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

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ABSTRACT

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

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

1 INTRODUCTION

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

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

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

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

This study aimed to evaluate the passage of brown trout at a low-head gauging weir before and after low cost baffle (LCB) fish pass construction. In order to achieve this aim the following objectives of this investigation were to measure the passage efficiency and passage time before and after LCB construction and determine the effect of flow and fish size on passage. Passage metrics were determined by the use of passive integrated transponder (PIT) telemetry at the weir, before and after modification.

2 MATERIALS AND METHODS

2.1 Study site

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

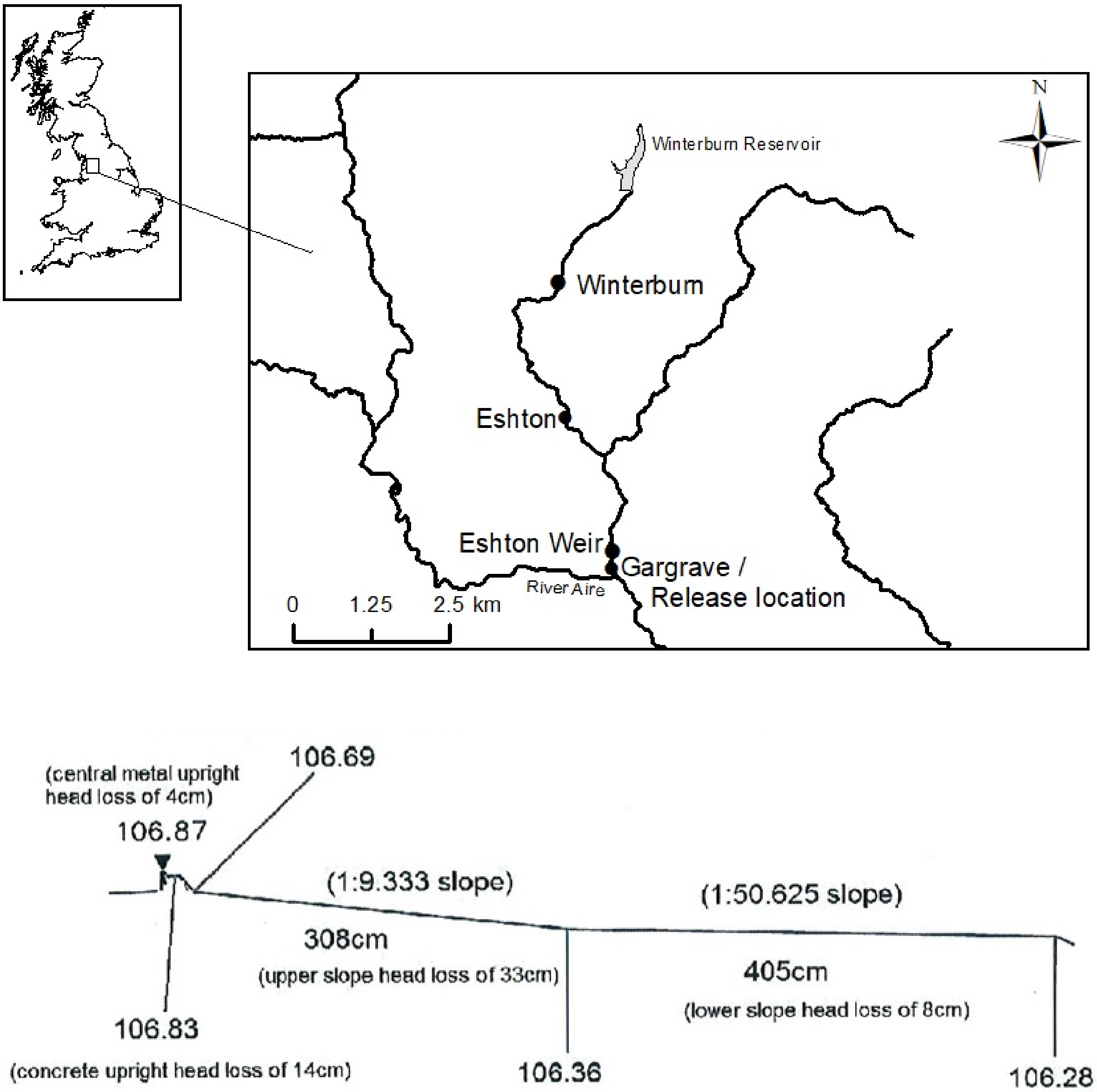

Figure 1: Location of Eshton Weir, capture locations and tagged fish release location (black circles) (top), and cross-section through the weir (bottom).

2.2 Sampling and tagging procedure

Fish were obtained from one site downstream (0.5-km) and two sites upstream (1.6 and 3.1-km) of Eshton Weir in March 2014 and July 2016 (Table 1). Fish were caught whilst wading with a single anode using pulsed DC (200V, 50 Hz, ~ 1.5A) electrofishing equipment, powered by a 2 kVA generator. Fish caught from Winterburn and Eshton (upstream sites) were initially monitored for any signs of injury during capture (e.g. not regaining normal buoyancy or posture, physical injuries or electric fishing marks). All captured fish that were considered to be fit for tagging were transported downstream of Eshton Weir. On arrival fish were moved into an aerated holding tank containing fresh river water for a period of one hour, during which time they were again monitored for any signs of stress before undergoing surgery.

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

Capture date	Site name	Location (Lat, Long)	Capture location relative to weir	Distance from weir (km)	*n*
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

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

2.3 Monitoring

Four flat-bed half-duplex PIT antennas were installed during the study. Two antennas were installed before LCB construction (A1 and A4) in March 2014 with a further two antennas (A2 and A3) installed after LCB construction in March 2016 (Figure 2). Specifically, A1 and A4 were ~0.5-m wide, constructed from 6-mm diameter copper cable and spanned the 13-m wide river 10-m downstream and 0.5-m upstream of Eshton Weir, respectively. A2 and A3 were constructed from multiple turns of single core 3-mm diameter copper cable, were 0.3-m by 0.1-m in diameter and monitored the most downstream and upstream gaps between the baffles, respectively. Each pair of antenna (A1-A2 and A3-A4) were connected to manual tuning boards (Oregon RFID) connected to a multi-antenna data logger (Oregon RFID), synchronously interrogated 10 times per second and powered by four 110 Ah, deep-cycle, lead-acid batteries connected in parallel, which were charged by three 90 Watt solar panels. Tag horizontal detection range was tested during initial set-up and at each site visit (on average once a month) to ensure the read range of the interrogated water column had not decreased. The read range of A1 and A4 was ~35-cm along the vertical plane and A2 and A3 was ~20-cm along the vertical plane, i.e. the height of the baffle. The read range for A1 and A4 exceeded river depth during 95.4 and 89.0% of the study period, respectively, and it is considered unlikely fish swam at the surface during elevated river level; the likelihood of fish passing the antenna beyond the read range was deemed to be negligible. Every time a tag was detected, the date, time, detection period, unique tag ID number and antenna number were recorded and stored on a SD card in the data logger; these were manually downloaded during site visits.

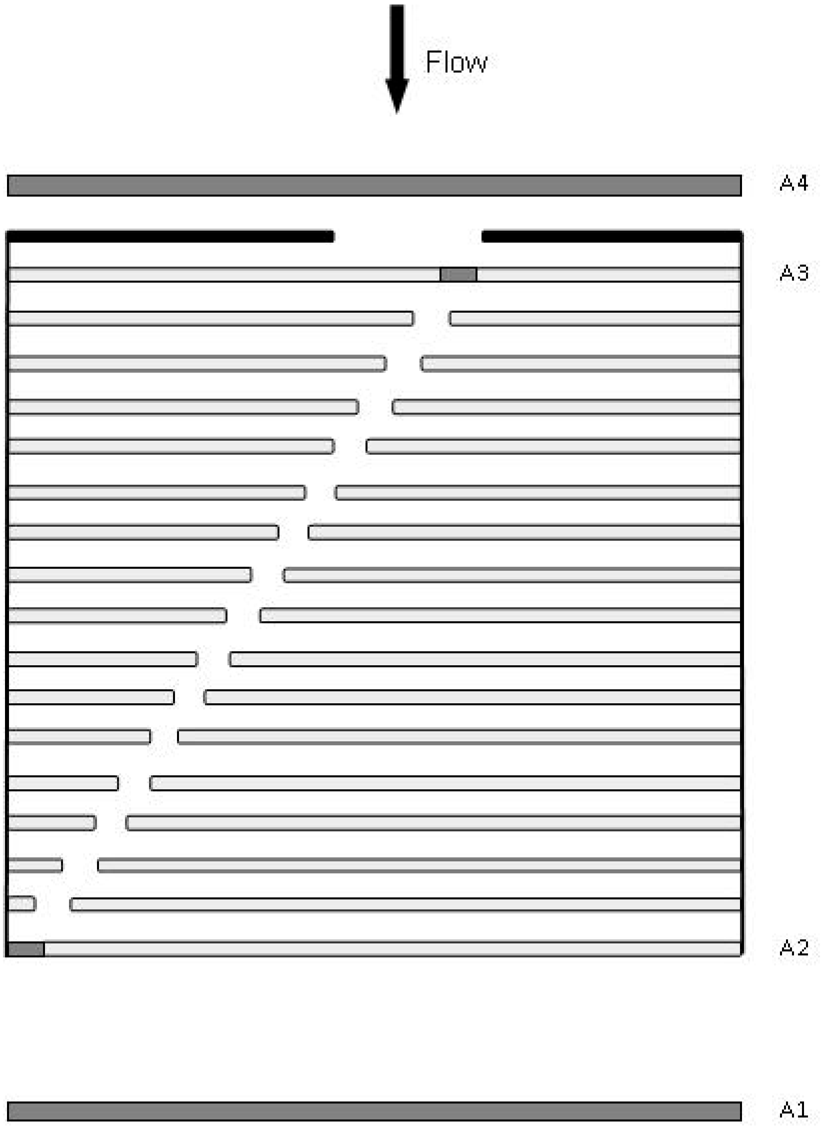

Figure 2: Schematic of Eshton Weir LCB placement (light grey) with placement of flatbed PIT antennas (A1 – A4; dark grey) and iron girder (black) (not to scale).

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

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

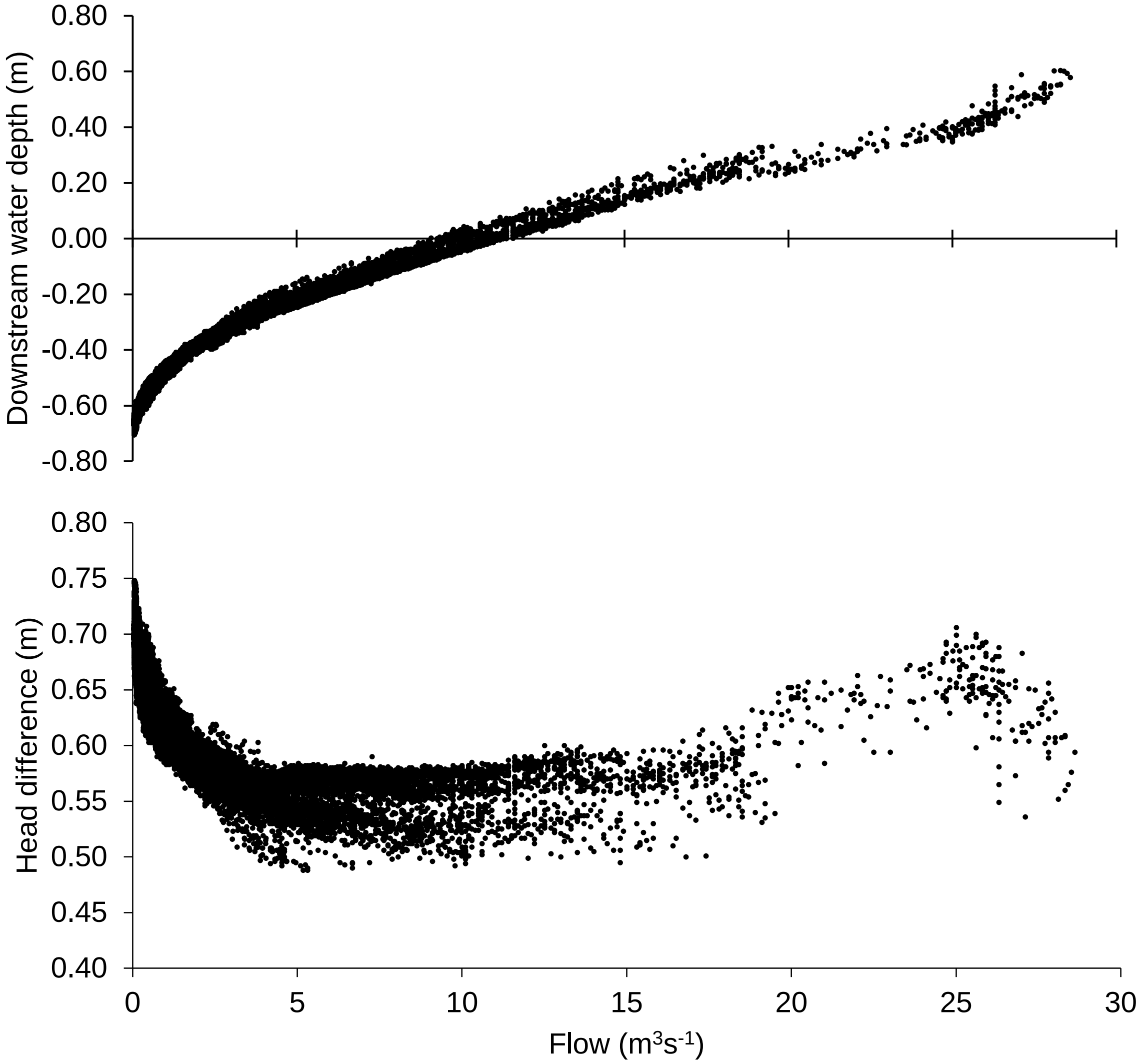

Figure 3: Correlation between gauged river flow (m^3 s^{-1}) and downstream gauged depth (m; top) and the head drop (m; bottom) at Eshton Weir during the study.

2.4 Data analysis

The number of available fish was calculated for before and after LCB construction as the number of tagged fish detected on the most downstream antenna (A1). Overall passage efficiency was calculated for before and after LCB construction as the percentage of available fish that ascended the obstruction. LCB notch entrance efficiency was only calculated for after LCB construction as the percentage of available fish (i.e. detected on A1) that entered the most downstream gap in the LCB baffle (i.e. detected on A2) when downstream water depth was shallower than the top of the bottom baffle (-0.23 m, gauged flow = 4.4 m^3s^{-1}). The majority of water exited through the bottom notch in the baffle below this gauged level to, in theory, guide fish towards the fish pass entrance (FAO, 2002).

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

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

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

3 RESULTS

3.1 Passage efficiency

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

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

3.2 Approach and passage times

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

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

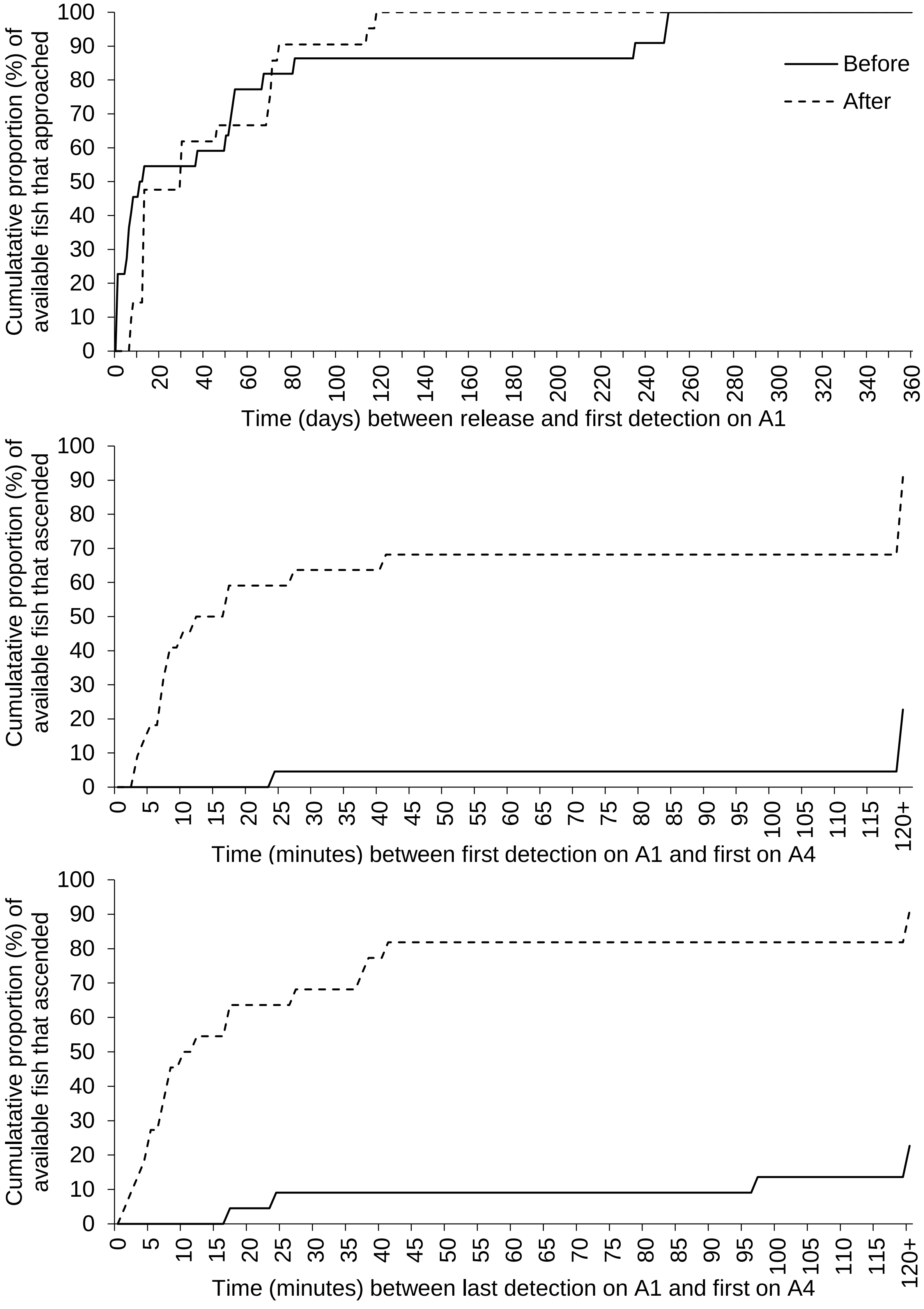
Cumulatative proportion (%) of available fish that approached
0
10
20
30
40
50
60
70
80
90
100
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
Time (days) between release and first detection on A1
Before
After
Cumulatative proportion (%) of available fish that ascended
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120+
Time (minutes) between first detection on A1 and first on A4
Cumulatative proportion (%) of available fish that ascended
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120+
Time (minutes) between last detection on A1 and first on A4

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

3.3 Flow and temperature during passage

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

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

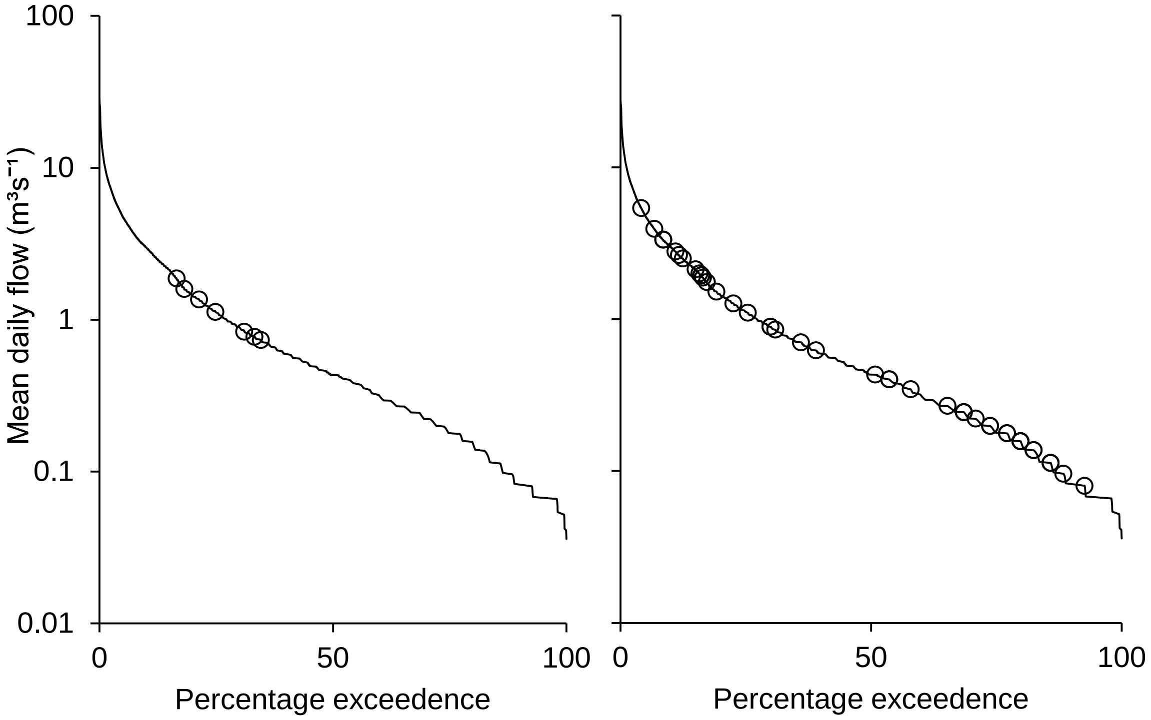

Figure 5: Percentage mean daily flow (m^3s^{-1}) exceedance curve during the study (March 14 – January 17), including the passages (circle symbol) that occurred before (*n* = 7; left) and after (*n* = 39; right) LCB construction.

3.4 Fish size

There was no significant difference in length at tagging between fish that did (median = 186-mm, range = 130-195-mm, *n* = 5) and did not (215-mm, 144-400-mm, *n* = 8) ascend the weir before LCB construction (Mann-Whitney *U* test: *Z* = -1.757, *n* = 13, *P* = 0.093). Fish that approached the weir (detected on A1) before (196-mm, 122-400-mm, *n* = 22) and after (212-mm, 148–269-mm, *n* = 21) LCB construction had similar length at tagging (Mann-Whitney *U* test: *Z* = 0.267, *n* = 43, p = 0.789). There was also no significant difference in length at tagging between fish that ascended before (186-mm, 130-195-mm, *n* = 5) and after (212-mm, 156-269-mm, *n* = 19) LCB construction (Mann-Whitney *U* test: *Z* = -1.592, *n* = 24, *P* = 0.139). Indeed, the second smallest fish detected at the weir during the whole study was 156-mm when tagged and ascended on 10 separate occasions between flows of 0.08–1.52 m^3s^{-1}. Binary logistic regression model on probability of passage before (P50 = 176-mm; Coefficient = -0.020, Std. Error = 0.016, z statistic = -1.263, *P* = 0.207) and after LCB construction (P50 = 148-mm and P90 = 180-mm; Coefficient = 0.069, Std. Error = 0.052, z statistic = 1.316, *P* = 0.188) was also not significant, probably because too few fish did and did not pass before and after LCB construction, respectively (Figure 6). There was no significant difference in size of fish that entered the fish pass through the gap in the bottom baffle and those that leapt over the bottom baffle (Mann-Whitney *U* test: *Z* = 1.404, *n* = 19, *P* = 0.179).

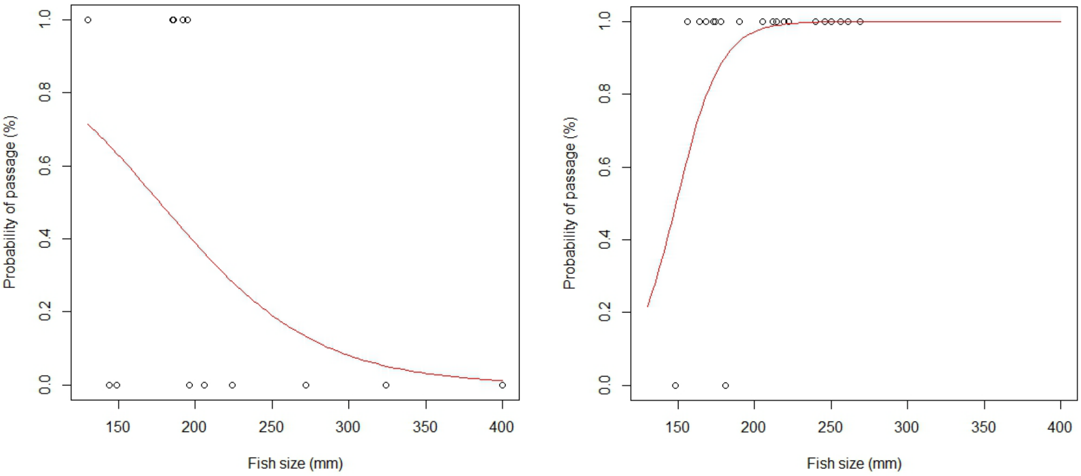

Figure 6: Binary logistic regression model of length at tagging (mm) for fish that did and did not ascend Eshton Weir before (left) and after (right) LCB construction.

4 DISCUSSION

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

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

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

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

Whether an obstruction can be ascended or not will often depend on the hydraulic conditions over and at the base of the obstruction (Larinier, 2001). This study has demonstrated that the addition of a LCB fish pass on the apron of a low gradient gauging weir enabled passage during both higher and lower flows than observed beforehand. While temperature is known to have an effect on swimming ability for many fishes (Wardle, 1980; Ojanguren *et al.,* 2001), the lowest temperature fish ascended the weir before and after LCB construction was comparable and thus flow was deemed to have an overarching influence during this study. Indeed, the addition of baffles onto the weir apron is to retard and significantly deepen the super-critical flow, with the aim of providing a suitable velocity and water depth for a variety of fish species and sizes to pass (Servais, 2006). In addition, it was expected that during high discharges fish might use both the low velocity channel (gaps in the baffles) as well as ascend over the baffles (Armstrong *et al.,* 2010). As expected, fish used both these routes after LCB construction over a wide range of flows, though a higher proportion were observed ascending over baffles at higher flows. Fish that ascend over the baffles when downstream water depths were shallower than the top of the baffle are considered to have leapt. Leaping behaviour has been observed for brown trout passing small obstacles and weirs by Ovidio *et al.* (2007). Regardless of route taken, passage through the LCB fish pass ($Q_{92.6}$ – $Q_{4.17}$) was across a wider range of flows than before construction ($Q_{34.5}$ – $Q_{16.5}$) and nearly occurred across the range of flow exceedances recommended (Q_{95} – Q_{10}) in the fish passage manual for England and Wales (Armstrong *et al*., 2010). The range of flow exceedances were also similar to those reported for brown trout passage through a nature-like bypass on the River Aire, England (Dodd *et al.,* 2017).

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

Fish were tagged at different times of year before (March) and after (July) LCB construction but were considered equally motivated to ascend the weir because the proportion of available fish were almost identical and the time between release and first approach to the weir was similar. It has also been observed that displaced brown trout will initiate a homing instinct after relocation (Harcup *et al.,* 1984; Armstrong and Herbert, 1997). The proportion of brown trout detected downstream and that passed Eshton Weir before LCB construction was comparable between fish captured downstream and upstream (and displaced) of the weir. Therefore, neither the timing of release or location of fish capture influenced the findings of the investigation; all fish detected at the weir were considered motivated to move upstream. Regardless of motivation to move (e.g. exploratory, homing and/or spawning), after LCB construction brown trout were physically capable of entering and swimming through or over the fish pass.

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

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