Potential large wood-related hazards at bridges: the Długopole bridge in the Czarny Dunajec River, Polish Carpathians

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ABSTRACT

Interaction between riparian vegetation and geomorphic processes in mountain streams can be amplified by abundant wood delivery to channels, high stream power and high sediment transport rates. At critical sections such as bridges, a quick succession of backwater can occur as a result of the reduction of the cross-sectional area. The aim of this work is to analyze wood transport and deposition during floods in the Czarny Dunajec River (Polish Carpathians) where it flows through the village of Długopole with a very narrow bridge cross-section. A numerical model which simulates the transport of large wood together with flow dynamics is applied and inlet and boundary conditions are determined based on field observations. Preliminary results showed that the bridge is easily clogged with wood under certain circumstances, although the blocking ratio and the probability of a log to be blocked depend on several factors. The final results will provide data to compute bridge clogging probability under the designed scenarios, and the potential impacts of the clogging on flood hazard.

KEYWORDS

driftwood, woody debris, clogging, flood, hazard

INTRODUCTION

The high potential risk associated with (flash) floods in mountain watercourses is a result of a rapid and complex hydrological catchment response (Borga et al., 2014). Besides high water levels in the drainage network, sediment transport and important morphological changes, the transport of large quantities of woody material must be considered an additional factor of flood risk in forested catchments (Mazzorana et al., 2011; Mao et al., 2013; Ruiz-Villanueva et al., 2014a). Interaction between riparian vegetation and geomorphic processes in mountain streams is amplified by abundant wood delivery to the channels, high stream power and high sediment transport rates. Recent floods across Europe highlighted some effects caused by large wood. An example can be the flood of August 2005 in Switzerland when, apart from flooding and enormous morphological changes in the streams, considerable amounts of wood

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were mobilized and deposited, resulting in high damage costs (Badoux et al., 2014; Rickenmann et al., 2015).
Large wood (LW) in rivers has been described in the scientific literature since the 1970s (Swanson et al., 1976; Harmon et al., 1986; Montgomery et al., 2003). The presence of LW in river systems has been demonstrated to have very positive effects, for instance by enhancing the hydromorphological diversity of riverine habitats and representing a source of organic matter in channels (Gregory et al., 2003; Wohl, 2013; Beckman and Wohl, 2014). Therefore, management of LW has evolved in many regions and some forest management plans include guidelines to maintain riparian forest density (i.e. number of trees per unit area),buffer width and instream LW abundance (Spence et al., 1996).

However, conflicts are usually greater in urban environments (Piégay and Landon, 1997), where the threat to infrastructure and public safety drives the most common management responses: to remove LW from the channel or to install debris racks to intercept LW transport (Bradley et al., 2005). Thus, LW management in urban areas implicitly assumes that wood is a problem and needs to be removed, with the practice resulting in degradation of aquatic habitats. It has been proved that wood removal often fails to prevent flooding, in part because of new input of LW during floods (Young, 1991; Gippel, 1995; Dudley et al., 1998). A more sustainable approach to manage LW in urban catchments is to redefine the problem as the inability of infrastructure to pass LW through the system (Lassettre and Kondolf, 2012). An alternative might be to modify the infrastructures. In addition the processes of LW input, storage and transport through the channel network might be accommodated by preserving zones of LW recruitment (forested hillslopes and riparian corridors) and areas of LW storage (gravel bars and floodplains) and maintaining pathways of LW transport, retaining the important ecological functions of LW (Lassettre and Kondolf, 2012).

The first step in the improved LW management is therefore to identify the critical structures and the potential consequences in case of clogging. The partial clogging of bridges can cause a quick succession of backwater effects due to the reduction of cross-sectional area, which is accompanied by bed aggradation, channel avulsion and local scouring processes, which can ultimately lead to embankment/bridge collapse and floodplain inundation (Diehl, 1997; Comiti et al., 2007; Lyn et al., 2007; Mao and Comiti, 2010; Comiti et al., 2012; Badoux et al., 2015; Lucía et al., 2015). As a result, flooded areas are likely to be different from those predicted from models where the presence of wood is not considered (Ruiz-Villanueva et al. 2013), and therefore, this may result in the incorrect/uncertain estimation of flood risk.

The ongoing research project FLORIST (Flood risk on the northern foothills of the Tatra Mountains), funded by the Polish-Swiss Joint Research Programme, aims at improving flood risk analysis in the region, including the analysis of large wood (Kundzewicz et al., 2014). During recent floods in Poland, such as those from 2001, 2010 and 2014, large quantities of wood were transported by mountain rivers, and large deposits of wood accumulated at some bridge cross-sections, with adverse consequences (Hajdukiewicz et al, 2015). Wood deposits increased the hazardousness of the floods, with some of the above-mentioned effects. Therefore, the aim of this work is to analyse potential hazards related to wood transport and deposition at bridges during floods. We focused our investigations on the Czarny Dunajec River in the Tatra Mountains foreland (Polish Carpathians), where the river flows through the village of Długopole. Buildings in the village are located very close to the river and the bridge has a narrow cross-section (27 m) and is thus threatened by wood-related phenomena. This paper describes ongoing work within the FLORIST project and only preliminary results can be shown here.

STUDY SITE

The Czarny Dunajec (Figure 1) drains the Inner Western Carpathians in southern Poland. The river rises at about 1500 m above sea level (a.s.l.) in the high-mountain Tatra massif, with the highest peak in the catchment at 2176 m a.s.l. In the Tatra Mountains foreland, the river formed a non-cohesive alluvial plain consisting of resistant granitic and quartzitic particles transported from the Tatras and sandstone gravel delivered to the Czarny Dunajec in the upper part of the foreland reach (Wyżga and Zawiejska, 2005).

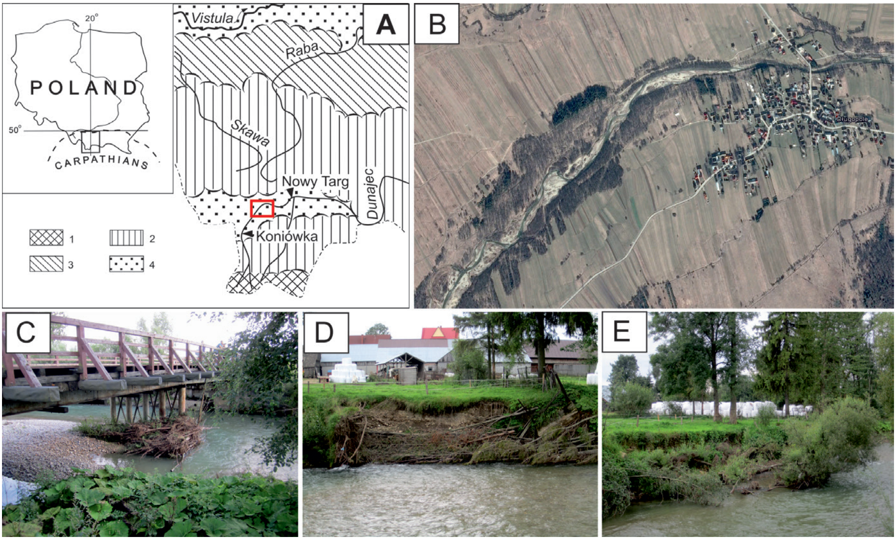

Figure 1: (A) Location of the study area in the Polish Carpathians and location of the Czarny Dunajec River in relation to physiogeographic regions of southern Poland. Red rectangle indicates the study reach shown in panel B. 1 – high mountains; 2 – mountains of intermediate and low height; 3 – foothills; 4 – intramontane and submontane depressions; (B) Czarny Dunajec study reach upstream of the Długopole bridge; (C) view of the bridge from the left, upstream bank; (D) bank erosion and wood recruitment on the right bank a few tens of metres upstream of the bridge; (E) trees fallen to the river channel as a result of bank erosion (flow is from right to left).

Characteristic features of the hydrological regime of the river are low winter flows and floods occurring between May and August due to heavy rainfall, sometimes superimposed on

snow-melt runoff. Mean annual discharge of the river amounts to 4·4 m^3 s–1 at Koniówka, where the catchment area is 134 km^2. The riparian forest is composed of alder and willow species with predominating young, shrubby forms of Alnus incana, Salix eleagnos, S. purpurea and S. fragilis, less frequent stands of older A. incana trees and occasional S. alba trees.
The study reach is 1300 m long, with a channel width varying between 70 m and 20 m and amounting to 35 m on average, longitudinal slope of 0.006, and a drainage area of 145.7 km^2.

METHODS

The numerical model developed by Ruiz-Villanueva et al. (2014a), called Iber-wood, is applied and inlet and boundary conditions are determined based on field observations. This model is fully coupled with a two-dimensional hydrodynamic model based on the finite volume method with a second-order Roe Scheme. Some of the parameters involved in the governing equations are wood density, angle of the log relative to flow, log length, log diameter, friction coefficient between the wood and the river bed, and the drag coefficient of the wood in water. The model includes two possible transport mechanisms for the movement of wood logs (floating or sliding/rolling) depending on wood density and water depth. In addition, translation and rotation (if one end of the wood piece is moving faster than the other) of logs are also included, based on flow velocity field. Interactions between logs and the channel boundaries and among logs themselves are also taken into account in the model. Therefore, log velocity and trajectory may change as a result of contacts with the banks or with other logs. The hydrodynamics and wood transport are coupled; thus, the hydrodynamics influence wood transport, but the presence of wood also influences hydrodynamics, adding a term to the bi-dimensional De Saint Venant equations (Ruiz-Villanueva et al., 2014a). The model reproduces interactions between wood and infrastructures, computing whether a log can pass under or above the bridge deck, or become trapped by the structure, depending on the gate opening and width, or the weir length, water depth and wood diameter and length. When logs are trapped at the bridge, the drag force represents an opposite action to water flow, producing a rise in water level and a decrease in velocity (Ruiz-Villanueva et al., 2014b). The model has been already applied in the same river for other purposes related to the analysis of large wood dynamics (Ruiz-Villanueva et al., 2015a and 2015b).

Topography of the studied reach is available from a LIDAR data from 2012; in addition, 23 channel cross-sections in the vicinity of the Długopole bridge (18 cross-sections upstream of the bridge and 5 downstream) were used to update and improve the geometry. As a result, we obtained a DEM with 0.5 m pixel size resolution. Data from the nearest stream gauge station Koniówka is used for the calculation of flood discharges of a given probability/ recurrence interval, whereas the available rating curve was used for roughness (Manning's n) calibration. In addition, water level observed during the flood of May 2014 was also used to validate model results.

To characterize each piece of wood entering the reach, we established ranges of maximum and minimum lengths, diameters, and wood density based on the main types of trees recruited to this river. Stochastic variations of these parameters together with the position and angle with respect to the flow were used as well. We define a number of logs per minute to enter the simulation, assuming that wood recruitment is only occurring upstream of the study reach.

The potential bridge clogging depends on many factors (Figure 2), such as (1) the approaching wood pieces (i.e. size and amount of wood transported in uncongested or congested manner, as defined by Braudrick et al., 1996), (2) the flow conditions (i.e. water level and flow velocity), (3) the geometry of the channel upstream the bridge (width, slope, curvature) and (4) the geometry of the bridge.

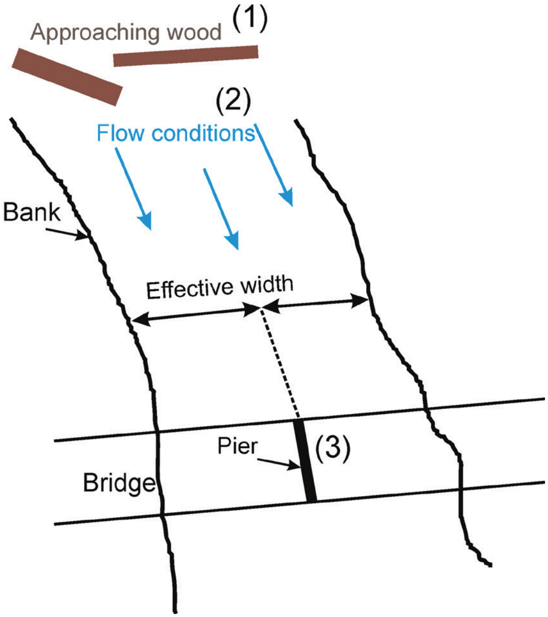

Figure 2: Schematic sketch showing the three main factors influencing bridge clogging: (1) approaching wood (different size and different amount of wood); (2) flow conditions (in terms of water level and velocity field); (3) the geometry of the bridge (the one at Długopole has a single pier in the middle of the channel which is formed by a few steel columns linked with thinner steel elements) and the geometry of the channel.

Running the model in a multiple scenario approach (to include the natural variability inherent to this process), we are analysing the three main factors affecting bridge clogging. We change the size and amount of wood pieces entering the river reach to determine the critical conditions in terms of wood. We also change the discharge to change the flow conditions.

In further steps we will include a potential increase in bank erosion (see pictures D and E in Figure 1) which can also modify the flow conditions (by changing the flow velocity field). A probability of a bridge clogging can be computed with the ensemble from all the scenarios.

PRELIMINARY RESULTS

First run scenarios revealed the bridge as a critical section in the river if clogged. While for relatively high-magnitude floods (Q = 105 $m^3 \cdot s$-1, 10-year return period), the bridge capacity is enough to convey the flow, a reduction in the bridge cross-section caused by wood clogging significantly increases the flooding hazard for the nearby areas (Figure 3).

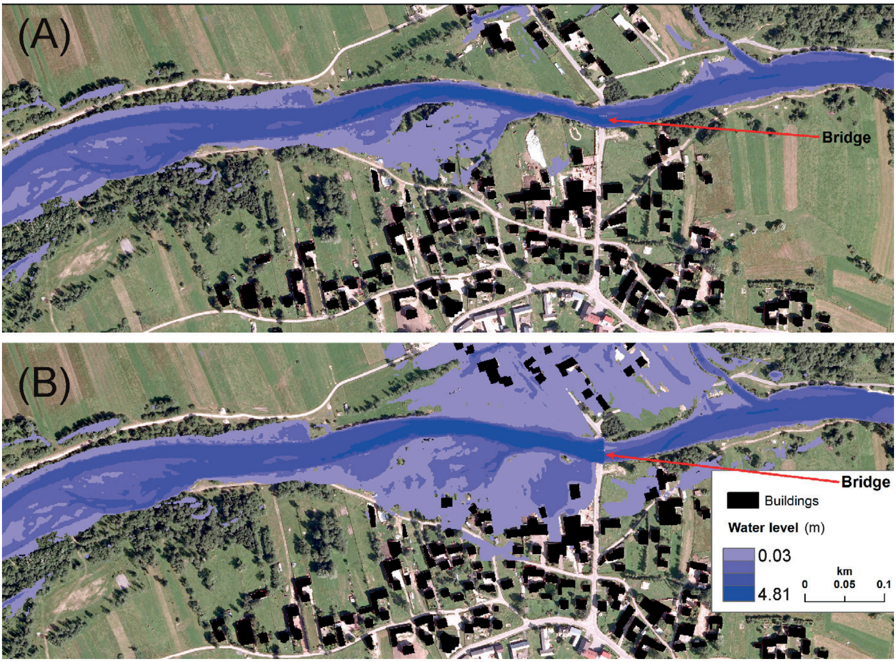

Figure 3: Model results: flooded area and water depths (in metres) for a discharge of 105 $m^3 \cdot s$-1 in the study reach of the Czarny Dunajec River for the bridge cross-section at full capacity (A) and reduced by 90% (B). Flow is from left to right

Preliminary results of the modelling of wood transport show that the bridge is easily clogged under certain circumstances, although the blocking ratio and the probability of a log to be blocked at the bridge depend on several factors. First of all, the size of the wood pieces, namely log length and diameter have a strong influence on the bridge clogging. Preliminary results show that the number of logs deposited at the bridge increases exponentially as log length and diameter increase (Figure 4). Log length seems to have a stronger effect on the entrapment than diameter.

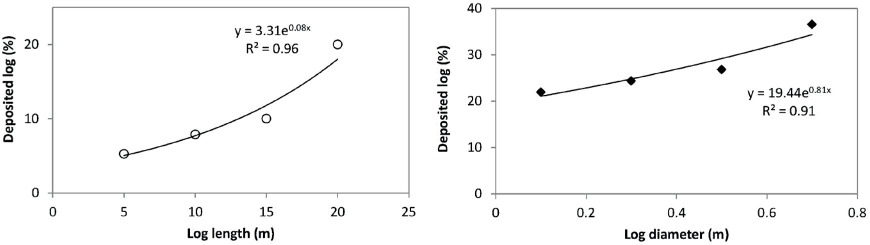

Figure 4: Model results: Percentage of deposited logs at the cross section upstream the bridge. Left: Simulated logs with fixed diameter of 0.2 m and different length values; right: Simulated logs with fixed length (equal to 10 m) and different diameters. In both graphs discharge is equal to 105 m^3·s-1.

Flow conditions and the magnitude of the flood play an important role as well as the wood supply to the river reach and transport mechanism, and further scenarios will analyse these factors. Further results will provide data to compute the probability of bridge clogging under the designed scenarios, and the potential impacts of the clogging on hydrodynamics, flooded area and effects on the bridge stability. This information will be very useful for flood risk assessment and management of the river.

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