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The role of flood hydrograph in the remobilization of large wood in a wide mountain river

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SUMMARY

Floods can mobilize large amounts of unconsolidated material, which also includes large wood in forested river basins. Yet, the influence of the shape and volume of flood hydrographs on wood dynamics in rivers remains poorly understood. Quantitative data on this relation are, however, critically needed to properly address management strategies and to improve the relevant understanding of wood dynamics in rivers. In this work we used a deterministic model, run in a multi-scenario mode, to simulate the transport of wood pieces fully coupled to hydrodynamics. The goal was to analyze how the transport of large wood occurs under different unsteady flood scenarios. We applied the model to two contrasting geomorphic configurations (channelized, single-thread and multi-thread reaches) in the Czarny Dunajec River in Poland, where extensive field observations of wood transport and deposition after floods of different magnitude were available to validate, interpret, and discuss model results. We show that the peak of wood transport is generally reached before the flood peak, and that the wood remobilization ratio is not always positively correlated to peak discharge. We found a positive correlation between the number of mobilized wood pieces and the duration of the rising limb. In addition, hysteresis was observed in the relationship between wood remobilization and discharge. We conclude that numerical modelling allows analysis of wood dynamics in a detail which cannot typically be achieved in field observations. Therefore, modelling improves our understanding of the process and helps disentangling the complex linkages between flood hydrographs and large wood transport dynamics in rivers.

1. Introduction

Under certain conditions, floods can mobilize large amounts of unconsolidated material (Marchi et al., 2009) which includes sediment and, in forested basins, large wood (LW). Flash floods, that are characterized by very short response times and high specific peak discharge (Gaume and Borga, 2008; Gaume et al., 2009; Borga et al., 2014), may entrain large amounts of wood in short time due to bank erosion, mobilization of previously stored pieces, and recruitment from landslides or debris flows (Wohl, 2011). Floods of longer duration may recruit wood mainly from continuous bank erosion and mobilization of wood previously deposited on bars or islands (Gurnell et al., 2002). Therefore, the high potential risk associated with floods as a result of high water levels, flow velocity, sediment transport, and important morphological changes can be amplified as a result of the transport of large quantities of wood material in forested catchments (Mazzorana et al., 2010). In particular, the effects of changing channel morphology and cross-sectional clogging imputable to the transport and deposition of woody material were found to significantly amplify process intensities and damage (Lyn et al., 2007; Badoux et al., 2015; Rickenmann et al., 2015; Lucía et al., 2015). These effects highlighted considerable shortcomings in the current procedures used for natural hazard and risk assessment (Berger et al., 2007). Therefore, LW is increasingly recognized as a key element in flood risk prediction in mountain streams (Rickenmann, 1997; Rickli and Bucher, 2006; Lange and Bezzola, 2006; Mazzorana and Fuchs, 2010; Kundzewicz et al., 2014).

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Despite the importance of wood transport during floods, the influence of flood characteristics (in terms of hydrograph shape and volume) on LW transport remains poorly understood. In addition, predictability is limited by high non-linearity in the hydrological response related to threshold effects and heterogeneity in both the temporal and spatial dimensions (Hrachowitz et al., 2013a,b; Chen, 2014). Understanding of wood dynamics in rivers requires *in-situ* observations and measurements during different flood conditions, but these remain very scarce in nature. Only a very limited number of monitored sites currently exist where innovative monitoring and tracking techniques have been used (MacVicar et al., 2009; MacVicar and Piégay, 2012; Bertoldi et al., 2014; Kramer and Wohl, 2014; Ravazzolo et al., 2015; Schenk et al., 2014). Some of these pioneering studies recorded wood transport during floods in the Ain River in France, comparing LW dynamics to flood hydrographs (Moulin and Piégay, 2004; MacVicar and Piégay, 2012). These studies showed that the intensity of LW transport during a flood changes similarly to sediment transport, with both increasing non-linearly during the rising limb of the hydrograph. Kramer and Wohl (2014) indicated that wood transport will begin at a threshold value close to bankfull discharge, after which it becomes much more variable, as shown by Ruiz-Villanueva et al. (2015b).

Besides the magnitude of floods, their sequence is also a key factor for LW movement (Haga et al., 2002; Wohl and Goode, 2008). As observed by MacVicar and Piégay (2012), two consecutive floods with similar peak discharges and volumes mobilized different quantities of wood; as a result of antecedent flood effects, the first flood mobilized most of the available material, whereas the second transported significantly less wood. This observation has also been corroborated by tracking experiments which revealed that the largest quantities of LW may be transported during a single flood event (Schenk et al., 2014). However, all these analyses were made during a very limited number of flood events, with a relatively low- to medium-magnitude flows and little is still known regarding the influence of flood hydrographs on wood dynamics. This work aims at filling this gap by combining numerical modelling with field observations. Numerical modelling may provide an alternative approach to explore different aspects which are difficult to observe in the field, giving detailed information about wood dynamics under different flood scenarios in the context of variations in the hydrograph and associated hydraulic forces. Therefore, in this work we used numerical simulations of wood transport combined with field observations to analyze the relation between LW transport and flood hydrographs in the mountainous Czarny Dunajec River in Poland. We used the numerical model developed by Ruiz-Villanueva et al. (2014a), which is based on a deterministic model to simulate the transport of individual wood elements of different sizes under complex hydraulic conditions at short timescales, and which is fully coupled to hydrodynamics. The numerical modelling was run in a multi-scenario mode and under different unsteady flow conditions, which enables analysis of wood dynamics in a controlled environment and which opens new possibilities for understanding and disentangling the complex linkages between flood hydrographs and LW transport dynamics in rivers. We hypothesize that besides flood peak, diverse flood durations would lead to differences in wood remobilization, and that therefore the shape of the hydrograph would have a significant influence on wood mobilization. We explore these hypotheses in two different river reaches of the Czarny Dunajec with contrasting morphologies, because it has been proved that the river morphology controls wood dynamics (Wyżga et al., 2015a). The study is intended to provide quantitative information on the wood dynamics during floods in single- and multi-thread mountain watercourses.

2. Study site

The Czarny Dunajec River drains the Inner Western Carpathians, originating in the high-mountain Tatra massif in southern Poland. In the studied section (Fig. 1A) within the Tatra Mountains foreland, the river is a fifth-order watercourse with mean annual discharge of 4.4 $m^3 s^{-1}$ in the middle course (catchment area: 134 km^2) and 8.8 $m^3 s^{-1}$ close to the confluence with the Biały Dunajec River (432 km^2).

The hydrological regime of the river is characterized by low winter flows and floods occurring between May and August (Ruiz-Villanueva et al., 2014d) due to heavy rains, sometimes superimposed on snow-melt runoff (Niedźwiedź et al., 2015).

The riparian forest is composed of alder and willow species with predominantly young, shrubby forms of *Alnus incana*, *Salix eleagnos*, *S. purpurea* and *S. fragilis*, as well as less frequent stands of older *A. incana* trees and occasional *S. alba* trees (Mikuś et al., 2013).

The studied section is at an altitude of 670–626 m and is 5.5-km long. The high variability of the river morphology allowed us to distinguish two different reaches with a single-thread, partially regulated channel (R1) and an unmanaged, multi-thread channel (R2) (Wyżga and Zawiejska, 2010). The study reaches represent large channels with respect to LW (Gurnell et al., 2002; Wohl, 2013; Wyżga et al., 2015a). R1 has a relatively small, uniform width (42 m on average) and banks partially reinforced with gabions or rip rap; moreover, a few drop structures reduce channel slope locally. In R2 the width of the active river zone amounts to 116 m on average, but varies considerably between 60 and 180 m.

Differences in hydrodynamics driven by these different morphologies (Fig. 1B and C) represent one of the more relevant contrasts between the reaches in terms of wood dynamics. In general terms, transport capacity is higher in R1 than in R2. High unit stream power and relatively high flow depths at flood conditions facilitate LW transport in R1. On the other hand, the lower unit stream power and the relatively low depth of flood flows in R2 facilitate deposition of wood, as it was recorded during field investigations at the study site (Wyżga and Zawiejska, 2005, 2010).

3. Materials and methods

3.1. Numerical model description, previous works and modelling setup

The 2D numerical model developed by Ruiz-Villanueva et al. (2014a) was applied to solve hydrodynamics and to simulate wood transport. This model fully couples a two-dimensional hydrodynamic model based on the finite volume method with a second order Roe Scheme and a Lagrangian model for wood dynamics. Wood initial motion is calculated based on the balance of forces acting on each log, and then the movement of logs is simulated with two possible transport mechanisms, floating or sliding. Besides translation, logs may rotate depending on the velocity field at either end of the log. Logs may also interact between each other or/and with the channel boundaries, including infrastructures. Thus, velocities and trajectories of logs may change when they interact with the river banks and bed, in-channel or bank structures (e.g. bridges, weirs, gates) or other logs. The coupling of wood transport and hydrodynamics is solved by including drag forces in the governing flow equations as an additional shear stress term in the 2D Saint Venant equations. This means that the presence of wood reduces the available storage volume at every finite volume, thereby adding a new shear stress (produced by the drag force of the logs).