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## The Impact of Inter-flood Duration on Non-Cohesive Sediment Bed Stability

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45 19 **Short Title: Inter- flood duration and bed stability**  
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## ABSTRACT

Limited field and flume data suggests that both uniform and graded beds appear to progressively stabilise when subjected to inter flood flows as characterised by the absence of active bedload transport. Previous work has shown that the degree of bed stabilization scales with duration of inter-flood flow, however, the sensitivity of this response to bed surface grain size distribution has not been explored. This paper presents the first detailed comparison of the dependence of graded bed stability on inter-flood flow duration. Sixty discrete experiments, including repetitions, were undertaken using three grain size distributions of identical  $D_{50}$  (4.8mm); near-uniform ( $\sigma_g = 1.13$ ), unimodal ( $\sigma_g = 1.63$ ) and bimodal ( $\sigma_g = 2.08$ ). Each bed was conditioned for between 0 (benchmark) and 960 minutes by an antecedent shear stress below the entrainment threshold of the bed ( $\tau_{c50}^*$ ). The degree of bed stabilisation was determined by measuring changes to critical entrainment thresholds and bedload flux characteristics.

Results show that (i) increasing inter-flood duration from 0 to 960 minutes increases the average threshold shear stress of the  $D_{50}$  by up to 18%; (ii) bedload transport rates were reduced by up to 90% as inter-flood duration increased from 0 to 960 minutes; (iii) the rate of response to changes in inter-flood duration in both critical shear stress and bedload transport rate is nonlinear and is inversely proportional to antecedent duration; (iv) there is a grade dependent response to changes in critical shear stress where the magnitude of response in uniform beds is up to twice that of the graded beds; and (v) there is a grade dependent response to changes in bedload transport rate where the bimodal bed is most responsive in terms of the magnitude of change. These advances underpin the development of more accurate predictions of both entrainment thresholds and bedload flux timing and magnitude, as well as having implications for the management of environmental flow design.

**Key Words;** inter-flood duration, entrainment threshold, bedload flux, grain size distribution

## 1. INTRODUCTION

In non-cohesive sediment beds it is traditionally assumed that bed structure and hence, resistance to entrainment, is only capable of being modified when the applied shear stress exceeds the threshold for incipient motion (Gomez, 1983; Reid *et al.*, 1985; Church *et al.*, 1998; Powell *et al.*, 1999). This theory suggests that low, inter-flood flow periods will have no effect on bed stability and bed restructuring will only occur during flood events which result in active bedload transport modifying surface stability. However, field (Reid and Frostick, 1984; Reid *et al.*, 1985; Masteller *et al.*, 2019) and flume (Paphitis and Collins, 2005; Monteith and Pender, 2005; Haynes and Pender, 2007; Ockelford and Haynes, 2012; Masteller and Finnegan, 2017) data suggests that both uniform and graded beds appear to progressively stabilise even when subjected to the low shear stresses experienced during inter-flood flow periods.

Given that most commonly used sediment transport formulae use empirical relationships between bedload transport rate and flow intensity (Meyer-Peter & Müller, 1948; Bagnold, 1980; Ashmore, 1988; Parker, 1990; Zhang and McConnachie, 1994; Hassan and Woodsmith, 2004; Barry *et al.*, 2008; Recking, 2010), and tend to rely on the assumption that a single critical value of shear stress can be used to predict the onset of motion (e.g., Meyer-Peter and Müller, 1948; Engelund and Fredsøe 1975; Wong and Parker, 2006) small errors in shear stress estimations can cause significant errors in bedload transport rate estimations (Buffington and Montgomery, 1997; Recking *et al.*, 2012; Schneider *et al.*, 2015). Thus, understanding how periods of prolonged, inter-flood flow, affect the onset of

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3 80 motion could be used to improve the predictive capability of certain sediment  
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5 81 transport formulae.

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7  
8 82 These periods of antecedent flow have been termed 'stress history', which describes  
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10 83 a time-dependent 'memory' effect, where the combined effect of the duration and  
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12 84 magnitude of antecedent flows influences entrainment thresholds and bedload flux.

13  
14 85 This typically describes the low flow period between significant sediment-transporting  
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16 86 events, where sediment transport rates are negligible or of very low exhibit low  
17  
18 87 partial-transport conditions. Field data from the non-cohesive graded river bed of  
19  
20 88 Turkey Brook showed entrainment thresholds up to three times higher during  
21  
22 89 isolated flood events compared to floods which occurred with a shorter return period.

23  
24 90 Although not specifically quantified, it was hypothesised that shorter inter-flood  
25  
26 91 durations left the bed material comparatively loose and more susceptible to  
27  
28 92 entrainment in the subsequent flood event. As inter-flood duration increased more  
29  
30 93 advanced bed re-structuring left the bed more resistant to entrainment with lower  
31  
32 94 bedload transport rates in the subsequent flood (Reid and Frostick, 1984; Reid *et al.*,  
33  
34 95 1985). Pfeiffer and Finnegan (2018) observed that regional trends linked with  
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36 96 hydrological regime controlled the bed surface mobility discussed in terms of the  
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38 97 proportion of time a channel is above the conditions of threshold mobility; rivers  
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40 98 characterised as having longer periods of high flow during snowmelt periods have  
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42 99 higher relative mobility as compared to those characterised by abrupt brief flood  
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44 100 events with longer inter- flood durations.  
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52 101  
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54 102 Direct laboratory evidence provides support for the importance of stress history  
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56 103 effects. Paphitis and Collins (2005) studied the entrainment threshold for uniform  
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58 104 sand beds subjected to antecedent flow durations of up to 120 minutes. Their data  
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3 105 indicated the critical shear stress increased by up to 61% following exposure to  
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5 106 prolonged durations of antecedent flow. Similarly, Monteith and Pender (2005) and  
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7 107 Haynes and Pender (2007) exposed a bimodal sand-gravel mixture to increasing  
8  
9 108 antecedent conditioning flow durations; up to a 48% increase in critical bed shear  
10  
11 109 stress was noted as antecedent duration was increased from 0 to 5760 minutes.  
12  
13 110 Bedload flux has also been shown to be responsive to the duration of antecedent  
14  
15 111 flow where the same authors noted a 38% reduction in total bedload flux as  
16  
17 112 antecedent duration was increased. Using a unimodal gravel distribution and  
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19 113 conditioning flow periods between 1 and 200 minutes Masteller and Finnegan (2017)  
20  
21 114 noted an 86% reduction in bedload flux. This reduction was characterised by a  
22  
23 115 linear reduction in cumulative bedload flux in the period following antecedent flows  
24  
25 116 which was attributed to the re-organisation of the highest protruding grains on the  
26  
27 117 bed surface. However, they note the antecedent durations they used needed to be  
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29 118 increased to more accurately constrain the bedload flux relationships with  
30  
31 119 antecedent flow. This link between changes in bedload transport rate and bed  
32  
33 120 topography in response to periods of sub threshold flow was also quantified by  
34  
35 121 Ockelford and Haynes (2012). Using the same distributions and antecedent time  
36  
37 122 periods as reported herein, they quantified changes to bed topography pre and post  
38  
39 123 application of sub threshold flows. They noted that stress history response of the  
40  
41 124 bed surface was grade specific, where bed roughness decreased in uniform beds  
42  
43 125 but increased in graded beds in response to the application of the antecedent flow  
44  
45 126 period. This was reasoned to be due to the uniform bed having larger pore spaces  
46  
47 127 and a greater freedom to rearrange (Ockelford and Haynes, 2012). Grade dependent  
48  
49 128 bed stability, related to both entrainment thresholds and bedload flux, has also been  
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51 129 linked to the proportion of fines within a distribution controlling its stability response.  
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3 130 Frostick et al. (1984) suggested that past floods control the proportion of fine  
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5 131 sediment infiltrated into the coarser matrix, changing the sediment transport  
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7 132 conditions of future floods. Marquis and Roy (2012) noted that bed  
8  
9 133 dilation/contraction caused by fine sediment infiltration or winnowing in a gravel  
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11 134 framework related to bed conditions left by previous events, highlighting the role of  
12  
13 135 flood history on sediment transport in gravel-bed rivers.  
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19 137 Research to date has therefore shown that when beds are exposed to periods of  
20  
21 138 antecedent flow they appear to stabilise. This has been shown as both a change to  
22  
23 139 the critical shear stress and the magnitude and timing of bedload flux. However, the  
24  
25 140 differences in the methodologies used, the different timeframes employed and the  
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27 141 single grades investigated within the small body of previous stress history literature  
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29 142 precludes direct comparison of data. To date no studies have directly compared the  
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31 143 response of both entrainment threshold and bedload flux within the same set of  
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33 144 experiments and thus it has been difficult to explicitly link one with the other.  
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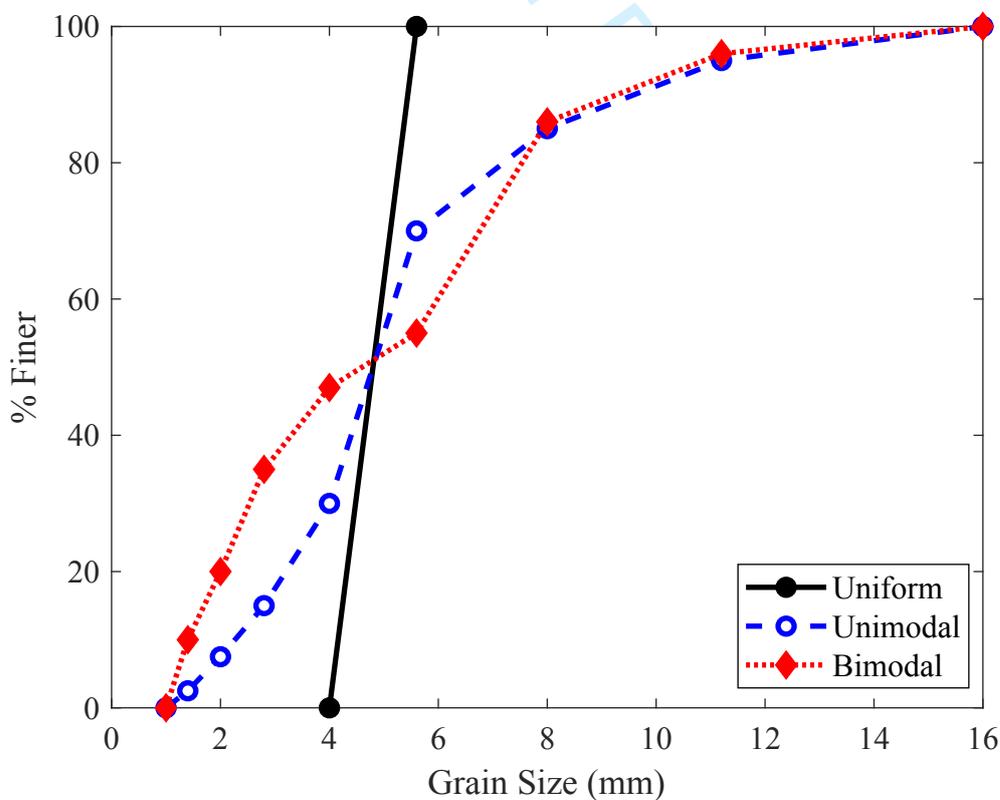
38  
39 146 This paper is the first to explore the relationship between the evolving critical shear  
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41 147 stress and bedload flux characteristics in response to varying inter-flood durations in  
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43 148 gravel bed rivers. We present a series of flume experiments that directly compares  
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45 149 three sediment grades of equivalent  $D_{50}$  and examines their response to changing  
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47 150 inter-flood duration. In so doing, we highlight a grade dependent response to inter-  
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49 151 flood duration which has implications for the deterministic definition of entrainment  
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51 152 and hence accurate prediction of the transition between river bed stability and  
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53 153 instability.  
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## 2. Methodology

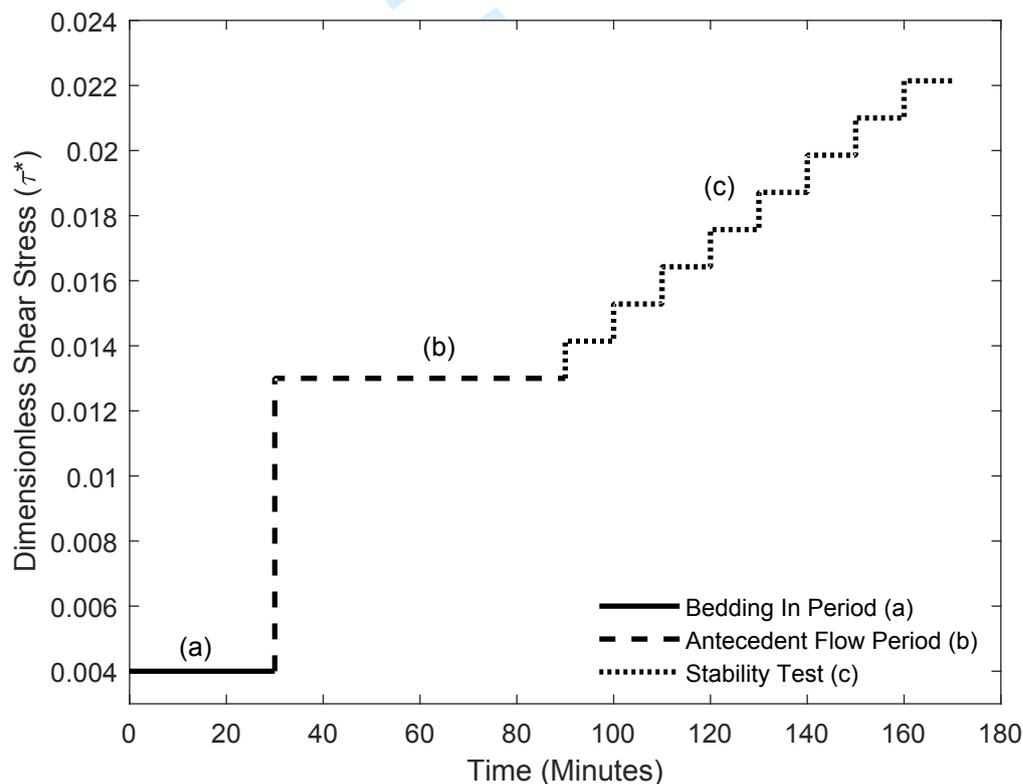
### 2.1 Experimental Procedure

Experiments were performed within a flow-recirculating, tilting flume (13m long × 1.8m wide × 0.35m deep), set to a bed slope of 1/200. Within the flume, a 2m length of coarse, immobile sediment located immediately downstream of the inlet (to help prevent scour and induce fully turbulent flow) preceded an 8m test length of mobile test sediments that was screeded to a 60mm depth (~4D<sub>max</sub> where D<sub>max</sub> is the maximum grain size of 16mm). Due to the low transport rates within experiments, no notable scour or water surface perturbations were discernible at the immobile-mobile bed transition.



**Figure 1:** Grain size distribution for the three test sediment grades. The is calculated according to  $\sigma_g = (D_{84}/D_{16})^{0.5}$

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4 170 Three grain size distributions of identical  $D_{50}$  (4.8mm); near-uniform ( $\sigma_g = 1.13$ ),  
5 171 unimodal ( $\sigma_g = 1.63$ ) and bimodal ( $\sigma_g = 2.08$ ) were generated using natural sub-  
6 172 rounded sand and gravel ranging from 1 to 16mm in diameter (Krumbein, 1941) with  
7 173 a density of  $2560\text{kg/m}^3$  (Figure 1). Sediments were dry sieved to obtain eight size  
8 174 fractions at standard  $\frac{1}{2}$  phi intervals and then recombined into the desired  
9 175 distributions with the  $D_{50}$  and  $D_{84}$  fractions painted for identification purposes (Table  
10 176 1). During each experiment three phases were run: (a) an initial bedding in period;  
11 177 (b) an antecedent flow period and; (c) a stability test (Figure 2).  
12 178



179  
180 **Figure 2:** Sample experimental hydrograph detailing the three stages of the  
181 experiment: (a) an initial bedding in period run for 30 minutes at  $\tau^* \sim 0.004$ ; (b) an  
182 antecedent flow period run at  $\tau^*_{c50}$  for 0, 60, 120, 240 or 960 minutes; and (c) a  
183 stability test run until  $\tau^*_{c50}$  is reached. The dimensionless shear stress values for  
184 each phase of each experiment are given in Table 1 with the example here given for  
185 the uniform bed exposed to 60 minutes of antecedent flow.  
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3 187 The bedding-in period employed a flow depth of 10 mm ( $\tau^* \sim 0.004$ ) for 30 minutes  
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5 188 duration; this was designed to remove any air pockets or unstable grains generated  
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7 189 within the bed screeding process. In line with the methodology of Ockelford and  
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10 190 Haynes (2012), flow was then increased to apply a shear stress equating to 50% of  
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12 191 the critical threshold for entrainment of the median grain size ( $\tau^*_{c50}$ ) benchmarked for  
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14 192 when no inter- flood flow was applied (i.e. 0 minutes of antecedent flow applied with  
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17 193  $\tau^*_{c50}$  values under these conditions given in Table 1). This was calculated using the  
18  
19 194 quantitative visual definition of threshold of Neill and Yalin (1969) in which the  
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21 195 number of grain detachments ( $m_i$ ) from a given bed area ( $A$ ) over a given time ( $t$ )  
22  
23 196 were counted, and the threshold determined according to Equation 1.

$$m_i = \frac{\varepsilon A t}{\sqrt{\frac{\rho D^5}{(\rho_s - \rho)g}}} \quad (\text{Eq. 1})$$

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32 198 where a lower limit of  $\varepsilon$  was defined by Neill and Yalin as  $1.0 \times 10^{-6}$ , and  $\rho_s$  and  $\rho$   
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34 199 are the sediment and fluid density respectively. The observation area ( $A$ ) was  
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36 200 located in the centre of the flume 11m downstream of the inlet, this was sized  $0.04\text{m}^2$   
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38 201 and the time of observation ( $t$ ) was set 180 seconds. Once the threshold number of  
39  
40 202 detachments was reached critical shear stress was estimated from the depth-slope  
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42 203 product corrected for the roughness effects of both the side walls and the bed  
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44 204 according to Manning's  $n$  and derived according to the methodology followed by  
45  
46 205 Monteith and Pender (2005). This second flow stage constituted the 'antecedent'  
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48 206 period, with applied dimensionless shear stress values of 0.016, 0.020, 0.019 of the  
49  
50 207  $D_{50}$  for the uniform, unimodal and bimodal beds respectively. Antecedent flows were  
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52 208 applied for either 0 (benchmark), 60, 120, 240 or 960 minutes. No sediment  
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54 209 entrainment was observed during this period and quasi-uniform sub-critical flow was  
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56 210 maintained throughout.

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5 212 A final flow stage, the 'stability test' was then applied in steps of increasing shear  
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7 213 stress. The shear stress was increased by approximately  $0.24 \text{ Nm}^{-2}$  during each  
8  
9 214 step which equated to a 5mm flow depth increase or a dimensionless shear stress  
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11 215 increase of 0.003 at each step. The stability test was run until the threshold criterion  
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13 216 derived from Neill and Yalin were satisfied. Flow steps were 600 second increments  
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15 217 which was sufficient to allow flow stabilisation and visual assessment, using the Yalin  
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17 218 criterion, of whether or not the new entrainment threshold had been reached. Since  
18  
19 219 the critical shear stress varied according to both grain size distribution and  
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21 220 antecedent duration the applied the stability test duration ranged from 50 to 80  
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23 221 minutes (Table 1). Each of these experiments was repeated three times. Reported  
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25 222 critical dimensionless shear stress values were calculated from an average of these  
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27 223 three experimental runs (first three experiments detailed for each experiment  
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29 224 combination in Table 1).

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37 226 Bedload data was collected from one additional, separate run for each of the  
38  
39 227 experiment combinations (the fourth experiment detailed in Table 1). During this  
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41 228 separate experiment, bedload data was collected at each step of the stability test,  
42  
43 229 where each step was 600 seconds long as per the entrainment threshold analysis  
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45 230 experiments. Flow was stopped once the critical entrainment threshold, as calculated  
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47 231 from the three previous entrainment threshold experiments, was reached. Mobile  
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49 232 sediment was collected in a trap located 12m downstream of the flume inlet with  
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51 233 sampling slot 75mm wide and of streamwise length 150mm. Bedload was collected  
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53 234 at each step of the stability test and collected material was air dried overnight and  
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55 235 sieved the individual size fractions. Bedload flux calculations were both integrated  
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3 236 over the entire stability test (Figure 4), as well as over the individual steps of the  
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5 237 stability test (Figure 5). Fractional transport rates were calculated from the total  
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7 238 bedload collected during the final step of the stability test which represents the  
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9 239 critical threshold conditions of the  $D_{50}$  (Figure 6). Sediment was not recirculated or  
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11 240 fed into the flume during the individual experiments but was returned to the flume  
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13 241 between experiments. The bed was fully mixed and re-screeded between  
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15 242 experiments to preclude inheritance effects from previous experiments. A total of 60  
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17 243 discrete experiments (including repeats) were undertaken (Table 1).  
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## 245 **2.2 Experimental Uncertainty**

246  
247 The experiments presented herein allow for the quantification of inter-flood duration  
248 effects on bed stability via the direct measurement of critical shear stress and  
249 bedload flux. However, methodological issues can introduce uncertainty into these  
250 measurements including: (i) inaccurate screeding such that the grain size distribution  
251 of the starting bed surface distribution varies between the different experiments; and,  
252 (ii) issues of subjectivity surrounding the derivation of threshold according to the  
253 Yalin Criterion. Given the  $D_{50}$  and  $D_{84}$  fractions were coloured, the effects of  
254 screeding were analysed using bed surface photographs taken after the initial  
255 screed. The numbers of grains belonging to each fraction were counted and the  
256  $D_{50}:D_{84}$  ratio calculated. Results indicate  $\leq 1.5\%$  variability between the screeded  
257 beds, providing confidence that any differences in bed composition stem solely from  
258 the active processes pertaining to the experiment itself. The subjectivity in use of the  
259 Yalin Criterion was minimised via data collection using a single operator.  
260 Comparison of multiple repeats of runs shows an average variability of 4.8% in terms

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3 261 of the calculated average critical dimensionless shear stress (Table 1; this is in line  
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5 262 with experimental error of similar laboratory studies (Piedra and Haynes, 2011). The  
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7 263 highest variability is typically associated with the shortest antecedent flow durations  
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9 264 where there is the greatest rate of change in the shear stress. As such the variability  
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11 265 in the average critical shear stress is never larger than the absolute change in shear  
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13 266 stress and does not therefore change the relationship between critical shear stress  
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15 267 and antecedent duration.  
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### 269 **3. RESULTS**

#### 271 **3.1 Inter-flood duration effects on entrainment threshold**

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273 The relationship between entrainment threshold and inter-flood duration is  
274 summarised by Figure 3. Under benchmark conditions with no inter-flood flow  
275 applied critical dimensionless shear stress shows a hierarchy to bed stability:  
276 unimodal (0.039): bimodal (0.033); uniform (0.031). After the application of the  
277 antecedent period there is a positive correlation with between the antecedent  
278 duration and dimensionless critical shear stress for all three grain size distributions.  
279 However, the magnitude of the increase in critical shear stress compared to the  
280 benchmark experiments is grade specific: near uniform (+18%) > bimodal (+12%)>  
281 unimodal (+9%).  
282

283 There is also an apparent difference between the rate of change in critical  
284 dimensionless shear stress in response to the applied antecedent flow. In order to  
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3 285 quantify the rate of change, parametric curves have been applied to the entrainment  
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5 286 threshold data. The fitted curves used herein are distinct from the only other  
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7 287 previous attempt to model growth of Paphitis and Collins (2005) whose 'exposure  
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9 288 correction' described logarithmic growth of their entrainment threshold function in  
10  
11 289 response to increasing inter-flood durations. Whilst their mathematical form correctly  
12  
13 290 describes progressive slowing of growth of inter-flood duration effects over  
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15 291 lengthening timeframes, it holds an implicit assumption of unbounded growth as time  
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17 292 tends towards infinity; i.e. if left for a prolonged period of time, the bed will keep  
18  
19 293 gaining in stability. As a sediment bed cannot become infinitely stressed, such a  
20  
21 294 logarithmic description is inaccurate; rather, it must tend to a limiting value  
22  
23 295 commensurate with the stability maxima of the bed. Two alternative mathematical  
24  
25 296 forms are, therefore, considered which both start and tend to finite values. Such  
26  
27 297 parametric curves have been used in ecological modelling (Noy-Meir, 1978) and in  
28  
29 298 enzyme kinetics (Michaelis and Menten, 1913) to describe similar rates of change  
30  
31 299 characterised by an initially linear increases which slows asymptotically towards  
32  
33 300 some maximal value. The first is described by Equation 2 below with the fit  
34  
35 301 parameters given in Table 2.

$$302 \quad \tau_c = \tau_{\max} - (\tau_{\max} - \tau_0)e^{-kt} \quad (\text{Eq. 2})$$

303 where  $\tau_c$  represents the critical dimensionless shear stress,  $t$  represents antecedent  
304 duration (minutes),  $\tau_{\max}$  is the maximal critical dimensionless shear stress,  $\tau_0$  gives the  
305 initial critical dimensionless shear stress and  $k$  is a free parameter (units mins<sup>-1</sup>)  
306 controlling how quickly  $\tau_c$  increases. This model assumes that there is a maximum  
307 possible stress and that the difference between the current stress and the maximum  
308 stress decreases exponentially.

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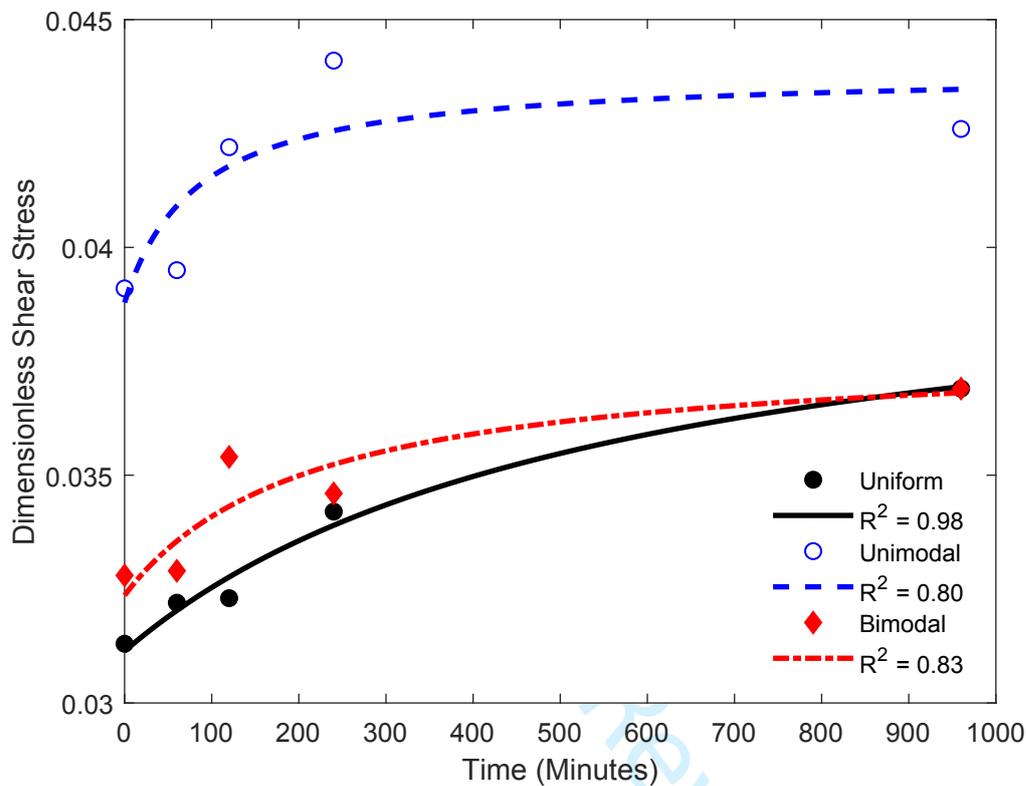
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3 310 The alternative model is described by Equation 3 with the fit parameters given in  
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5 311 Table 3:

$$312 \quad \tau_c = \tau_0 + t \left( \frac{\tau_{\max} - \tau_0}{t + t_{1/2}} \right) \quad (\text{Eq. 3})$$

13  
14 313 where  $\tau_c$  represents the critical dimensionless shear stress,  $t$  represents antecedent  
15  
16 314 duration (minutes),  $\tau_{\max}$  is the maximal critical dimensionless shear stress,  $\tau_0$  gives  
17  
18 315 the initial critical dimensionless shear stress and  $t_{1/2}$  is the time until half the maximal  
19  
20 316 shear stress has been reached (minutes). Thus, both Eq. 2 and Eq. 3 assume that  
21  
22 317 when  $t = 0$  then  $\tau_c = \tau_0$ ; when  $t \rightarrow \infty$  then  $\tau_c \rightarrow \tau_{\max}$ . The best fit models were selected  
23  
24 318 based on minimising the squared error between the model and the observed data  
25  
26 319 points.

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31 320  
32  
33 321 The  $R^2$ , RSME and SSE data are similar for both model fits and describe the data  
34  
35 322 well (Tables 2 and 3); the fits derived from Equation 2 are shown in Figure 3 given  
36  
37 323 the greater model skill and are described below. As reported, the parametric curve  
38  
39 324 indicates the uniform bed to be the most responsive to the effects of antecedent flow  
40  
41 325 duration and the unimodal the least (Figure 3, Table 2). The model indicates that the  
42  
43 326 rate of increase in critical dimensionless shear stress in response to increased inter-  
44  
45 327 flood duration varies between distributions as indicated by the time to half-life. The  
46  
47 328 unimodal bed has the greatest rate of response to inter-flood flows where the time to  
48  
49 329 half-life occurs within 74 minutes. This is compared to the bimodal and uniform beds  
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51 330 which take approximately twice and three times as long respectively. However, both  
52  
53 331 models predict that if antecedent duration continues to increase there will be very  
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332 little further stability gains; there will be a further percentage increase in stability of  
 333 5%, 2% and 1% for the uniform, unimodal and bimodal beds respectively.

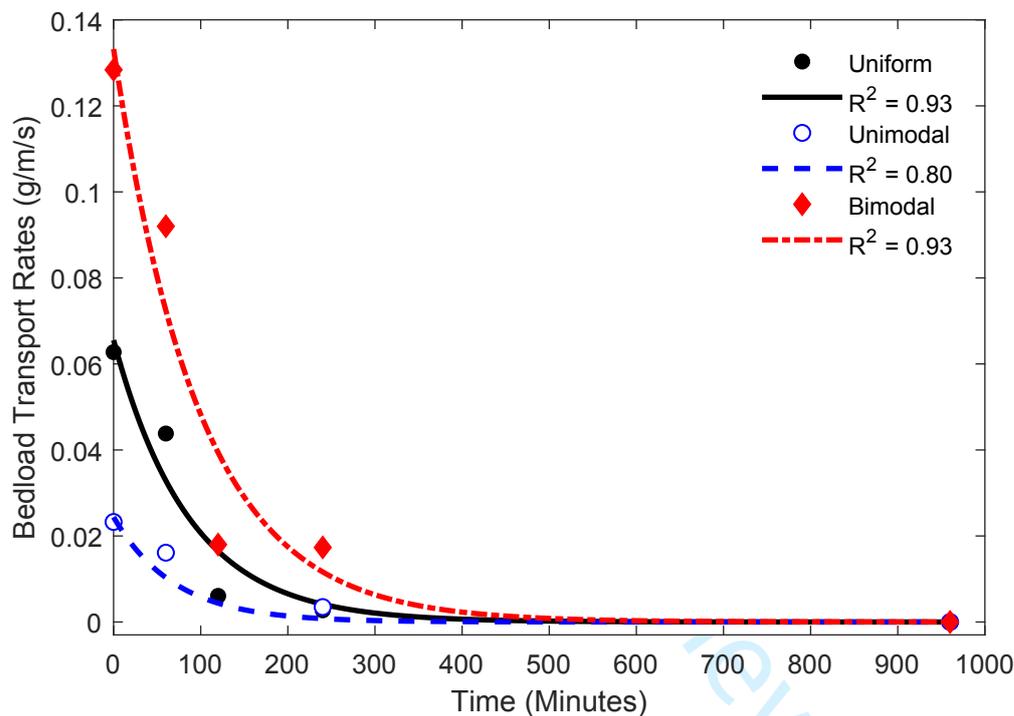


336 **Figure 3:** The relationship between antecedent duration, average critical  
 337 dimensionless shear stress and grain size distribution with fits plotted derived  
 338 according to Equation 2.

### 341 3.2 Inter-flood duration effects on bedload transport rate and characteristics

343 Both the magnitude and rate of response to the applied antecedent flow is grade  
 344 dependent. Given most sediment transport formulae rely on the use of a single  
 345 critical value of shear stress (e.g., Meyer-Peter and Müller, 1948; Engelund and  
 346 Fredsøe 1975; Wong and Parker, 2006) understanding how periods of prolonged,  
 347 inter-flood flow affect the onset of motion could be used to reduce the uncertainty in

these. Previous research has linked changes to entrainment thresholds in response to periods of sub threshold flow with changes to the magnitude and rate of bedload flux (Haynes and Pender, 2007; Masteller and Finnegan, 2017). As such, transport rate and fractional analysis of the bedload transported during the stability test was undertaken to provide insight into the links between changes to entrainment thresholds and the subsequent bedload flux characteristics.



**Figure 4:** Inter-flood duration relationships with bedload transport rate, including the fitted exponential decay function of form  $\Sigma Q_{bi} = \Sigma Q_{bi0} + (\Sigma Q_{bi\infty} - \Sigma Q_{bi0})e^{-kt}$  with  $R^2$  values of 0.93, 0.80 and 0.93 for the uniform, unimodal and bimodal beds respectively.

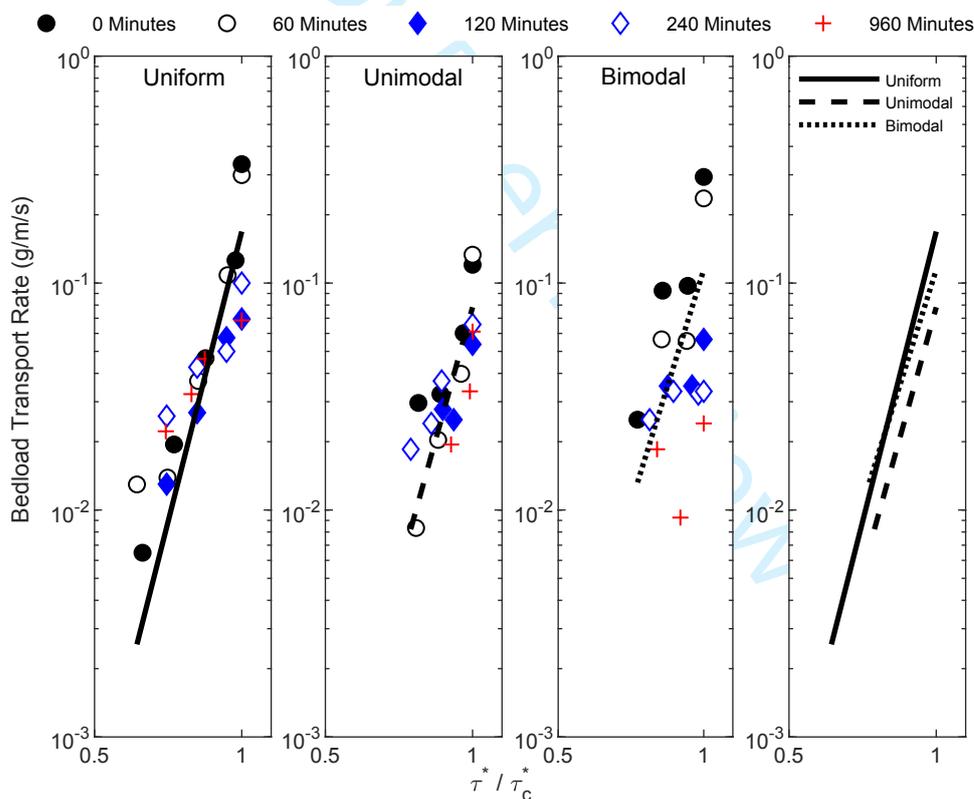
Following 960 minutes of antecedent conditioning, bedload transport rates were reduced by 91% for bimodal beds, 80% for near uniform beds, and 60% for unimodal beds (Figure 4, Table 4). The relationship between antecedent duration and bedload transport rate can be described by an exponential decay, however, akin to the entrainment threshold data, the rate of change is grade sensitive as indicated by the

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3 365 half life value. The unimodal bed has the most rapid rate of decline with a half-life  
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5 366 time of approximately 48 minutes compared to the uniform and bimodal beds which  
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7 367 have half live times of 60 and 68 minutes respectively. Further, data indicates that  
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9 368 rate of reduction is linked with the predicted minimal transport rate value derived in  
10  
11 369 Table 4. Specifically, the unimodal bed decays the fastest but has a higher overall  
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13 370 predicted minimal transport rate as compared to the bimodal bed which decays over  
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15 371 the longest time period but decays to a lower minimal transport rate, as given in  
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17 372 Table 4.  
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24 374 In addition to reported relationships between inter-flood duration and bedload flux,  
25  
26 375 previous data has indicated that prolonged periods of sub threshold flow also have  
27  
28 376 the potential to delay to the onset of entrainment in the following flood (Reid and  
29  
30 377 Frostick, 1984). The first three subplots of Figure 5 plot  $\frac{\tau^*}{\tau_c^*}$  at each step of the  
31  
32 378 stability test as a function of the bedload transport rate for the same step of the  
33  
34 379 stability test. The fitted trend line given in each of the subplots combines all of the  
35  
36 380 data for each bed and collapses them onto a single straight line using a least-square  
37  
38 381 error fitting approach; the power law fitted follows that of previous studies (Parker,  
39  
40 382 1990; Wilcock and Crowe, 2003; Recking 2010; Piedra, 2010) applicable to ranges  
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42 383 of  $\frac{\tau^*}{\tau_c^*} < 1.3$ . The final subplot of Figure 5 directly compares the trend lines derived for  
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44 384 each sediment bed.  
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53 386 For all three grain size distributions, there is the expected positive correlation  
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55 387 between dimensionless shear stress and total load such that increased time into the  
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57 388 stability test is correlated with an increase in transported load for each step of the  
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3 389 stability test. An inverse relationship is also noted between the antecedent duration  
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5 390 and transported load in each step of the stability test whereby a decrease in total  
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7 391 load is correlated to an increase in antecedent duration. Finally, there is an offset  
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10 392 noted on the abscissa in the two graded beds such that transport does not  
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12 393 commence until later in the stability test (i.e. at higher shear stresses) as antecedent  
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14 394 duration is increased; this is particularly noted within the bimodal bed. This suggests  
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16 395 that the mechanisms responsible for stabilising the bed are different between the  
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18 396 uniform and graded beds.  
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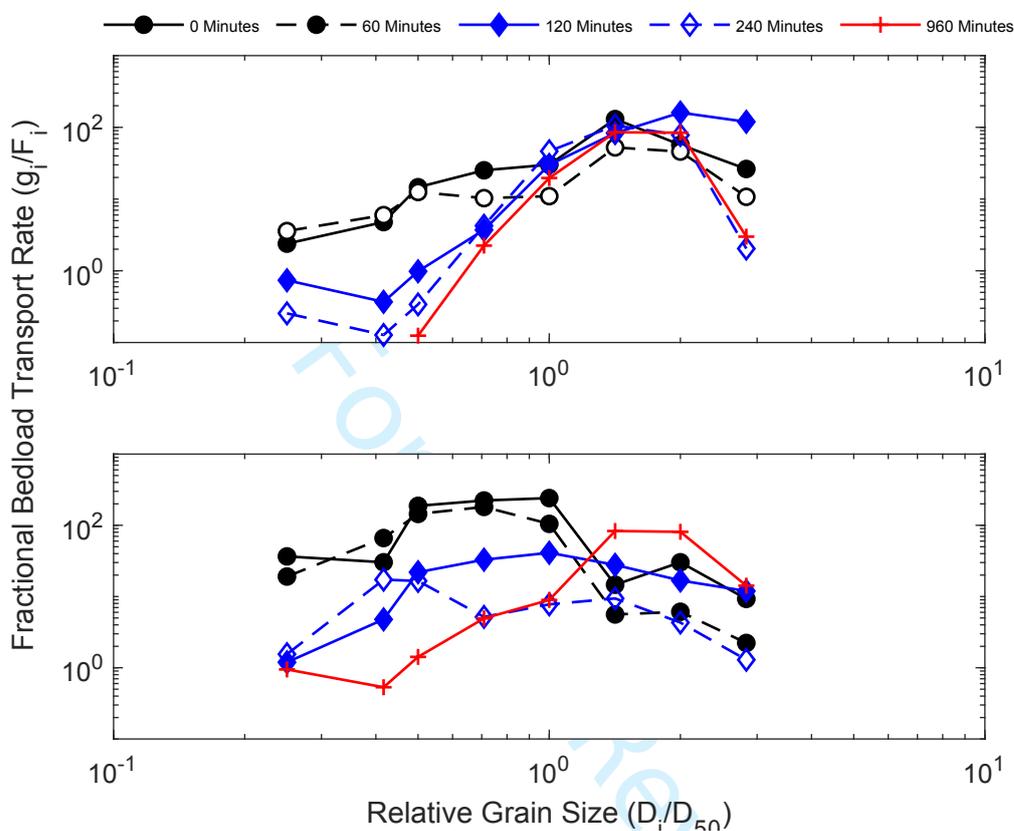
399 **Figure 5:** Relationship between  $\frac{\tau^*}{\tau_c^*}$  at each step of the stability test as a function of  
400 the bedload transport rate for the same step of the stability test for the uniform,  
401 unimodal and bimodal beds respectively (subplots 1-3). The fitted trend line given in  
402 each of the subplots combines all of the data for each bed and collapses them onto a  
403 single straight line. The final subplot directly compares the trend lines derived for  
404 each sediment bed. The exponent of the power law relationship is 11.06, 10.09 and  
405 8.77 and the  $R_2$  values of those fits are 0.63, 0.75 and 0.29 for the uniform, unimodal  
406 and bimodal beds respectively.

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6 409 When the data is scaled in terms of excess shear stress ( $\frac{\tau^*}{\tau_c^*}$ ), the data appear to  
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9 410 collapse onto a single relationship. However, it is also clear that whilst the data  
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11 411 seems to more readily collapse for the uniform and unimodal beds the bimodal bed  
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13 412 exhibits significant scatter and the data derived from the longest inter-flood durations  
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15 413 (240 and 960 minutes) is not described well by the trend line.  
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20 415 Given the different rate and magnitude of response of the graded beds to increasing  
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22 416 inter-flood durations the following section uses fractional bedload transport patterns  
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24 417 to analyse the stability-mobility patterns of individual fractions within each bed in  
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26 418 order elucidate upon the underpinning bed stabilisation processes (Figure 6). Given  
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28 419 that the stability test was curtailed at the threshold for  $D_{50}$ , if size selective  
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30 420 entrainment is prominent no grains greater than the  $D_{50}$  should be moving ( $g_i/F_i \neq 1$ );  
31  
32 421 however, if grains greater than the  $D_{50}$  are moving then there is a tendency towards  
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34 422 equal mobility conditions ( $g_i/F_i = 1$ ).  
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41 424 The unimodal bed is characterised by equal mobility conditions under 0 and 60  
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43 425 minutes of antecedent flow. However as antecedent duration is increased beyond  
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45 426 that the bedload response becomes more strongly size selective in the coarse and  
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47 427 fine end members of the distribution such that these grains stabilise and leave the  
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49 428 middle fractions of the transported distribution as being comparatively mobile. In  
50  
51 429 comparison, under benchmark conditions, the bimodal bed is characterised by equal  
52  
53 430 mobility particularly for in the grain fractions containing and surrounding the median  
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55 431 grain size. As antecedent duration is increased although size selective transport  
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57 432 conditions begin to develop in the finest members of distribution the degree of size  
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selectivity which develops is not as strong as that which develops in the unimodal bed.



**Figure 6:** Fractional bedload transport rate of the unimodal (top plot) and bimodal bed (bottom plot) scaled by the abundance of each size ( $g_i$ ) in the bulk mix ( $F_i$ ) plotted against dimensionless grain size for antecedent durations 0-960mins. Given the stability test was stopped once the critical entrainment threshold of the  $D_{50}$  had been reached the data in this figure represent bedload which was collected during the last step of the stability test under these conditions.

## 4. DISCUSSION

### 4.1 Effect of inter-flood duration on bed stability

This paper has provided the first direct quantification of the response of different grain size distributions to inter-flood duration effects in terms of both entrainment threshold and bedload flux response. Analysis shows that all three grain size distributions responded to changes in antecedent duration. This is supportive of field

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3 450 (e.g. Reid and Frostick, 1984; Reid *et al.*, 1985; Willetts *et al.*, 1987; Oldmeadow and  
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5 451 Church, 2006; Pfeiffer and Finnegan, 2018) and laboratory (Paphitis and Collins,  
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7 452 2005; Monteith and Pender, 2005; Haynes and Pender, 2007; Masteller and  
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9 453 Finnegan, 2016) data which have both indirectly and directly suggested that  
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11 454 antecedency may be an important control on entrainment thresholds and bedload  
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13 455 flux.  
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19 457 Critical shear stress of the median grain size increases by up to +18% after being  
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21 458 exposed 960 minutes of antecedent flow, with the uniform grain size distribution  
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23 459 being the most responsive and the unimodal least responsive. The changes to  
24  
25 460 entrainment threshold in this study are under half that noted by Paphitis and Collins  
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27 461 (2005) and Haynes and Pender (2007) who observed up to a 56% and 46% increase  
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29 462 in critical bed shear stress respectively. The sediment beds reported by Paphitis and  
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31 463 Collins (2005) were finer (0.19 to 0.77mm sand) and there were differences in the  
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33 464 bed preparation techniques between studies which is likely to explain the differences  
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35 465 in the observed results; screeded beds (this study; Church, 1978; Cooper and Tait,  
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37 466 2008) form more resistant initial structures than those formed under still water  
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39 467 conditions (Paphitis and Collins, 2005). Although Haynes and Pender (2007) used  
40  
41 468 the same bimodal mixture as this current paper the timescales were significantly  
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43 469 longer than those reported herein and they also used a discharge was above-  
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45 470 threshold for the  $D_{50}$ .  
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53 472 The changes to entrainment threshold have been linked with bed reorganisation  
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55 473 during the sub threshold flow period (Hassan and Church, 2000; Haynes and  
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57 474 Pender, 2007; Ockelford and Haynes, 2012; Masteller and Finnegan, 2016). Given  
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3 475 that the applied antecedent flow in this paper was set at  $\tau_{c50}^*$ , active, large scale  
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5 476 processes of reorganisation as a result of grain entrainment are unlikely and thus  
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7 477 significant bed surface composition change should not occur (Sutherland, 1991;  
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9 478 Hassan and Church, 2000; Whiting and King, 2003). Instead inter-flood processes  
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11 479 appear to increase the importance of passive, grain scale processes which, in turn,  
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13 480 alter a beds resistance to entrainment via a change to surface texture (Dietrich *et al.*,  
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15 481 1989; Kirchner *et al.*, 1990; Fenton and Abbott, 1997; Schmeeckle and Nelson,  
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17 482 2003; Ockelford and Haynes, 2012). Specifically, Masteller and Finnegan (2016)  
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19 483 observe that the largest change in the bed surface elevation distribution occurs in the  
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21 484 tails of the distribution and this change is positively correlated to antecedent flow  
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23 485 duration. They attribute this to pivoting of unstable grains into more stable positions,  
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25 486 the filling of pockets left by displaced grains and the oscillation, reorientation and  
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27 487 reduced relative protrusion of grains which occur throughout the antecedent flow  
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29 488 period.  
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38 490 Results from this paper have also shown that grain size distribution is a key control  
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40 491 on the magnitude of response to inter-flood duration in terms of entrainment  
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42 492 threshold response; direct comparison shows uniform beds to be up to twice as  
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44 493 responsive as graded beds. Ockelford and Haynes, (2012) suggest the differences  
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46 494 in response between the uniform and graded beds is related to changes in bed  
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48 495 roughness which develop during the antecedent period. Using bed surface  
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50 496 topography data collected pre and post antecedent flows they observed a 12%  
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52 497 decrease in roughness of uniform beds as compared to a 15% and 40% increase in  
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54 498 roughness of unimodal and bimodal beds respectively. In the uniform bed the  
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56 499 decrease in bed roughness reduced the relative depth of localised pores and hence  
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3 500 reduced both the shear stress magnitude and variability across the bed surface (Li  
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5 501 and Komar, 1986; Kirchner *et al.*, 1990; Rollinson, 2006). Within the graded beds,  
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7 502 the magnitude of the inter-flood flow response is controlled by the rearrangement of  
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9 503 the bed which is permitted due the range of grain sizes. During the sub threshold  
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11 504 flows vertical winnowing of the finer grains serves to consolidate the framework  
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13 505 gravels and hence increase bed stability (Frostick *et al.*, 1984; Reid *et al.*, 1985;  
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15 506 Carling *et al.*, 1992; Allan and Frostick, 1999; Marion *et al.*, 2003; Ockelford and  
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17 507 Haynes, 2012).  
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24 509 However, data in this paper also indicates that the degree of response to increasing  
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26 510 inter-flood duration in graded beds is strongly linked to the percentage of fines in the  
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28 511 distribution such that the bimodal bed, which has the highest proportion of fines  
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30 512 (20% of the distribution between 1-2mm compared to 7.5% in the unimodal bed)  
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32 513 responds to a greater degree than the unimodal bed. It is thought that the process of  
33  
34 514 consolidation of the beds due to the infiltration of fines as described above drives this  
35  
36 515 response. This is in agreement with Cooper *et al.*, (2009), who assessed the  
37  
38 516 resistance to bedload transport of unimodal and bimodal deposits of similar  $D_{50}$  by  
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40 517 linking stability with the organisation of the surface deposits. Initially, their bimodal  
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42 518 beds had a higher degree of mobility due to a higher proportion of the fluid force  
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44 519 being carried by the finer grain fractions. However, as flow periods were increased,  
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46 520 a higher proportion of the fluid force was carried by the larger grains due to grain  
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48 521 sheltering (Schmeeckle and Nelson, 2003) and the development of grain structures  
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50 522 (Hassan and Church, 2000), such that the differences in the stability of the two beds  
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52 523 decreased.  
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3 525 The greatest rate of change in critical shear occurs for the shortest antecedent  
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5 526 durations which is in line with previous stress history research Paphitis and Collins,  
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7 527 2005; Monteith and Pender, 2005; Haynes and Pender, 2007; Ockelford and Haynes  
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9 528 2012; Masteller and Finnegan, 2016. However, interestingly the rate of change is  
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11 529 also grade specific where the unimodal bed responds to increasing inter-flood flow  
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13 530 duration is 2.5 times faster than the bimodal bed and 3 times as fast as the uniform  
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15 531 bed. Given the applied antecedent shear stress is set at  $\tau_{c50}^*$ , it seems logical that  
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17 532 the uniform bed is less mobile under antecedent flows hence, it will take longer to  
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19 533 respond but once the bed has reorganised it will not be able to rearrange any further.  
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21 534 Within the graded beds the rearrangement processes responsible for stabilising the  
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23 535 bed will occur rapidly during the onset of the higher discharge conditions  
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25 536 experienced during the antecedent flow period but once the fines have winnowed  
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27 537 through the surface and consolidated the bed very little further rearrangement will  
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29 538 occur (Ockelford and Haynes 2012).  
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38 540 In relation to the bedload response to inter-flood duration up to a 91% reduction in  
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40 541 the bedload transport rate after 960 minutes of applied antecedent flow is observed.  
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42 542 Akin to the response of critical shear stress, the reduction in bedload transport rate  
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44 543 with increasing antecedent duration is nonlinear. This agrees with the previous  
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46 544 results of Haynes and Pender (2007) who also note an exponential decline in  
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48 545 transport rates as antecedent duration is increased. Whilst Masteller and Finnegan  
49  
50 546 (2016) fitted a linear model to their cumulative bedload flux data as a function of  
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52 547 increased conditioning flow, they do state that an exponential decline function also  
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54 548 fitted their data, albeit with lower model skill. Thus, these results are consistent with  
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56 549 an overall reduction in grain mobility, implying an increase in critical Shield's stress  
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3 550 with increased conditioning time. Such behaviour is similar to that of many  
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5 551 degradation experiments (Tait *et al.*, 1992; Proffitt and Sutherland, 1983; Pender *et*  
6  
7 552 *al.*, 2001). Haynes and Pender (2007) attributed this decay to the progressive  
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9 553 stabilisation of larger areas of the bed surface such that grains became unavailable  
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11 554 for transport. The decay to a constant flux even under the low shear stresses is  
12  
13 555 possible due to turbulent fluctuations in the flow (e.g. Grass, 1970; Paintal, 1971;  
14  
15 556 Graf and Pазis, 1977; Lavelle and Mofjeld, 1987; McEwan *et al.*, 2004; Paphitis and  
16  
17 557 Collins, 2005; Bottacin *et al.*, 2008) or to the fact that a population of high protruding  
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19 558 grains is always available for transport (Masteller and Finnegan, 2016).  
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26 560 There is an observable delay to the onset of entrainment in periods of unsteady flow  
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28 561 subsequent to sub threshold flow periods. During floods a hysteresis loops often  
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30 562 develop in sediment flux measurements, whereby different magnitudes of bedload  
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32 563 flux are produced on the rising and falling limbs of hydrographs for the same flow  
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34 564 magnitude (Reid *et al.*, 1985; Church *et al.*, 1998; Hassan *et al.*, 2006; Waters and  
35  
36 565 Curran, 2015; Mao, 2018). These studies have proved an intrinsic link between bed  
37  
38 566 structure characteristics and the total load transported (Reid *et al.*, 1985; Reid *et al.*,  
39  
40 567 1997), which serve to alter entrainment thresholds and hence bedload flux. Although  
41  
42 568 this paper has not run a full hydrograph after the sub threshold flow period, the  
43  
44 569 theoretical underpinnings behind the links between stability, surface structure and  
45  
46 570 sediment flux are transferable. This is evidenced by the fact that not only does the  
47  
48 571 data in this paper show a an offset in the initiation of motion, but that the total loads  
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50 572 are also be reduced for comparable shear stresses of the unsteady flow as sub  
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52 573 threshold flow duration is increased.  
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3 575 Although the bedload flux data appears to collapse readily for the uniform and  
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5 576 unimodal beds the bedload transport rates associated with the longest inter-flood  
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7 577 durations in the bimodal bed are not well described. This is supported by Piedra  
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9 578 (2010) who analysed five commonly employed sediment transport equations and  
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12 579 found that the rapid increase in transport rates with shear stress for approximately  $\frac{\tau^*}{\tau_c^*}$   
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15  
16 580  $< 1.3$  and the drastic reduction of the rate of increase of sediment transport rate at  $\frac{\tau^*}{\tau_c^*}$   
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18  
19 581  $> 1.3$  (Wiberg and Smith, 1989 Hassan and Woodsmith, 2004; Bathurst, 2007) did  
20  
21 582 not explain the relationships shown when sediment beds had been exposed to  
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23 583 prolonged periods of antecedent flow. Piedra related the deviation caused by the  
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25 584 effects of antecedent duration, as shown by the data herein, to stabilisation of the  
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28 585 bed surface and the delay to the onset of entrainment caused by bed surface  
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30 586 rearrangement. Neither factor are taken into account in commonly used transport  
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32 587 equations which derive critical entrainment thresholds purely based on bed grain  
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35 588 size distribution data and bed slope (Reid and Frostick, 1986; Gomez and Church,  
36  
37 589 1989; Wong 2003; Recking, 2010).

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42 591 A change in the fractional transport rates following the antecedent conditioning  
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44 592 phase is reported. Typically, fractional bedload rates would tend towards moving  
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46 593 from size selective transport patterns under low shear stress, partial transport  
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48 594 conditions to equal mobility conditions under high shear stress, full mobility  
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51 595 conditions (Wilcock and McArdell, 1997; Shvidchenko and Pender, 2000). Since the  
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53 596 stability test in this paper was run until  $\tau^*_{c50}$  it is assumed that the fractional mobility  
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55 597 patterns would be characterised by size selective entrainment owing to the partial  
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58 598 mobility conditions. This would be irrespective of the preceding applied antecedent  
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60 599 duration. In the unimodal bed there is a trend towards equal mobility in the

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3 600 intermediary size fractions with selective entrainment of the end members of the  
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5 601 distribution (Ashworth and Ferguson, 1989; Wilcock and Southard, 1988; Kuhnle,  
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7 602 1992; Wilcock and McArdell, 1993; Laronne *et al.*, 1994). However as antecedent  
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9 603 duration is increased the bedload response becomes more strongly size selective in  
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11 604 the coarse and fine end members of the distribution; as this typically goes hand-in-  
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13 605 hand with an increase in grain hiding the effect is on mobility of the middle fractions  
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15 606 of the transported distribution (Brayshaw *et al.*, 1983; Li and Komar, 1986; Dietrich *et*  
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17 607 *al.*, 1989; Fenton and Abbott, 1997). Conversely in the bimodal bed, under  
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19 608 benchmark conditions, the bimodal bed is characterised by equal mobility particularly  
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21 609 for in the grain fractions containing and surrounding the median grain size. As  
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23 610 antecedent duration is increased, size selectivity begins to develop, particularly in  
24  
25 611 the finest members of distribution which appear to have stabilised on the bed  
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27 612 surface. This leaves the coarsest fractions to be over represented in the bedload.  
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29 613 This suggests that there are significant hiding effects which develop in response to  
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31 614 increasing inter-flood durations and underpin the theory that it is the relative size  
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33 615 effects which drive the response to inter-flood duration (Jackson and Beschta, 1984;  
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35 616 Ikeda and Iseya, 1988; Wilcock, 1988).  
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## 618 **4.2 Implications**

619 A number of important implications for river flows emerge from our results.  
620 Increased bed stability in response to increased inter-flood duration manifests itself  
621 via increased critical shear stress which may preclude reliable estimates of bedload  
622 transport, as most predictive models reply on a specified critical shear stress (e.g.,  
623 Meyer-Peter and Müller, 1948; Engelund and Fredsøe 1975; Wong and Parker,  
624 2006). Despite numerous revisions to the Sheild's function, a single value of flow

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3 625 intensity at particle entrainment is not just a disputed concept (Lavelle and Mofjeld,  
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5 626 1987) but its value has been shown to depend on a range of particle parameters  
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8 627 such as shape, size distribution and armouring (Parker et al., 1982; Carsons and  
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10 628 Griffiths, 1985; Carling et al., 1992; Buffington and Montgomery, 1997; Church et al.,  
11  
12 629 1998). These observations of an evolving, or history-dependent critical shear stress  
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14 630 which is related to grain size distribution makes the transition towards gravel bed  
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16 631 instability and active sediment transport difficult to predict and could form the basis  
17  
18 632 for incorporating an inter flood-duration 'correction factor' into existing entrainment  
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20 633 equations.  
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26 635 In order to correct for the effects of inter-flood flows entrainment thresholds need to  
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28 636 be based on experimental data derived from beds which have been exposed to  
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30 637 antecedent flows. The relationship between bedload transport rate and excess  
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32 638 shear stress used herein can be described by a power law similar with similar  
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34 639 exponent values to that used by previous authors (Parker, 1990; Wilcock and Crowe,  
35  
36 640 2003; Recking 2010; Piedra, 2011). However, as supported by Piedra (2011) data  
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38 641 in this paper also indicates that there is no unique equation with fixed parameters  
39  
40 642 capable of describing bedload transport behaviour for gravel channels which have  
41  
42 643 been exposed to differing inter-flood flow periods. Further, given changes in bed  
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44 644 stability in response to inter-flood flow duration are grade sensitive our results  
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46 645 indicate the not only is predicting entrainment based on a single critical Shields value  
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48 646 inaccurate but also that the  $D_{50}$  may not be the best grain fraction from which to  
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50 647 estimate entrainment thresholds (MacKenzie et al, 2018). This study has shown that  
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52 648 the finest and coarsest fractions are most responsive to inter-flood flow duration and  
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54 649 hence more realistic entrainment models might consider using these fractions to  
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3 650 define bed stability (Carling, 1987,1988; Ashworth and Ferguson,1989; Eaton and  
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5 651 Church, 2004; Tamminga et al., 2015; Eaton et al., 2015; MacKenzie and Eaton,  
6  
7 652 2017).

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12 654 Increased pressure on water resources will require sophisticated environmental flow  
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14 655 guidelines to maintain habitat diversity, ensure ecosystem health and functioning,  
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16 656 and enable effective water resource management planning (Poff et al., 1997;  
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18 657 Tharme, 2003; 2010; Rolls & Arthington, 2014). Given managed flows are designed  
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20 658 to mimic natural flow regime and sediment dynamics, periods of prolonged low flow  
21  
22 659 prior to release will have a fundamentally different sediment transport response than  
23  
24 660 those with shorter low flow periods. Hence this research has significant implications  
25  
26 661 for the management and design of such flows (Lytle & Poff, 2004; Arthington et al.,  
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28 662 2006; Kiernan et al., 2012; Olden & Naiman, 2010; Poff and Schmidt, 2016).

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## 32 33 34 35 664 **5. CONCLUSION**

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37 665 Novel laboratory experiments in a recirculating flume have quantified the effects  
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39 666 between grain size distribution and inter-flood duration on gravel river bed stability.  
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41 667 Inter-flood duration effects have been shown to be ubiquitous regardless of surface  
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43 668 grain size distribution where direct entrainment threshold analysis shows that critical  
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45 669 shear stress of the median grain size increases by up +18% due to the applied inter-  
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47 670 flood duration of 960 minutes at  $\tau_{c50}^*$ . The magnitude of response is contingent upon  
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49 671 grain size distribution; uniform beds are more responsive as compared to the graded  
50  
51 672 beds. The effects of inter-flood duration on entrainment thresholds can be well  
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53 673 predicted using models which both start and tend to finite values such that when  $t =$   
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55 674 0 then  $\tau_c = \tau_0$ ; when  $t \rightarrow \infty$  then  $\tau_c \rightarrow \tau_{max}$ . Bedload transport rate has also been  
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3 675 shown to be responsive to inter-flood duration where up to a 91% reduction in  
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5 676 bedload was recorded for the longest antecedent flow periods. However, akin to the  
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8 677 entrainment threshold data there is also a grade dependent response which has  
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10 678 been attributed to the ability of the bed to rearrange into a more stable configuration  
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12 679 during the sub threshold flow periods. Changes in the transport pattern reflect this  
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14 680 stabilisation process where the percentage of fines within a distribution control the  
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17 681 extent to which equal mobility or size selective conditions are noted.  
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21 683 Results have implications for the prediction of entrainment thresholds, the accurate  
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23 684 prediction of bedload flux timing and magnitude and have implications for the  
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25 685 management of environmental flow design. However questions still remain as to  
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27 686 how antecedent shear stress magnitude may affect the stability gains and whether  
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29 687 there may be a threshold at which inter-flood flows may serve to destabilise the bed  
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31 688 surface. Further, an understanding of the interaction of the bed surface with the  
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33 689 overlying fluid flow regime with respect to the changes in the turbulent patterns  
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35 690 during inter-flood sub-threshold flows would also be a significant step forward in this  
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38 691 emerging research field.  
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Experiment Number	Distribution	Antecedent Flow Duration (Minutes)	Stability Test Duration (Minutes)	Critical Flow Depth (m)	Recorded Critical Dimensionless Shear Stress values	Average Critical Dimensionless Shear Stress
1,2,3,4	Near - Uniform	0	70	0.051 (0.025)	0.021, 0.019, 0.019	0.020 (0.013)
5,6,7,9		60	70	0.052	0.021, 0.02, 0.022	0.021
9,10,11,12		120	70	0.052	0.023, 0.021, 0.022	0.022
13,14,15,16		240	80	0.056	0.022, 0.021, 0.023	0.022
17,18,19,20		960	90	0.060	0.025, 0.022, 0.024	0.024
21,22,23,24	Unimodal	0	80	0.063 (0.032)	0.026, 0.024, 0.024	0.025 (0.010)
25,26,27,28		60	80	0.064	0.026, 0.025, 0.025	0.026
29,30,31,32		120	90	0.069	0.028, 0.027, 0.026	0.027
33,34,35,36		240	100	0.072	0.029, 0.028, 0.030	0.029
37,38,39,40		960	90	0.070	0.030, 0.029, 0.029	0.029
41,42,43,44	Bimodal	0	60	0.053 (0.030)	0.022, 0.019, 0.021	0.021 (0.012)
45,46,47,48		60	60	0.054	0.021, 0.02, 0.022	0.021
49,50,51,52		120	70	0.057	0.025, 0.021, 0.024	0.023
53,54,55,56		240	70	0.056	0.024, 0.022, 0.02	0.022
57,58,59,60		960	80	0.060	0.024, 0.025, 0.024	0.024

**Table 1;** Experimental information for all experiments detailing the length of the antecedent flow, the stability test duration, the critical flow depths and the recorded dimensionless shear stress values at the critical entrainment threshold for all experiments. Values in brackets for the critical flow depth represents the depth at  $T^*_{C_{50}}$  i.e. the flow depth which was applied during the antecedent flow period. Values in brackets for the average critical dimensionless shear stress represent the  $T^*_{C_{50}}$  values under benchmark conditions i.e. the shear stress which was applied during all of the antecedent flow periods calculated from where no antecedent flow is applied.

Bed Fit Parameters	Uniform	Unimodal	Bimodal
Maximal dimensionless shear stress	0.038	0.043	0.037
$k$ (Minutes <sup>-1</sup> )	0.003	0.010	0.004
Time to half saturation ( Minutes)	234	74	198
$R^2$	0.98	0.80	0.83
RMSE	0.0003	0.0013	0.0007
SSE	1.71e-07	1.59e-06	8.84e-07
% increase in dimensionless shear stress between 0-960 minutes	18	9	12
Predicted % increase in dimensionless shear stress between 0- and Max predicted	19	11	13

1043 **Table 2;** The parameters associated with the growth in shear stress over time  
 1044 according Equation 2

Bed Fit Parameters	Uniform	Unimodal	Bimodal
Maximal dimensionless shear stress	0.040	0.044	0.037
Half Saturation Constant (Minutes)	285	84	214
$R^2$	0.98	0.71	0.82
RMSE	0.0004	0.0017	0.0011
SSE	5.15E-07	2.27E-06	9.54E-07
% increase in dimensionless shear stress between 0-960 minutes	18	9	12
Predicted % increase in dimensionless shear stress between 0 and Max predicted	24	11	13

1046 **Table 3;** The parameters associated with the growth in shear stress over time  
 1047 according Equation 3.

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Bed Fit Parameters	Uniform	Unimodal	Bimodal
Minimal Bedload Transport rate (g/m/s)	0.015	0.018	0.012
$k$ (Minutes <sup>-1</sup> )	0.0115	0.0143	0.0102
Half Life (Minutes)	60.22	48.37	68.29
R <sup>2</sup>	0.93	0.80	0.93
RMSE	0.009	0.006	0.017
SSE	2.38e-04	1.04e-04	8.96e-04

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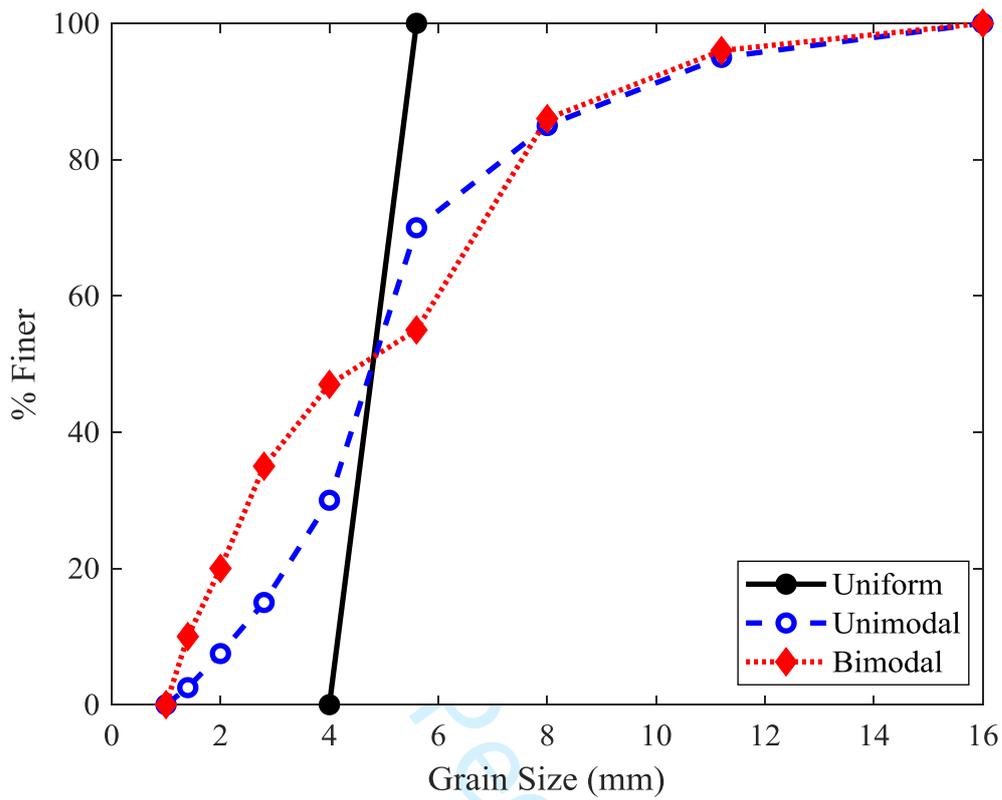
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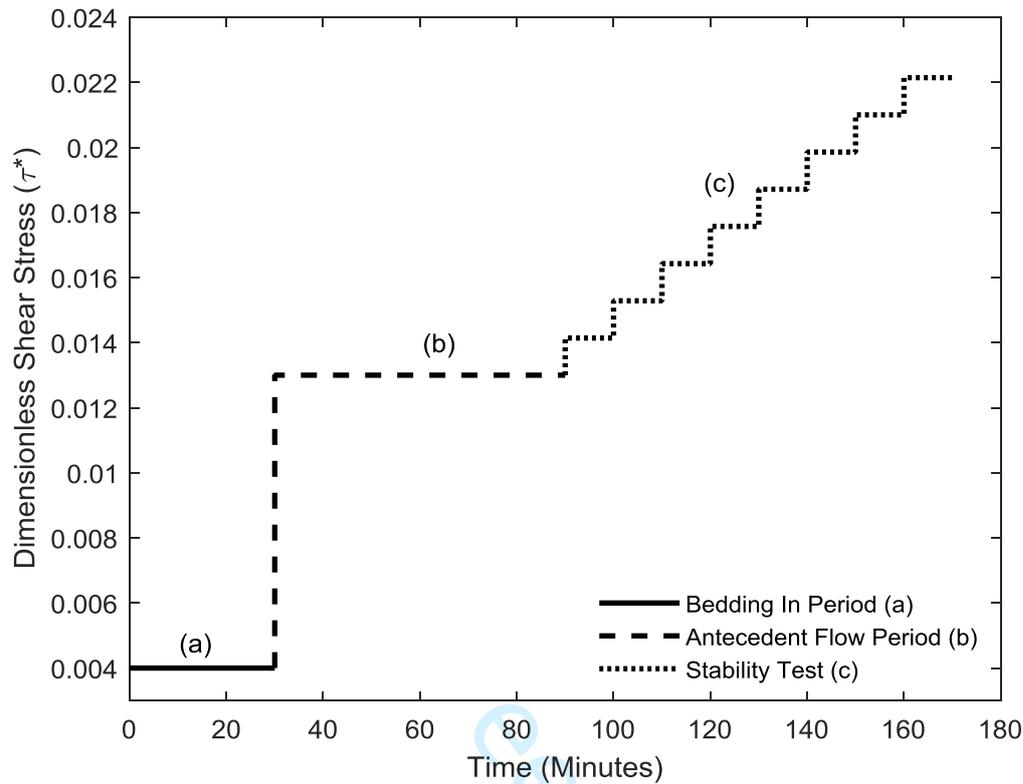
**Table 4;** The parameters associated with the decay in bedload transport over time according to an exponential decay function

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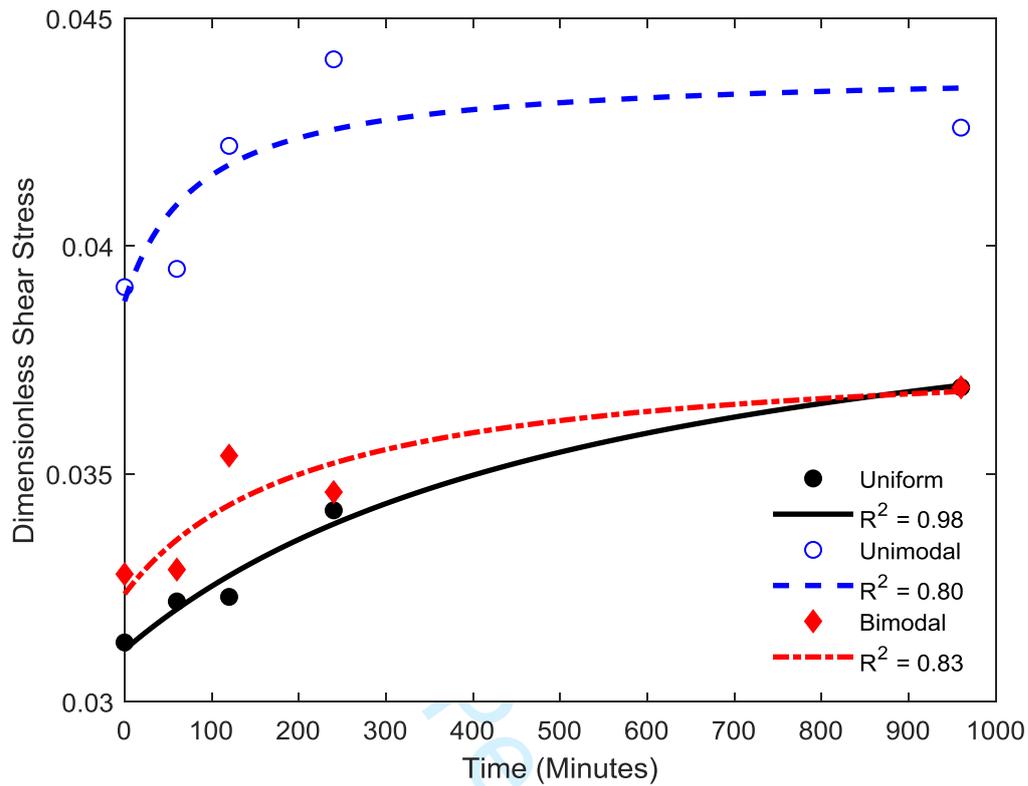
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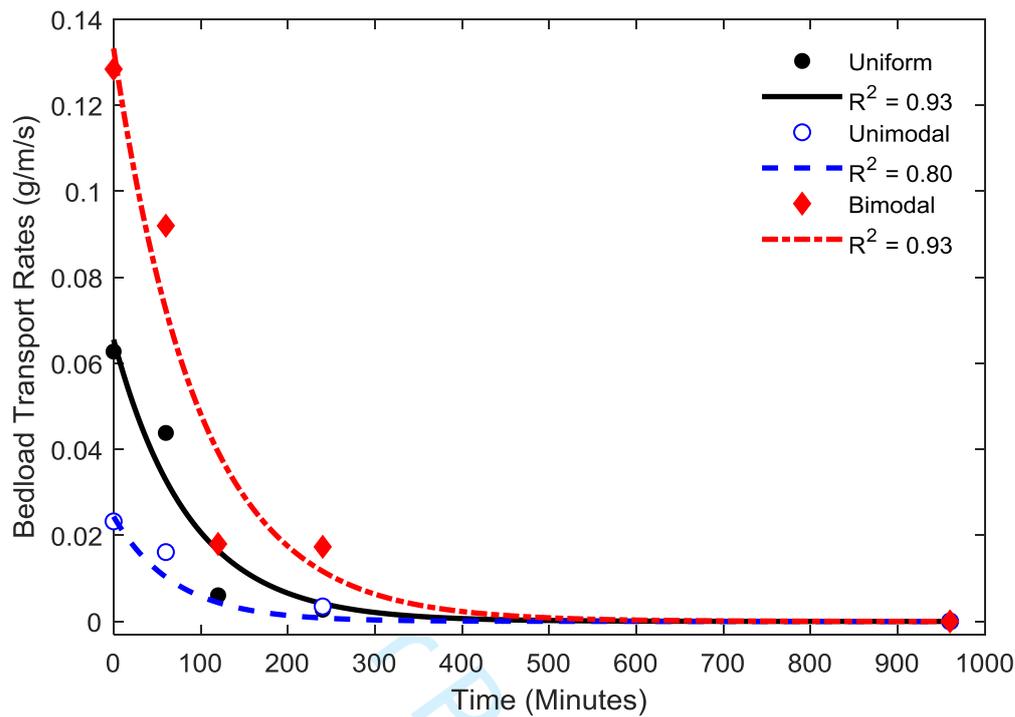
**Figure 1:** Grain size distribution for the three test sediment grades. The is calculated according to  $\sigma_g = (D_{84}/D_{16})^{0.5}$



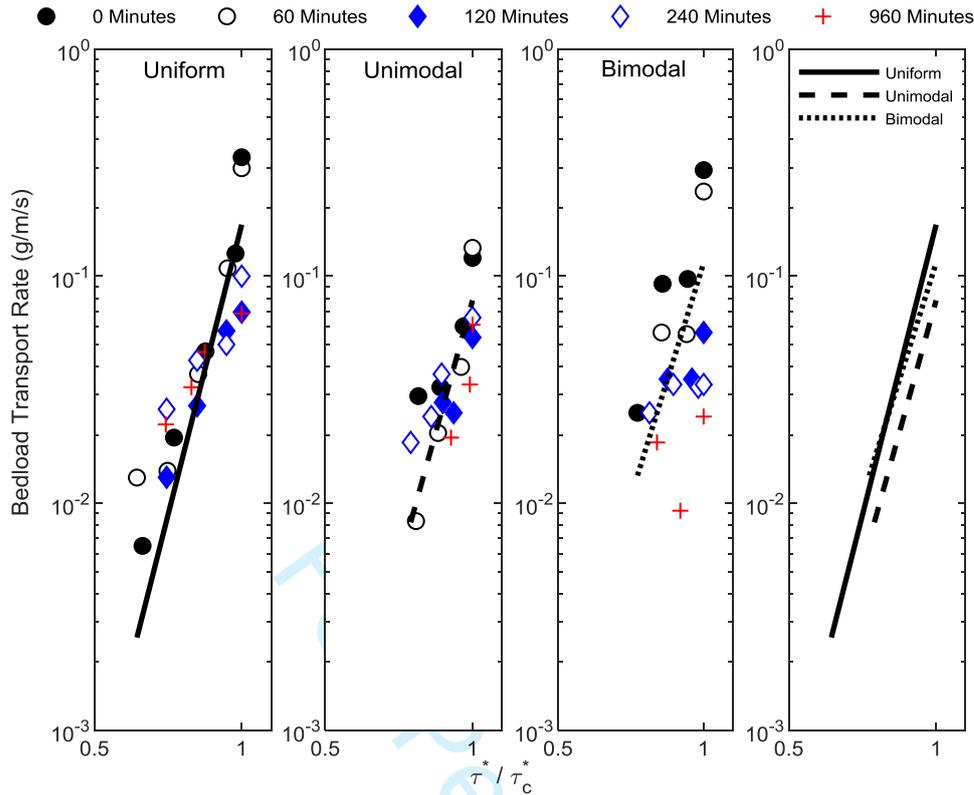
**Figure 2:** Sample experimental hydrograph detailing the three stages of the experiment: (a) an initial bedding in period run for 30 minutes at  $\tau^* \sim 0.004$ ; (b) an antecedent flow period run at  $\tau^*_{c50}$  for 0, 60, 120, 240 or 960 minutes; and (c) a stability test run until  $\tau^*_{c50}$  is reached. The dimensionless shear stress values for each phase of each experiment are given in Table 1 with the example here given for the uniform bed exposed to 60 minutes of antecedent flow.



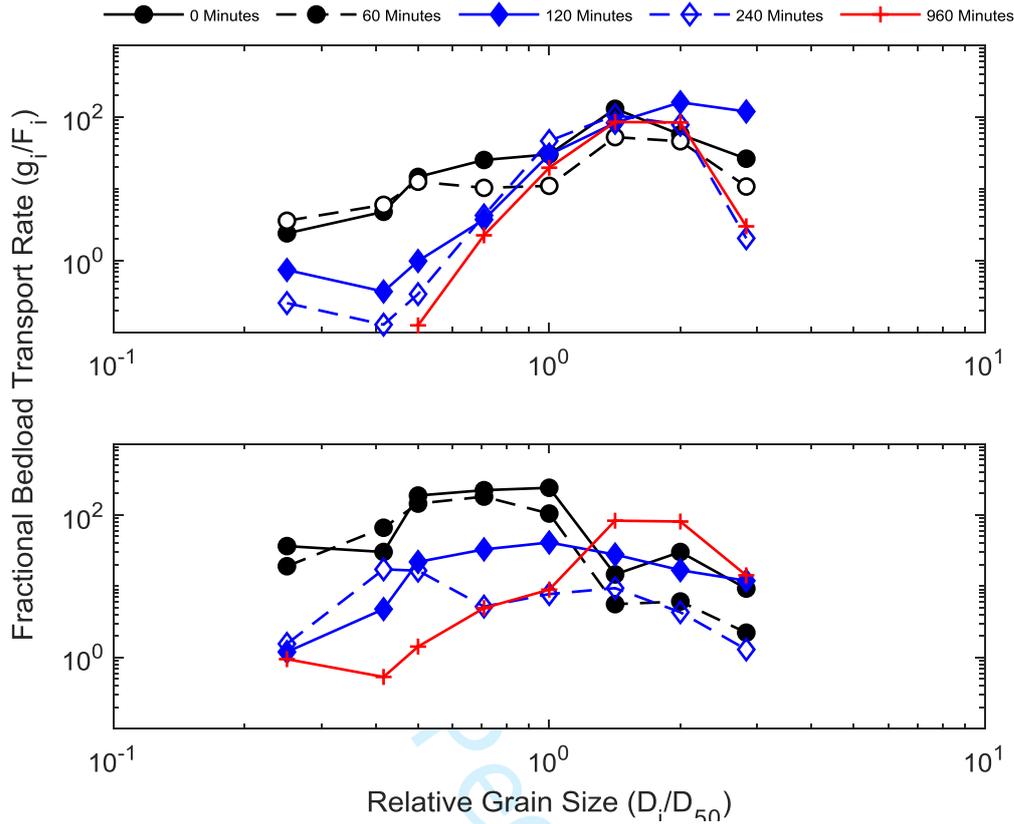
**Figure 3:** The relationship between antecedent duration, average critical dimensionless shear stress and grain size distribution with fits plotted derived according to Equation 2.



**Figure 4:** Inter-flood duration relationships with bedload transport rate, including the fitted exponential decay function of form  $\Sigma Q_{bi} = \Sigma Q_{bi0} + (\Sigma Q_{bi\infty} - \Sigma Q_{bi0})e^{-kt}$  with  $R^2$  values of 0.93, 0.80 and 0.93 for the uniform, unimodal and bimodal beds respectively.



**Figure 5:** Relationship between  $\frac{\tau^*}{\tau_c^*}$  at each step of the stability test as a function of the bedload transport rate for the same step of the stability test for the uniform, unimodal and bimodal beds respectively (subplots 1-3). The fitted trend line given in each of the subplots combines all of the data for each bed and collapses them onto a single straight line. The final subplot directly compares the trend lines derived for each sediment bed. The exponent of the power law relationship is 11.06, 10.09 and 8.77 and the  $R_2$  values of those fits are 0.63, 0.75 and 0.29 for the uniform, unimodal and bimodal beds respectively.



**Figure 6:** Fractional bedload transport rate of the unimodal (top plot) and bimodal bed (bottom plot) scaled by the abundance of each size ( $g_i$ ) in the bulk mix ( $F_i$ ) plotted against dimensionless grain size for antecedent durations 0-960mins. Given the stability test was stopped once the critical entrainment threshold of the  $D_{50}$  had been reached the data in this figure represent bedload which was collected during the last step of the stability test under these conditions.