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Environment-friendly reduction of flood risk and infrastructure damage in a mountain river: Case study of the Czarny Dunajec

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A B S T R A C T

Migration of a mountain river channel may cause erosional risk to infrastructure or settlements on the valley floor. Following a flood of 2010, a cutbank in one of the bends of the main channel of the Czarny Dunajec, Polish Carpathians, approached a local road by 50 m. To arrest the erosion of the laterally migrating channel, water authorities planned construction of a ditch cutting the forested neck of the bend, reinforcement of the ditch banks, and damming the main channel with a boulder groyne. In order to avoid channelization of the highly valued, multithread river reach that would deteriorate its ecological status and cause increased flood risk to downstream reaches, an alternative approach to prevent bank erosion was proposed. The new scheme, applied in 2011, included opening of the inlets to inactive side braids located by the neck of the bend of the main channel. This solution reestablished the flow in the steeper low-flow channels, allowing us to expect a cutoff and abandonment of the main channel during subsequent floods. Gravelly deflectors were constructed directly below the inlets to the reactivated side channels to divert the flow into the channels and prevent the water from entering the main channel. Hydraulic measurements performed before and after the implementation of the scheme confirmed that it enabled shifting the main water current, with the highest average velocity and bed shear stress, from the braid closest to the road to the most distant braid. Similar surveys of fish and benthic macroinvertebrate communities indicated that flow reactivation in the side channels was beneficial for these groups of river biota, increasing their abundance and taxonomic richness in the reach. Not only was the implemented solution significantly less expensive, but it also enhanced ecological functions of the multithread channel and the variability of physical habitat conditions and maintained the role of the reach as a wood debris trap. However, avulsion of the main channel in the river bend immediately upstream during the flood in May 2014 again caused erosional risk to the road, although at another location. This indicates that with the highly unstable, multithread channel pattern of the Czarny Dunajec, the best practice of river maintenance in a relatively unmanaged valley reach would be allowing free channel migration within the floodplain area and reinforcing, where necessary, the boundary between the erodible river corridor and the managed terrace.

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1. Introduction

Floods are not only a powerful agent of geomorphic change in rivers and valley floors but also a considerable hazard to human property and life (Merritts, 2011). Therefore, people have long attempted to mitigate the flood hazard, modifying rivers (e.g., channelization, dam construction) and placing protection structures along the channels (Bravard and Petts, 1996). Such attempts were especially important in mountain areas where floods have high energy, and are thus highly erosive, and where settlements are frequently located on valley floors. However, the high energy of mountain watercourses, making them highly hazardous for man, is also the reason for their high sensitivity to human disturbance. Over the last decades it has become increasingly evident that traditional, hard-engineering solutions to the reduction of flood risk result in a number of detrimental effects, such as reduced complexity of river habitats (Stanford et al., 1996; Muhar and Jungwirth, 1998) and the impoverishment of river communities (e.g., Roux et al., 1989; Muhar et al., 2008), a loss of geomorphic dynamic equilibrium leading to river incision (Darby and Simon,

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1999; Wyżga, 2001; Habersack and Piégay, 2008), and an increase in flood peaks downstream of the modified reaches (Wyżga, 1996).

The recognition of negative impacts of river-engineering disturbances has stimulated numerous restoration activities (e.g., Hillman and Brierley, 2005; Habersack and Piégay, 2008) and the development of environment-friendly methods of river management. The latter are a diverse group of methods from a long-term management of rivers based on the geomorphological approach to a balanced functioning of fluvial systems (Thorne et al., 1997; Bravard et al., 1999) through the use of new techniques of bank or bed stabilization (e.g., Bariteau et al., 2013; Cavaillé et al., 2013) to the concept of increased space for rivers based on a comparison of the long-term costs of lost or limited human use of riparian areas and the benefits of avoiding costs of protecting these areas by means of hard-engineering structures (Piégay et al., 2005; Buffin-Bélanger et al., 2015).

The integration of geomorphic and ecological knowledge is crucial for the success of these river management actions, be they restoration or environment-friendly management activities (Kondolf et al., 2003). However, many such activities are not subjected to the evaluation of their ecological effects and/or long-term monitoring of river functioning. At the same time, many such actions fail in achieving their ecological aims (Palmer et al., 2010) or in the long-term persistence of their geomorphic and hydrological effects (e.g., Kondolf et al., 2001; Geerling et al., 2008). Thorough evaluation of geomorphic and ecological effects of the actions is thus essential for gaining and sharing knowledge on the utility of new river management methods (Gumiero et al., 2013).

River bank erosion and the associated channel migration during floods can present serious problems to river engineers and local communities through a loss of riparian lands and danger to valley-floor infrastructures and settlements (Lawler et al., 1997; Merritts, 2011). At the same time, bank erosion is a geomorphic process promoting riparian vegetation succession and creating dynamic habitats for aquatic and riparian biota; as such, it is a crucial attribute of fluvial systems (Florsheim et al., 2008). A preventive measure to the hazard caused by bank erosion, traditionally employed by water managers in the Polish Carpathians and many other areas worldwide, was river channelization combined with bank reinforcement. With a large number of detrimental effects of this hard-engineering solution apparent in the rivers of the region (Wyżga, 2001; Bojarski et al., 2005), its further use should be limited to valley sections with urbanised riparian areas; whereas in undeveloped valley sections environment-friendly methods of managing the erosional hazard should be employed. For instance, rivers can be allowed to develop their channels freely within the delimited space on valley floors (e.g., Piégay et al., 2005; Rohde et al., 2005), with the measure requiring a complete change in the paradigm of the management of river mobility (Piégay et al., 1996). Another option is a localized intervention relocating the path of high-velocity flow within the river's active zone away from the bank threatened by erosion.

In the nineteenth century the valleys of floodplain rivers in European mountains were typified by a lack or only a scarce occurrence of riparian forest (Kondolf et al., 2002; Rinaldi et al., 2013), and the same situation was also typical of the valleys of Polish Carpathian rivers (Wyżga et al., 2012b, 2015a). In the twentieth century an expansion of riparian forest took place in river valleys of the Polish Carpathians (Wyżga et al., 2012b, 2015a) and other mountain areas in Europe (Rinaldi et al., 2013). One of the effects of this environmental change is the rapid recruitment of substantial amounts of large wood to river channels during floods (Wyżga, 2007); subsequent transport and deposition of the wood at critical river sections such as bridges can be an important factor of flood risk in mountain watercourses (Ruiz-Villanueva et al., 2013; Kundzewicz et al., 2014; Hajdukiewicz et al., 2016, in this issue). To mitigate the risk, engineering structures can be constructed in smaller watercourses to trap wood from floodwater upstream of urbanised valley reaches (Comiti et al., 2012). In floodplain rivers, wide, multi-thread channel sections can trap considerable amounts of large wood as they exhibit high retention potential reflecting relatively low unit stream power, the occurrence of a complex network of interconnected channels, and the abundance of retention features such as bars or islands (Wyżga and Zawiejska, 2010).

In this paper, we present an environment-friendly measure applied to reduce erosional risk to valley-floor infrastructure in the multithread reach of the mountainous Czarny Dunajec River in southern Poland. The study aims (i) to explain erosional risk to valley-floor infrastructure in terms of geomorphic tendencies of the river in periods with different flood characteristics; (ii) to discuss potential effects of hard-engineering and environment-friendly solutions to the reduction of the erosional risk on large wood-related flood hazard to downstream river reaches; (iii) to verify hydraulic and environmental effects of the applied environment-friendly measure; and (iv) to assess long-term suitability of the measure.

2. Field setting

Located in the Inner Western Carpathians in southern Poland, the Czarny Dunajec (Fig. 1) is one of two headwater watercourses of the Dunajec, the second largest Carpathian tributary to the Vistula River. The headwater part of the Czarny Dunajec is situated in the high-mountain Tatra massif, with elevations in the catchment up to 2176 m asl. The river rises at an altitude of about 1500 m; and in the Tatra Mountains foreland, it flows 38 km, joining with the Biały Dunajec River at 578 m asl (Fig. 1).

The Tatra part of the catchment has cool to moderately cold climate with annual precipitation ranging from 1200 to 1700 mm (Niedźwiedź and Obrębska-Starklowa, 1991; Niedźwiedź et al., 2015). The Tatra Mountains foreland has moderately cool climate and annual precipitation totals ranging from 800 to 900 mm in the Orawa–Nowy Targ basin to 900–1200 mm within the Gubałówka hills (Niedźwiedź and Obrębska-Starklowa, 1991). The high-mountain part of the catchment determines the hydrological regime of the river, with low winter flows and floods occurring between May and August; the latter typically are caused by a few days long orographic rainfall (Niedźwiedź et al., 2015), sometimes superimposed on snowmelt runoff.

Throughout most of the Holocene the Czarny Dunajec flowed in a multithread channel formed on a noncohesive, coarse-grained alluvial plain in the foreland of the Tatra Mountains (Wyżga et al., 2015a). In the twentieth century, and especially in its second half, considerable channel changes took place in this river section (Zawiejska and Wyżga, 2010; Wyżga et al., 2012b). In-channel gravel mining and channelization works resulted in the change of the former multithread channel pattern to a single-thread one, which was combined with considerable narrowing and incision of the river in most of its foreland course (Zawiejska and Krzemień, 2004; Zawiejska and Wyżga, 2010). These channel changes have led to considerable degradation of the hydromorphological river quality (Wyżga et al., 2010) and the impoverishment of fish and benthic macroinvertebrate communities (Wyżga et al., 2009, 2012a) in the modified reaches. In unmanaged reaches the river retained its multithread morphology; but with a reduction in catchment sediment supply and the resultant decrease in the river dynamics in the twentieth century, the former bar-braided channel pattern changed to an island-braided one (Wyżga et al., 2012b) and an average width of the river's active zone decreased approximately by one-third. Where the multithread morphology was preserved, the river maintains vertical channel stability or slowly aggrades (Zawiejska and Wyżga, 2010) and its hydromorphological quality is high (Wyżga et al., 2010). With greater complexity of physical habitat conditions than in the modified single-thread reaches, the multithread channel exhibits relatively high diversity of fish and benthic macroinvertebrate communities (Wyżga et al., 2009, 2012a). Moreover, the occurrence of vegetated islands at various stages of development highly contributes to the overall floristic diversity of the river corridor (Mikuś et al., 2013).

In the nineteenth century the valley floor and the active zone of the Czarny Dunajec were practically devoid of forest as a result of

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