1   **Upstream passage of adult sea trout (*Salmo trutta*) at a low-head weir with an**

2   **Archimedean screw hydropower turbine and co-located fish pass**

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25   **Abstract**

26   The exploitation of riverine systems for renewable energy has resulted in large numbers of

27   small-scale hydropower schemes on low-head weirs. Although considered a clean and 'green'

28   energy source in terms of emissions, hydropower can impact upstream migrating species by

29   diverting flow away from viable routes over the impoundment and attract fish towards the

30   turbines outfall. In an attempt to reduce this negative effect hydropower outfalls with co-

31   located fish passage entrances are recommended; utilising turbine flows to attract fish towards

32   the fish pass. This study used acoustic telemetry to understand the performance of a co-located

33   Larinier fish pass at low-head hydropower scheme at a weir on the tidal Yorkshire Esk, England.

34   The majority of the sea trout (anadromous *Salmo trutta* L.) that approached the impediment

35   were attracted to the hydropower and co-located fish pass. Fish ascended through the pass

36   under a wide range of river flows, tide heights, downstream river levels and hydropower flows,

37   and there was no evidence that the hydropower operation affected fish pass ascent. The

38   information presented is urgently required to inform management decisions on the operation

39   of hydropower schemes during the migratory period of salmonid fish, and help determine best

40   practice designs and operation at these facilities.

41   **Running head:** Passage at hydropower with a co-located fish pass

Introduction

Rivers worldwide are becoming increasingly exploited for renewable energy from hydropower (Jansson, 2002; Murchie *et al.*, 2008). Although harnessing energy and conversion to electrical power from water discharge began in the mid-19th Century (Poff and Hart, 2002), it has made a resurgence in recent years and is now considered the most important renewable electricity source worldwide (Bratrich *et al.*, 2004), accounting for between 16-19% of global electricity (Balkhair and Rahman, 2017). This is because hydropower is considered the most reliable and cost-effective renewable energy source (Bruno and Fried, 2008), which has led to legislation supporting its development, such as the EU Renewables Directive (2009/28/EC) in Europe.

Hydropower requires a difference in head height between the intake and outfall, often achieved by an impounding structure. Schemes can vary greatly in size and the current largest scheme is the Three Gorges Dam, China, which is 181 m high and has an output of 22,500 MW (Winemiller *et al.,* 2016). Small-scale schemes (1-25 MW output, i.e. micro-hydropower (<1 MW) not included) outnumber large schemes by an estimated eleven to one, with an estimated 82,891 small plants currently in operation or under construction globally; with the expectation that this number could triple in the coming years (Couto and Olden, 2018). For example, there are around 26,000 impoundments in England and Wales that have the potential for hydropower schemes (Environment Agency, 2010), with Archimedean Screw Turbines (AST) increasingly being favoured at low-head impoundments (Elbatran *et al*., 2015).

Although hydropower is presented as a clean and 'green' energy source in terms of emissions (Rosenberg *et al.*, 1995; Bratrich *et al.*, 2004), it can have important impacts on ecosystems. These include the alteration of hydrological regimes, loss, damage to and fragmentation of riverine habitats and the alteration of sediment flow and suspended solids (Stanford *et al.,* 1996; O'Hanley and Tomberlin, 2005; Abbasi and Abbasi, 2011; Lin, 2011). Hydropower installations can also have impacts on important freshwater fauna, especially on fishes during their migrations (e.g. diadromous and potamodromous species). For example, the Three Gorges Dam Scheme has been shown to have caused detrimental ecological impacts that are expected to cost an estimated $26 billion to mitigate (Winemiller *et al.,* 2016). Abstraction of water for power generation may cause injury and mortality to downstream migrating fishes through impingement on screens or entrainment through high-head turbines (Eyler *et al.,* 2016; Havn *et al*., 2018) and low-head ASTs (Buysse *et al.,* 2015; Havn *et al.,* 2017). Furthermore, flows diverted through large hydropower turbines have been shown to distract fish from, and reduce

74 flows through, other viable routes over impoundments (e.g. Arnekleiv and Kraabøl, 1996;

75 Thorstad *et al.,* 2003; Scruton *et al.,* 2007) thus reducing the efficiency of fish passes and

76 impacting on the ability of fishes to pass over impoundments. Despite the proliferation of

77 small-scale schemes, past research on the impacts of hydropower on upstream migrating fish

78 has been mainly restricted to larger schemes. However, there is a perception that the potential

79 impacts of hydropower largely remain the same, irrespective of the scale of the scheme

80 (Robson *et al.* 2011). There is therefore currently a paucity of investigations on the upstream

81 migration of fish around ASTs, and thus their impacts remain poorly understood. Given the

82 potential increase in the number of AST schemes, it is imperative that evidence is collected to

83 enable potential negative impacts to be understood, effective mitigation measures to be

84 identified and facilitate sustainable development of hydropower as a renewable energy.

85 Remediation of reductions in riverine ecosystem connectivity caused by dams and

86 impoundments is driven by legislation (e.g. America-Anadromous Fish Conservation Act

87 (1965); New Zealand-Freshwater Fisheries Regulations (1983); European Water Framework

88 Directive (EC; 2000/60/EEC)). The ideal solution, from a fish migration and environmental

89 policy perspective, would be to remove obstacles and re-establish natural river connectivity.

90 When an obstruction cannot be removed, possibly due to a new hydropower development,

91 longitudinal connectivity must be restored through the construction of an efficient fish passage

92 solution. In the UK, a new low-head hydropower scheme must be designed to incorporate best

93 practice mitigation measures to protect fish passage, with the onus being on the hydropower

94 developer to maintain or improve passage at the site (Environment Agency, 2016). This

95 currently includes having a co-located fish passage solution (where the discharge from the

96 turbine and fish pass are parallel) (Armstrong *et al*., 2010). In theory, the discharge from a co-

97 located hydropower turbine (which is often far greater than flow through the fish pass) is used

98 to attract migrating fish towards the fish pass and thus enhance the ability of fish to pass the

99 impoundment. However, while co-located discharges may attract migrating fish towards the

100 vicinity of a fish pass the complex flow environments created by competing discharges may

101 prevent fish from locating or accessing the fish pass efficiently (Gisen *et al.,* 2017). Other

102 current best practice mitigation measures to protect upstream migrating fish include ensuring

103 sufficient water goes through the fish pass at all times, which may lead to the turbine not

104 operating during low flows (also known as "hands-off flows"), and operational shutdown

105 during critical migration periods. However, there is a dearth of real-world evidence on the

106 applicability or effectiveness of these mitigation measures for low-head hydropower schemes.

107 This study investigated the upstream passage of sea trout (anadromous *Salmo trutta* L.) at
108 Ruswarp Weir on the River Esk in North Yorkshire, England, which has a low-head AST
109 hydropower scheme with a co-located Larinier (super active baffle) fish pass. The objectives
110 were to 1) assess attraction and passage efficiencies of the Larinier fish pass and the
111 impediment; 2) determine the influence of time of day, tide height, river flow, downstream
112 river level and turbine flow on the attraction and passage to the AST and fish pass; and 3)
113 evaluate the time taken to approach and pass the impediment. Specific focus was given to the
114 effectiveness of a co-located fish pass, hands-off flows and the possibility of identifying critical
115 migration periods for targeted operational shutdown to facilitate fish passage. Such information
116 is urgently required to inform management decisions on the operation of hydropower schemes
117 during the migratory period of salmonid fish, and help determine best practice designs and
118 operation at these facilities.

119 **Materials and methods**

120 *Study site*

121 The Yorkshire Esk, England, flows approximately 45 km from its source upstream of
122 Westerdale (54.408996, -0.988639) on the North York Moors to its mouth on the North Sea
123 coast in the harbour town of Whitby (54.490053, -0.613349) (Fig. 1). The Esk supports
124 migratory salmonid populations, namely sea trout and Atlantic salmon (*Salmo salar* L.) and a
125 population of endangered freshwater pearl mussel (*Margaritifera margaritifera* L.), which is
126 dependent on a healthy salmonid population to complete its lifecycle. The tidally influenced
127 reach of the Esk extends from Whitby to Ruswarp Weir (54.468258, -0.633729), which was
128 constructed to divert water through a mill that is no longer active (Fig. 1). The weir was 270 m
129 long (right bank to left bank) spanning a channel width of 50 m, had an apron length of 10 m
130 and was positioned at approximately 15° angle to the main river flow. Two fish passes were
131 intended to facilitate upstream migration at Ruswarp Weir; a diagonal V notch / baulk pass
132 (approx. 0.5 m^3s^{-1} discharge at low flow) in the centre of the weir and a Larinier pass (approx.
133 1.0 m^3s^{-1} discharge; hereafter referred to as the FPS) adjacent to an AST on the right-hand bank
134 at the most upstream limit of the weir (Fig. 1).

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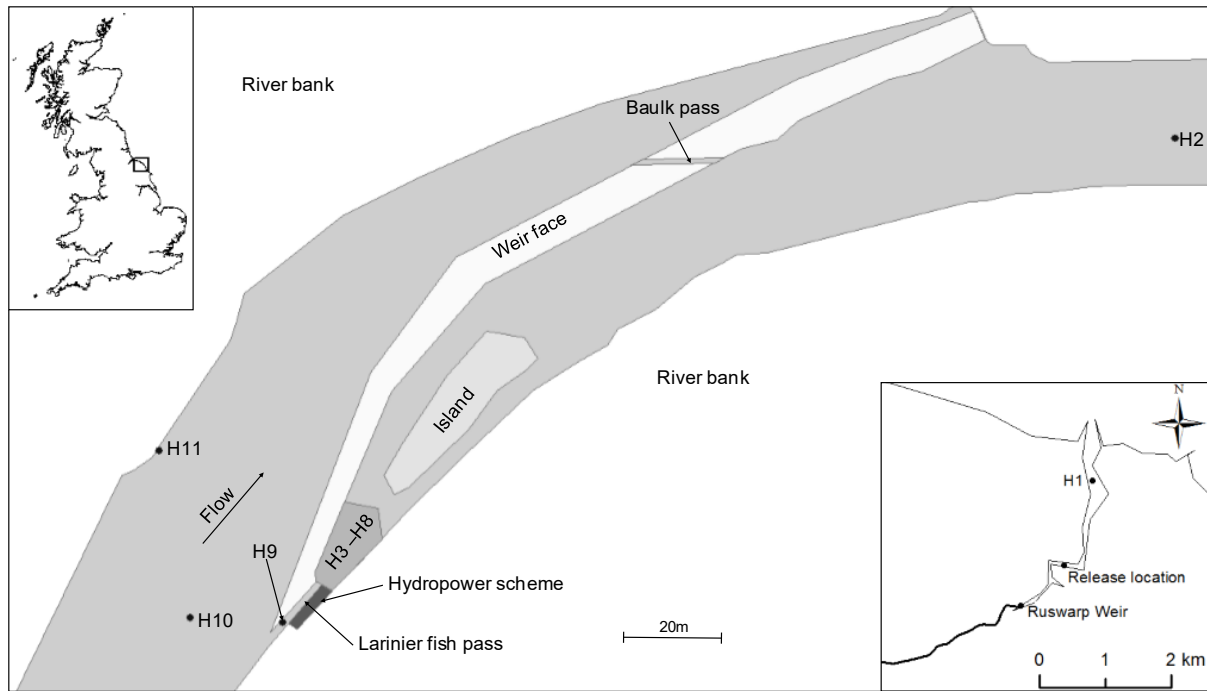
Figure 1: A map of Ruswarp Weir on the Yorkshire Esk, England, including the location of fish passes, hydropower scheme and monitoring equipment (hydrophones H1-H11).

The AST (diameter = 2.9 m) was licenced to abstract up to 4 m^3s^{-1}, generate approximately 50 kW of electricity and its discharge velocity could not exceed 1.0 ms^{-1}. The operating head varied from 1.6 - 2.0 m depending on tidal state downstream. The scheme could not abstract (i.e. licenced hands-off flow) when intake river level was below 3.492 metres above Ordnance Datum (mAOD) (equating to river flow of 0.92 m^3s^{-1}), thus ensuring a sufficient flow of water through fish passes at low flows. The AST could not abstract when river discharge exceeded approximately 50 m^3s^{-1} and during high spring tides, maintenance or clearing of debris from the intake.

Sampling and tagging procedure

Sea trout (*n* = 131) were caught between 24 September and 23 November in three consecutive years (2013 = 46, 2014 = 44 and 2015 = 41) in the reach of river 400 m downstream of Ruswarp Weir using pulsed DC (50 Hz) electric fishing equipment, either whilst wading at low tide or from a boat at high tide. The condition of all fish caught was screened to ensure they were suitable for tagging. Prior to tagging in the field, fish were anaesthetised using MS-222 (40 mg L^{-1}). Species, sex, fork length (nearest mm) and weight (nearest 25g) were recorded. Fish were placed ventral side up in a clean V-shaped foam support. Tags (Model 795LG acoustic tags; 11 mm x 25 mm, 4.6-g weight in air, expected life of 220 days, 307 kHz, Hydroacoustic

155   Technology Inc., Seattle, USA) were activated and tested with a hand held detector

156   immediately prior to tagging (Model 492 Acoustic Tag Detector, Hydroacoustic Technology

157   Inc., Seattle, USA) to verify the tag was successfully transmitting (pulse rate ranged from 2500-

158   2822 msec.), sterilised and rinsed with distilled water prior to use. Tags were inserted into the

159   body cavity of fish through a 20-mm long, ventro-lateral incision made with a scalpel, anterior

160   to the muscle bed of the pelvic fins. The incision was closed with an absorbable suture. In all

161   cases tag weight did not exceed 2% of the fish body mass (Winter, 1996). After surgery fish

162   were held in a well-aerated and oxygenated observation tank until they regained balance and

163   were actively swimming. Tagged fish were then transported approximately 1.5 km downstream

164   of Ruswarp Weir (54.474629 -0.618624) to be released. All tagging was undertaken after

165   ethical review and in compliance with the UK Animals (Scientific Procedures) Act 1986: Home

166   Office licence number PPL 60/4400.

167   *Monitoring*

168   Fish were tracked using a combination of a Model 290 acoustic tracking system and Model

169   300 hydrophones (Hydroacoustic Technology Inc., Seattle, USA). One hydrophone (H1) was

170   located downstream from the release location (54.482663, -0.611294), a second (H2) was

171   located 30 m downstream of the base of Ruswarp Weir (54.469114, -0.630446) and seven

172   hydrophones (H3-H8) were installed immediately downstream of the AST/fish passage

173   solution (FPS) (Fig. 1). Three hydrophones (H9-H11) were located upstream of Ruswarp Weir

174   to confirm pass and impediment ascent. The performance of the tracking system was tested

175   using a Model 795LG tag manually drawn through the river.

176   *Environmental data*

177   River flow (discharge m^3s^{-1}) was measured at 15-min intervals at Briggswath gauging station

178   (54.462012, -0.654322), 1.6 km upstream of Ruswarp Weir. Predicted tide height (mAOD)

179   measured at 5-min intervals at Whitby Harbour were obtained from Admiralty Total Tide

180   software (The United Kingdom Hydrographic Office, Taunton, UK); tide height less than 4.5

181   m at Whitby Harbour did not reach Ruswarp Weir. Downstream river level (mAOD) and

182   Turbine flow (m^3s^{-1}) at 15-min intervals were obtained from Esk Energy UK Ltd (the

183   hydropower owner). Daylight timings were obtained from HM Nautical Almanac Office

184   (http://astro.ukho.gov.uk/surfbin/first_beta.cgi).

Data analysis

186   To evaluate the upstream migration at Ruswarp Weir five metrics were defined. *Available fish*
187   was the number of tagged fish that approach Ruswarp Weir (on H2-H8). *AST/FPS attraction*
188   *efficiency* was the percentage of *available fish* that were attracted to the AST/FPS (detection
189   on H3-H8). *FPS passage efficiency* was the percentage of fish attracted to the AST/FPS that
190   passed through the FPS. *Overall FPS efficiency* was the percentage of *available fish* that passed
191   through the FPS. As multiple routes were available for passage over the weir, *impediment*
192   *passage efficiency* was the percentage of *available fish* that passed the weir via any route. All
193   passage metrics were reported as frequencies and as percentages with associated confidence
194   intervals calculated as 95% Bayes Credible Intervals for proportions e.g. 33% [25-41% CI].
195   *Number of AST/FPS approaches* was a count of the number of times each tagged fish was
196   attracted to the AST/FPS (H3-H8).

197   The diurnal timing of AST/FPS approaches and FPS passages were tested using a Chi-square
198   contingency test for assessing frequency distributions, with expected frequencies for night and
199   day set at 62% and 38%, respectively, based on the average number of darkness and daylight
200   hours during the study period (twilight split evenly between groups). River flow, tide height,
201   downstream river level and turbine flow are presented as exceedance values during the study
202   period (1 October – 31 December in each study year).

203   The time to pass Ruswarp Weir were characterised using four metrics. *AST/FPS attraction time*
204   was the time from first detection at the weir (first detection on H2) to first detection downstream
205   of the AST/FPS (H3-H8). *FPS passage time* was the time between first detection downstream
206   of AST/FPS (H3-H8) and first detection upstream of the weir, for fish that passed through the
207   FPS. *Overall FPS passage time* (the combination of the previous two metrics) was the time
208   from first detection at the weir (first detection on H2) and first detection upstream of the weir,
209   for fish that passed through the FPS. *Overall impediment passage time* was the time from first
210   detection at the weir (first detection on H2) and first detection upstream of the weir via any
211   route. *Individual approach duration* was the time between first and last detection downstream
212   of the AST/FPS (H3-H8) during each approach. All four time metrics had non- normal
213   distributions (Kolmogorov Smirnov test), thus non-parametric Mann-Whitney *U*-tests (two-
214   tailed) were performed to compare medians between groups (reported with minimum and
215   maximum values).

216 The influence of AST operation and hydrological conditions experienced by tagged sea trout
217 during each AST/FPS approach on the probability of passing and time to pass Ruswarp Weir
218 (time-to-event) were analysed using binary logistic regression models (passage) and Cox
219 Proportional Hazard models in R (version 3.4.3 R Core Team, 2017). A binary logistic model
220 (Model 1 – package: lme4; Bates *et al.,* 2015) was fitted to assess the probability of successful
221 passage during each approach. Environmental variables (Turbine flow, Residual River Flow
222 [total River flow – Turbine flow], the rate and direction of change of River flow ($\pm m^3 s^{-1} hr^{-1}$)
223 and downstream river level) were all entered into the model to test for their coefficient and
224 their significance with individual fish being considered a random effect. Residual flow was
225 used to represent the component of the river flow available to the fish pass and to pass over the
226 weir irrespective of the activity of the turbine. All-subsets variable selection by Akaike
227 Information Criterion (AIC) was then used to determine the most useful explanatory variables.

228 Cox Proportional Hazard (time-to-event) models were fitted to determine the influence of the
229 Turbine flow and hydrological conditions on the *FPS passage time* (Model 2 considering only
230 the fish at the AST/FPS as being "at risk" of passing – package: survival; Therneau, 2017), the
231 time from each subsequent approach to passage (Model 3 with observations censored when
232 fish left the vicinity of the AST/FPS – package: coxme; Therneau, 2018), and the *individual*
233 *approach duration* (Model 4 approaches end with either passage or non-passage and no
234 observations censored – package: coxme; Therneau, 2018). The predictor variables (same as
235 above) were all entered into all models to test for their coefficient and their importance, and in
236 models 3 and 4 individual fish were considered a random effect. All-subsets variable selection
237 by AIC was then used to determine the most useful explanatory variables.

238 Data analysis was prepared and analysed in Microsoft Excel, IBM SPSS Statistics (version
239 24.0) and R (version 3.4.3) (R Core Team, 2017).

240 **Results**

241 *Passage efficiency*

242 Eighty-four of 131 tagged sea trout approached Ruswarp Weir, i.e. *available fish* = 64% (56-
243 72% CI). *AST/FPS attraction efficiency* was 96% (91-99% CI, *n* = 81/84) with 81 sea trout
244 making a total of 784 different approaches (median *number of AST/FPS approaches* per fish =
245 6, min – max = 1 - 50). Fifty-three tagged sea trout passed through the FPS, i.e. *overall FPS*
246 *passage efficiency* = 63% (52-73% CI, *n* = 53/84) and *FPS passage efficiency* = 65% (55-75%
247 CI, *n* = 53/81). A further eight fish ascended via other routes, i.e. *impediment passage efficiency*

248 = 73% (62-81% CI, n = 61/84), only one of which did not approach the AST/FPS. Twenty-

249 three sea trout detected at the weir did not ascend, though 21 of these fish approached the

250 AST/FPS (91%, 73-97% CI). Eight of the *available fish* that did not ascend were last detected

251 on H1 in the lower estuary (35%, 19-55% CI) and 15 were last detected immediately

252 downstream of the weir (H2-H8) (65%, 45-81% CI).

253 *Time of day*

254 Sea trout approached and ascended through the FPS during almost all hours of the day (Fig. 2).

255 Sea trout approached the AST/FPS more times at night (69%, n = 539) than during the day

256 (31%, n = 245), but was not significantly different to the frequency of daylight/darkness during

257 the study (Chi-Square Test: χ^2 = 2.08, d.f. = 1, n = 784, P = 0.149). Similarly a higher proportion

258 of fish ascended the FPS at night (70%, n = 37) than during the day (30%, n = 16) but this was

259 also not significantly different to the frequency of daylight/darkness during the study (Chi-

260 Square Test: χ^2 = 2.72, d.f. = 1, n = 53, P = 0.099). *Individual approach duration* of non-

261 passage approaches was shorter at night (2.52 min (0.03 – 353.42), n = 503) than during the

262 day (3.05 min (0.03 – 408.87), n = 229), but the difference was not significant (Mann Whitney

263 U-test: Z = -0.935, n = 732, P = 0.350). *Individual approach duration* of passage approaches

264 was also shorter at night (3.85 (0.08 – 197.13) min, n = 37) than during the day (6.17 (0.37 –

265 94.70) min, n = 16), but the difference was not significant (Mann Whitney U-test: Z = -1.511,

266 n = 53, P = 0.131).

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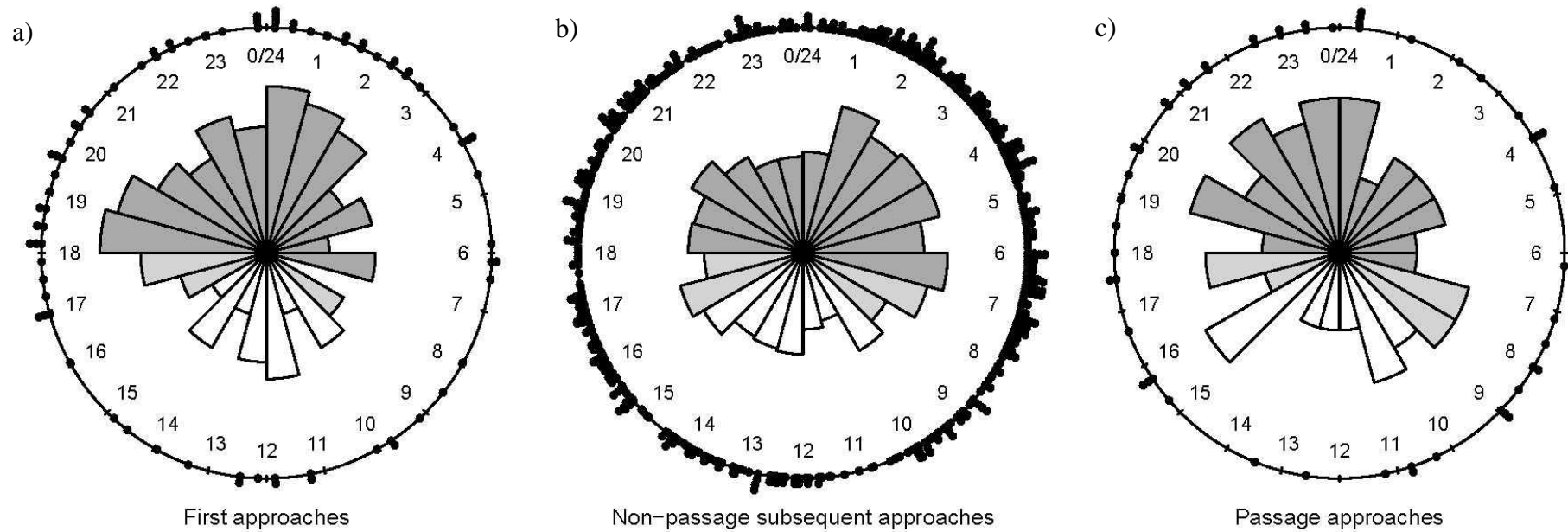
Figure 2: Circular plot with rose diagram on the number of AST/FPS approaches in each hour of the day during first approach (a) (n = 81), subsequent non-passage approaches (b) (n = 661) and passage approaches (c) (n = 53). Dark grey, light grey and white shading represent average darkness, twilight and daylight, respectively, during the study period.

Hydrological conditions

273   River flow during the study ranged from 0.44 to 88.00 m^3s^{-1}, and sea trout first approached the

274   AST/FPS between 1.59 and 32.79 m^3s^{-1} ($Q_{84.9} - Q_{1.6}$), and ascended the FPS between 1.65 and

275   31.00 m^3s^{-1} ($Q_{83.7} - Q_{1.8}$). There was no significant difference in river flow between when fish

276   approached the AST/FPS but did not ascend (median = 6.48 m^3s^{-1}, 1.59 – 41.50 m^3s^{-1} ($Q_{84.9} -$

277    $Q_{0.9}$)) and when fish ascended (median = 6.22 m^3s^{-1}) (Mann Whitney U-test: $Z = 0.614$, $n =$

278   778, $P = 0.539$) (Fig. 3). Predicted tide height during the study ranged from 0.40 to 6.10 m,

279   and both first AST/FPS approaches ($n = 79$) and FPS ascents ($n = 53$) occurred between tide

280   heights of 1.01 and 5.80 m ($Q_{97.6} - Q_{0.1}$) (Fig. 3), although fish approached the AST/FPS
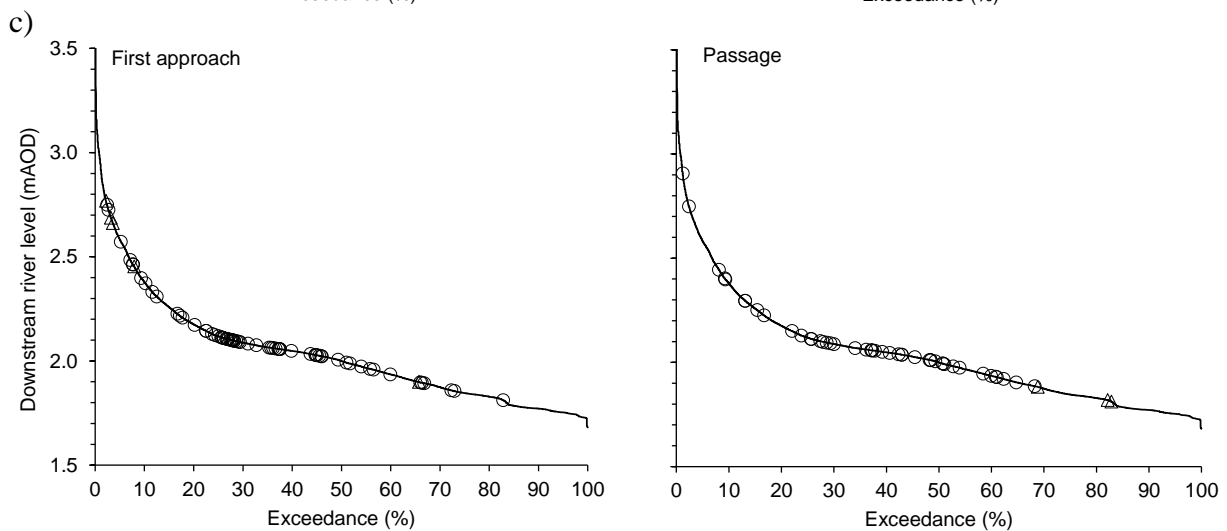
281   between 0.60 and 5.80 m ($Q_{99.9} - Q_{0.1}$).

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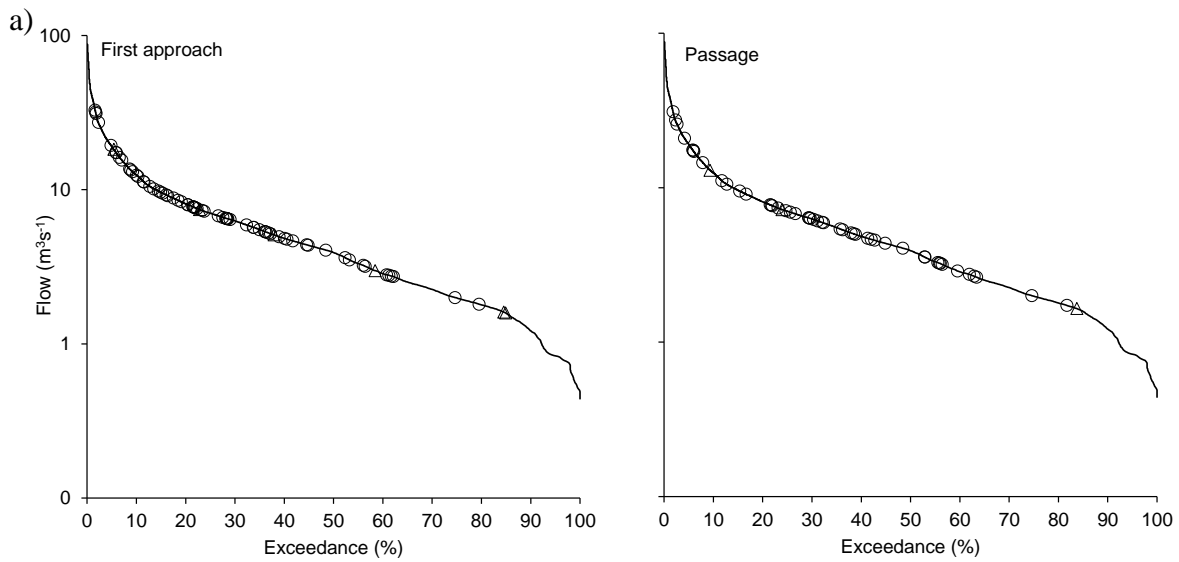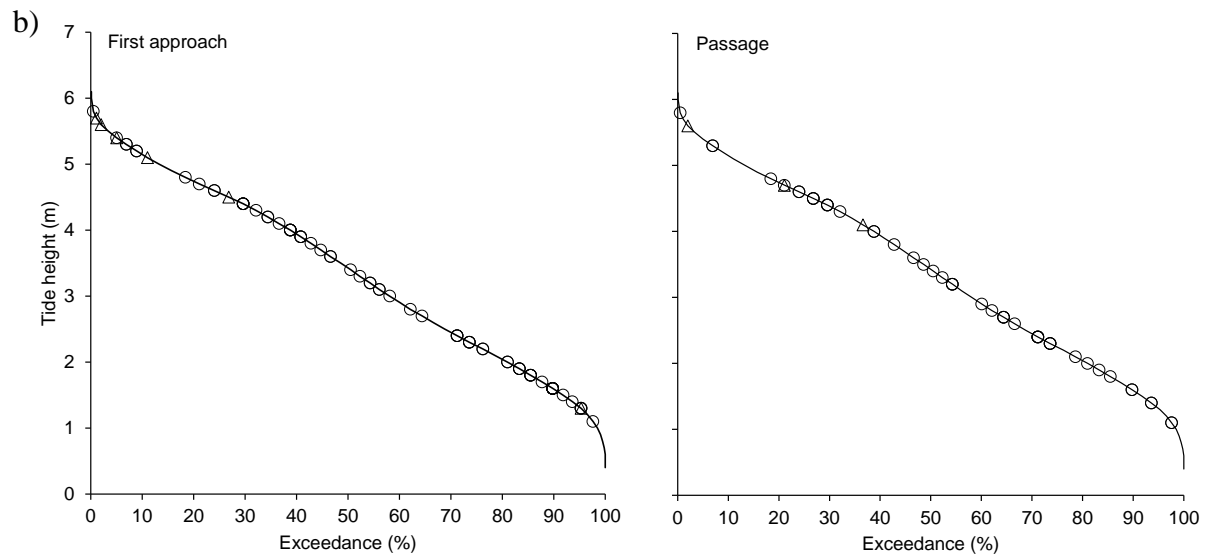
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286 Figure 3: Sea trout first AST/FPS approach (left) and FPS passage (right) in relation to a) river

287 flow (m³s⁻¹), b) tide height (m) and c) downstream river level (mAOD (AST shuts-off at 2.79

288 mAOD)) exceedance during the study period when the AST was on (circles) or off (triangles).

289   Downstream river level during the study ranged from 1.68 to 4.24 mAOD, fish first approached
290   the AST/FPS between 1.81 and 2.77 mAOD ($Q_{82.8}$ – $Q_{2.2}$) and ascended the FPS between 1.81
291   and 2.91 mAOD ($Q_{82.8}$ – $Q_{1.2}$) (Fig. 3). Fish ascended the FPS on significantly lower
292   downstream river levels (median = 2.05) than non-passage approaches to the AST/FPS (median
293   = 2.09, 1.75 – 3.16 mAOD ($Q_{95.3}$ – $Q_{0.2}$)) (Mann Whitney U-test: Z = -2.704, n = 742, P =
294   0.007). The highest frequency of first AST/FPS approaches (25%), subsequent non-passage
295   AST/FPS approaches (22%) and FPS passages (22%) all occurred when the downstream river
296   level was 2.10-2.14 mAOD (Fig. 4), despite 1.80-1.84 mAOD being the most frequent
297   downstream river level during the study. Over half of first AST/FPS approaches (51%, n =
298   41/81), subsequent non-passage AST/FPS approaches (53%, n = 332/630) and FPS passages
299   (51%, n = 25/49) occurred when downstream river level was between 2.00 and 2.19 mAOD,
300   despite this only representing 32% of the study period (41% of hydropower operation time).
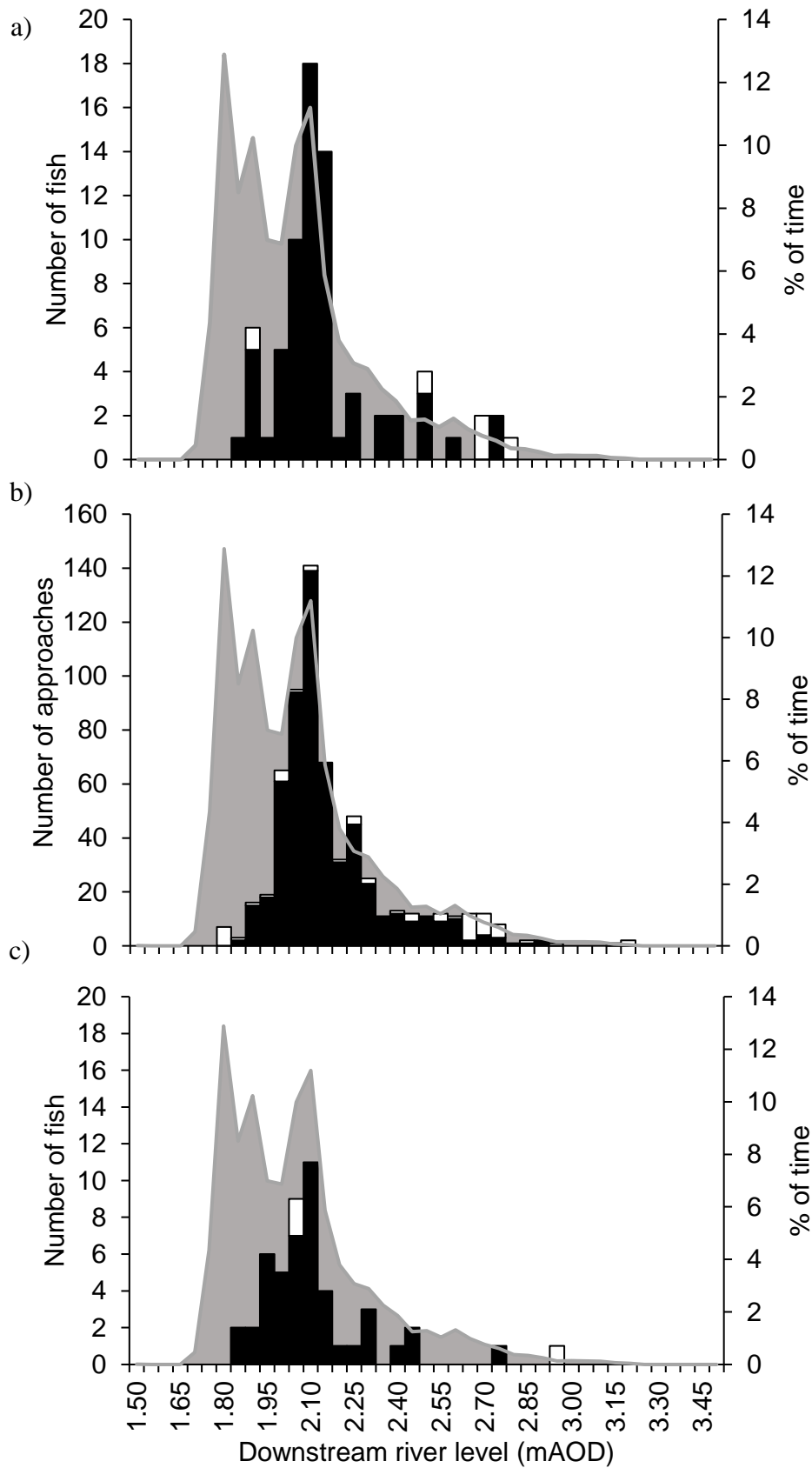
301
302 Figure 4: Relationship between downstream river level (mAOD) and first AST/FPS approach
303 (a), subsequent non-passage AST/FPS approaches (b) and FPS passage (c) during periods when
304 the hydropower is on (black) and off (white).

305

Hydropower operation

No fish approached the AST/FPS when the AST was not operational because the river flow was too low, i.e. below the hands-off flows ($>Q_{92.9}$). The majority of AST/FPS approaches occurred when the AST was operational (91%, $n = 688/756$), which represented 76% of the study period, and occurred across almost the entire range of turbine flows (0.11 - 3.96 m^3s^{-1} (maximum permitted = 4 m^3s^{-1}), $Q_{97.7} - Q_{0.1}$). Six tagged sea trout approached the AST/FPS on 65 different occasions (river flow = 1.59 – 41.54 m^3s^{-1}; tide height = 1.30 – 5.80 m; downstream river level = 1.75 – 3.16 mAOD) and 3 fish ascended the FPS (river flow = 1.65 – 12.96 m^3s^{-1}; tide height = 4.10 – 5.60 m; downstream river level = 2.04 – 2.91 mAOD) when the turbine was not operating (i.e. high tide downstream, maintenance or to clear debris from the intake). Fish passed through the FPS across almost the entire range of AST flows, i.e. 0.11 – 3.83 m^3s^{-1} ($Q_{97.7} - Q_{0.6}$) (Fig. 5). Turbine flow during FPS passage and non-passage AST/FPS approaches were similar (Mann Whitney U-test: $Z = -0.660$, $n = 688$, $P = 0.509$).
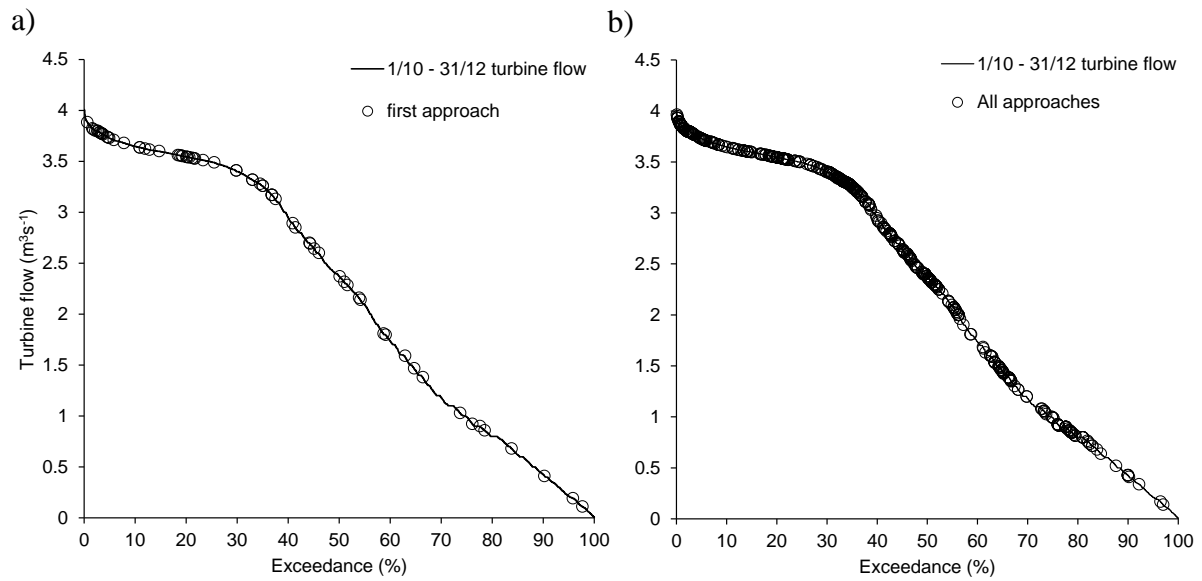
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a)

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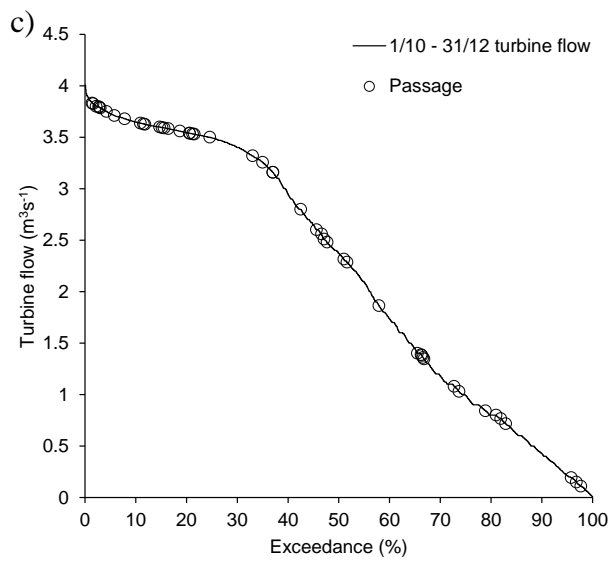
Figure 5: First AST/FPS approaches (a), subsequent non-passage AST/FPS approaches (b) and
FPS passages (c) in relation to AST flow exceedance curves during operation (i.e. turbine flow
= 0, not plotted).

Approach and passage times

Seventy-one percent of tagged sea trout were first detected at the weir within 24 hrs of release,
with a further nine percent detected within 48 hrs. Fifteen percent took between three and seven

332   days and five percent took more than one week to be first detected at the weir after release (Fig.

333   6a). The median *AST/FPS attraction time*, *FPS passage time* and *individual approach duration*

334   were 30.57 min (4.80 – 818.77, $n = 64$), 2.63 hr (0.03 – 195.03, $n = 53$) and 2.75 min (0.02 –

335   408.87, $n = 784$), respectively. The median *overall impediment passage time* was 4.02 hr (0.33

336   – 195.41, $n = 48$) and there was no significant difference between fish that ascended through

337   the FPS (3.34 hr (0.44 – 195.41), $n = 42$) and those that took an alternative route (12.28 hr

338   (0.33 – 86.02), $n = 6$) (Mann Whitney U-test: Z= -0.561, $n = 48$, $P = 0.594$).

339

340
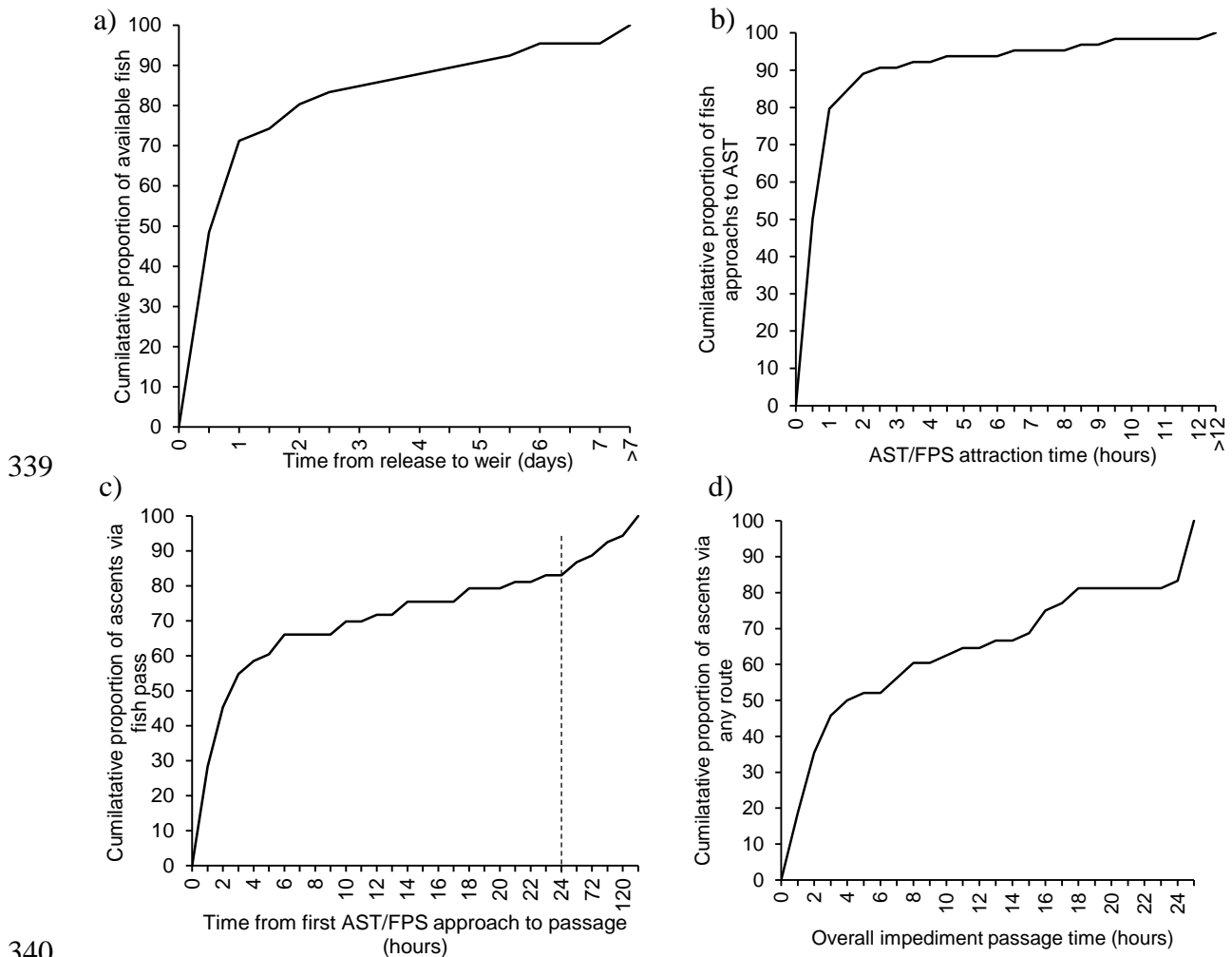
341   Figure 6: Cumulative proportions (%) for time between a) release and first approach to the weir

342   (days), b) *AST/FPS attraction time* (hours), c) *FPS passage time* (hourly intervals for first day

343   and 24 hour intervals thereafter (dotted line)) and d) *overall impediment passage time* (hours).

344

345 *Time-to-event analyses*

346 Turbine flow was never selected as a predictor variable by the all-subsets variable selection
347 and had no significant influence over the probability of passage via the fish pass during each
348 approach (Model 1), *individual approach duration* (Model 4), *FPS Passage time* (Model 2) or
349 time to pass after each approach (Model 3) (Table 1).

350 The residual flow (Total River Flow – Turbine Flow) and the downstream river level were
351 consistently selected as predictors for the probability and duration of passage. The probability
352 of passage was higher at high residual flows (effectively higher river flows) and the time taken
353 to pass via the fish pass (positive coefficient) was lower at higher river flows. Higher
354 downstream river levels reduced the probability of passage (Model 1) and the time taken to
355 pass via the fish pass (Models 2 and 3) was longer when the downstream river level was high.
356 Only downstream river level was selected by all-subsets variable selection by AIC to explain
357 the duration of each approach (Model 4). An increase of 10 cm in downstream river level
358 increased the risk of leaving the vicinity of the AST/FPS by ~ 4% (Model 4, exp(coef.) = 1.004)
359 and an increase of 50 cm made leaving the AST/FPS ~ 22% more likely, reduced the odds of
360 passage during an approach by ~ 73% (Model 1, exp(coef.) = 0.974) and decreased the rate of
361 passage by ~ 70% (Model 3, exp(coef.) = 0.976). This corresponds to the duration of individual
362 approaches being shorter, successful passage taking longer and ultimately being less likely at
363 higher downstream river levels.

364 Table 1: Coefficients and p-values of predictor variables entered into models predicting the probability of passage (Model 1 Binary Logistic), time

365 taken to pass via the fish pass (Models 2 and 3 – Cox PH) and *Individual approach duration* (Model 4 – Cox PH). Variables selected in the final

366 models using all-subsets variable selection by AIC are indicated in bold.

Variable	Model 1 Probability of Passage during each approach			Model 2 *FPS Passage time*			Model 3 Passage time after each approach			Model 4 *Individual approach duration*		
	Coef.	exp(coef.)	p	Coef.	exp(coef.)	p	Coef.	exp(coef.)	p	Coef.	exp(coef.)	p
Turbine flow	-0.125	0.883	0.43	0.051	1.053	0.78	-0.070	0.933	0.63	-0.023	0.977	0.53
Residual flow	**0.065**	**1.067**	**0.08**	**0.167**	**1.182**	**0.00**	**0.101**	**1.106**	**0.00**	0.014	1.014	0.07
Downstream level	**-0.027**	**0.974**	**0.03**	**-0.025**	**0.975**	**0.16**	**-0.025**	**0.976**	**0.05**	**0.004**	**1.004**	**0.09**
Change in flow	-0.003	0.997	0.97	**-0.147**	**0.863**	**0.05**	-0.071	0.931	0.36	-0.023	0.978	0.13

367

Discussion

This study used acoustic telemetry to track upstream migrating adult sea trout to determine the influence of an Archimedean hydropower screw turbine on fish passage through a co-located fish pass on a low-head weir at the tidal limit. Whilst the *impediment passage efficiency* (73%) and the *overall FPS passage efficiency* (63%) were lower than the desirable target of 90-100% for attraction and passage efficiencies suggested by Lucas and Baras (2001) for diadromous fishes, they were within the typical range of pass efficiencies for salmonids globally (61.7% ± 5.9, Noonan *et al.*, 2012). Importantly, the co-located turbine outfall facilitated high attraction to the pass (*AST/FPS attraction efficiency* = 96%) and activity of the AST did not have a significant influence on *FPS passage efficiency*. Indeed, residual flow (river flow – turbine flow) and downstream river level were consistently predictors for the probability and duration of FPS passage (Models 1-3), with higher river flows making FPS passage more likely but higher downstream river levels (related to high spring tides) making FPS passage less likely. Thus confirming prevailing river level and tidal state had a stronger influence on sea trout passage via the FPS than hydropower operation.

Current best-practice guidance in England states low-head hydropower must have a co-located fish pass, based on the theory that turbine discharge can be used to attract migrating fish towards a fish pass (Environment Agency, 2016). This is based on the premise that migratory salmonids are attracted by high flows (Banks, 1969; Thorstad *et al.,* 2008). For example, Lundqvist *et al.* (2008) found upstream migrating Atlantic salmon on the River Umealven, Sweden, were attracted to a high-head hydropower outfall during periods of high turbine discharge rather than a fish bypass with low flow many kilometres away. Although the idea of co-location has been around for a number of years (Larinier, 2008), there is a paucity of peer-reviewed literature that has assessed the performance of this approach. *AST/FPS attraction efficiency* was 96% and 91% of all approaches to the AST/FPS were during hydropower operation, and thus strongly suggests that AST and FPS co-location was a viable method of attracting salmonid fish towards the entrance of the fish pass.

Once fish have been attracted to the combined flow from the hydropower and fish pass, they must be able to locate and access the fish pass efficiently, which may be negatively impacted by potentially competing and/or confusing flows from the hydropower turbine. The *FPS passage efficiency*, i.e. the proportion of fish attracted to the AST/FPS that passed through the FPS, was 65%. There was no evidence to suggest turbine operation negatively impacted fish pass efficiency. Indeed, fish ascended the fish pass across all turbine flows ($Q_{97.7} - Q_{0.6}$) and

401   these flows were comparable between passage and non-passage approaches to the AST/FPS.

402   Turbine flow was also not a predictor variable and did not have a significant influence on

403   Probability of FPS passage (Model 1), *FPS passage time* (Model 2), FPS passage time

404   remaining after each approach (Model 3) or *individual approach duration* (Model 4). Whilst

405   the *FPS passage efficiency* observed here was below the desirable targets suggested by Lucas

406   and Baras (2001) it was similar to efficiencies for upstream migrating salmonids observed for

407   other pass types (Noonan *et al.* 2012, Bunt *et al*. 2016). Therefore, the performance of the FPS

408   is comparable to other fish passes in general. There is little evidence to suggest how the design

409   could be improved as there is a dearth of evidence for the efficiency of Larinier fish passes for

410   salmonids in general. For example, there were no data for upstream migrating anadromous

411   salmonids at Larinier passes in the recent meta-analysis by Bunt *et al*. (2016). The lack of real-

412   world evidence for the efficiency of Larinier passes, coupled with the performance of the FPS

413   in this study, and the efficiencies of other types of passes worldwide (Bunt *et al*. 2016),

414   highlight how imperative adequate research and monitoring of co-located AST/FPS are.

415   Further research is required to ensure fish passage efficiency objectives are being both

416   appropriately defined and met and to ensure the overall performance of best practice designs

417   and operation for new schemes. The suggestion that higher downstream river level (affected

418   by high tides) had a negative influence on successful passage in this study might suggest that

419   further research is specifically required on the best practice pass designs for tidally influenced

420   conditions and their near-field attractiveness and accessibility when co-located with an AST.

421   One possible mechanism that should be explored is the influence of high tides on the location

422   and extent of attraction plumes from the mouth of the FPS in relation to other competing flows.

423   *Impediment passage efficiency*, i.e. the proportion of *available fish* that pass the weir via any

424   route, was 73%. Upstream passage at Ruswarp Weir would need to improve to meet the

425   desirable targets of 90-100% for *impediment passage efficiency* suggested by Lucas and Baras

426   (2001) for passage of diadromous fish at an impediment to maintain healthy populations.

427   Whilst the *FPS* and *impediment passage efficiencies* observed during this study were lower

428   than this desirable target, and therefore may be of concern, the pass performance cannot be

429   attributed to the hydropower scheme and/or to the performance of the FPS *per se*. Furthermore,

430   biotic variables, such as individual motivation (i.e. behaviours related to straying and

431   physiological changes when passing from salt to fresh water) and predation, may have also

432   influenced the movements and fate of fish, thus impacting upon the passage efficiencies both

433   in terms of their measurement and the definition of suitable targets. Fish that did not approach

434   (36% of all tagged fish) or ascend (27% of tagged fish that approached) Ruswarp Weir during

435   this study may have been predated upon by grey seals (*Halichoerus grypus* (Fabricus)) (e.g.

436   Bendall and Moore, 2008), caught by fishermen (licenced or illegal) in the estuary or may have

437   strayed from other rivers (e.g. Atlantic salmon = 50% (Stewart *et al.,* 2009) and sea trout = >10%

438   (King *et al.,* 2016)). However, the risk of capture by predators or humans, and the prevalence

439   of non-passage behaviours may have been elevated by the presence of Ruswarp Weir and

440   therefore ideally their effect needs to be quantified enabling a complete interpretation of

441   impediment passage efficiencies and the definition of appropriate pass performance targets.

442   In addition to elevating estuarine predation risk, delay in adult sea trout spawning migration

443   can increase energy expenditure whilst trying to pass the obstruction. For example, Caudill *et*

444   *al.* (2007) found migrating salmonids that reached spawning grounds on the Columbia River

445   (1300 river km) had shorter passage times than fish that did not reach spawning grounds, with

446   median passage time at individual dams ranging from 0.2 - 2.7 days depending on species and

447   year. The majority (83%) of sea trout passed Ruswarp Weir in less than a day, median passage

448   time was 0.16 days and the longest passage time was eight days. The minor delays observed

449   were considered unlikely to affect migration to spawning grounds, especially given the short

450   length of the River Esk (45 km from source to sea). Indeed, the delay compares favourably

451   with those reported for upstream migrating adult salmonids at weirs (without a low-head

452   hydropower turbines) (Webb, 1990 = 0.6 - 43 days; Gowans *et al.,* 2003 = 1 - 40 days; Newton

453   *et al.,* 2018 = 0.01 - 31 days).

454   In addition to the co-located fish pass, hands-off-flows (< 0.92 m^{3}s^{-1}) was another mitigation

455   measure specified in the abstraction licence to protect upstream migrating salmonids at low

456   river levels. No fish approached the impediment while this mitigation measure was in effect.

457   Operational shutdown is an alternative mitigation measure that has been applied when fish

458   migrate at highly predictable times and had been suggested as a management option if the

459   operation of the AST was shown to impact on fish passage at the site. For example, this

460   measure has been used for downstream migrating silver American eel (*Anguilla rostrate* (L.),

461   Smith *et al*., 2017), silver European eel (*Anguilla anguilla* (L.), Trancart *et al.,* 2013) and

462   Atlantic salmon smolts (Stich *et al*., 2015), though this could also potentially be applied to

463   upstream migrating fish. While untested during this investigation, information on

464   environmental conditions can be used to identify the potential for implementing operational

465   shutdown at Ruswarp Weir or elsewhere in the future. In this study, sea trout ascended the FPS

466   during all hours of the day and across a wide range of river flows ($Q_{83.7}$ - $Q_{1.8}$), tide heights

467   ($Q_{97.6} - Q_{0.1}$), and downstream river levels ($Q_{82.8} - Q_{1.2}$). Therefore, the range of environmental

468   conditions during upstream migration were too broad to define appropriate periods of targeted

469   hydropower shutdown and their application would in this case be unjustified and lead to a

470   substantial loss of power production. Further, there is a risk that operational shutdown would

471   reduce attraction flow to the AST/FPS and thus potentially reduce overall FPS passage

472   efficiency; which is contrary to the principles of co-locating a fish pass.

473   *Implications of the findings*

474   This investigation identified that a low-head hydropower turbine with a co-located fish pass

475   can attract a high proportion of upstream migrating adult salmonids to the pass, and thus is a

476   useful best-practice mechanism to attract fish to a FPS and potentially facilitate upstream

477   migration of salmonids. However, the FPS and impediment passage efficiencies were below

478   the desirable target suggested for diadromous fishes by Lucas and Baras (2001). Crucially,

479   there was no evidence to suggest AST operation influenced the probability of FPS passage,

480   FPS passage time or approach duration, with prevailing hydrological conditions having an

481   overriding influence. However, FPS passage success did appear to be negatively influenced by

482   high river levels at the entrance to the FSP. As such, it is possible that the efficiency of co-

483   location was determined by the performance of the FPS itself in relation to the complex tidal

484   environment and not by the presence of the hydropower turbine. However, there is no evidence

485   to suggest which aspect of the FPS could be modified to improve performance. Therefore,

486   future research is required to improve understanding of fish pass performance and thus best

487   practice designs, particularly at tidally influenced sites with complex flow environments. A

488   combination of fine-scale fish movement data and hydrological data in the pool surrounding

489   the co-located fish pass and hydropower scheme would help to identify the performance of the

490   pass in terms of near-field attraction and entrance efficiency as well as helping to determine

491   any potential distraction from complex flow environments caused by competing turbine and

492   fish pass flows. Whilst the passage efficiencies in this study were below desirable targets, the

493   influence of predation and straying may have had an unquantified impact on the findings and

494   these natural factors (whilst influenced by the presence of the weir itself) make interpretation

495   and definition of appropriate target passage efficiencies difficult. Therefore, further research is

496   required to establish the effects of predation, exploitation and straying behaviours on fish

497   passage studies and the setting of appropriate targets for passage metrics. Fundamentally, given

498   the results of this study, and the paucity of other well-studied examples, further research is

499   required on upstream migrating adult fish at similar low-head hydropower turbines with co-

500   located fish passes. This is required, along with further studies on Larinier passes in general,

501   to increase our knowledge and understanding of best practice designs for co-location as a

502   mitigation measure and for fish pass designs *per se*. Such evidence would enable an improved

503   understanding of upstream migration and thus more effective fish pass designs, improved best

504   practice mitigation measures and definition of appropriate passage targets for hydropower

505   schemes.

506

Conflicts of Interest

517   The authors declare no conflict of interest and the views in this paper are the views of the

518   authors and not necessarily those of the Environment Agency.

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