Dunajec River with a mean width of 52 m. In the stream, both the number and the mean mass of wood deposits were unrelated to channel width, and this was reflected in a lack of the relationship between total wood storage (the amount of stored wood per channel length) and channel width. In turn, specific wood storage (the amount of stored wood per channel area) decreased nonlinearly with increasing channel width. In the wide Czarny Dunajec, the number and the mean mass of wood deposits increased as the river widened, and this was reflected in a marked trend of increasing total wood storage with increasing river width. Here, the width-related variation in total wood storage was so high that it overcame the influence of increasing channel area on calculated values of specific wood storage, which also increased with increasing river width. This study shows that different mechanisms known to govern large wood retention in the channels narrower and wider than the height of riparian trees are reflected in the contrasting patterns of wood storage in mountain watercourses of different relative width. Different relations between the tendencies of total and specific wood storage in the two types of channels emphasise the need of identifying the spatial density and the total amount of large wood.

1. Introduction

Extensive research carried out over recent decades has brought an increasing understanding of the beneficial influence that trees falling into river channels exert on the functioning of fluvial systems. Large wood increases flow resistance (Dudley et al., 1998; Merten et al., 2010), facilitating dissipation of stream energy (Gippel, 1995; Manga and Kirchner, 2000), and enhances the potential for in-channel sediment storage (Mosley, 1981; Keller et al., 1995). Wood deposits in channels increase their morphological complexity (Gurnell et al., 1995), hence leading to the increased variability of flow velocity (Gippel, 1995) and depth in the watercourses. Consequently, wood enhances availability and diversity of aquatic habitats in forest channels (Harmon et al., 1986; Gurnell et al., 1995; Gregory et al., 2003). It may also provide shelter from predation for riverine biota (Everett and Ruiz, 1993). Moreover, driftwood promotes establishment of vegetation on floodplains and channel bars (Abbe and Montgomery, 1996; Gurnell, 2007; Moggridge and Gurnell, 2009), facilitating development of islands and riparian forest (Fetherston et al., 1995; Gurnell et al., 2001; Gurnell and Petts, 2002; Mikuś et al., 2013) and increasing biocomplexity of terrestrial habitats in river corridors (Gurnell et al., 2005; Francis et al., 2008). At the same time, considerable damage can result from collision of floated wood with in-channel and bank structures, scour of bridge piers and abutments by the water jets induced by wood accumulations (Wallerstein, 2003), or elevation of flood stage by the wood jammed at bridge cross sections (Schmocker and Hager, 2011; Ruiz-Villanueva et al., 2013). The environmental benefits and the threats to property and infrastructure resulting from the occurrence of large wood in channels have stimulated interest in the pattern of its distribution in watercourses.

Many studies have indicated a tendency for the amount of large wood per channel area to decrease with the increasing stream width (e.g., Swanson et al., 1982; Bilby and Ward, 1989, 1991; Nakamura and Swanson, 1994; Bilby and Bisson, 1997; Chen et al., 2006; Comiti et al., 2006; Wohl and Jaeger, 2009; Rigon et al., 2012). This pattern of wood storage within the river network has been attributed to (i) generally invariable bank length, determining equal lateral input of wood, coupled with an increasing area of channel bed as width

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increases; (ii) an increasing mobility of wood as the ratio of piece length to channel width decreases; (iii) a downstream decrease in the importance of channel storage in favour of floodplain storage (Gurnell et al., 2002); and (iv) the elimination of valley sides as a source of large wood where streams emerge from narrow valleys onto wide valley floors (Wyżga et al., 2003; Seo and Nakamura, 2009).

The above-mentioned studies were mostly performed in the streams draining catchments up to 50 km^2 in area. The observation that streams at the downstream end of the study domain are supply-limited with respect to large wood (e.g., Marcus et al., 2002; Wohl and Jaeger, 2009) implies that the trend of decreasing spatial densities of wood continues in wider river channels. However, the trend also may be forced by human modification to channels in the lower reaches of the watercourses, which increases their transport capacity, and to riparian forests, reducing the amount and size of recruited wood. Under natural conditions, mountain rivers flowing in flat-bottomed valleys formed wide, multithread channels (Gurnell et al., 2009) with numerous forested islands in their active zone (Gurnell and Petts, 2002). The potential for large wood retention increases with decreasing depth (Haga et al., 2002; Montgomery et al., 2003; Bertoldi et al., 2013) and unit stream power of flood flows (Wyżga and Zawiejska, 2005, 2010; Rigon et al., 2012), which accompany channel widening of mountain rivers. The occurrence of wooded islands also enhances wood retention as trees growing within the river's active zone form obstacles against which wood pieces transported in the flow can be braced (Bocchiola et al., 2006). All this suggests that the trend of decreasing spatial densities of wood may reverse at some threshold channel width because of (i) decreasing ability of wood pieces to float at increasingly shallow flow and (ii) increasing potential for wood retention on roughness elements such as bars or vegetated islands. Indeed, recent studies have shown that considerable amounts of large wood may be stored in relatively natural, wide rivers (Gurnell et al., 2000a, 2000b) or unmanaged sections of wide rivers (Piégay and Gurnell, 1997; Piégay et al., 1999; Wyżga and Zawiejska, 2005, 2010).

Longitudinal patterns of wood storage in mountain watercourses of different size should be considered with the notion of the classification of river channels that relates their width to the length of wood pieces delivered to the channels (Gurnell et al., 2002; Gurnell, 2003). Based on this criterion, Gurnell et al. (2002) distinguished small, medium, and large rivers. However, the term "large rivers" is also used in physical geography to designate rivers draining catchments of vast size and conveying substantial flows (cf. e.g., Gupta, 2007). This meaning does not refer to mountain rivers that characteristically occur within the upper reaches of river networks, although they tend to exhibit large channel widths reflecting high width/depth ratio typical of bedload-dominated fluvial systems (Schumm, 1985). Therefore, while maintaining the sense of the subdivision introduced by Gurnell et al. (2002), in this paper we write about narrow, medium, and wide watercourses (cf. also Wyżga and Zawiejska, 2005) instead of small, medium, and large ones. In narrow headwater streams, trees falling to the channels are longer than the channel width and even if some of them break up during fall, the majority of the resultant wood pieces are longer than the channel width. Large wood pieces in such streams are relatively immobile and remain where they enter the channels. In watercourses of medium width, only a small proportion of wood pieces are long enough to span the channels, whereas most pieces are shorter than the channel width and can be transported during floods until they become anchored on stable, longer wood pieces, boulders and bedrock exposures in the channels, or on trees growing along channel margins. Finally, in wide watercourses, all trees fallen to the channels are shorter than the channel width and can be transported by flood water until they become anchored to a roughness element such as a bar or an island.

The amounts of stored wood can be expressed in relation to channel area or channel length. Most of the previous studies on large wood indicated its amount per channel area (in this study called specific wood storage) as this parameter allows comparison between watercourses of different size. The amount of wood per channel length (in this study called total wood storage) was analysed in very few studies (Hering et al., 2000; Wyżga and Zawiejska, 2010; Wohl and Cadol, 2011). However, this parameter also deserves attention as it is useful for characterising such environmental features as the absolute abundance of wood-related habitat features or the amount of wood that might be flushed out to downstream channel sections during a flood. Moreover, it jointly reflects variations in the number of wood deposits and in their average mass/volume along a river (Wyżga and Zawiejska, 2010). The character of the interaction between wood pieces and channel boundary in watercourses of different size, described above, suggests that the distribution pattern of stored wood differs between channels narrower and wider than the height of trees growing on the banks.

In this paper we use raw data collected for the study on large wood storage in the Czarny Dunajec River (Wyżga and Zawiejska, 2005, 2010) and compare them with the results of recent wood inventory in Kamienica Stream, Polish Carpathians, to contrast the patterns of wood storage in mountain watercourses narrower and wider than the height of riparian trees. The paper aims to demonstrate and explain how the patterns of total and specific wood storage change with changing channel width and how the two parameters are related in both types of watercourses.

2. Study areas

Watercourses with marked variability of channel width were selected for the study (Table 1). Kamienica Stream drains the Outer Western Carpathians (Beskidy Mountains) in southern Poland (Fig. 1A). Its catchment, underlain by flysch, comprises mountains of medium height, with the highest peak at 1311 m asl. In its upper course, the stream runs through a narrow, mostly V-shaped valley within the Gorce Mountains National Park (established in 1980), where 90% of the catchment area is covered by forest. The investigations were carried out along 7.0 km of stream length in two reaches located at 0.3–4.9 km and 6.7–9.1 km from the stream source (Fig. 1B). The catchment area increases from 0.1 km^2 at the beginning of the first reach to 14.9 km^2 at the end of the second reach (Table 1). Channel slope decreases from 0.1 m m^{-1} in the uppermost studied segments of the stream to 0.035 m m^{-1} in the lowermost ones, and its average value is 0.059 m m^{-1} (Table 1). Kamienica is a second- to fourth-order stream in the upper reach and a fourth-order stream in the lower reach. The surveyed reaches are located in the strict reserve of the national park, and no large wood has been removed from them since the national park was established in 1980.

The section between 4.9 and 6.7 km of the stream length was omitted because of difficult access and safety reasons (unstable boulders on the valley slopes), but channel morphology and the character of wood deposition in it do not differ from those typifying the adjacent channel sections. Instead, the change in these characteristics occurs rather at the boundary between the second- and third-order sections of the stream. In the 2.1-km second-order section, the channel occupies the whole width of the valley bottom and its width amounts to 5.9 m on average, varying between 4.0 and 9.0 m. The stream exhibits a step-pool channel pattern, with numerous steps developed on wood dams (Kaczka, 2003, 2009), and most wood pieces are oriented perpendicular to the channel (Kaczka, 1999; Wyżga et al., 2003). In the third- and fourth-order stream sections 1.2 and 5.5 km in length, respectively, downstream variability in the resistance of flysch rocks is reflected in the alternation of V-shaped and flat-bottomed valley morphology. Here, channel widths are 10.3 m on average and vary irregularly between 6.0 and 20.9 m, with step-pool channel pattern occurring in narrower parts of the stream and riffle-and-pool pattern in its wider parts. Wood dams are scarce (Kaczka, 2003, 2009), and the longitudinal and oblique orientation of wood pieces predominate (Kaczka, 1999; Wyżga et al., 2003).

Stream banks are almost fully forested, with the upper subalpine forest composed of spruce (*Picea abies*) occurring to about 8 km of the stream length (to an altitude of 850 m) and the subalpine forest with spruce, beech (*Fagus sylvatica*), and fir (*Abies alba*) growing farther