

TRAPPING LARGE WOOD DEBRIS IN RIVERS: EXPERIMENTAL STUDY ON A NOVEL DEBRIS RETENTION SYSTEM

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ABSTRACT

Large wood debris can cause critical damage to bridges and other riverine structures, and increase flood risk. Although their effects on hydrodynamic actions and flood levels have been investigated in recent research, little effort has been devoted to reducing the amount of debris that can accumulate at structures. This paper proposes and experimentally tests a new type of large wood debris retention system in which a series of alternating porous and rack-type modules, is placed in-line with the current. Laboratory tests illustrate that the proposed retention system can offer high levels of efficiency in trapping large wood in rivers. The geometrical features of the structure are observed to play a major role and can be carefully chosen to optimise trapping efficiency. Results also show that large wood debris trapped by these structures have limited effects on the increase of the upstream water levels. Further development of the solution proposed in this work can pave the way for use of low-cost, highly-effective debris retention systems for effective river management and large wood debris removal in practice.

1 INTRODUCTION

2 Engineers face a major challenge in managing the consequences of the complex interactions
3 between flow and structure for engineering works in rivers. Hydraulic structures (e.g. a bridge
4 pier or abutment) in watercourses often cause obstructions to the flow that lead to a rise in the
5 upstream water level, often referred to as afflux, which may increase the flood risk for adjacent

6 areas. Localised scour is also likely to develop at such structures. This can undermine the found-
7 dations of structures and lead to significant structural damage and even collapse. Accumulations
8 of large wood debris (also referred to as woody debris or debris in this manuscript), resulting
9 from woody debris transported by rivers after recruiting them from their banks, can dramatically
10 exacerbate the aforementioned effects of scour and afflux. For example, tree logs can become
11 entrapped at in-channel structures such as bridge piers and then trap other large wood debris such
12 as twigs and tree branches to form large accumulations (*Diehl, 1997; Lagasse et al., 2010; Panici*
13 *and de Almeida, 2018*). The size of these accumulations can be such that they obstruct a signif-
14 icant portion of the channel. Therefore these can have a noticeable effect on the flow around the
15 structure, and particularly worsen afflux and scour. In fact, debris-induced scour remains one of
16 the main causes of bridge failures in US, UK and Ireland (*Diehl, 1997; Benn, 2013*). For example,
17 debris blockage was cited as the primary reason for the failure of the masonry arch bridge on
18 the river Crane near Feltham (UK) in 2009 (*RAIB, 2010*). The blockage caused scour-induced
19 subsidence of the abutments and resulted in closure of the bridge and the supported major railway
20 line for many months. Another notable example is the large flooding event in Switzerland in 2005
21 that resulted in over 100 bridges being damaged by large wood debris (*Schmocker and Hager, 2011*).

22
23 Several experimental studies have investigated the formation of debris accumulations and their
24 hydrodynamic effects. For example, *Bocchiola et al. (2008)* observed that the probability of logs
25 being retained by a series of randomly distributed obstacles depends on flow velocity and log
26 length. Similar observations were made by *De Cicco et al. (2020)*. They showed that the initiation
27 of a debris accumulation at a bridge pier depends significantly on the Froude number of the flow.
28 Other studies considered the probability of large wood accumulating at bridge decks (*Schmocker*
29 *and Hager, 2011; Gschnitzer et al., 2017*) or at bridges with a single pier (*Gschnitzer et al., 2017;*
30 *Panici and de Almeida, 2018, 2020a*). For piers, the process of accumulation formation is known to
31 involve three stages (*Panici and de Almeida, 2018*). Individual debris elements first get trapped at
32 an hydraulic structure (e.g. a bridge pier); these elements then entrap further debris pieces until the

33 accumulation reaches a maximum size that is dependent on the length of individual debris and the
34 approach velocity of the flow; eventually, when the accumulation reaches a certain maximum size,
35 the flow removes the accumulation and transports it downstream of the structure (*Panici and de*
36 *Almeida, 2018*). Debris accumulations, by blocking a large portion of the flow area (*Schalko et al.,*
37 *2019a*), can significantly increase the afflux - by up to two times the undisturbed upstream flow
38 depth in the worst cases. Several studies have also examined the scour effects of debris accumula-
39 tions. *Ebrahimi et al. (2018)*, using an experimental study, investigated the scour hole at a bridge
40 pier for a large range of debris shapes and sizes and observed that the maximum scour depth in
41 the presence of debris could be up to 3 times the depth without debris. Other experimental studies
42 on the scour effects of debris (e.g. *Melville and Dongol, 1992; Lagasse et al., 2010; Pagliara and*
43 *Carnacina, 2011*) have also shown comparable results, although these differed in the debris shapes
44 and sizes used.

45

46 Debris mitigation measures can offer a sensible, cost-effective approach for reducing the scour
47 and flooding consequences for structures prone to debris accumulations. However there has been
48 limited research to date on the use of such measures for the protection of riverine structures (es-
49 pecially bridge piers) beyond a few full-scale applications, mostly within the USA. For example,
50 sweepers and hydrofoils have been employed to divert the debris from the upstream face of bridge
51 piers (*Bradley et al., 2005*), whereas fins and sacrificial piles have been used to accumulate debris
52 away from the pier and hence reduce the size of the forming scour hole (*Bradley et al., 2005; Lyn*
53 *et al., 2003*). *Franzetti et al. (2010)* also tested another solution - a ramp to accumulate debris
54 upstream from a bridge pier. These measures, except in a few selective applications (e.g. *Franzetti*
55 *et al., 2010*), have not demonstrated satisfactory levels of performance in terms of protection offered
56 to downstream structures from debris (*Bradley et al., 2005*).

57

58 A potentially better solution than mitigation is the removal of floating debris from a river prior
59 to it reaching the structure as this will eliminate the risks due to potential accumulations. Although

60 the reintroduction of large wood in riverine environments may have positive effects to protection to
61 fish habitat and micro-organism stabilisation (*Gregory et al.*, 1993; *Abbe and Montgomery*, 1996;
62 *Lagasse et al.*, 2010), the risks and costs posed by debris to human lives, structures and networks
63 (*Lassetre and Kondolf*, 2012) can be much larger and exceed the potential environmental benefits
64 in many cases. Furthermore, trapped wood can be reintroduced back in rivers (*Thomas and Nisbet*,
65 2007) in a controlled manner, as is now common practice, for aquatic conservation as well as to
66 improve channel stability and flood management (*Abbe and Montgomery*, 1996; *Gurnell et al.*,
67 2002). Few studies have provided useful insights into potential systems for debris retention and
68 removal. *Lange and Bezzola* (2006) tested a series of horizontal racks, partly covering the width of
69 the channel, for partial retention of transported debris; the racks in this study were perpendicular to
70 the banks and did not consider the influence of the angle relative to the bank on trapping efficiency.
71 *Lyn et al.* (2003) tested a deflector and a groin-like submerged structure to divert the large wood
72 debris away from a bridge pier; results however showed limited benefits, with these structures even
73 occasionally increasing the quantity of debris accumulating at the pier. Although *Bradley et al.*
74 (2005) listed debris fins as potential effective measures to protect bridges from large wood debris,
75 a recent study by *Schalko et al.* (2019b) showed that the probability of debris accumulating at a
76 bridge was not affected. *Schalko et al.* (2019b) also tested bottom sills, that may offer a better
77 performance than fins (e.g. a reduction up to 30% of accumulation probability) but strongly depend
78 on flow conditions and sediment transport. *Schmocker and Weitbrecht* (2013) experimentally tested
79 a debris retaining basin in a bend of a channel, where debris can be collected in flood conditions
80 using their inertia to get them into the basin. However, this type of solution has some limitations.
81 For example, the basin is functional only when the water level reaches a threshold value, while
82 debris, on the other hand, may also be transported in much lower flow conditions. Furthermore,
83 retention basins would require a large amount of available land, which may not be feasible for many
84 rivers, for example in uplands and hilly environments.

85

86 In this paper, we propose an innovative type of debris retention system to protect riverine

87 structures (e.g. bridge piers) from large wood debris accumulations. This system, which will be
88 built upstream of a protected structure, is designed to trap a high percentage of floating debris while
89 limiting costs for removal and remedial works and applicable to the broadest number of rivers and
90 type of event, and having limited effects on the backwater. The system proposed includes a set of
91 highly porous alternating rack-type modules where each module is placed such that it is in-line with
92 the flow and extends partially across the river. The reason for the system only partially extending
93 across the river is to avoid the following issues that are encountered when using regular full-width
94 rack poles:

- 95 • Removal of logs can be difficult and costly, especially if access is limited from the banks
96 (*Panici et al., 2020b*);
- 97 • River navigation including for simple leisure activities may be impeded unless expensive
98 and complex structures (e.g. gates, locks) are built;
- 99 • The increase in upstream water level is often significant (e.g. *Schmocker and Weitbrecht,*
100 *2013; Schalko et al., 2019a*), which has considerable implications for flood risk.

101 We experimentally test the efficiency of this system in catching debris elements for a range of
102 geometries and configurations of the modules, as well as for different flow and debris conditions.
103 Results are used to understand the relationship between module parameters and efficiency, and
104 thereby make recommendations on the design of the retention system. Findings will have impli-
105 cations for river management in practice and will pave the way for further developments in debris
106 mitigation measures.

107

108 **METHODOLOGY**

109 The type of debris retention system proposed in this paper is shown in Figure 1. The system
110 consists of a series of modules, each of which is an in-line structure designed such that it captures
111 large wood debris with a desired level of efficiency while

- 112 • providing hydraulic continuity,

- 113 • having minimum impact on flow level increase, and
- 114 • offering ease of access for debris removal.

115 Each module has a width S and is placed transversely to the direction of the flow at an angle α
116 (see Figure 1). At full-scale, each module may be realised using a series of intertwined poles that
117 are driven in to the river bed. However this paper investigates only the hydrodynamic interactions
118 between the system and the debris; the structural design and analysis of the modules are beyond the
119 scope of this study.

120

121 **Dimensional analysis**

122 In order to provide similarity between model and prototype as well as to determine the main
123 variables influencing the performance of the debris retention system, we performed a dimensional
124 analysis. The following parameters related to the flow, debris and retention system are considered:
125 the acceleration due to gravity g , the flow velocity v , the channel width T , the density of the fluid ρ ,
126 the dynamic viscosity of the fluid μ , the undisturbed water depth h , the length of a debris element L ,
127 the diameter of a debris element d , the stream-wise length of a module R , the width of a module S
128 and the spacing between modules m . As described below, in our experiments the amount of trapped
129 debris is found to grow approximately linearly with the amount of supplied debris. We therefore
130 choose as dependent variable the efficiency e of the debris retention system. This efficiency
131 (defined as the amount of debris pieces trapped by the structures divided by the total number of
132 debris transported) is likely to be functionally dependent on the flow, debris and retention system
133 parameters outlined previously. This dependency can be represented mathematically as follows:

$$e = f(v, \rho, \mu, h, g, L, d, R, S, m, T). \quad (1)$$

134 Applying Buckingham's Π theorem, three repeating variables - i.e. S , v and ρ , have been
135 selected from (1) to form 8 dimensionless groups:

$$e = f \left(\frac{\mu}{vS\rho}, \frac{h}{S}, \frac{gS}{v^2}, \frac{L}{S}, \frac{d}{S}, \frac{R}{S}, \frac{m}{S}, \frac{T}{S} \right). \quad (2)$$

Some simplifications can be made to Equation (2).

- Replicating Reynolds similarity in the experiments is extremely difficult as the Reynolds number for prototype conditions is likely to be very large. Hence, assuming Reynolds number invariance, the corresponding term in (2) is ignored. Reynolds numbers for the experimental scenarios are however kept reasonably large, i.e. in the turbulent regime; this is an accepted practice and has been employed in similar experimental studies in past hydraulic research (e.g. *Wallerstein et al.*, 2001; *Bocchiola et al.*, 2008; *Panici and de Almeida*, 2018).
- Debris elements of different lengths but with equal diameter (on average) are used in the experiments, so that the ratio d/S can be neglected from (2). The inherent assumption is that debris diameter will have much smaller influence on the performance of the debris retention system than debris length. This assumption is supported by previous studies on debris-structure interactions at bridge piers (e.g. *Panici and de Almeida*, 2018) that have shown debris diameter to be of only secondary importance to debris entrapment and build-up processes. However, debris diameter may play a role in the porosity of the accumulation, which in turn may affect afflux; this aspect is not investigated in this paper.
- The spacing between the two modules that constitute the debris retention system is assumed to be sufficiently large to avoid interactions between individual debris elements; this would ensure that the performance of the system is not determined by the distance between subsequent modules. Hence, m/S can be removed from (2).
- The influence of the water depth on system efficiency e is assumed to be negligible since debris tends to float and accumulate at the free surface. In the experiments, therefore flow depth is kept sufficiently large to avoid interactions of debris with the channel bed.
- The Froude number relative to the characteristic length S , which is one of the dimensionless

160 groups, can be expressed instead with respect to L - i.e. as a debris Froude number
161 $Fr_L = v/\sqrt{gL}$; this is consistent with past studies on debris entrapment (*Bocchiola et al.*,
162 2008; *Panici and de Almeida*, 2018, 2020a).

163 Consequently, Equation 2 can be simplified as follows:

$$e = f\left(\frac{v}{\sqrt{gL}}, \frac{L}{S}, \frac{R}{S}, \frac{S}{T}\right). \quad (3)$$

164 (3) relates the efficiency of the debris retention system to the flow characteristics and the ge-
165 ometry describing the retention system. Therefore, the flume experiments (described in the next
166 section) and the data analysis are designed to explore the influence of the dimensionless variables
167 in (3) on the efficiency of the debris retention system.

168 **Experiments**

169 The experiments were conducted in a large, recirculating hydraulic flume at the University of
170 Exeter. The prismatic flume is 14 m long, 0.61 m wide, and 0.70 m deep. Figure 1 shows sketches
171 of the flume and the experimental setup adopted for this work as well as a photograph of the scale
172 model of the retention system in the flume. The flume (glass-walled and with stainless steel bottom)
173 was kept flat. Flow straighteners were present at its inlet to eliminate turbulence. The water depth
174 was controlled using a flap gate at the downstream end of the flume. Discharge in the flume was
175 varied between 0.042 m³/s and 0.156 m³/s, and was continuously monitored with a magnetic flow
176 meter having a nominal accuracy of 0.5%. The water depth was measured at the flume centreline,
177 0.5 m upstream from the experimental area, using a digital point gauge (nominal accuracy of 0.05
178 mm) and it ranged between 0.209 m and 0.339 m. The average velocity at this section varied
179 between 0.255 m/s and 0.763 m/s, and the Froude number ($Fr = v/\sqrt{gh}$) ranged between 0.145 and
180 0.426, reflecting a wide range of Fr for floods in lowland and hilly rivers. Prior to each flow
181 scenario, multiple measurements of the water depth across the experimental area were taken to
182 ensure that differences in depth were minimal. This ensured a gradually varied flow with negligible
183

184 convective accelerations.

185

186 The debris elements employed for these experiments were defoliated and non-branched natural
187 sticks as recommended by past studies on debris (*Lyn et al., 2003; Panici and de Almeida, 2020a*).
188 Furthermore, natural sticks would display similar physical properties (e.g. density, elasticity) to
189 large wood in rivers. The twigs used in this work were of two types: uniform and non-uniform in
190 length, following the experiments by *Panici and de Almeida (2018)*, to represent different types of
191 debris in rivers. Scenarios with uniform length debris consisted of debris elements with the same
192 length L . Experiments were run for two distinct values of L , namely $L = 0.25$ m and $L = 0.175$ m.
193 On the other hand, scenarios with non-uniform debris used a mixture of debris elements with three
194 lengths, namely $L_1 = 0.100$ m, $L_2 = 0.175$ m and $L_3 = 0.250$ m, with each constituting the same
195 proportion in the mixture. All debris elements had, on average, a diameter of 13.14 mm.

196

197 Four different types of debris retention systems were tested. These are referred to as experi-
198 mental groups A, B, C, and D. Each system consisted of two modules: a primary module (i.e. the
199 first module that debris would encounter) and a secondary module; both are shown in Figure 1.
200 The modules are rectangular in shape with an aluminium frame on the outside. The inside of the
201 rectangle is made up of a wire mesh - thin wires (0.25 mm) forming a square mesh of side 12.7 mm;
202 the resulting porosity (i.e. the ratio between the void area and the area occupied by the modules)
203 was always greater than 90%. The upstream tip of the first module was placed 7 m upstream from
204 the flume outlet, and overall the system occupied the area between 5.3 m and 7 m from the outlet.
205 The span-wise length S of the modules in groups A, B and C was kept equal to half-channel width
206 - 0.305 m, or $S/T = 0.5$. However the streamwise length R of the modules is different for each
207 group; this is to study the influence of the angle α (Figure 1), related to the dimensionless group
208 R/S as $\alpha = \arctan(R/S)$, on the efficiency of the system. α was 15° , 30° and 45° for groups A, B
209 and C respectively with corresponding values for R being 0.082 m, 0.176 m and 0.305 m. Group
210 D however differed from A, B and C. It had an angle α of 30° , but different values of S/T for the

211 primary and secondary modules - namely $S/T = 0.25$ for the primary module, i.e. half the width
212 S of the other modules, and $S/T = 0.50$ for the secondary module. In all the experimental groups,
213 the modules were placed as shown in Figure 1, i.e. such that the primary module was mounted on
214 the right bank and the secondary module from the left bank.

215

216 The performance of each of the retention systems, represented by the groups A, B, C and D,
217 were evaluated using three debris scenarios as summarised in Table 1. The scenarios are identified
218 using a numerical suffix alongside the group name of the retention system used in the experiment
219 (e.g. A1, A2 and A3). Suffix 1 indicates scenarios run with debris having length $L = 0.25$ m; 2
220 indicates that scenarios run with $L = 0.175$ m; and 3 indicates scenarios that used debris elements of
221 three different lengths in roughly equal proportion, i.e. $L_1 = 0.250$ m, $L_2 = 0.175$ m and $L_3 = 0.100$
222 m. Each debris scenario was studied for five different values of Fr_L , with two experimental runs
223 conducted for each Fr_L value and the results averaged to compute system efficiency. The only
224 exception is the system configuration with $\alpha = 30^\circ$ (experimental groups B1-B3), for which tests
225 were repeated four times for statistical robustness and to determine the standard deviation of the
226 system efficiency. In total, 150 experiments were performed.

227

228 Experiments were carried out by dropping 100 sticks one-by-one in sequence at a cross-section
229 6 m upstream of the primary module. The number of debris elements was chosen based on two
230 factors.

- 231 1. *Past research:* Past experimental studies (e.g. *Gschnitzer et al., 2017; De Cicco et al., 2020*)
232 that have investigated the probability of formation of large wood debris accumulations at
233 riverine structures have used between 50 and 100 debris elements.
- 234 2. *Field observations of large wood debris:* Several field surveys have noted that the total
235 volume of water-borne wood during floods is typically between 100 and 1000 m³ (*Ruiz-*
236 *Villanueva et al., 2016; Steeb et al., 2017*), although values lower than 90 m³ have also
237 been observed in some instances (*Waldner et al., 2007; Gschnitzer et al., 2017*). A notable

238 example is the 2005 event in Switzerland in which wood volumes were observed for many
239 rivers in the range $50 \text{ m}^3 - 1000 \text{ m}^3$ (Waldner *et al.*, 2007; Schmocker and Weitbrecht, 2013;
240 Steeb *et al.*, 2017). For the chosen experimental configuration, volumes of 90 and 1000 m^3
241 correspond to scaling factors of 30 and 66 respectively, for which the flume width would
242 correspond to rivers having a channel width of 18 m and 40 m respectively.

243 The sticks were dropped at the flume centreline from a height of (approximately) 50 mm from
244 the water surface. They were kept parallel to the flow direction and released at a frequency of
245 approximately one element every 3 seconds. This frequency was selected to avoid interactions
246 between individual elements, since previous research has shown that large wood debris move in
247 rivers as individual elements rather than clusters (Braudrick *et al.*, 1997; Diehl, 1997; Lyn *et al.*,
248 2003, 2007; Lagasse *et al.*, 2010) although large masses of logs have also been occasionally ob-
249 served, especially in mountainous areas (Ruiz-Villanueva *et al.*, 2019). A fixed camera placed 1
250 m upstream of the experimental area monitored continuously the entrapment of debris elements
251 by the retention system. At the end of each test, the number of debris elements trapped at each
252 module were counted. The number of debris elements that escaped the retention system and were
253 captured at a wire mesh screen placed downstream of the flume were also counted. The water depth
254 upstream of the modules was also measured at the beginning and at the end of each experiment to
255 estimate the afflux caused by the accumulated debris. The depth was measured 0.50 m upstream
256 from the most upstream tip of the first module, as shown in Figure 1, to allow sufficient room for
257 the full development of the debris accumulation (i.e. the upstream extension of the accumulation
258 from the first module was always less than 0.50 m). The afflux was measured as the ratio $\Delta h/h$,
259 where h is the undisturbed flow depth and Δh is the increase in water depth, relative to h , at the
260 end of the experiment.

261

262 RESULTS

263 Results from the experiments show common features upon collation. These are discussed in

264 detail in the following sections.

265 **General observations**

266 The trapping of debris with time is analysed by using data from a set of 15 experiments involving
267 groups C1, C2 and C3, covering all the tested Fr_L conditions. Figure 2 shows how the cumulative
268 number of retained logs (vertical axis) varies with the total number of debris elements released
269 (horizontal axis); the latter is proportional to time as the debris elements are released into the flume
270 at a constant rate. The resulting relationship is essentially linear for all conditions with only minor
271 variations (mostly due to individual elements passing through or being removed from the structures
272 by impact with other incoming logs). The video footage of the same set of 15 experiments is
273 also analysed to evaluate the variation in the number of logs trapped by individual modules of the
274 retention system with time, and the results are shown in Figure 3. This figure, compared to Figure
275 2, however only shows data for three Fr_L conditions to ensure the plots are legible. Figure 3 shows
276 that nearly equal number of debris elements are trapped by the two modules in the early stages
277 of the experiments. However, this phenomenon is short-lived; the first module at low Fr_L , (and,
278 conversely the second module at high Fr_L), traps a disproportionately larger number of debris with
279 the progress of the experiment. These observations, based on Figures 2 and 3, are also true for the
280 other experimental groups; the corresponding plots are not shown for reasons of brevity.

281

282 Image frames extracted from the footage of the experiments provide important insights in the
283 process of accumulation of large wood debris at the trapping structures. Figure 4 shows four
284 images (each for a different Fr_L) of the debris accumulations at the modules for the experimental
285 group C2 (chosen here as a representative example) at the end of each experiment. For low Fr_L ,
286 the accumulation is in the form of a debris mat that extends into the upstream reach with most
287 logs being retained at the first module, whilst only a small amount of large wood debris is trapped
288 at the second module. However, increase in Fr_L gradually changes the size and geometry of the
289 accumulated debris, and the distribution of logs between the two modules is also very different.
290 There is a smaller number of logs at the first module and a larger number of logs at the second

291 module. Also, the surface area of the accumulation has decreased while the vertical dimension
292 (depthwise) of the accumulation has increased.

293

294 The analysis of video recordings can help understand the mechanism by which debris elements
295 occasionally passed through the system. Figure 5 shows a sketch of the most commonly observed
296 mechanism: the escaping elements reached the first module approximately at the centreline; then,
297 after passing the first module, the elements followed the main flow lines (that on the surface were
298 altered by the presence of the modules and accumulated debris) and, as a result, also passed by the
299 second module. On a few occasions, these elements impacted the modules and then rotated about
300 the outside frame of the rack. Other less frequent mechanisms involved oncoming logs impacting
301 an accumulation and causing removal of one or a few debris elements. Analysis of the recordings
302 show that all escaping elements follow a similar path after passing the second module. They are
303 observed to be re-routed on the half-channel opposite to the second module. At larger Fr_L , the
304 elements are seen to move further towards the far side of the flume, i.e. at high Fr_L most escaping
305 elements are observed near the flume wall after the second module. This indicates that any obstacle
306 (e.g. a bridge pier) in the downstream reach located away from this preferential path (i.e. away
307 from the banks) is unlikely to interact with debris elements that may pass through the system.

308

309 **Efficiency**

310 The efficiency of the tested debris retention system is observed to be dependent on the debris
311 Froude number Fr_L as well as on the type of debris employed. This is initially illustrated using
312 results for groups B1 to B3 due to their relatively higher statistical robustness compared to those
313 for other groups as a result of the larger number of experimental runs conducted for each value of
314 Fr_L . Figure 6 shows on the vertical axis the percentage of debris (relative to the total number of
315 debris elements released) trapped at the first and the second module as well as the percentage of
316 debris that passed through the system for scenarios B1, B2 and B3 with respect to various values of
317 Fr_L . Figure 6, using error bars, also displays the standard deviation in test results for groups B1-B3

318 for the four experimental runs conducted for each Fr_L value. It can be observed that the dispersion
319 in results is typically small at high values of Fr_L , while being significant at low Fr_L . Furthermore,
320 the levels of dispersion are generally similar for the three different debris scenarios, although, for
321 $L=0.175$ m, a slightly smaller dispersion is visually discernible from the plots.

322

323 In general, better efficiency, between 85% and 92%, is observed for longer debris elements
324 (group B1) compared to that for shorter debris elements (B2) or mixed debris (B3), for which the
325 efficiency varies between 79% and 90% and between 72% and 81% respectively. Figure 6 also
326 shows that, for low values of Fr_L , the primary module traps a higher percentage of debris elements
327 than the secondary module across all groups B1, B2 and B3. Nevertheless, for large values of
328 Fr_L , the trend is reversed; in these cases, the secondary module traps a higher percentage of debris
329 elements with the primary module showing a markedly reduced ability to trap debris. While Figure
330 6 only shows results for one type of debris retention system (group B), the same tendency is also
331 observed for the other systems.

332

333 Most experimental groups, i.e. configurations of the debris retention system, show a high debris
334 entrapment efficiency. However, marked differences are observed between a few groups. Figure
335 7 shows the box plot of the debris retention efficiency for the four groups - A, B, C and D, for
336 all flow conditions and debris types. The figure shows the average, upper and lower interquartiles
337 and the total range of the efficiency of the various systems. Structures in groups C1 to C3 with
338 $\alpha = 45^\circ$ have the highest efficiency, which varies between 84% and 99% (92% on average) across
339 all tested values of Fr_L and L . The efficiency decreases with decreasing α : for $\alpha = 30^\circ$, i.e. groups
340 B1 to B3, efficiency ranges between 74% and 97% (average 85%), whilst for $\alpha = 15^\circ$, i.e. groups
341 A1 to A3, efficiency ranges between 49% and 94% (average 70%). A different result is observed
342 for group D in which the width of the first module is halved. The efficiency drops significantly; it
343 ranges between 32% and 83% and has an average of 54%.

344

345 The efficiency results are now examined in relation to the size of debris elements. The ob-
346 servations are similar to those made for experimental group B from Figure 6. The size of debris
347 elements do not have a notable influence on the system efficiency across all experimental groups,
348 although a trend is evident. Figure 8 shows the efficiency versus Fr_L for all structures for different
349 debris lengths L . The system is observed to have a high overall efficiency at the lowest range of
350 Fr_L and the efficiency tends to decrease (or, conversely, the pass rate of debris elements increases)
351 with increase in Fr_L . Furthermore, the highest efficiency (e.g. 99% for C1 within group C) for an
352 experimental group is generally observed for the longest debris elements ($L=0.25$ m) and this is
353 especially true for low Fr_L values. Figure 9 shows the efficiency of the four tested structures for each
354 tested debris length. For all structures except for structure type A, the efficiency is slightly lower
355 for runs with shorter debris elements and runs with mixtures containing debris of different lengths.
356 This trend is however less clear and definitive than for other variables (e.g. α) for structure types
357 A, B and C; on the other hand, structure type D shows marked differences among groups D1, D2
358 and D3. Furthermore, the general trend of efficiency e decreasing with increasing Fr_L irrespective
359 of the type of debris elements used, already observed in Figure 8, is also confirmed by the results
360 given in Figure 9. A similar observation can also be made for the influence of the inclination
361 of the retention system on efficiency; $\alpha = 45^\circ$ shows the highest efficiency, with e reducing with
362 decreasing α .

363

364 **Afflux**

365 The increase of the upstream water level (i.e. afflux) was also measured for each experiment.
366 Figure 10 plots the afflux (calculated as the percentage increase in water level measured at the end
367 of an experiment relative to the original undisturbed upstream water depth h) for the four tested
368 structures versus Fr_L for the three debris scenarios. There is a clear trend of the afflux increasing
369 with increase in Fr_L . Nevertheless, the magnitude of the increase depends on the type of debris
370 used: longer debris elements typically produce a larger increase in afflux than short elements or a
371 mixture of debris having different lengths. For instance, the highest afflux (average of 11%), which

372 is higher than that for short (B2) and mixed (B3) debris (average 7.8% and 7.4% respectively), is
373 observed at $Fr_L \approx 0.41$ for test B1 ($\alpha = 30^\circ$). The afflux is also dependent on the configuration of the
374 retention system, i.e. the experimental group: the afflux is significantly higher for groups A and
375 B ($\alpha = 15^\circ$ and 30°) than for group C ($\alpha = 45^\circ$) - e.g. the maximum afflux for group C is 6.9%,
376 below the maxima of 8.9% and 11.0% for groups A and B. For group D, the afflux is very low
377 (maximum is 4.8%), although this can be explained by the generally low capacity of this structure
378 to trap debris elements.

379 **DISCUSSION**

380 **Efficiency**

381 Experimental results clearly highlight the importance of the ratio S/T and the angle α . Group D,
382 using modules with $S/T = 0.25$, exhibits the least efficiency (Figure 7) amongst the tested groups.
383 This result is according to expectation; the efficiency e is observed to drop with a decrease of
384 the width of the module. These results also suggest that there may be potential to adjust S/T to
385 obtain a desired efficiency; this may be useful to enable downstream transport of a certain level
386 of large wood debris. Similar to the influence of S/T , the efficiency of the system is observed
387 to rise with an increase in the angle α , with the best efficiency obtained for group C (Figure 7)
388 with $S/T = 0.5$ and using the highest angle ($\alpha = 45^\circ$) among the tested groups. While this finding
389 may seem counter-intuitive, experimental observations revealed that, at small α values, the debris
390 elements tended to rebound or be easily dislodged when they get entrapped near the edge of the
391 modules. On the other hand, a sharper angle allowed debris to be dragged inward of the module
392 toward the flume wall (i.e. the river bank at full-scale), effectively preventing debris elements from
393 drifting away.

394

395 The influence of the log length on efficiency is less evident than that of α . Nevertheless, longer
396 lengths are observed to lead to a higher trapping efficiency. This result, which aligns with findings
397 from previous studies (*Bocchiola et al., 2008; De Cicco et al., 2020*) on debris accumulations, may
398 be a consequence of the increased probability of interactions occurring between log and structure

399 as well as amongst logs themselves, including interlocking. However, further research is required
400 to accurately explain this behaviour. An important inference can also be made on the basis of the
401 relationship between retention efficiency and wood volumes for the range tested in this study. The
402 trend observed in Figure 2 highlighted that the amount of wood trapped by the system generally
403 scales linearly with the amount of wood released. Therefore, the trapping efficiency can be expected
404 to remain in the same observed range for the spectrum of volumes tested in this work.

405
406 Analysing the efficiency of the individual modules of the retention system over the duration
407 of the experiments offers interesting insights. At the initial stages of each test, the proportion of
408 trapped debris was roughly the same for the two modules, as shown visually for a few experimental
409 runs in Figure 3. However, for low values of Fr_L , as the accumulation at the first module extended
410 into the opposite side of the channel (e.g., as observed in Figure 4a) its trapping capacity increased
411 dramatically, resulting in most debris accumulating at the primary module and few elements being
412 conveyed to the secondary module. Nevertheless, the exact opposite happens at high Fr_L values. In
413 this case, elements at the edge of the first module were effectively removed by the flow and directed
414 towards the second module, which was able to trap most of the debris elements. Therefore, the
415 increase in Fr_L not only changed the physical conditions for which debris could accumulate at the
416 two modules but also altered the size and geometry of the accumulation of logs (Figure 4). This
417 behaviour is possibly due to the increase in drag force applied to the logs which then pulls the
418 debris elements together and accumulates them under water.

419
420 Inferences can be drawn from the results on the need for a minimum of two modules within
421 the proposed debris retention system. In the experiments, the two modules are spaced so that the
422 efficiency of the primary module is independent of the presence of the secondary module (i.e. the
423 secondary module's effects on flow do not extend up to the primary module). Consequently the
424 results can be analysed to understand the efficiency of the primary module. Figure 6 shows the
425 number of debris elements trapped by the primary and secondary modules in experimental group

426 B for various values of Fr_L . The common trend amongst all experiments within group B (and
427 also groups A and C) is that the trapping efficiency of the primary module decreases with Fr_L ;
428 the exception is group D, i.e. for $S/T = 0.25$, for which the trapping efficiency tends to increase
429 slightly with Fr_L , although it remains extremely low compared to other cases. The results shown
430 in Figure 6 reveal that a single module could be efficient at low values of Fr_L . However, for large
431 values of Fr_L , a single module is likely to be inefficient; a second module would be required to trap
432 the majority of debris elements.

433
434 Results enable comparing the performance of the proposed debris retention system with similar
435 systems previously studied in literature. Table 2 shows a detailed analysis of these systems including
436 standard debris racks. The table shows that group C1 ranks among the most efficient configurations.
437 It demonstrates performance comparable to or better than *Schmocker and Weitbrecht* (2013). Only
438 the structure proposed by *Hartlieb* (2017) performs better (i.e. 100%) than group C1, which may be
439 a consequence of *Hartlieb's* (2017) structure using a fine mesh and covering the complete channel
440 width. Other measures either show a negative efficiency (e.g. *Lyn et al.*, 2003) or lower retention
441 capacity (e.g. *Lange and Bezzola*, 2006).

442 443 **Afflux**

444 The afflux measurements provide useful insights on the potential flood risk impact of the em-
445 ployment of the proposed debris retention systems. The worst case for afflux are the scenarios with
446 the highest Fr_L values, with the maximum afflux observed to be 11% of the water depth amongst
447 all the tested scenarios. Nonetheless, the afflux is dependent on α ; modules with $\alpha=45^\circ$ would
448 create the least afflux, and therefore minimise the increase in flood risk, whilst for $\alpha=15^\circ$ and
449 $\alpha=30^\circ$ the afflux is more substantial, especially for higher Fr_L . This result is potentially due to
450 the accumulations causing a smaller reduction in the flow cross-section at $\alpha=45^\circ$ because of the
451 larger surface area (and consequently the larger volume) available for the debris to accumulate over
452 relative to the other configurations.

453

454 The lowest levels of afflux are observed for Group D (Figure 10). This is likely because this
455 group with an angle $\alpha = 30^\circ$ has the lowest volume of accumulated wood of all the tested config-
456 urations. Similar results are also observed when the log lengths are different, as shown in Figure
457 10. The afflux for all four experimental groups was smaller for debris with length $L = 0.175$ m and
458 debris of mixed lengths than for debris with length $L = 0.25$ m. The larger afflux was potentially due
459 to the larger accumulation produced for $L = 0.25$ m than for the other two debris length scenarios.

460

461 Using Buckingham's Π theorem and making assumptions similar to those used for dimensional
462 analysis of retention efficiency in the Methodology section, the increase in water depth arising
463 from a debris accumulation at the proposed debris retention system can be defined by a functional
464 relationship of the type:

$$\Delta h = f(h, V, S, R, v, g) \quad (4)$$

465 where V is the volume of accumulated debris. Therefore, together with the flow conditions,
466 the increase in water depth Δh is caused by a relationship between the volume V of the debris
467 accumulation and the maximum debris volume that each structure can hold as determined by the
468 water depth h , and the size of the modules, i.e. S and R . This volume, which is denoted by V_C ,
469 is the volume of fluid enclosed by the two modules that can be occupied by the debris elements
470 once they get trapped, i.e. for identical geometries of the two modules $V_C = hSR$. Thus, Equation
471 (4) becomes:

$$\frac{\Delta h}{h} = f\left(Fr, \frac{V}{V_C}\right). \quad (5)$$

472 A non-linear least-squares regression (with a bisquare weights method) on the afflux data given
473 in Figure 10 was used to relate the non-dimensional parameters given in Equation (5) and resulted
474 in the following function:

$$\frac{\Delta h}{h} = 5.01 \text{Fr}^{3.67} \left(\frac{V}{V_C} \right)^{0.50} . \quad (6)$$

475 For ease of representation on a 2D plane, if the product including Fr and V/V_C is defined as the
 476 accumulation factor $A_F = \text{Fr}^{3.67} (V/V_C)^{0.50}$, Equation (6) becomes:

$$\frac{\Delta h}{h} = 5.01 A_F . \quad (7)$$

477 Figure 11 shows the experimental data compared to the regression in Equation (7), with the
 478 afflux $\Delta h/h$ on the vertical axis and the accumulation factor A_F on the horizontal axis. The 95%
 479 prediction interval is also shown. The resulting regression from Equation (7) provided a regression
 480 coefficient $R^2 = 0.93$ and p-value $\ll 0.01$. Equation (7) and Figure 11 can facilitate afflux assess-
 481 ment for full-scale applications of the proposed retention system. In addition, since the volume of
 482 trapped large wood debris showed to accumulate linearly in time, up to the amount of volume V
 483 tested, it can be inferred that estimation of afflux through (7) is valid for the range of V/V_C tested.

484
 485 Finally, the afflux for the proposed system is compared to those for debris retention structures
 486 tested in previous works (Table 2). The table shows that the system proposed in this paper causes
 487 minimal (i.e. up to 11%) increase in the upstream water level in contrast to full-width horizontal
 488 racks. For example, *Schalko et al.* (2019a) demonstrated that, depending on Fr and the wood pack-
 489 ing density, backwater level can increase by up to 250% in conventional racks. Other systems (e.g.
 490 *Schmocker and Weitbrecht*, 2013) also typically doubled the upstream water level. Therefore the
 491 system proposed in this paper can offer superior performance in terms of afflux and consequential
 492 flood risks over other debris racks for the flow and wood variables tested.

494 Case study

495 In this section, the potential efficiency and effects of the four structures are evaluated for a real-
 496 world situation - a reach of the river Torridge in Devon, UK. Figure 12 shows the proposed location

497 of the two modules and the first bridge structure that would be protected from large wood debris,
498 namely Taddiport Bridge. Figure 12 also shows an accumulation of large wood debris that occurred
499 at this bridge in 2012. The location chosen for this case study is in between Great Torrington and
500 Taddiport. Downstream of this location, there are seven bridges known to be highly susceptible
501 to large wood debris accumulations (*Panici et al.*, 2020b), with Old Rothern and Rothern (Rolle)
502 bridges the worst affected. The area upstream of the considered location is not known to have
503 flooding issues and an increase of backwater in the range observed in this study would not affect
504 the risk of flooding. Also, the areas where the modules will be placed can be easily accessed from
505 the banks for debris removal. The average channel width at the location in Figure 12 is 33.7 m,
506 which corresponds to a model-prototype length scale factor of approximately 55. Table 3 shows
507 the efficiency and afflux evaluated for the four different modules studied in the experiments. The
508 performance of the retention system is assessed for six flood events (corresponding to different
509 return periods) and for a large wood debris length of 13.8 m (corresponding to the model-scale
510 length of 0.25 m). Assuming that 100 debris elements get transported during the events considered
511 (consistent with the experimental conditions), the total equivalent volume of large wood debris at
512 real-scale will equal 612 m³. Such a volume is realistic; for example, a similar wood volume was
513 observed at the river Emme in Switzerland in 2014 (*Ruiz-Villanueva et al.*, 2019).

514 The results shown in Table 3 highlight that flow conditions and wood characteristics (i.e. Fr
515 and Fr_L) are within the experimental range tested in this work for all return periods. Thus, the
516 up-scaling can be performed to acceptable levels of accuracy. As revealed with the experimental
517 data, the system efficiency varies according to the structure type. Type C (i.e. $\alpha = 45^\circ$) provides
518 the highest efficiency (96-99% of retained wood) and is also most robust, i.e. shows the smallest
519 variation in efficiency across Fr_L . In contrast, type A structure is less robust, with efficiency varying
520 significantly across Fr_L . The afflux increase is smallest for type B but only slightly worse for type
521 C. Therefore, if the goal of the application of the retention system is to reduce as much as possible
522 the amount of debris that can be transported downstream and at the same time limiting the afflux,
523 the type C structure would provide the best performance.

524 **Practical applications and future outlook**

525 Using Froude similarity (and assuming that scale effects are negligible), results from this study
526 can be up-scaled for full-scale scenarios. However, for scaling to be realistic, the values for flow and
527 debris parameters including debris volume must be such that the computed dimensionless variables
528 (e.g. Fr , Fr_L) have values within the range studied in this paper. Considering the values of Fr_L , Fr ,
529 and other variables tested in this work, results may be applicable mostly to hilly and/or lowland
530 rivers. Practical issues may also need to be considered according to the structure that the system
531 is designed to protect. For example, when applied to bridge piers in very wide rivers, the width
532 of the racks may end up being significantly larger than the pier width, thus suggesting that other
533 measures should be considered. Other aspects should also be accounted for when designing this
534 structure: for example, the spacing between the mesh elements should be wide enough to minimise
535 disturbance to the flow but also to avoid logs escaping through the gaps; the height of the modules
536 should also exceed the water level of the design flood event plus any allowance for debris volume.

537

538 The retention system proposed in this paper may also be utilised to meet environmental re-
539 quirements on river ecosystem continuity. The configuration of the racks enables removal of
540 large wood debris from the banks during low flow. The removed debris can also be subsequently
541 reintroduced at a downstream location. The system may instead also be designed to a certain effi-
542 ciency to allow for a certain percentage of wood to be conveyed to the downstream reach of the river.

543

544 Further development of the proposed debris retention system requires consideration of other
545 parameters that have been altogether excluded from or only partially investigated or in this work.

- 546 • Localised flow changes may have an effect on bank erosion: the flow components (especially
547 on the surface) tend to display lateral components that may impact the stability of the channel
548 banks. This would depend on the flow characteristics, the obstructed area and the condition
549 of the channel banks (e.g. vegetation, soil).
- 550 • Large amounts of wood volume, moving *en masse* (also known as congested or hyper-

551 congested transport), were not tested in this study. Practical applications in which this
552 situation is expected - e.g. mountainous rivers in which wood transport can be very high
553 (*Ruiz-Villanueva et al.*, 2019), may result in inaccurate estimations.

- 554 • Finally, localised scour should be considered, since a likely configuration in full-scale
555 would include poles embedded into the river bed. Nonetheless, these poles are likely to be
556 typically small in width and pose minimal obstruction to the flow by themselves; hence, the
557 resulting scour depth due to the racks themselves is expected to be manageable. However,
558 accumulated large wood debris is likely to result in scour and this needs to be evaluated and
559 accounted for in the design and operation of the retention system. Measures should also
560 be considered to allow continuity of bed-load sediment transport by, for example, limiting
561 the blockage at bed level. Moreover, accumulated large wood debris may change sediment
562 transport rates at the racks depending on the debris blockage area.

563 CONCLUSIONS

564 In this paper, we proposed a large wood debris retention system for use in rivers for bridge
565 protection and effective management of debris mitigation measures, and experimentally tested its
566 efficiency using scale models. The system consists of two modules, which were designed as meshed
567 racks placed from the side to the middle of the channel and with an inclination relative to the flow
568 direction. The experiments were aimed at evaluating how the debris trapping efficiency of the sys-
569 tem was influenced by the geometrical properties of the modules and the flow and debris parameters.

570
571 Experimental results support the following conclusions.

- 572 • The angle α between the system and the flow direction has a major influence on the system
573 efficiency. The efficiency is maximum for $\alpha=45^\circ$ for all the flow conditions and types of
574 debris used and decreases with decreasing values of α .
- 575 • Highest efficiency is reached when the ratio S/T is equal to 0.50, i.e. the width of the
576 structure is greater or equal than the channel width. The use of systems with smaller widths

577 resulted in a significantly smaller overall efficiency.

- 578 • A dual-module layout was crucial for the high efficiency achieved in the tests. At low
579 Fr_L values, most of the debris are trapped by the primary module. As Fr_L increases the
580 contribution of the secondary module to overall efficiency increases while that of the
581 primary module reduces.
- 582 • The system has a relatively low impact on upstream afflux. For the case of $\alpha=45^\circ$, the water
583 level increase ranged between 0.5% and 10%. Other tested values of α produced slightly
584 higher values of afflux.

585 The systems tested in this paper represent the first evaluation of a novel concept of a debris
586 retention system. Compared to regular full-width debris racks, the concept proposed in this paper
587 has (i) a high retention efficiency (equal or similar to full-width racks) and (ii) causes limited
588 increase in backwater levels (and thus flood risk) compared to the very high increases (up to
589 300%) observed with other solutions. The system also provides continuity for navigation as well
590 as reduced costs, both constructional and operational. The former, since it would not occupy
591 large areas or require construction of further structures (e.g. a gate); the latter, since it would
592 require low maintenance and the removal of logs can be carried out from the banks, minimising
593 or avoiding the costs for use of heavy machinery and impacts on traffic if removing debris from
594 within the river. Further research is required in order to better understand structural design and its
595 practical application at full scale. Its application at full scale might be expected to significantly
596 reduce the amount of debris conveyed along a river and to provide bridge owners or overseeing or-
597 ganisations an easier and more cost-effective way to remove and relocate large wood debris in rivers.

599 **DATA AVAILABILITY STATEMENT**

600 Some or all data, models, or code generated or used during the study are available in a repository
601 online in accordance with funder data retention policies. Data supporting the results presented in
602 this paper are openly available from the University of Exeter repository at doi: <http://doi.org/...>

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705 efficiency and afflux for flood events with return periods of 2, 5, 10, 25, 100 and

706 200 years. 33

TABLE 1. Summary of experimental tests conducted in this work

Group	S/T	L/S	α	Flow depth range (mm)	Fr range
A1	0.50	0.82	15	248 - 318	0.143 - 0.426
A2	0.50	0.57	15	248 - 318	0.143 - 0.426
A3	0.50	0.57*	15	248 - 318	0.143 - 0.426
B1	0.50	0.82	30	209 - 275	0.143 - 0.418
B2	0.50	0.57	30	209 - 275	0.143 - 0.418
B3	0.50	0.57*	30	209 - 275	0.143 - 0.418
C1	0.50	0.82	45	317 - 335	0.145 - 0.421
C2	0.50	0.57	45	317 - 335	0.145 - 0.421
C3	0.50	0.57*	45	317 - 335	0.145 - 0.421
D1	0.25**	0.82	30	314 - 339	0.147 - 0.414
D2	0.25**	0.57	30	314 - 339	0.147 - 0.414
D3	0.25**	0.57*	30	314 - 339	0.147 - 0.414

* average length of debris mixture

** only for the first module

TABLE 2. Comparison among experimental results on debris retention structures

Study	Rack characteristics	Retention efficiency	Afflux range ($\Delta h/h$)
<i>Lyn et al. (2003)</i>	Submerged groin-like structure to deflect the flow	Smaller than without structure	N/A
<i>Lyn et al. (2003)</i>	Single pile deflector	Smaller than without structure	N/A
<i>Lange and Bez-zola (2006)</i>	Horizontal racks in alternate order placed across the channel (steep-gradient rivers)	42-87% (27-35% if excluding deposition on river bed)	N/A
<i>Schmocker and Weitbrecht (2013)</i>	Bypass retention basin	90-95%	100-170%
<i>Hartlieb (2017)</i>	Retention racks at spillways	100%	5-45%
<i>Schalko et al. (2019a)</i>	Accumulated large wood debris at a rack with fixed and mobile bed	N/A	0-250%
<i>This work</i>	Alternate racks spanning half-channel and at an angle to the flow	Depending on α and S/T , between 91-99% (group C1) and 32-64% (group D2)	Depending on α and S/T , between 0-3.8% (group D2) and 0-11% (group B1)

TABLE 3. Application to a case-study on the river Torridge in Devon (UK): Estimation of efficiency and afflux for flood events with return periods of 2, 5, 10, 25, 100 and 200 years.

Quantity	Flood event return period					
	2	5	10	25	100	200
Discharge (m^3s^{-1})	250	327	385	472	638	743
Froude number Fr	0.343	0.348	0.352	0.357	0.365	0.369
Debris Froude number Fr_L	0.164	0.182	0.195	0.211	0.238	0.253
Efficiency e (group A) (%)	88	86	85	83	80	78
Efficiency e (group B) (%)	91	92	92	92	91	90
Efficiency e (group C) (%)	99	98	98	97	96	96
Efficiency e (group D) (%)	83	82	81	80	78	78
Afflux $\Delta h/h$ - group A (%)	14.9	14.2	13.9	13.5	13.1	12.8
Afflux $\Delta h/h$ - group B (%)	10.3	10.0	9.86	9.70	9.48	9.37
Afflux $\Delta h/h$ - group C (%)	10.5	10.5	10.6	10.6	10.8	10.9
Afflux $\Delta h/h$ - group D (%)	12.4	11.97	11.71	11.5	11.1	11.0

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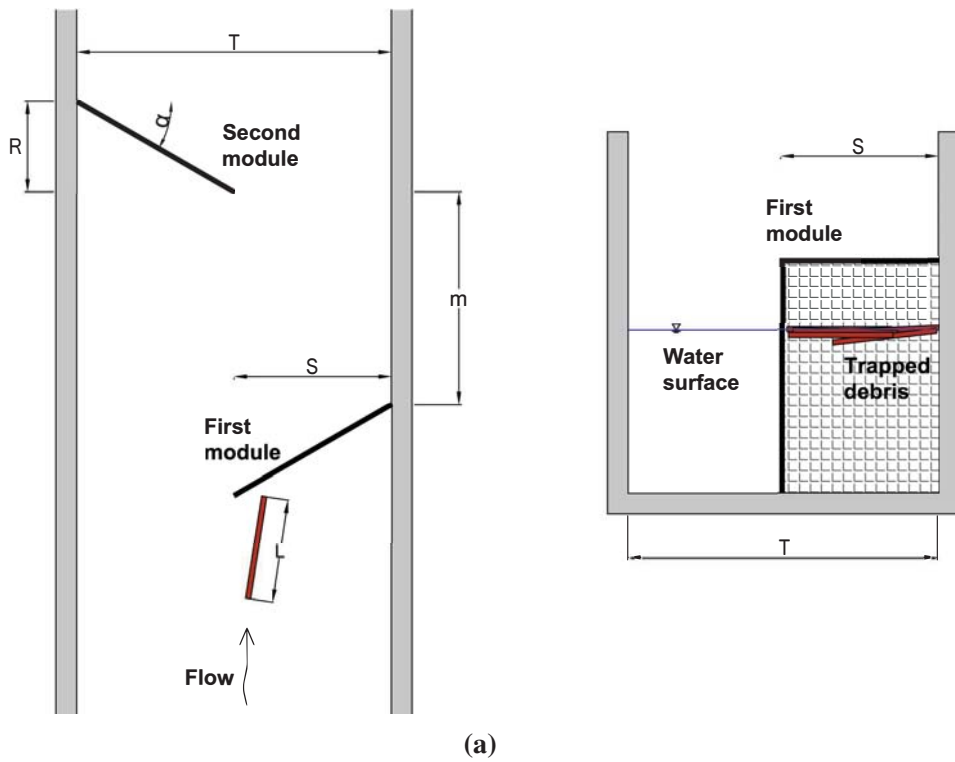
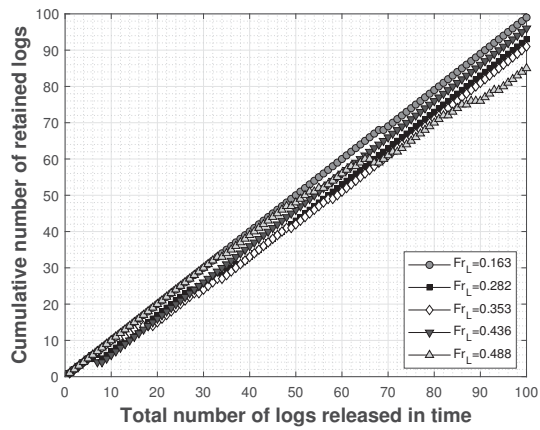
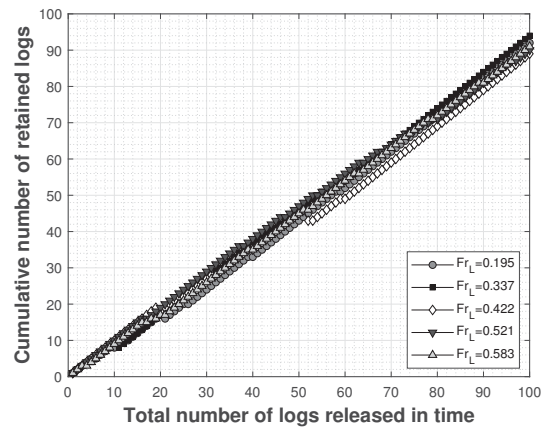


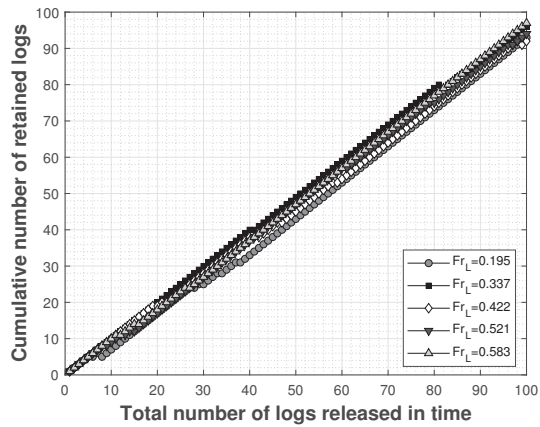
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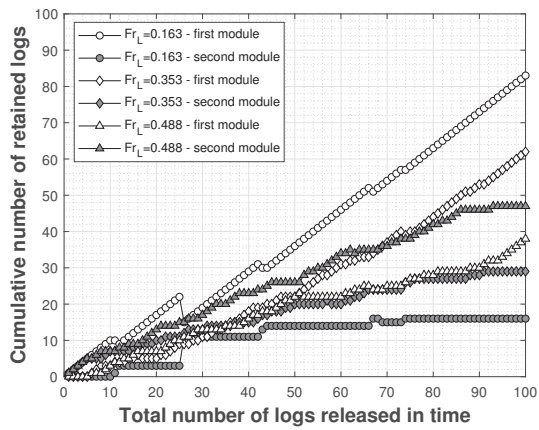


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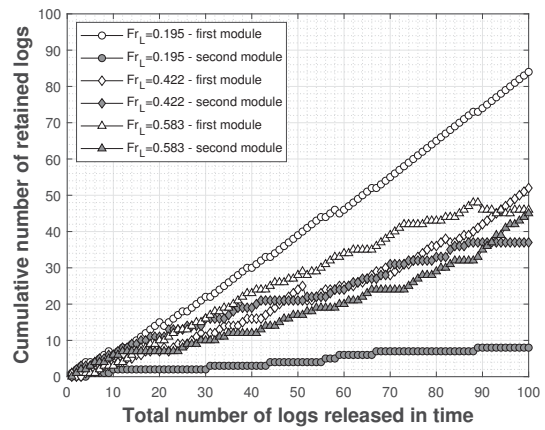


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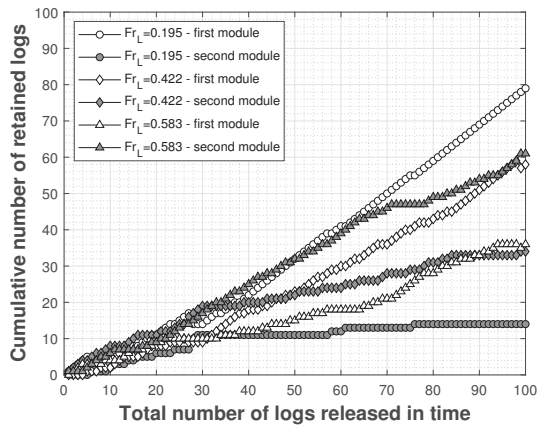
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(a)



(b)

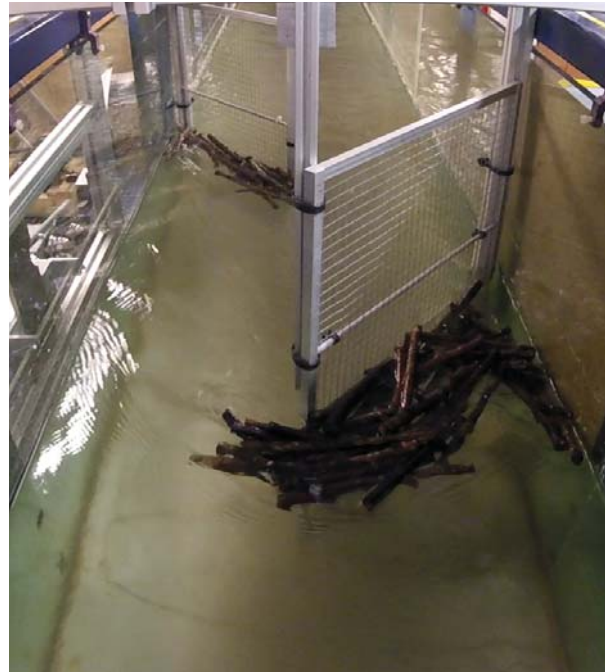


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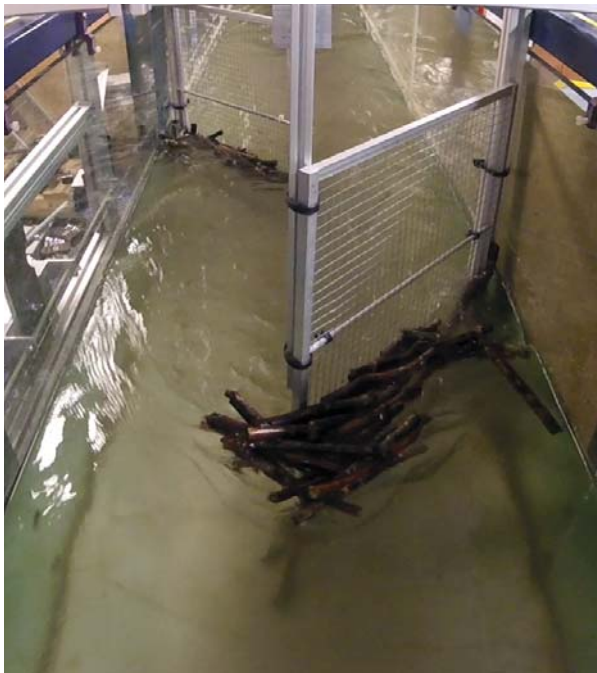
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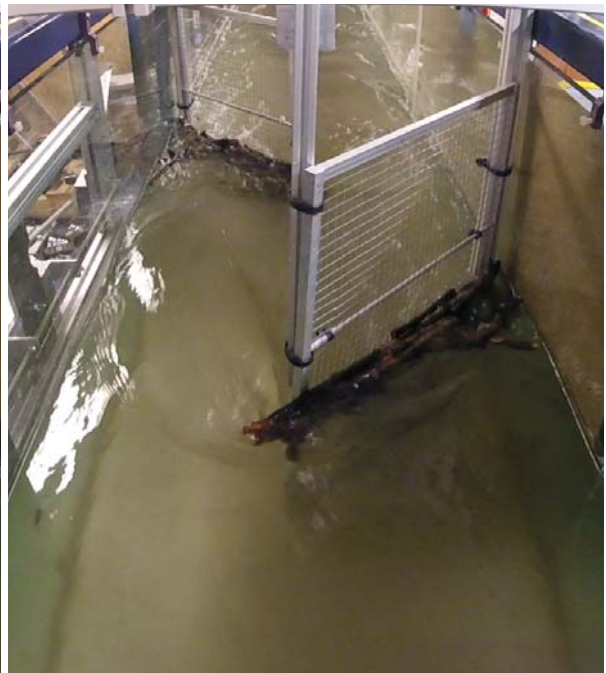
(a)



(b)



(c)



(d)

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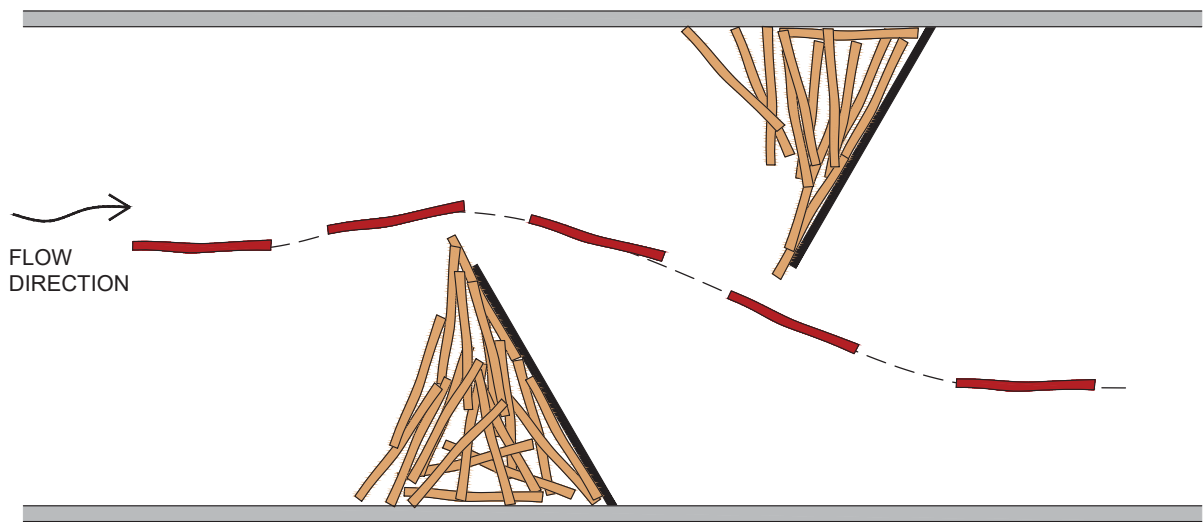
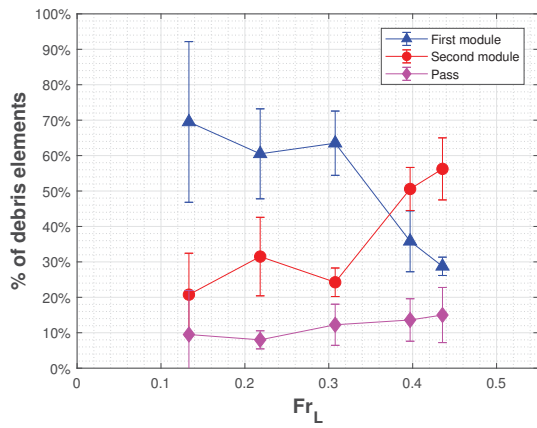
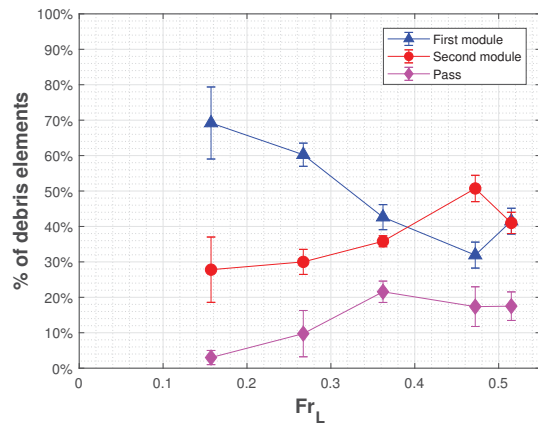


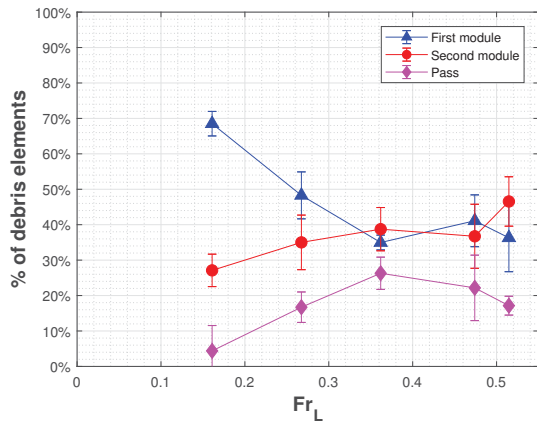
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(a)



(b)



(c)

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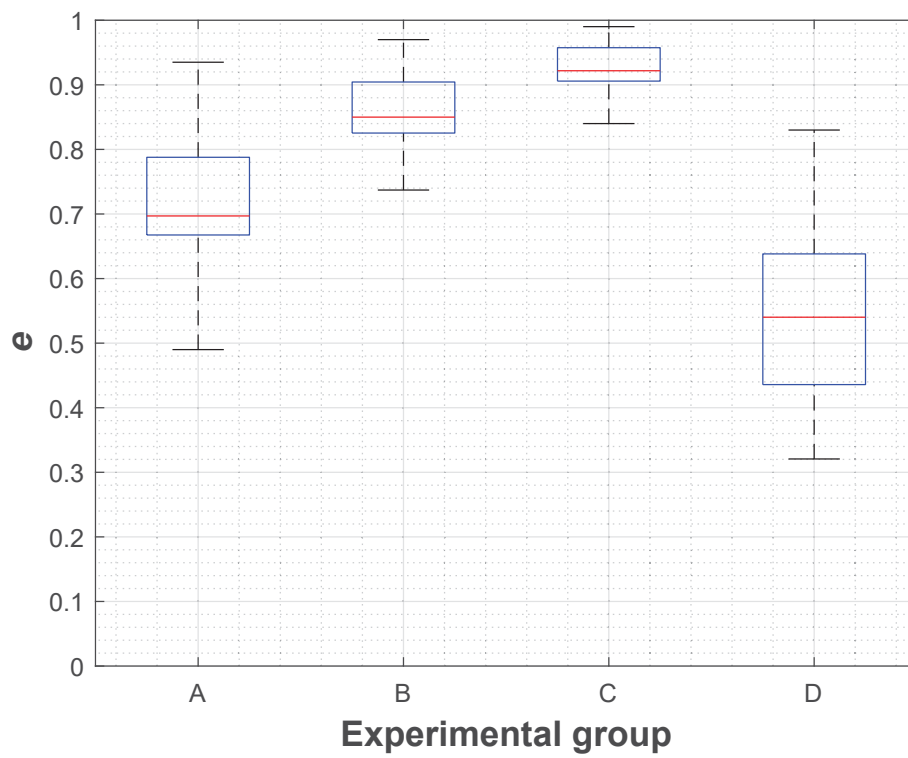
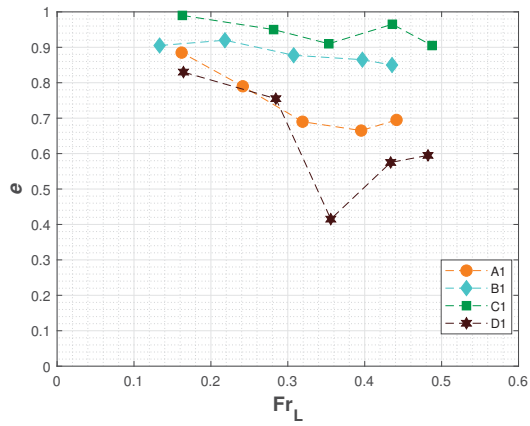
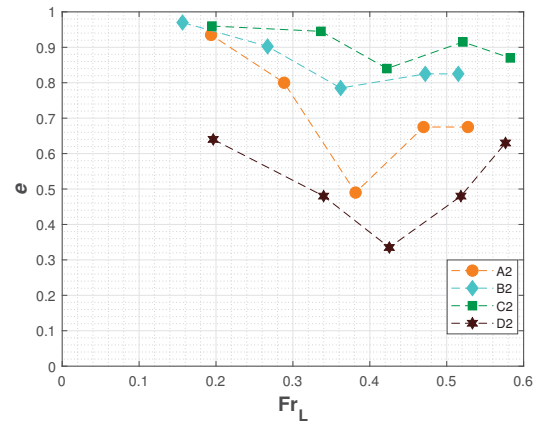


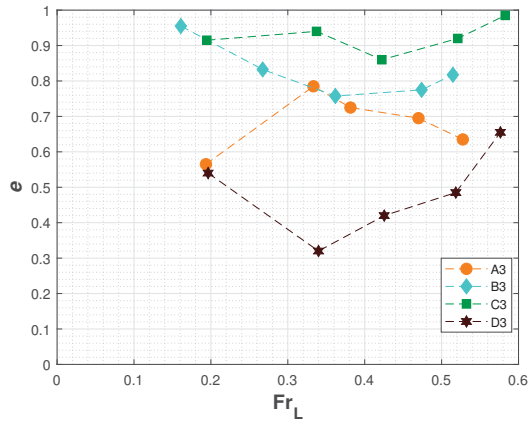
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(a)



(b)



(c)

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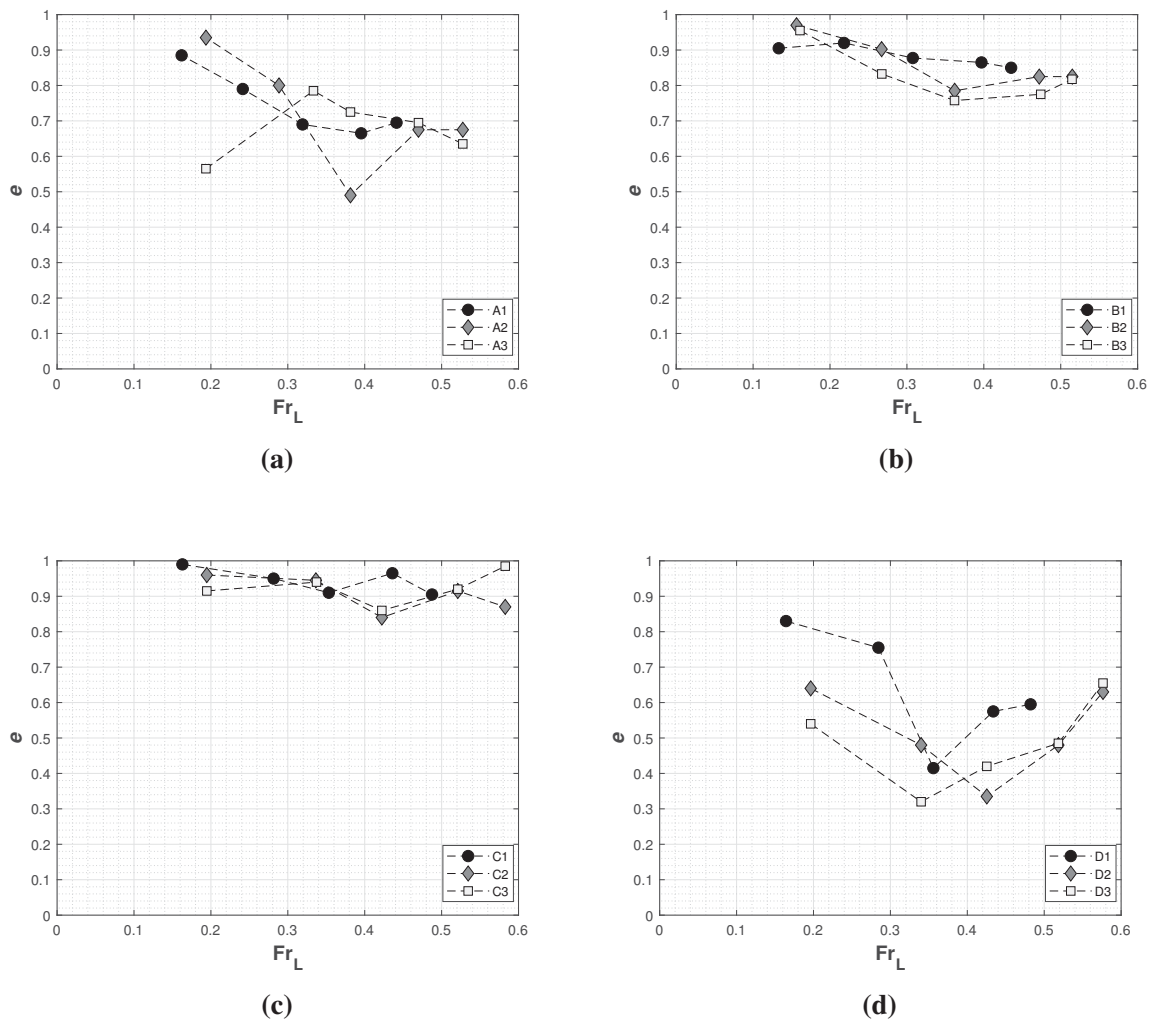


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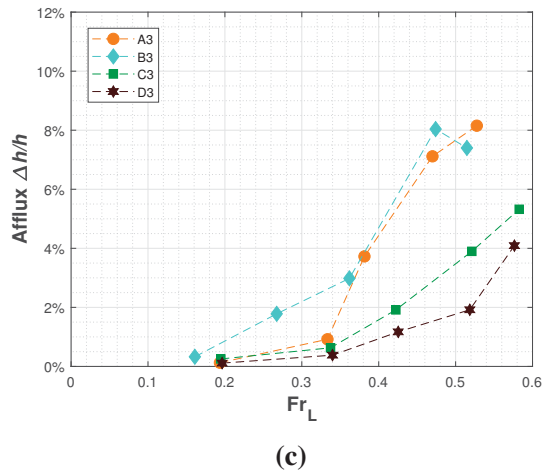
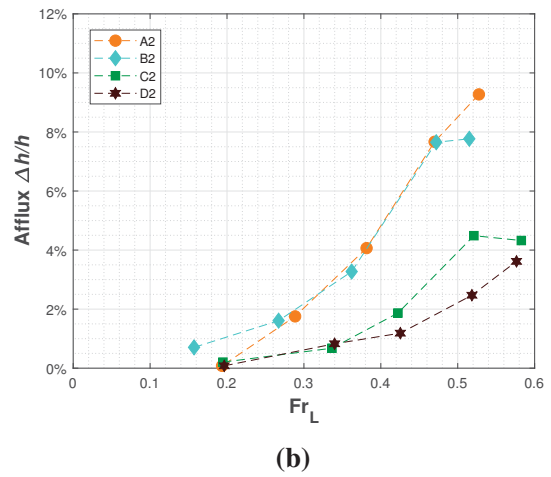
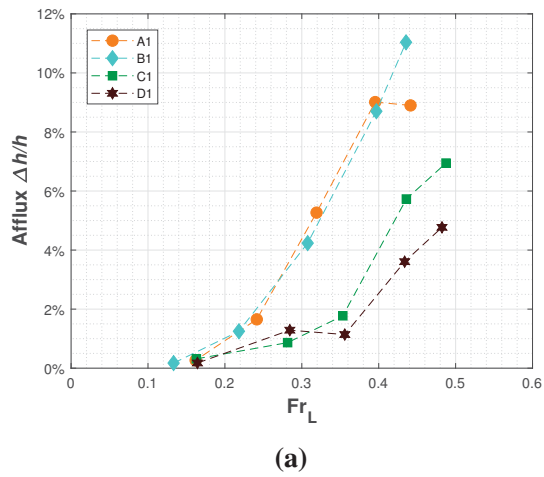


Fig. 10. Afflux (as a percentage of the undisturbed upstream flow depth) due to the accumulation of debris at the debris retention system plotted versus Fr_L for debris lengths $L = 250$ mm (10a) and $L = 175$ mm (10b) and for mixed debris (10c)

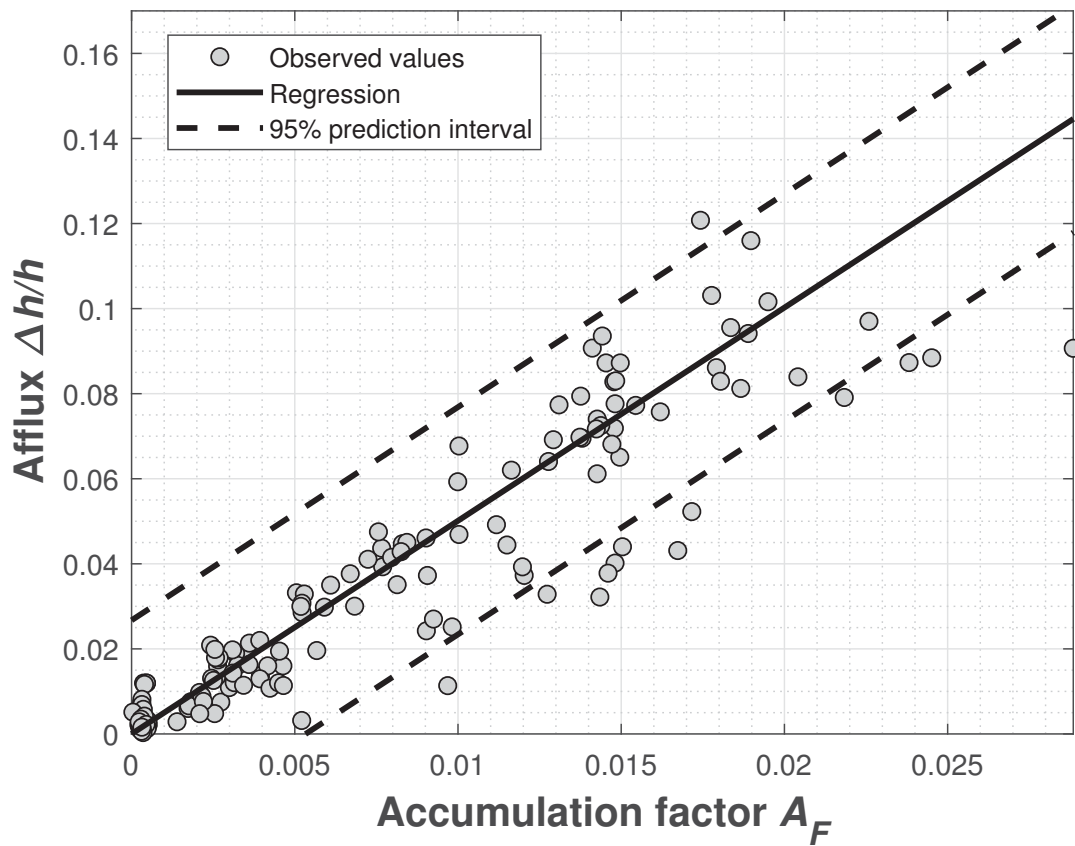
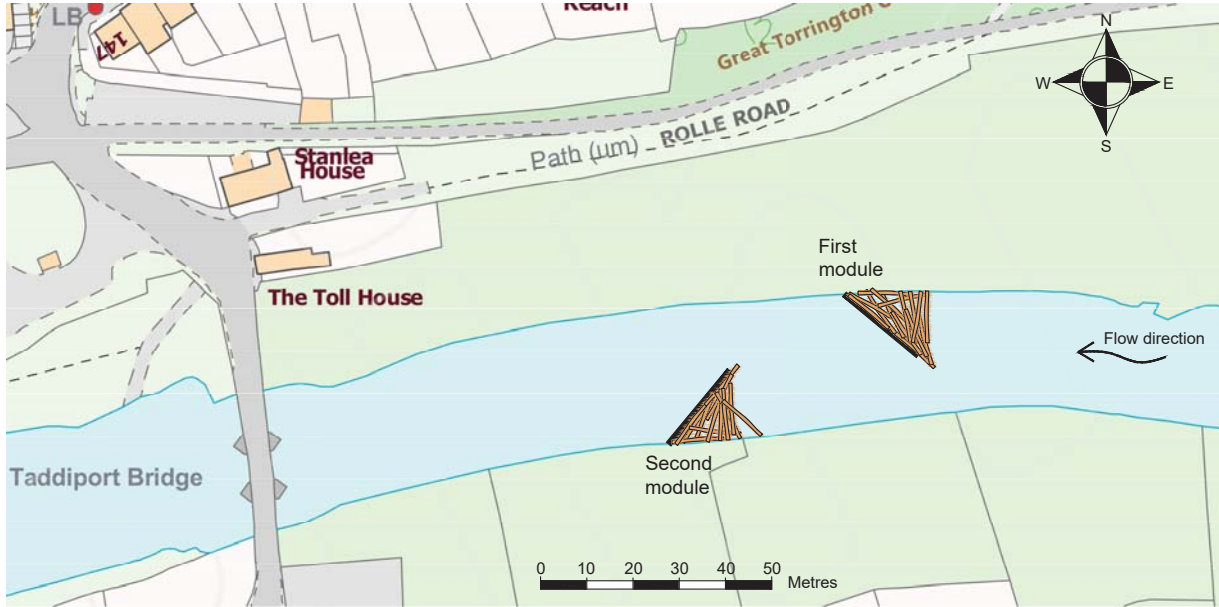


Fig. 11. Experimental data (circle points) and regression (solid line) from Equation (7) for afflux versus the accumulation factor A_F . The 95% prediction interval is also included (dashed lines).



(a)



(b)

Fig. 12. Potential location for the retention system on the river Torridge between Great Torrington and Taddipport (12a) - basemap: © Crown copyright and database rights 2020 Ordnance Survey (100025252). An example of large wood debris accumulations at the nearby Taddipport Bridge (12b), photo courtesy by Devon County Council.