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Corresponding Author: Prof. luca mao,

Corresponding Author's Institution: Pontificia Universidad Catolica de Chile

First Author: luca mao

Order of Authors: luca mao; Andrea Dell'Agnese; Francesco Comiti

Abstract: RFID passive integrated transponders (PIT) have become a popular method to investigate bedload dynamics at the particle scale in the river channel network, with PIT-tagged clasts usually located after bedload events by means of portable antennas. Stationary PIT antennas have been scarcely deployed so far, probably for technical constraints, despite they present the great advantage to identify the actual discharge at the moment of sediment motion. This study focuses on incipient motion of tracers measured by means of a stationary antennas system in a steep mountain channel (Saldur River, drainage area 18.6 km², Italian Alps) where significant daily discharge fluctuations and bedload transport occur as a result of its nivo-glacial regime. A total of 629 PIT-tagged clasts were inserted in study reach in the period 2011-2014, ranging in size from 35 mm to 580 mm. Results show that the relationship between the size of transported tracers and the discharge measured at the time clasts were passing past the stationary antenna is weak. Hence, the influence of antecedent flows on incipient motion was investigated by dividing the peak discharge recorded between each PIT deployment and the subsequent entrainment by the actual critical discharge at the time of movement (ratio Q_{max}/Q_c). Results show that only 35% of tracers moved at $Q_{max}/Q_c \leq 1.1$, and that 70% of tracers moved at $Q_{max}/Q_c < 1.5$. Therefore, about 30% of tracers had to previously experience a discharge substantially higher than the one which actually mobilized them. Also, coarser particles moved at higher Q_{max}/Q_c ratios, suggesting that higher antecedent flows may be needed for destabilizing the bed clustering. Virtual velocity of PIT-tagged clasts turned out to be highly variable and weakly related with both particle size and flow discharge. However, a better relationships exists between the virtual velocity and the ratio between the maximum discharge experienced by a clast and the difference between this and a percentile of the flow duration curve. This evidence further stresses the importance of flow history on sediment entrainment and transport.

Suggested Reviewers: Kristin Bunte
Colorado State University
kbunte@engr.colostate.edu

Marwan Hassan
The University of British Columbia
marwan.hassan@geog.ubc.ca

Bruce MacVicar
University of Waterloo
bmacvica@uwaterloo.ca

1 **Sediment mobility and velocity in a glacier-fed stream**

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3 Mao L.^{1*}, Dell’Agnese A.², Comiti F.²

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5 ¹ Pontificia Universidad Católica de Chile, Department of Ecosystems and Environments,
6 Santiago, Chile

7 ² Faculty of Science and Technology, Free University of Bolzano, Bozen-Bolzano, Italy

8 * Correspondence to: Luca Mao, Department of Ecosystems and Environments, Pontificia
9 Universidad Católica de Chile, Av. Vicuña Mackenna 4860, Macul, Santiago, Chile. Email:
10 lmao@uc.cl

11

12 **Abstract**

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14 bedload dynamics at the particle scale in the river channel network, with PIT-tagged clasts
15 usually located after bedload events by means of portable antennas. Stationary PIT antennas have
16 been scarcely deployed so far, probably for technical constraints, despite they present the great
17 advantage to identify the actual discharge at the moment of sediment motion. This study focuses
18 on incipient motion of tracers measured by means of a stationary antennas system in a steep
19 mountain channel (Saldur River, drainage area 18.6 km², Italian Alps) where significant daily
20 discharge fluctuations and bedload transport occur as a result of its nivo-glacial regime. A total of
21 629 PIT-tagged clasts were inserted in study reach in the period 2011-2014, ranging in size from
22 35 mm to 580 mm. Results show that the relationship between the size of transported tracers and
23 the discharge measured at the time clasts were passing past the stationary antenna is weak.
24 Hence, the influence of antecedent flows on incipient motion was investigated by dividing the
25 peak discharge recorded between each PIT deployment and the subsequent entrainment by the

26 actual critical discharge at the time of movement (ratio Q_{\max}/Q_c). Results show that only 35% of
27 tracers moved at $Q_{\max}/Q_c \leq 1.1$, and that 70% of tracers moved at $Q_{\max}/Q_c < 1.5$. Therefore, about
28 30% of tracers had to previously experience a discharge substantially higher than the one which
29 actually mobilized them. Also, coarser particles moved at higher Q_{\max}/Q_c ratios, suggesting that
30 higher antecedent flows may be needed for destabilizing the bed clustering. Virtual velocity of
31 PIT-tagged clasts turned out to be highly variable and weakly related with both particle size and
32 flow discharge. However, a better relationships exists between the virtual velocity and the ratio
33 between the maximum discharge experienced by a clast and the difference between this and a
34 percentile of the flow duration curve. This evidence further stresses the importance of flow
35 history on sediment entrainment and transport.

36 **Keywords:** PIT tag; Stationary antennas; Virtual velocity; Antecedent flows; Glacial regime;
37 Alps

38

39 **Introduction**

40 The evaluation and prediction of coarse sediment movement and transport is crucial for
41 understanding and prediction of fluvial morphodynamics, for designing flood hazard mitigation
42 structures, and stream habitat restoration. However, bedload is notoriously challenging to
43 measure in the field with samplers (e.g Vericat et al., 2006), and difficult to predict within one to
44 two orders of magnitude using available formulas, especially in mountain rivers (e.g. Barry et al.,
45 2004; Recking et al., 2012). Indeed, bedload equations are usually empirical and derived from
46 data acquired through flume experiments (e.g. Wilcock & Crowe, 2003), when simplifications
47 are made regarding the size and rate of sediment supply (Parker & Wilcock, 1993), the hysteresis
48 of bedload transport (Mao, 2012; Mao et al., 2014), and the presence of armor layer (Mao et al.,
49 2011).

50 Almost all of the existing sediment transport formulas contain a grain size-related threshold to
51 predict the sediment incipient motion. A plethora of sediment entrainment methods and formulas
52 have been proposed, but none of these give consistent answers even when they are applied to

53 apparently similar conditions. This is evident from the work of Buffington & Montgomery (1997)
54 who reported an order of magnitude difference (0.015 to 0.10) in the calculated dimensionless
55 critical shear stress (Shields parameter). This is in part due to the subjectivity in defining
56 threshold conditions (Buffington & Montgomery, 1997), but mainly due to relative submergence
57 effect (e.g. Shvidchenko & Pender, 2000), and to the sensitivity of threshold entrainment to grain
58 protrusion and local turbulent fluctuations (e.g. Lamb et al., 2008). In steep mountain rivers, the
59 variability in incipient motion threshold is even more pronounced (Lenzi et al., 2006a; Bunte et
60 al., 2013)

61 A further factor strongly influencing incipient motion - almost neglected until a decade ago is the
62 range of flows lower than the critical threshold for grain incipient motion under which a channel
63 bed is exposed prior to the movement of particles. Monteith & Pender (2005) and Haynes &
64 Pender (2007) reported that higher antecedent shear stresses reduce bed stability due to the
65 selective entrainment of the fine matrix within the bed. Piedra et al. (2012) explored this very
66 process in flume experiments in a gravel bed, and highlighted the role of coarse-grain clusters in
67 stabilizing the bed surface. Curran & Waters (2014) further observed that the percentage of sand
68 on the channel bed can also exert a strong influence over the change in surface roughness and
69 structure during armouring developed under rising flow rates.

70 All the above highlights the fact that the antecedent flows can have a strong influence on the
71 dynamics of sediment transport, and that there is the need of exploring the effects of previous
72 flows on sediment entrainment. However, because it is difficult to identify and monitor
73 thresholds for sediment entrainment in mountain streams with traditional methods (i.e.
74 competence calculations using data provided by samplers, e.g. Andrews, 1983), advanced studies
75 involving the use of Passive Integrated Transponders (PIT) tags have increasingly being used
76 over the last decade. PIT tags are encrypted with unique identification code and, inserted in
77 individual grains, they can be used to track coarse particle movement in streams, allowing the
78 measurement of displacement distances, thickness of active sediment layer, and development and
79 maintenance of sediment structures and bedforms (e.g. Lamarre et al., 2005; Houbrechts et al.,
80 2012; Bradley & Tucker, 2012; Chapuis et al., 2014, 2015; Phillips & Jerolmack, 2014;
81 Dell'Agnese et al., 2015). PITs are not equipped with a battery and rely on an external power

82 source, delivered by the reader through an antenna. The antenna is usually connected to a
83 portable reader, thus PITs are searched for on the channel bed after floods. However, stationary
84 antennas fixed on the channel bed have the potential to identify the actual discharge at the time of
85 transport, and dynamics of sediment movement during floods. Using motion-sensing radio
86 transmitters implanted in sediments and two stationary receiving stations, May & Pryor (2014)
87 determined that the sequence of flood events and the history of under-threshold flows may be
88 important to determine surface bed structures and sediment mobility.

89 Stationary antennas and PIT tags can also provide crucial information on velocity of sediments,
90 which can be used to calculate bedload transport rates. In fact, the so-called virtual velocity
91 approach involves the estimate of the virtual velocity of particle movement, the thickness of the
92 active layer, and the active width of the streambed for calculating the rate of transport of bed
93 material (Haschenburger & Church, 1998; Liebault & Laronne, 2008). The velocity of particle
94 movement is considered “virtual” because it is generally calculated using the displacement of
95 tracers and the interval between two subsequent surveys in the field. Even if one consider only
96 over-threshold flows occurred between the two surveys (e.g. Dell’Agnese et al., 2015), by
97 incorporating theoretical periods of both particles motion and rest, the calculated velocity tends to
98 be less than the actual velocity during particle movements.

99 This paper presents a field investigation on bedload mobility and virtual velocities by stationary
100 antennas and PIT-tagged clasts in a steep mountain river (Saldur River) of the Italian Alps, which
101 is characterized by frequent bedload events due to its nivo-glacial hydrological regime. The
102 objectives of the paper are to i) determine how strong is the relation between flow discharge and
103 the size of transported sediments in steep channels (typically characterized by supply-limited
104 conditions); ii) verify the extent to which antecedent flow conditions play a role on motion
105 threshold discharges; iii) determine how virtual velocities vary with sediment size and flow
106 conditions.

107

108

109 **Methods**

110 The study area is the upper Saldur basin (18.6 km² in drainage area, located in the Eastern Italian
111 Alps), which ranges in elevation from 2150 m a.s.l. (bedload monitoring site, LSG in Figure 1)
112 and 3738 m a.s.l. (Weisskugel/Palla Bianca peak), and features a metamorphic substrate mostly
113 composed of orthogneiss (Habler et al., 2009). The catchment was entirely glaciated during the
114 Pleistocene, whereas now only a small glacier (2.3 km² in 2013) is present in its upper part. The
115 land use is characterized by alpine shrubs and grasslands up to 2700 m. a.s.l. and 2400 m. a.s.l on
116 south and north faced slopes, respectively. The mean annual precipitation is estimated to range
117 approximately from 800 mm in the lower part to 1500 mm in its upper portion, where 80% falls
118 as snow (Penna et al., in review). Precipitation occurs as snowfall from November to late April,
119 but snow storms often take place also during the summer at the higher elevations. The relatively
120 low amount of liquid precipitation, a complete snow cover lasting until late April-late, and the
121 presence of the glacier determine a characteristic nivo-glacial regime in the main Saldur River
122 (Penna et al., 2014), where melt flows dominate the annual water budget. Snowmelt dominates
123 from June to mid-July, when glacier melt takes over lasting until September or even later (Engel
124 et al., in press; Penna et al., in review).

125 The longitudinal profile of the river displays a series of valley steps, the largest and steepest of
126 which are in bedrock, the others due to the alluvial fans built by the tributaries (Mao et al., 2014).
127 The average channel slope is 12.6%. The reach just upstream of the monitoring station is
128 confined by the adjacent hillslopes and features a 6% slope, 5-6 m width, and a bed morphology
129 transitional from plane-bed to step-pool. Surface grain size distribution is characterized here by
130 the following percentiles (in mm): $D_{16} = 43$, $D_{50} = 108$, $D_{84} = 304$, and $D_{90} = 417$. Subsurface
131 sediments – sampled after removing the surface layer – are finer (D_{50} and D_{84} equal to 15 and 46
132 mm, respectively). More details on the Saldur channel morphology are given in Mao et al.
133 (2014).

134 The monitoring station at 2150 m a.s.l. was installed in May-June 2011 and includes: i) a
135 pressure transducer to record flow stage at 10 min intervals (flow rating curves were obtained by
136 82 salt dilution discharge measurements taken under different flow conditions between 2011 and

137 2014; ii) a 0.5m long acoustic pipe sensor, manufactured by Hydrotech Company (Japan), the
138 same measuring instrument deployed in several Japanese streams since the 1990s (Mizuyama et
139 al., 2010); iii) four stationary antennas for Passive Integrated Transponders (PIT), controlled by a
140 specific module with datalogger manufactured by the company Aquartis (Canada), originally
141 developed for fish monitoring. An interesting, seasonally-varying bedload dynamics –
142 characterized by marked differences in the flow-bedload relationship between snowmelt and
143 glacier melt periods – was inferred through the continuous records of the pipe sensor, and
144 described in Mao et al. (2014). The calibration of the acoustic sensor through bedload samples –
145 collected using portable bedload traps – was instead presented by Dell’Agnese et al. (2014).

146 This paper focuses only on the data gained from the combined use of PIT-tagged clasts and the
147 stationary antennas to detect their passage at given sections, which offer valuable insights into
148 bedload mobility and virtual velocity in steep channels. A stationary antennas for PIT tags is
149 essentially a loop of normal electrical wire, spanning the entire width of the channel. Four of
150 these electrical circuits were connected to the Aquartis controlling module “Quatro”, which was
151 powered by two car-size batteries (6V and 240Ah each), charged by a large solar panel (110
152 Watt). All these components were hosted on an electrical box installed near the bank of the
153 Saldur channel (Figure 2a). The system registers on a SD card the time of passage (at 1 s
154 resolution) of PIT-tagged clasts above/below the antennas, along with PIT identification number
155 and the number of the detecting antenna (1 to 4, labelled from upstream to downstream in our
156 case).

157 One antenna (antenna 4, the most downstream one) could be firmly installed on the stream bed
158 (wires were first protected by PVC pipes and junctions, to create a rectangular semi-rigid frame)
159 in close proximity of the acoustic pipe sensor (Figure 2b), thanks to the availability – at the
160 section only – of an excavator which could fix the plastic frame by placing large flat boulders on
161 it. Additional metal braces secured the lateral sides of the frame to the banks. The other 3
162 antennas were initially installed on the bed in the upstream reach (spaced approximately 50 m
163 apart, covering a 150m-long reach) by hammering long, U-shaped rebars into the bed.
164 Unfortunately, these were not able to keep the antennas at place once bedload initiated.
165 Therefore, the three upper antennas were then placed above the channel (at about the bankfull

166 stage elevation), without the PVC frame, fixing them by ropes and steel nails on the banks
167 (Figure 2c). The vertical detection range was set to the maximum achievable with the available
168 power supply, and varied between 0.5 m and 0.7 m in the different antennas, and such values
169 were sufficient to detect PIT passages from the suspended antennas in the shallow Saldur flows.
170 Figure 3 shows the lower part of the monitored reach, between antenna number 4 and antenna
171 number 3.

172 The system was kept operational from June to September in the years 2011-2014, as the
173 suspended antennas – as well as the batteries – were removed in early fall and reinstalled in late
174 spring. Antenna 4, the only one secured at the streambed, provided the most continuous records
175 of PIT passages from 2011 to 2014, as the others required maintenance after high flows due to
176 small bank erosions and direct damages to the wires caused by the fast flows, and therefore for
177 some periods they were not properly functioning. Antenna 1, the most upstream one and located
178 in the least favorable section (easily erodible banks), functioned for the shortest time and could
179 not detect any particles passage.

180 A total of 629 PIT-tagged clasts were inserted in study reach in the period 2011-2014, ranging in
181 size (b-axis diameter) from 35 mm to 580 mm. Only natural clasts present in the Saldur channel
182 were equipped with PIT tags (standard, 23 mm-long) directly in the field, by i) drilling holes 5
183 mm in diameter; ii) inserting a PIT in the hole; iii) applying a water-resistance glue; iv) leaving
184 the glue to dry out for about a day. The three diameters of each tagged particles were then
185 measured by a digital caliper for the smaller sizes and by a tree caliper for the larger clasts. 417
186 clasts were also weighed by a digital scale in the field, in order to determine the relationship
187 between b-axis diameter and weight, and to test whether the use of particle weight brings about
188 better statistical relationships, as found by Dell’Agnese et al. (2015).

189 Once tagged clasts were ready, they were placed on the bed surface at different positions,
190 immediately upstream of the antennas, and their longitudinal distance from each antenna was
191 noted. An exception were 50 tagged particles (60 mm – 300 mm in diameter) which were laid 2
192 km upstream from the bedload monitoring station (near the weather station marked as WS in
193 Figure 1) in 2012. These additional clasts were inserted to determine how virtual velocity (in case

194 of their detection by the stationary antennas) can be affected by the spatial scale of transport. At
195 the end of each summer season, until October 2013, the location of PIT-tagged clasts remained
196 within the study reach (i.e. only between antenna 1 and 4) was detected by a portable PIT
197 antenna, the same used in a different stream by Dell’Agnese et al (2015). For logistical reasons
198 (inaccessibility of the site) these surveys could not be performed at the end of the summer 2014.

199

200 **Results and discussion**

201 *General observations*

202 During the 2011-2014 period, 275 particles were detected by at least one antenna, 24 were
203 detected by two antennas, and only 2 by three antennas. None was detected by all the four
204 antennas, also because – as mentioned above – the upstream-most one (antenna 1) could be
205 operational for a very short period due to the unstable banks of that cross-section. The range of
206 detected particle size is from 40 mm to 450 mm (0.1 kg – 78 kg), thus spanning almost entirely
207 the size range laid on the bed. Indeed, the grain size distribution of the detected particles is almost
208 identical to the one of the entire tagged dataset (Figure 4).

209 At the end of summer 2013, 103 tagged clasts were found – thanks to the portable PIT antenna –
210 to be still within the study reach, indicating that, in the period 2011-2013, 236 clasts became
211 either deeply buried in the bed and thus not detectable or were transported downstream of
212 Antenna 4 without being “caught” by the system. We think the latter hypothesis is more likely,
213 because i) relevant bed changes were not evident in the Saldur River by performing repeated
214 cross-section surveys and visual observation of the streambed; and ii) the PIT system was – for
215 some days – made “blind” by tagged clasts which stopped below the antennas, preventing the
216 acquisition system to read other possible PIT passages below the other antennas until the
217 “disturbing” particle was removed. As already said, multiples passages of the same clast below
218 two different antennas were 24, and most of them derives from signals at antenna 2 and 4. In
219 these cases the time interval between the two consecutive passages ranged from 1 min to 10 hr,
220 on average 2 hr. This means that some particles already in motion below antenna 2 could travel to

221 antenna 4 (106 m downstream) within the time of daily bedload transporting events associated to
222 snow- and glacier melt runoff, which typically last – based on the acoustic pipe signal – from 12-
223 14 hours (during late summer glacier melt) to the entire day (hot spells during snowmelt). On the
224 other hand, 22 tagged particles passed below antenna 2 and were not either detected by antenna 3
225 or 4 or found by the mobile antenna. Details on melt flow hydrographs in the Saldur River during
226 the study period are given in Engel et al. (in press). The analysis of particle velocities will
227 presented later.

228 Remarkably, none of the tagged particles placed at the end of July 2012 about 2 km upstream of
229 the monitoring station was detected by the antennas. Unfortunately, for the reasons just
230 mentioned, we could not achieve a 100% detection range in our monitored reach, and thus we
231 cannot actually claim with certainty that these tagged clasts did not travel down to the antennas
232 by the end of 2014. However, it seems likely that many – if not most – of the clasts inserted 2 km
233 upstream of the station were not transported for such a distance within the monitored period. This
234 hypothesis would match the lowest values of virtual velocities – determined from the placement
235 time to the detection time – observed for the tagged particles within the study reach (see later).

236

237 *Critical discharge for motion and antecedent flows*

238 Figure 5 shows that the grain size of the transported sediments – detected by at least one antenna
239 – is only weakly correlated with the flow discharge at the time of their passage past the stationary
240 antennas ($r = 0.19$, $p < 0.05$), also considering the upper boundary of the scatterplot only. Such
241 pattern is not substantially modified when adopting the particle weight instead of the b-axis of the
242 clasts, and thus we prefer to analyze transported particles in terms of grain size, as usually done
243 (but differently from Dell’Agnese et al., 2015, in a stream where probably more irregularly
244 shaped clasts made the use of weight beneficial). In more detail, Figure 5 shows that tracers of
245 around 100 mm (corresponding to the D_{50} of the bed surface) were transported even at very low
246 discharges ($1.4 \text{ m}^3 \text{ s}^{-1}$), very close to the bedload motion threshold (as determined by Dell’Agnese
247 et al. 2014 by direct bedload sampling). The largest measured flow rate in the study period (14.3
248 $\text{m}^3 \text{ s}^{-1}$) mobilized tagged clasts up to 300 mm, but the largest tagged particle (450 mm,

249 corresponding to about the D_{90} of the bed surface) was transported by a discharge of
250 approximately $3 \text{ m}^3 \text{ s}^{-1}$, that is lower than the bankfull stage (estimated in the study reach to be
251 between 4 and $4.5 \text{ m}^3 \text{ s}^{-1}$, Dell’Agnese et al., 2014). On the other hand, visual observations of the
252 channel bed indicated that (non-tagged) clasts up to 0.7 – 0.8 m were mobilized by the largest
253 flows ($10\text{-}15 \text{ m}^3 \text{ s}^{-1}$) associated to rainstorms, which anyhow cannot be considered as infrequent
254 floods based on regional values of specific discharges. Unfortunately, a reliable magnitude-
255 frequency relationship cannot be obtained due to the short time series available so far.
256 Nonetheless, the mobility of the bed sediments in the Saldur River seems overall much more
257 pronounced than in other steep channels (Lenzi et al., 2006a; Bunte et al., 2013) characterized by
258 a different, non-glacial hydrological regime. In fact, Lenzi et al. (2006b) showed that the
259 entrainment discharge for the $D_{90}D_{84}$ of the channel bed in the Rio Cordon (a high-gradient
260 stream of the Italian Alps) needed a discharge much more infrequent than the bankfull (i.e. 4.55
261 $\text{m}^3 \text{ s}^{-1}$, with a recurrence interval of 4.2 years). The fact that the discharge is not a good predictor
262 of the grain size of transported sediments can suggest the lack of size-selectivity. As originally
263 formulated by Parker et al. (1982), strong hiding/protrusion effects can lead the same value of
264 discharge or dimensional shear stress to be critical for all particle sizes, i.e. small and large clasts
265 are entrained under the same flow rate, a conditions known as equimobility. Near-equimobility
266 conditions have been identified by many authors (e.g. Andrews, 1983; Church et al., 1991;
267 Batalla & Martin-Vide, 2001), although in other high-gradient streams a certain degree size-
268 selective transport have also been reported (e.g Marion & Weirich, 2003; Carling, 1983; Lenzi et
269 al., 2006a). However, the lack of a strong correlation between discharge and transported grain
270 size (evident also by the results of the bedload sampling carried out by Dell’Agnese et al., 2014)
271 might not be due to hiding/protrusion effects alone, but also to the fact that the discharge at the
272 time of PIT’s passages past the stationary antennas is not necessarily the only predictor of critical
273 conditions for sediment entrainment.

274 The availability of flow discharges monitored between the placement of each tracer on the
275 channel bed and its passage by the stationary antennas allows us to consider the magnitude of
276 discharges occurred before the actual motion of the tracers. In particular, the influence of
277 antecedent flows on incipient motion was investigated using the ratio between the maximum
278 discharge recorded between each PIT deployment and the subsequent entrainment, and the actual

279 “critical” discharge at the time of movement (i.e. the Q_{\max}/Q_c ratio). The conceptual illustration of
280 Figure 6 shows how the Q_{\max}/Q_c ratio can be considered in a system characterized by daily
281 fluctuation of discharges due to snow and glacier melting as is the Saldur River. If a conceptual
282 sequence of flood events is considered, a tracer is entrained at a ratio Q_{\max}/Q_c equal to one if no
283 flows higher than the critical discharge for entrainment were experienced before the displacement
284 (continuous line in Figure 6). Conversely, the larger the flow occurred before the actual
285 entrainment, the higher the Q_{\max}/Q_c ratio.

286 Figure 7 shows only 35% of tracers moved at $Q_{\max}/Q_c \leq 1.1$, and that 70% of tracers moved at
287 $Q_{\max}/Q_c < 1.5$. Therefore, about 30% of tracers had to previously experience a discharge
288 substantially higher than the one which actually mobilized them. In fact, 23.5% of tracers (i.e. 36
289 PITs) experienced a flow double than the value of the critical discharge (i.e. $Q_{\max}/Q_c > 2$), and 2.5
290 % of tracers moved at a discharge than was previously exceeded by 3 times (i.e. $Q_{\max}/Q_c > 3$).
291 Interestingly, coarser particles tended to move at higher Q_{\max}/Q_c ratios (Figure 8). For instance,
292 88 % of tracers finer than 45 mm moved at $Q_{\max}/Q_c < 1.5$, whereas only 60 % of particles coarser
293 than 256 mm moved with such small Q_{\max}/Q_c ratio. On the other hand, no tracers finer than 45
294 mm moved at $Q_{\max}/Q_c > 2$, but 20 % of particles coarser than 256 mm needed to experience a
295 flow twice the critical discharge before being entrained.

296 This evidence suggests that higher antecedent flows may be needed for destabilizing the bed
297 before particles can be entrained. In fact, early field works from the 1980s began to show that
298 bedload transport showed hysteresis during floods, implying different conditions for sediment
299 entrainment or supply during events. Klingeman & Emmett (1982) reported that the critical shear
300 stress for incipient motion was greater in the rising limb of a flood due to the enhanced bed
301 stability produced from the development of an armour layer. Later, Frostick et al. (1984) were the
302 first to suggest that antecedent flows may control the proportion of matrix fines in the bed and to
303 explain why entrainment thresholds vary for individual flood events. Frostick et al. (2006) further
304 showed using flume experiments that the infiltration of fine sediments into a gravel bed during
305 high flows causes the dilatation of the gravel matrix. More recently, in analyzing bedload
306 dynamics of a small gravel-bed river of Canada, Marquis & Roy (2012) discovered that
307 morphological channel changes were not necessarily related with the mobility of sediment

308 surfaces, leading to the identification of processes of bed dilation (due to fine sediment
309 infiltration) and contraction (due to sediment winnowing) that occurred on the surface sediments.
310 Marquis & Roy (2012) related the processes of bed dilation/contraction to the bed conditions left
311 by the antecedent event, explicitly highlighting the role of previous floods on sediment transport
312 and morphological changes in gravel-bed rivers. Furthermore, by flume experiments, Mao (2012)
313 and Water & Curran (2015) showed that sediment transport hysteresis during floods is due to
314 surface structure adjustments.

315 The evidence provided by the tagged particles in the Saldur River adds to these findings,
316 shedding further light on the important role of flow history on sediment entrainment. In
317 particular, high antecedent flows seem to favour mostly the transport of the coarser particles
318 composing the bed. In the Saldur River the role of fine sediments cannot be assessed from the
319 available data. However, even if dilation/contraction due to fine sediments infiltration and
320 winnowing cannot be discarded, it seems more likely that the need of higher discharges before
321 the actual entrainment could be related with the bed destabilization at the scale of sediment
322 clusters taking place during the antecedent high flows. Destruction of morphological units (steps)
323 were instead not observed during the monitoring period.

324

325 *Virtual velocity of tracers*

326 The virtual velocity of each particle was calculated either i) by knowing the time interval between
327 the passage of the same clast by two antennas, and the distance among them (for the cases of
328 multiple detection only, see above); or ii) by knowing the distance (ranging from 1 to 15 m) at
329 which tagged particle were laid upstream of each antenna and the duration of over-threshold
330 flows between their placement and detection by one antenna (for all the detected clasts). Even if
331 here the velocity is calculated using the actual time of travel between two fixed points rather than
332 the positions at which particles are found on two successive search (as usually done if only
333 portable antennas are used), we call it virtual velocity as particles can clearly experience
334 moments of movement and rest between antennas.

335 Figure 9a shows the relationships between virtual velocity and the size of tagged particles. It
336 appears that the two variables are negatively but very weakly correlated ($r = -0.04$), and that
337 velocities measured on different sub-reaches (i.e. segments between antennas) appears to be
338 comparable. Indeed, the data is very scattered, as the virtual velocity can vary among more than 5
339 orders of magnitude for particles finer than 200 mm. This was somehow expected, as sub-reaches
340 can be 30 to 70 m long, and particles can rest on sediment clusters and bedforms as rapids, steps,
341 and pools, which are found in the study site. The maximum measured virtual velocity is 35 m
342 min^{-1} (i.e. 0.59 m s^{-1}), which is reasonable, as reach-averaged flow velocity during discharges of
343 around $2.5 \text{ m}^3 \text{ s}^{-1}$ – at which the particle moved – is approximately $1.2 - 1.3 \text{ m s}^{-1}$ (determined
344 based on flow continuity principle and measured discharges at LSG). If one plots a curve
345 enveloping the higher measured velocity, the regression would be $VV = 200e^{-0.03D}$, which could
346 help determine the maximum virtual velocity (VV, in m min^{-1}) of sediments of different diameter
347 (D, in mm) in a reach with the slope and morphological characteristics similar to the Saldur
348 River. Interestingly, this upper envelope is similar to what proposed by Liebault et al. (2012) who
349 traced PIT tags over long distances using a portable antenna in a wider (24 m) and gentler sloped
350 (0.016 m m^{-1}) stream of the French Alps. The exponential decrease of virtual velocity with grain
351 size reported by Liebault et al. (2012) showed a strong decrease in mobility for sediments coarser
352 than 4 times the D_{50} of the bed surface. In the case of the Saldur River, this strong decrease
353 appears to occur at a grain size about the double of the surface D_{50} , closer to what reported by
354 Church & Hassan (1992) as a threshold for a rapid decline in grain mobility with increasing
355 grain-size. The observed decrease of virtual velocity for coarser particles agree with findings of
356 Ferguson & Wathen (1998) using tracers in a small stream of the Scottish Highlands, and with
357 later investigations reported by Church & Hassan (2002), but not with more recent observations
358 of Milan (2013) and Dell’Agnese et al. (2015) who calculated virtual velocity by dividing the
359 displacement of tracers by the duration of competence time between two surveys. Instead,
360 Liedermann et al. (2013) found decreasing transport distances with increasing tracer sizes in a
361 large and regulated Austrian river (the Danube).

362 Figure 9b shows also the relationships between the virtual velocity and the maximum discharge.
363 The two variables are weakly ($R^2 = 0.184$) and negatively correlated ($r = -0.05$). This is
364 counterintuitive, as one would expect higher virtual velocities measured for intervals with larger

365 discharges. Indeed, Ferguson & Wathen (1998) showed that virtual velocity tends to increase
366 with shear stress. However, this could also suggest that the instantaneous maximum discharge
367 experienced by a particles moving from one antenna to the following could not represent alone a
368 good predictor for the virtual velocity, as also argued by Dell’Agnese et al. (2015).

369 Because the discharge was continuously measured along the monitoring seasons near the antenna
370 4 (LSG in Figure 1), the flow duration curve from the passage between the upper and lower
371 antennas for each single particles have been calculated. Significant percentiles of the flow
372 duration curves were calculated too. The better relationships have been found with a ratio
373 between the maximum discharge and the difference between the maximum discharge and a
374 percentile of the flow duration curve. Table 1 shows that the coefficients of determination are
375 significantly higher (around 0.54) than using the Q^{\max} alone, and that using percentiles closer to
376 the maximum discharge seems to improve the performance of the empirical regression to predict
377 the virtual velocity. Figure 10 shows the relationships between the virtual velocity and the
378 $Q_{\max}/(Q_{\max}-Q_{10})$ ratio. Data plotted in the upper right portion of the graph represents particles that
379 experienced higher maximum discharge but also long periods with high discharge (close to the
380 maximum). Conversely, tracers that travelled with low virtual velocity experienced longer
381 periods with lower discharge (e.g. late snow melting season). This suggests that the maximum
382 discharge is not crucial in determining the virtual velocity of particles, at least during ordinary
383 transport events results, and highlights the importance of magnitude and duration of antecedent
384 flows. Among others, Hassan et al. (1992) and May & Pryor (2014) previously suggested that the
385 magnitude of antecedent events has an influence on entrainment and displacement length or bed
386 surface sediments. May & Pryor (2014) further observed that tracers moved preferably during the
387 rising rather than the falling limbs of hydrographs, relating this with the dynamics of bed
388 structures, as done before by Church & Hassan (1992) too.

389

390 **Final remarks**

391 This paper presents a novel set of evidence provided by a PIT-tagged experiment in a glacierized
392 stream of the Italian Alps, where a 150-m long reach was instrumented with a set of 4 stationary

393 antennas. Evidence shows that in this environment characterized by abrupt daily discharge
394 fluctuations due to the nivo-glacial regime, the size of transported sediments is only weakly
395 correlated with the discharge. The history of flows occurred before the actual movement of
396 particles seems to play an important role on incipient motion in this environment, as 65% of PIT-
397 tagged clasts experienced a discharge higher than the value of discharge at the time of
398 entrainment (i.e. $Q_{\max}/Q_c > 1.1$), and 30% of them moved at $Q_{\max}/Q_c > 1.5$. Also, the virtual
399 velocity of a PIT-tagged clasts resulted highly scattered and only weakly related with either
400 particle size or the flow discharge. Again, including the flow history in the analysis by
401 considering a ratio between the maximum discharge and the difference between this and a
402 percentile of the flow duration curve proved to increase the significance of the relationship
403 between the discharge and the virtual velocity of bed particles. Overall, this study highlights the
404 important role of the magnitude and frequency of antecedent flows on sediment entrainment and
405 displacement velocity in glacierized streams.

406

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549

550

Tables

551 **Table 1.** Coefficients, exponents, and coefficients of determination, for the power law
552 regressions relating virtual velocity (VV in m min⁻¹) and a ratio between the maximum discharge
553 and a significant percentile of the flow duration curve (numbers in bold are significant at p <
554 0.05).

	a	b	R ²
$VV = a(Q_{\max} / (Q_{\max} - Q_{50}))^b$	0.0003	1.6332	0.5413
$VV = a(Q_{\max} / (Q_{\max} - Q_{25}))^b$	0.0003	1.3886	0.5509
$VV = a(Q_{\max} / (Q_{\max} - Q_{10}))^b$	0.0002	1.1777	0.5517

555

556

557

Figure Caption

558

559 **Figure 1.** Location and map of the Saldur catchment showing the position of the monitoring
560 station for bedload and water discharge (LSG). WS marks the location of the weather
561 station managed by EURAC.

562 **Figure 2.** Case hosting the PIT detection system in the Saldur River (a), the antenna 4 being
563 fixed in the channel bed at the downstream end of the study reach (b), and the antenna 2,
564 placed above the channel after being damaged during a high flow, and detecting tagged
565 particles passing below it.

566 **Figure 3.** A view of the Saldur River showing most of the study reach, with the location of the
567 antenna's control unit and two antennas (3 and 4), placed 70 m apart. Antenna 2, not
568 visible, is just behind the curve 36 m upstream of antenna 3.

569 **Figure 4.** Grain size distribution of the surface sediments, tagged particles and particles that were
570 transported and detected by the stationary antennas.

571 **Figure 5.** Relationship between the intermediate diameter of the PITs and the discharge at the
572 time of passage above an antenna.

573 **Figure 6.** Conceptual image showing an idealized sequence of flood events occurring after a PIT
574 is placed in the channel bed. The largest the discharge occurred before the movement of
575 the particle (thus the passage near an antenna), the higher the Q_{\max}/Q_c ratio.

576 **Figure 7.** Frequency of Q_{\max}/Q_c values experienced by the PIT tags monitored using the
577 stationary antennas in the Saldur River.

578 **Figure 8.** Distribution of Q_{\max}/Q_c ratios divided by grain size classes.

579 **Figure 9.** Relationships between the virtual velocity the size of PIT tags (on the left), and the
580 discharge (on the right).

581 **Figure 10.** Relationship between the ratio of maximum discharge and the ratio between the
582 maximum discharge and the percentile 10 of the flow duration curve (i.e. the discharge
583 exceeded for 10% of the time in the flow duration curve) and the virtual velocity of
584 tagged particles.

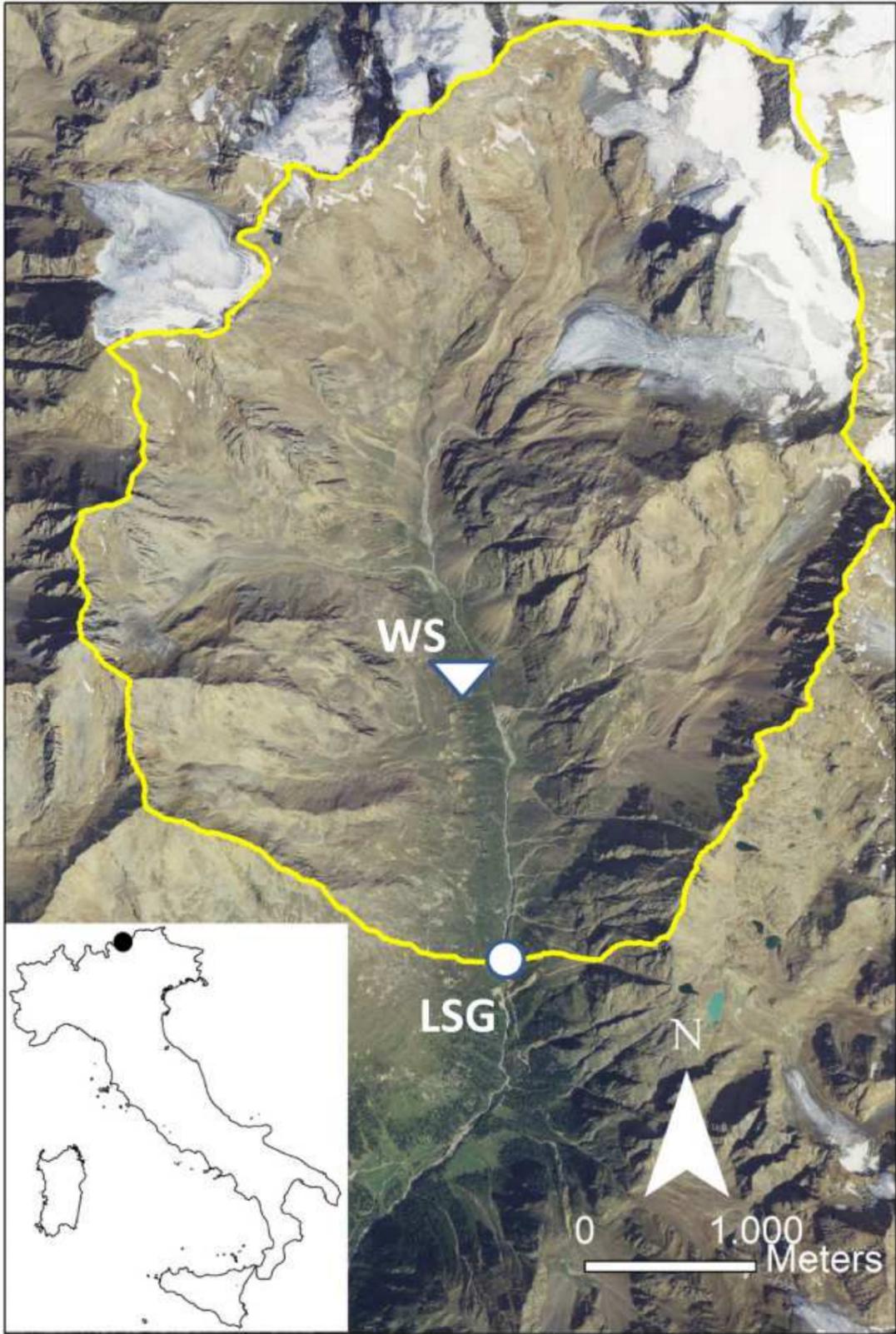


Figure (Greyscale)



Figure (Greyscale)



Antennas' control unit

Antenna 3

Antenna 4

Datalogger for the acoustic pipe

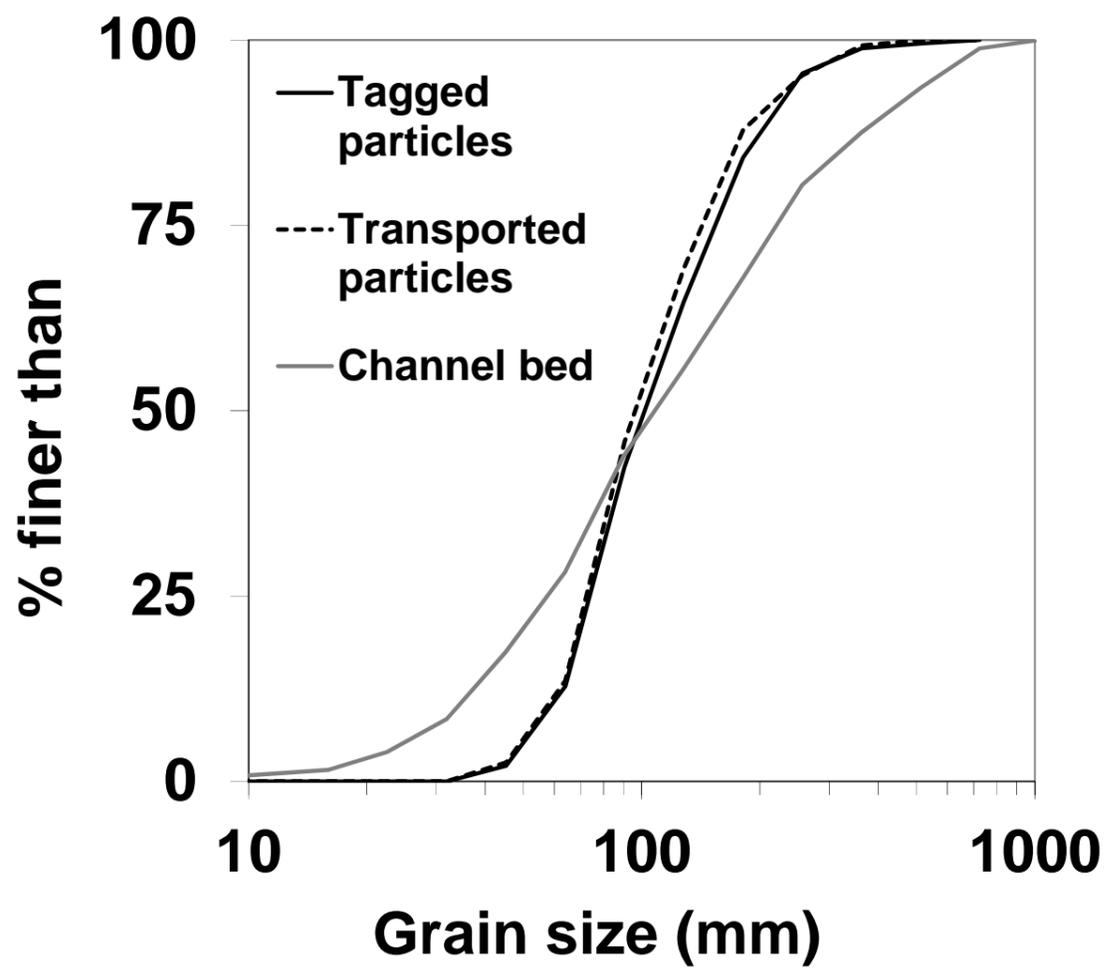


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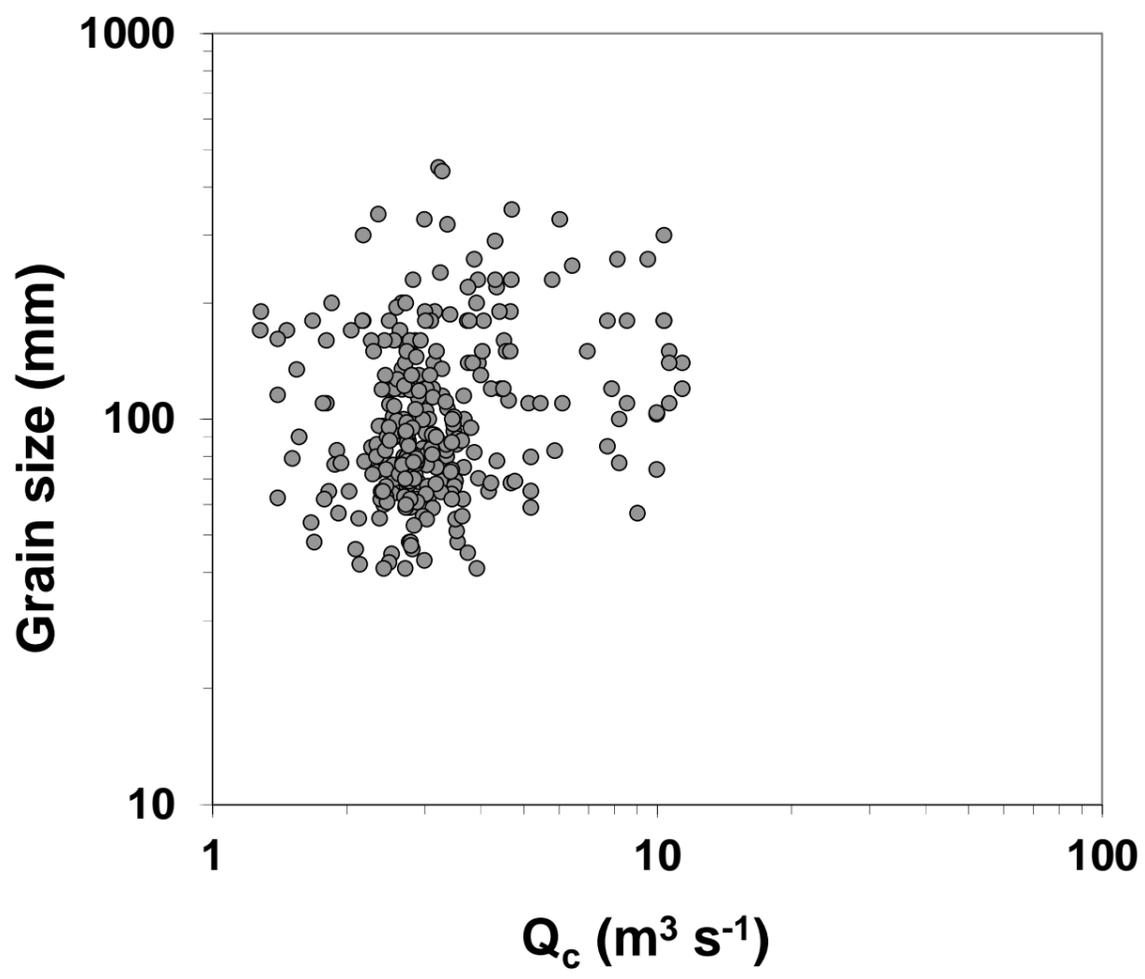


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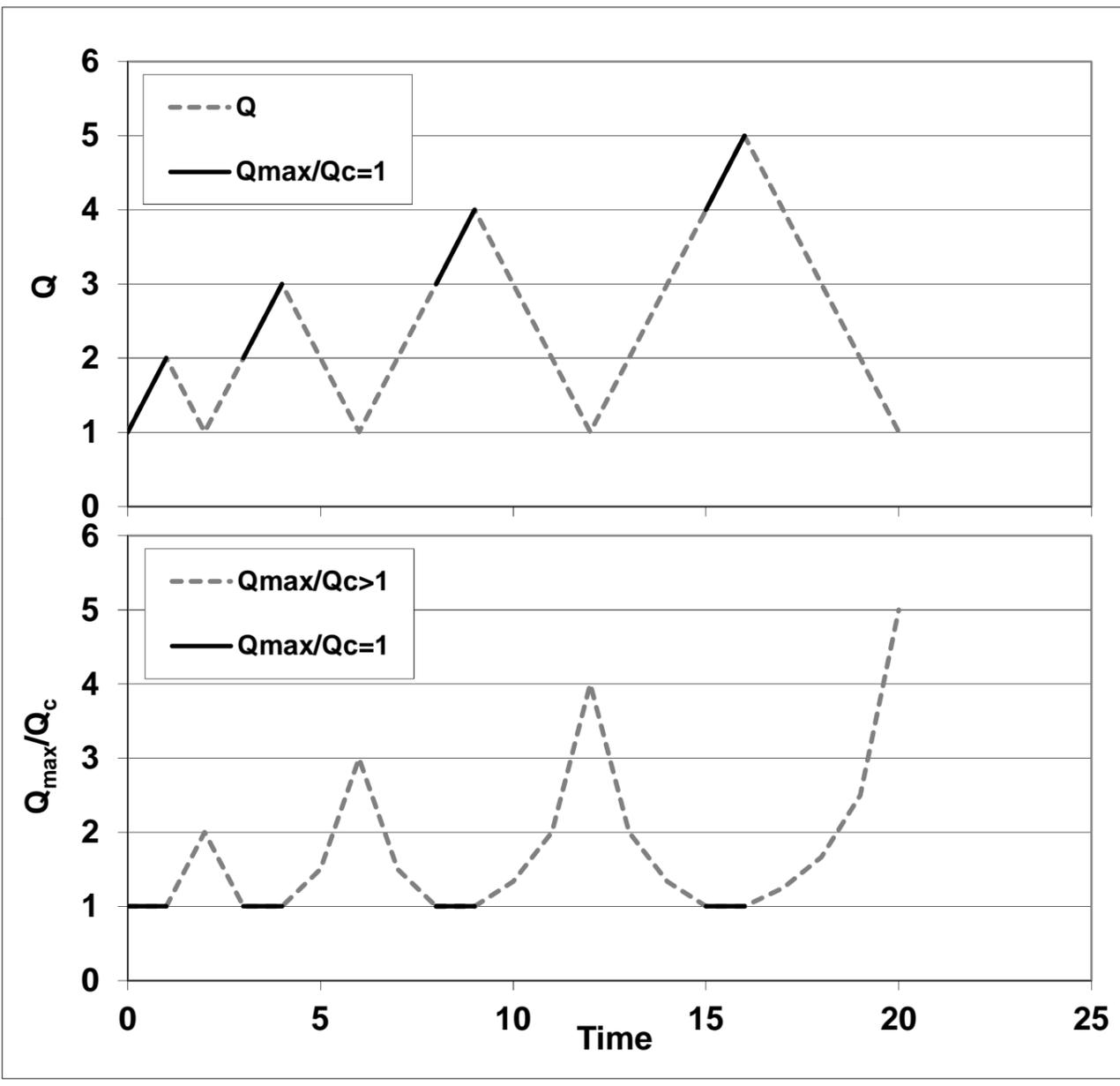


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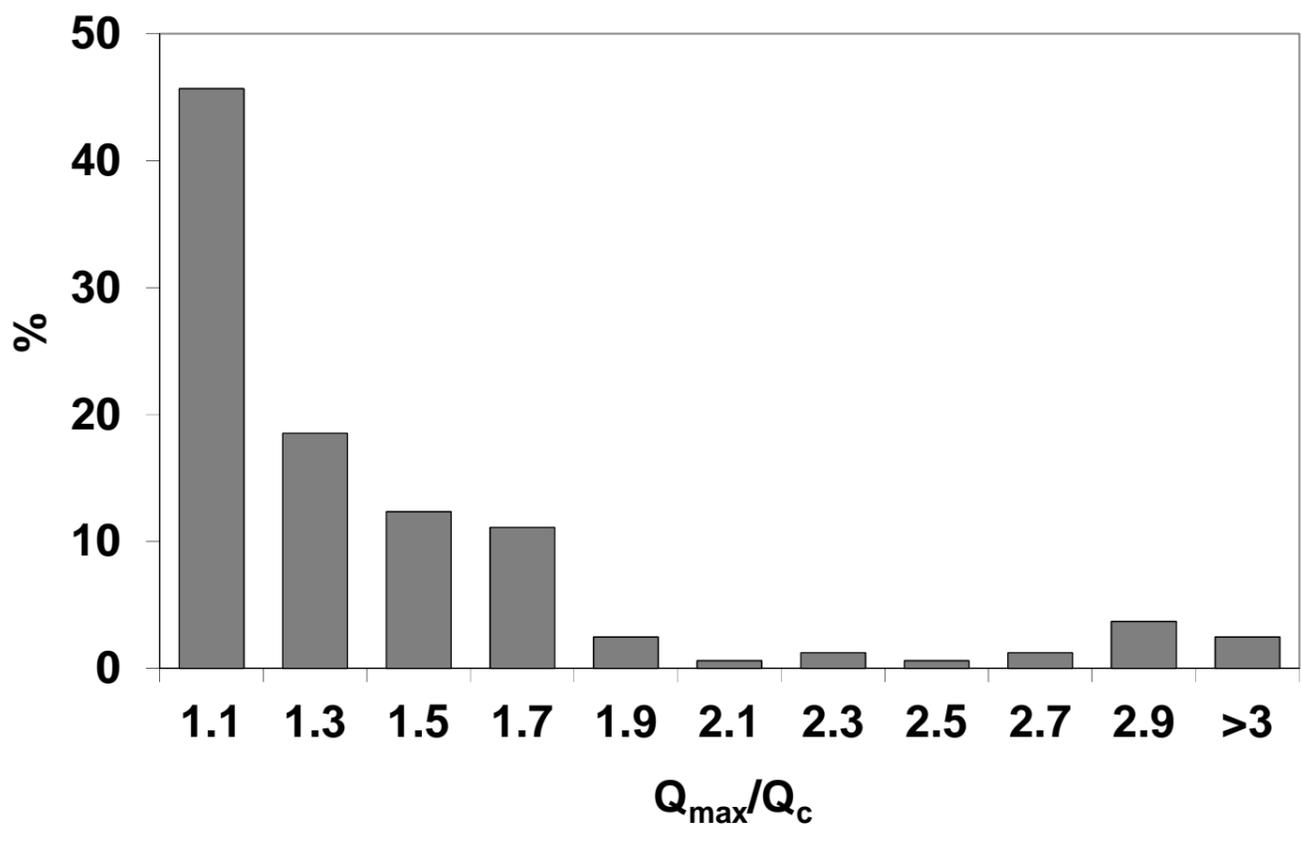


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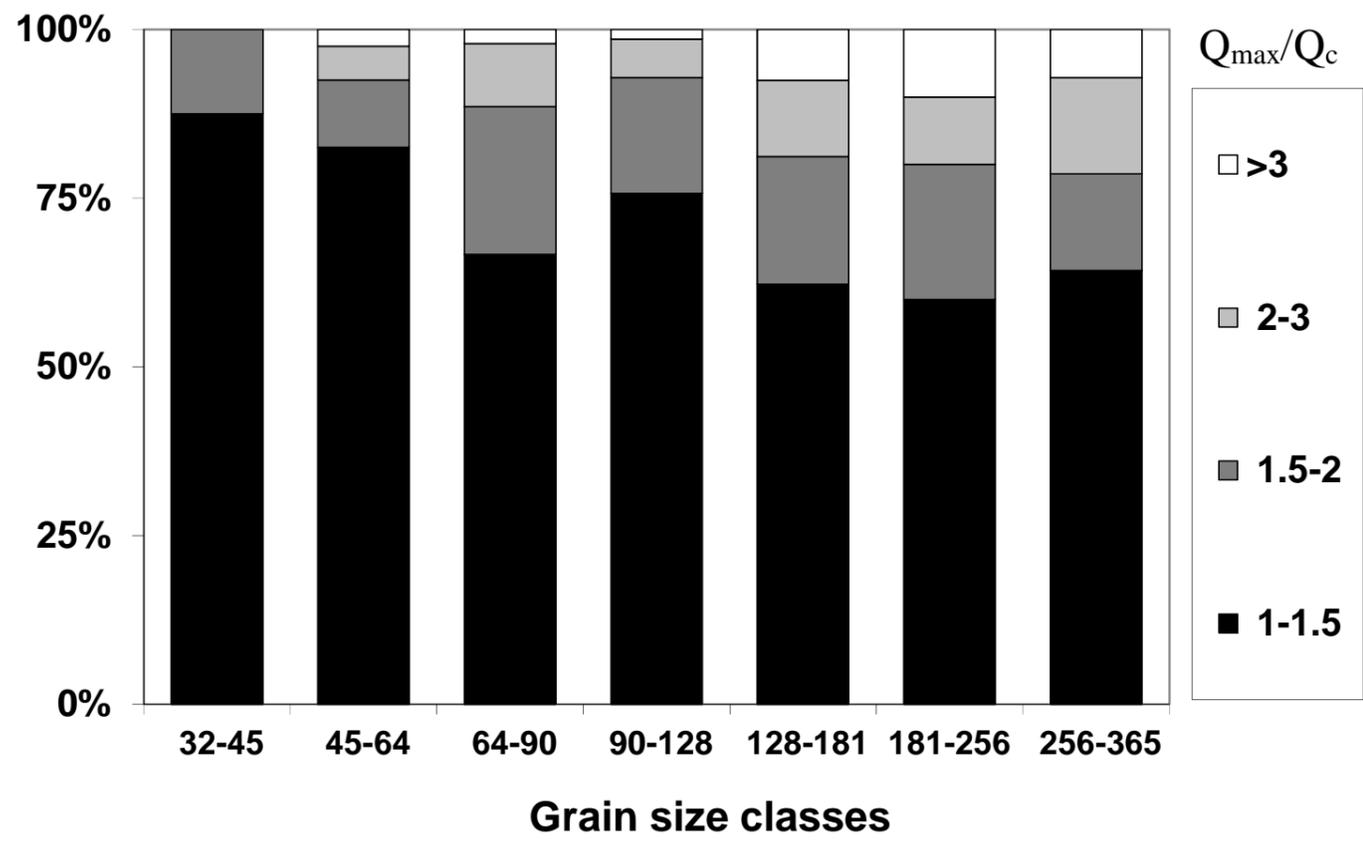


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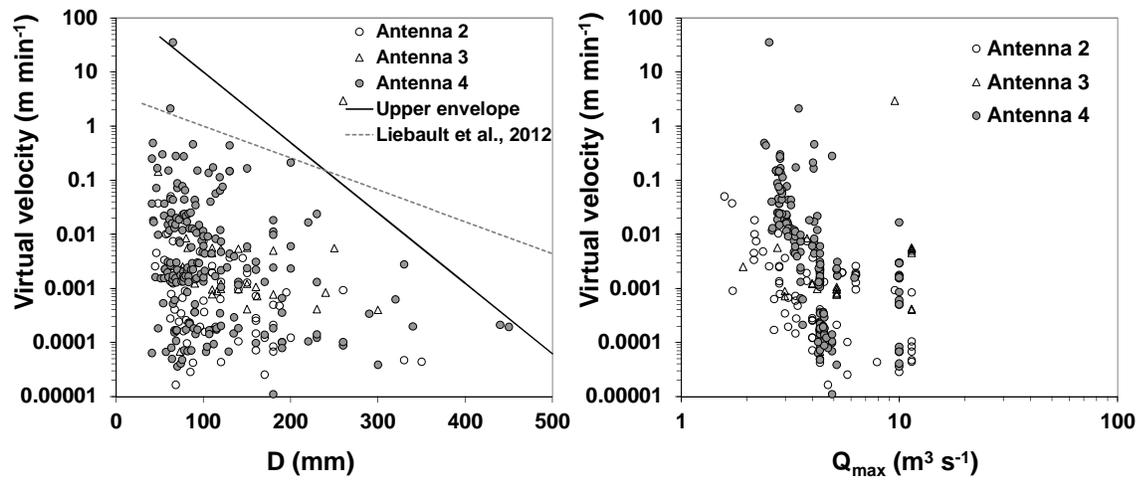


Figure (Greyscale)

