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EXPERIMENTAL STUDY OF THE VARIABILITY OF SEDIMENT TRANSPORT PROCESSES UNDER OUTBURST FLOOD CONDITIONS IN MOUNTAIN STREAMS --Manuscript Draft--

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Abstract:	<p>To date, little is known on the features of sediment transport processes that can be triggered by an outburst flood for given field conditions. We present the results of 94 experiments carried out in a 5.0 m-long, 0.2 m-wide flume, mimicking the conditions of outburst floods on steep slopes, where water is suddenly released upstream of an erodible bed constituted of sand. Investigated slope gradients cover the range 1.7 to 38.0 %. Flow features are qualitatively analysed using pictures taken by video cameras. We emphasize analysis of the flow front features, and internal shear inside the flow. At gentle slope, the wave propagation is mainly constituted of water with limited sediment transport. When increasing the slope, a series of processes are evidenced, and lead to very concentrated rapid mass flows. We try to classify the observed flows in reference to well-known field phenomena. We finally suggest a continuum of sediment transport processes from bedload to debris flows.</p>
Author Comments:	
Response to Reviewers:	<p>Dear reviewers,</p> <p>Thank you for your comments on this paper, which have helped me identifying weaknesses of the previous version.</p> <p>I have notably included a discussion on other flume experiments to explain that, even if they technically are very similar to our own, differ in terms of objectives, and in that sense, are quite original and inevitably prospective (see notably the new introduction to the METHODS section).</p> <p>This also stressed the necessity to explain better the specific features and related scientific challenges of outburst floods. I have tried to improve the paper that way. I notably tried to evidence that we focus more on triggering conditions than on flow propagation.</p> <p>I also tried to evidence the specific challenge for practitioners dealing with potential outburst floods.</p> <p>Parts which have been modified: abstract, introduction, methods, and conclusion.</p> <p>Best regards Dominique Laigle</p>

1 EXPERIMENTAL STUDY OF THE VARIABILITY OF SEDIMENT TRANSPORT PROCESSES UNDER OUTBURST
2 FLOOD CONDITIONS IN MOUNTAIN STREAMS

3 ABSTRACT

4 To date, little is known on the features of sediment transport processes that can be triggered by an
5 outburst flood for given field conditions. We present the results of 94 experiments carried out in a 5.0
6 m-long, 0.2 m-wide flume, mimicking the conditions of outburst floods on steep slopes, where water
7 is suddenly released upstream of an erodible bed constituted of sand. Investigated slope gradients
8 cover the range 1.7 to 38.0 %. Flow features are qualitatively analysed using pictures taken by video
9 cameras. We emphasize analysis of the flow front features, and internal shear inside the flow. At gentle
10 slope, the wave propagation is mainly constituted of water with limited sediment transport. When
11 increasing the slope, a series of processes are evidenced, and lead to very concentrated rapid mass
12 flows. We try to classify the observed flows in reference to well-known field phenomena. We finally
13 suggest a continuum of sediment transport processes from bedload to debris flows.

14 INTRODUCTION

15 Outburst floods in mountain areas result from many initiation processes like, for instance, the
16 breaching of morainic or ice dams in glacial context when a periglacial lake has formed under the effect
17 of climate change, or the sudden melting of huge quantities of ice, notably in volcanic context. They
18 also result from the breaching of a natural dam, often following the clogging of a valley floor by a lateral
19 landslide. They may also result from the collapse of a man-made dam whose number has drastically
20 increased in Alpine environment over the last decades under the increasing need of water resources
21 available for snow-making.

22 Outburst floods are, by nature, very unsteady flows generally propagating as a wave of water and
23 sediment. Their intensity, notably in terms of peak discharge, is generally much higher than that of
24 hydrological floods likely to occur in a given mountain stream catchment. It may even sometimes affect
25 areas where no hydrological floods could occur. In Alpine environment, the presence of steep slopes
26 and loose sediment, combined with the specific features of outburst floods can lead to very intense
27 erosion and sediment transport processes, even catastrophic debris flows (e.g. Schuster, 2000 ; Laigle
28 & Bardou, 2022).

29 To date, little is known on the features of sediment transport processes that can actually be triggered
30 by an outburst flood for given field conditions. For the point of view of practitioners in charge of hazard

31 assessment and risk mitigation, such lack of knowledge leads to uncertainty on the kind of phenomena
32 to be dealt with, and potentially to the risk of choosing inappropriate tools and methods.

33 The general objective of the present work is to try to reduce the uncertainty mentioned above. More
34 precisely, we aim at prospectively analysing the features of sediment transport processes triggered by
35 the sudden release of pure water upstream of a reach of erodible material. This work is carried out in
36 controlled conditions in a laboratory flume and aims at establishing a typology of flow features, as well
37 as evidencing the role played by parameters such as the slope gradient or the volume of water
38 released.

39 METHODS

40 Sediment transport processes have very often been studied in laboratory flumes, and the related
41 scientific literature is abundant. However, a large majority of these experiments were carried out
42 under conditions of constant or slowly varying input water discharge. Hence, not fully coherent with
43 the very unsteady flows we aim to address. A famous example of experimental facility used to study
44 flows triggered in dam-break conditions is the USGS debris-flow flume, notably presented by Major
45 (1997). However, in these experiments, a mixture of water and sediment, and not only water, is
46 released. Hence, once again not fully coherent with the study of sediment scouring and entrainment
47 by clear water that we aim to address. To our knowledge, Spinewine & Zeck (2007), among other
48 publications from this research team, have presented the most advanced experimental and modelling
49 work on the propagation of dam-break waves on a moveable bed. However, their flume experiments
50 were carried out only in flat or very gentle slope gradient flumes. Finally, we made the choice to adopt
51 the same principle as the experiments by Spinewine & Zeck (2007), but to investigate a large range of
52 slope gradients.

53 Our experiments are carried out in a 5 m-long and 0.2 m-wide flume (Figure 1) equipped with lateral
54 glass walls. The flume is supported by a metallic structure that makes it possible to easily adjust the
55 slope gradient from 0. % to 51.8 %. A tank with a capacity up to 0.35 m³ is directly connected to the
56 upstream extremity of the flume by a sluice gate. This sluice gate can be quickly opened, thanks to a
57 pneumatic actuator, to release the water initially stored in the tank. A 0.08 m-thick layer of sand is
58 deposited uniformly on the flume bottom over a 0.03 m-thick plastic grating to avoid sliding of the
59 sand once the flume is inclined. A small vertical plate, 0.08 m high, is also placed at the downstream
60 extremity of the flume to avoid sliding of the sand. A sill, parallel to the flume bed, is placed
61 immediately below the sluice gate to avoid the possible direct impact of sub-vertical flows coming out
62 of the tank. A tank located downstream collects water and sediment exiting the flume. We use some

63 calibrated sand with a size ranging from 0.5 to 2 mm. Additional analysis revealed that 16 % of this
64 sand is finer than 0.5 mm.

65 The set of devices used to characterize the flows is composed of ultrasonic distancemeters, the
66 downstream tank in which the sand exiting the flume is collected, and later dried and weighted, and 4
67 video cameras. Only qualitative observations carried out with these video cameras are presented
68 hereafter. 3 video cameras are located laterally and take pictures through the lateral glass walls. 1
69 video camera is located above the axis of the flume pointing downwards.

70

71 Figure 1 Sketch of the experimental device.

72 Considering the classical similitude based on the Froude number, these experiments can be reasonably
73 interpreted in the field considering a 1/25 geometric scale.

74 RESULTS AND DISCUSSION

75 94 experiments were carried out on 16 slope gradient values ranging roughly from 1.7 to 38. %, and
76 volume of water released ranging from 12. to 58. liters.

77 Experiments show common features independently of the slope gradient and volume of water
78 released:

- 79 • As the water is suddenly released from the upper tank, the propagation systematically exhibits
80 a wave front. However, the features of this front strongly vary from one experiment to
81 another, according to the quantity of sediment entrained.
- 82 • Considering the sediment transport, each experiment exhibits erosion of the mobile bed
83 upstream of the flume, followed by sediment transport, and then deposition of the sediment
84 downstream. The location of these two latter processes varies with the slope gradient and
85 volume of water released. Large quantities of sediment may exit the flume, and are then
86 collected in the downstream tank.

87 We analyze hereafter the evolution of the flow features versus the imposed experimental conditions,
88 which are mainly the flume gradient and volume of water released. The flow front features appeared
89 particularly relevant for this analysis. Their variability is illustrated in Figures 2 and 3. Additionally, the
90 variability of the internal shear inside the flow is illustrated in Figure 4.

91 On gentle slope (Figure 2-A, 5.12 %), the maximum flow thickness is 3 cm, and the mean velocity about
92 0.75 m/s. Only the water propagation can be visually identified. The sediment transport remains
93 limited in an active layer located below the water layer. This can be seen for instance in Figure 4-A.

94 On Figure 2-B (8.55 %), the maximum flow thickness is 3 cm, and the mean velocity is about 0.5 m/s.
95 The features of the propagation are similar to the latter, except the presence of a clearly visible cord
96 of sediment, about 4 cm wide and 2 cm thick, located at the tip of the wave.

97 On Figure 2-C (20.88 %), the maximum flow thickness is 4 cm, and the mean velocity is about 0.35 m/s.
98 A sediment front, about 3 to 4 cm thick, is present at the wave tip, but its volume remains limited
99 (yellow arrow shows the length). This front is unstable in time and space. It takes the form of fingers
100 where the sediment is pushed by the flow for a few seconds and then stops. Subsequently, the flow
101 diverges and forms another finger with a different position along the flume width.

102

103 Figure 2 Shape of the flow front with slope gradient and volume of water released respectively: A/ 5.12
104 % - 58. l, B/ 8.55 % - 58. l, C/ 20.88 % - 26. l.

105 On Figure 3-A (24.56 %), the maximum flow thickness is 4.5 cm, and the velocity is about 0.26 m/s.
106 Processes are somewhat similar to those observed in Figure 2-C, except that the volume of the
107 sediment front is larger, and its instability in time and space has slightly reduced, compared to the
108 latter. Sometimes, the water may overflow the sediment front.

109 On Figure 3-B (36.24 %), the maximum flow thickness is 8 cm, and the mean velocity is about 0.26 m/s.
110 Most of the sediment is mobilized in a mass flow, with a long front (yellow arrow shows the length),
111 up to 8 cm thick, which occupies the whole flume width. Furthermore, the front tip is followed by some
112 visually homogeneous mixture of water and sediment, which is sheared over the whole flow thickness
113 (Figure 4-B). The flow appears quite stable in time and space when compared to the flows presented
114 so far.

115 On Figure 3-C (34.0 %), the maximum flow thickness is 3.5 cm, and the velocity is less than 0.1 m/s. In
116 this case, conditions are similar to Figure 3-B, except for the volume of water released, which is less
117 important. At the beginning of the experiment, a large front has formed as in the previous case, and
118 stopped in the flume. Under the effect of the water still circulating inside the sediment mass, the front
119 has slowly dislocated. Figure 3-C shows the front after dislocation.

120

121 Figure 3 Shape of the flow front with slope gradient and volume released respectively: A/ 24.56 % - 27.
122 l, B/ 36.24 % - 28. l, C/ 34. % - 12. l, dislocation of the front.

123 Figure 4 shows the thickness (yellow arrow) and features of flows seen through the lateral walls. Except
124 at the front tip, the flows previously presented in Figure 2 and Figure 3-A show features similar to
125 Figure 4-A, with a basal layer of active sediment transport underneath a layer of almost clear water.
126 The flow thickness varies according to the imposed experimental conditions, though. The thick sheared
127 zone of visually homogeneous material presented in Figure 4-B appears as typical of mass flows and
128 has been observed in a limited number of our experiments related to conditions given in Figure 3-B.

129

130 Figure 4 Thickness of the sheared zone with slope gradient and volume released respectively: A/ 28.33
131 % - 20. l, B/ 36.24 % - 28. l.

132 On slopes ranging from about 30. to 36. % were sometimes observed some kind of transitional flows
133 where, within the same experiment, features of flows presented in Figure 3-A (non-homogeneous
134 flow, with separate movements of water and sediment, as in all previous figures) and Figure 3-B
135 (homogeneous mass flow), even Figure 3-C, could be observed alternatively.

136 Even though the previous presentation shows that the slope gradient greatly influences the features
137 of our experimental flows and favor the development of mass flows, it must be noticed that each
138 individual feature has showed up progressively. For instance, an unsteady front was sometimes
139 observed in conditions where some mass flow was observed in a previous experiment, or dislocation
140 was sometimes observed at relatively gentle slope. Consequently, it is quite difficult to establish a
141 typology of flows with well-bounded categories. Only a fuzzy classification (not presented here) was
142 possible, based on consideration and combination of several individual features (e.g. volume or
143 stability of the front, material internal shear). This leads us to think that the different phenomena we
144 have observed should be seen as a continuous evolution determined by a series of individual
145 processes.

146 Our series of observations leads us to try to connect the features of our experimental flows to features
147 of well-known field processes of sediment transport in mountain streams. We notably notice that, on
148 gentle slope, our experimental flows look very similar to classical bedload transport. On slopes of the
149 order of 30. to 36. %, many features related to debris flows (e.g. large and highly concentrated mass

150 flow showing internal shear) are present. According to the remarks of the last paragraph, any attempt
151 to connect our experimental observations to categories of field phenomena can only lead to a tentative
152 classification. Anyhow, we suggest the following classification based on the range of slope gradients
153 that we investigated experimentally:

- 154 - [1.70 % ; 20.88 %]: bedload transport ;
- 155 - [20.88 % ; 28.32 %]: hyperconcentrated flow (e.g. Pierson, 2005)
- 156 - [28.32 % ; 36.24 %]: debris flow (e.g. Takahashi, 2014, Laigle & Bardou, 2022)

157
158 Inside these large domains, sub-domains can be identified showing slightly different features, which
159 also seem influenced by the volume of water released:

160

- 161 - [8.55 % ; 20.88 %]: intense bedload transport
- 162 - [30.26 % ; 36.24 %]: immature debris flow (e.g. Takahashi, 2014)
- 163 - dislocation: over a large range of slope gradients

164

165

166 CONCLUSIONS

167 Outburst floods in mountain areas result from many initiation processes, and are very unsteady flows
168 generally propagating as a wave of water and sediment. Little is known on the features of sediment
169 transport processes that can actually be triggered by an outburst flood for given field conditions, and
170 for practitioners in charge of hazard assessment and risk mitigation, such lack of knowledge leads to
171 uncertainty on the kind of phenomena to be dealt with. In order to try to reduce such uncertainty, we
172 have carried out laboratory experiments mimicking the effect of outburst floods. The main objective
173 of the present work was to study the variability of flow features under conditions of sudden release of
174 water upstream of an erodible streambed, and their evolution versus series of factors including notably
175 the slope gradient.

176 The 94 laboratory experiments we carried out have shown a large variability of flow features, ranging
177 from rather diluted diphasic bedload transport to very concentrated, apparently monophasic, mass
178 flows. These experiments have also evidenced a series of intermediate phenomena where instability
179 in time and space is very often present. We have shown that, depending upon the slope gradient, our
180 experimental flows showed features similar to phenomena classically observed in steep mountain
181 streams, and described in the related scientific literature. We have evidenced the important role
182 played by the slope gradient in the progressive evolution of flow features towards mass flows.
183 However, it was not possible to establish a well-bounded typology of phenomena based uniquely upon

184 consideration of the slope gradient, and other parameters will require further investigation. Indeed,
185 the global flow features appear as the result of a combination of individual processes, some of them
186 becoming dominant according to the experimental conditions. This suggests a continuous evolution,
187 and the existence of transitions between the rather well-known field phenomena – bedload,
188 hyperconcentrated flows, debris flows - as they are defined in the current scientific literature.

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