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Large wood dynamics in a wide mountain river: The Czarny Dunajec, Polish Carpathians

V. Ruiz-Villanueva & M. Stoffel
Dendrolab.ch, Institute of Geological Sciences, University of Bern, Switzerland
Institute for Environmental Sciences, University of Geneva, Switzerland

B. Wyżga & P. Mikuś
Faculty of Earth Sciences, University of Silesia, Sosnowiec, Poland
Institute of Nature Conservation, Polish Academy of Sciences, Cracow, Poland

Z.W. Kundzewicz
Institute for Agricultural and Forest Environment, Polish Academy of Sciences, Poznań, Poland

ABSTRACT: The aim of this contribution is to improve the knowledge of some interactions between floodplain and large wood in the Czarny Dunajec River in Poland, combining direct field observations and a probabilistic approach with 2D numerical modeling. Numerical modelling provides an alternative approach to addressing some of the unknowns in the dynamics of large wood in rivers. The model represents a controllable virtual world which replicates the real world and can be analysed fully at any space and time to test hypotheses and to run scenarios. Preliminary results gave information about large wood transport ratio, wood retention capacity, log travel distance, antecedent flood effect and relationship with the river morphology.

1 INTRODUCTION

Several techniques to quantify large wood dynamics in watercourses are described in the literature, such as field surveys of wood distribution or dating and tracking the movement of wood pieces. These techniques allow calculation of the probability of wood mobilization in various depositional environments. Nowadays, there are still few direct observations of wood transport (MacVicar & Piegay, 2012; Bertoldi et al., 2013). Physical models and flume experiments have been used to overcome these constraints, contributing greatly to the present knowledge of wood dynamics (Braudrick & Grant, 2000; Braudrick and Grant., 2001; Haga, 2002; Bocchiola et al., 2002; Welber, 2009; Schmocker & Hager 2011). Some works have applied 1D or 2D numerical models (Mazzorana et al., 2010; Merten et al., 2010; Comiti et al., 2012), first computing the hydraulics (in 1D or 2D) and then using the results to calculate wood mobilization.

Recently, a numerical model for predicting wood transport was proposed by Ruiz-Villanueva et al. (2013). It simulates large wood transport together with hydrodynamics. This model was incorporated as a new module into the existing *Iber 2D model*, a two-dimensional hydrodynamic software application (www.iberaula.es; Bladé et al., 2012a and 2012b) based on the finite volume method. *Iber 2D model* simulates turbulent free-surface unsteady flow and environmental processes in river hydraulics. The ranges of application of *Iber 2D model* cover river hydrodynamics, dam-break simulation, flood zones evaluation, sediment transport calculation and wave flow in estuaries. The new coupled module is able to predict and simulate patterns of wood transport and deposition, and reproduce the interactions between wood, stream and floodplain. Applying this numerical model to different case studies allowed to define the main depositional zones or areas prone to the formation of wood jams, and the probability of a log to be blocked in a bridge section etc. Moreover, the increase in water level and the change in flow velocity due to the presence of wood were also reproduced by the model. As it is a modelling approach, some simplifications should be assumed and field data and an in-depth knowledge of the riparian forest and in-stream wood must be obtained to properly set up the model and validate its results. It may also be used as an alternative and supplementary tool for generating scenarios and testing different hypothesis.

The aim of this work is to improve the knowledge of some floodplain-large wood interactions in the Czarny Dunajec River in Poland, combining direct field observations and a probabilistic approach to the numerical modelling. Setting different scenarios, we tried to find relationships between wood deposits and geomorphic configuration/sediment deposits, wood transport rates and discharge (defining mobility thresholds and relating water levels with wood size) as well as between wood size and sediment grain size. We analysed these relationships for two different river reach configurations: a wide multi-thread channel reach and a narrower, partially channelized single-thread reach. Results provide information on the large wood dynamics and deposition, improving understanding of the interactions between large wood and fluvial corridor. However, it should be mentioned that other important processes such as bank erosion, bedload transport and braiding processes are not considered in this study.

2 STUDY SITE

The Czarny Dunajec River (Fig. 1) drains the Inner Western Carpathians in southern Poland. It 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. The studied reach falls from an altitude of 670 to 626 m and is 5 km long.

Characteristic features of the hydrological regime of the river are low winter flows and floods occurring between May and August due to heavy rains, sometimes superimposed on snow-melt runoff. Mean annual discharge of the river amounts to 4·4 $m^3 s^{-1}$ at Koniówka, where the catchment area is 134 km^2 and where the model was calibrated. This gauging station is situated a few kilometres upstream of the study reaches, but catchment area and river discharges increase little between the station and these reaches (Wyżga & Zawiejska, 2005).

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.

An interesting feature of the selected part of the river course is the high variability of the river width and morphology. This enabled us to distinguish two different reaches, representing single-thread (reach 1) and multi-thread (reach 2) channel morphologies. The single-thread reach is partially

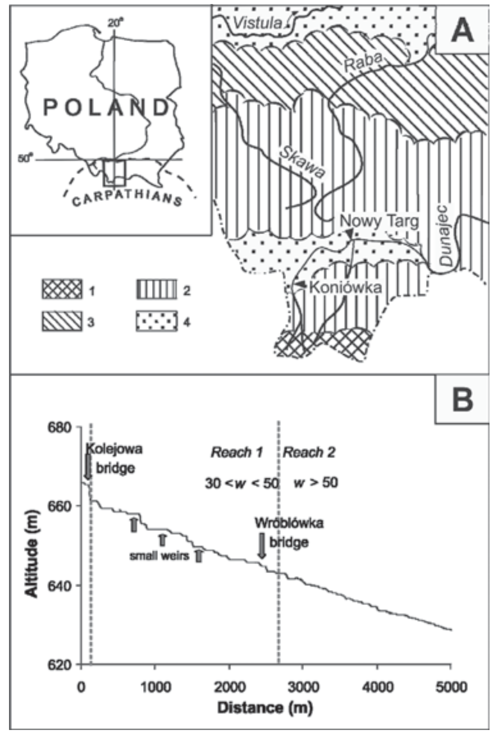

Figure 1. (A) Location of the study area in the Polish Carpathians and location of the Czarny Dunajec River in relation to physiogeographic regions of southern Poland: 1—high mountains; 2—mountains of intermediate and low height; 3—foothills; 4—intramontane and submontane depressions; (B) Longitudinal profile of the Czarny Dunajec studied reaches; w—averaged channel width in metres.

channelized with one or both channel banks lined with gabions or rip-rap, and a few drop structures reduce the slope locally. Both studied reaches may be considered large channels with respect to instream wood (Gurnell et al., 2002; Wohl, 2013).

The high width variation in the study reaches must be reflected in considerable variability of the transporting power of flood flows. At the same time, the substantial variation in the geomorphological style of the river results in differences in the availability of large-wood retention sites and in the wood delivery. As already observed by Wyżga & Zawiejska (2005 and 2010), the largest quantities of wood (up to 33 t · ha^{-1} according to some field inventories after floods) were stored in wide, multi-thread sections where transporting ability of the river was low. In contrast, very low amounts of wood were retained in narrow single-thread sections of regulated or bedrock channels, where unit stream power of flood flows was higher.

Table 1. Studied reaches and some morphometric and hydraulic parameters. C* is the calibration reach.

Reach	Channel or active zone width (m)	Reach longitudinal slope ($m \cdot m^{-1}$)	Reach length (m)
C*	40	0.008	1000
1	42	0.007	2300
2	118	0.005	3200

These observations were made after a 7-year flood in 2001 (peak discharge of 94 $m3 \cdot s^{-1}$) during an intensive post-event field campaign when wood storage was analyzed.

Some morphometric and hydraulic parameters of the studied reaches are summarized in Table 1.

3 MATERIAL AND METHODS

3.1 *Description of the hydraulic and wood transport models*

To solve the hydrodynamics and simulate wood transport, the new module mentioned above and coupled to *Iber 2D model* (Bladé et al., 2012) was applied. *Iber 2D model* uses the finite volume method with a second order Roe Scheme. The hydrodynamic module solves the conservation of mass and momentum equations in the two horizontal directions (depth-averaged Shallow Water Equations (2D-SWE). To solve a differential equation using the finite volume method, it is first necessary to spatially discretize the study domain. To do that, the study domain is divided into relatively small cells (calculation mesh). *Iber 2D model* works with non-structured mesh of elements which may have 3 or 4 sides. To obtain this non-structured mesh the detailed geometry of the entire reach is required. The reach geometry was determined by using available Digital Elevation Models (DEM) and a topographical survey performed to improve the DEM in those sections where it was necessary (critical sections such as bridges, dikes or bends). As a result we obtained detailed (1 × 1 m) geometry of the studied reaches.

The wood transport module is described in detail in Ruiz-Villanueva et al. (2014). This wood transport module presented here allows the inclusion of wood pieces in the simulations by means of a Langrangian discretization. The method couples the flow variables calculated with the hydrodynamic module to update the position and velocity of the wood logs at every time step. It considers incipient wood motion, performing a balance of forces (the gravitational force acting in a downstream direction; the friction force in the direction opposite to flow; and the drag force, acting in the flow direction) acting on each single piece of wood (assuming logs as cylinders). The hydrodynamics and wood transport are coupled; thus, the hydrodynamics influence the wood transport, but the presence of wood also influences the hydrodynamics. An additional term in the 2D Saint Venant equations is included in the flow model as an additional shear stress at every finite volume, resulting from the presence of logs.

3.2 *Inlet flow and wood scenarios*

Data from the Koniówka water-gauge station was used to characterize the inlet flow. The data was used first for the calculation of flood discharges of given probability/recurrence interval (for running different inlet discharge scenarios) and next, the available rating curve was used to calibrate roughness (Manning's n). Roughness coefficients were obtained from the delineation, both in the channel and the flooding areas, of homogeneous land units in terms of their roughness (roughness homogeneous units; RHU) and using in situ measurements of sediment size in selected transects. All RHUs delimited in the field were digitized using a GIS, and afterwards a possible range of roughness values was assigned to them following the criteria of Chow (1959) and applying different empirical equations (Meyer-Peter Muller, Bray and Strikler) in the transects. Different discharge ranges were run to calibrate the obtained Manning roughness values for high and low flows, and estimate the obtained error.

Several estimations on potentially recruited wood volumes (in terms of the number of logs) were used to set the different scenarios based on the wood storage inventories carried out in the area after several flood events (see Wyżga & Zawiejska, 2005 and 2010). In any case, an exact number of logs are simply approximations (we set reliable amounts based on the knowledge of the study river), so we treat the results from a relative perspective (i.e. the percentage of deposited logs of the total number of logs recruited to the channel, or transport ratio) to reduce uncertainty in this regard.

To characterize each piece of wood entering the simulation, we established ranges of maximum and minimum lengths, diameters and wood density. Stochastic variations of these parameters together with log position and angle with respect to the flow were then used. We tried to distinguish between the main types of trees recruited to this river (Table 2). Large alders (*Alnus incana*) and mature willows (*Salix eleagnos*) with a single trunk and a relative small crown are usually 10 to 15 m in height and 0.15 to 0.3 m in diameter, usually produce logs of simple geometry after their recruitment to the river. Large willows with a single trunk and a large, three

Table 2. Log types used in the modelling.

Log type	Length (m)	Diameter (m)	Wood density ($gr \cdot cm^{-3}$)
Long and dense	10–18	0.3–0.8	0.85–0.95
Long	10–15	0.15–0.3	0.4–0.7
Short	3–10	0.1–0.2	
Branches and coarse wood	1–3	0.05–0.1	

dimensional crown (*Salix fragilis* and *S. alba*), after falling to the channel, a large proportion of the tree mass (crown) remains emerged and duo to the lack of buoyancy, the trees remain where they fall or are transported only very short distances (length 10–18 m; diameter 0.3–0.8 m). Young willows (especially *S. purpurea* and *S. eleagnos*) and alder are typically 3–10 m in height. Their relatively thin stems and branches can be easily broken during transport, providing much of the material subsequently aggregated and stored in jams. Finally, representing branches broken from the stems and crown, we simulated logs with 1–3 m in length and 0.05–0.1 m in diameter.

3.3 *Predicting wood dynamics: Model set-up*

Integration of numerical modelling systems and field measurements will lead to so-called hybrid or composite modelling: field data provides boundary conditions as well as calibration and verification material.

No single model run is assumed to predict wood dynamics; instead, multiple runs provide a range of potential conditions for a given volume, type of wood and timing of wood-recruitment rate. In addition, an iterative process was also carried out, establishing the final time step of one simulation as the initial time step for a new simulation. With this approach, we established initial wood conditions, log position within the river corridor according to the model results, we compared these results with in-situ wood inventories and we run the model again applying different rates of wood recruitment to analyse the possible response, in terms of wood mobility.

4 PRELIMINARY RESULTS AND DISCUSSION

The model calibration was focused on the Manning roughness and it used the rating curve at the calibration reach (Fig. 2).

The error was up to 22.5% for low flows, while for high magnitude floods it was less than 10%.

Figure 3 shows an example of two model simulations for the two river reaches. In both cases the

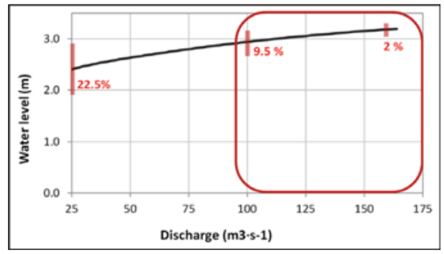

Figure 2. Model calibration and error estimation.

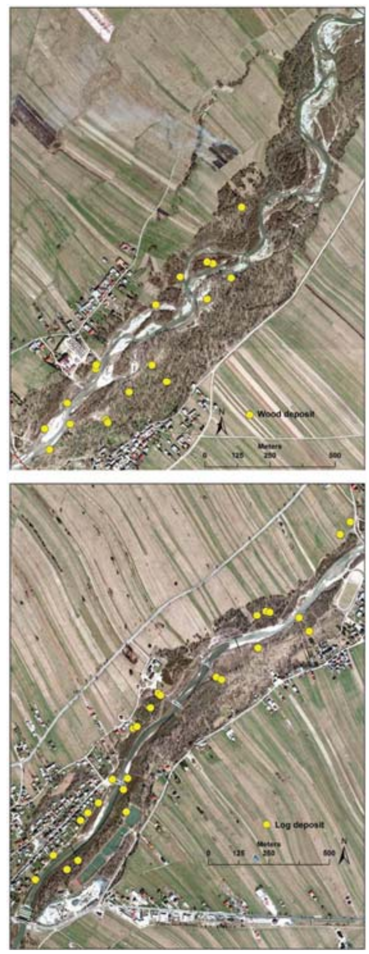

Figure 3. Modelling results: spatial distribution of wood deposits along the two reaches (multi-thread channel above and single-thread below).

simulated discharge was 183 $m^3 \cdot s^{-1}$ and the same amount and type of wood were used as input data. The maps show the spatial distribution of wood deposits along the riverbanks and floodplain Running the model several times makes it possible to calculate the probability of wood deposition along the longitudinal profile and in a given cross-section. However, this probability changes depending on the flooded area.

The wood transport ratio (transport ratio = output/input), calculated on the basis of the model run with the same discharge and the same amount of wood but different type (size) of logs, indicated different patterns for each river reach (Fig. 4A and C).

A common preliminary observation is that the number of pieces in transport strongly decreased with increasing log size. We also observed that the wood retention capacity (inverse of transport ratio) is higher in Reach 2, the multi-thread reach (Fig. 4C), with transport ratios up to 0.35 for the smallest logs. In contrast, the transport ratio in Reach 1 increased up to 0.9 (Fig. 4A). This was previously observed by Wyżga & Zawiejska (2005 and 2010) during two flood events; and it is also in agreement with observations of Wohl (2011).

The multi-run modelling allowed running a wide range of discharges (difficult to observe in the field) and estimating regression models for the relationship between log size and discharge (Fig. 4). Although a linear model could fit ($R^2 > 0.7$) the preliminary set of data, it seems that the relationship is not linear.

Other important observation can be made based on Figure 4B and D. These graphs show the preliminary results for simulations with the same amount and types of wood but different discharges. First of all, the two reaches exhibit a different threshold discharge below which wood transport is negligible. This threshold is higher in the multi-thread channel reach ($45\ m^3 \cdot s^{-1}$; Fig. 4D) than in the single-thread reach ($25\ m^3 \cdot s^{-1}$; Fig. 4B). A second preliminary observation is that the transport ratio increases with discharge (again this relationship is non-linear) until it reaches a threshold (likely related to bankfull flow) or the point of inflection, and then stays constant or even decreases (Fig. 4B).

We also observed that wood is deposited in units with the highest roughness within the wood depositional area (flooded area), in agreement with the findings of Piégay, 2003 and Moulin et al., 2011. But these units change depending on the discharge. The same is true for the elevation of wood deposition, which is constrained by the flood stage (in agreement with observations in the Tagliamento River—Bertoldi et al., 2013).

The iterative approach allowed us to analyse the remobilization of wood. Logs deposited by the $105\ m^3 \cdot s^{-1}$ flood were used as an initial wood pattern for the next simulation, the $147\ m^3 \cdot s^{-1}$ flood. Modelling of wood transport for this more extreme flood indicated that most of the pieces were transported (pink dots), with a transport ratio equal 0.78; 26% of the pieces were transported out of the reach and 22% remained at the initial locations. For the logs in motion, the average distance travelled was 580 metres (Fig. 5). If we define residence time as the length of time that a piece of wood remains in one location within a stream (Wohl & Goode, 2008), then we could affirm that wood mobility (transport rate) is inversely related to residence time. So the return period of the threshold discharge to move the pieces is related to residence

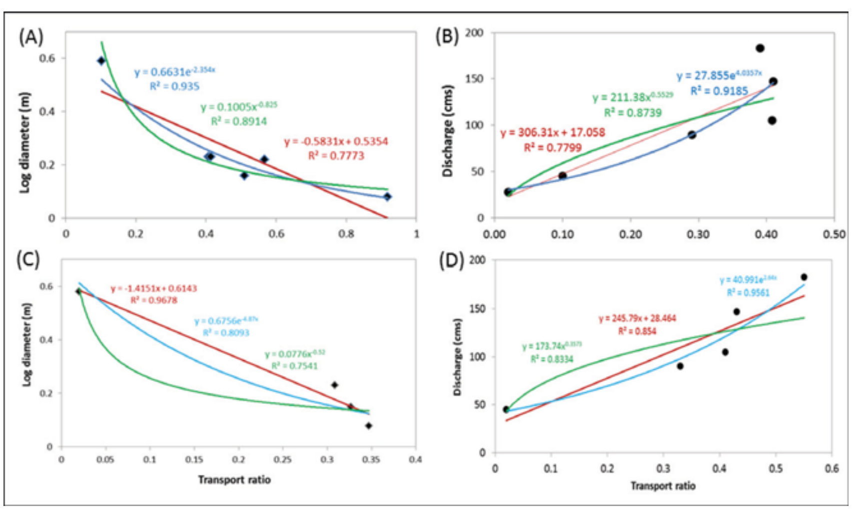

Figure 4. Preliminary relationships between wood transport ratio and either wood size (A, C) or discharge (B, D). Diagrams A–B indicate the relationships for the narrow reach, while C–D those for the wide reach. Explained in the text.

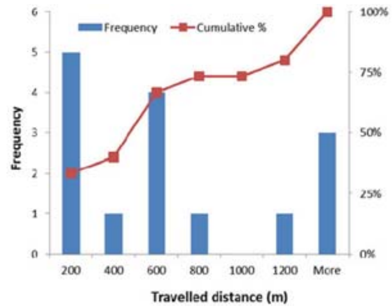

Figure 5. Frequency distribution of wood distance travelled.

time. Further research based on the simulations with a multi-run and iterative approach will help to understand how residence time can be related to flood return period.

5 CONCLUSIONS

The modelling approach allows to simulate the transport of large wood and its influence on the hydrodynamics to predict the LW deposition and analyse interactions between LW and channel morphology.

Models are abstract representations of our knowledge about a given process and are inherently limited by the information from which they are developed. Likewise empirical or field observations are limited.

The power of both simulation modelling and field investigations is greatest at the interfaces between these methods of inquiry. Patterns of wood dynamics predicted by models together with in situ field observations can increase our understanding of the dynamics of wood in rivers.

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