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Flume experiments on the geomorphic effects of large wood in gravel-bed rivers

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ABSTRACT: Besides enhancing the ecological diversity of fluvial environments, large wood (LW) abundance in rivers heavily affects channel morphology and flow hydraulics. The formation of LW accumulations at constricted cross-sections in the channel and the resulting local geomorphic effects are still poorly understood to date. In this study, a flume experiment was conducted using live-bed conditions that are representative of a New Zealand headwater river. The model includes an abundance of scaled LW elements (wooden dowels) and a one-lane bridge with 3-pier row. Model runs leveraged the use of novel SmartWood - scaled LW elements with embedded nine-degree-of-freedom smart sensors - for quantification of LW transport and accumulation dynamics. We use novel Structure from Motion (SfM) data for accurate quantification of changes in channel morphology and for providing information about scour depth and net volume change. Results have revealed that, during low discharges, logs are more likely to be accumulated at an orientation perpendicular to the flow direction. Otherwise, logs seem to be suitable to accumulate at a random orientation during high discharges. This study aims to improve our current understanding of complex interaction processes between flow, wooden elements and sediments.

1 INTRODUCTION

In-channel large wood (a wood piece with a diameter ≥ 0.1 m and length ≥ 1 m; hereafter LW) is an essential element in wild, forested river systems. Numerous studies have demonstrated the benefits of in-channel LW for processes related to the ecology, hydrology, hydraulics, sedimentology, and morphology of such river systems (Gurnell et al. 2002; Gregory et al. 2003 and references therein). Alongside these positive effects, LW can also pose risk: potentially dangerous obstructed conditions may develop along the river network, as wood is transported downstream during flood events. In particular, entrained wood may accumulate at river crossings and hydraulic structures. Comiti et al. (2008) and Marchi et al. (2009) analyzed a flash flood that occurred in the Slovenian Alps in 2007, highlighting the hazardous channel avulsions that occurred as large quantities of wood accumulated upstream of a bridge. Another flood event in Switzerland in 2005 transported almost 30.000 t of wood, resulting in numerous problems along the channel network (Bezzola & Hegg 2007). In 2018, an event occurred in Gisborne, New Zealand, about 40.000 m3 of wood were transported, which clogged channels and covered beaches (https://www.stuff.co.nz/business/farming/117141715/tolaga-bay-a-beach-covered-in-forestry-waste). It is also evident that this type of impoundment can have an effect on bedload transport, disrupting the sediment continuity and modifying bed characteristics and channel morphology. We know that on the one hand, upstream bed aggradation due to logs (Wohl & Scott, 2017) can lead to an increase of the bed roughness, affecting the hydraulic conditions (Gippel, 1995). On the other hand, bed scour and flow-structure interaction can result in backwater rise (Schalko et al. 2019a). Therefore, understanding wood transport dynamics, and characterizing interactions amongst wood, bedload transport and bed morphology, are deemed to be important research topics, especially for streams that are subject to recruitment of woody elements.

1.1 *Objective*

In this study, a flume experiment is conducted to assess the nature of interactions amongst flow, sediment and wood, upstream of a constricted cross-section. Specifically, we seek to recreate the conditions that lead to jam formation, and then measure the trajectory of woody elements, the forces involved in jam development, and the resultant topographic changes to the river bed. This provides some important quantitative insight into the effects of wood-altered river hydraulics. The work is mainly a proof of concept, demonstrating that we can capture all of the key phenomena involved in jam emplacement and resultant changes to river morphology, in an intermediate-scale laboratory river model.

2 MATERIAL AND METHODS

2.1 *Flume setup*

The experiments were conducted in a 6 m-long, 1.5 m-wide and 1 m-deep flume, with a fixed slope of 0.002 $m \cdot m^{-1}$. The setup represents a characteristic New Zealand gravel-bed river, scaled at a ratio of 1:15. The flow rate was controlled via an electromagnetic valve and the unit discharge ranged from 5 to 80 $l \cdot s^{-1}$. The experiment was based on the simulation of a symmetrical nine-step hydrograph, designed to represent a flood event for a prototype catchment of an area of about 100 km^2.

Bed material used in the experiment is a mixture of water-worked sediment from 4 to 45 mm with D_{16} = 8.1 mm, D_{50} = 13 mm, and D_{84} = 26.3 mm. Bed material was manually mixed and then screeded homogenously to cover the entire channel. During the experiment, woody material was supplied from a custom-designed conveyor-belt system, situated above the inlet-structure.

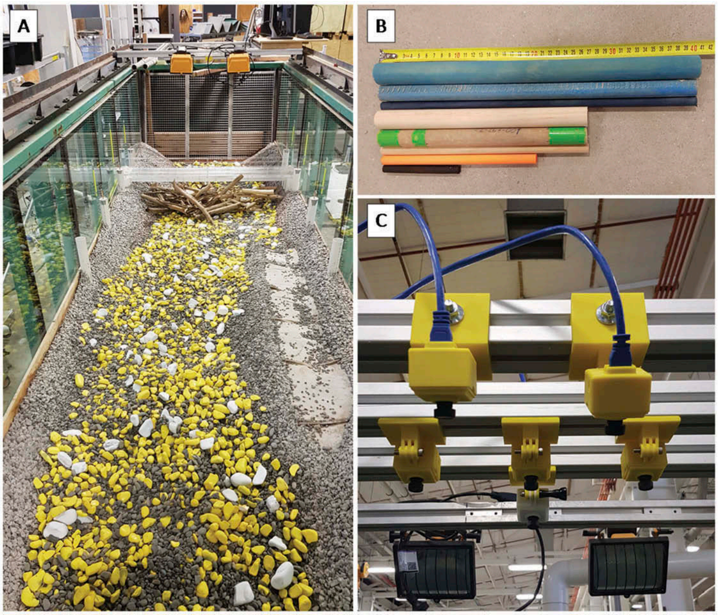

Figure 1. Experimental setup with LW accumulation at the bridge (A); cylindrical wooden dowels used during the experiment (B); camera module setup above the channel bed (C).

A one-lane bridge with piers in stream-wise direction was placed in the center of the channel, 4 m downstream from the inlet. The bridge simulates a prototype structure, with dimensions of 22.5 m in length and a width of 3.6 m.

2.2 *Wood accumulation and LW modelling*

A total of 134 cylindrical wooden dowels were used to simulate LW elements of eight different sizes, ranging from 10 to 25 mm in diameter and from 100 to 400 mm in length (Figure 1b). The wood has a uniform density of 0.5 g cm^{-3}, similar scaling to logs used by Braudrick & Grant (2001) and Gschnitzer et al. (2017). Additionally, five SmartWood dowels were employed to monitor impacts and dowel trajectory (see Spreitzer et al. (2019) for further details on the sensors). SmartWood uses a nine-Degree of Freedom (9-DoF) smart sensor, implanted into wooden dowels with a length of 267 mm, and a diameter of 22 mm (representing prototype wood log dimensions of 4 m in length and 0.33 m in diameter).

Given that the model woody elements have no branches or rootwad, a nucleating structure is required to initiate jam formation. A fixed structure was constructed of natural wood collected from the field, with dimensions of 50 to 450 mm in length and 5 to 45 mm in diameter. The structure was placed upstream of the bridge piers, using screws and wire to fix the individual elements into a rigid LW accumulation.

2.3 *Camera-array module and video recording setup*

One GoPro Hero 6 video camera was fixed on the righthand glass wall to record the evolution of the wood transport dynamics over time. VirtualDub software was used to analyze the footage frame by frame. In addition, information of the bed topography was obtained using Structure from Motion (SfM). A six-camera array was mounted on a mobile carriage above the flume channel, similar to the setup used by Spreitzer et al. (2018). The carriage was moved in steps of 0.1 m along the longitudinal axis of the flume, at a constant height of 1 m. Five cameras were arranged in pentagon-shape, at a distance of 0.25 m between them and an inclination of 15 ° around a center camera, which was fixed with perpendicular orientation in respect to the channel floor (Figure 1c).

Full coverage of the stream bed comprised 282 images, with an image overlap of approximately 80 %. The point-clouds were generated using Agisoft Photoscan, and data processing was conducted in CloudCompare. Digital Elevation Models (DEMs) of the bed elevation were analyzed in ArcMap. Pre- and post-experiment DEMs (DEMpre and DEMpost respectively) were used to generate DEMs of difference (hereafter DoD; = DEMpost − DEMpre).

2.4 *Experimental procedure*

After setting up the experiment channel bed, a base flow of 5 $l \cdot s^{-1}$ was maintained for 20 hours. This flow allowed for a natural re-arrangement of the grain particles. SfM was used to survey the bed topography when the 20 hours were completed (SfM1). Subsequently, the first step of the hydrograph was initiated, increasing the discharge by 16 $l \cdot s^{-1}$, with high steady flow conditions being maintained for a duration of 15 min. Wood dowels were introduced half way through the high flow phase, at each step of the hydrograph's rising limb (four steps plus the peak). Dowels were fed from the conveyor-belt in a congested regime and one SmartWood dowel was supplied in each hydrograph phase. At the end of the experiment, logs were carefully removed without disturbing the channel bed and a second (post-flood) SfM survey of the channel bed was conducted.

3 RESULTS

3.1 *Wood dynamics*

Video footage from the GoPro camera, as well as sensor data from the five SmartWood dowels, were used for estimating the transport dynamics of the dowels. Of the 134 dowels that were introduced, only 81 remained trapped by the LW accumulation at the end of the experiment. Most of the dowels left the accumulation during the peak of the hydrograph. Almost 66 % of the bypassing dowels were of small sizes (1 cm in diameter and 10 cm in length) and 33 % of medium and larger sizes (from 1 to 2 cm in diameter and from 20 to 40 cm in length).

SmartWood recorded transport velocities from 0.9 $m{\cdot}s^{-1}$ at the first step to 1.4 $m{\cdot}s^{-1}$ at the peak of the hydrograph. Sensor data show a gradual increase in the acceleration impact force on the LW accumulation (from 1000 to 2034 mg, respectively), in line with the steps of the hydrograph. SmartWood also revealed that logs were transported parallel to the flow (phases I, II and II in Figure 2b, c), yet most of the dowels accumulated perpendicular to the flow, especially during lower discharges (lines green, yellow, blue and red in Figure 2c). During the peak of the flood, wooden dowels accumulated more randomly (dowel corresponding on the purple line in Figure 2c and, phases IV and V in Figure 2a, b).

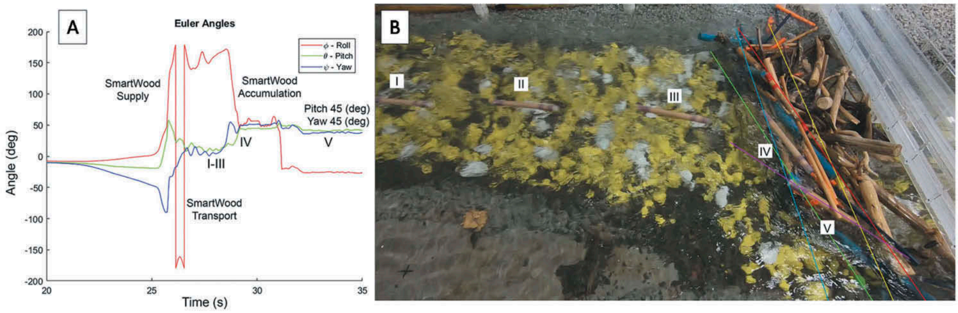

Figure 2. SmartWood Euler angle (A), and a screenshot tracking the purple SmartWood dowel during transported and accumulation at the peak of the hydrograph (B). Yellow, magenta, green and purple lines correspond to the SmartWood dowels added during the first, second, third, fourth and fifth (peak) step of the hydrograph, respectively.

3.2 *Changes on bed topography*

The DEM of Difference (DOD) between the DEMs pre- and post-flood event shows a disruption of the sediment flux between reaches upstream and downstream of the critical cross section (Figure 3). Results show that no significant topographic changes occurred in the upstream section (green color), with very little erosion (red color) and deposition (blue color) near the inlet. The DoD shows the main areas of sediment erosion and deposition below and downstream the LW accumulation, respectively. The standard deviation of the bed elevation of the two DEMs was calculated. A higher standard deviation was determined for DEMpost (0.017) than DEMpre (0.013).

4 DISCUSSION

Understanding the geomorphic interactions between wood and sediment is crucial for determining the mechanisms of creation and maintenance of potential habitats for different organisms (Abbe & Montgomery, 1996). To optimize opportunities for habitat along the river network, an appropriate regime of wood recruitment should be encouraged (Crispin et al.,

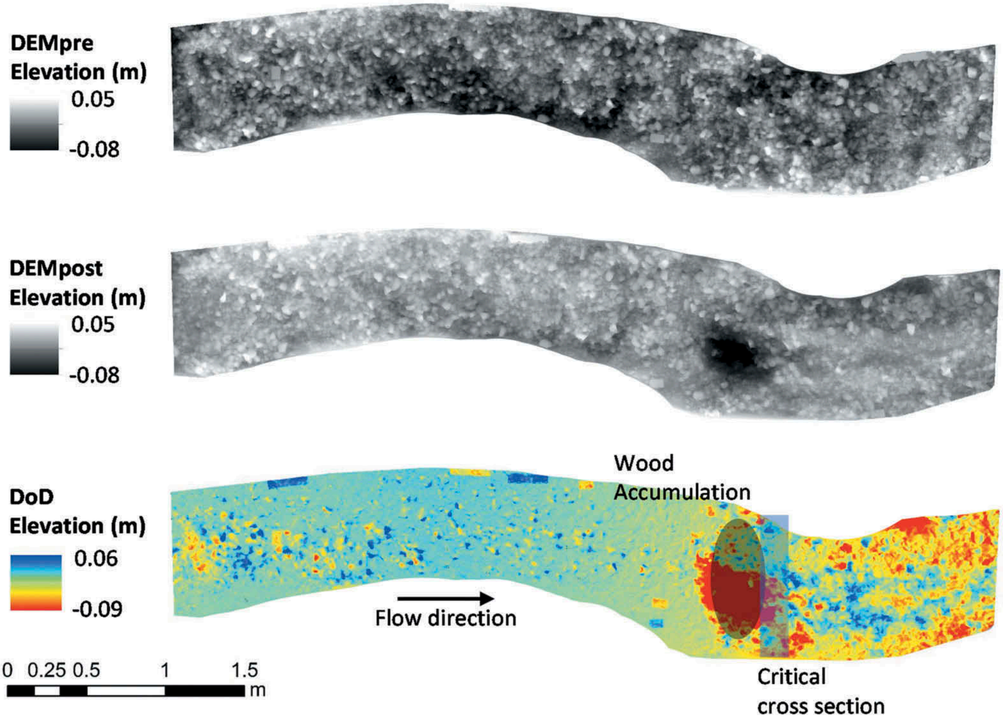

Figure 3. DEM of Difference (DOD) between the DEMpre and DEMpost the flood event for a LW impaired channel.

1993). However, during flood events, wood may accumulate at bridge piers, leading to concerns for the integrity of the infrastructure.

We observed that during low discharges, the low shear stress exerted by the flow is not able to create significant geomorphic effects around wood accumulations. SmartWood data revealed that logs tend to be rafted parallel with the flow, until they encounter the obstruction, at which point they are pushed into an orientation perpendicular to the main flow direction. On the other hand, the shear stress exerted during high discharges is able to create geomorphological effects around the wood accumulations. Logs travel faster, and then accumulate randomly with respect to the main flow direction.

The DoD obtained from the simulated flood event revealed a discontinuous sediment flux from upstream to downstream of the critical cross section. Sediments were more likely to be mobilized downstream and below the wood accumulation. Flow diversion, and the visible backwater caused by the wood accumulation, produced a supercritical turbulent flow condition that induced a higher sediment mobilization. Especially below the wood accumulation, turbulences mobilized coarser sediments (d_{50} = 45 mm), developing local scour that reached the bottom of the flume. Similar local scouring processes were observed by Schalko et al. (2019b), using homogeneous sediment.

The combination of orientation and impact data, along with bed change, provides an integrated picture of jam dynamics that cannot be accomplished any other way. The data from multiple smart sensor elements offer contrasting insights for conditions at different flow levels and states of jam development. Data on collisional forces, and intra-component kinetics, provide insights into jam stability and forces transferred to the bridge. Future experiments will consider variations in flood magnitude and different resultant jam dynamics. Constrictions and diversions of flow imparted by wood necessarily lead to scour and bed change; the example shown here highlights focused scour. Overflow, underflow, different jam configuration and porosities are expected to give rise to different morphologic responses and feedbacks.

5 CONCLUSIONS AND OUTLOOK

The experiments presented herewith were conducted with the objective to provide insights on individual log trajectories, sediment transport and relative morphological change associated with LW dynamics in a critical cross section during a flood event.

As revealed in other studies (Ravazzolo et al. 2017; Ruiz-Villanueva et al. 2019), video footage provides a satisfactory means of establishing wood transport velocity. SmartWood sensors provide further crucial information about wood orientation and impacts during floods, revealing that during low discharges, logs are more likely to accumulate at an orientation perpendicular to the flow direction. Otherwise, logs will accumulate at a random orientation during high discharges. The SfM technique yielded DEMs with a resolution of 2 mm (half of the smallest bed grain size). In combination, the use of in-flow sensor elements (Smartwood) and models of morphologic change provide a uniquely integrated view of jam emplacement dynamics, and resultant feedbacks amongst wood, sediment and flow.

Since wood-sediment-flow interactions are complex and scarcely explored, there are abundant opportunities for further study. Future experiment approaches should be improved in order to increase the overall understanding of such interactions:

a. Different wood transport regime. Based on the flume experiments of Braudrick et al. (1997), a congested, semi-congested or uncongested wood transport regime can result in different interactions with sediment and flow. Large logs within congested wood flow can snag on the channel bed and act as pivoting elements, thus likely increasing frictional stress on the channel bed. These dynamics can increase in-channel geomorphic effects.
b. The effects of varying density and strength (bending, flexural and tensile) of wood elements, as well as the presence/absence of branches and rootwad, should be considered.
c. Discharge variability and flood occurrence timing. Here, we simulated a symmetrical stepped hydrograph mimicking a flood event with flow restrained by the bank. However, future experiments should represent hydrographs with different shapes, including exploration of the effects of overbank flows.
d. More detailed studies of bed morphology evolution before and after jam emplacement. As demonstrated in this study, SfM technique is able to provide DEMs with a very detailed resolution that can provide an accurate model of grain-scale interactions. Thus, the creation and disintegration of bed microforms, upstream and downstream the critical cross section, should be considered.

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REFERENCES

Abbe, T.B. & Montgomery, D.R. 1996. Large woody debris jams, channel hydraulics, and habitat formation in large rivers. *Regulated Rivers Research & Management* 12: 201–221.

Bezzola, G.R. & Hegg, C. 2007. Ereignisanalyse Hochwasser 2005 Teil 1: Prozesse, Schäden und erste Einordnung (Analysis of 2005 flood, Part 1: Processes, damages and classification). Federal Office for the Environment FOEN, Swiss Federal Institute for Forest, Snow, and Landscape Research WSL. *Umwelt-Wissen*: 0825 (in German).

Braudrick, C.A. & Grant, G.E. 2001. Transport and deposition of large woody debris in streams: a flume experiment. *Geomorphology* 41: 263–283.

Braudrick, C.A., Grant, G.E., Ishikawa, Y., Ikeda, H. 1997. Dynamics of wood transport in streams: a flume experiment. *Earth Surface Processes and Landforms* 22: 669–683.

Comiti, F., Mao, L., Preciso, E., Picco, L., Marchi, L., Borga, M. 2008. Large wood and flash floods: evidences from the 2007 event in the Davča basin (Slovenia). In: De Wrachien, D., Lenzi, M.A., Brebbia, C.A. (Eds.), Monitoring, Simulation, Prevention and Remediation of Dense and Debris Flow II. WIT-Press. 173–182.

Crispin, V., House, R., Roberts, D. 1993. Changes in instream habitat, large woody debris, and salmon habitat after restructuring of a coastal Oregon stream. *North American Journal of Fisheries Management* 13: 96–102.

Gippel, C.J. 1995. Environmental hydraulics of large woody debris in streams and rivers. *Journal of Environmental Engineering* 121(5): 388–395.

Gregory S, Boyer KL, Gurnell AM. 2003. The ecology and management of wood in world rivers. *American Fisheries Society Symposium* 37: 431.

Gschnitzer, T., Gems, B., Mazzorana, B., Aufleger, M. 2017. Towards a robust assessment of bridge clogging processes in flood risk management. *Geomorphology* 279: 128–140.

Gurnell, A.M. & Petts, G. 2006. Tree as riparian engineers: the Tagliamento River, Italy. *Earth Surface Processes and Landforms* 31: 1558–1574.

Gurnell, A.M., Piegay, H., Swanson, F.J., Gregory, S.V. 2002. Large wood and fluvial processes. *Freshwater Biology* 47: 601–619.

Marchi, L., Borga, M., Preciso, E., Sangati, M., Gaume, E., Bain, V., Delrieu, G., Bonnifait, L., Pogačnik, N. 2009. Comprehensive post-event survey of a flash flood in Western Slovenia: observation strategy and lessons learned. *Hydrological Processes* 23: 3761–3770.

Ravazzolo, D., Mao, L., Mazzorana, B., Ruiz-Villanueva, V. 2017. Brief communication: The curious case of the large wood-laden flow event in the Pocuro stream (Chile). *Natural Hazards and Earth System Sciences* 17: 2053–2058.

Ruiz-Villanueva, V., Mazzorana, B., Blade, E., Burkli, L., Iribarren-Anacona, P., Mao, L., Nakamura, F., Ravazzolo, D., Rickenmann, D., Sanz-Ramos, M., Stoffel, M., Wohl, E. 2019. Characterization of wood-laden flows in rivers. *Earth Surface Processes and Landforms* 44: 1694–1709.

Schalko, I., Lageder, C., Schmocker, L., Weitbrecht, V., Boes, R.M. 2019a. Laboratory Flume Experiments on the Formation of Spanwise Large Wood Accumulations: I. Effect on Backwater Rise, *Water Resources Research* 55(6): 4854–4870.

Schalko, I., Lageder, C., Schmocker, L., Weitbrecht, V., Boes, R.M. 2019b. Laboratory Flume Experiments on the Formation of Spanwise Large Wood Accumulations: Part II-Effect on local scour. *Water Resources Research* 55(6): 4871–4885.

Spreitzer, G., Friedrich, H., Tunnicliffe, J. 2018. Effects of large woody debries accumulation on channel-bed morphology during flood events. *E3S Web of Conferences* 40: 02024.

Spreitzer, G., Gibson, J., Tang, M., Tunnicliffe, J., Friedrich, H. 2019. SmartWood: Laboratory experiments for assessing the effectiveness of smart sensors for monitoring large wood movement behaviour. *Catena* 182: 104145.

Wohl, E. & Scott, D.N. (2017). Wood and sediment storage and dynamics in river corridors. *Earth Surface Processes and Landforms* 42(1): 5–23.