Large wood clogging during floods in a gravel-bed river: the Długopole bridge in the Czarny Dunajec River, Poland

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ABSTRACT

During floods, large quantities of wood can be mobilized and transported downstream. At critical sections, such as bridges, the transported wood might be entrapped and a quick succession of backwater effects can occur as a result of the reduction of the cross-sectional area. The aim of this work is to explore large wood-related hazards during floods in the gravel-bed river Czarny Dunajec (Polish Carpathians), where the river flows through the village of Długopole. This work is based on the numerical modelling of large wood transport together with flow dynamics in which inlet and boundary conditions were designed based on field observations. The exploratory approach developed

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in this study uses multiple scenarios (193) to analyse the factors controlling bridge clogging: wood size, wood supply, flow conditions, morphology and obstacles in the riverbed. Results highlighted the strong control of log length (stronger than that of log diameter) on potential blockage probability; however, according to our results the main factor controlling the bridge clogging was the flood discharge. River morphology and wood supply play an important role as well. Especially the river morphology may reduce bridge blockage, as it influences flow velocity and depth, and creates natural retention zones for wood. In addition, the impacts of the bridge blockage were analysed in terms of afflux depth and length, and flooded area. Results showed that the bridge blockage may result in a significant increase in the water depth (up to 0.7 m) and flooded area (up to 33% more), therefore increasing flood risk in the village.

KEYWORDS: driftwood, woody debris, wood transport, bridge clogging, flood risk

Introduction

The presence of large wood (LW) in gravel-bed rivers has been proved to be beneficial, by enhancing the physical (i.e., morphological, sedimentary and hydraulic) and biological diversity of fluvial systems (Gregory *et al.*, 2003; Gurnell, 2013; Wohl, 2013; Ruiz-Villanueva *et al.*, 2016d). Therefore, management of LW has evolved in many regions, from the historical removal of wood from streams (Wohl, 2014) to the development of some management plans including guidelines to maintain riparian forest density and in-stream LW abundance (Spence *et al.*, 1996). Moreover, LW has been re-introduced to watercourses in many river restoration projects in recent years (Bisson *et al.*, 2003; Reich *et al.*, 2003; Brooks *et al.*, 2004; Kail and Hering, 2005; Kail *et al.*, 2007; Millington and Sear, 2007; Antón *et al.*, 2011). Nevertheless, public perception of wood in rivers is still generally quite negative (Piégay *et al.*, 2005; Le Lay *et al.*, 2008). This is partially explained by considering the transport of woody material during floods as an additional factor of flood risk in forested catchments

(Mazzorana *et al.*, 2011; Mao *et al.*, 2013; Ruiz-Villanueva *et al.*, 2014a). Recent floods across Europe highlighted that the interactions between riparian vegetation and geomorphic processes (especially in mountain streams) might be amplified not only by the high stream power and high sediment transport rates, but also by the abundant wood delivery to the channels (Badoux *et al.*, 2015; Lucía *et al.*, 2015; Rickenmann *et al.*, 2015; Steeb *et al.*, 2016). The negative consequences are usually greater in urbanized environments where transported LW may threat infrastructures and public safety (Piégay and Landon, 1997). The partial clogging of bridges causes a quick succession of backwater effects induced by the reduction of cross-sectional area, which can be accompanied by bed aggradation, channel avulsion and local scouring processes that can ultimately lead to floodplain inundation and bridge collapse (Diehl, 1997; Lyn *et al.*, 2007;;; Mao and Comiti, 2010; Comiti *et al.*, 2012). As a result, the extent of flooded areas upstream the bridge is likely to be larger than that predicted by the models that do not consider the presence of wood (Ruiz-Villanueva *et al.*, 2013) and, therefore, this may result in the underestimation of flood risk in these areas (Ruiz-Villanueva *et al.*, 2014b).

LW management in urban areas has traditionally assumed that wood was a problem; however, its removal from channels results in degradation of aquatic habitats (Benke and Wallace, 2003; Tockner *et al.*, 2009). Therefore, the management needs to be redefined to a more sustainable approach, understanding the inability of infrastructures to pass LW through the system (Lassettre and Kondolf, 2012). The first step in the improved LW management should, therefore, be to identify the potentially critical structures and the consequences in case of their clogging. The Polish-Swiss Joint Research Project FLORIST aims at improving flood risk analysis in the northern foothills of the Tatra Mountains, including the risk caused by large wood (Kundzewicz *et al.*, 2014). During recent floods in Poland, such as those in 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.*, 2016).

Therefore, the aim of this work was to explore bridge clogging and potential hazards related to LW transport and deposition during floods. We focused our investigations on the gravel-bed Czarny

Dunajec River in the foreland of the Tatra Mountains (Polish Carpathians), where the river flows through the village of Długopole. Buildings in the village are located very close to the river and the Długopole bridge has a narrow cross-section (27 m, up to three times less than the river width a few hundred metres upstream of the bridge). We analysed 1.3 km-long reach, in which the river morphology changes from a multi-thread channel to a single-thread, regulated channel (Wyżga *et al.*, 2015). In the upstream part of the reach, the river still maintains a bar-braided morphology which favours LW retention, but the dense riparian vegetation in this area is the main source of wood delivery due to bank erosion during floods. In the lower part of the reach, beginning 300 m upstream the bridge, the river is channelized and significantly narrower, without any obstacle to the passage of LW. We used numerical modelling and field observations to analyse the transport and deposition of LW in this river reach under different scenarios, examining the potential bridge clogging and its consequences, and evaluating the river morphology as an important factor controlling the clogging process.

Bridge clogging

Large wood accumulation at bridges is a widespread problem, and published accounts represent only a small fraction of the cases that have occurred. Some of the first published works are summarized by Diehl (1997) who also analysed 144 sites across the U.S. where LW accumulation at bridges contributes to more than one-third of the bridge failures. According to this study, one important aspect affecting wood accumulation and blocking of bridges is the geometry of the bridge itself (e.g., the presence and shape of piers). Generally square-nosed piers, which provide a flat surface against the flow are more prone to trap wood (Lagasse *et al.*, 1991; Richardson and Davis, 1995; Lyn *et al.*, 2003; DeCicco *et al.*, 2015). At bridges with more than one pier, the spaces between them can be clogged with wood (Lagasse *et al.*, 1991) depending on the spans (i.e., long spans are less prone to blockage). Other authors observed that the location of the piers within the fluvial corridor is also important for avoiding blockage (Pangallo *et al.*, 1992; Wyżga *et al.*, 2016). Besides the bridge piers, also the bridge deck influences the blockage probability (Schmocker and Hager, 2011). In general terms, bridges that have adequate freeboard during the design flood are less prone to LW accumulation (Lange and Bezzola, 2006). Therefore, the clogging process is also influenced by approaching flow conditions, especially Froude number or flow velocity, and water level (Lyn *et al.*, 2003; Schmocker and Hager, 2011; Gschnitzer *et al.*, 2015). Flume experiments revealed that clogging probability usually decreases with increasing Froude number and water level, for initial water levels below a bridge deck (Gschnitzer *et al.*, 2015). However, under certain conditions (i.e., subcritical flow), the backwater effect upstream of a wood accumulation at piers or racks is usually rising linearly with increasing flow velocity (and thus Froude number) and decreasing porosity of the wood accumulation (as smaller logs fill the interstices between larger logs; Schmocker *et al.*, 2015). Increased backwater is often combined with increased hydrostatic forces acting on the wood accumulations, increased flow velocities and contraction scour, thereby resulting in the flooding of the structure and nearby areas. The flow conditions are partially defined by the morphology of the river, which also has a major effect on the blockage probability (Bezzola *et al.*, 2002; Schmocker and Hager, 2011), although this has not been analysed in depth as most of the works dealing with bridge clogging have been carried out in straight flumes. This work aims at bringing some insight into the role of river morphology on hazards related to large wood.

Together with these factors (i.e., bridge geometry, flow conditions and river morphology), the size and amount of approaching wood (i.e., the shape, size and amount of wood transported in uncongested or congested manner, as defined by Braudrick *et al.*, 1997) determine the potential blockage (Ruiz-Villanueva *et al.*, 2014b). These factors are summarized in Figure 1 and analysed in this work.

<Figure 1>

The Czarny Dunajec River crossing the village of Długopole

The Czarny Dunajec (Figure 2) 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 2>

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. At the Koniówka gauging station located in the middle river course, where the catchment area is 134 km^2, mean annual discharge amounts to 4.4 $m^3\ s^{-1}$. 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 total 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. To optimize the computational time of the model simulations and to focus analysis on the bridge clogging process, we reduced the study reach to a subreach closest to the bridge. This subreach (see red rectangle in Figure 2) was 420 metres long (360 metres upstream the bridge and 60 metres downstream). The model results obtained using this subreach were used for the calculations of the potential blockage probability, while the impacts of the bridge clogging were analysed using the entire river reach (1300 m).

Material and methods

Two dimensional modelling of large wood dynamics

We apply two-dimensional numerical modelling and field data to simulate the transport and deposition of LW in the study reach under different scenarios. We used the numerical model *Iber-Wood* developed by Ruiz-Villanueva *et al.* (2014c), with inlet and boundary conditions determined based on field observations. This fully coupled model uses a second-order Roe Scheme to solve numerically the 2D Saint Venant or Shallow Water Equations based on the finite volume method and a Lagrangian or discrete element approach for wood. Some of the parameters involved in the governing equations for wood transport 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 initial motion of cylindrical logs is determined by the balance of forces acting on the centre mass of the log. When the log is entrained, the model includes two possible transport mechanisms: floating or sliding/rolling, depending on wood density and water depth. In addition, rotation (when one end of the wood piece is moving faster than the other, the log rotates) and translation of logs are also included, based on flow velocity field. Log velocity is computed using the log density, log diameter and water depth to define the motion: resting, floating, or by traction (i.e., sliding or rolling). If the log floats, the velocity is the same as the water velocity (as observed by D'Agostino *et al.*, 2000; Degetto and Righetti, 2004; and MacVicar *et al.*, 2009), unless turbulence is included in the calculation (see below). If the log slides on the river bed, the log velocity is different from the water flow velocity, with friction controlling log velocity.

Interactions between logs and 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 channel banks and bed or with other logs (assuming this process as an elastic collision). The hydrodynamics and wood transport are coupled; thus, the hydrodynamics influence wood transport, but the presence of wood also influences hydrodynamics, adding a drag term to the two-dimensional Saint Venant equations (Ruiz-Villanueva *et al.*, 2014c). The model reproduces interactions between wood and infrastructures, computing whether a log can pass under or above a bridge deck, or become trapped by the structure, depending on the gate opening and width, the weir length, water depth and wood diameter and length.

The model has been already applied in the Czarny Dunajec River, but in other reaches and for other purposes related to the analysis of controls on large wood dynamics in different river morphologies (Ruiz-Villanueva *et al.*, 2016a, 2016b, 2016c).

The role of turbulence

Water flow in gravel-bed river channels is generally turbulent (Buffin-Bélanger *et al.*, 2001), but for river smooth morphologies where no re-circulation zones appear, roughness acts as the principal factor of vortex stabilization and the inclusion of turbulence models usually has little or no effect on the velocity field (Cea Gómez, 2005). Nevertheless, in gravel-bed rivers, small swirls may appear and disappear with an almost chaotic movement, and this turbulence may affect wood transport. Moreover, the stochastic nature of turbulent flow around bridge piers is well known (Tseng *et al.*, 2000). The hydrodynamic model *Iber* includes several turbulence models (constant viscosity coefficient, parabolic, mixing length, and k–ε), but when considering the influence of turbulence on wood transport, only the Rastogi–Rodi k–ε model (Rastogi and Rodi, 1978) can be used. In this model, k represents the turbulent kinetic energy and ε the rate of dissipation of the turbulent energy. The approach considers turbulence caused by bed friction, velocity gradients and convective transport. For wood transport, the k–ε model is used to recalculate the log velocity based on the fluctuations in the turbulent velocity (Kleinstreuer and Zhang, 2003) as follows:

$$u' = \lambda\left(\frac{2}{3}k\right)^{1/2} \qquad [1]$$

where k is the turbulent kinetic energy, λ is a random number, and wood velocity is calculated using the reconstructed instantaneous water velocity u'. Use of this approach basically means introducing a random component into the motion of logs transported by a turbulent flow. In this way, identical logs dropped into the same spot may end up in different places, depending on the turbulent kinetic energy.

This adds a random component which allows getting slightly different results in each simulation keeping the same model parameters. This random component together with the stochastic characterization of the logs at the inlet boundary (see next section), enabled repetition of each simulation 3 times to ensemble model results and analyse them statistically. Therefore, the reproducibility requirement cannot be strictly applied here as the results have a partial non-deterministic nature.

Model set up

Topography of the study reach was available from 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 representation of the channel geometry in summer 2015 (after the flood of 2014). As a result, we obtained a DEM with 0.5 m pixel size resolution to design the unstructured calculation mesh for the numerical model. We defined the geometry of the bridge defining the bridge deck as an internal condition; the pier was also included in the calculation mesh.

The same model has been applied to other reaches of the Czarny Dunajec, upstream of the study area and closer to the Koniówka stream gauge where a rating curve is available. Because the current study reach is distant from the stream gauge (Koniówka is located 12.8 km upstream of the bridge at Długopole), we recalibrated the model in the studied reach using the data collected after the flood in 2014. We used the peak water level of the 2014 flood, reconstructed on the basis of high-water marks (see Radecki-Pawlik *et al.*, 2016), to calibrate roughness values (i.e., Manning roughness coefficient). Values of roughness coefficient were assigned, both in the channel and the floodplain, to homogeneous land units in terms of their roughness (Table 2).

Wood inlet conditions were established based on the knowledge of wood and riparian vegetation along the river. To characterize each piece of wood entering the reach, we established the ranges of maximum and minimum lengths, diameters, and wood density based on the main types of trees recruited to this river (see details in Ruiz-Villanueva *et al.*, 2016a, 2016b), assuming that wood recruitment is only occurring upstream of the study reach. We computed stochastic variations of these parameters together with the angle with respect to the flow at the inlet boundary in the main channel. Then, we defined a number of logs per minute to enter the simulation domain.

To address the inherent stochastic behaviour of this natural process and related uncertainties, a multiple scenario approach was applied. First, we considered different dimensions of logs, changing the size of wood pieces entering the river reach to determine the critical size in terms of bridge clogging. Second, we changed the discharge to change the flow conditions, simulating very frequent floods (1.2-year return period and discharge of 28 $m^3 s^{-1}$) to extreme floods (50-year return period and discharge of 183 $m^3 s^{-1}$) under steady-state conditions. Third, we changed the amount of wood entering the river, simulating fully uncongested to semi-congested transport regime (according to Braudrick *et al.*, 1997). Congested transport is very unlikely to occur in the Czarny Dunajec River. Low wood supply, assuming only recruitment from upstream the reach was considered to be fully uncongested with 2 logs per minute and a total of 132 logs; medium wood supply was simulated with 3 logs per minute and a total number of 199 logs; and high wood supply was simulated with 5 logs per minute and a total of 332 logs. All these variations form the modelling Set 1 (applied to the subreach near the bridge), with a total of 38 scenarios repeated 3 times, which resulted in 114 simulations.

The role of river morphology

We argue that river morphology controls the flow conditions upstream of the bridge. Therefore, if morphology changes, and flow conditions change as well, we hypothesize that conditions of bridge clogging may change too. To test this hypothesis, we modified the morphology of the river subreach near the bridge obtaining a new DEM based on field observations. Recent floods resulted in the destruction of bank reinforcements (rip rap) at a few sites upstream of the bridge (Figure 3). The location of the destroyed rip rap indicates a sinuous course of the eroding current during floods that hit successively opposite channel banks at the distance of 60-80 m equal to about three channel widths. This, together with observations of the morphology of the Czarny Dunajec in other reaches with more sinuous, single-thread channel, allowed us to design morphological evolution of the channel subreach upstream of the bridge, provided that the eroded bank reinforcements will not be repaired before the next flood. In that case, even a moderate flood should result in bank retreat at the sites by 5-10 m, formation of a sinuous thalweg with flow inflection points situated 60-80 m apart and deposition of initial alternate bars, elevated about 0.5 m above the previous bed surface, opposite the retreating banks. This anticipated channel morphology was reflected in modification of the DEM upstream of the bridge (Figure 3). In order to compare this new set with the previous model set, we designed similar scenarios, varying the size and the amount of inlet wood and the inlet flow conditions to obtain 42 simulations (14 scenarios repeated 3 times) with this new morphology for the subreach near the bridge. These simulations form the model Set 2.

<Figure 3>

As a result of the bank erosion described above, trees can be easily recruited to the main channel (as Figure 3E shows). Large trees grow on the banks close to the channel. As shown in Figure 3A, there is an old alder (45-50 cm in diameter and 20 m high), a large poplar (45 cm in diameter, 18-19 m high), a spruce (35-40 cm in diameter, 18 m high) and a large willow (about 60 cm in diameter, 20 m high with a very large crown). These trees should not be moved much after falling to the river, or just by a very large flood, potentially resulting in a spanning obstacle in the channel damming its entire width. If this happens just upstream the bridge, the transport of logs might be affected. Therefore, we designed a third model set, using the modified morphology of the subreach near the bridge and placing these large trees in the channel; running 5 scenarios under different discharges and with different amounts of wood resulted in 15 further model runs.

As explained above, we reduced the study domain to the subreach close to the bridge (shown by red rectangle in Figures 2 and 3). However, , we analysed clogging impacts of the log deposition along the entire study reach (1300 m long) in other 16 runs. Clogging impacts were analysed by reducing the cross-sectional area of the bridge, simulating an accumulation of wood against the pier, and we analysed the effects on the water depth and flooded area.

All the scenarios described above together with the model calibration process resulted in a total of 193 model runs. Table I summarizes all the combinations of wood properties, flow conditions, river morphology and wood supply used in these runs.

<Table I>

Computing bridge potential blockage probabilities

The main fixed element controlling the blockage probability is the bridge pier. The expected effect of wood transported during floods is the accumulation of wood in a pile upstream the pier as shown earlier in Figure 1B.

Wood single-pier accumulations, as the one formed during the flood in 2014 (Figure 1B), typically contain one or more logs extending over the whole width of the accumulation perpendicular to the approaching flow and often take on a form roughly resembling an inverted half-cone, sometimes reaching from the water surface to the river bed (Diehl, 1997). These accumulations have the same structural pattern as the upstream ends of some large accumulations that form across spans and on island heads. They typically terminate in a raft with a curved upstream edge when viewed from above, and with the centre of its downstream side resting across thicker parts of the accumulation that support the raft against lateral hydraulic forces (Diehl, 1997; Lyn *et al.*, 2003).

The formation of the pile or raft is a fully 3D process, and so is the flow in front of an obstacle, which cannot be fully reproduced by a 2D model. However, we attempted to reproduce a quasi-3D process for logs that are lying (resting) on the river bed or bank; if another piece floats above it, these two may interact, depending on the water depth and log diameters, and the lying log may start to move or the floating log may stop according to the force balance. This approach has some limitations as the superposition of floating logs is not simulated by the model, , the interaction between logs is assumed to be an elastic collision and logs are considered to be cylindrical. Therefore, it is very likely that the obtained blockage is different than the one actually observed in the river.

For this reason we assumed that logs touching the pier (and not only resting towards the pier) might be potentially blocked in a 3D space. Therefore, we counted all logs touching the pier or resting against it in all scenarios and we computed a potential blockage probability as a probability of the potential occurrence of clogging. In this way we may artificially modify the calculated potential blockage probability, however, this allowed us for easy comparison between the different model sets which is the goal of the study and not to calculate the actual probability of a log to get blocked at the bridge pier.

Results

Model calibration

Model calibration focused on the hydrodynamics calibration based on Manning roughness coefficient. The calibration process resulted in slightly reduced (compared to previous values used in other reaches) values of roughness coefficient (Table II). The comparison of simulated and observed water levels at the peak of the 2014 flood at three cross-sections showed less than 20 cm difference in all cases. We found a relatively large error in cross-section 2, with an overestimation of 14 cm in the water level indicated by the model. This difference, together with a larger inundated area on the right bank just upstream this cross-section, may be explained by the difference in riverbed elevation between (i) the flood peak and our survey conducted in summer 2014, shortly after the flood, and (ii) the time of DEM correction in 2015. Another difference was observed at the bridge cross-section where the estimated water level during the flood in 2014 was 3.6 m and the model indicated 3.4 m.

This difference is explained by the occurrence of the log jam shown in Figure 1B, which blocked the cross-section and might increase the water level at this point. At cross-section 1, the difference between observed and simulated water level was 7 cm and no difference was observed at cross-section 3.

<Table II>

Set 1: The role of wood size, flow conditions, and wood supply

Results from the Set 1 simulations (114 runs) show that the maximum bridge potential blockage probability is 20% (mean = 11%, SD = 4.2%). We observe greater differences in the potential blockage probability when we changed the log length, but smaller when the diameter was changed (Figure 4A, B). In both cases, however, differences are not statistically significant. The most important factor influencing the blockage of the bridge is driven by the flow conditions, according to the statistically significant differences between the simulation results obtained for different discharges (Figure 4C). The amount of wood supplied to the study reach also influences the potential blockage probability, but the differences in the median between the three scenarios are not statistically significant (Figure 4D).

<Figure 4>

We further analysed the effect of log length under different flood scenarios (Figure 5A), and we observe that the variability of potential blockage probability is smaller for short than for longer logs, but the pattern is similar in all cases. For logs of the same length, the increase in discharge significantly increases the potential blockage probability (*p-value* < 0.05), at least for the length up to 12 m (corresponding to the ratio of log length to bridge cross-section width of 0.44 and equal to 0.85 and 1 for the ratio of log length to bridge pier-abutment spans). For longer logs, the pattern is the same but the differences between the different flood scenarios are not significant (*p-value* > 0.05). The critical value seems to be 15 m, for which we found the highest potential blockage probability. Surprisingly, for 20 m-long logs the potential blockage probability is slightly lower. However, this is explained by the higher proportion of logs deposited upstream of the bridge, which reduced the number of logs approaching the bridge.

Wood supply was also further analysed under different flood scenarios (Figure 5B). For low wood supply (2 logs per minute) resulting in fully uncongested transport, the potential blockage probability does not change with the increase in discharge. However, during semi-congested wood transport (medium and high wood supply with 3 and 5 logs per minute, respectively), the bridge potential blockage probability increases with increasing discharge (although differences are not significant).

<Figure 5>

Set 2: The role of river morphology

The modified river morphology designed for Set 2 resulted in significantly different distributions of water levels and flow velocities (Kolmogorov-Smirnov test, *p-value* < 0.01) in comparison with those existing under current morphology conditions (Figure 6).

<Figure 6>

As histograms and cumulated frequency functions in Figure 6 show, water depth for the same flood discharge is different under the modified morphology (Figure 6 A and B); as the flooded area increased, the frequency (i.e., number of pixels) of water depth less than 1 m increased as well due to floodplain inundation. Flow velocity is also different; in this case, flow velocity decreased under the modified morphology, reducing the frequency of velocity values higher than 2.2 $m \cdot s^{-1}$ and increasing the frequency of values lower than 0.4 $m \cdot s^{-1}$.

For a flood similar to that in 2014 (discharge of 130 $m^3 s^{-1}$), the flooded area is much larger with the modified morphology, due to the bank erosion and the occurrence of new alternate bars, which reduce the flow capacity of the channel (Figure 7).

<*Figure 7*>

Therefore, we used the modified morphology to analyse bridge clogging, and results from Set 2 simulations (42 runs) show that the maximum bridge potential blockage probability is slightly lower than in the previous set (maximum = 15%, mean = 9.5%, SD = 3%). But we do not find significant differences in the potential blockage probability between the medians of the two sets (Figure 8). The reduction in the potential blockage probability can be explained by the higher water depth and flooded area, accompanied by the reduced flow velocity (and thus the Froude number of the approaching flow) upstream of the bridge, and the deviation of the flow direction caused by the bank erosion. More logs are deposited upstream of the bridge section and when logs approach the bridge at smaller velocities, the potential blockage probability is reduced.

<*Figure 8*>

We observe statistically significant differences in the potential blockage probability between logs of different lengths (Figure 9A), but even though we find differences in the potential blockage probability between scenarios of different floods, they are not significant (Figure 9B). However, in this set we observe differences in the bridge potential blockage probability between the three wood supply scenarios, with an increase of the probability from 8% to 13% between the low and high supply scenarios (Figure 9C).

<*Figure 9*>

When we compare scenarios with different log lengths and different wood supplies between Set 1 and Set 2, we do not find statistically significant differences (*p-value* > 0.05).

Set 3: The role of falling trees

Trees fallen into the channel have some influence on the flow and wood transport, especially at low flood discharges. Results of the simulations show that the trees are able to trap other logs, hence reducing the blocking at the bridge, especially for medium and high wood supply (Figure 10).

<Figure 10>

However, at higher flood discharges, water depth above the trees is enough to allow the downstream transfer of logs, so that they reach the bridge.

Wood deposition and bridge clogging impacts

We analysed the deposition of wood along the entire river reach under different flood conditions and we observe that the upper part of the reach, where braided morphology persists, is a zone of natural wood retention (Figure 11). Under low-magnitude floods (discharge of 28 $m^3 s^{-1}$), 47% of the logs supplied to the river are stored in this area, although some others are deposited along the channelized reach upstream of the bridge as well (Figure 11).

This retention capacity of the braided reach is, however, reduced at higher flood discharges. For discharges that partially inundate the bars (55 $m^3 s^{-1}$), a proportion of the logs deposited in this area is significantly reduced (only 16% of the total number of deposited logs).

<Figure 11>

The main impact of bridge clogging is the backwater effect of afflux produced by the reduction in the cross-sectional area, and the enlarged flooded area (Table III). For instance, at a 10-year flood (105 $m^3 s^{-1}$), an afflux upstream of the bridge ranged from 0.15 m (for 10-15% blockage) to 0.72 m (for 55-60% blockage). This backwater effect produced an increase in the flooded area up to 4.4 hectares, that is 33% more than without any blockage at the bridge (Table III), consequently affecting several buildings in the village.

<Table III>

Figure 12 shows the difference in the water depth at the 10-year flood between the situation without any obstruction to flow and the worst-case scenario simulated, with a 55-60% reduction of the cross-sectional area. It is evident that the afflux caused inundation of the nearby area, extending to the village, with many buildings potentially affected.

<Figure 12>

Discussion

Potential blockage probability

This work analysed large wood-related hazards at bridges using the case study of the gravel-bed Czarny Dunajec River crossing Długopole village in Poland. Analysis was mainly based on numerical modelling, although we used the model in an exploratory framework supported by the knowledge of the river and field observations. The analysis of main factors influencing bridge blockage indicated a strong control exerted by log length (stronger than that of log diameter), as already pointed out by Diehl (1997) and Lagasse *et al*. (2010). However, the size of wood pieces is not the most important factor controlling bridge blockage; according to our results, the flow condition (i.e., flood discharge) is the main driver. The intensity of wood supply and river morphology also have some influence on the final blockage. Semi-congested transport of wood may result in increased potential blockage probability as shown in our study. Based on the knowledge of the river, we designed three reliable scenarios of steady wood supply (i.e., high, medium and low); however, recruitment processes during a flood might be variable (Benda and Sias, 2001) producing wood pulses or fluxes that would require further research, which is out the scope of this work. Nevertheless, we believe that the ability to accurately determine wood fluxes not only is a statement about completeness of fundamental understanding of wood transport processes but also constitutes a critical need in river and flood management (Ruiz-Villanueva *et al.,* 2016c).

One important aspect controlling large wood dynamics and therefore bridge clogging is river morphology. We found that the modification of the river morphology (resulting from bank erosion and the formation of alternate bars) reduced the bridge potential blockage probability. This is because the initial straight channel changed to a sinuous channel upstream of the bridge, changing the flow velocity (reducing Froude number) and water depth. In the initial straight channel, logs tend to move aligned with the higher flow velocity. In this case, the highest velocity area crosses the location of the pier, the trapping potential (or potential blockage probability) of which is then higher than in the case of an oblique path of high-velocity flow (Diehl, 1997; Lyn *et al.*, 2007). The morphology of the river just upstream of the bridge is therefore important, but the proximal part of the study reach with the braided morphology showed a significant retention capacity of wood. High morphological complexity has been shown to increase the retention of large wood (Wyżga and Zawiejska, 2010). These natural retention zones, in our case the upstream reach with multi-thread morphology, provide enormous environmental benefits (Wohl *et al.*, 2016) and reduce the potential wood-related hazards downstream (Wyżga *et al.*, 2010). On the contrary, river modifications such as channelization reduce the wood retention capacity, allowing wood inputs to be rapidly flushed through the system (Bilby and Likens, 1980; Gregory *et al.*, 1991; Allan, 1995; James and Henderson, 2005). Therefore, flood management and restoration projects should take this into consideration, and the increases in retention capacity (in terms of flow, sediment, and large wood; James and Henderson, 2005) should be a priority.

The study allowed us to analyse main factors controlling bridge clogging and to quantify their effects on the potential blockage probability. The 2D modelling approach appeared to be a powerful tool to analyse this process; however, the calculated probability is very likely to be different than the one observed in the river. We obtained maximum blockage probabilities up to 20% at the bridge pier, but some limitations need to be emphasized. One of them is related to the simplified shape of logs, assumed as cylinders. Wood pieces with branches or roots will significantly increase the blockage probability, as observed by Schmocker and Hager (2011). In addition, the accumulation of wood towards the bridge pier is a 3D process, which cannot be fully reproduced by a 2D model. The accumulation of logs usually occurs at the water surface; therefore, if the water level changes, the following logs would accumulate over the previously clogged ones (thus forming a partially submerged accumulation; Diehl, 1997; Lagasse *et al.*, 2010). The turbulence (i.e., eddy) triggered by the bridge pier makes the flow go down pushing the logs towards the river bed, which also contributes to the formation of a partially submerged accumulation. Finally, the interaction between logs is another factor to be considered. During semi-congested transport logs may collide and continue moving together, due to the presence of branches or other irregularities. When this floating accumulation finds an obstacle, the constituent logs may clog together. Especially, if some logs have already clogged at the bridge pier, the entrapment of subsequent logs is facilitated. All these processes are not well reproduced by the model, which assumes elastic interactions among logs and does not allow for the transport of several logs forming a multi-log mass. Further research is needed to include this important interaction between logs in the modelling approach.

Another important aspect is related to the assumption of steady conditions when simulating the different flood scenarios. Because simulating the clogging process *per se* was out of scope within this study as it rather focused on the analysis of factors controlling the clogging, and flood hydrographs were not available for the entire range of peak discharges analysed here, we decided to run the model under steady conditions using peak discharges. Therefore, the effects of the hydrograph shape and the timing of the flood peak could not be analysed. These aspects were analysed in a previous work (see Ruiz-Villanueva et al., 2016c) but with respect to river reaches without bridges, whereas the effects of different hydrographs on bridge clogging have not been analysed in detail yet. They will be considered in future works.

We indicated the consequences of the bridge clogging in terms of the increase in water depth (and consequently a decrease in flow velocity), but other processes may also occur. Sediment deposition may occur among the logs and in the eddy just downstream, producing a bar surrounding a pier or located in the lee of the wood accumulation, and resulting in channel widening and migration (Diehl, 1997). This process was not considered, as we did not simulate sediment transport. However, it also may have some effects on the final potential blockage probability and impacts on the water depth.

Implications for flood management

LW is increasingly recognized as one of the main problems in risk prediction and management in mountain watercourses (Rickenmann, 1997; Rickli and Bucher, 2006; Lange and Bezzola, 2006; Hubl *et al.*, 2008). In the case considered in this study, clogging of the bridge with wood will lead to inundation of developed riparian areas and considerable material losses among the inhabitants of the village of Długopole. Interestingly, the flood hazard to the village is only partly related to potential bridge clogging but also results from insufficient flow conveyance of the bridge cross-section. This is why the relative effects of the bridge clogging (i.e., increases in water depth and flooded area as well as in afflux length) are highest for the 10-year flood (Table III), the discharge of which approximates channel conveyance upstream of the bridge. At lower discharges, clogging of the bridge cross-section causes a marked increase in water depth but is not reflected in a substantial increase in the flooded area of the valley floor. In turn, high-magnitude floods inundate riparian areas even without any bridge clogging, and thus partial blockage of the bridge cross-section results in relatively small increases in water depth and flooded area.

In the described case, the threat resulting from potential bridge clogging might be substantially limited by replacement of the current narrow bridge with a central pier by a wider bridge accommodating more flow and having a larger span between bridge abutments and the pier, or by a bridge with the same cross-section width but lacking a pier located in the channel. The second type of bridge reconstruction has recently been practiced in another reach of the Czarny Dunajec, with the new bridge enabling undisturbed transfer of large wood during floods and successfully eliminating a possibility of bridge clogging (Wyżga *et al.*, 2016).

It should be emphasized that the efficient retention of large wood in a 4 km-long, upstream reach with a wide, multi-thread channel reduces significantly the potential bridge clogging, as observed in the river and indicated by this study. Even though the unmanaged character of this reach with erodible channel banks enables wood recruitment to the river, the reach predominantly operates as a sink for LW as relatively low unit stream power and the abundance of retention features (islands, bars) facilitate its entrapment from floodwaters (Wyżga and Zawiejska, 2010; Mikuś *et al.*, 2016b).

Preservation of such river reaches upstream of vulnerable sites (narrow bridge cross-sections, urban reaches) is thus crucial for the efficient reduction of large wood-related flood hazard (Mikuś *et al.*, 2016a).

Concluding remarks

This study examined the main factors influencing the potential blockage by large wood of a relatively narrow bridge with a single central pier. Moreover, the study analysed potential impacts to the nearby village resulting from the bridge blockage during floods of different magnitude. Simulations conducted with a 2D hydrodynamic model indicated that potential blockage probability increases with increasing flood discharge and revealed a strong influence of log length and the intensity of wood supply on the potential blockage probability. River morphology upstream of the bridge was found to have double significance for bridge potential blockage probability. First, assumed temporal change resulting from bank erosion and the formation of sinuous thalweg just upstream of the bridge may reduce the potential blockage probability as a result of induced modification to the flow velocity field and water depth. Second, the spatial variation of river morphology in a longer upstream reach, and in particular the occurrence of multi-thread river morphology with the high capacity for wood retention, affects the amount of logs that are transferred along the reach and can clog the bridge cross-section.

Clogging of the bridge cross-section with large wood may markedly increase the flooded area on the valley floor and its potential impact on the flood hazard to the village is most pronounced for the flood flows approximating channel capacity just upstream of the bridge. Because in this and other densely developed areas near bridges threatened by wood clogging the flood hazard may translate to considerable flood risk and flood damage, further studies on large wood phenomena occurring during floods at bridges and in their vicinity are of high practical importance. However, the previous approach to mitigate the hazard by the clearance of riparian forests (Shields and Nunnally, 1984) is no longer possible in the light of environmental requirements of the Water Framework Directive and thus alternative approaches are necessary. One of them consists of the installation of racks or other structures that trap large wood from floodwaters upstream of vulnerable sites/reaches (Bradley *et al.*, 2005; Piton and Racking, 2015), and of the reconstruction of bridges to facilitate transfer of wood and eliminate the potential for its clogging (Wyżga *et al.*, 2016). Another one represents a holistic approach to large wood management at a watershed scale, that tends to accommodate the processes of wood input, storage, and transport through the channel network by preserving zones of large wood recruitment (Boyer *et al.*, 2003) and areas of wood storage, thus retaining the important ecological functions of large wood (Lassettre and Kondolf, 2012), while minimizing the related flood hazard.

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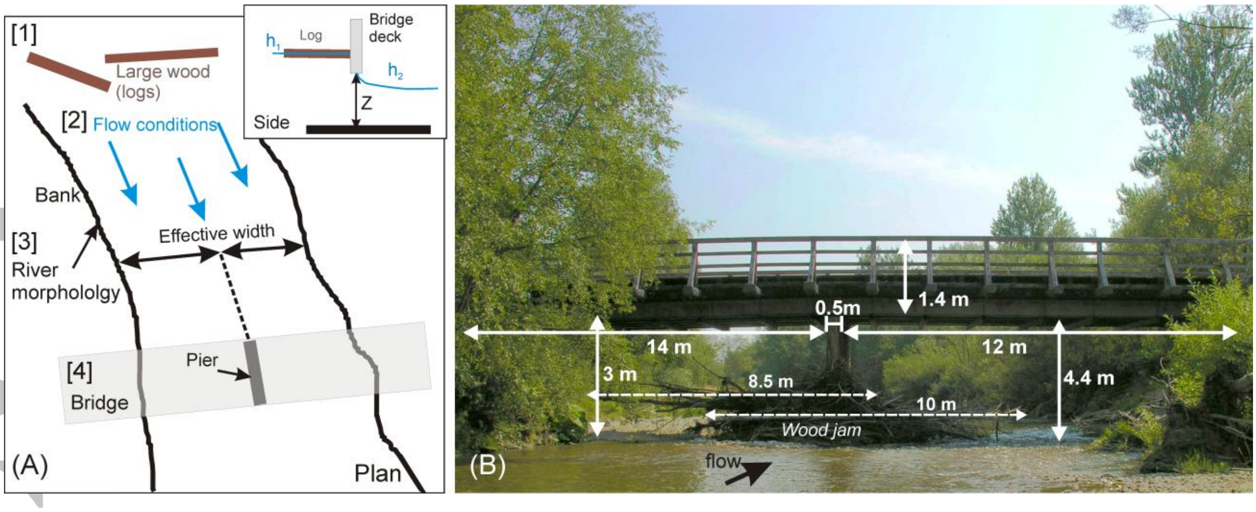


Figure 1. (A) Orthogonal sketch showing the four main factors influencing bridge clogging: (1) approaching wood (different size and different amount of wood); (2) flow conditions (in terms of water level and velocity field); (3) river morphology upstream the bridge; and (4) the geometry of the bridge (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). The small graph shows the lateral view of a bridge cross-section showing the bridge deck, the bridge opening (Z), the water level (h1: upstream, and h2: downstream) and an entrapped log. (B) Wood single-pier accumulation against the pier in the Długopole bridge after the flood in 2014. Black arrow shows flow direction.

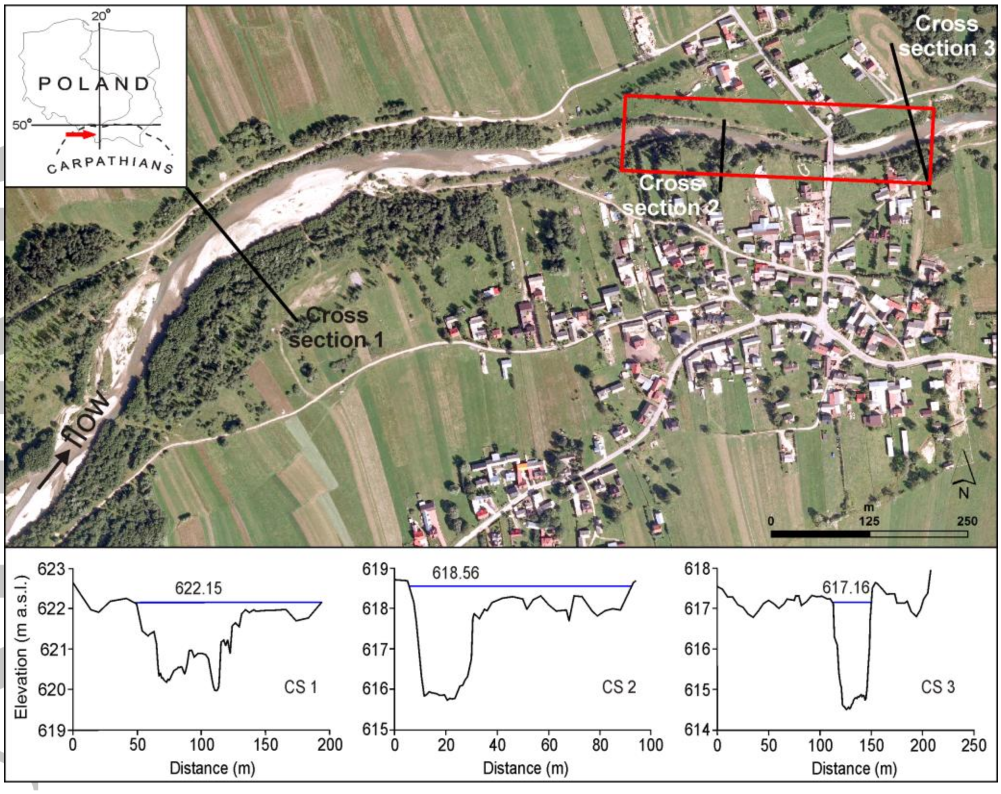


Figure 2. Location of the study area in the Polish Carpathians and the study reach of the Czarny Dunajec River crossing the village of Długopole. Graphs show the reconstructed water level during the flood in May 2014 (20-year return period and 130 m^3 s^{-1} discharge) at three different cross-sections (CS). Red rectangle shows the subreach close to the bridge used for modelling.

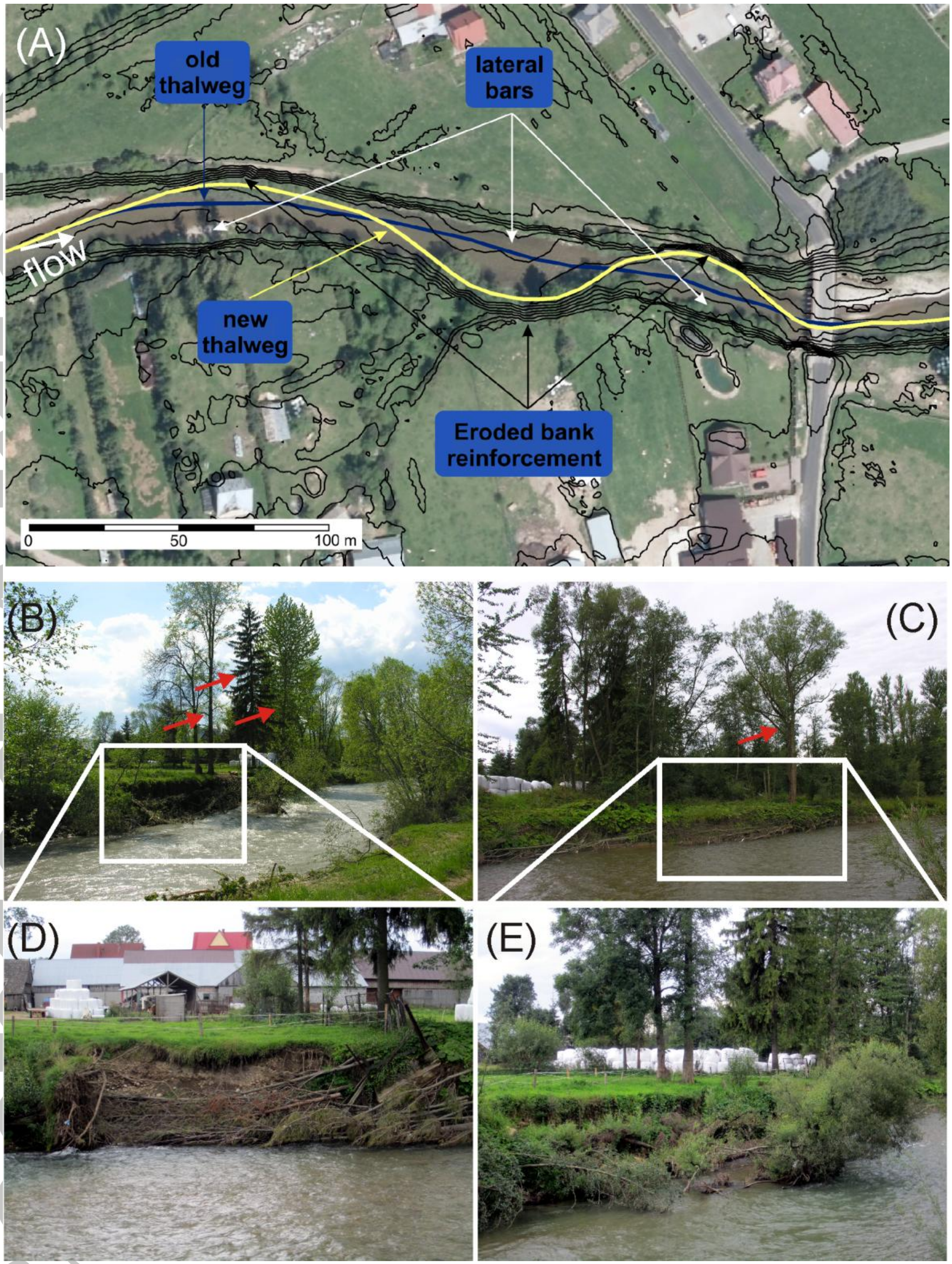


Figure 3. (A) DEM modification of the subreach near the bridge based on morphological changes observed in the river (explained in the text). Flow is from left to right; (B) river reach upstream the bridge, red arrows show three large trees located close to the right bank (details in the text); (C) river reach upstream the bridge, red arrow shows a large tree located close to the right bank (details in the text); (D) erosion in the right river bank; (E) erosion in the right river bank and trees fallen dwon in the river channel.

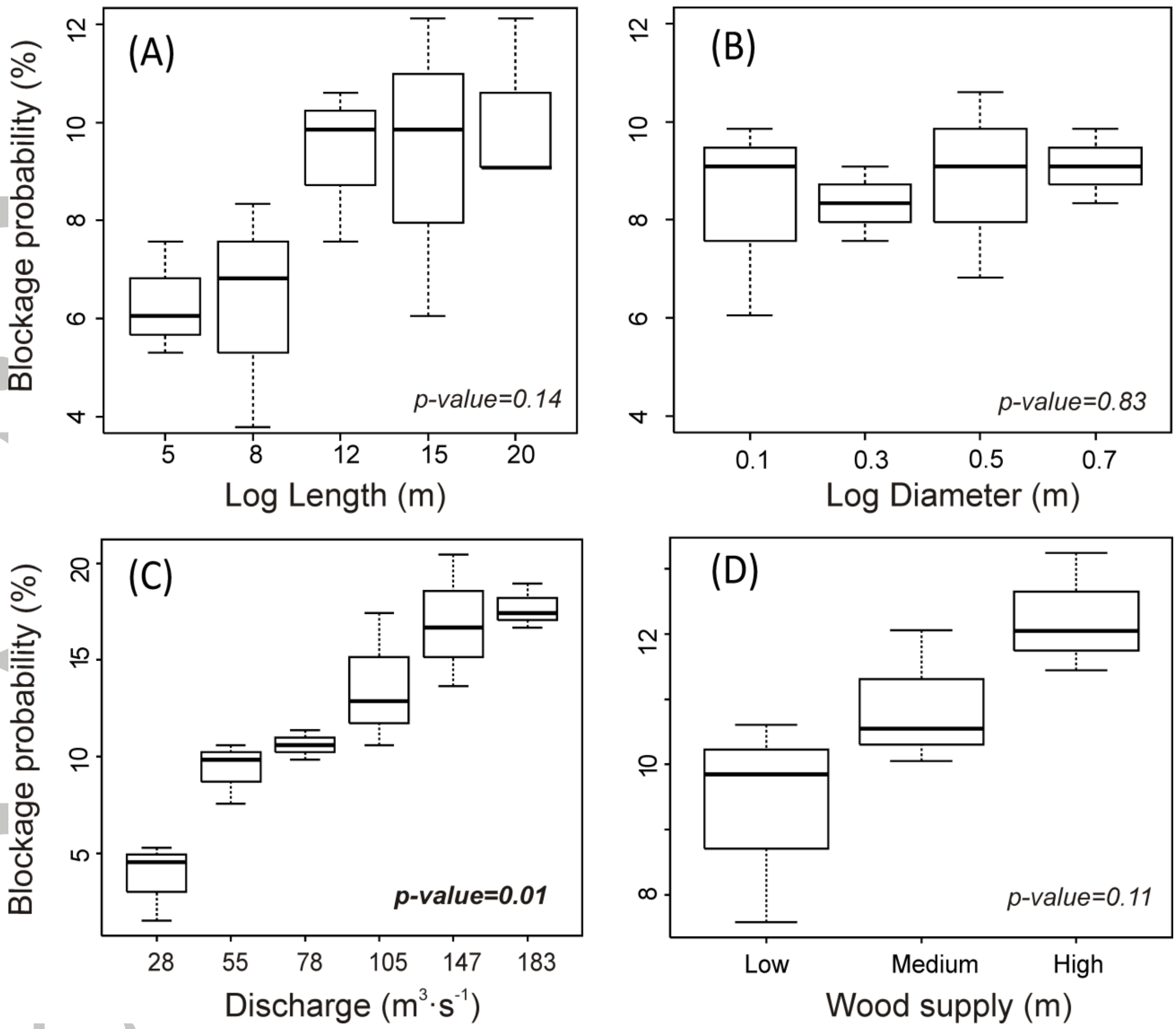
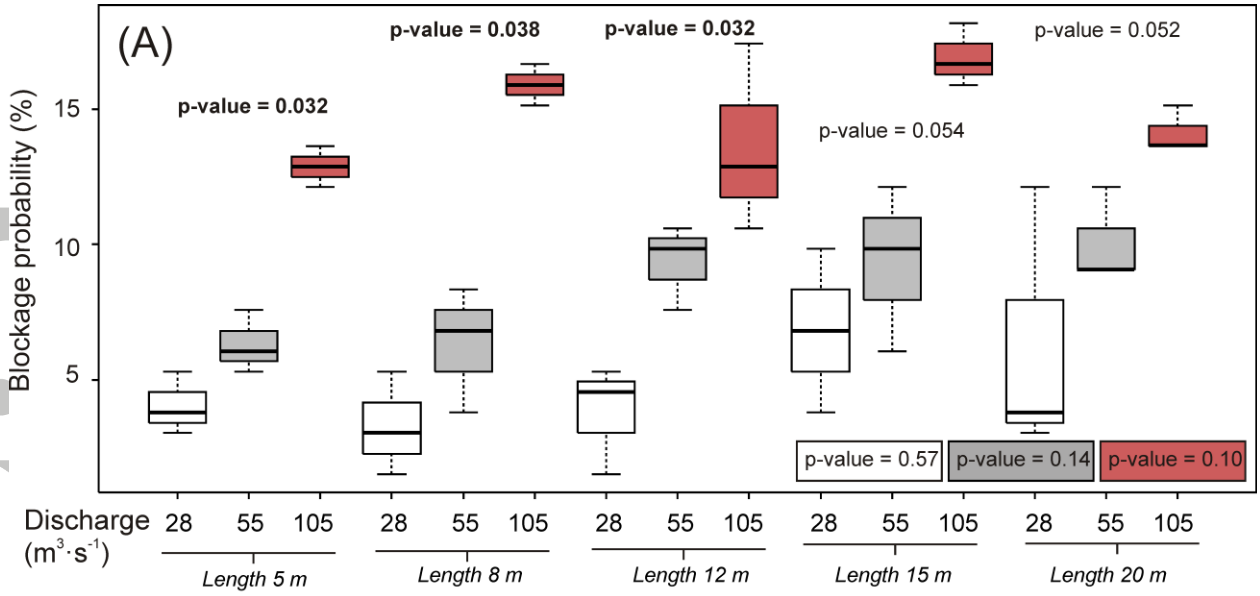


Figure 4. Bridge potential blockage probability computed for the scenarios of different log lengths (fixed diameter equal to 0.2 m) (A); log diameter (fixed length of 12 m) (B); discharges (logs 12 m long and 0.2 m in diameter) (C) and the amount of wood supplied (logs 12 m long and 0.2 m in diameter) (D). The discharge for the scenarios shown in A, B and D was 55 m^3 s^{-1}. P-values show the results of the Kruskal-Wallis test (significance is marked in bold, *p-value* < 0.05).



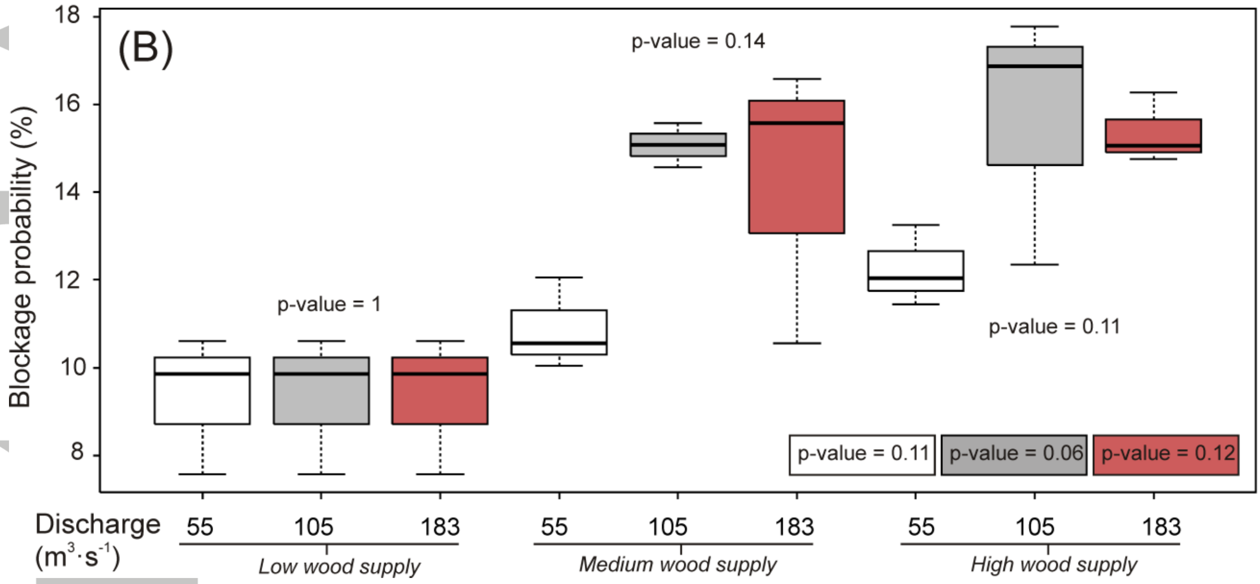


Figure 5. (A) Bridge potential blockage probability for logs of different lengths and under different flood scenarios. In all cases log diameter equals 0.2 m and wood is supply uncongested (low supply). (B) Bridge potential blockage probability for three wood supply scenarios and under different discharges. In all cases logs are 12 m long and 0.2 m in diameter. P-values show the results of the Kruskal-Wallis test (significance is marked in bold, *p-value* < 0.05).

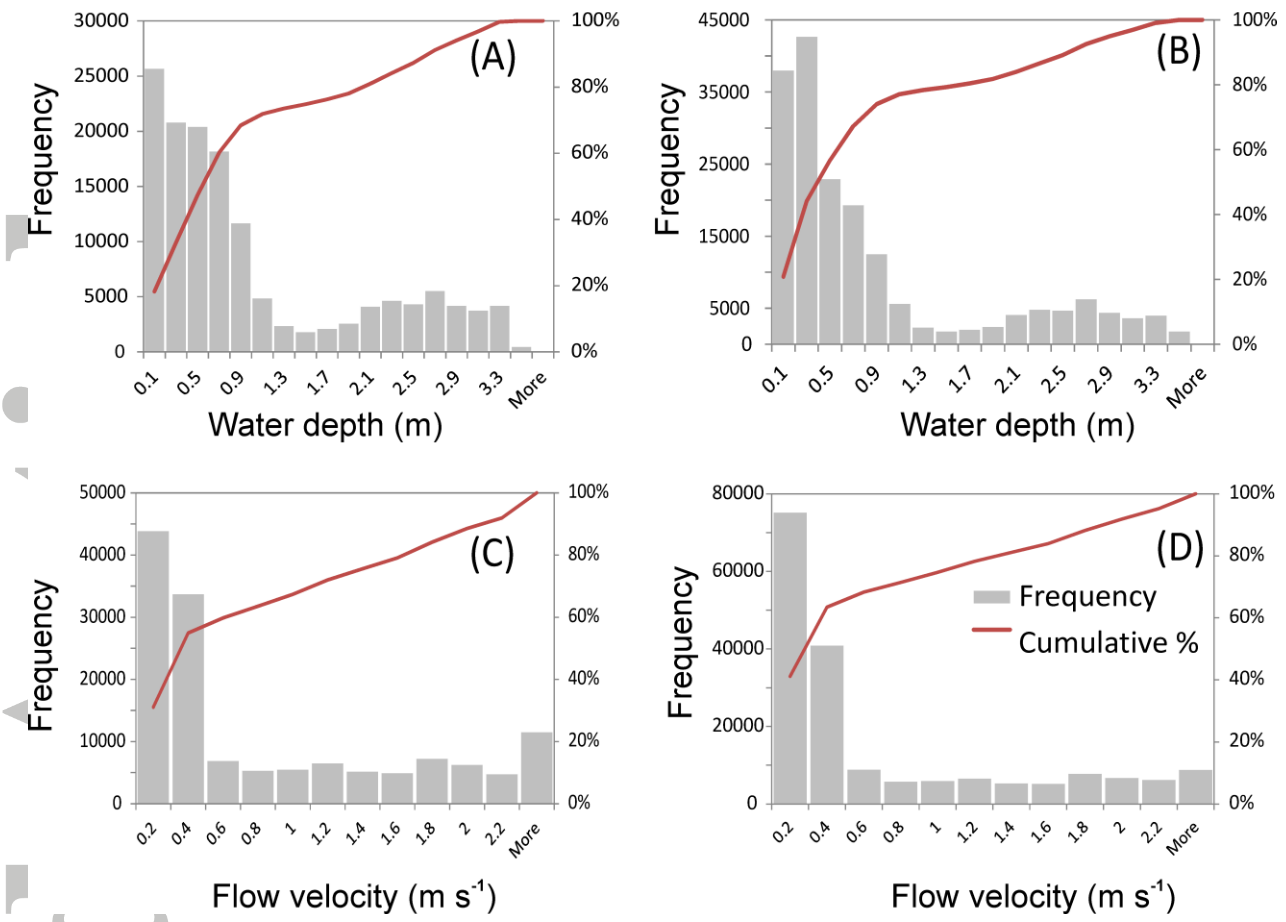


Figure 6. Frequency distributions of water depth (A, B) and flow velocity (C, D) for the 20-year flood (130 m^3 s^{-1}) in the analysed reach with the real morphology in 2015 (left diagrams) and the modified morphology (right diagrams).

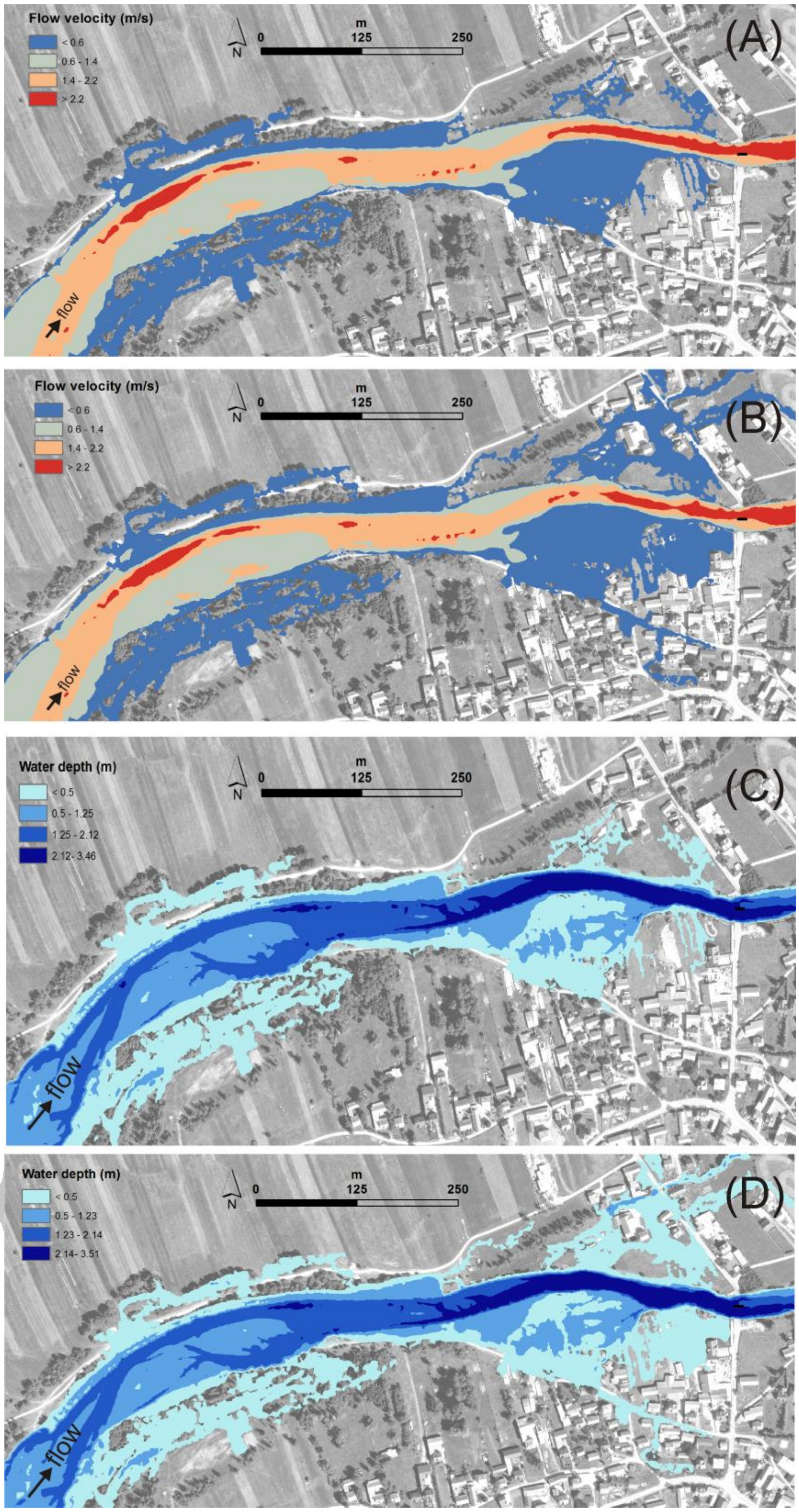


Figure 7. Simulated water depth and flow velocity for a discharge of 130 m^3 s^{-1} (20-year flood) with the current morphology used to obtain the DEM in 2015 (A, C) and the modified morphology (B, D).

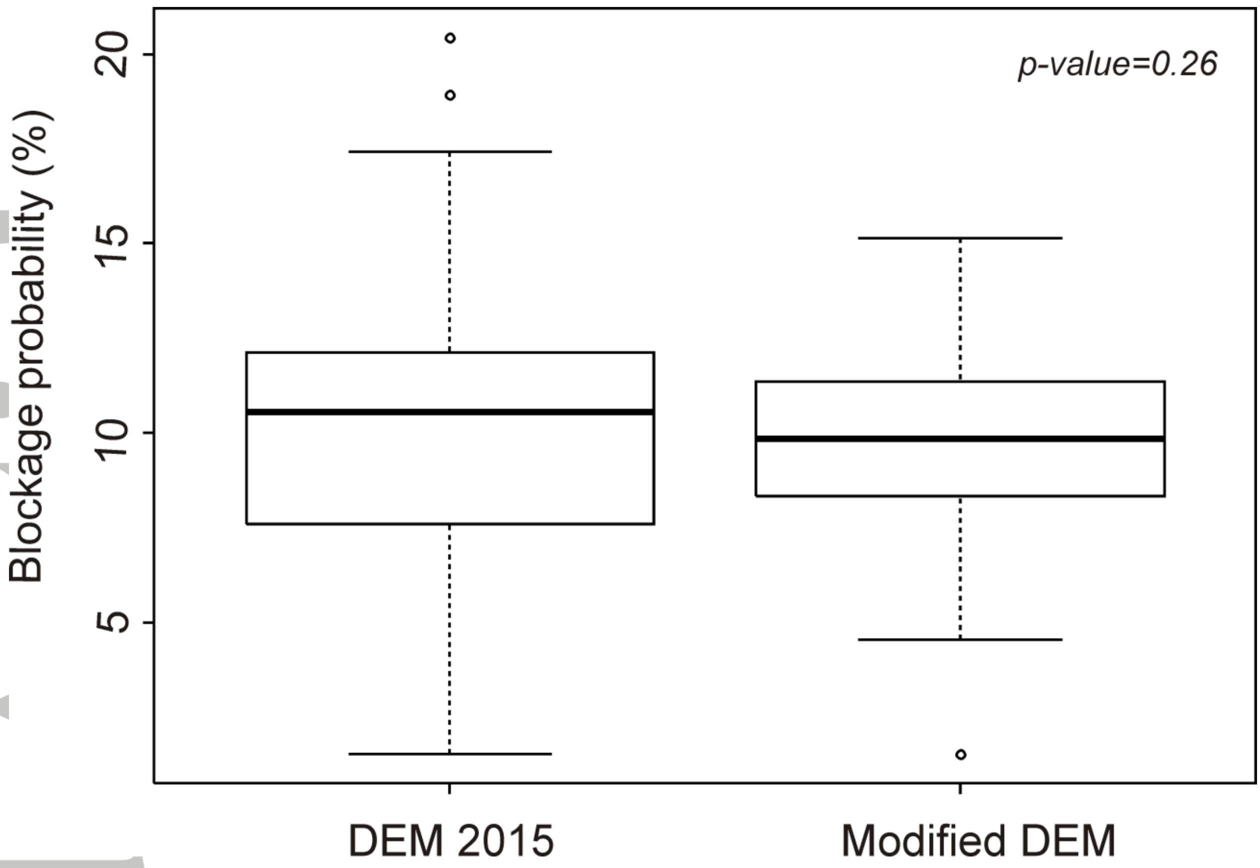


Figure 8. Potential blockage probability for all common scenarios in Set 1 (DEM 2015) and Set 2 (Modified DEM). P-value shows the result of the Mann-Whitney test.

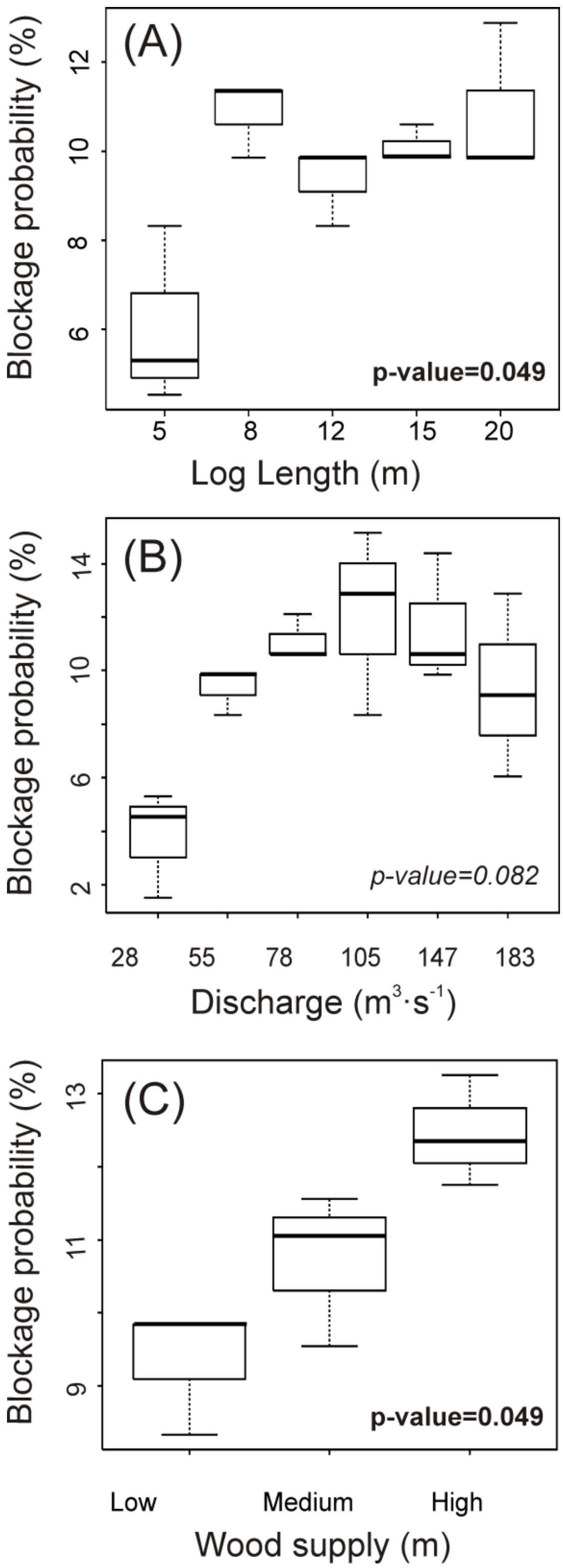


Figure 9. Bridge potential blockage probability computed for the scenarios of different log lengths (fixed diameter of 0.2 m) (A); discharges (logs 12 m long and 0.2 m in diameter) (B) and the amount of wood supplied (logs 12 m long and 0.2 m in diameter) (C). The discharge for the scenarios represented in A and C was 55 $m^3 s^{-1}$. P-values show the results of the Kruskal-Wallis tests (significance is marked in bold, *p-value* < 0.05).

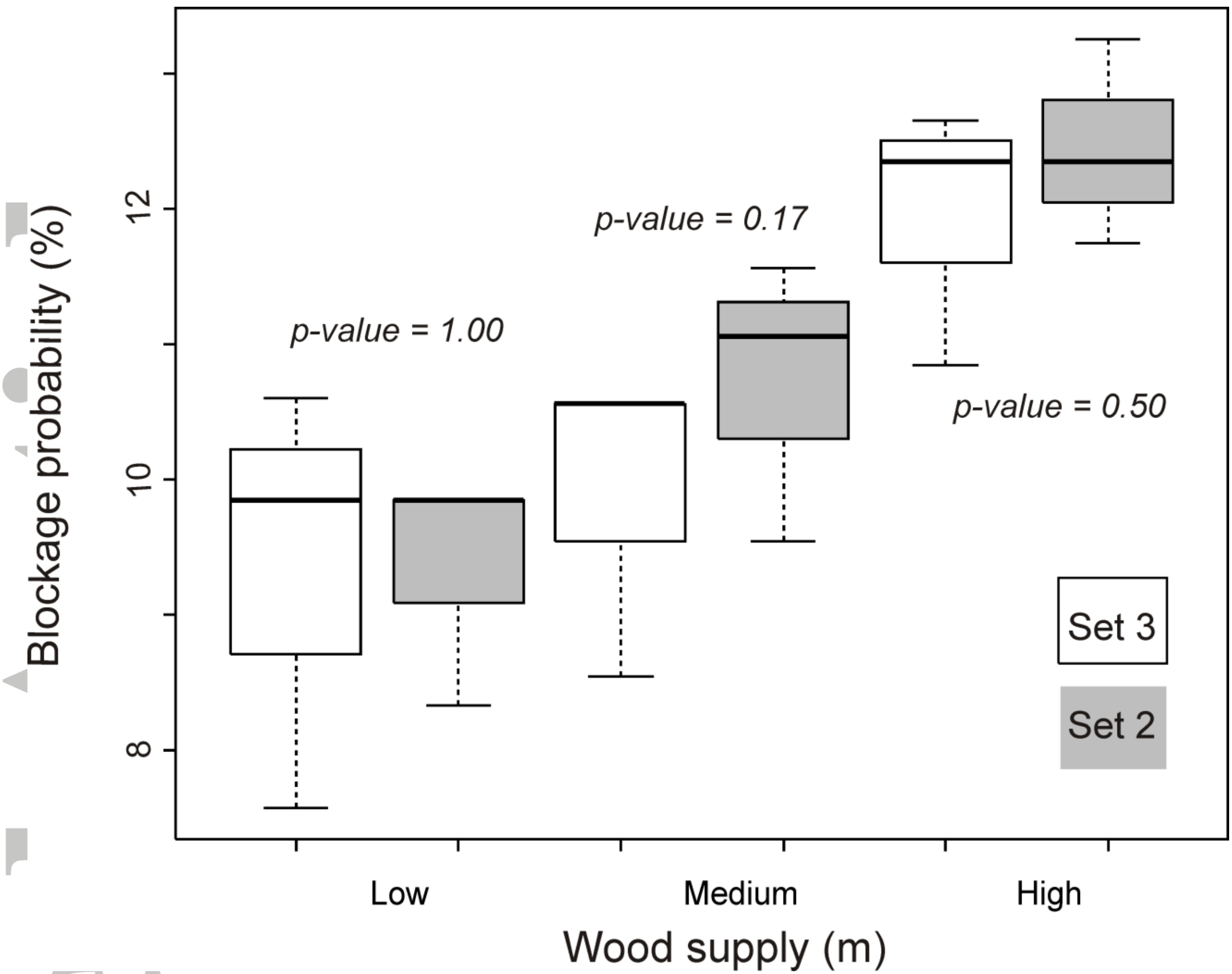


Figure 10. Bridge potential blockage probability of Set 2 and Set 3 for the simulations with 55 m^3 s^{-1} discharge and different wood supplies. P-values show the results of the Mann-Whitney tests.

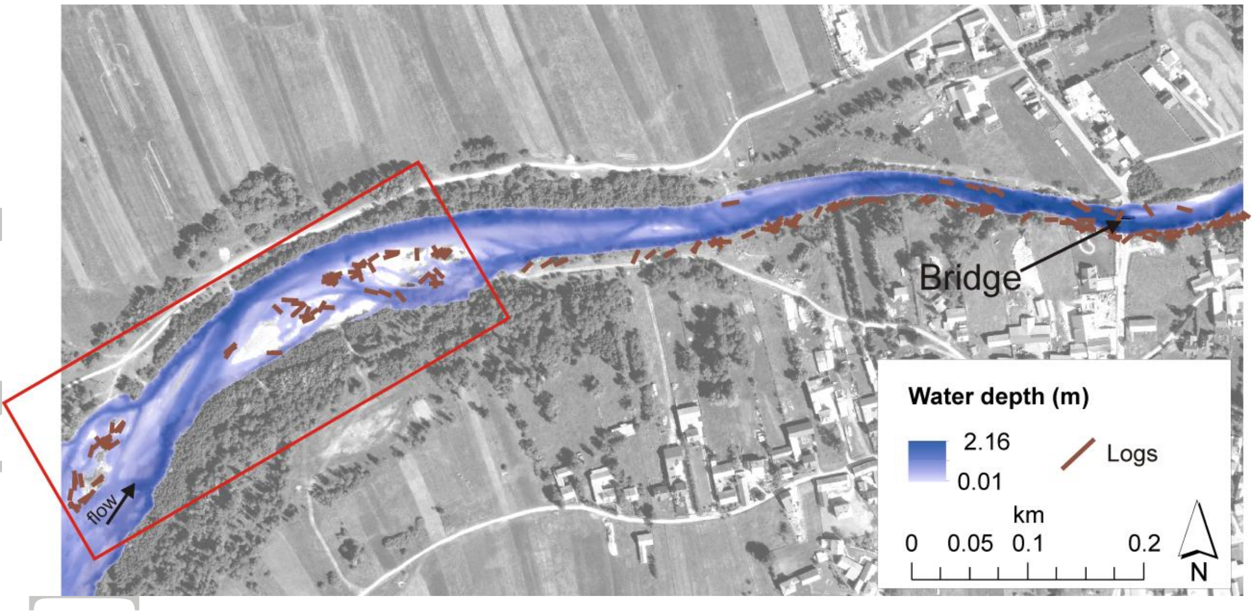


Figure 11. Water depth and logs deposited along the study reach at a discharge of 28 m^3 s^{-1} and under high wood supply. The red rectangle shows the natural wood retention zone.

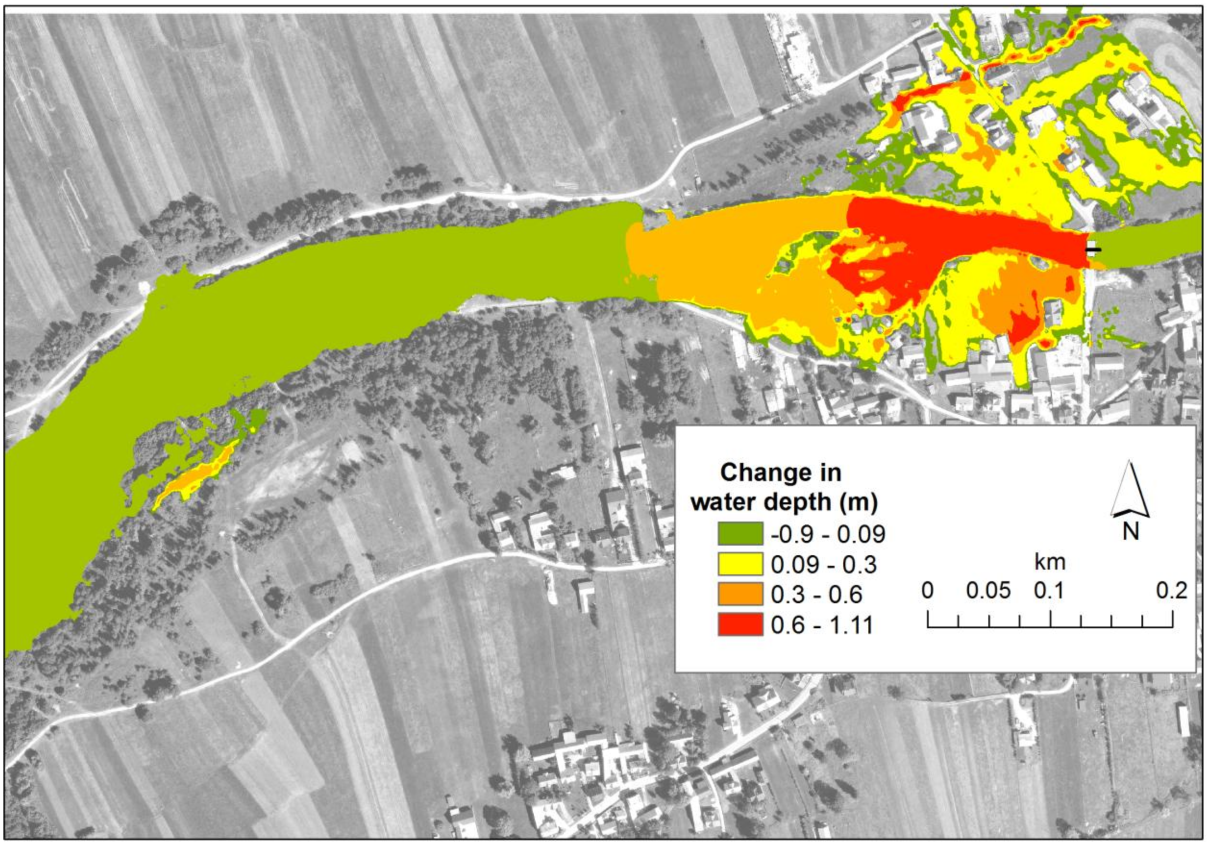


Figure 12. Change in water depth (in metres) between model results of a 10-year flood (discharge of 105 $m^3 s^{-1}$) without any obstruction and with 55-60% of the bridge cross-section blocked. The afflux length is marked by the orange colour, and it is equal to 375 m. Flow is from left to right.

Table I. Combinations of wood properties, flow conditions, river morphology and wood supply used in all model sets.

Model set	Diameter (m)	Length (m)	Discharge ($m^3 s^{-1}$)	River morphology	Large wood supply	Scenarios	Runs (each scenario repeated 3 times)
Set 1	0.1-0.7	12	28, 55	Short DEM 2015	Low	8	24
	0.2	5-20	28, 55, 105	Short DEM 2015	Low	15	45
	0.2	12	28-183	Short DEM 2015	Low	6	18
	0.2	12	55, 105, 183	Short DEM 2015	Low-High	9	27
Subtotal Set 1						38	114
Set 2	0.2	5-20	55	Short Modified DEM	Low	5	15
	0.2	12	28-183	Short Modified DEM	Low	6	18
	0.2	12	55	Short Modified DEM	Low-High	3	9
Subtotal Set 2						14	42
Set 3	0.2	12	28,55	Short Modified DEM + Trees	Low	2	6
	0.2	12	55	Short Modified DEM + Trees	Low-High	3	9
Subtotal Set 3						5	15
Calibration	0.2	12	130	2015 DEM entire reach	High	6	6
Wood deposition			28,55	2015 DEM entire reach		2	2
Clogging impacts			55, 105, 147, 183	2015 DEM entire reach		12	12
Subtotal						22	22
Total						**79**	**193**

Table II. Description of roughness homogeneous units and the values of Manning n coefficient used for model calibration.

	Name	Description	Roughness coefficient
Floodplain	Forest	Dense stand of willows and alder	0.15
	Paths/trails	Gravel and sand	0.05
	Shrubs	Medium to dense shrubby trees	0.06
	Meadows/cultivated	Grassland/crops	0.03
	Mature forest	Dense stand of large willows and alder	0.18
	Road	Asphalt	0.012
	Scattered trees	Cleared land with some tree stumps	0.06
River channel	BAR	Gravel bars without vegetation	0.07
	IS	Vegetated islands	0.10
	IMF	Forested islands	0.15
	IH	Islands with shrubs	0.07
	LFC	Clean low-flow channel with pebbles and cobbles	0.04

Table III. Main impacts of bridge clogging in terms of upstream water level, an increase in water depth (in metres and in percentage with respect to no blockage scenario) and in flooded area (in hectares and percentage), and the length of afflux.

Discharge (m^3 s^{-1}); Return period (years)	Bridge blockage (%)	Water level upstream of the bridge (m)	Afflux (increase in water depth; m)	Afflux (increase in water depth; %)	Flooded area (ha)	Increase in flooded area (ha)	Increase in flooded area (%)	Afflux length* (m)
55; 2.5	0	2.48			6.28			
	10-15	2.54	0.06	2	6.29	0.02	0	262
	30-35	2.68	0.2	7	6.32	0.04	1	270
	55-60	2.93	0.45	15	6.46	0.18	3	283
105; 10	0	3.13			8.99			
	10-15	3.28	0.15	5	9.33	0.35	4	365
	30-35	3.53	0.4	11	9.97	0.98	10	373
	55-60	3.85	0.72	19	13.39	4.40	33	375
147; 25	0	3.34			18.61			
	10-15	3.42	0.08	2	19.06	0.45	2	193
	30-35	3.55	0.21	6	19.85	1.25	6	196
	55-60	3.71	0.37	10	21.04	2.43	12	216
183; 50	0	3.37			23.83			
	10-15	3.44	0.07	2	23.87	0.03	0	214
	30-35	3.55	0.18	5	24.53	0.70	3	216
	55-60	3.66	0.29	8	25.23	1.40	6	223

*Afflux length refers to the longitudinal extension of the backwater effect or afflux upstream of the bridge (see Figure 12).