Proceedings of the 39th IAHR World Congress
19–24 June 2022, Granada, Spain
doi://10.3850/IAHR-39WC2521716X20221853

INFLUENCE OF LARGE WOOD TRANSPORT ON RIVER BED STRUCTURING PROCESSES IN STEEP RIVER REACHES

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Abstract

Large wood (LW) has an influence on river morphology and sediment dynamics. Protruding blocks might trap LW and allow the formation of local deposits and scour. Such blocks are used as macro-roughness elements in river engineering structures to protect against bed erosion. We conducted three series of flume experiments investigating the influence LW on the bed morphology and stability of a dynamic ramp. LW deposits formed around protruding blocks and persisted until these were fully submerged. The altered flow conditions downstream of the deposits influenced the erosion of the bed material. The effect was pronounced upon increased hydraulic loading, leading to a formation of persistent and distinct alternate bar features. The final stability of the structure was not compromised by the presence of LW.

Keywords: Large wood, Steep channel; Flume experiment; Bed morphology; Bed stability

1. INTRODUCTION

Large wood (LW) is an integral part of alpine rivers that is mobilized during flood events. If LW accumulates, it alters the flow field (Gippel, 1995; Schalko et al., 2021) and can have a significant impact on river morphology and sediment dynamics (Ruiz-Villanueva et al., 2016; Wohl & Scott, 2017). It is thus important to understand where LW will deposit, how long it will remain and what will be its effect on bed morphology. Braudrick & Grant, 2001 introduced the so-called debris roughness that describes the factors promoting LW deposition in a river. This proxy incorporates the ratios of LW piece length to channel width, LW piece length to channel radius of curvature and LW buoyant depth to channel depth but does not consider local obstructions. Large boulders have been identified to interact with the transport of LW by trapping key pieces, leading to the formation of deposits (Nakamura & Swanson, 1994; Faustini & Jones, 2003; Bocchiola et al., 2006).

Protruding boulders are naturally present in rivers but are also artificially placed in river engineering structures. In the effort of ecologically valuable bed stabilization measures, several types of block ramps relying on dispersed configurations of block clusters have been developed (Tamagni et al., 2010). Dynamic ramps are engineering structures of this type, using material with a widely graded grain size distribution ranging from fine material to large blocks. The material is installed as a plane bed with a higher slope, so that a stable, natural structure with the sizing slope will form upon sizing runoff (Weichert et al., 2007).

The present research investigates the influence of LW on the progressive structuring of the riverbed on a dynamic ramp. We report on several series of flume experiments conducted at the Laboratorium[3D] in Biasca, Switzerland. We analyze the flow conditions under which LW deposits form and investigate the direct and long-standing influence of the deposits on the morphology and stability of the ramp.

2. METHODS

Channel geometry, hydrology and LW quantities of the test setup are loosely based on a 1:35 Froude-scaled model of the Ticino River in Piumogna, Switzerland.

2.1 Model flume

The physical flume experiments were conducted in an 8.50 m long and 1.00 m wide flume with a movable bed. The geometry of the model flume is illustrated in Figure 1, a photography is given in Figure 2.

Upstream, a 1.00 m long inlet section with larger stable roughness elements at a slope of 3% was installed to gain a fully developed turbulent flow. The buffer zone had a length of 2.25 m and a slope of 3%, the ramp a length of 3.75 m at an initial slope of 7%. Downstream of the ramp the model had a length of 1.50 m where the movable bed was also installed at a slope of 3%.

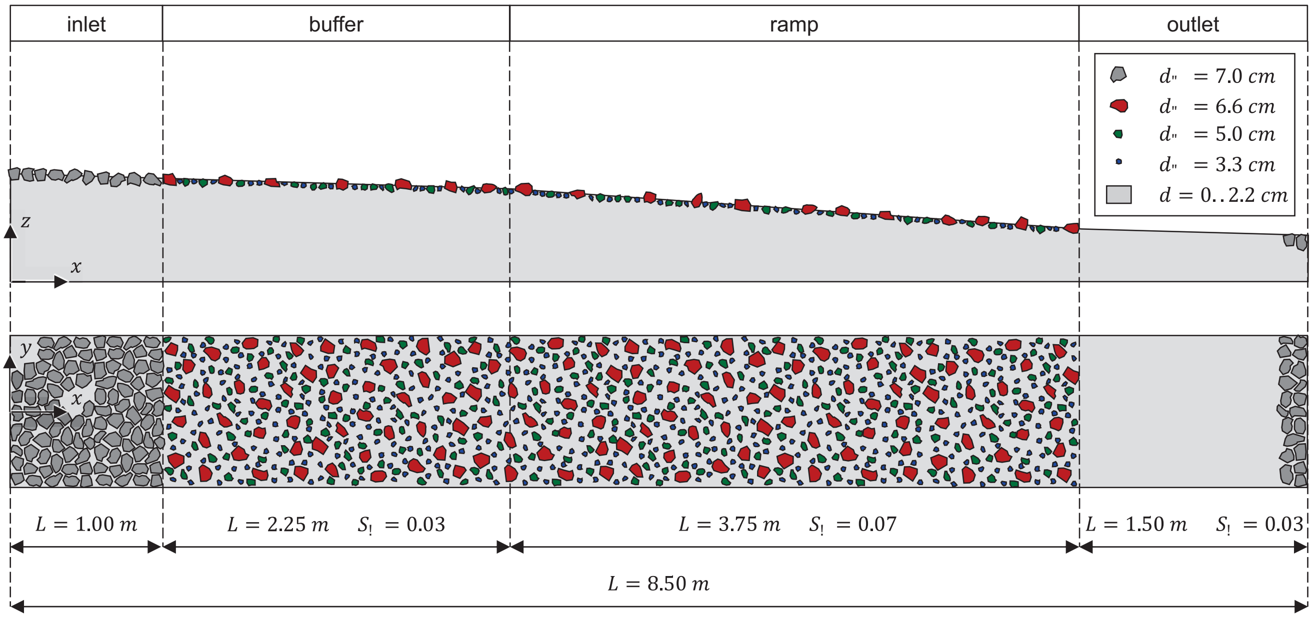

Figure 1. Schematic drawing of the flume, length profile and plan view.

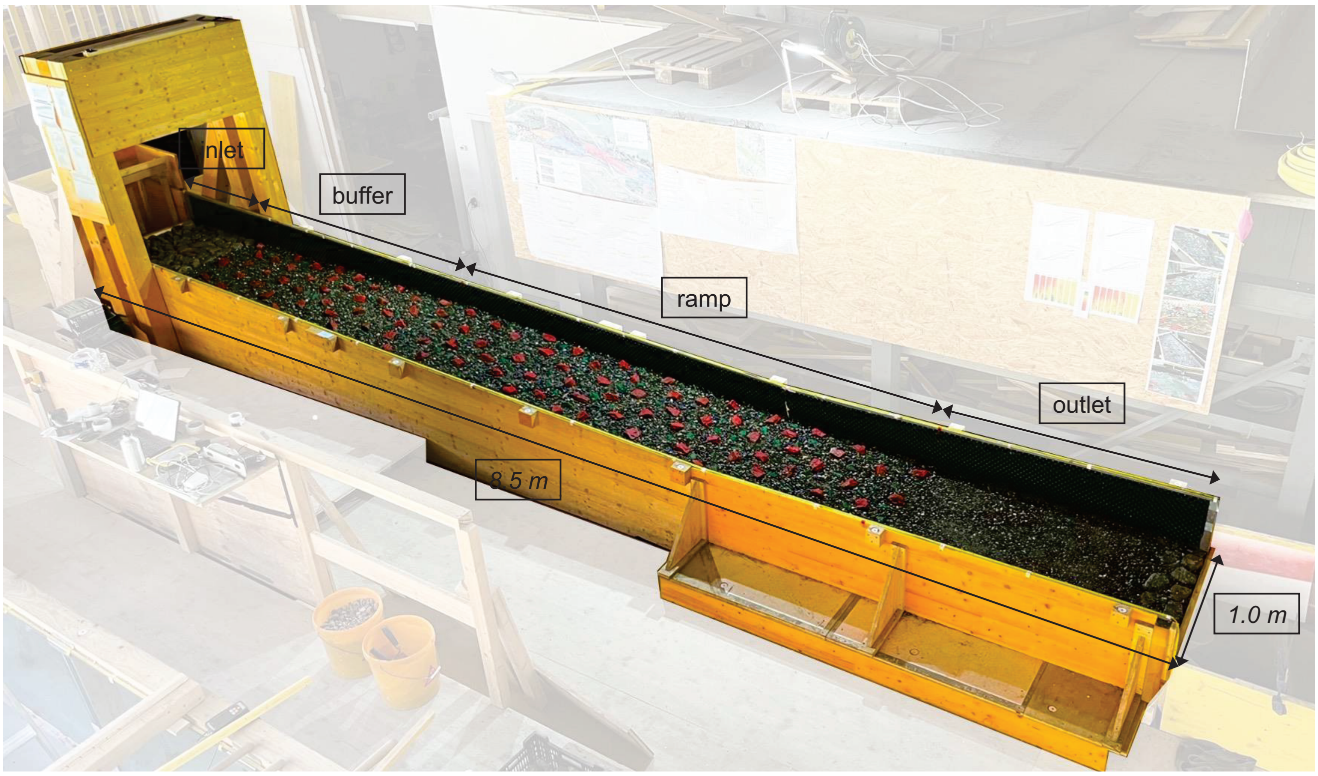

Figure 2. Photograph of the model flume in its initial condition.

Table 1. Mean equivalent spherical diameter d_m, block placement density λ of and protrusion P of the three block classes in the initial condition.

color	d_m [cm]	λ [-]	P [cm]
red	6.6	0.075	3.3
green	5.0	0.081	0.0
blue	3.3	0.176	0.0

The base material had a widespread grain size distribution with a maximum diameter of 2.2 cm. The buffer zone and the ramp were accoutered with three block classes of different sizes that were marked with the colors red, green and blue. These block classes made up for the coarse fraction of the grain size distribution suggested by Weichert et al., 2007. Their density can be quantified by the proportion of the surface area covered by the blocks of the specific class, referred to as the block placement density λ. The red blocks protruded from the base material, while the blue and green blocks were fully embedded. The equivalent spherical diameter, the placement density and the protrusion of the blocks are given in Table 1.

2.2 Experimental procedure

The influence of LW on the riverbed structuring was investigated, by comparing the erosion processes on the riverbed upon loading without LW (experiment series S1) to those including LW (experiment series S2). A series including LW was repeated (experiment series S3) to test reproducibility. The three experiment series consisted each of a set of ten runs with incrementing specific discharge ranging from 2.8 l/(sm) to 62.4 l/(sm). q =35 l/(sm) corresponds to the Froude-scaled 30-year flood in Piumogna, q =42 l/(sm) the 100-year and 48 l/(sm) to the 300-year flood respectively. Water was run through the flume at a constant discharge, which was measured by a magnetic-inductive flow meter (MID), until sediment transport had ceased, and a stable channel configuration was formed. All experiments were carried out without upstream sediment supply.

A coordinate system was used with x measured along the flume length, y across the flume centered on the flume axis and z as elevation. We measured both water surface and bed elevations at intervals of 0.25 m in the x direction, and of 0.10 m in the y direction. The equilibrium slope of the ramp S_e was determined after each run based on a linear regression of the mean bed elevation in every cross section. Furthermore, the bed topography was recorded photographically, allowing photogrammetrical analysis at a resolution of <1mm.

LW was supplied in series S2 and S3 at time intervals of 5 min in packages with five classes of different length and diameter. The size distribution was based on Steeb et al., 2019. The dimensions of the LW classes as well as their relative share (by count) are provided in Table 2. The wood pieces of each package were introduced individually into the top of the flume, randomly oriented and distributed over the channel width. Packages were introduced until morphological equilibrium was reached, resulting in total solid LW volumes V_s varying from 0.002 to 0.01 m^3. The position of the logs was recorded after each run. LW pieces were not manually removed, to allow larger deposits to form and to observe the mobilization upon increasing discharge.

Table 2. Log length L_L and diameter d_L and relative share n/N of the five LW classes.

L_L [cm]	d_L [cm]	n/N [-]
11	0.6	0.55
17	0.9	0.22
23	0.9	0.10
29	1.1	0.07
40	1.4	0.06

3. RESULTS AND DISCUSSION

3.1 Formation of LW deposits

In both experiment series including LW loading (S2, S3), LW deposits formed and grew up to a specific discharge of 15 l/(sm). At an incremented discharge of 22 l/(sm) the wood budget was negative, hence LW was not deposited, and existing deposits were mobilized. In both series the relative submergence of the red blocks, defined as the ratio of block protrusion to mean flow depth, exceeded 1 at this threshold (Figure 3). This reveals that LW deposits persisted until the protruding blocks were fully submerged. A direct influence of LW deposits is conceivable up to this threshold.

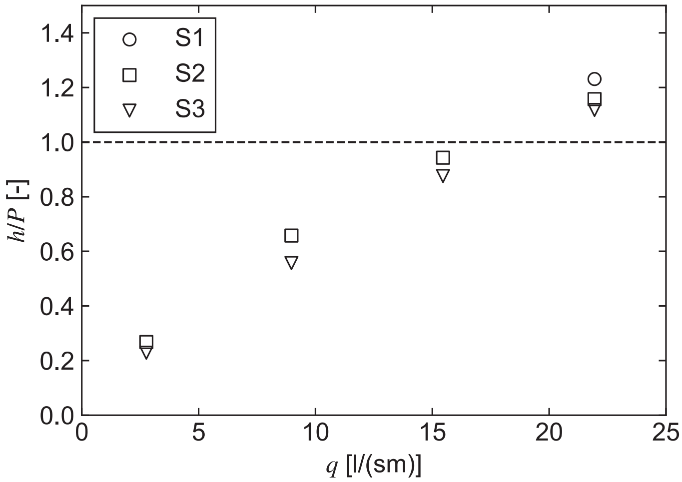

Figure 3. Relative submergence h/P of the red blocks. The blocks were fully submerged at a specific discharge of 22 l/(sm). The graph range is limited to the runs, in which the bed was plane. At higher hydraulic loading alternate banks formed, and the protrusion of the red blocks varied accordingly.

3.2 Direct influence of LW deposits

An analysis of the orthophoto after the critical loading of 15 l/(sm) allows the examination of the direct impact of LW deposits. Since the blue blocks were initially fully embedded into the base material, their visibility indicates an erosion of the latter. The proportion of their visible surface in the uppermost layer of the bed, which can be understood as the block placement density of the blue blocks λ_b, is presented in Figure 4. In all three experiments series λ_b is higher on the ramp than on the buffer zone. In S2 a dominant LW deposit formed on the buffer zone at x = 1.5 m on the left side. Downstream of this deposit (x = 2-3 m), the right side shows an increased density of visible blue blocks, while on the left side almost no blue blocks are visible. Also in the wake of the deposits on the ramp around x = 4 m, λ_b is reduced. In S3 multiple LW deposits were formed on the right channel side. A gradient of λ_b in y can be observed with higher visibility of blue blocks on the ramp the left side with respect to the right side.

The higher erosion on the ramp with respect to the buffer zone can be associated to the difference in slope, leading to a difference in drag force acting on the bed. The alteration of the flow field induced by log deposits seems to be strong enough to provoke an effect on erosion.

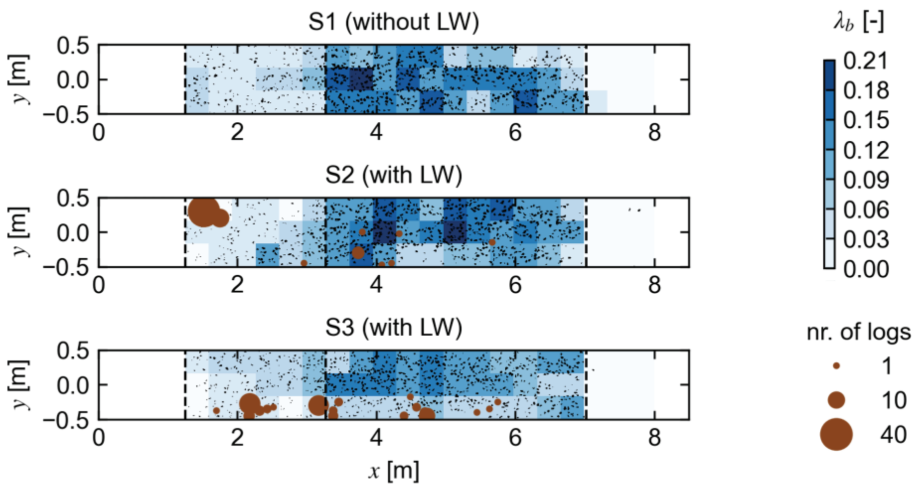

Figure 4: Analysis of the orthophoto of the model flume at the morphological equilibrium after q = 15 l/(sm), flow from left to right. The black dots represent visible blue blocks. The density of these blocks is presented in a raster of 33 x 33 cm^2 large cells. The brown dots indicate LW deposits with their size corresponding to the number of logs in the cluster. The limits of the buffer zone (S_0= 3%) and the initial ramp (S_0= 7%) are indicated by dashed lines.

3.3 Ramp stability and development of bedforms

The decisive parameter in terms of ramp stability is the resulting equilibrium slope S_e for a certain specific discharge q corresponding to a certain experimental run. This relationship is given in the stability diagram in Figure 6a. In all three series a major alteration of the slope was observed at specific discharges around 30 l/(sm). In some cases, LW might lead to an acceleration of structuring processes: In S2 (with LW) the decrease in slope was more rapid and pronounced than in S1. This behavior was not observed in the second run with LW (S3). The final ramp stability was not compromised by the presence of LW.

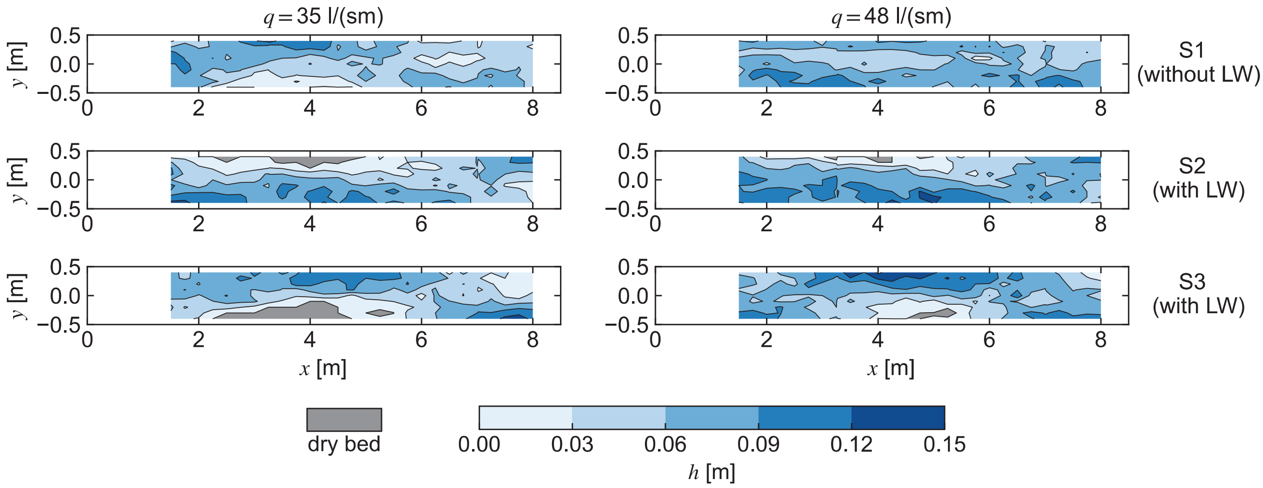

Figure 5. Comparison of the flow depth established in the three series (flow from left to right). In the series with LW more pronounced alternate bar features formed upon $q = 35$ l/(sm) and persisted even after $q = 48$ l/(sm)

Upon the morphologically strongly active specific discharges around 30 l/(sm), alternate bar features were developed in all three experiment series. Compared to the series without LW, in the series with LW loading, the bar features were more pronounced and persistent (see Figure 5). On an individual cross section, a high variation of measured bed elevations is an indicator for a non-plane bed since the measuring intervals of 0.10 m do not capture the macro- and micro-scale roughness. As a reach-scale indicator for the variability of bed elevation, the standard deviations of the bed elevations of each cross section were averaged over the ramp:

$$\bar{\sigma_z} = \frac{1}{n}\sum_{i}^{n} \sigma_{z,i} \qquad [1]$$

where is n the number of cross sections on the ramp and $\sigma_{z,i}$ the standard deviation of the bed elevations z on the cross section i. This size is presented in Figure 6b. Upon specific discharges between 35 and 50 l/(sm) $\bar{\sigma_z}$ was 50% higher in the series with LW loading. In both series the banks were situated on the side, where dominant LW deposits were formed in the previous runs with lower specific discharge (see Figure 4). The effect of LW deposits on bed elevations diversity tends to vanish for higher discharges compared to test run S1.

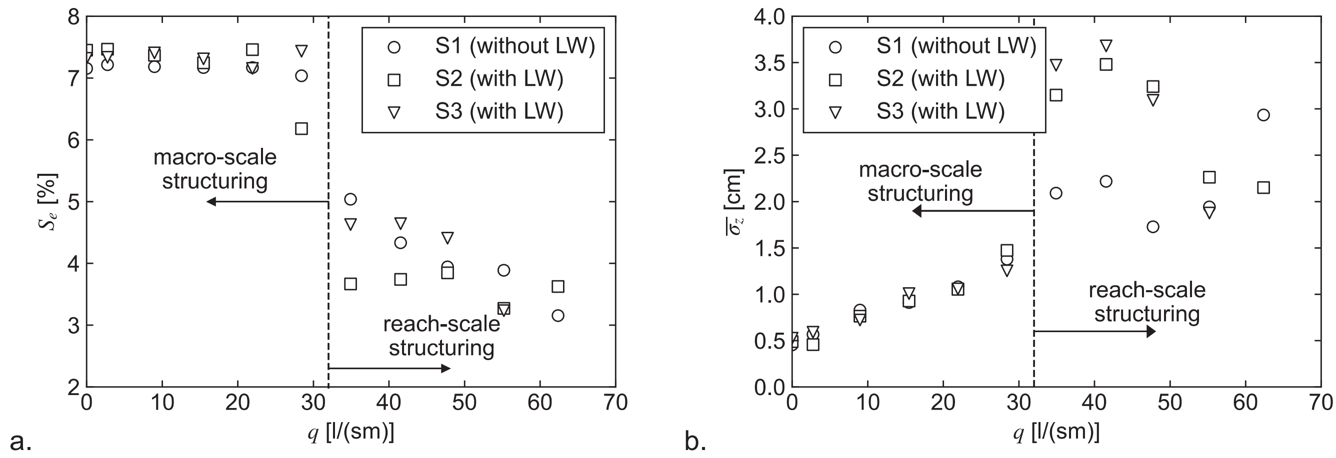

Figure 6. Development of the structure upon hydraulic loading. a. Stability diagram of the ramp. The equilibrium slope S_e for a certain specific discharge q is determined as the slope of the linear regression of the mean bed elevation of each cross section. b. Variability of the bed elevation on the cross sections of the ramp. High variability indicates pronounced bar features. A change in the regime can be observed around $q =$ 30 l/(sm). Up to this threshold the channel responded to increasing discharges mainly by macro-scale structuring. Above the threshold the ramp slope decreased and $\overline{\sigma_z}$ increased significantly. The increase in variability was much more pronounced in the series with LW.

4. CONCLUSIONS AND OUTLOOK

Hydraulic model tests were conducted to study the accumulation of LW on a dynamic ramp with macro-roughness elements and the effect of deposits on morphology. The experiments were performed with versus without addition of LW. Wood deposits persisted only until all protruding blocks were fully submerged, but the effect of the altered flow field had a delayed effect on the morphological structures. The bedforms formed under the influence of LW showed more pronounced and predominant bank features, while the final stability of the entire structure was not impacted. Furthermore the presence of LW might lead to an acceleration of the structuring processes. LW might thus have a beneficial impact on flow and habitat diversity without compromising the functionality of the engineered flood protection measure. Further analysis of this hypothesis by means of an ecomorphological index evaluation may provide additional results.

5. ACKNOWLEDGEMENTS

This research was supported by the Giovanni Lombardi Foundation. We appreciate the laboratory assistance provided by Chiara Benedetti and Enea Toschini.

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