**Fluvial evacuation of landslide material from bedrock-confined
channels under controlled experimental conditions**

Edwin R.C. Baynes^{1,2*}, Charline Bardin^{1,3}, Heide Friedrich¹

¹ Department of Civil and Environmental Engineering, University of Auckland, Auckland, New Zealand

² Geography and Environment, Loughborough University, United Kingdom

³ Département Génie Énergétique et Environnement, Institut National des Sciences Appliquées, Lyon, France

*Corresponding author email address: e.baynes@lboro.ac.uk

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Abstract

The supply of sediment from hillslopes to channels is rarely constant, with discrete events (e.g., landslides) known to transfer large volumes of sediment in geologically-short periods of time, especially in tectonically active areas. Understanding the rates and patterns of subsequent sediment evacuation is important for understanding variability of landscape evolution, as well as mitigating the risk of geohazards associated with bed aggradation and the loss of channel capacity to convey flood waters. Here, we performed a series of controlled laboratory flume experiments to explore the controls on sediment transport after a single sediment input in scenarios with (i) different initial input volumes (4 – 25 kg) under constant flow conditions (40 l/s), (ii) a constant initial input volume (12 kg) under different flow magnitudes (5 – 60 l/s), and (iii) a repeat of the input sediment volumes in scenario (i) but with the same volume of water delivered using a ramped hydrograph (0 – 60 – 0 l/s). We find the presence of sediment piles impacts the flow hydraulics, with a backwater effect developing upstream of the pile that causes a flow acceleration around the location of the pile. For a given discharge, larger sediment piles have a greater impact on the flow hydraulics, which in turn induces higher rates of sediment transport and erosion of the pile. In all cases, sediment remains at the initial pile input location for the duration of the sediment evacuation, acting to protect the bed from erosion. We highlight the role of geomorphic-hydraulic interactions in controlling the sediment evacuation, and suggest there is an optimal combination of pile size and flow conditions (flow magnitude and hydrograph shape) for accelerated rates of sediment transport, which are important for the short-term and long-term channel dynamics and the landscape evolution variability.

1. Introduction

The rate of erosion within bedrock-confined channels sets the wider pace of landscape evolution, exhibiting a bottom-up control on the elevation and stability of hillslopes (Korup and Schlunegger, 2007; Norton et al., 2008; Larsen and Montgomery, 2012; Callahan et al., 2019). Consequentially, destabilisation and input of hillslope material into the channel

network can limit or halt erosion by overwhelming the channel network with sediment and protecting the bedrock surface through the 'cover effect' (Sklar and Dietrich, 2001; Hoffman and Gabet, 2007; Yanites et al., 2010; Attal et al., 2015; Tunncliffe et al., 2018; Glade et al., 2019). The supply of sediment from hillslopes to channels is rarely constant, with discrete events (e.g., landslides) known to transfer large volumes of sediment in geologically-short periods of time, especially in tectonically active areas (Korup et al. 2004; Li et al., 2016; Hovius et al., 2011; Massey et al., 2018). This discrete rather than continuous coupling of hillslope material with the channel network results in non-constant fluvial sediment transport through time, with periods of heightened fluvial sediment evacuation following large inputs of sediment (Lin et al., 2008; Hovius et al., 2011; Croissant et al., 2017; East et al., 2018; Tunncliffe et al., 2018). The subsequent switching on and off of channel bed erosion through the 'tools' and 'cover' effects (e.g., Sklar and Dietrich, 2001) could have a previously unrecognised impact on the variability of landscape evolution that is not captured when typically reporting long-term average incision rates nor is it currently considered in many traditional landscape evolution modelling studies (Yanites et al., 2010; Lague, 2014; Li et al., 2016).

Beyond implications for long-term landscape evolution, understanding the evacuation of large sediment inputs in the channel network is important in the context of mitigating the risk of geohazards, and for understanding short term geomorphic response to disturbances (e.g., East et al., 2018). Large sediment volumes input within the fluvial network tend to lead to the relatively rapid aggradation of the river bed (Croissant et al., 2017; Tunncliffe et al., 2018; East et al., 2018), reducing channel capacity for flood flows (Slater et al., 2015; Wang et al., 2015) and, where rivers become unconstrained laterally at the mountain front, leading to channel avulsion (Reitz et al., 2010), which poses a hazard for populations and infrastructure downstream (Korup et al., 2004). Quantifying the processes that control the sediment evacuation following large inputs is therefore important for improving both, the understanding of the long-term role of the valley network in mediating the response of landscapes to

extreme events or variability in forcing over multiple timescales (Hoffman and Gabet, 2007; Larsen and Montgomery 2012; Li et al., 2016), and mitigating short-term hazards in directly-affected catchments (Korup et al., 2004).

Two end-member scenarios exist for the evacuation of large sediment volumes from a point source: (i) translation of the sediment downstream as a wave and (ii) by gradual dispersion of the pile through time (Gilbert, 1917; Sutherland et al., 2002; Cui et al., 2003a; Sklar et al., 2009). In natural channels, both scenarios of sediment evacuation have been observed, with a sediment pulse in the Chehalis River, Washington State, USA, translating like a wave (Nelson and Dube, 2016), although significant translation has not been observed in many other channels (Lisle et al., 2001), including the Navarro River, California, USA (Sutherland et al., 2002), and in the Sapphire Mountains, Montana, USA (Hoffman and Gabet, 2007), where evacuation of sediment pulse was dispersive with little measurable translation.

Laboratory (e.g., Cui et al., 2003a; Sklar et al., 2009) and numerical modelling (e.g., Cui et al., 2009b; An et al., 2017) investigations have shown that typically dispersion is favoured over translation, in particular when pulse volumes are large relative to the channel dimensions or when the Froude number is high (Cui et al., 2003a; Sklar et al., 2009; An et al., 2017). When the flow regime is able to transport the median grain size of the pulse, it is possible for the majority of the sediment to be transported and there will be some component of translation, but if the flow is not competent enough to transport the median grain size, dispersion is likely to dominate (Sklar et al., 2009). The difference in grain size between the pulse material and the existing bed material also controls the mechanism of sediment export (e.g., Venditti et al., 2010a; Venditti et al., 2010b), because of possible smoothing effects on the bed roughness that accelerate near bed velocities and mobilise additional material.

Venditti et al. (2010a) found that, for the same total pulse volume, the bed material mobilisation rate declines as the pulse grain size increases and coarser pulses have a longer lasting effect on the composition of the bedload flux, indicating a longer residence time for the pulse particles in the flume.

Beyond a threshold sediment input volume, the channel morphology can self-adjust by narrowing to increase the sediment transport capacity, leading to a non-linear increase in the removal efficiency for larger sediment volumes (Croissant et al., 2017). This morphological adjustment demonstrates the potential for feedbacks between sediment inputs and fluvial processes that lead to accelerated sediment evacuation from the source areas. Interactions between sediment, channel/valley morphology, flow hydraulics and erosion processes have also been shown to be important in bedrock canyons (e.g., Venditti et al., 2014). Plunging velocity flow fields develop in response to bedrock constrictions, and alluviation upstream of bedrock constrictions, directing flow against the canyon walls and potentially leading to increased erosion potential in these locations (Venditti et al., 2014; Hunt et al., 2018; Cao, 2018). Large sediment piles could have a similar impact on the flow as bedrock constrictions, demonstrated by the largest landslides creating dams that can persist in landscapes for long periods of time (Korup et al., 2004), and the presence of large rocks in the channel increasing hydraulic roughness (e.g., Shobe et al., 2016; 2018; Glade et al., 2019). Feedbacks between the presence of large piles, the impact on flow hydraulics and sediment transport remain uncertain, despite potentially being important for the long-term pattern and rate of sediment evacuation from the source areas.

1.1 Objective

Here, we hypothesise that where piles are large enough to impact the characteristics of flow hydraulics by forced channel narrowing, heightened local slope or increasing the hydraulic roughness (Venditti et al., 2014; Shobe et al., 2016; Croissant et al., 2017; Hunt et al., 2018; Glade et al., 2019), a complex feedback is developed whereby the sediment pile, flow hydraulics and the pattern and rate of sediment transport co-evolve. We present a laboratory physical modelling study to test the above hypothesis, by exploring the mechanisms of sediment evacuation from a point source under controlled conditions. We investigate the roles of initial sediment pile volume and discharge regime (both magnitude and hydrograph shape) on the pattern and rate of sediment transport, and the nature of the flow conditions.

This work builds on investigations of sediment export from discrete sources (e.g., Cui et al., 2003a; 2003b; Sklar et al., 2009; Venditti et al., 2010a; Croissant et al., 2017) and on the interactions between geomorphic and hydraulic processes (e.g., Venditti et al., 2014; Hunt et al., 2018; Baynes et al., 2018a), and will increase the quantitative physical process-based understanding of the role of hillslope-channel coupling, sediment production and export in wider landscape evolution studies.

2. Experimental approach

2.1 Laboratory setup and experimental parameters

Experiments were performed in a 19 m long, 0.45 m wide, flume at the University of Auckland that has been used extensively for gravel sediment transport testing in the past (e.g., Chin et al., 1994; Heays et al., 2014; Bertin et al., 2015; Bertin and Friedrich, 2018; Groom and Friedrich, 2019). The setup of the flume was designed to replicate a bedrock-constrained channel, with a hydraulically rough bed and glass side-walls to represent the relatively smooth bedrock lined walls of a canyon (Fig. 1A). It is important to note that we did not aim to replicate any particular natural system with our experimental set up, aiming rather to explore the variability in processes relative to each other under different scenarios (sediment input, flow regime), within a setup that provides qualitatively similar, although simplified, conditions compared to a natural system (e.g., Hooke, 1968; Baynes et al., 2018b). To maintain uniform bed roughness conditions in the test section throughout all experiments, a 3D-printed plastic bed (Fig. 1B) was manufactured, using a representative Digital Elevation Model (DEM) of a gravel-bed surface ($D_{50} = 9.2$ mm) that had been fluvially worked in the same flume during previous experiments (Bertin and Friedrich, 2018). The sediment mixture used in the previous experiments was sourced from the Tukituki River in New Zealand, and therefore represents a 'natural' grain size distribution that was slightly bimodal with 9% sand and 91% gravel (Bertin and Friedrich, 2018). We elected to use a water-

worked roughness pattern from previous experiments over manually sticking sediment to the bed in the test section, to add some element of a 'realistic' roughness pattern. This helps to maintain the similarity of the processes studied in the experimental setup, namely a natural bedrock-constrained canyon system with a gravel bed.

For each of the experiments, sediment of a uniform grain size (D_{50} between 6.7 – 9 mm) was poured into the test section of the flume without water flowing, enabling the formation of a natural conical-shaped pile at the angle of repose (Fig. 1C). We recognise that the uniform grain size that we used is a simplification of the typical grain size of hillslope material that enters the river network (e.g., Attal et al., 2015), but opted to use this sediment in order to limit the internal complexity of the pile. Future experiments that explore the interactions between sediment piles and flow that utilise a broader sediment grain size distribution should be a priority, but the experiments presented here represent the reference case with a single uniform grain size, upon which other complexities can be compared against. The pile was inserted from one side of the flume, rather than the middle, to represent the input of landslide material into a canyon from one of the valley sides. Before each experiment, the water depth was slowly increased within the flume, using the tailgate to set the required flow depth for the target constant discharge for that experiment. At the start of the experiment, the inlet valves were programmed to open to the target discharge and the tailgate was lowered to the required height for flow of a uniform flow depth and velocity throughout the length of the flume. All experiments were performed with a bed slope of 0.5%.

In this study, we present the findings from three sets of experiments (eight tests per set), exploring the impact of changing both the volume of the initial sediment pile, and the flow conditions (Table 1; Fig. 2). In the first set of experiments, a constant flow discharge of 40 l/s was used for all experiments and the initial sediment pile size was varied from 4 kg to 25 kg (Table 1), exploring the impact of pile size on the rate and pattern of sediment evacuation. We selected this discharge as it was above the threshold of motion for the grain size, so we would expect to see sediment transport, but not so high as to generate significant surface

waves that would affect the image quality for the cameras or risk overtopping the edges of the flume. In the second set of experiments, the sediment pile size was maintained constant at 12 kg, but the discharge used in the experiments was between 5 and 60 l/s, testing the impact of flow magnitude on the rate and pattern of sediment evacuation. The third set of experiments was a repeat of set 1, but instead of a constant flow of 40 l/s, the discharge was delivered to the flume following a hydrograph containing a linear increase in flow for the first half of the experiment from 0 to 60 l/s, and a linear decrease in flow for the second half of the experiment from 60 l/s to 0 l/s, similar in shape to the hydrographs used in the An et al., (2017) study. The total volume of water delivered to the flume in set 3 experiments was the same as the total volume of water delivered in experimental set 1 (constant discharge of 40 l/s), enabling a comparison of these experimental sets to explore the impact of hydrograph shape on the rate and pattern of sediment evacuation.

Fig. 1: A. Schematic diagram of the flume set up at the University of Auckland (adapted from Bertin and Friedrich, 2018). B. Photograph of the 3D printed bed (yellow plastic) in the test section of the flume. The dark sections upstream and downstream of the test section are

192 gravel fixed to the bed to provide roughness. C. Example of the sediment pile at the start of
193 the experiments. Sediment is poured from the edge of the flume to generate a pile at the
194 angle of repose, replicating the input of sediment from the adjoining hillslope into a bedrock
195 canyon.
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Experimental Set	Initial pile mass (kg)	Initial pile height (cm)	Discharge magnitude (l/s)	Initial water depth upstream of pile (cm)	Initial shear stress upstream of pile (Pa)	Discharge shape
1	4	9.8	40	19.1	9.4	Uniform
	6	11.1	40	16.4	8.0	Uniform
	8	12.5	40	18.5	9.1	Uniform
	10	13.0	40	18.2	8.9	Uniform
	12	13.7	40	19.8	9.7	Uniform
	16	16.1	40	17.5	8.6	Uniform
	20	18.8	40	18.0	8.8	Uniform
	25	22.6	40	22.5	11.0	Uniform
2	12	14.5	5	8.5	4.2	Uniform
	12	14.7	10	9.5	4.7	Uniform
	12	17.0	15	10.7	5.2	Uniform
	12	14.4	20	12.5	6.1	Uniform
	12	16.4	30	15.5	7.6	Uniform
	12	15.1	40	17.8	8.7	Uniform
	12	15.8	50	20.7	10.1	Uniform
	12	15.7	60	22.5	11.0	Uniform
3	4	10.2	0 -> 60 -> 0	N/A	N/A	Ramp
	6	12.9	0 -> 60 -> 0	N/A	N/A	Ramp
	8	14.1	0 -> 60 -> 0	N/A	N/A	Ramp
	10	15.0	0 -> 60 -> 0	N/A	N/A	Ramp

12	15.5	0 -> 60 -> 0	N/A	N/A	Ramp
16	16.1	0 -> 60 -> 0	N/A	N/A	Ramp
20	18.8	0 -> 60 -> 0	N/A	N/A	Ramp
25	20.6	0 -> 60 -> 0	N/A	N/A	Ramp

Table 1: Experimental parameter list

Fig. 2: Initial conditions for pile size (width and height) relative to the flow depth, recorded from the side and top-facing cameras. Black points are those from experimental set 1 (see Table 1), red points from experimental set 2, and blue points from experimental set 3. Red dashed lines indicate the water depth for corresponding discharges used in experimental set 3.

2.2 Data collection and image analysis

During the experiments, two Lumenera high-speed cameras were used to collect images of the evolution of the (i) sediment pile and (ii) the flow conditions throughout the duration of the experiment. One camera was located directly above the sediment pile and one camera was located looking through the glass wall at the side of the sediment pile. Analysis of the images was performed using the Tractrac Particle Tracking Velocimetry software (Heyman, 2019) to measure the velocity of sediment transported from the pile, and to identify the location within

the pile where the sediment was moving from. Pile size (height and width; e.g., Fig. 3) and flow depth (upstream and downstream of the pile) were also measured using the scaled images from the cameras.

Fig. 3: Example images from (A) side-facing and (B) aerial view cameras used for tracking sediment velocities and evolution of pile morphologies. Flow direction is shown by the blue arrows. The 3D-printed DEM of a water-worked gravel-bed surface can be clearly seen in both images. Images shown are from the start of the experiment, with a 6 kg pile at constant water discharge of 40 l/s. Red lines indicate for method for measuring the maximum height of the pile and with width (radius) of the pile.

3. Results

3.1 Interactions between pile and flow

In all experiments, except the one conducted at 5 l/s, the presence of the sediment pile has a clear impact on the flow conditions within the flume, with the pile generating a backwater effect upstream of the pile that induced a change in the water depth between the upstream and downstream limits of the pile. This change in water depth around the pile (hereafter referred to as δH) generates an increased local water surface slope, and flow acceleration around the sediment (Fig. 4). In some experiments, δH was greater than 100 mm, and for the experiments with a constant discharge (40 l/s), δH scaled with the initial size of the pile (Fig. 4A; Fig S1). As sediment was eroded from the initial pile location, and the height of the pile decreased through time, δH also decreased (Fig. 4A). For the initial stages of the ramped hydrograph experiments, δH was generally small because of the lower discharge magnitude during the rising limb (Fig. 4B), but an associated relation between the reduction in pile height and δH as the pile is eroded is present.

There was not a clear relation between pile height and δH for the experiments performed with a constant pile size (12 kg) and a range of discharges (5 – 60 l/s). The calculated critical shear stress for incipient motion was calculated using the Shields formula ($\tau_c = \tau_* (\rho_s - \rho_w) g D_{50}$), where τ_* is the Shields criterion (0.045; Buffington and Montgomery, 1997), ρ_s is the density of the sediment (2750 kg m⁻³), ρ_w is the density of water (1000 kg m⁻³), g is the acceleration due to gravity (9.81 m s⁻²) and D_{50} is the median sediment size (7.85 mm), to be 6.1 Pa. Water depth did not change around the pile during the 5 l/s experiment, and the pile remained intact throughout the duration of the experiment, with no sediment transport. The shear stress acting on the bed ($\tau = \rho_w g h S_w$, where h is the water depth and S_w is the water surface slope) for the flow at 5 l/s was 4.2 Pa, below the critical shear stress for transporting the sediment, which explains the lack of sediment evacuation from the initial pile location. At higher discharges, there was a change in water depth around the piles and

larger δH were associated with a higher acceleration of the flow velocity around the pile (Fig. 4F)

Fig. 4. Evolution of sediment pile height and δH , coloured through time, from selected experiments with a constant discharge (A), (B) constant pile size, but different discharges and (C) with a ramped hydrograph. (D-F): Relation between δH and the acceleration in flow

velocity around the pile. In all three experimental sets, where there is a larger δH induced by size of the pile (A-C), there is a coincident increase in the flow velocity around the pile.

3.2 Rate and pattern of sediment evacuation from pile location

The images from the camera positioned directly above the initial sediment pile provides evidence on the rate and pattern of sediment evacuation from the input location. Images were recorded at 30 frames per second, and the area of pile coverage calculated through a thresholding approach of the grayscale images (Fig. 5). Images from tests with a 10 kg pile (Fig. 5A-C) and a 25 kg pile (Fig. 5D-F) show the evolution of the piles during the experiment, with the transported sediment covering a larger proportion of the bed surface. In the 25 kg pile experiment, the light blue areas of Fig. 5F show the area at the edges of the initial pile, where the bed has been exposed because of sediment transport. In all of the experiments, the bed below the initial sediment pile remained covered in sediment at the end of the experiment, with the primarily morphologic evolution of the pile being the reduction in the pile height.

Except for the 5 l/s experiment (pile size = 12 kg), sediment was transported from the initial pile location. The area of the bed covered by sediment increased during the course of the experiments (Fig. 6). In Fig. 6, the x-axis for time is the time since the first movement of sediment was documented by the cameras, to allow for comparison on the duration of sediment transport between experiments. The mechanism of sediment evacuation was dispersive in all experiments where sediment was transported, demonstrated by the downstream migration of the pile edge and the continual coverage of the bed by sediment at the initial pile location, with the exception of the largest piles (Fig. 5). For smaller piles (4 – 8 kg), the ramped hydrograph experiments transported more sediment from the initial pile location (normalised by the initial pile area) by the end of the experiment, but the rate that the bed coverage area increased was similar for both a constant and ramped hydrograph (slope

286 of the lines in Fig. 6A-C). In contrast, for the largest piles (20 – 25 kg), the rate of increased
 287 bed coverage was larger for the experiments with a constant flow, as compared to the
 288 ramped hydrographs. The overall bed area covered at the end of the experiment was higher
 289 for the constant experiments (Fig. 6G,H). This was possibly caused by the presence of larger
 290 δH around the pile for the period at the beginning of the constant flow experiments, as
 291 compared to the lower discharges in the early stages of the rising limb of the ramped
 292 hydrograph experiments (see Fig. 4A, B). It should be noted that the apparent trend in
 293 decreased bed coverage in these experiments was caused by sediment being transported
 294 beyond the downstream limit of the camera frame, coupled with the continual removal of
 295 sediment from the initial location (see Fig. 5F). For a constant pile size (12 kg), increasing
 296 the flow magnitude increased both the rate of the increase in bed coverage during the early
 297 part of the experiment, and the overall proportion of the bed that was covered by the end of
 298 the experiment (Fig. 6E).

A. 10 kg - t_0

D. 25 kg - t_0

B. 10 kg - t_{end}

E. 25 kg - t_{end}

C. 10 kg - Evolution Map

F. 25 kg - Evolution Map

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Fig. 5: Examples of the evolution of the sediment pile from the top-facing camera. Panels (A) and (D) show the initial pile at the start (t_0) of the 10 kg pile and 25 kg pile experiment, respectively. Panels (B) and (E) show the same piles at the end of the same experiments (t_{end}). Flow is from right to left in the images, and the eroded material can be seen deposited downstream of the initial pile area. Panels (C) and (F) show a colour-map comparison of the two images, with black areas indicating where sediment from the initial pile is still in place, red areas indicate where material has been deposited and light blues areas indicate where parts of the bed that were covered by the initial sediment pile have been exposed.

Fig. 6: Evolution of the sediment pile coverage through time, normalised by the initial pile area. Blue lines indicate the experiment performed with a ramped hydrograph, and black lines had a constant discharge of 40 l/s. In panel (E), red dashed lines indicate the evolution for different discharges, all with a 12 kg sediment pile.

Using the particle tracking software Tractrac (Heyman, 2019), we calculated the mean sediment velocity across the pile for each image from the side-looking camera (at 39 frames per second). Through time, this allows the identification of the rate and pattern of sediment movement at, and from, the initial pile location (Fig. 7), and can also be compared to the evolution of the sediment pile height and the size of δH (from Section 3.1). For a given discharge (Fig. 7A-H), there is a clear difference in the rate and pattern of sediment velocity for piles of different sizes. Larger piles experience an asymmetrical behaviour, with a steep increase in sediment velocity after the sediment input, before reaching a peak value that is short-lived, and then a gradual decay in the sediment velocity until it reaches zero (Fig. 7E-H). The decay in sediment velocity coincides with the reduction in pile height and δH through time (Fig. 4). By contrast, smaller piles experience a more symmetrical pattern of sediment velocity, with a lower peak velocity that is sustained for longer before gradually decaying to zero (Fig. 7A-E). In general, the experiments with a ramped hydrograph experienced higher average sediment velocities for longer than the constant discharge experiments, with higher peak values for the smaller piles, but similar peak sediment velocities for the larger piles at the early stages of the experiments. For the experiments with a constant pile size (Fig. 7I-P), there is no clear difference in the average sediment velocity through time across the range of discharges above 15 l/s. For the 10 l/s experiment, the average sediment velocity was very low for the duration of the experiment and there was no reduction in the initial pile height. This also matches the small increase in bed sediment coverage relative to the other experiments identified from the top-camera images (Fig. 6E). In all experiments, the decay of average sediment velocities to zero follows a similar trend in the change in pile height and the size of δH to a constant value.

Fig. 7: Plot highlighting the co-evolution of pile height, δH and the mean sediment velocity through time. Mean velocity of sediment in motion was calculated using the Tractrac particle tracking algorithm (Heyman, 2019). Mean velocity is calculated across all transported particles in a given image. Panels A-H show data from the 40 l/s constant discharge (black) and ramped hydrograph (blue) experiments. Panels I-P show data from the constant 12 kg pile experiments. Points indicate the height of the pile normalised by the initial height and crosses indicate δH normalised by the water depth upstream of the pile.

In Fig. 8, the peak average sediment velocity during the experiments is compared to the pile mass (Fig. 8A), discharge (Fig. 8B) and the height of the initial pile relative to the initial water depth (Fig. 8C). Systematically, the ramped hydrograph experiments have a higher peak average sediment velocity for a given pile size compared to a constant discharge regime. Importantly, the difference in peak sediment velocity between ramped and constant hydrograph experiments is generally greater where the pile is smaller and decreases for the larger piles (Fig. 8A), except for the experiment with the 6 kg pile. For a given pile size (Fig. 8B), there is not a linear increase in peak mean sediment velocity with discharge, possibly because of the threshold for motion and the decreasing interaction between the pile and the local flow hydraulics. The piles are smaller relative to the flow depth and less likely to induce large δH around the pile location (Fig. 4). The size of the initial pile relative to the water depth is not necessarily an indicator of peak mean sediment velocity. The flow can be below the threshold of motion (i.e., 5 l/s; Fig. 8C), for when there will not be any sediment transport, despite the pile being significantly larger than the flow depth (pile height / water depth > 1.5). Where the experiments in this set sit within the same conditions as the constant and ramped hydrograph tests in terms of being above the threshold for motion and having initial pile height / initial water depth < 1 (i.e., experiments where $Q > 30$ l/s), they follow the same pattern of an increasing mean sediment velocity with increasing initial pile height / water depth (Fig. 8C).

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Fig. 8: Summary plots of peak sediment velocity against (A) pile mass, (B) discharge, and

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(C) the initial pile height relative to the water depth.

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373 4. Discussion

374 4.1 Mode of sediment evacuation from source area

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The main findings of these experiments for observed sediment evacuation patterns from a

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discrete source are similar to previous experimental and field observations (e.g., Sutherland

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et al., 2002; Hoffman and Gabet, 2007; Nelson et al., 2015): the sediment was dispersed

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rather than translated, as the bed remained covered with the pulse material at the input

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location (Fig. 5). In all of the experiments where sediment transport occurred, the pile

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evolved from the initial conical shape to a tapering wedge oriented in the downstream

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direction, in the same form as those observed by Hoffman and Gabet (2007). Sklar et al.

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(2009) observed in experiments the translation of the three main components of the pile

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(upstream and downstream edges, and the pile centroid) to some degree, which was

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enhanced for smaller piles relative to the channel dimensions. Where dispersion occurred in

the Sklar et al. (2009) experiments, sediment was primarily sourced from the downstream edge of the pile, in effect leaving sediment from the pile behind, similar to the observations in this study (Fig. 5).

Over long-time scales, numerical modelling has shown that gravel-bed channels adjust, for the most part, to the average constant conditions, despite repeated cyclical flow and sediment inputs (An et al., 2017). Exceptions to this are the upstream limit of the study reach and the input location for the variable sediment supply (An et al., 2017). Humphries et al. (2012) found that the nature of discharge to the channel can impact the pattern of pulse evacuation; a constant flow regime (60% above entrainment threshold) led to a mix of dispersive and translation behaviour, whereas a broad crested hydrograph (peak flow 2.5 times entrainment threshold) led to pulse dispersion and a peaked hydrograph (peak flow > 3 times entrainment threshold) caused pulse dispersion with some translation. For the peaked hydrograph tests, higher bedload transport rates on the rising limb, compared to the falling limb, led to a hysteresis effect and an asymmetric pattern of sediment transport through the hydrograph (Humphries et al., 2012). In our experiments, we compare the sediment evacuation during a single cyclical hydrograph and constant flow conditions (same total volume of water over the duration of the experiment), and find differences in both the peak sediment transport velocity (Fig. 8A), the duration of sediment transport (Fig. 7E-H) and the bed sediment coverage through time (Fig. 6). We suggest that our experiments capture the local transient dynamics induced by the higher peak discharges and hysteresis between the rising and falling limb associated with the ramped hydrograph, highlighting the role of variable forcing in controlling channel dynamics despite the same long-term average conditions.

From the analysis of the bed sediment coverage (Fig. 6) and the non-symmetrical mean sediment velocities through time (Fig. 7), it is clear that sediment evacuation and adjustment to the pile morphology occurs rapidly in the time period shortly after the sediment pile input, with a gradual decay in transport rates through time. Larger piles exacerbate this

phenomenon for a given discharge, because of a larger impact on the local flow hydraulics, discussed in more detail in Section 4.2. Sutherland et al. (2002) documented a similar mode of sediment evacuation, with high flows in later years following the sediment input contributing less to the overall sediment transport rate. Sediment evacuation from a discrete source and location is therefore non-uniform in time and space, and this study provides further evidence for the dominance of the dispersal mechanism in gravel-bed rivers.

4.2 Importance of hydraulic-geomorphic interactions

Here, we demonstrate that complex interactions can occur between geomorphic processes (i.e., sediment transport) and hydraulic processes (i.e., flow velocity), and should not be treated as independent variables. The rate and pattern of sediment evacuation from the piles is clearly controlled by interactions between both elements, supporting our hypothesis stated in Section 1.1. Where piles are large enough to induce local instabilities in the hydraulics (i.e., a backwater effect that generates a change in water depth and flow acceleration around the pile), the initial rate of sediment transport is higher than for scenarios where the hydraulic processes are not perturbed (Fig. 7). Such interactions between hydraulic and geomorphic processes have been shown to be important for channel evolution in the past, including for terrace generation over long timescales (e.g., Baynes et al., 2018a) and for the development of complex flow fields in bedrock canyons (Venditti et al., 2014; Hunt et al., 2018; Cao, 2018). In canyons, constrictions in the channel geometry, such as bedrock sills on the channel bed or alluviated sections, can impact the hydraulic processes by inducing flow velocity inversions that direct high energy flow into the canyon bed, potentially enhancing the local bedrock erosion rate and the development of scour pools (Venditti et al., 2014; Hunt et al., 2018; Cao, 2018). Hunt et al. (2018) also demonstrated experimentally that taller sills enhance a backwater effect in the flow upstream of the constriction that super-elevates the water surface to a greater extent than smaller sills, enhancing downward flow and generated supercritical flow over the lee side of the sill, successfully producing supercritical flow and a

plunging flow structure. Cao (2018) also showed that lateral constrictions can initiate the formation of a scour pool, as the deceleration of flow upstream of the constriction promotes alluviation that causes flow and sediment to plunge towards the bed within the canyon and promoting scour.

We propose here that a similar mechanism enhances the heightened rates of sediment transport for the larger piles in our experiments. The large piles induce a larger backwater effect that enhances the downward flow acceleration around the pile, as demonstrated by the development of the change in water depth around the piles (Figs. 4 and 7), which leads to the observed higher sediment velocities. Importantly, previous studies of sediment evacuation from a discrete location have suggested that supercritical flow and higher Froude numbers are more likely to induce a dispersive transport mechanism (Cui et al., 2003), and the δH observed in our experiments, combined with the dispersive nature of the sediment transport, support these findings. The constrictions that induce the enhanced hydraulic processes in our tests are not fixed in space nor time, because of the mobile nature of the sediment compared to bedrock sills. As a result, the hydraulic-geomorphic interactions are reduced as the sediment pile evolves from the initial conical shape to the tapered wedge morphology through time (Figs. 4, 5 and 7). For the larger piles, a negative feedback exists, whereby the larger piles induce a larger δH . The flow around the pile is accelerated (Fig. 4), leading to heightened sediment transport rates that disperse the pile (Fig. 7), which in turn reduces the impact of the pile on the flow hydraulics (Fig. 7), highlighting the importance of short-lived hydraulic-geomorphic interactions in channels for the first time.

The interactions between hydraulic and geomorphic processes are complex (Fig. 9), as we show that simply a larger pile or higher discharge does not necessarily lead to accelerated sediment transport rates through the mechanism described above. Where flow conditions are below the threshold for motion (e.g., Fig. 7I), no sediment transport will occur regardless of the size of the pile. Additionally, where sediment piles are so large that they block the flow completely (e.g., valley blocking landslides), a different set of processes and interactions

control the sediment transport (e.g., ‘width enhanced removal’; Croissant et al., 2017; or dam failure; Dunning et al., 2006), which are not discussed in this study because of the limitations of creating dams in our flume. In Fig. 9, we highlight how geomorphic and hydraulic processes interact to enhance the rate and pattern of sediment transport above the background rate. A limiting hydraulic threshold flow exists for the movement of sediment (i.e., the critical shear stress), that is widely established and known. As the geomorphic processes increase (i.e., a larger pile), a larger hydraulic response is created (e.g., larger backwater effect) compared to a smaller pile, for the same flow conditions, which leads to enhanced sediment transport (Fig. 9). For scenarios that have the same average discharge over the duration of the experiment but the flow is delivered using a ramped hydrograph reaching a higher peak discharge, the sediment transport is more enhanced (i.e., higher transport rate, asymmetrical pattern) than constant flow conditions (shown by the darker red colours in the squares in Fig. 9). We therefore propose that sediment evacuation from a pile location is expected to be greatest when the pile is large enough relative to the flow depth, to induce a significant backwater effect during the rising limb of a flood, thus mobilising sediment that can be transported at faster rates during the peak flow (Figs. 7 and 9)

Fig. 9: The role of hydraulic-geomorphic interactions in enhancing sediment transport. Initial pile mass is plotted against the average discharge over the duration of the experiment. Squares indicate experiments where the flow was delivered through a ramped hydrograph and circles indicate experiments where the flow was constant throughout. The degree of red shading indicates the extent to which the hydraulic-geomorphic interactions alter the sediment transport behaviour above the background rate, based on the results shown in other figures related to sediment transport rate and duration. A hydraulic threshold exists below which no sediment is transported, as the shear stress is below the critical shear stress. The most enhanced sediment transport occurs for the biggest pile (25 kg) when an average of 40 l/s was delivered using the ramped hydrograph (starting at 0 l/s, linearly increasing to a peak of 60 l/s before linearly decreasing back to 0 l/s by the end of the experiment).

4.3 Implications for channel dynamics and landscape evolution

The rate and pattern of sediment evacuation following a sudden input (i.e., a landslide) documented in these experiments has important implications for channel dynamics at the input location and downstream, over both short and long timescales. The evolution of the pile from a conical shape to a tapered wedge leads to aggradation downstream (Fig. 5), with the majority of this occurring in the immediate aftermath of the sediment input (Fig. 7). This evolution matches observations from natural settings, including rapid aggradation downstream of the Elwha River dam removal sites (USA) after sediment release from the former reservoirs (East et al., 2018), and in the Waiapu River catchment (New Zealand) following the large influx of hillslope material following Cyclone Bola in 1988 (Tunncliffe et al., 2018). Importantly, the rate of aggradation downstream is non-linearly related to the size of the input, because of the hydraulic-geomorphic interactions that accelerate sediment transport for larger piles (Figs. 7, 8 and 9). Where increasing bed levels are important for reducing the channel capacity to convey high stage flows (Slater et al., 2015), enhanced non-linear rates of aggradation driven by hydraulic-geomorphic interactions may become more significant factors in the management of heightened flood risk (Korup et al., 2004).

The channel bed at the input location remains buried throughout the duration of all but one of our experiments, burying bed elements that provide roughness and bed complexity in favour of the mobile bed surface of the migrating bedload (Fig. 5). Additionally, the area of channel bed that is buried expands downstream as the sediment input disperses (Fig. 5), protecting the bed from erosion. The dispersive nature of the sediment evacuation has important implications for the long-term evolution of the channel, as the rate of bedrock erosion is reduced to zero for the duration that the bed is protected. Bedrock erosion sets the pace of wider landscape evolution through the base level control on hillslope-channel coupling (e.g., Korup and Schlunegger, 2007; Norton et al., 2008). If the channel bed is protected, it would be expected that hillslope processes driven by undermining of the base by channel erosion would also cease. However, if the bed is protected from vertical channel incision, then bedload impacts will be focused on the channel sides, potentially driving lateral channel

widening (e.g., Gilbert, 1877; Fuller et al., 2016; Li et al., 2020), which may also alter the base-level control on hillslope evolution. Usually, catchment-wide erosion rates derived from geochemical techniques, such as cosmogenic radionuclide dating, are assumed to give average background erosion rates, with effects of stochastic sediment inputs buffered in large catchments (discussed in Dingle et al., 2018). Although no direct prediction between the spatial pattern and temporal duration of sediment evacuation from a naturally occurring landslide in any particular channel can be made from the experiments, it can be argued that the experimental behaviour can inform the understanding of natural settings (Paola et al., 2009; Baynes et al., 2018b). Here, we demonstrate that bed protection following sudden sediment inputs (i.e., landslide material that may be delivered to the channel by earthquakes or large storms), can be sustained because of the dispersive nature of the sediment evacuation and that the sediment transport rate returns to low values before the pile has been fully removed (Figs. 6 and 7). This potentially could leave a lasting legacy, depending on the natural characteristics of the setting, by reducing the local erosion rate and generating a spatially variable pattern of erosion within the catchment. We therefore suggest that understanding the patterns and rate of sediment transport following discrete sediment inputs is critical for developing the understanding of the complexities of landscape evolution processes, over both short and long timescales.

5. Conclusion

Here, we demonstrate that the rate and pattern of dispersive sediment evacuation from discrete input in a bedrock constrained channel is controlled predominantly by interactions between the sediment mass and the flow. Where the sediment volume is large enough, local flow hydraulics, such as a backwater effect inducing a local flow acceleration, can be altered and enhance the rate of sediment transport. These local processes can have an impact on the short-term and long-term channel dynamics, as rapid aggradation occurs downstream of the input location, acting to protect the bed from erosion for a sustained period of time that may impact wider variability in landscape evolution through a disruption to hillslope-channel

coupling processes and periodic switching on and off of erosion in specific locations. Further investigation of interactions between hydraulic and geomorphic processes are required in order to fully understand channel response to extreme perturbations such as sediment inputs from landsliding.

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