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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 set-up

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).

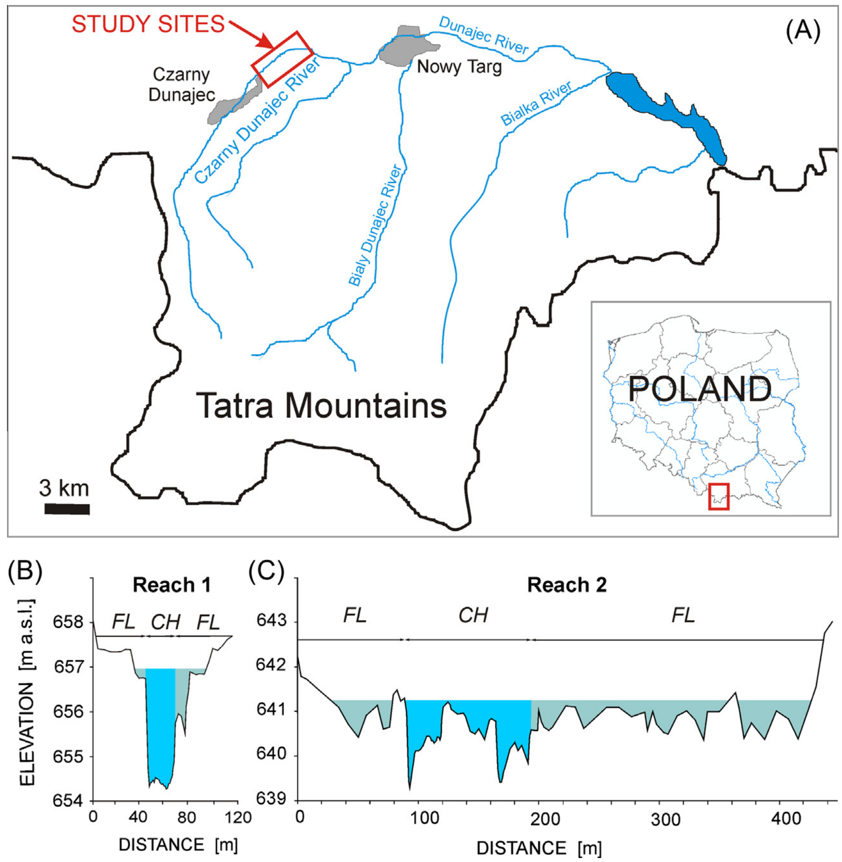

Fig. 1. (A) Location of the Czarny Dunajec River and the study reaches. (B, C) Cross sections of studied reaches 1 (B) and 2 (C). CH – channel; FL – floodplain. Location of the cross-sections is shown in Fig. 7.

Table 1
Main findings from previous works regarding wood dynamics in the Czarny Dunajec River analyzed using numerical modelling under steady state scenarios (Ruiz-Villanueva et al., 2015a,b).

	Single-thread reach 1	Multi-thread reach 2
Wood dynamic control factors		
Transport ratio: mean (SD)	0.43 (0.2)	0.26 (0.16)
Retention capacity: mean (SD)	0.57 (0.21)	0.74 (0.17)
Control factor in wood transport[a]	Wood length	Wood diameter
Maximum piece volume transported	>6 m^3	<4 m^3
Threshold discharge to transport wood downstream[b]	>25 $m^3\,s^{-1}$	>45 $m^3\,s^{-1}$
Control factor in wood deposition[c]	Water level (=flood magnitude)	Water level (=flood magnitude)
Preferential site for wood deposits		
Frequent floods	Low-flow channel	Bars and forested islands
Ordinary floods	Areas covered by shrubs and forest	Areas covered by shrubs and crops within the floodplain
Extreme floods	Agriculture zones	Crops and agriculture zones

[a] Wood transported downstream the study reach assuming that wood is entering from upstream in a steady and non-congested regime.
[b] Peak discharge used under steady stage conditions needed to transport wood downstream the study reach.
[c] Besides river morphology (clearly illustrated by the contrasting results in each reach), factor controlling the depositional sites of wood.

The model has been applied to various rivers (Ruiz-Villanueva et al., 2014b,c) and also to the Czarny Dunajec which is the object of this study. Therefore, we do not go into details with respect to the calculation mesh generation and calibration, but refer to existing publications (Ruiz-Villanueva et al., 2015a,b). Field observations allowed model calibration and validation before simulating different scenarios. One key strength of numerical modelling is that it can be used to run scenarios that are difficultly observed in the field; moreover, values of different parameters can be changed to analyze controls on wood dynamics, or to compute probabilities. In the work of Ruiz-Villanueva et al. (2015a), the factors controlling wood motion were investigated using a multi-run–multi-scenario approach, by analyzing the transport ratio (ratio between inlet and outlet wood) and various parameters (wood diameter and length, wood density, peak discharge). In turn, the work of Ruiz-Villanueva et al. (2015b) presents the analysis of wood deposition and retention in the mountain river. In this case, the preferential sites for wood deposition (in terms of probability of deposition) were identified for different geomorphic units and different peak discharges. In addition, factors controlling wood retention were also analyzed, such as wood size, discharge and river morphology. In these works more than 170 scenarios were designed under steady-state conditions, so only the peak discharge was simulated. Table 1 summarizes the main findings of previous

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works where the numerical model was used to analyze wood dynamics in the Czarny Dunajec.

However, a significant feature in wood dynamics is the temporal dimension, and this is represented by simulating floods under unsteady stage scenarios, and by simulating the entire flood hydrograph. To design these unsteady scenarios, initial and boundary conditions were defined for flow using existing discharge data series (1966–2010; Fig. 2C) from the nearest stream-gauge station (Koniówka). The flood frequency analysis, fitting the Generalized Extreme Value function (GEV), provided discharge quantiles of different recurrence intervals. In addition, the available rating curve was used for roughness (Manning's n) calibration. Different discharge quantiles were selected, including very frequent flood (5-year return period; peak discharge 78 $m^3\ s^{-1}$), ordinary (10-year return period; 105 $m^3\ s^{-1}$) and extraordinary (25-year event; 147 $m^3\ s^{-1}$) floods. Synthetic unit hydrographs were designed based on recorded hydrographs in the Czarny Dunajec as shown in the examples in Fig. 2A and B. To design the hydrographs, we used the Dimensionless Unit Hydrograph method of the Soil Conservation Service (SCS, 1972). This method uses the ratio between the discharge at one time step and the peak discharge ($Q \cdot Qp^{-1}$) and the ratio between time and the time to peak ($t \cdot tp^{-1}$) to build the final hydrograph. Subsequently we modified the resultant common hydrographs (i.e. the hydrographs with the most common shape in the river) to obtain flashy and flattened flood waves with the same flow volume (Fig. 2D).

The designed synthetic hydrographs were based on floods recorded in the river; however, considerable differences between floods can be expected because of different rainfall patterns. For instance, the flood of 1934, known as the largest twentieth-century flood in the Polish Carpathians, had two peaks, a scenario which was not considered in this study. The most recent flood from April 2014 was preceded by a prolonged period of dry conditions and was quite flashy, whereas long wet conditions preceded the flood of June 2001 with common hydrograph shape (Fig. 2A and B). A more flattened flood scenario may result from prolonged rainfall of relatively small intensity or some rainfall superimposed on snow melting. Based on this knowledge, we defined the common flood scenario ($Q \cdot Qp^{-1} = 1$ and $t \cdot tp^{-1} = 1$) where the flood peak is reached 5 h after the beginning of the flood wave, and the total flood duration equals 25 h. In the flattened flood wave scenario ($Q \cdot Qp^{-1} = 0.5$ and $t \cdot tp^{-1} = 2$), floods have a total duration of 35 h and the peak is reached after 10 h, whereas in the flashy flood scenario ($Q \cdot Qp^{-1} = 1.5$ and $t \cdot tp^{-1} = 0.5$), floods last for 17 h and the peak is passing after 3 h. In all scenarios, the shape of the hydrographs reflects the shape of flood waves occurring in the river, with a rising limb being steeper than the falling limb. The time to peak and the total duration of the hydrograph scenarios have been scaled compared to recorded flood waves (time to peak and the total duration may be up to 2 times shorter in some cases). This was necessary to reduce the computational effort of the model (which can range between 5 and 12 h for a single unsteady run). We also checked potential effects of scaling (temporal reduction) on the attenuation of the flood waves along the river reaches and designed hydrographs in a way to get the best compromise between model computational efforts and reliable scenarios. Therefore, the scaling of the time to peak and of the total duration of the final flood scenarios is considered negligible and without any influence on wood-related phenomena. Table 2 indicates the peak discharges of the simulated flood scenarios.

Wood initial and boundary conditions were then defined based on detailed knowledge of the fluvial corridor, riparian vegetation, and wood storage in the river (Wyżga and Zawiejska, 2005, 2010). To characterize each piece of wood entering the simulation, we established ranges of maximum and minimum lengths, diameters and wood density according to the riparian vegetation and

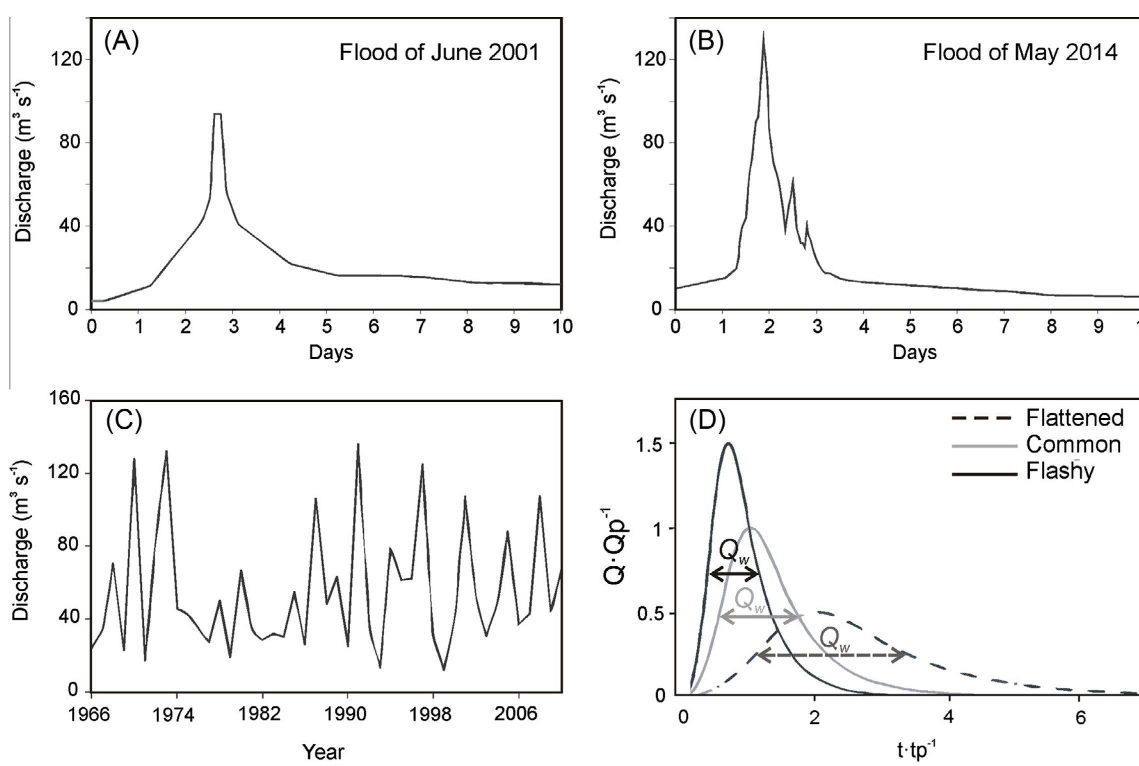

Fig. 2. (A) Hydrograph of the flood of June 2001 (peak discharge of 94 $m^3\ s^{-1}$ and 7-year return period); (B) Hydrograph of the flood of May 2014 (peak discharge of 130 $m^3\ s^{-1}$ and 20-year return period); (C) Annual maximum discharge series from the years 1966–2010 for the Koniówka stream gauge station in the Czarny Dunajec; (D) Dimensionless synthetic unit hydrographs designed for modelling different flood scenarios. Q_w indicates discharge assumed to be associated with the beginning and cessation of wood transport.

Table 2
Characteristics of log types used in the simulations (L_w – mean length, D_w – log diameter, ρ_w – wood density), based on the riparian vegetation in the Czarny Dunajec, and flood scenarios used to design flood hydrographs.

ID	Vegetation type (species)	L_w (m)	D_w (m)	ρ_w (g·cm^{-3})
	Logs			
1a	Large alders (*Alnus incana*)	10–18	0.3–0.8	0.85–0.95
1b	Large willows with single trunk (*Salix fragilis* and *S. alba*).	10–15	0.15–0.3	
2	Young willows (especially *S. purpurea* and *S. eleagnos*) and alders	3–10	0.1–0.2	0.4–0.7
3	Branches broken from stems and crowns	1–3	0.05–0.1	

Type	Peak discharge (m^3 s^{-1})[a]	Return period (year)	Peak of flashy hydrograph[b]	Peak of flattened hydrograph[b]
		Floods		
Frequent	78	5	117	39
Ordinary	105	10	157	52
Extraordinary	147	25	220	73

[a] Values used to design the common hydrographs.
[b] Values for flood waves with the same water volume as in the common hydrographs but with changed duration of the flood.

wood inventories (Table 2). Stochastic variations of these parameters together with the angle with respect to the flow were then used at the inlet boundary.

As an initial condition, we defined the wood pieces already deposited along the river reaches. To do this, the calibrated model was run under steady conditions of low flood flow (discharge of 28 m^3 s^{-1} equivalent to a 1.2-year flood). After the flow had been stabilized, individual pieces of wood were entering the simulation from upstream in the main channel. Around 50 logs of each type of logs described in Table 2 (for a total of 198 logs) entered the river reaches, and under this very frequent flood flow most of the recruited wood was not flushed out downstream but deposited along the reaches. The spatial distribution of deposited logs during this first scenario was used as initial condition for unsteady flow scenarios. Because the goal of this study is to analyze how instream wood transport occurs under different unsteady flood scenarios, we first assumed that wood recruitment is not occurring upstream from the study reaches or laterally (due to bank erosion), but that only the initially deposited wood is being remobilized.

In a second step, we added also wood recruited upstream of the reaches. To define this inlet boundary condition, we hypothesized that wood transport commences before flood peak, approximately when $Qp/2$ is reached, and continues for some time during the recession limb until the discharge again approximates $Qp/2$ (Fig. 2D). We based our assumptions on previous observations and the tracking of logs performed during a flood in 2014 (see Wyżga et al., 2015b), although the timing and duration of wood transport could differ from one event to another. We assumed that wood transport lasts 3 h in the case of flashy hydrographs, 5 h during common hydrographs and 7 h in the case of flattened hydrographs. Inlet wood is assumed to be uncongested and steady (as observed in the river) during these times, and to have a rate of 6 logs per hour (1 log every 10 min). This means that during common floods 30 logs are coming from upstream, 19 during flashy floods and 42 during flattened flood scenarios. To characterize each log, we varied stochastically the size of log types 1b, 2 and 3 described in Table 2 (we hypothesized that type 1a is not transported from upstream reaches) with values between 0.1 and 0.5 m for diameter, 1 and 10 m for length and 400 and 700 g cm^{-3} for wood density.

Combining the different flood quantiles with the three different hydrograph shapes, different wood types and initial conditions resulted in the final set of model runs composed of 46 scenarios for river reaches R1 and R2.

3.2. Data analysis and field observations

Wood dynamics were analyzed in terms of remobilized logs (calculated as a percentage of logs initially deposited within the reach or all logs including inlet wood from upstream) at each time step within the river reach. Logs were considered mobile if their velocity differed from 0 and they were transported downstream. We also determined the percentage of logs flushed out downstream the river reach (both remobilized pieces and inlet logs). Flushed wood is used here in a similar way as wood transport ratio (here referred as remobilization ratio), which is defined as the ratio between the outlet and inlet number of logs (pieces transported downstream of the studied reach/all logs). Then, relations between wood dynamics and potential controlling variables were investigated. These variables were the peak discharge of the flood (related to the magnitude of the flood) and the time to peak (related to the shape of the hydrograph). Normality in the distributions of these variables was tested with the Shapiro–Wilk test; if normality was rejected, a non-parametric approach was used for analysis. To study relationships between variables, regression analysis and the non-parametric Spearman correlation test were applied. We used the non-parametric Mann–Whitney test to assess differences between the two study reaches. Correlation, regression relationships and differences were considered statistically significant if the p-value was <0.05. Finally, a bootstrap version of the univariate, two-sided Kolmogorov–Smirnov test was used to test differences in cumulative distributions. Statistical analyses were conducted using R version 3.1.2 software (www.r-project.com).

Field observations regarding wood transport were realized during and after recent floods in 2001, 2010, and 2014 (Wyżga and Zawiejska, 2005, 2010; Wyżga et al., 2015a). Data obtained during these floods allowed calibration, validation and comparison of model results in previous and this work. Especially the tracking of logs during a flood in May 2014 provided data to better understand wood dynamics during unsteady flood conditions (Wyżga et al., 2015b). During the flood (peak discharge of 130 m^3 s^{-1}), 30 logs tagged with radio transmitters (length: 3 m; diameter: ca. 20 cm) were placed into the river just before its peak. The flood magnitude (20-year return period) was high enough for the flow to overtop reach 1 and to activate all low-flow channels and inundate gravel bars and islands in reach 2. The deposition of tagged logs related to other wood deposits provided valuable information about wood dynamics under unsteady flow conditions.

4. Results

4.1. Wood transport under unsteady flow conditions

The initial conditions given by the initial scenario resulted in the wood spatial distribution and a number of logs equal to 168 pieces deposited in the single-thread reach R1 and 194 in the multi-thread reach R2. Of these, 49 logs in R1 were of type 1a, 47 of type 1b, 44 of type 2 and 28 of type 3. In R2, 49 logs represented type 1a, 48 type 1b, 49 type 2, and 48 type 3. These results indicate that wood is more easily transported in R1, with 16% of the logs being flushed out downstream, and more easily retained in R2 where only 3% of the logs were transported downstream of the reach, as it was also observed in the field and during previous simulations under steady flow conditions.

When only initially stored wood is simulated and no inlet wood enters the reach, wood transport starts during the rise of the hydrograph, and we observed a time lag between the beginning of the flood and wood mobilization (Fig. 3). The highest wood remobilization ratio (i.e. the largest number of logs in motion) is systematically reached before the flood peak in all scenarios and in both reaches.

When wood was also supplied from upstream, the number of deposited logs increased in both river reaches, but especially in R2. For common hydrographs, the final number of logs deposited in R1 and R2 was 198 and 224, respectively, 187 and 213 logs were deposited in these reaches under flashy hydrographs, whereas the flattened hydrograph scenarios left 210 and 236 logs. This also confirmed the higher wood retention capacity of R2.

Regarding wood mobilization, we observe a similar behavior when initial and inlet wood was simulated. A time lag exists between the beginning of the hydrograph and the wood mobilization and the peak of the wood mobilization is reached before the maximum discharge (Fig. 4). Statistically significant differences (Kolmogorov–Smirnov test, $p < 0.05$) between the cumulative distribution of water flow and that of the mobilized wood confirmed also this observation.

As Figs. 3 and 4 show, the maximum number of remobilized logs was always reached before the flood peak in all scenarios. Even though we did not find statistically significant differences ($p > 0.05$) between the cumulative distributions of mobilized wood for the two river reaches in all simulated scenarios, some contrasts were observed between the reaches, with the larger amounts of remobilized logs occurring in R2.

The tracking of tagged logs during the flood in 2014 confirmed these results. Tagged logs were in most cases deposited on the downstream side of wood jams, indicating that they were placed in the river and transported downstream before the peak of wood transport. Logs were placed in the river at the stage 20–25 cm lower than the peak stage of the flood and this allowed the logs to be deposited on the river banks and high parts of channel bars. The logs were relatively small (3 m in length and 16–24 cm in diameter) and thus highly mobile. If they were put to the river at lower water stages (e.g. at the very beginning of the flood wave), they might flow in low-flow channels and easily pass the whole study reach.

4.2. Impacts of flood hydrograph on wood remobilization

Common and flashy hydrographs with higher peak discharges remobilized more logs than the equivalent flattened floods for the two wood supply scenarios (only initial wood and initial plus inlet wood scenarios). As shown in Fig. 5, we observed nonlinear relationships between the percentage of flushed logs (remobilization ratio) and the peak discharge of a flood. A relatively small increase in flood magnitude above the threshold of wood mobilization largely increased the percentage of logs flushed out of the reach (with the values being higher in R2), whereas further increases in flood magnitude were reflected in progressively smaller increases in wood export (Fig. 5).

Fig. 5 also shows that when inlet wood is added from upstream, the mobilization ratio slightly changes in both reaches, but still the relationship with discharge maintains the same nonlinear behavior (as it was also observed in the previous works shown in Table 1).

The hydrograph shape and the duration of the flood also significantly influence the mobilization of in-stream wood and its

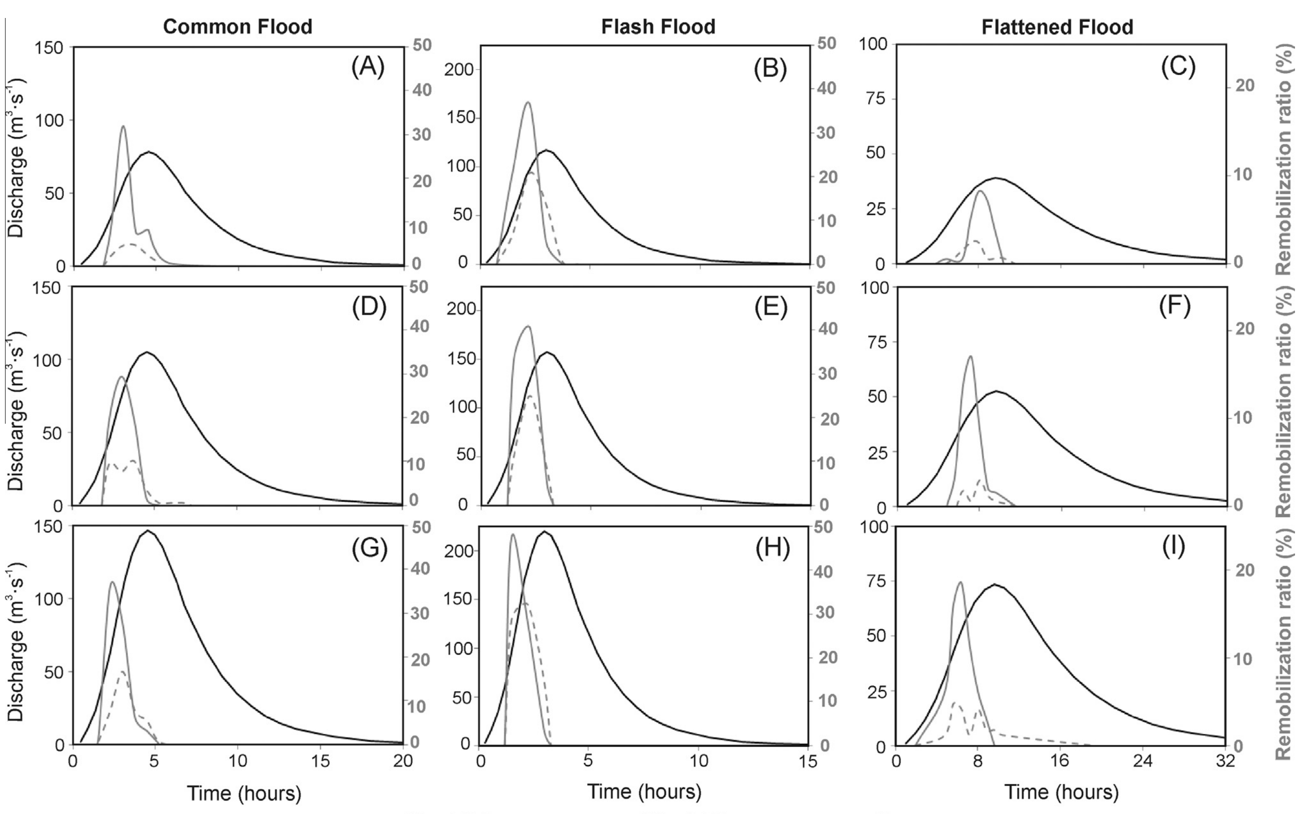

Fig. 3. Flood hydrographs (black solid lines) and temporal variation in the mobilization of initial wood pieces (in %) in R1 (dashed gray lines) and R2 (solid gray lines).

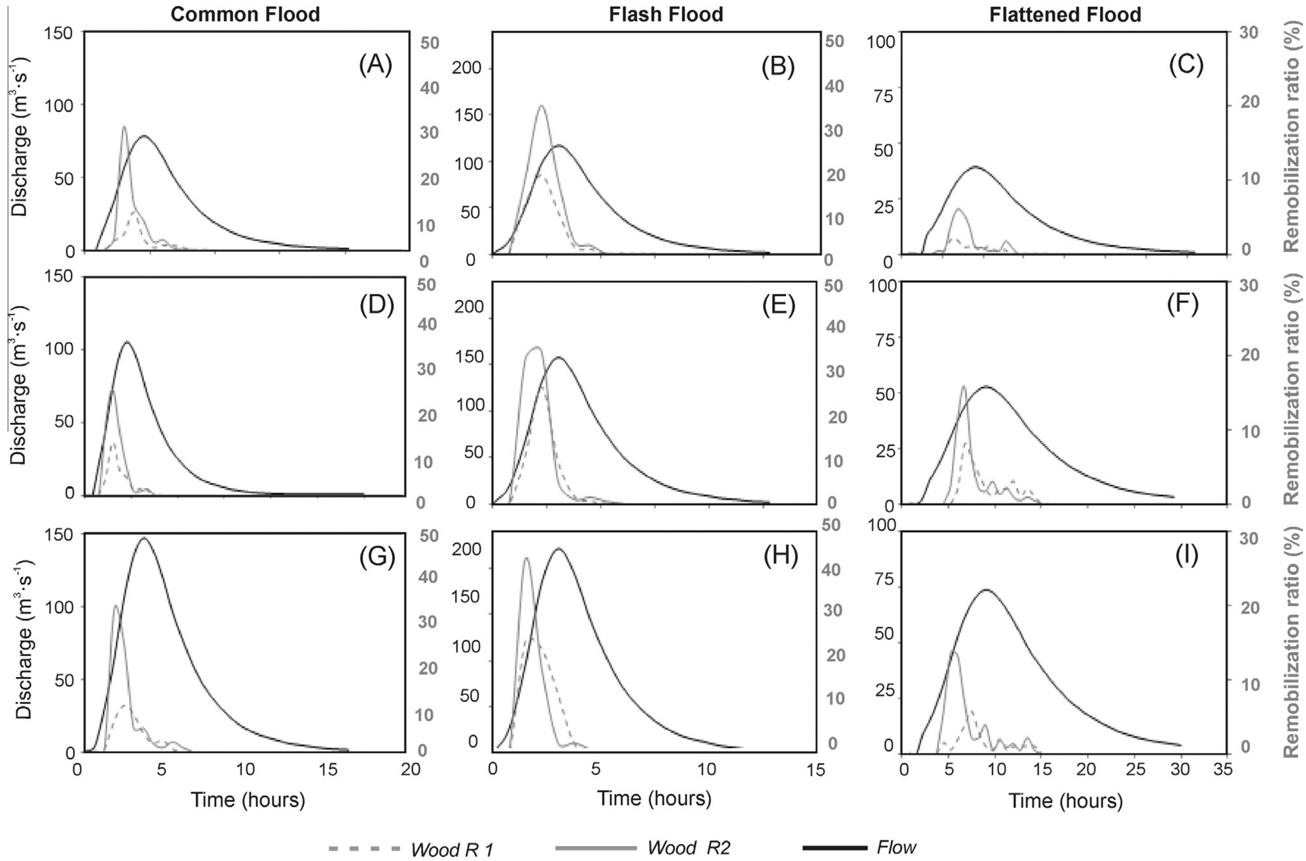

Fig. 4. Flood hydrographs (black solid lines) and temporal variation (in %) in the mobilization of wood pieces (initially deposited and inlet wood) in R1 (dashed gray lines) and R2 (solid gray lines).

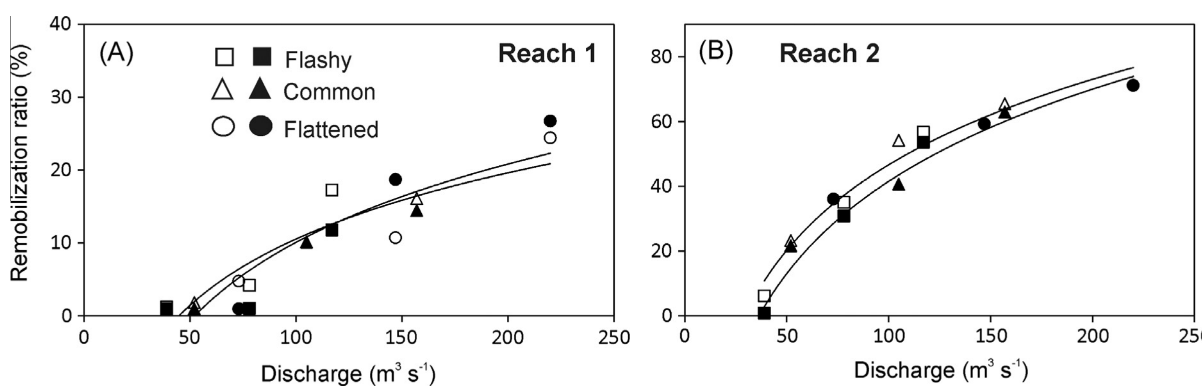

Fig. 5. Relationships between the percentage of logs flushed out downstream the reach and flood peak discharge shown for R1 (A) and R2 (B) and only initially deposited wood or initial and inlet wood. Open marks refer to initially deposited wood only and solid marks to initial and inlet wood.

Table 3
Percentage of wood (only initially deposited wood and initial plus inlet wood) flushed downstream the study reaches by 5-, 10-, and 25-year floods with common hydrograph shape and their flashy and flattened equivalents.

Reach	Number of initial logs	Initially deposited wood flushed downstream the reach (% of logs)								
		5-year flood			10-year flood			25-year flood		
		Flashy	Common	Flattened	Flashy	Common	Flattened	Flashy	Common	Flattened
R1	168	17	4	1	16	10	2	24	11	5
R2	194	57	35	6	65	54	23	71	59	36
		Initial wood plus inlet wood flushed downstream the reach, % of logs (total number of logs)								
R1		12 (187)	1 (198)	1 (210)	14 (187)	10 (198)	1 (210)	27 (187)	19 (198)	1 (210)
R2		54 (213)	31 (224)	1 (236)	63 (213)	41 (224)	22 (236)	69 (213)	62 (224)	19 (236)

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Table 4
Spearman correlation matrix for characteristics of flood waves and the duration of wood remobilization by the floods (in bold statistically significant correlations, *p*-value <0.05).

Reach 1	Time to peak (rising limb duration; h)	Duration of remobilization of initially deposited wood (h)	Peak discharge	Duration of remobilization of initial plus inlet wood (h)
Reach 1				
Time to peak (rising limb duration; h)	1	0.1054	**−0.896**	**0.9487**
Duration of remobilization of initially deposited wood (h)		1	0.200	0.3667
Peak discharge			1	**−0.7167**
Duration of remobilization of initial plus inlet wood (h)				1
Reach 2				
Time to peak (rising limb duration; h)	1	**0.873**	**−0.896**	**0.738**
Duration of remobilization of initially deposited wood (h)		1	**−0.795**	**0.686**
Peak discharge			1	−0.483
Duration of remobilization of initial plus inlet wood (h)				1

duration. As Table 3 shows, a 5-year flood with the common hydrograph shape and the flattened equivalent of a 25-year flood have similar peak discharges (78 $m^3 s^{-1}$ and 73 $m^3 s^{-1}$, respectively), but a slightly higher percentage of mobilized wood is associated with the latter when only initial wood was remobilized, although the flattened hydrograph transported less number of logs when wood was also added from upstream (Table 3).

While the number of mobilized logs was positively related to flow peak, the time during which wood is transported was negatively related to peak discharge, but positively to the duration of the flood, particularly to its rising limb (time to peak) (Fig. 6 and Table 4). Fig. 6 and Table 4 show that the relationship between the duration of the wood remobilization and the peak discharge is more complex in R2 than in R1 (illustrated by the larger scatter in the graphs and the contrasting correlations found in the Spearman test).

Flashy floods which generally have higher peak discharges were related to the highest remobilization ratio, and the lowest remobilization ratio was associated with the equivalent flattened flood scenarios. The common hydrograph scenarios represented an intermediate situation.

Despite the importance of a flood hydrograph for wood mobility, morphology represents another significant factor of the river systems. The planform configuration of water level, flow velocity field and wetted area for different floods differ considerably between the two river reaches. In R1, the initial scenario left most of the wood pieces deposited along the channel margins, or in some cases on the floodplain. During floods, water stage is higher than the bankfull level in all the considered scenarios. Under these overbank flow conditions, water depth and flow velocity in the floodplain area are insufficient to allow wood to be transported over long distances and most pieces are thus deposited. During the simulated flood scenarios where flow falls below the bankfull stage, wood previously deposited in the floodplain area can no longer be transported to the main channel, and therefore cannot be flushed out downstream (Fig. 7A and C). In fact, the number of possible locations for relatively permanent wood deposition increases if water is flowing over the floodplain. Moreover, the low ratio of mobilized wood from R1 not only results from low flow velocity and water depth on the relatively high floodplain, but also from the partitioning of the floodplain by wing dikes of drop hydraulic structures, which cause logs to be trapped on the upstream side of the dikes (Fig. 7C).

In R2, the simulated floods inundate larger surfaces within the active river zone, activating and connecting secondary channels and flooding bars and islands where most of the wood was

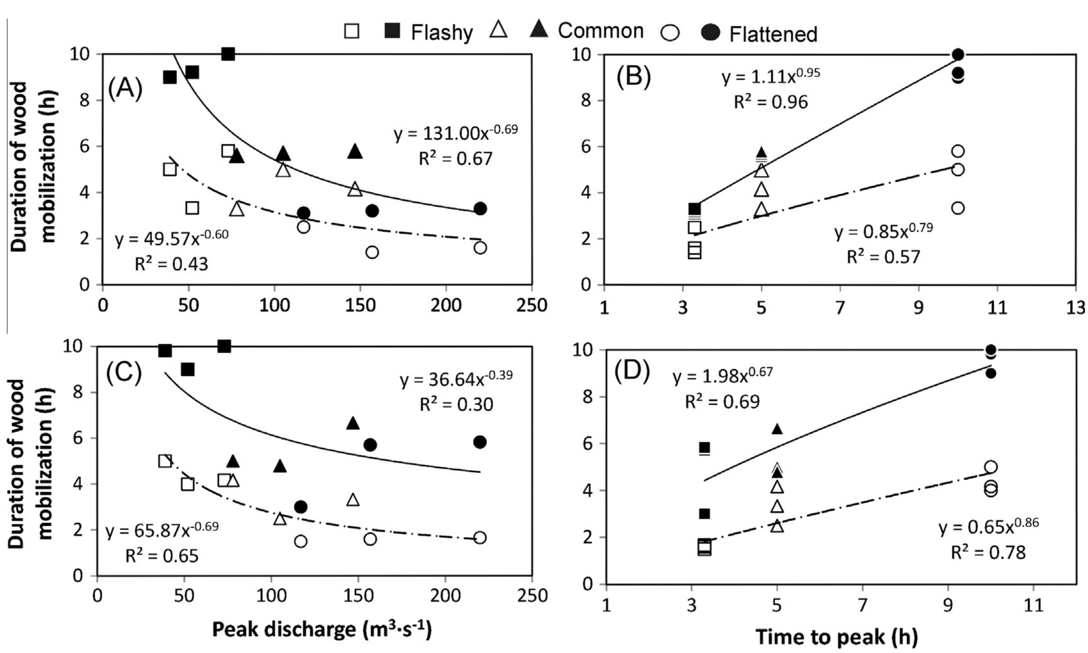

Fig. 6. Relationships between the duration of wood mobilization and flood peak discharge for R1 (A) and R2 (C) and between the duration of wood mobilization and flood duration represented by the time to peak for R1 (B) and R2 (D). Open marks refer to initially deposited wood only and solid marks to initial and inlet wood.

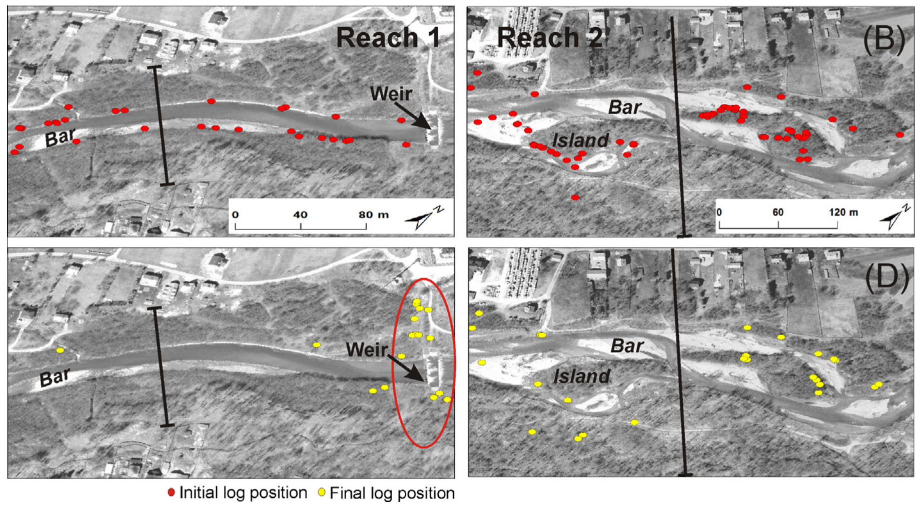

Fig. 7. Logs stored at the initial time step in R1 (A) and R2 (B), and logs redeposited during a 25-year flood with a common hydrograph shape in R1 (C) and R2 (D). Black lines indicate the location of cross-sections shown in Fig. 1B and C.

previously deposited (Fig. 7B). Therefore, most of the pieces were remobilized and many were flushed out (Fig. 7D). In this case, the proportion of wood pieces flushed downstream was not only related to peak discharge but also to hydrograph shape.

A larger number of wood pieces were stored in R2 than in R1 (194 and 168 logs, respectively), and this difference mainly results from the larger number of type 3 logs stored in R2 (20 pieces, i.e. over 10%). Logs of this type were the smallest and were easily

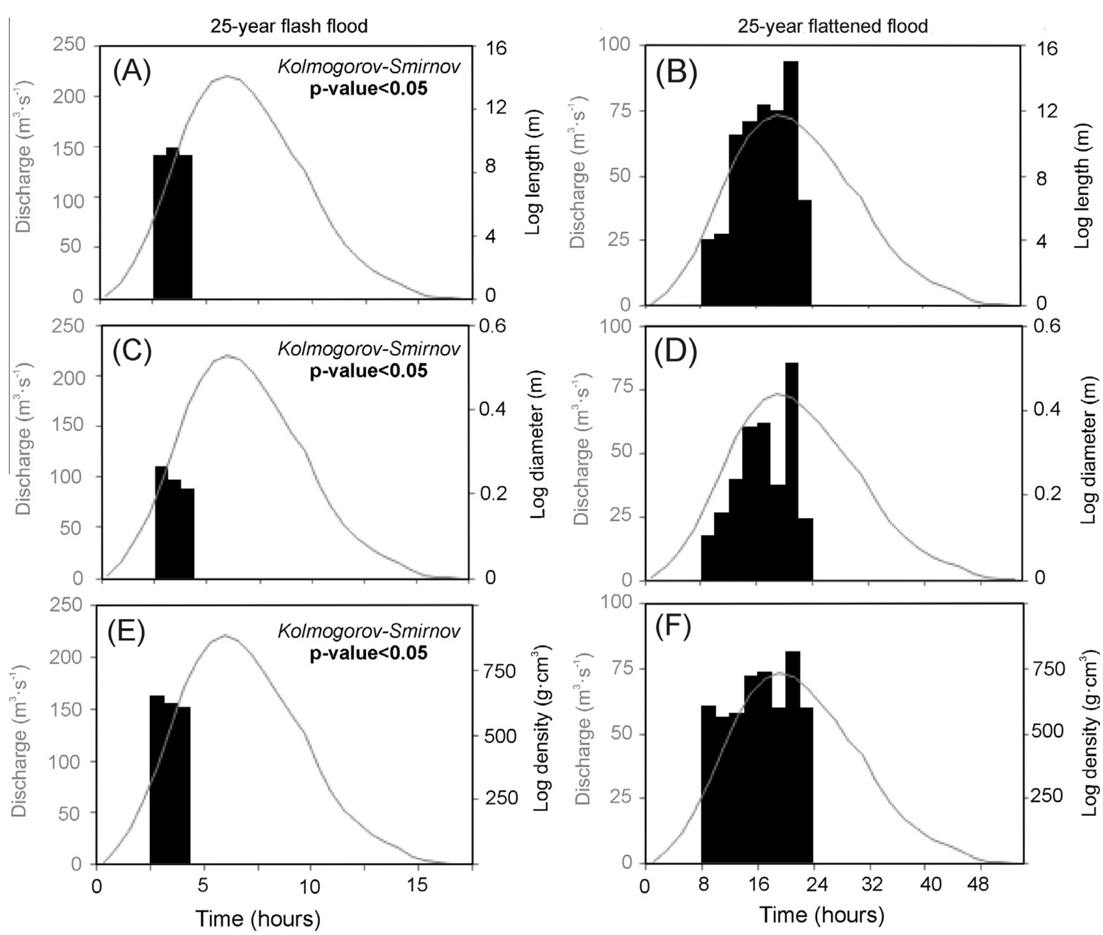

Fig. 8. Temporal variability of wood piece mobility with different characteristics in R1 during the flashy (A, C, E) and flattened (B, D, F) equivalents of the 25-year flood. (A and B) log length; (C and D) log diameter; (E and F) wood density. Results of the Kolmogorov–Smirnov test for the significance of difference between the distributions of lengths, diameters and densities of logs mobilized by the flash and the flattened floods are also shown.

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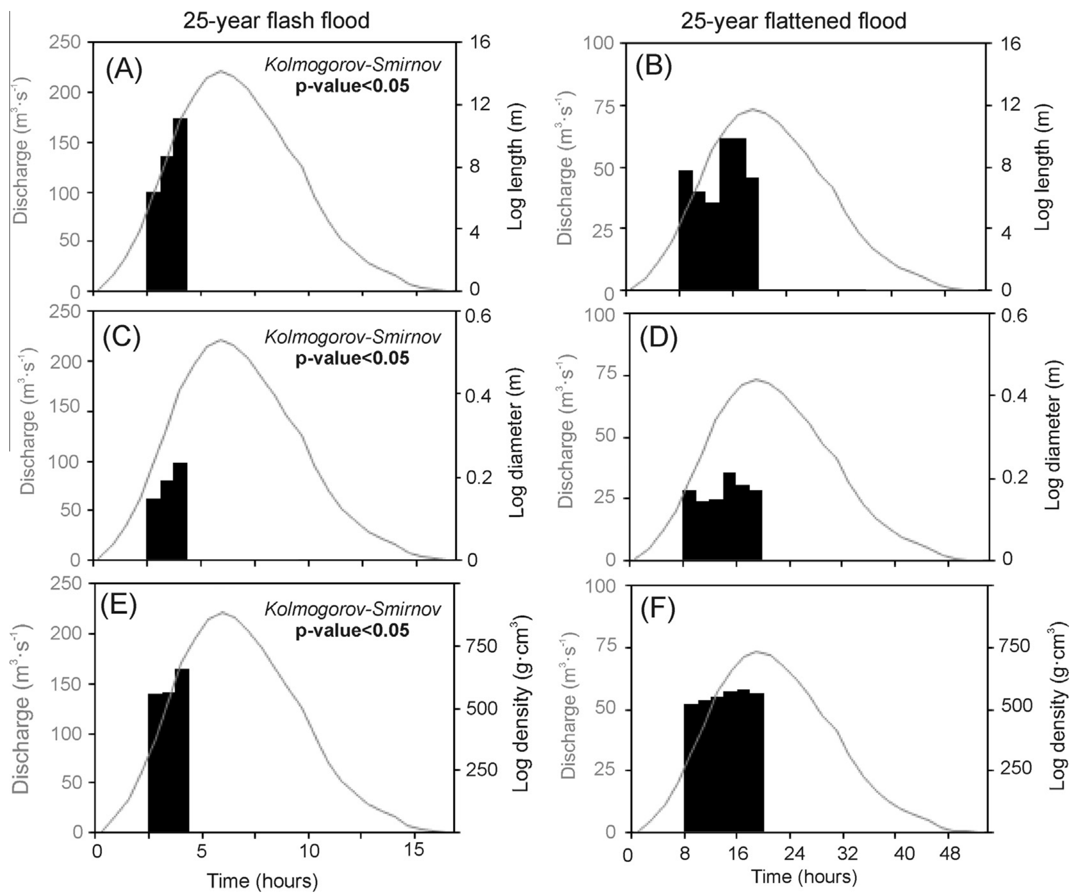

Fig. 9. Temporal variability of wood piece mobility with different characteristics in R2 during the flashy (A, C, E) and flattened (B, D, F) equivalents of the 25-year flood. (A and B) logs length; (C and D) log diameter; (E and F) wood density. Results of the Kolmogorov–Smirnov test for the significance of difference between the distributions of lengths, diameters and densities of logs mobilized by the flash and the flattened floods are also shown.

transported during the simulated floods, and thus also contributed to the higher ratio of wood remobilization from R2.

4.3. Influence of wood characteristics on wood dynamics

To identify the influence of wood characteristics on the potential for remobilization, we analyzed which types of the initially deposited wood are remobilized during different stages of simulated floods. We show here results for the flashy and flattened equivalents of the 25-year flood (Figs. 8 and 9).

Figs. 10 and 11 show that the timing of and the duration of wood motion during floods are strongly related to flood wave duration, especially to the flooďs rising limb. In addition, we could observe that in R1 the flattened flood was able to move larger and heavier pieces than the flash flood, despite the higher peak discharge and the greater proportion of mobilized wood during the latter. This can be explained because under the flattened hydrograph scenarios (generally with relatively lower peak discharge) wood was mobilized along the main channel, whereas during flashy floods (with higher discharges) wood was easily transported to the floodplain where it was deposited due to low water levels and flow velocities. Although differences in the median values of the wood characteristics were not statistically significant (Mann–Whitney test, p-value >0.05), the distributions of the characteristics significantly differed between the floods with different hydrograph shape (Kolmogorov–Smirnov test, p-value <0.05).

The transport of wood commenced during the rising limb and ceased before the peak of the flood wave in the flash flood scenario, whereas it extended into the early phase of flood recession in both reaches in the flattened flood scenario. Here, the largest pieces were moved during the flood peak, whereas in the case of the flash flood with a higher discharge, the largest pieces were already transported before the peak. When both reaches are compared, we observe that floods in R2 moved pieces of smaller sizes and lower density than in R1 (Fig. 10). This is because of differences in water level and flow velocity between the reaches.

5. Discussion and conclusions

5.1. Controls of flood hydrograph on wood dynamics

In this work we studied the effects that different flood hydrographs have on wood remobilization. When wood is transported into the reach, both model and field observations agree on preferential transport in R1, and for a tendency for retention in R2 (Wyżga et al., 2015a). These results are in agreement with the findings of Ruiz-Villanueva et al. (2015a,b) who applied numerical modelling under steady flow conditions, assuming that wood is recruited just upstream of the studied reaches. Results also converge with data from wood inventories performed in the river reaches under investigation after a series of recent floods (Wyżga et al., 2015a).

However, in case that previously deposited wood is remobilized, wood dynamics tend to be different. One of the reasons for the greater ratio of wood remobilization from R2 was the relatively low magnitude of the preceding flood—consequently, in this reach the flood deposited wood pieces mostly within the active river

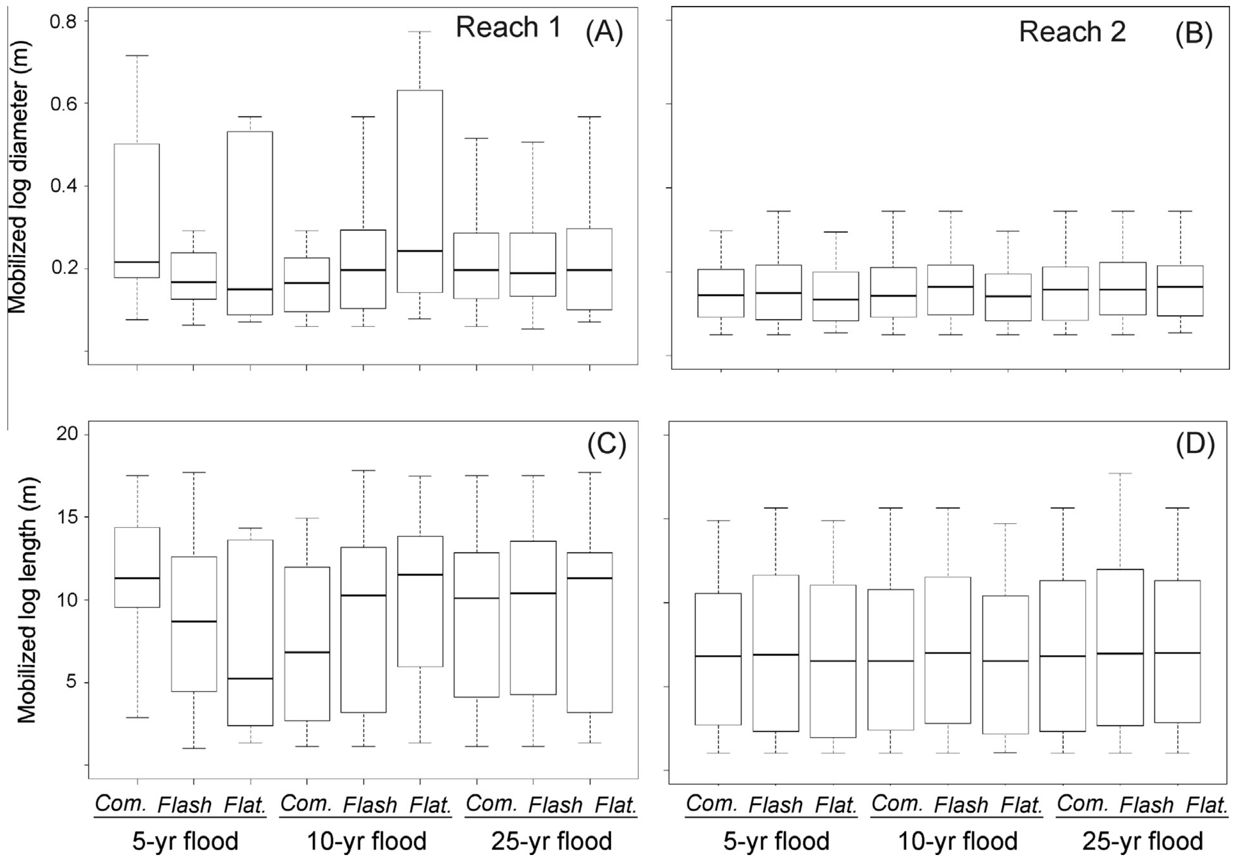

Fig. 10. Boxplots of the diameters (A and B) and lengths (C and D) of mobilized logs during all the flood scenarios for the two river reaches R1 (A and C) and R2 (B and D). The bottom and top of the boxes indicates the first and third quartiles, respectively, the line inside the boxes is the mean and the whiskers indicate minimum and maximum values.

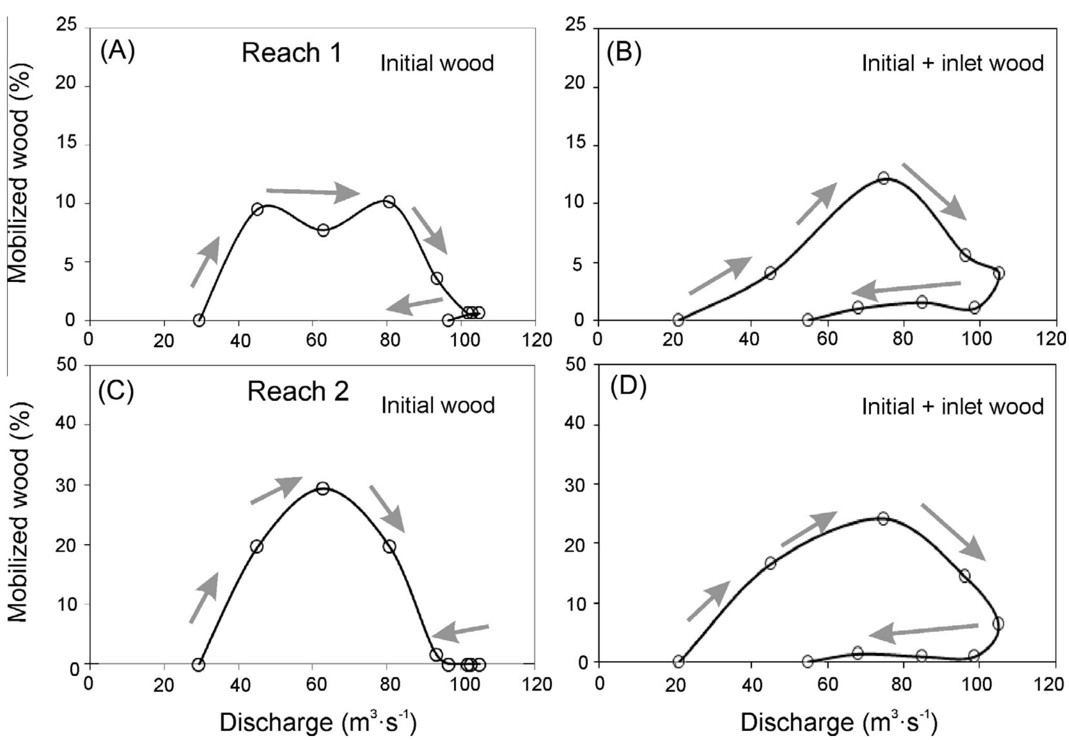

Fig. 11. Clockwise hysteretic loops of the percentage of wood mobilized by the 10-year flood with a common hydrograph for the case of remobilization of only initially deposited wood (A and C) and mobilization of initial and inlet wood (Band D).

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zone. If the former flood were greater, more pieces might be deposited on the floodplain in R2 and the disparity in wood remobilization ratio between the reaches might be reduced, eliminated, or maybe reversed, depending on the magnitude of the antecedent flood. We thus emphasize the importance of the magnitude of the preceding flood in predisposing the potential of deposited wood for remobilization during a subsequent flood.

Field observations performed after the flood of July 2001 indicated that more wood was retained in R2 than in R1, but in R1 a greater proportion of wood was aggregated into jams (Wyżga and Zawiejska, 2010). The aggregation of logs into jams is an efficient mechanism of preventing further mobility of wood, because it will tend to be entrained only if the surface on which the jam is deposited (e.g., gravel bar, river bank) will be eroded. So, not only the geomorphic configuration and the disruption of longitudinal continuity of the floodplain by drop hydraulic structures explain the lower ratio of wood remobilization from R1, but also the greater potential for wood aggregation into jams.

Based on these modelling results, we also observed a lag between the beginning of a flood and the beginning of wood mobilization. MacVicar and Piégay (2012) suggested that this lag is related to the threshold needed to lift logs. Accordingly, we should find different thresholds for R1 and R2, as suggested by Ruiz-Villanueva et al. (2015a). As this threshold is here related to the antecedent flood (28 $m^3 s^{-1}$) responsible for the wood deposition, it is the same in both reaches.

If wood is being mobilized, the peak in wood transport is generally reached before the flood peak. This observation is in agreement with Schenk et al. (2014) who state that most wood is mobilized at the very beginning of the flood in the Roanoke River. This result has also been confirmed by Ravazzolo et al. (2015) who, in addition, observed that most of their tagged logs were deposited right at the flood peak in the Tagliamento River. This outcome should be taken into account to perform the right interpretation of wood deposition when performing post-flood surveys to estimate peak discharge.

Our findings also confirm that wood transport decreases near or slightly after hydrograph peaks. This result suggests that the mobilization of in-stream wood is likely negligible (unless there is an additional supply of wood to the river) during the falling limb of the hydrograph as wood has already been subject to the same or larger discharges during the rising flood and wood pieces have already been deposited in the highest possible locations, braced against obstacles or interlocked with other pieces in wood jams. All these observations should be of great interest for the management of potential wood-related hazards during floods. The knowledge about timing and duration of wood transport might be crucial for a proper management strategy, especially for flood hazard and risk assessments.

We observed that wood motion and wood dynamics (in terms of the duration of wood transport and the number of mobilized pieces) are not only determined by the flood peak, but also by the flood duration and in particular the duration of the rising limb of the hydrograph. Our results are thus in concert with those of Ravazzolo et al. (2015) and MacVicar and Piégay (2012) who emphasized that the shape of flood waves was likely to have a strong influence on wood recruitment and transport. The use of the hydraulic model allowed quantifying the strong relationship between wood motion and the duration of flood hydrograph.

The very different geomorphic configurations of reaches R1 and R2 not only have an important influence on the propagation of flood hydrograph, but also affect resultant flow velocity and water level configuration, which in turn affect the capability of the flow to transport logs of different sizes or density. If both reaches are compared, it becomes obvious that a flood of the same magnitude and hydrograph shape will systematically mobilize smaller pieces in R2. Larger and thicker logs thus require a higher discharge (i.e. higher water level or higher flow velocity) to be entrained and transported as ratified by previous numerical and physical modelling of wood transport as well as the tracking of logs (Welber et al., 2013; Bertoldi et al., 2014; Schenk et al., 2014; Ruiz-Villanueva et al., 2015a). In addition, we observed that the number of remobilized wood pieces was smaller in R1 than in R2 (Fig. 3). By contrast, wood transport ratio was higher in R1 than in R2 under steady flow conditions (Ruiz-Villanueva et al., 2015b), an observation which was corroborated in the field (Wyżga et al., 2015a). However, in this work we are analyzing the remobilization of stored wood, while in the previous work only wood entering the study reaches in the flow and in the main channel was simulated. Therefore, depending on the magnitude of the first steady flow used to set up the initial scenario, the initial distribution of wood deposits may differ, and thus can result in different remobilization patterns by unsteady floods. When additional wood was supplied from upstream in the simulation, this pattern did not change significantly. This is influenced by the design of the inlet wood supply, which was set to start before the peak of the flood and finish during the recession limb with a steady uncongested transport. However, recruitment processes upstream might vary and wood can be supplied in the form of unsteady pulses (because of wood jam breaching for example), resulting in a different dynamic transport.

The presence of LW in the river may also influence flow conditions by reducing the average velocity and locally elevating the water surface profile in a similar way to roughness elements (Gippel et al., 1996; Wenzel et al., 2014). LW may generally cause a deceleration of flood-wave progression, changing the shape of the hydrograph (Gregory et al., 1985; Gippel, 1995). As a result of these changes in flow conditions, a potential influence on erosional and depositional processes can be expected. The in-channel erosion capacity of flood flows is determined not only by discharge and riverbed erodibility, but also by the duration of flooding, so that a reduction in flood peak is accompanied by a shorter duration of the related erosion process. We tested the influence of the initially deposited wood on the flood hydrographs to verify whether the presence of wood in the river influenced the propagation of the floods. Therefore, we compared simulations of hydrographs with and without wood, but we found no significant differences. We thus find that in this type of rivers where wood is typically shorter than channel width and is very dispersed within the active channel, the effect of wood on the flow occurs only locally; generally, individual pieces do not modify significantly the hydrograph propagation along the river reach unless large jams are formed.

5.2. Relationship between wood motion and discharge: the role of hysteresis

Wood transport in rivers is a nonlinear process, and the relation between the proportion of mobilized wood and discharge during floods is complex. Simulated in-stream wood started to move as soon as a certain discharge was reached, and in the case of previously deposited wood, this threshold was clearly related to the magnitude of the antecedent/initial flood (28 $m^3 s^{-1}$). Therefore, similar threshold discharges for wood movement exist in reaches R1 and R2, and wood motion tends to cease as soon as peak discharge is reached, if not already before. In both cases, the number of mobilized pieces increases with increasing discharge until the maximum amount of transported wood is reached. After this point, even if discharge is still increasing, the number of wood pieces in motion decreased and eventually the motion ceased completely (Fig. 11). This loop is influenced by the supply of wood from upstream. As Fig. 11 shows, the relationship is even enhanced when wood is also delivered to the river reaches. We attribute this phenomenon to the hysteresis in mobilization of wood pieces with discharge as previously proposed by Marcus et al. (2011) and MacVicar and Piégay (2012). However, we realize that this process is more complex in R1 where a second peak in wood motion was observed for certain flood scenarios. We explain this difference with fundamentally different geomorphic configurations of the two reaches under investigation and related differences in flood hydrodynamics. If bankfull stage is reached, a further increase in discharge is required to increase the water level in both reaches, and we observed that this hysteresis is stronger in the case of flattened hydrographs (Fig. 11). These findings are again in agreement with the three-stage relation between wood transport and discharge proposed by MacVicar and Piégay (2012), where crossing a threshold discharge for initial wood movement is followed by an increase in wood transport rate with discharge and an inflection point above bankfull discharge. The effect of the hysteresis is so strong that transport of remobilized wood on the falling limb of flood waves is almost negligible. Similar patterns have been observed for relationships between discharge and sediment transport, where the increase of connectivity of the sediment sources to the channel results in clockwise loops (Mao et al., 2014).

5.3. Potential applicability to other rivers and implications for flood hazards

The results of this study will contribute to a better understanding of the complex relationships between floods and wood motion, despite the fact that several relevant processes that occur at the field scale—such as sediment transport and bank erosion—were not considered in the modelling approach. In addition, the presence of roots may influence the movement of fallen trees as pointed out by Braudrick and Grant (2000) or Bertoldi et al. (2014), and this fact has been ignored as well in the study where logs were assumed to be cylinders. Moreover, very limited information still exists on the actual mechanics of wood recruitment to streams, such that we still do not know how the timing of individual tree fall, mass recruitment, jam formation or jam breakup will correspond to stream hydrographs (Wohl, 2011).

Another important aspect in mountain rivers flowing through riparian forests composed of Salicaceae, such as the Czarny Dunajec (Wyżga and Zawiejska, 2010; Mikuś et al., 2013) or the Tagliamento (Gurnell et al., 2001; Bertoldi et al., 2011), is the vegetative regeneration of living wood which might reduce the future remobilization of deposited wood.

Despite these limitations and possible shortcomings, we remain convinced that the results from this study can be generalized and therefore extrapolated to other rivers with similar characteristics, provided that special attention is given to the following aspects. First, the Czarny Dunajec generally lacks natural levees along its channel. In R1, the current floodplain was formed by bulldozers in the 1990s in the course of river channelization; natural levees have not formed since because of the relatively large bank height (and thus infrequent inundation) and relatively low suspended load in the Czarny Dunajec being a typical bedload river. In R2, in turn, where the banks are lower, rapid channel migration prevents longer preservation of natural levees. However, rivers with larger suspended loads and lower rates of floodplain turnover typically have prominent natural levees along their channel. In such rivers, water inundating the floodplain returns to the channel during flood recession through crevasses or slowly infiltrates into the ground (Lewin and Hughes, 1980). In this configuration, wood floated into the floodplain area during a flood crest becomes trapped on the floodplain as it cannot be carried to the channel when the flood recedes. Such rivers may be typified by even a lower proportion of the remobilized wood than reach 1 of the Czarny Dunajec.

Furthermore, we believe that our findings will facilitate a more realistic design of wood inlet boundary conditions in future modelling works, which has been inflicted with major uncertainties in the past (Ruiz-Villanueva et al., 2014a). The same statement holds true for the duration of wood transport, which we demonstrate to be related to the duration of the rising limb of a flood under supply-limited conditions, whereas wood transport is likely to cease at the beginning of the falling flood limb.

In proper flood hazard assessment in forested mountain basins, wood should be considered in addition to water and bedload. One important aspect is the deposition of wood at bridges; therefore, the better knowledge about the relationship between the wood flux and the flow under different hydrological scenarios is extremely important to estimate the potential clogging and its consequences. It should be emphasized that the risks associated with LW are strongly dependent on the degree of human presence within a catchment such as the frequency and type of road crossings, and the proximity and density of human settlements adjacent to the channels. It is thus evident how a balanced, integrated management of LW is needed. The better knowledge of wood dynamics and the outcomes regarding the timing and duration of wood-load transport and the influence of flood hydrograph presented in this paper are crucial for developing adaptive management of the potential hazards of LW to human communities and infrastructure.

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