Effects of a large woody debris accumulation on channel-bed morphology during flood events

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Abstract. A novel experimental setup for the laboratory was designed in order to investigate large woody debris accumulations and their influence on hydraulic flow conditions and channel morphology at a river cross-section. Real wood and mobile gravel bedload material were used to simulate morphodynamic interactions in a headwater stream, based on a New Zealand prototype river. The survey methodology employs Structure from Motion techniques, using an advanced multi-camera-array. In this study we present the experimental setup and initial results from our first experiments. With this research project we aim to investigate the dynamics of jam initiation and the characteristic evolution of the jam, for a given discharge, sediment load, and distribution of woody material. Furthermore, this study will elaborate more practical and efficient methodologies for observing wood jams, both in the laboratory and in the field. The project expands current knowledge about interaction processes between flow, sediment and woody debris, which are presently poorly understood and still represent a gap in research.

1. Introduction

Numerous studies have been carried out to investigate the influence and effects of large organic material in stream systems. Large Woody Debris (LWD) is a characteristic feature in forested water courses all over the world, influencing both flow patterns and channel morphology to varying extents. Depending on size, relative to channel width, and capacity for jamming, LWD can be a significant moderator of river morphodynamics, shaping the resultant channel pattern. This is considered to be an important process for nurturing a diversity of river flow environments for habitat [1, 2] and enhancing dynamic processes, such as meander migration and floodplain reworking.

However, at bridges, weirs, culverts, intakes and other engineered river constrictions, situations may arise where LWD jams strongly divert flow against a bank, causing flooding, erosion and undermining vital infrastructure (Fig. 1) [3, 4]. Most debris is mobilised from riparian zones and transported downstream on the rising limb of flood events [5-8]. The critical cross-section (CCS), where the blocking probability of wood is highest, might already start to become blocked at lower water levels, resulting in a fully developed LWD accumulation at peak discharge, when most water and sediment is transported.

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Fig. 1. LWD accumulation at critical cross-sections in New Zealand. Log jam formation at a state highway bridge in Gisborne, New Zealand (a [9]) , and a debris blockage at an underpass structure at the Coromandel Peninsula, New Zealand (b [10]).

The emplacement of jammed wood and debris is likely to cause backwater effects in confined channels. During flood events, constriction and diversion of flows at key cross-sections can influence a river's downstream runoff conditions significantly [11-14], often with concurrent changes in channel morphology [15]. Depending on nearby environmental conditions, such as channel configuration and riparian zone topography, overtopping of stopbanks or the hydraulic structure itself may occur. LWD exerts important controls on the passage of sediment [16]; storage behind jams may modulate the rate of passage of sediment pulses or waves, but may also induce aggradation locally, leading to flood issues.

Our objective in the present study is to assess the interaction dynamics of wood and sediment coming into a constricted cross-section, in this case, a typical bridge crossing with a 3-pier footing, as commonly found in steepland catchments of New Zealand. The aim is to assess the jamming mechanics of wood with varying size, shape, and protruding branches, the characteristic timescales of formation, and the attendant effects on the hydraulic profile and bedload transport rates. We have used a scaled laboratory simulation approach, with a 1:15 scale physical model of the jam and surrounding terrain built into a flume environment. These experiments will be a valuable first step for developing more broadly applicable numerical models of jam development, as well as providing more general guidance on managing for the development of LWD jams in headwater streams.

Capturing the interactions of wood, sediment and water is a central challenge for this study, owing to the many elements in transit, the rapid and non-linear changes in system configuration, and the three-dimensional nature of the developing jams. To solve this, we have developed a novel Structure from Motion (SfM) photogrammetry technique that employs a mobile multi-camera array. The high-resolution surveys allow for precise capture of a time-series of volumetric changes, and estimates of jam volume, as well as tracking the trajectory and influence of individual wood pieces. In the following work, we review the development of this novel experimental setup and share some of the preliminary results from channel morphological surveying in the laboratory using SfM.

2. Experimental Setup

2.1. Flume and stream channel

Our hydraulic flume experiments are run in a custom designed, 6 m long, 1.5 m wide and 1 m high flume in the Water Engineering Laboratory at the University of Auckland. The flume is set up with a slope of 0.02, although it can be adjusted to relatively steep slopes of up to 0.1. An inlet structure and flow straightener at the top end of the flume assures smooth initial flow conditions. Inside the glass-sided flume a fully scaled meandering stream channel with floodplain and CCS (Fig. 2) has been installed. The substructure of the channel course and embankments consists of 17 lamellar cross-sections, filled with sand and covered with a 50 mm thick cement layer. All modelling details are based on field observations for a typical New Zealand forested catchment. The discharge capacity of the flume is up to 150 $l \cdot s^{-1}$, however, the current setup is operated with 75 $l \cdot s^{-1}$. About 4 meters downstream of the inlet structure a bridge with three piers (aligned with flow) was installed to represent the CCS. In order to reproduce channel morphodynamics, a conveyor-belt sediment feeder (located shortly downstream of the flow straightener) provides coarse-grained material to the flow. The custom-designed conveyor-belt feeder (Fig. 3, b), operates on a variable step-less speed control unit. This allows us to introduce sediment mixtures, as well as woody debris (for further experiments), of varying calibre at a range of delivery rates. The 3 m long and 0.5 m wide conveyor-belt system has capacity for up to 100 kg of material with a maximum particle size of 500 mm. Without reloading, the feeding-time ranges from 3 to 15 minutes. Bypassing bedload is collected at a sediment trap, situated in the outlet-structure at the bottom end of the flume. Finer organic debris is filtered from the flow via a screen located a short distance upstream of the sediment trap. A tail gate in the outlet-structure allows the regulation of the water level at the downstream end of the flume.

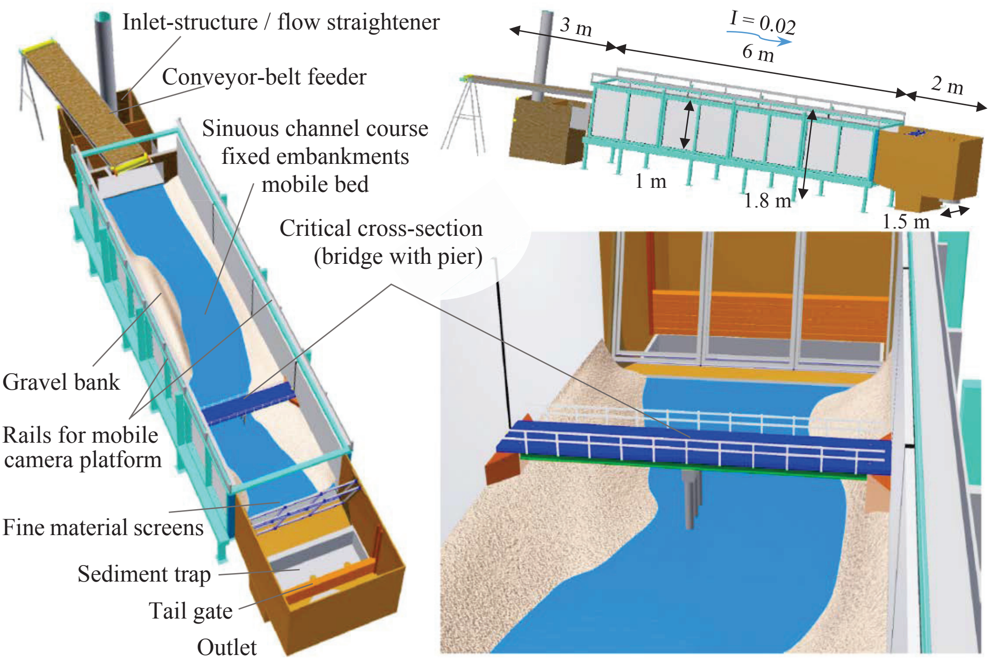

Fig. 2. Experimental setup with natural channel course, live-bed conditions and critical cross-section in the fluid laboratory at the University of Auckland.

2.2. Modelling materials

2.2.1. Gravel

The channel bed was modelled using a graded mixture of crushed gravel (4 - 63 mm) that was deposited in the model floor as a 70 mm thick layer. In order to render more realistic hydraulic flow conditions, the embankments of the channel were fixed with a thin gravel/concrete layer. Graded gravel material with a size of 8 to 16 mm was embedded to maintain roughness on the side banks. To distinguish between initial installed bed material and the bedload feed via conveyor-belt, the feed material was coloured in five different colours - one for each grain size fraction.

2.2.2. Organic debris

Natural wood was collected from the field, to be introduced as scaled wood 'logs' in the flume experiments. Previously accumulated fine material at the bridge pier was simulated using a wire mesh covered with a textile layer. Scaled LWD pieces with diameters of 5 to 45 mm and lengths of 50 to 450 mm were then placed manually at the CCS. The LWD accumulation was randomly assembled to a rigid debris jam using screws and wire (Fig. 3, a). The installed debris accumulation is compact and can be displaced without changing its geometry or structure, to ensure a repeatable experimental setup.

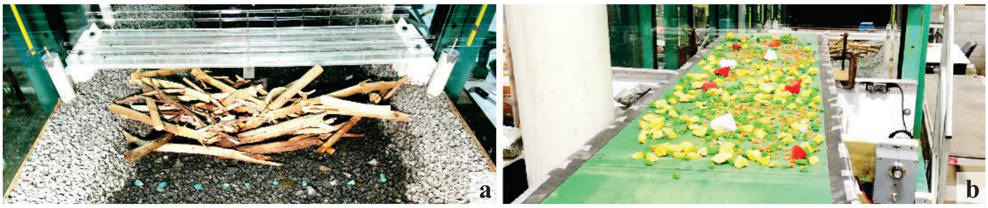

Fig. 3. Critical cross-section: One-lane-bridge with a three column pier and LWD accumulation (a). Conveyor-belt feeder with colour gravel, supplying sediment 0.5 m downstream the inlet-structure (b).

2.3. Scaling

A New Zealand catchment area with a size of roughly 100 km^2 was considered, accordingly an undistorted Froude model. The scaling ratio was evaluated to 1:15 for the entire experimental setup, modelling parts and the simulation of our experiments. The model is fully scaled in geometric similarity, kinematic similarity and dynamic similarity. This allows the flume channel to be fitted with a scaled prototype river section, equivalent to an average width of 15 to 20 m and a depth of up to 3 m, representing natural hydraulic runoff conditions. The design discharge for the flume was set to 75 l·s^{-1} to align with an annual flood event in the range of 60 to 80 m^3·s^{-1} for the prototype catchment. A New Zealand characteristic 'one-lane-bridge' – 22.5 m long, 4 m wide resting on a single pier row with a total height of 3.5 m and 1.2 m high railings on the bridge deck – spans the channel in the flume at the CCS. The gravel mixture and wood logs were scaled accordingly. Since the present work only considers a fixed installed LWD accumulation at the CCS, without any mobile wood pieces, no further dynamic scaling parameters are considered. Steepland rivers show a poorly sorted grain size distribution, with material ranging up to very large boulders, some reaching more than a meter in diameter. Our model headwater river, accordingly, had grains ranging from 4 to 63 mm equivalent sieve size.

3. Methodology

The survey technique that we employed for our initial experiments is based on Structure from Motion (SfM), which is more typically used in field studies. SfM uses a combination of multi-view stereo and bundle adjustment techniques [17, 18] to generate a three-dimensional model from camera images taken of a study area from slightly different perspectives. Over the last few years this photogrammetric technique has become more attractive for a multitude of field and laboratory studies purposes [18-20], particularly with the rise in popularity of drone-based camera platforms.

3.1. Data Collection

For our research purposes we are using a multi-camera array consisting of five See3Cam - CU130 cameras developed by e-con-Systems. Each camera is equipped with a 5.5 mm lens, fixed focus and a 13 MP image sensor. A maximum field of view in horizontal direction (HFOV) is given with 58°. The cameras support image and video resolutions of up to 4224 x 3156 pixels and allow to stream Ultra-HD (4K) with up to 30 fps.

All five cameras are fixed on a cart that moves along the longitudinal axis of the flume. The cart stops every 100 mm to take an image with each camera, generating an overlap of 84 % for SfM reconstruction. A complete data set consists of 250 images taken from 50 stations over the entire length of the channel. The position of the cameras was chosen to capture the entire width of the flume. One camera was placed in the flume centre, perpendicular and at a vertical distance of 1 m to the channel bed surface. Four more cameras were installed in square formation at a distance of 125 mm around the central camera, aligned along the longitudinal and lateral axis of the flume, each with an inclination of 15° from vertical to the flume centre. Camera inclination is beneficial for increased image overlap as well as to avoid capturing information from outside the stream channel. Due to the fixed position of the cameras, in combination with only longitudinal movement of the cart along the flume axis, smooth 3D-models can be assembled without collecting overly redundant image information. This helps to increase the efficiency of our low-cost camera equipment (5 x 279.00 USD), resulting in quick imaging times in the laboratory and high quality processing of the data.

3.2. Experimental Procedure

Investigation of interaction processes between LWD and sediment is undertaken in line with the following procedure to ensure the same initial conditions for each experiment (Table 1). Each test series started with the configuration of the mobile channel bed into the meandering stream course. This was achieved by distributing equal measures of graded gravel material for each of the 17 sections of the model channel. The material was laid down as three layers, with coarser material in the lowest layer. Afterwards, these layers were mixed up with a stick by crossing the section three times, every 100 mm in longitudinal direction, from the left to the right embankment.

A complete set of images was obtained after the installation of the channel bed (Run 0). This step is also useful to show formation processes of a manually installed channel bed in contrast to a channel bed developed during a higher base discharge. For our experiments, a higher base discharge of 8 $l \cdot s^{-1}$ was used to provide the initial condition (Run 1). Afterwards, an annual flood event (75 $l \cdot s^{-1}$) worked on the channel for 30 minutes, allowing measurement of changes in channel morphology in the presence of a LWD accumulation (Run 2). The sediment trap was cleaned once a run was finished, to assess the mass of accumulated bedload during the run. For all test runs, the same LWD accumulation was used. After each test series, the entire channel bed was cleared and later on reinstalled.

Table 1. Overview: Data collection and designation.

Experiment	I	II	III
Data-Set	Run 0	Run 1	Run 2
Discharge ($l \cdot s^{-1}$)	-	8	75
Time (min)	-	240	30
Images	250	250	250

3.3. Data Processing

All imagery was processed with Pix4D, a commercially available SfM package (5.000 USD), to assemble single pictures to compact point clouds (Fig. 4) and generate digital elevation models (DEMs). A reasonable alternative may be DroneMapper, which is freely available as rapid version with small limitations. The data set obtained after the simulated flood event was compared with the data set obtained before the major flood event using CloudCompare, an open source point cloud analysis package. The volumetric difference between the two point clouds provides an estimate of the transported sediment volume. SfM data, together with the knowledge of the coloured sediment fed into the channel, the amount of previously installed mobile bed material and the amount of bedload material ending up in the sediment trap, are used for the observation of channel morphological processes.

4. Results

The presence of the LWD accumulation at the CCS had a significant influence on the water level and bedload transport processes, during a simulated annual flood event. Backwater effects upstream of the CCS resulted in a water surface level increase of up to 55 mm, with a maximum water depth of 150 mm. Eddies accompanied the backwater surge forming at the CCS, circulating in the upstream direction along the left and right side embankments and back to the centre of the channel. Upstream of the LWD accumulation, hardly any bedload transport occurred, however, significant changes could be clearly discerned at the downstream reach of the bridge.

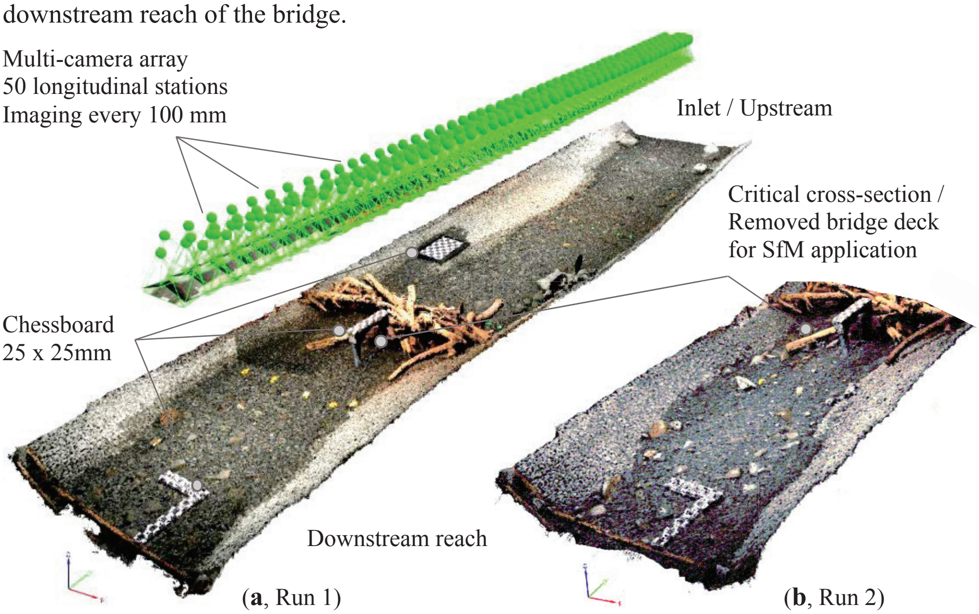

Fig. 4. Initial data set processed to a dense point cloud of the channel before (a) and after the simulation of an annual flood event (b).

Initial results from DEM of Difference (DoD) of Run 1 ($8\ l\cdot s^{-1}$) and Run 2 ($75\ l\cdot s^{-1}$) revealed a total volume difference of $0.0172\ m^3$, which is equal to a sediment freight of 27.6 kg, using a dry bulk density of $1{,}600\ kg\cdot m^{-3}$, while 11.8 kg have been added and 15.8 kg removed (Table 2). Our manually measured transport rates allow for 7.5 kg sediment input via the conveyor-belt feeder, and another 19.5 kg that was collected at the sediment trap in the outlet structure, summing up to a total bedload freight of 27.5 kg.

Table 2. Characteristics and transport rates from the initial experiments.

Data-Set	Discharge ($l \cdot s^{-1}$)	Run time (min)	Formation processes	Manually measured Input / Output rate (kg)	Calculated (DoD) Input / Output rate (kg)
I (Run 0)	-	-	No	-	-
II (Run 1)	8	240	Yes	+ 0 / - < 0.5	-
III (Run 2)	75	30	Yes	+ 7.5 / - 19.5	+11.8 / -15.8

As shown in (Fig. 4, a), natural formation processes formed a realistic channel bed with emerging boulders, small riffle and bars for Run 1. In the DEM, significant changes in channel morphology could be observed, especially downstream of the CCS with LWD jam (Fig. 4, b). The model orthoimagery revealed that single particles of the yellow tracer stone line, with a mean diameter of 16 to 25 mm, directly downstream the CCS (Fig. 4, a) moved, whereas larger particles have been exposed. In total, six particles with a diameter of 43 to 63 mm got caught at the sediment trap with the origin from the downstream reach of the bridge, to illustrate emerging flow forces. Fed sediment mainly aggraded immediately downstream from the input section, due to the resulting backwater effect formed at the CCS. An elevated gravel bank, of about 100 mm elevation (Fig. 2 and Fig. 4, a), which can be flooded at higher runoff conditions, is shown in the light grey section on the left side in the upper half of the flume. The chequerboards that are placed in the channel after each run are used for SfM scaling purposes in Pix4D.

5. Discussion and Conclusion

Laboratory experiments were conducted to show the effects of a LWD accumulation on channel morphology. Our initial tests have shown that bedload transport processes upstream of the LWD accumulation were less than expected, but consistent with the energy drop imparted by the backwater effect. Flow diversions and backwater effects at the CCS cause turbulent flow conditions. Even coarse gravel material, with a mean diameter of up to 63 mm, was exposed and mobilised by the runoff. Our study supports the findings of [13, 21, 22], where LWD pieces in stream channels cause backwater effects, a reduction of flow velocity upstream and step formation processes with coarse bedload material downstream of log jams.

In addition to these findings of LWD effects on flow hydraulics, it was found that SfM is an effective means to capture morphologic changes in the experiments. We generated point clouds with more than $11 \cdot 10^6$ points for the relative small area (≈ 7.5 m^2) in the flume, which provides detailed resolutions and average point cloud densities of up to 95 points/cm^2. The precision of the applied survey technology (0.29 mm/pixel) allows the detection of the full grain (4 to 63 mm) and wood range in the flume, which equals a 4 mm raster in prototype resolution. Our introduced SfM methodology has potential for very accurate 3D-structure creation, but also for future identification processes of individual gravel particles and wood pieces (particle tracking), as well as processing of surface roughness and skin friction. Quick data generation and processing times, whilst obtaining high quality results with low-cost equipment, are one of the main advantages. However, problems can arise while working on rough surfaces and especially LWD accumulations, which might also result in increased error effects due to shadows, as described in recent studies [18, 23].

Since interactions between LWD accumulations and sediments, such as erosion and aggradation, are complex and presently not clearly understood [24], further experiments are needed. Our imminent experiments will also consider a mixture of LWD together with organic fine material to add a further element of complexity to simulations of debris accumulations and its effects on channel formation processes. In future, this research project will elaborate on more practical and efficient methodologies for observing LWD dynamics in stream channels, in the laboratory as well as in-situ. The research is needed to inform freshwater- and flood management, but also to advance our general understanding of open - channel hydraulic systems.

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