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Modelling the flooding capacity of a Polish Carpathian river: A comparison of constrained and free channel conditions

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ABSTRACT

The gravel-bed Biała River, Polish Carpathians, was heavily affected by channelization and channel incision in the twentieth century. Not only were these impacts detrimental to the ecological state of the river, but they also adversely modified the conditions of floodwater retention and flood wave passage. Therefore, a few years ago an erodible corridor was delimited in two sections of the Biała to enable restoration of the river. In these sections, short, channelized reaches located in the vicinity of bridges alternate with longer, unmanaged channel reaches, which either avoided channelization or in which the channel has widened after the channelization scheme ceased to be maintained. Effects of these alternating channel morphologies on the conditions for flood flows were investigated in a study of 10 pairs of neighbouring river cross sections with constrained and freely developed morphology. Discharges of particular recurrence intervals were determined for each cross section using an empirical formula. The morphology of the cross sections together with data about channel slope and roughness of particular parts of the cross sections were used as input data to the hydraulic modelling performed with the one-dimensional steady-flow HEC-RAS software. The results indicated that freely developed cross sections, usually with multithread morphology, are typified by significantly lower water depth but larger width and cross-sectional flow area at particular discharges than single-thread, channelized cross sections. They also exhibit significantly lower average flow velocity, unit stream power, and bed shear stress. The pattern of differences in the hydraulic parameters of flood flows apparent between the two types of river cross sections varies with the discharges of different frequency, and the contrasts in hydraulic parameters between unmanaged and channelized cross sections are most pronounced at low-frequency, high-magnitude floods. However, because of the deep incision of the river, both cross section types are typified by a similar, low potential for the retention of floodwater in floodplain areas. The study indicated that even though river restoration has only begun here, it already brings beneficial effects for flood risk management, reducing flow energy and shear forces exerted on the bed and banks of the channel in unmanaged river reaches. Only within wide, unmanaged channel reaches can the flows of low-frequency, high-magnitude floods be conveyed with relatively low shear forces exerted on the channel boundary. In contrast, in channelized reaches, flow velocity and shear forces are substantially higher, inevitably causing bank erosion and channel incision.

1. Introduction

During the last century or more, a vast majority of mountain rivers in densely populated regions were severely modified by channelization and/or channel incision (e.g., Bravard and Petts, 1996; Habersack and Piégay, 2008; Wyżga, 2008). Apart from their adverse effects on physical habitat conditions in mountain rivers, these disturbances have also modified flood conditions in mountain and foreland reaches of the rivers. Floods on mountain rivers typically are highly erosive and most flood damage on the rivers is associated with the erosion of channel boundary coupled with abrupt lateral channel movement rather than with valley-floor inundation. Straightening and narrowing of mountain rivers in the course of their channelization increases flow velocities and unit stream power associated with given discharges (Wyżga, 1993, 2001a), and usually the increase is further augmented by inducing bed degradation and the resultant increased concentration of flows in the deepened channels (Wyżga, 2001b; Wyżga et al., 2016-in this issue). This may lead to a dramatic channel widening during an extreme flood when the tractive forces become sufficiently large to overcome the resistance of artificially reinforced channel banks (Naef and Bezzola, 1990). Flow concentration in incised channels limits channel–floodplain connectivity to major flood events (Croke et al., 2013); this considerably reduces the role of floodplains along incised rivers as sediment sinks during floods (Wyżga, 2001b) and enhances the potential of sediment-laden channel flows for scouring channel boundaries. Finally,

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a reduction in the floodwater retention on floodplains caused by the concentration of flood flows in the incised channels reduces attenuation of flood waves, with the resultant increase in flood hazard to downstream river reaches (Wyżga, 1997).

With increasing recognition of the detrimental effects of river channelization and incision, several river restoration techniques were proposed that either directly aimed at reducing flood risk or the reduction was a valuable byproduct of the activities focused on the improvement of the ecological river state. Construction of stone weirs in incised streams (Shields et al., 1995) not only improves physical habitat conditions for aquatic biota but also reduces flow capacity of the channels. Reconstruction or reconnection of secondary channels along channelized rivers (Schropp, 1995; Hornich and Baumann, 2008; Muhar et al., 2008) increases channel storage of floodwater and reduces bed shear stress in the channel during flood events. Construction of a compound channel through floodplain excavation along an incised stream (Fischenich and Morrow, 2000) reconnects the channel to a new floodplain, allowing high flows to spread over a wider cross-sectional area and thus reducing their erosional power (MacWilliams et al., 2010). Floodplain restoration attained through the removal or relocation of embankments farther away from the channel increases floodwater retention on the floodplain reflected in decreased peak flows downstream (Acreman et al., 2003). A reduction in downstream-recorded peak flows also may be attained as a result of forest establishment on the floodplain (Thomas and Nisbet, 2007) as it increases water stages and thus also the retention of floodwater at the site.

While the above-mentioned measures focus on the restoration of channel/floodplain forms (Smith and Prestegaard, 2005) rather than on reestablishing natural processes and consist in modification of single elements of modified rivers, such restoration projects have only limited beneficial impact on the river ecosystems and their hydraulic and hydrological effects may be temporary. For instance, the hydraulic effect of floodplain excavation along the Waal River, The Netherlands, was lost after only nine years as a result of accelerated sediment accretion on the lowered floodplain coupled with lateral channel stability and the resultant lack of erosion of riverbank sediments (Geerling et al., 2008). More comprehensive and sustainable effects may be associated with reestablishing a natural course of fluvial processes within erodible river corridors (Piégay et al., 2005). In recent years the concept of erodible river corridor has been increasingly often applied in European countries (e.g., Rohde et al., 2005; Nieznański et al., 2008; Rinaldi et al., 2009).

At the end of the 2000s an erodible corridor was established in two sections of the Biała, a Polish Carpathian river that was previously heavily modified by channelization and channel incision. Viability of the concept on the Biała was soon proved during the passage of an 80-year flood in June 2010, during which most flood damage occurred in channelized river reaches and only its tiny percentage affected freely developing river reaches within the erodible river corridor (Hajdukiewicz et al., 2016-in this issue). The flood considerably increased channel width in the unmanaged reaches, hence initiating the reestablishment of more close-to-natural functioning of the river within the erodible corridor. In 2013 we performed a field survey on the Biała followed by numerical modelling of the data with HEC-RAS software to determine the effects of the river functioning in the erodible corridor on flood conditions. This study uses results from the modelling to answer the following questions:

- How do particular hydraulic parameters of flood flows differ between neighbouring, unmanaged and channelized river cross sections?
- How does the pattern of differences in all studied hydraulic parameters of flood flows among the cross sections vary with the discharges of different frequency?
- What is the potential of unmanaged and channelized river cross sections for the conveyance and the retention of floodwater at the discharges of given frequency?

2. Materials and methods

2.1. Study area

The Biała is a 102-km-long, gravel-bed river in the Polish Carpathians (Fig. 1). It drains a catchment of 983 km^2, flowing north through the low mountains of Beskid Niski, the Ciężkowice foothills, and the submontane Sandomierz basin. The first two physicogeographical units represent more than 90% of the catchment area (Fig. 1) and are underlain by flysch complexes of different lithology and resistance to erosion. In its mountain course, the Biała is fed with coarse to medium-sized sandstone material; and in unmanaged channel reaches, it forms a wide, multithread channel. In the foothill course, the river flows across alternating sandstone and shale complexes delivering cobble to pebble clasts together with large volumes of fines to its channel; here, the Biała tends to form a sinuous channel in its unmanaged reaches.

Annual precipitation totals in the catchment range from ca. 950 mm in its highest parts to 650–700 mm in the lowest parts (Niedźwiedź and Obrębska-Starklowa, 1991), with the respective values of the coefficient of runoff varying from 50% to <30% (Dynowska, 1991). At the Ciężkowice gauging station located at 58 km from the river source (catchment area of 526 km^2; Fig. 1), mean annual discharge amounts to 5.9 $m^3 s^{-1}$, and the average for the maximum annual discharge is 203 $m^3 s^{-1}$. The hydrological regime of the river is typified by frequent, moderate floods caused by snowmelt and rare occurrence of large floods resulting from summer rainfall.

In the twentieth century, and especially in its second half, the Biała was considerably modified by human activities. Channel narrowing and the simplification of flow pattern caused by channelization works increased river transport capacity (cf. Wyżga, 1993, 2001a), whereas uncontrolled, widespread in-channel gravel mining (Rinaldi et al., 2005; Wyżga et al., 2010) reduced availability of bed material for fluvial transport. As a result of these impacts, the river width decreased by up to a sixth of its value from the second half of the nineteenth century and the channel incised by up to 2 m in the lower part of the mountain course and along the foothill course of the Biała. These channel changes might have been aggravated by a reduction in catchment sediment supply (Lach and Wyżga, 2002) induced by a considerable increase in forest cover in the mountains in the second half of the century (Kozak et al., 2007).

A number of adverse effects of channel regulation and incision were recognized in Polish Carpathian rivers, including reduced floodplain inundation at given flood discharges (Wyżga, 2001b) leading to increased flood hazard to downstream river reaches (Wyżga, 1997, 2008) as well as decreased physical habitat complexity (Wyżga et al., 2012) and the resultant degradation of the ecological state of the rivers (Wyżga et al., 2013). Aimed to mitigate the adverse effects of the channel changes and to initiate river recovery, an erodible corridor was delimited in the mountain and foothill sections of the Biała with the length of 14.5 and 5.9 km, respectively (Fig. 1). However, as a few bridges occur on the river in the sections, each section of the corridor consists of alternating longer (1–3 km) unmanaged reaches and shorter (0.1–0.3 km) channelized reaches in the vicinity of bridges.

We selected 10 sites for the study; 7 sites are located in the upper section of the erodible corridor in the mountain river course and 3 other in the lower section of the corridor in the foothill course of the Biała (Fig. 1). Each study site consists of a pair of cross sections located in neighbouring unmanaged and channelized reaches. These pairs of cross sections are situated between major tributaries (Fig. 1) and thus represent similar hydrological conditions. At 6 sites the cross section running across the unmanaged reach is located upstream of that from the channelized reach and the opposite situation occurs at the remaining 4 sites. The analysed cross sections are located at a distance of 8.2 to 44.3 km from the river source and characterize catchments with an area between 17.3 and 365 km^2.