

1 **WIN, WIN, WIN: LOW COST BAFFLE FISH PASS PROVIDES IMPROVED**
2 **PASSAGE EFFICIENCY, REDUCED PASSAGE TIME AND BROADENED**
3 **PASSAGE FLOWS OVER A LOW-HEAD WEIR**

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18 ABSTRACT

19 The number of low-head barriers to fish migration far outweighs the number of large magnitude
20 barriers and thus the cumulative negative impact on fish communities could also be far greater.
21 Removal of man-made obstructions to fish migration is the most beneficial mitigation measure
22 for reconnecting fragmented rivers but is not always possible and thus fish passes must be
23 constructed. Given the large number of low-head barriers, cheap but effective fish passes
24 must be identified. This study measured passage of brown trout (*Salmo trutta* L.) at a low-
25 head gauging weir on Eshton Beck, England, before and after low cost baffle (LCB) fish pass
26 construction using passive integrated transponder (PIT) telemetry. The LCB fish pass
27 significantly improved overall passage efficiency from a maximum of 64% to 91%. There was
28 a significant decrease in delay at the obstruction after the LCB fish pass was constructed and
29 fish passed on a greater range of flows ($0.08 - 5.39 \text{ m}^3\text{s}^{-1}$) in comparison to before ($0.56 -$
30 $1.92 \text{ m}^3\text{s}^{-1}$). Fish ascended the fish pass through the low velocity channel (gaps in the baffles)
31 as well as over the baffles, though a higher proportion were detected ascending over baffles
32 at higher flows. It was therefore concluded that similar low-head structures should incorporate
33 this style of fish pass to improve longitudinal connectivity for brown trout and other species
34 with similar passage capabilities.

35 **Key words:** habitat fragmentation, barrier, longitudinal connectivity, salmonid, telemetry

36 1 INTRODUCTION

37 Anthropogenic alterations to rivers such as construction of barrages, dams and weirs have
38 caused fragmentation of river systems globally (Katopodis and Aaland, 2006; Lucas *et al.*,
39 2009). This break-up of longitudinal connectivity has reduced the bidirectional migration and
40 dispersal of fish species resulting in restricted access to key life stage habitats to complete
41 their life cycles which can cause declines in fish populations (Petts, 1984; Harris and Mallen-
42 Cooper, 1994; Cowx and Welcomme, 1998; Lucas *et al.*, 1999; Lucas and Baras, 2001;
43 Radinger and Wolter, 2014). Barriers can also indirectly affect organisms such as unionoid
44 bivalve molluscs that require movements of host fish for dispersal of their larvae (Watters,
45 1996). Small low-head obstructions may not present an absolute barrier to migration and
46 dispersal but they outnumber large dams by a magnitude of two to four orders globally and
47 thus the cumulative negative impact on fish communities could be greater (Lucas *et al.*, 2009)
48 while also altering flow and sediment regimes (Nilsson *et al.*, 2005; Poff *et al.*, 2007; Xu and
49 Milliman, 2009). Removal of man-made obstructions to fish migration is the most beneficial
50 mitigating measure for reconnecting fragmented rivers (Kurby *et al.*, 2005) but is not always
51 possible and thus fish passes must be constructed.

52 Gauging weirs constantly monitor river flow (hydrometry) for societal demands such as
53 preparation for flood events in both Europe (White *et al.*, 2006) and worldwide (Wessels and
54 Rooseboom, 2009). Indeed, there are over 1500 gauging stations in England and Wales
55 (Turnpenny *et al.*, 2002; Peirson *et al.*, 2013). Such structures are known to have a negative
56 impact on upstream fish migration (White *et al.*, 2006; Russon *et al.*, 2011). This can be during
57 both periods of low river level when shallow depth on the weir apron can impede fish
58 movement and elevated river level when flow over the weir can exceed the swimming
59 capability of fish (Fraser *et al.*, 2015; KLTAP, 2015). Additionally the reduction in velocity at
60 the base of the obstruction can cause a hydraulic jump and increase turbulence that can
61 potentially disorientate fish and act as an additional barrier (Beach, 1984; Boiten, 2002). The
62 requirement to monitor river flow for societal purposes dictates such weirs cannot be removed

63 and thus a cheap but effective fish pass must be identified to adequately conserve aquatic
64 ecosystems.

65 Servais (2006) identified that the introduction of baffles to the apron of small low-head sloping
66 weirs to retard water velocities and retain depth may be a relatively cheap method for
67 improving fish passage. In theory, low cost baffles (LCB) provide passage at low flow when
68 fish swim upstream through gaps between baffles and during high flow when fish can traverse
69 the baffles. Forty *et al.* (2016) found LCB fish pass efficiency was 68% and 82% in 2013 and
70 2014, respectively, for brown trout (*Salmo trutta* L.) on Swanside Beck, England. However,
71 Forty *et al.* (2016) did not report the passability of the weir prior to LCB construction and route
72 choice over the obstacle was not established. Therefore, it remains unknown whether LCB
73 fish passes increase the rate of upstream passage at both low and high flow and whether fish
74 use the gaps in the baffles or traverse the baffles during such flows.

75 Efforts to address reductions in longitudinal connectivity of aquatic ecosystems has largely
76 focused on anadromous salmonid fishes (Noonan *et al.*, 2012). There is a general paucity of
77 information on the efficiency of fish passes for potamodromous and river-resident species,
78 despite free passage of fishes throughout river systems globally being a key legislative
79 requirement, e.g. the European Union Water Framework Directive (WFD) (EC; 2000/60/EEC).
80 Therefore, passage efficiency assessments are urgently required to determine if they are
81 operationally effective, overcome WFD failures and help conserve river-resident species and
82 ecotypes. River-resident brown trout were studied because they undertake migrations over
83 many kilometres and are often the dominant fish species in upland rivers – where low-head
84 barriers are most prevalent – in many regions, either in their native range or where introduced
85 (Budy *et al.*, 2013).

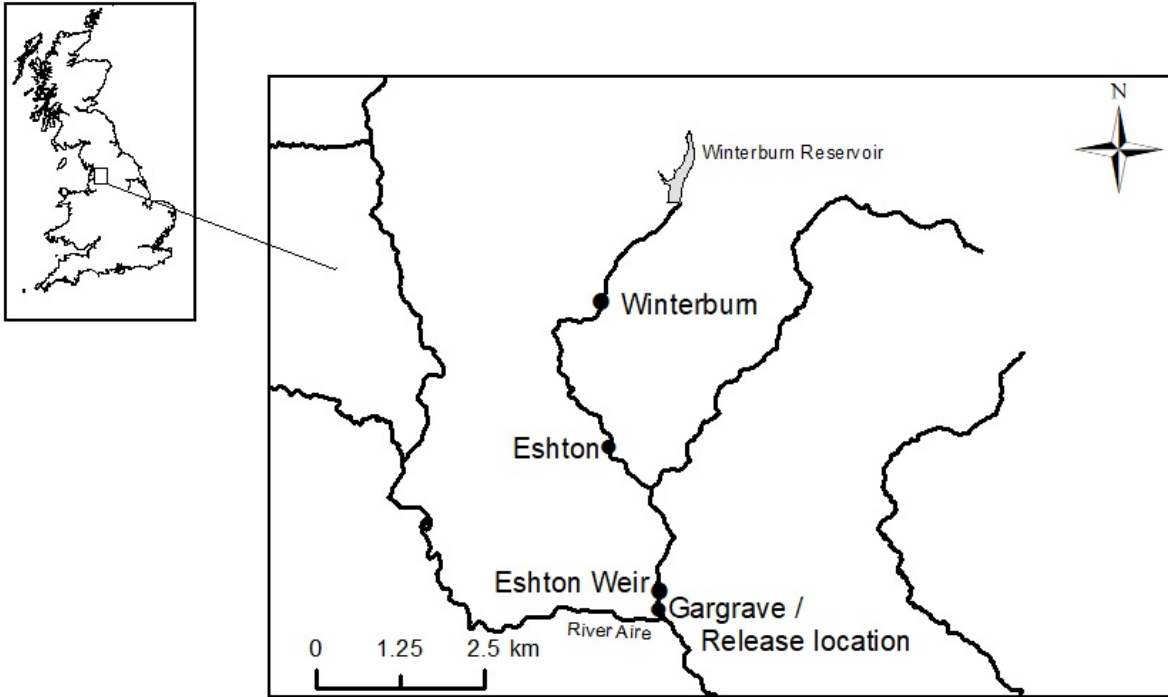
86 This study aimed to evaluate the passage of brown trout at a low-head gauging weir before
87 and after low cost baffle (LCB) fish pass construction. In order to achieve this aim the following
88 objectives of this investigation were to measure the passage efficiency and passage time

89 before and after LCB construction and determine the effect of flow and fish size on passage.
90 Passage metrics were determined by the use of passive integrated transponder (PIT)
91 telemetry at the weir, before and after modification.

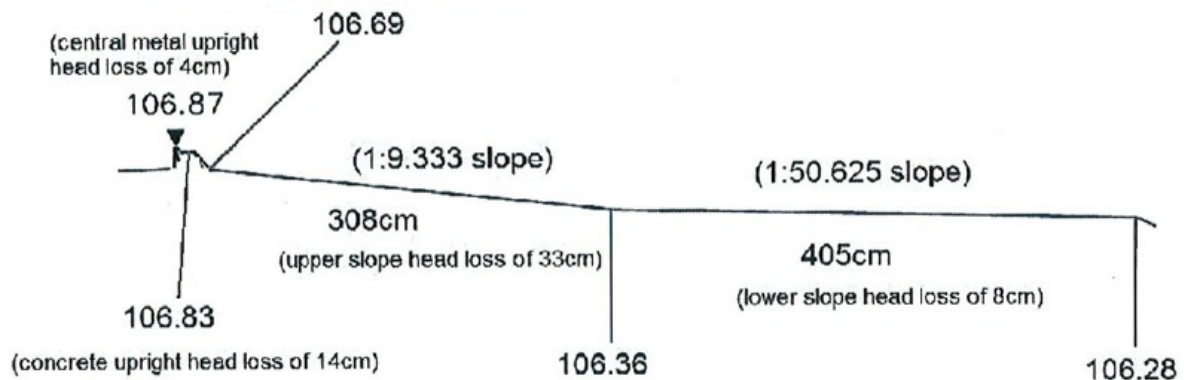
92 2 MATERIALS AND METHODS

93 2.1 Study site

94 The study was conducted between March 2014 and January 2017 at Eshton Beck gauging
95 weir (53.988886, -2.0890425; hereafter referred to as Eshton Weir) on Eshton Beck, a tributary
96 to the River Aire (53.981699, -2.0880099), which is regulated by Winterburn Reservoir
97 (54.039685, -2.0852512) (Figure 1). The weir allows for abstraction of water to maintain water
98 level in Leeds and Liverpool Canal for navigation (53.984599, -2.0856656). The thin plate weir
99 was 14.00-m wide, with a 0.59-m head and a 7.13-m flat concrete apron downstream of the
100 crest, divided into two sections, with the upper section (3.08-m) having a slope of 1:9 while
101 the downstream section (4.05-m) has a slope of 1:51 (Figure 1). An iron girder at the crest of
102 the weir aided water retention by the weir (Figure 1). A LCB fish pass consisting of 17 recycled
103 plastic baffles (0.2-m high and 0.1-m thick) that lay horizontally across the weir apron 90° to
104 the flow was constructed in September 2015. Each of the baffles had a 0.3-m gap and these
105 were progressively offset across the weir apron, resulting in an oblique corridor of notches,
106 located from the right hand bank at the downstream end of the weir, to the centre of the river
107 at the upstream end of the weir. Due to construction issues the most downstream baffle was
108 not drowned sufficiently to create a constant streaming flow over the bottom baffle, as per best
109 practice (Armstrong *et al.*, 2010).



110



111

112 Figure 1: Location of Eshton Weir, capture locations and tagged fish release location (black
 113 circles) (top), and cross-section through the weir (bottom).

114 **2.2 Sampling and tagging procedure**

115 Fish were obtained from one site downstream (0.5-km) and two sites upstream (1.6 and 3.1-
 116 km) of Eshton Weir in March 2014 and July 2016 (Table 1). Fish were caught whilst wading
 117 with a single anode using pulsed DC (200V, 50 Hz, ~ 1.5A) electrofishing equipment, powered
 118 by a 2 kVA generator. Fish caught from Winterburn and Eshton (upstream sites) were initially
 119 monitored for any signs of injury during capture (e.g. not regaining normal buoyancy or

120 posture, physical injuries or electric fishing marks). All captured fish that were considered to
 121 be fit for tagging were transported downstream of Eshton Weir. On arrival fish were moved
 122 into an aerated holding tank containing fresh river water for a period of one hour, during which
 123 time they were again monitored for any signs of stress before undergoing surgery.

124 Table 1: Summary of capture date, site name, location (Lat, Long), capture location relative to
 125 Eshton Weir (upstream/downstream), in-channel capture site distance from Eshton Weir (km)
 126 and number of brown trout PIT tagged (*n*).

Capture date	Site name	Location (Lat, Long)	Capture location relative to weir	Distance from weir (km)	<i>n</i>
19/03/2014	Gargrave	53.984072, -2.0892625	Downstream	0.5	37
20/03/2014	Eshton	54.006378, -2.1009971	Upstream	1.6	5
20/03/2014	Winterburn	54.022651, -2.1025608	Upstream	3.1	13
22/07/2016	Gargrave	53.984072, -2.0892625	Downstream	0.5	2
22/07/2016	Eshton	54.006378, -2.1009971	Upstream	1.6	13
22/07/2016	Winterburn	54.022651, -2.1025608	Upstream	3.1	36

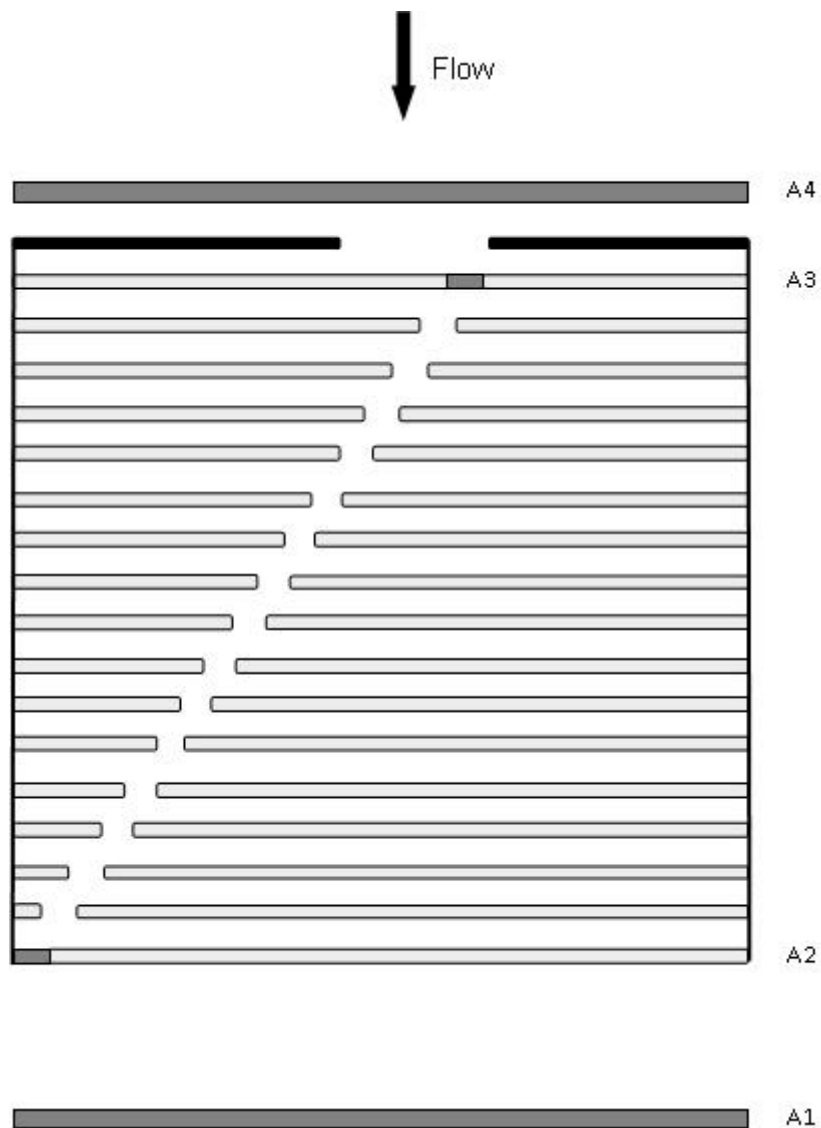
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128 All brown trout >120-mm were tagged with 23-mm (half-duplex, 23.0-mm long x 3.4-mm
129 diameter, 0.6-g weight in air) PIT tags. Larsen *et al.* (2013) reported a 100% survival and tag
130 retention rate for >90-mm Atlantic salmon (*Salmo salar* L.) tagged with 23.0-mm PIT tags.
131 Prior to tagging in the field, fish were anaesthetised using buffered tricaine methanesulphonate
132 (MS-222). Once anaesthetised the fork length was measured (mm) and recorded. During
133 surgery fish were placed ventral side up in a clean V-shaped foam support. The skin of the
134 fish was disinfected with a dilute iodophore wipe. Tags were tested with a hand held detector,
135 disinfected with alcohol and rinsed with distilled water before being inserted into the body
136 cavity through a 5-mm long ventro-lateral incision made with a scalpel, anterior to the muscle
137 bed of the pelvic fins. After the surgery, fish were continuously monitored in a well aerated
138 tank of fresh river water. Once fish had regained balance and were actively swimming they
139 were released into the river approximately 0.5-km downstream of Eshton Weir (53.984411, -
140 2.0889916; Figure 1). All fish were treated in compliance with the UK Animals (Scientific
141 Procedures) Act 1986 Home Office licence number PPL 60/4400.

142 **2.3 Monitoring**

143 Four flat-bed half-duplex PIT antennas were installed during the study. Two antennas were
144 installed before LCB construction (A1 and A4) in March 2014 with a further two antennas (A2
145 and A3) installed after LCB construction in March 2016 (Figure 2). Specifically, A1 and A4
146 were ~0.5-m wide, constructed from 6-mm diameter copper cable and spanned the 13-m wide
147 river 10-m downstream and 0.5-m upstream of Eshton Weir, respectively. A2 and A3 were
148 constructed from multiple turns of single core 3-mm diameter copper cable, were 0.3-m by
149 0.1-m in diameter and monitored the most downstream and upstream gaps between the
150 baffles, respectively. Each pair of antenna (A1-A2 and A3-A4) were connected to manual
151 tuning boards (Oregon RFID) connected to a multi-antenna data logger (Oregon RFID),
152 synchronously interrogated 10 times per second and powered by four 110 Ah, deep-cycle,
153 lead-acid batteries connected in parallel, which were charged by three 90 Watt solar panels.
154 Tag horizontal detection range was tested during initial set-up and at each site visit (on

155 average once a month) to ensure the read range of the interrogated water column had not
156 decreased. The read range of A1 and A4 was ~35-cm along the vertical plane and A2 and A3
157 was ~20-cm along the vertical plane, i.e. the height of the baffle. The read range for A1 and
158 A4 exceeded river depth during 95.4 and 89.0% of the study period, respectively, and it is
159 considered unlikely fish swam at the surface during elevated river level; the likelihood of fish
160 passing the antenna beyond the read range was deemed to be negligible. Every time a tag
161 was detected, the date, time, detection period, unique tag ID number and antenna number
162 were recorded and stored on a SD card in the data logger; these were manually downloaded
163 during site visits.

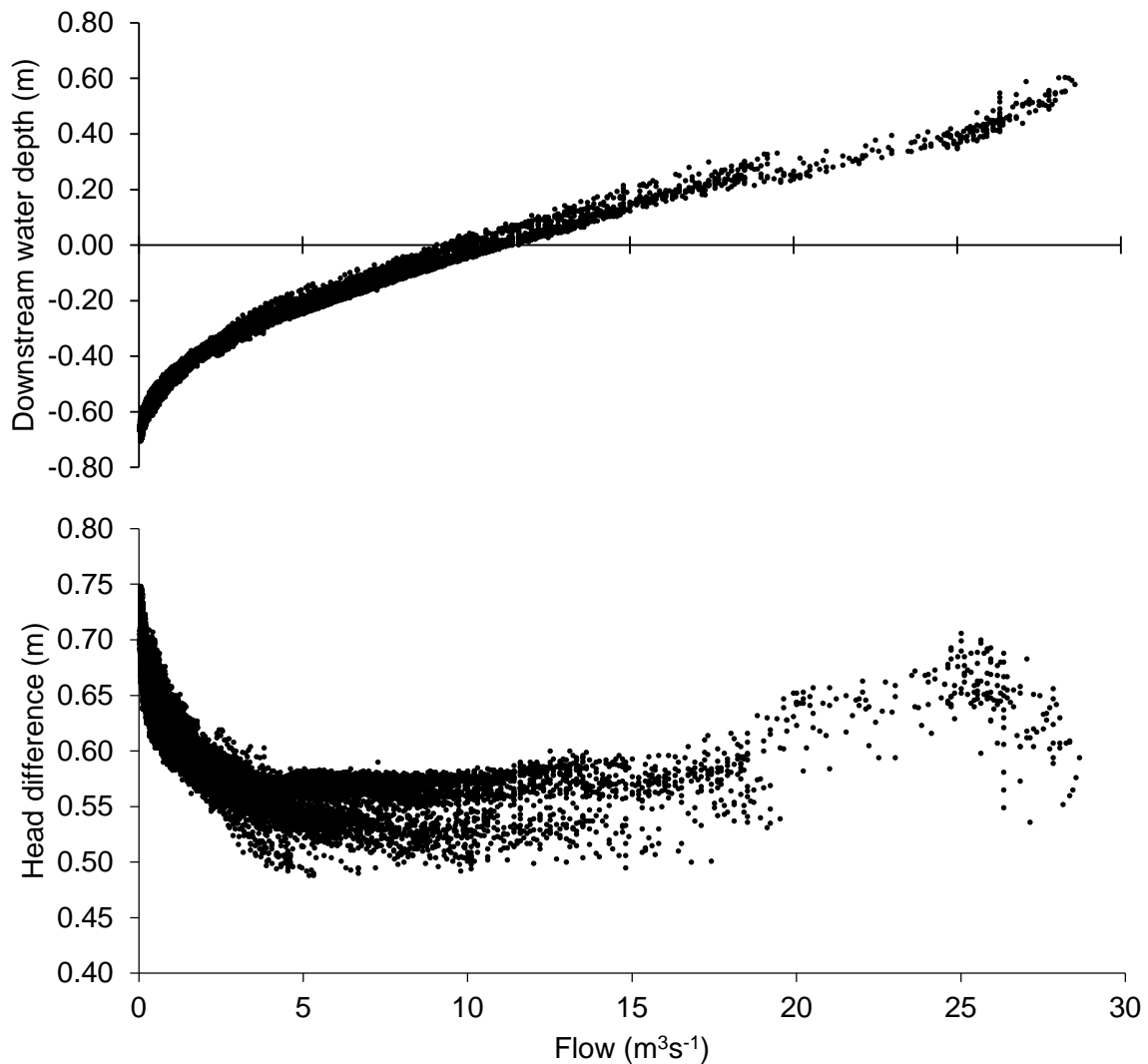


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165 Figure 2: Schematic of Eshton Weir LCB placement (light grey) with placement of flatbed PIT
166 antennas (A1 – A4; dark grey) and iron girder (black) (not to scale).

167 A1 and A4 were operational for 83% and 82% of the whole study and A2 and A3 were
168 operational for 96% and 100% of the study after LCB construction, respectively. Periods of
169 non-operation were caused by damage during high flow events and low battery power during
170 periods of insufficient sunlight for solar panels to recharge batteries. A1 detection efficiency
171 during the whole study was 100% (26/26), based on location of first detection after release,
172 i.e. no fish were first detected on A2, A3 or A4 after release. There were no fish first detected
173 on A2, A3 or A4 after release when A1 was not operational.

174 Upstream and downstream water depth (m) and river flow ($\text{m}^3 \text{s}^{-1}$) were recorded at 15-min
175 intervals at Eshton Weir, enabling head drop (m; difference between upstream and
176 downstream river level) to be calculated (Figure 3). Downstream water level was deeper than
177 the crest of the weir when gauged downstream water depth exceeded 0-m. A head drop was
178 present at Eshton Weir throughout the study, i.e. the upstream river level exceeded the
179 downstream river level although downstream river level exceeded the height of the weir. Prior
180 to LCB construction, water depth on the weir apron was 0.01 – 0.68 m and water velocity was
181 $0.19 - 4.30 \text{ ms}^{-1}$ during flows from $0.07 - 26.6 \text{ m}^3\text{s}^{-1}$ ($Q_{95.0} - Q_{0.1}$). After LCB construction, the
182 minimum water depth in the 0.3-m gap between the baffles was 0.20 m during all studied flows
183 ($> 0.03 \text{ ms}^{-1}$ (Q_{100})). Temperature was recorded at 15-min intervals on a Tinytalk logger
184 (Gemini Data Loggers; www.geminidataloggers.com) between 20/03/2014 and 02/01/2015,
185 and local air temperature (4.2-km; 53.997022, -2.0600027) was modelled (linear regression;
186 $r^2 = 0.926$) (<http://www.ceda.ac.uk/>) during periods of missing data (03/01/2015 – 01/01/2017).



187

188 Figure 3: Correlation between gauged river flow ($\text{m}^3 \text{s}^{-1}$) and downstream gauged depth (m;
 189 top) and the head drop (m; bottom) at Eshton Weir during the study.

190 2.4 Data analysis

191 The number of available fish was calculated for before and after LCB construction as the
 192 number of tagged fish detected on the most downstream antenna (A1). Overall passage
 193 efficiency was calculated for before and after LCB construction as the percentage of available
 194 fish that ascended the obstruction. LCB notch entrance efficiency was only calculated for after
 195 LCB construction as the percentage of available fish (i.e. detected on A1) that entered the
 196 most downstream gap in the LCB baffle (i.e. detected on A2) when downstream water depth

197 was shallower than the top of the bottom baffle (-0.23 m, gauged flow = 4.4 m³s⁻¹). The majority
198 of water exited through the bottom notch in the baffle below this gauged level to, in theory,
199 guide fish towards the fish pass entrance (FAO, 2002).

200 Descents were fish that moved back downstream (i.e. detection on A1) after ascending the
201 weir (i.e. detection on A4). LCB passage efficiency was only calculated after LCB construction
202 as the percentage of all ascents (including fish that performed a descent and reascended) that
203 passed through the gaps in the baffle (i.e. detected on A2 and A3). Overall passage time was
204 calculated for before and after LCB construction as the time from first approach (i.e. first
205 detection on A1) to ascending the obstruction (i.e. first detection on A4). Time to pass was
206 calculated for before and after LCB construction as the time between approaching the
207 obstruction during passage (i.e. last detection on A1) and ascending (i.e. first detection on
208 A4). LCB entrance time was only calculated for after LCB construction as the time between
209 approaching the obstruction during passage (i.e. last detection on A1) and entering the most
210 downstream gap in the LCB baffle (i.e. first detection on A2). One fish tagged before LCB
211 construction was first detected after LCB construction and was included in the after study
212 analysis for available fish, overall passage efficiency, time to pass, overall passage time and
213 flow analysis.

214 All passage metrics were reported as frequencies and summarised as percentages with
215 associated confidence intervals calculated as 95% Bayes Credible Intervals for proportions
216 e.g. 33% [19-51% CI, $n = 10/30$]. There was no significant difference between available fish
217 (χ^2 contingency test, $\chi^2 = 2.698$, $d.f. = 1$, $P = 0.100$) and (maximum assumed) overall passage
218 efficiency ($\chi^2 = 1.023$, $d.f. = 1$, $P = 0.312$) metrics between brown trout caught downstream (n
219 = 12/37 (32% [20-49% CI]) and 6/12 (50% [25-75% CI]), respectively) and upstream (10/18
220 (55% [33-75% CI]) and 8/10 (80% [48-94% CI]), respectively) of Eshton Weir before LCB
221 construction, and thus capture locations were not separated during analysis. Too few fish were
222 captured downstream of Eshton Weir after LCB construction ($n = 2$) to compare available fish
223 and overall passage efficiency metrics between capture locations.

224 Mann-Whitney *U*-tests were conducted to compare between the length of fish (at tagging) that
225 approached before and after LCB construction, passed and did not pass before LCB
226 construction and passed before and after LCB construction. Mann-Whitney *U*-tests were also
227 conducted to compare between the time to approach, overall passage time, time to pass
228 before and after LCB construction and route choice after LCB construction (values are
229 presented with the median value and range). Spearman rank correlation was used to assess
230 if mean river flow during ascent influenced time to pass before and after LCB construction.
231 The effect of fish length (at tagging) on passage success before and after LCB construction
232 was tested using binary logistic regression. Chi-squared and Mann-Whitney *U* tests were
233 conducted using SPSS 22 and binary logistic regression was conducted using R version 3.3.1
234 (R Core Team, 2016).

235 3 RESULTS

236 3.1 Passage efficiency

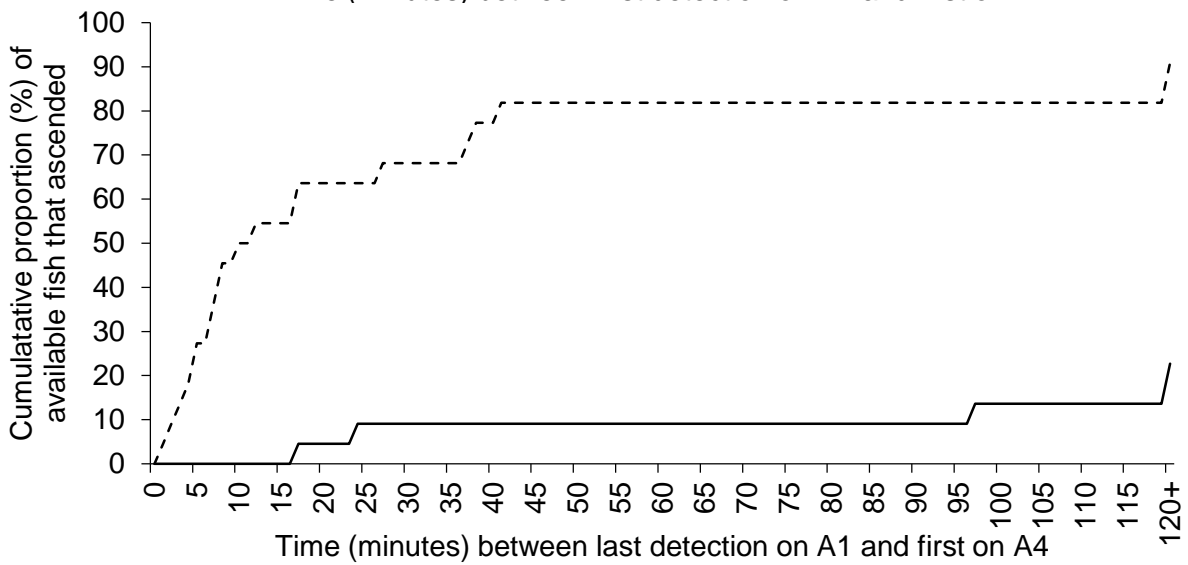
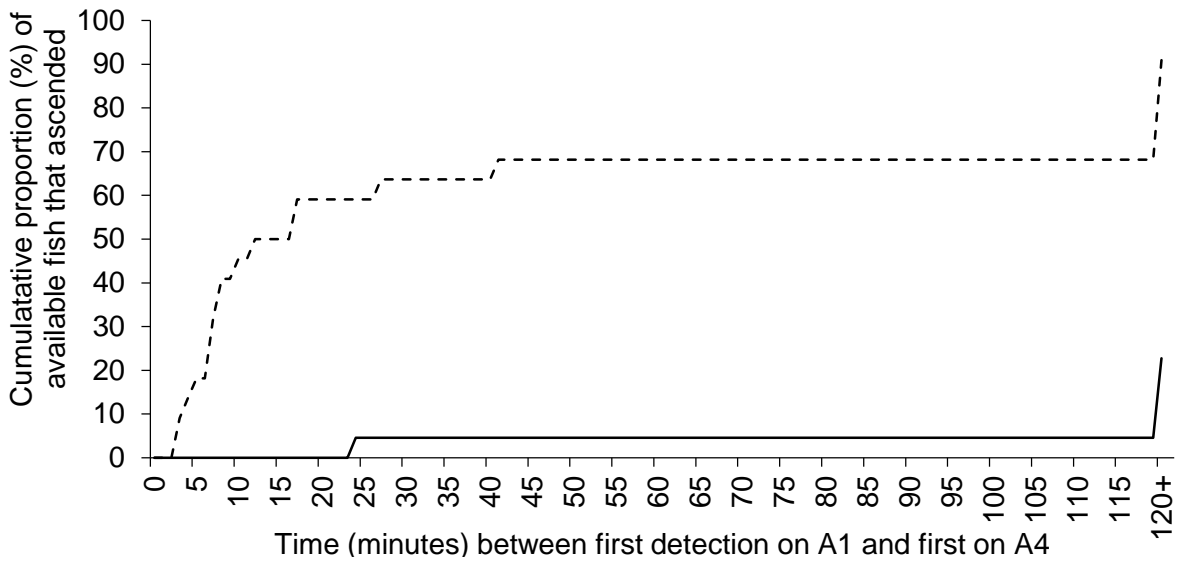
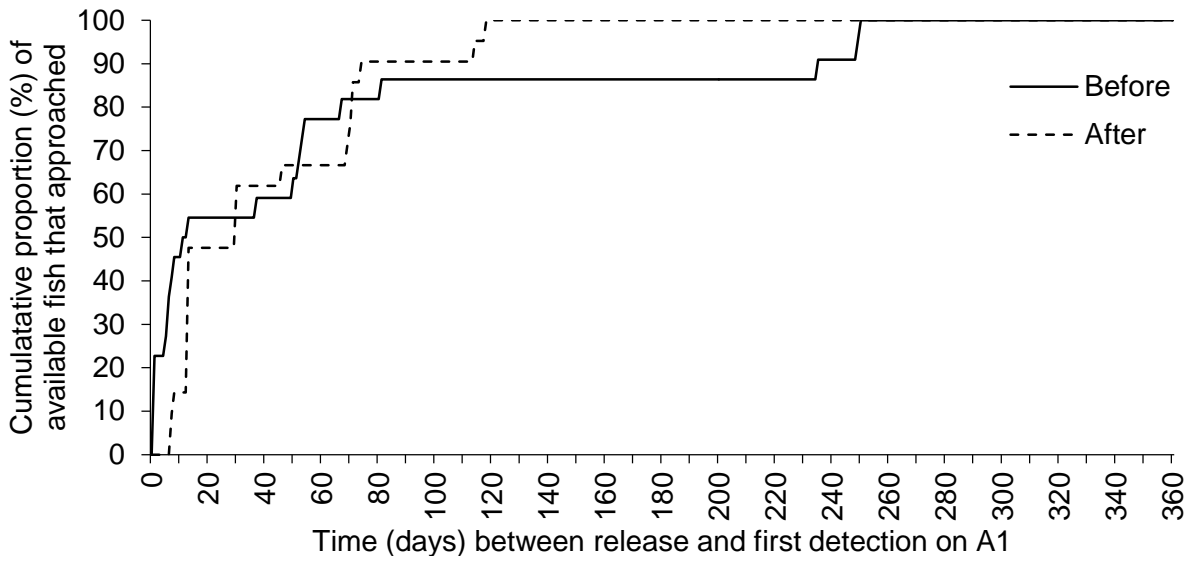
237 The number of available fish before and after LCB construction were 22 (40%, 28-53% CI)
238 and 22 (42%, 30-56% CI), respectively. The minimum passage efficiency before LCB
239 construction was 22% (10 – 44% CI, $n = 5/22$), but nine fish were detected at A1 within two
240 weeks of release when A4 was non-operational. These fish were not detected again on any
241 antenna, and thus the maximum passage efficiency before LCB, assuming passage of these
242 fish, was 64% (43-80% CI, $n = 14/22$). Overall passage efficiency after LCB construction was
243 91% (72-97% CI, $n = 20/22$) and was significantly larger than a maximum assumed 64% before
244 LCB construction (χ^2 contingency test, $\chi^2 = 4.659$, $d.f. = 1$, $P = 0.030$).

245 Of the two fish that did not ascend Eshton Weir after LCB construction, one was only detected
246 approaching the weir (detected on A1) while the other was last detected on A3 (not
247 subsequently detected on A1 or A4), and thus may have ascended but was not detected on
248 A4 (which was operational). LCB notch entrance efficiency, i.e. when downstream water depth
249 was shallower than the top of the bottom baffle (-0.23 m, gauged flow = $4.4 \text{ m}^3\text{s}^{-1}$), was 42%
250 (28-58% CI, $n = 16/38$ (all monitored ascents)). Two fish moved back downstream after
251 ascending the weir (descent) before LCB construction, both of which reascended. Eleven fish
252 descended the weir after LCB construction; four reascended once, one reascended five times
253 and one reascended ten times. Of the 38 ascents recorded whilst full monitoring equipment
254 was in place (including reascents), 11 passed through both the most downstream and most
255 upstream gaps in the baffles, i.e. LCB passage efficiency = 29% (17-45% CI, $n = 11/38$).
256 Twenty-eight descents occurred after LCB construction, 20 fish (71%, 53-85% CI) were only
257 detected on the most upstream (A4) and downstream (A1) antennae, not on A2 or A3, i.e. fish
258 moved over the baffles rather than through the gaps, though one fish was detected passing
259 through the most upstream gap in the baffles (A3).

260 3.2 Approach and passage times

261 There was no significant difference in the time between release and first approach to the weir
262 (i.e. first detection on A1) before (median = 12.37 days, range = 0.27 – 249.76 days, $n = 22$)
263 and after (29.26 days, 6.40 – 117.19 days, $n = 22$) LCB construction (Mann-Whitney U test: Z
264 = 1.361, $n = 43$, $P = 0.174$) (Figure 4 top). Overall passage time was significantly shorter after
265 LCB construction (0.01 days, 0.01 - 7.56 days, $n = 20$) than before (1.75 days, 0.02 – 16.39
266 days, $n = 5$) (Mann Whitney U -test: $Z = -2.523$, $n = 24$, $P = <0.01$) (Figure 4 middle). Thirteen
267 of the 20 fish that ascended the weir (65%, 43-82% CI) after LCB construction did so within
268 twenty minutes of first detection at the weir, and a further 6 fish ascended within the hour.
269 Whereas only one fish ascended within the 1st hour after first detection on A1 before LCB
270 construction, taking 23 minutes, and the longest time was 16.39 days. The median LCB
271 entrance time was 3.45 minutes (1.37–16.10 minutes, $n = 6$).

272 The time to pass was significantly less after LCB construction (0.14 hours, 0.01 - 13.66, $n =$
273 20) than before LCB construction (1.61 hours, 0.27 – 23.03, $n = 5$) (Mann Whitney U -test: $Z =$
274 -2.378, $n = 25$, $P = 0.015$) (Figure 4 bottom). The shortest and longest time to pass during the
275 study were 0.2 and 8818 minutes, respectively, both after LCB construction, with the latter fish
276 assumed to have remained in the weir pool upstream of A1 before ascending the weir. There
277 was no significant difference in time to pass between fish that entered the fish pass through
278 the gap in the most downstream baffle and those that leapt over the baffle (Mann-Whitney U
279 test: $Z = -1.755$, $n = 19$, $P = 0.087$). The time between ascent and descent was similar before
280 (2.37 days, 0.33 – 4.42, $n = 2$) and after (0.74 days, 0.00 – 115.40, $n = 28$) LCB construction.



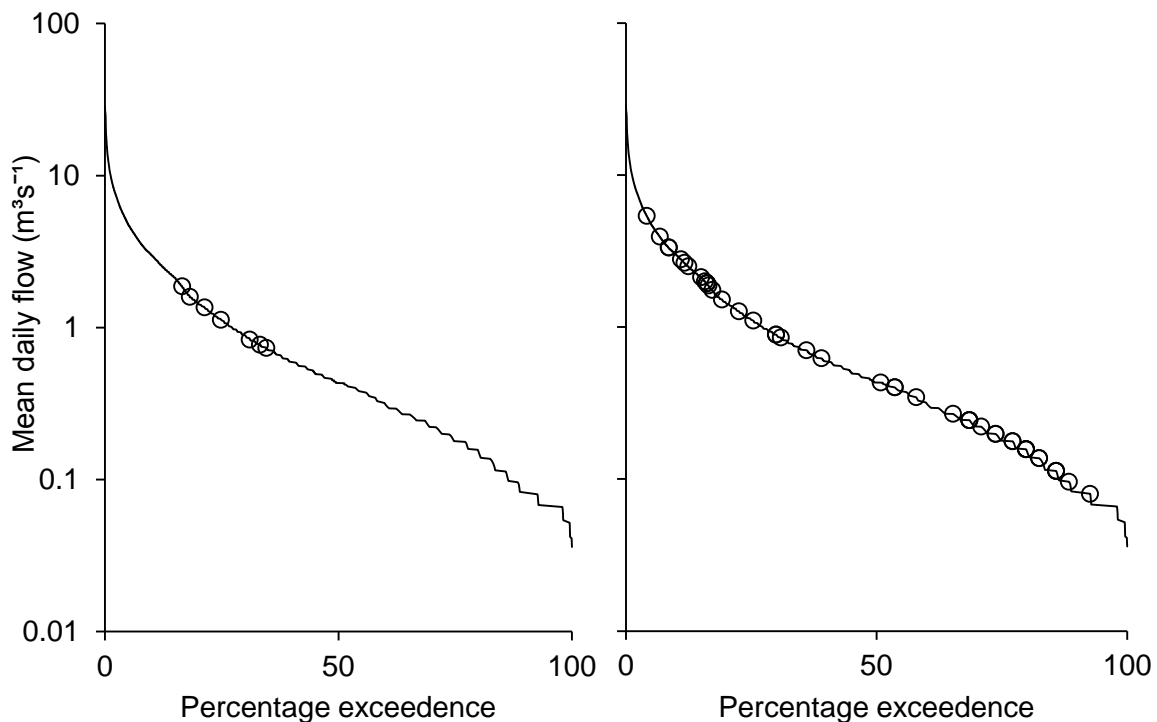
283 Figure 4: Time (days) between release and first approach to the weir (top), overall passage
284 time (minutes) (middle) and the time to pass (minutes) (bottom), as a proportion (%) of
285 available fish before (solid line) and after (dotted line) LCB construction.

286 3.3 Flow and temperature during passage

287 Fish ascended the weir on a greater range of flows after the LCB construction (0.08 - 5.39
288 m^3s^{-1} ($Q_{92.6} - Q_{4.2}$)) in comparison to before (0.74 - 1.87 m^3s^{-1} ($Q_{34.5} - Q_{16.5}$)) (Figure 5), with
289 all ascents occurring when downstream gauged depth was lower than the crest of the weir
290 (maximum before = -0.36 m, after = -0.26 m). The lowest temperature fish ascended the weir
291 was comparable before (6.1 °C) and after (5.9 °C) LCB construction but the highest
292 temperature was 19.8 °C after LCB construction, in contrast to 13.2 °C before. There was no
293 correlation in mean river flow during ascent and time to pass before (Spearman rank: $r = -$
294 0.100, $n = 5$, $P = 0.873$) and after ($r = -0.245$, $n = 20$, $P = 0.299$) LCB construction. Descents
295 occurred on flows between 0.92 – 1.06 m^3s^{-1} ($Q_{29.2} - Q_{26.3}$) before LCB construction and 0.10
296 – 12.60 m^3s^{-1} ($Q_{88.4} - Q_{0.6}$) after.

297 Thirty-seven ascents occurred when downstream water depth was shallower than the top of
298 the bottom baffle (-0.23 m, gauged flow = 4.4 m^3s^{-1}), with 16 fish (43%, 29 - 59% CI) detected
299 passing through the gap in the bottom baffle and thus the remaining 21 fish (57%, 41 - 71%
300 CI) leapt over the bottom baffle to enter the pass. There were a similar number of ascents
301 after the LCB construction ($n = 8$) within the flow band fish passed on before LCB construction
302 ($n = 7$). Nineteen of all 38 ascents after LCB construction (including reascents) occurred on
303 flows that were lower than when fish passage occurred before LCB construction, i.e. 0.74 m^3s^{-1}
304 (Figure 5); 16 fish (84%) passed through at least one of the gaps in the baffles (downstream
305 only = 1, upstream only = 6 and both = 9) and 3 fish (16%) passed over the baffles. Likewise,
306 12 ascents after LCB construction occurred on flows higher than observed before LCB
307 construction, i.e. 1.87 m^3s^{-1} (Figure 5); 4 fish (36%) passed through at least one of the gaps
308 in the baffles (downstream only = 3 and both = 1) and 7 fish (64%) passed over the baffles,

309 with one fish doing so when the downstream water depth was deeper than the top of the
310 bottom baffle.



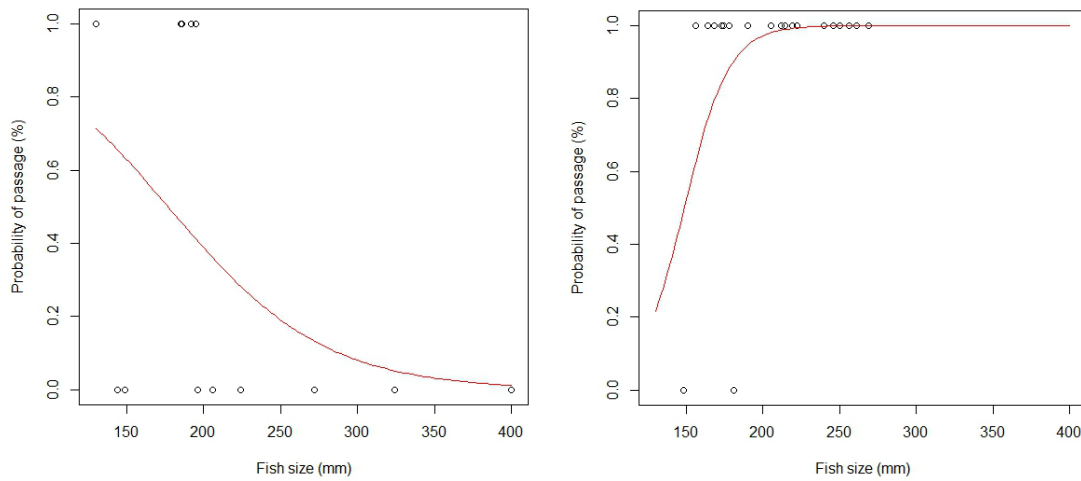
311

312 Figure 5: Percentage mean daily flow (m^3s^{-1}) exceedance curve during the study (March 14 –
313 January 17), including the passages (circle symbol) that occurred before ($n = 7$; left) and after
314 ($n = 39$; right) LCB construction.

315 3.4 Fish size

316 There was no significant difference in length at tagging between fish that did (median = 186-
317 mm, range = 130-195-mm, $n = 5$) and did not (215-mm, 144-400-mm, $n = 8$) ascend the weir
318 before LCB construction (Mann-Whitney U test: $Z = -1.757$, $n = 13$, $P = 0.093$). Fish that
319 approached the weir (detected on A1) before (196-mm, 122-400-mm, $n = 22$) and after (212-
320 mm, 148–269-mm, $n = 21$) LCB construction had similar length at tagging (Mann-Whitney U
321 test: $Z = 0.267$, $n = 43$, $p = 0.789$). There was also no significant difference in length at tagging
322 between fish that ascended before (186-mm, 130-195-mm, $n = 5$) and after (212-mm, 156-
323 269-mm, $n = 19$) LCB construction (Mann-Whitney U test: $Z = -1.592$, $n = 24$, $P = 0.139$).
324 Indeed, the second smallest fish detected at the weir during the whole study was 156-mm

325 when tagged and ascended on 10 separate occasions between flows of 0.08–1.52 m³s⁻¹.
 326 Binary logistic regression model on probability of passage before (P50 = 176-mm; Coefficient
 327 = -0.020, Std. Error = 0.016, z statistic = -1.263, *P* = 0.207) and after LCB construction (P50
 328 = 148-mm and P90 = 180-mm; Coefficient = 0.069, Std. Error = 0.052, z statistic = 1.316, *P* =
 329 0.188) was also not significant, probably because too few fish did and did not pass before and
 330 after LCB construction, respectively (Figure 6). There was no significant difference in size of
 331 fish that entered the fish pass through the gap in the bottom baffle and those that leapt over
 332 the bottom baffle (Mann-Whitney *U* test: *Z* = 1.404, *n* = 19, *P* = 0.179).



333

334 Figure 6: Binary logistic regression model of length at tagging (mm) for fish that did and did
 335 not ascend Eshton Weir before (left) and after (right) LCB construction.

336 4 DISCUSSION

337 The overall passage efficiency of the low-head gauging weir on Eshton Beck was between a
338 minimum of 22% and a maximum of 64%, albeit with the maximum assuming all brown trout
339 ($n = 9$) that approached during equipment failure (A4) and were not subsequently detected
340 had ascended. Despite assuming these fish ascended, a LCB fish pass significantly increased
341 the overall passage efficiency to 91%. In addition, a significant decrease was observed in
342 overall passage time (i.e. first arrival to ascent), time to pass (i.e. approaching the obstruction
343 to ascent) and fish also ascended across a wider range of flows in comparison to before LCB
344 construction. Indeed, collection of data before LCB construction allowed an understanding of
345 the negative influence the obstruction had on fish migration, as well as providing data to
346 assess improvements in longitudinal connectivity afterwards. Without such data only
347 assumptions could be made as to whether the introduction of the fish pass had a positive
348 impact on passage past the obstruction. These findings suggest that LCB fish passes are a
349 cheap and effective solution to improving longitudinal connectivity at low head barriers.

350 The overall passage efficiency (91%) observed after LCB fish pass construction was greater
351 than previously reported for brown trout (67-82%) through a LCB fish pass at a gauging weir
352 with a higher head, as well as a steeper gradient (1:4; Forty *et al.*, 2016), which is known to
353 have a negative impact on passage efficiency (Baker and Boubée, 2006; Noonan *et al.*, 2012;
354 Baker, 2014). The overall passage efficiency reported here also far exceed that reported for
355 cyprinids through a LCB fish pass (chub [*Squalius cephalus*] (40%), dace [*Leuciscus*
356 *leuciscus*] (33%) and roach [*Rutilus rutilus*] (50%)) (Armstrong *et al.*, 2010) and upstream
357 migrating salmonids across all types of fish passes (mean = 61%; Noonan *et al.*, 2012).
358 Increases in overall passage efficiency from 14% to 80% have also been found for diadromous
359 common jollytail (*Galaxias maculatus*) and spotted galaxias (*Galaxias truttaceus*) through a
360 culvert after the construction of baffles (MacDonald and Davies, 2007). Crucially, the overall
361 passage efficiency at Eshton Weir meets the minimum (90%) recommended for sustaining
362 and recovering diadromous fish populations and for species that show marked potamodromy

363 (Lucas and Baras, 2001). Indeed, the findings are particularly encouraging because upstream
364 passage was not an obligatory requirement for brown trout tagged during this investigation,
365 with spawning and nursery habitats downstream of Eshton Weir.

366 The overall passage time, i.e. the time from first approach to ascending the obstruction, was
367 significantly shorter after LCB construction. It is well established that the presence of an
368 obstruction can result in large delays in upstream migration, with some studies reporting
369 delays of many days for anadromous migratory species often with fish detected descending
370 back downstream in a possible attempt to find suitable habitat (Gowans *et al.*, 2003; Caudill
371 *et al.*, 2007; Frank *et al.*, 2009). Comparison of actual passage time between studies is difficult
372 because other factors such as fish species, fish size, fish pass design, flow conditions and
373 water temperature will all influence speed of fish movement. Crucially, the reduction in overall
374 passage time found in this should decrease the risk of potential negative impacts associated
375 with fish congregation at barriers, such as predation (Peake *et al.* 1997; Schilt, 2007), energy
376 expenditure (Jonsson *et al.*, 1997) and transfer of disease (Garcia de Leaniz, 2008).

377 Whether an obstruction can be ascended or not will often depend on the hydraulic conditions
378 over and at the base of the obstruction (Larinier, 2001). This study has demonstrated that the
379 addition of a LCB fish pass on the apron of a low gradient gauging weir enabled passage
380 during both higher and lower flows than observed beforehand. While temperature is known to
381 have an effect on swimming ability for many fishes (Wardle, 1980; Ojanguren *et al.*, 2001), the
382 lowest temperature fish ascended the weir before and after LCB construction was comparable
383 and thus flow was deemed to have an overarching influence during this study. Indeed, the
384 addition of baffles onto the weir apron is to retard and significantly deepen the super-critical
385 flow, with the aim of providing a suitable velocity and water depth for a variety of fish species
386 and sizes to pass (Servais, 2006). In addition, it was expected that during high discharges fish
387 might use both the low velocity channel (gaps in the baffles) as well as ascend over the baffles
388 (Armstrong *et al.*, 2010). As expected, fish used both these routes after LCB construction over
389 a wide range of flows, though a higher proportion were observed ascending over baffles at

390 higher flows. Fish that ascend over the baffles when downstream water depths were shallower
391 than the top of the baffle are considered to have leapt. Leaping behaviour has been observed
392 for brown trout passing small obstacles and weirs by Ovidio *et al.* (2007). Regardless of route
393 taken, passage through the LCB fish pass ($Q_{92.6} - Q_{4.17}$) was across a wider range of flows
394 than before construction ($Q_{34.5} - Q_{16.5}$) and nearly occurred across the range of flow
395 exceedances recommended ($Q_{95} - Q_{10}$) in the fish passage manual for England and Wales
396 (Armstrong *et al.*, 2010). The range of flow exceedances were also similar to those reported
397 for brown trout passage through a nature-like bypass on the River Aire, England (Dodd *et al.*,
398 2017).

399 A binary logistic regression model of brown trout fork length on movements through a LCB
400 fish pass in Swanside Beck was significant, with a P50 of 113-mm and larger individuals
401 having a greater success rate (Forty *et al.*, 2016). The increase in probability of passage was
402 associated to the increased swimming performance of larger fish (Clough and Turnpenny,
403 2001), however, this was not found in this study, possibly because Eshton Weir had a
404 shallower gradient (1:9.3) than Swanside Beck (1:4; Forty *et al.*, 2016). In addition, the size of
405 PIT tag used in Eshton Beck (23-mm) to obtain adequate tag detection range dictated no
406 information was gathered on passage of fish smaller than 120-mm. Ideally future fish passage
407 studies will incorporate the smallest fish possible, subject to technical limitations (i.e. tag
408 detection range) so a larger database of evidence on fish pass performance can be gathered.

409 Fish were tagged at different times of year before (March) and after (July) LCB construction
410 but were considered equally motivated to ascend the weir because the proportion of available
411 fish were almost identical and the time between release and first approach to the weir was
412 similar. It has also been observed that displaced brown trout will initiate a homing instinct after
413 relocation (Harcup *et al.*, 1984; Armstrong and Herbert, 1997). The proportion of brown trout
414 detected downstream and that passed Eshton Weir before LCB construction was comparable
415 between fish captured downstream and upstream (and displaced) of the weir. Therefore,
416 neither the timing of release or location of fish capture influenced the findings of the

417 investigation; all fish detected at the weir were considered motivated to move upstream.
418 Regardless of motivation to move (e.g. exploratory, homing and/or spawning), after LCB
419 construction brown trout were physically capable of entering and swimming through or over
420 the fish pass.

421 The fragmentation caused by low-head weirs, which outnumber large dams by a magnitude
422 of two to four orders globally (Lucas *et al.*, 2009), are contributing towards the extinction of
423 fish species globally (Dias *et al.*, 2017). There is a current paucity of quantitative assessments
424 of effects of habitat fragmentation on aquatic ecosystem functioning prior to attempts to restore
425 connectivity. This study has provided empirical insights to river managers and policy makers
426 about the impact a low-head gauging weir had on the dominant species present, brown trout.
427 There is also a paucity of information on the efficiency of fish passes for river-resident species
428 and ecotypes, despite legislative drivers, e.g. the European Union Water Framework Directive
429 (WFD) (EC; 2000/60/EEC). This empirical investigation has demonstrated that a LCB fish
430 pass is a viable method for improving longitudinal connectivity at low-head obstruction for the
431 prevailing river-resident brown trout community. Given their low cost and ease of installation,
432 LCB fish passes should be implemented on low-head weirs elsewhere to help protect, restore
433 and conserve aquatic ecosystems, though further investigation should be performed on
434 steeper gradient weirs and with a wider range of species.

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