This is the pre-publication version of an article published at https://doi.org/10.1071/MF18125

Upstream passage of adult sea trout (*Salmo trutta*) at a low-head weir with an Archimedean screw hydropower turbine and co-located fish pass

Jamie R. Dodd[1], Jonathan D. Bolland[1], Jon Hateley[2], Ian G. Cowx[1], Sam E. Walton[1], Marco E. G. V. Cattaneo[3], Richard A. A. Noble[1]

[1] Hull International Fisheries Institute

University of Hull, Hull, England, HU6 7RX

+44 (0)1482 466429

[2] Environment Agency

Richard Fairclough House, Knutsford Road, Warrington, Cheshire, England, WA4 1HG

+44 (0)20302 50698

[3] School of Mathematics and Physical Sciences

University of Hull, Hull, England, HU6 7RX

+44 (0)1482 466566

J.Bolland@hull.ac.uk

M.Cattaneo@hull.ac.uk

I.G.Cowx@hull.ac.uk

J.R.Dodd@outlook.com

Jon.Hateley@environment-agency.gov.uk

R.A.Noble@hull.ac.uk

S.Walton2005@gmail.com

Abstract

The exploitation of riverine systems for renewable energy has resulted in large numbers of small-scale hydropower schemes on low-head weirs. Although considered a clean and ‘green’ energy source in terms of emissions, hydropower can impact upstream migrating species by diverting flow away from viable routes over the impoundment and attract fish towards the turbines outfall. In an attempt to reduce this negative effect hydropower outfalls with co-located fish passage entrances are recommended; utilising turbine flows to attract fish towards the fish pass. This study used acoustic telemetry to understand the performance of a co-located Larinier fish pass at low-head hydropower scheme at a weir on the tidal Yorkshire Esk, England. The majority of the sea trout (anadromous *Salmo trutta* L.) that approached the impediment were attracted to the hydropower and co-located fish pass. Fish ascended through the pass under a wide range of river flows, tide heights, downstream river levels and hydropower flows, and there was no evidence that the hydropower operation affected fish pass ascent. The information presented is urgently required to inform management decisions on the operation of hydropower schemes during the migratory period of salmonid fish, and help determine best practice designs and operation at these facilities.

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 flows through, other viable routes over impoundments (e.g. Arnekleiv and Kraabøl, 1996; Thorstad *et al.,* 2003; Scruton *et al.,* 2007) thus reducing the efficiency of fish passes and impacting on the ability of fishes to pass over impoundments. Despite the proliferation of small-scale schemes, past research on the impacts of hydropower on upstream migrating fish has been mainly restricted to larger schemes. However, there is a perception that the potential impacts of hydropower largely remain the same, irrespective of the scale of the scheme (Robson *et al.* 2011). There is therefore currently a paucity of investigations on the upstream migration of fish around ASTs, and thus their impacts remain poorly understood. Given the potential increase in the number of AST schemes, it is imperative that evidence is collected to enable potential negative impacts to be understood, effective mitigation measures to be identified and facilitate sustainable development of hydropower as a renewable energy.

Remediation of reductions in riverine ecosystem connectivity caused by dams and impoundments is driven by legislation (e.g. America-Anadromous Fish Conservation Act (1965); New Zealand-Freshwater Fisheries Regulations (1983); European Water Framework Directive (EC; 2000/60/EEC)). The ideal solution, from a fish migration and environmental policy perspective, would be to remove obstacles and re-establish natural river connectivity. When an obstruction cannot be removed, possibly due to a new hydropower development, longitudinal connectivity must be restored through the construction of an efficient fish passage solution. In the UK, a new low-head hydropower scheme must be designed to incorporate best practice mitigation measures to protect fish passage, with the onus being on the hydropower developer to maintain or improve passage at the site (Environment Agency, 2016). This currently includes having a co-located fish passage solution (where the discharge from the turbine and fish pass are parallel) (Armstrong *et al*., 2010). In theory, the discharge from a co-located hydropower turbine (which is often far greater than flow through the fish pass) is used to attract migrating fish towards the fish pass and thus enhance the ability of fish to pass the impoundment. However, while co-located discharges may attract migrating fish towards the vicinity of a fish pass the complex flow environments created by competing discharges may prevent fish from locating or accessing the fish pass efficiently (Gisen *et al.,* 2017). Other current best practice mitigation measures to protect upstream migrating fish include ensuring sufficient water goes through the fish pass at all times, which may lead to the turbine not operating during low flows (also known as "hands-off flows"), and operational shutdown during critical migration periods. However, there is a dearth of real-world evidence on the applicability or effectiveness of these mitigation measures for low-head hydropower schemes.

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

Materials and methods

Study site

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

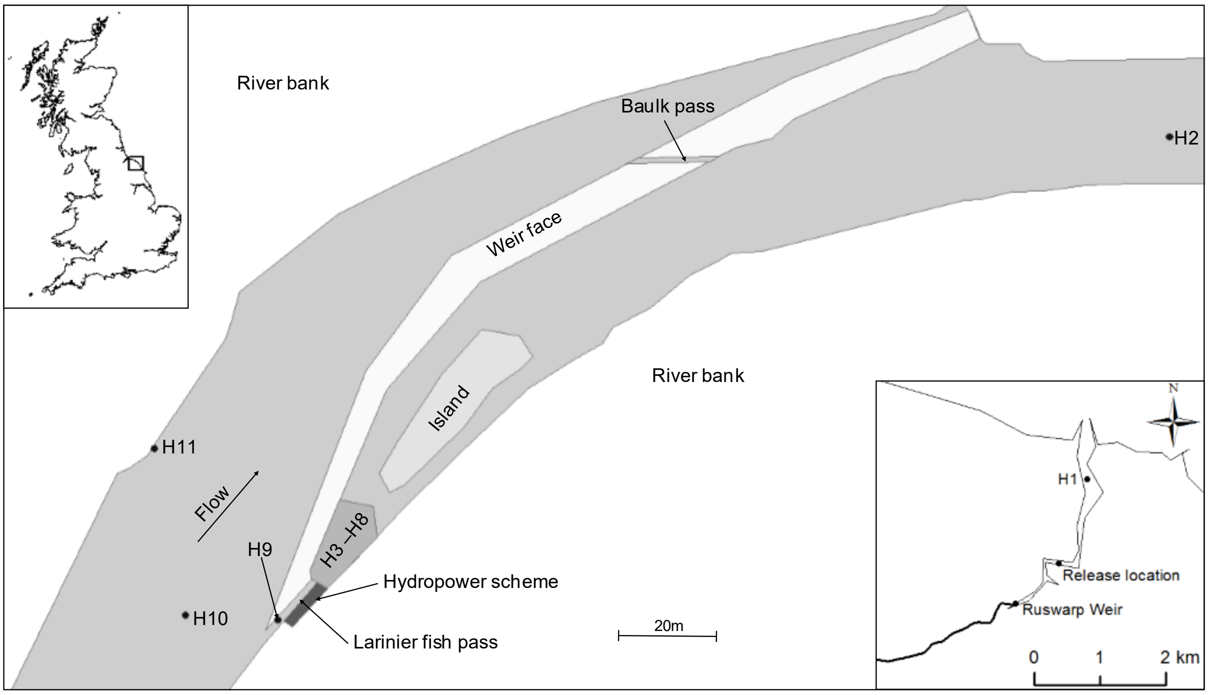


Figure 1: A map of Ruswarp Weir on the Yorkshire Esk, England, including the location of fish passes, hydropower scheme and monitoring equipment (hydrophones H1-H11).

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

Technology Inc., Seattle, USA) were activated and tested with a hand held detector immediately prior to tagging (Model 492 Acoustic Tag Detector, Hydroacoustic Technology Inc., Seattle, USA) to verify the tag was successfully transmitting (pulse rate ranged from 2500-2822 msec.), sterilised and rinsed with distilled water prior to use. Tags were inserted into the body cavity of fish through a 20-mm long, ventro-lateral incision made with a scalpel, anterior to the muscle bed of the pelvic fins. The incision was closed with an absorbable suture. In all cases tag weight did not exceed 2% of the fish body mass (Winter, 1996). After surgery fish were held in a well-aerated and oxygenated observation tank until they regained balance and were actively swimming. Tagged fish were then transported approximately 1.5 km downstream of Ruswarp Weir (54.474629 -0.618624) to be released. All tagging was undertaken after ethical review and in compliance with the UK Animals (Scientific Procedures) Act 1986: Home Office licence number PPL 60/4400.

Monitoring

Fish were tracked using a combination of a Model 290 acoustic tracking system and Model 300 hydrophones (Hydroacoustic Technology Inc., Seattle, USA). One hydrophone (H1) was located downstream from the release location (54.482663, -0.611294), a second (H2) was located 30 m downstream of the base of Ruswarp Weir (54.469114, -0.630446) and seven hydrophones (H3-H8) were installed immediately downstream of the AST/fish passage solution (FPS) (Fig. 1). Three hydrophones (H9-H11) were located upstream of Ruswarp Weir to confirm pass and impediment ascent. The performance of the tracking system was tested using a Model 795LG tag manually drawn through the river.

Environmental data

River flow (discharge m^3s^{-1}) was measured at 15-min intervals at Briggswath gauging station (54.462012, -0.654322), 1.6 km upstream of Ruswarp Weir. Predicted tide height (mAOD) measured at 5-min intervals at Whitby Harbour were obtained from Admiralty Total Tide software (The United Kingdom Hydrographic Office, Taunton, UK); tide height less than 4.5 m at Whitby Harbour did not reach Ruswarp Weir. Downstream river level (mAOD) and Turbine flow (m^3s^{-1}) at 15-min intervals were obtained from Esk Energy UK Ltd (the hydropower owner). Daylight timings were obtained from HM Nautical Almanac Office (http://astro.ukho.gov.uk/surfbin/first_beta.cgi).

Data analysis

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

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

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

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

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

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

Results

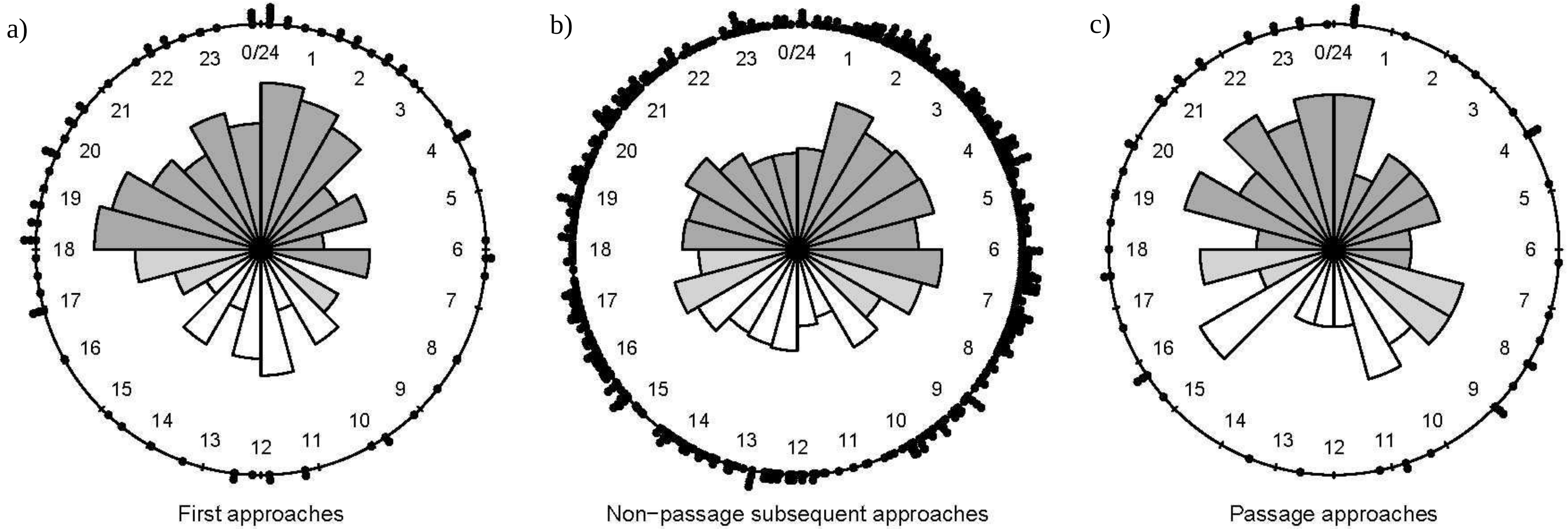
Passage efficiency

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

= 73% (62-81% CI, *n* = 61/84), only one of which did not approach the AST/FPS. Twenty-three sea trout detected at the weir did not ascend, though 21 of these fish approached the AST/FPS (91%, 73-97% CI). Eight of the *available fish* that did not ascend were last detected on H1 in the lower estuary (35%, 19-55% CI) and 15 were last detected immediately downstream of the weir (H2-H8) (65%, 45-81% CI).

Time of day

Sea trout approached and ascended through the FPS during almost all hours of the day (Fig. 2). Sea trout approached the AST/FPS more times at night (69%, *n* = 539) than during the day (31%, *n* = 245), but was not significantly different to the frequency of daylight/darkness during the study (Chi-Square Test: χ^2 = 2.08, d.f. = 1, *n* = 784, *P* = 0.149). Similarly a higher proportion of fish ascended the FPS at night (70%, *n* = 37) than during the day (30%, *n* = 16) but this was also not significantly different to the frequency of daylight/darkness during the study (Chi-Square Test: χ^2 = 2.72, d.f. = 1, *n* = 53, *P* = 0.099). *Individual approach duration* of non-passage approaches was shorter at night (2.52 min (0.03 – 353.42), *n* = 503) than during the day (3.05 min (0.03 – 408.87), *n* = 229), but the difference was not significant (Mann Whitney U-test: *Z* = -0.935, *n* = 732, *P* = 0.350). *Individual approach duration* of passage approaches was also shorter at night (3.85 (0.08 – 197.13) min, *n* = 37) than during the day (6.17 (0.37 – 94.70) min, *n* = 16), but the difference was not significant (Mann Whitney U-test: *Z* = -1.511, *n* = 53, *P* = 0.131).



First approaches

Non−passage subsequent approaches

Passage approaches

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

River flow during the study ranged from 0.44 to 88.00 m^3s^{-1}, and sea trout first approached the 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 31.00 m^3s^{-1} ($Q_{83.7} – Q_{1.8}$). There was no significant difference in river flow between when fish approached the AST/FPS but did not ascend (median = 6.48 m^3s^{-1}, 1.59 – 41.50 m^3s^{-1} ($Q_{84.9} – Q_{0.9}$)) and when fish ascended (median = 6.22 m^3s^{-1}) (Mann Whitney U-test: $Z = 0.614$, $n = 778$, $P = 0.539$) (Fig. 3). Predicted tide height during the study ranged from 0.40 to 6.10 m, and both first AST/FPS approaches ($n = 79$) and FPS ascents ($n = 53$) occurred between tide heights of 1.01 and 5.80 m ($Q_{97.6} – Q_{0.1}$) (Fig. 3), although fish approached the AST/FPS between 0.60 and 5.80 m ($Q_{99.9} – Q_{0.1}$).

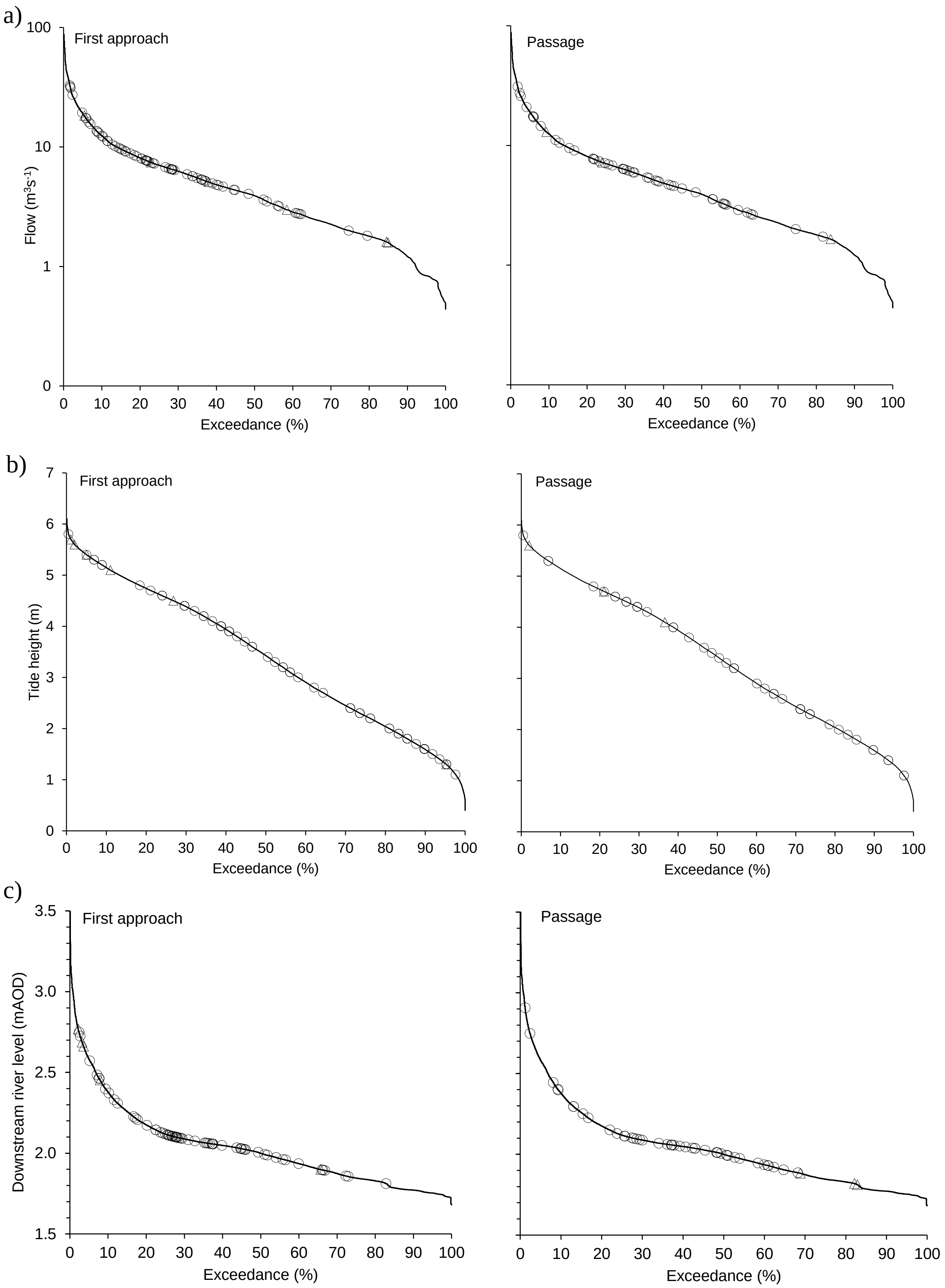


Figure 3: Sea trout first AST/FPS approach (left) and FPS passage (right) in relation to a) river flow (m^3s^{-1}), b) tide height (m) and c) downstream river level (mAOD (AST shuts-off at 2.79 mAOD)) exceedance during the study period when the AST was on (circles) or off (triangles).

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

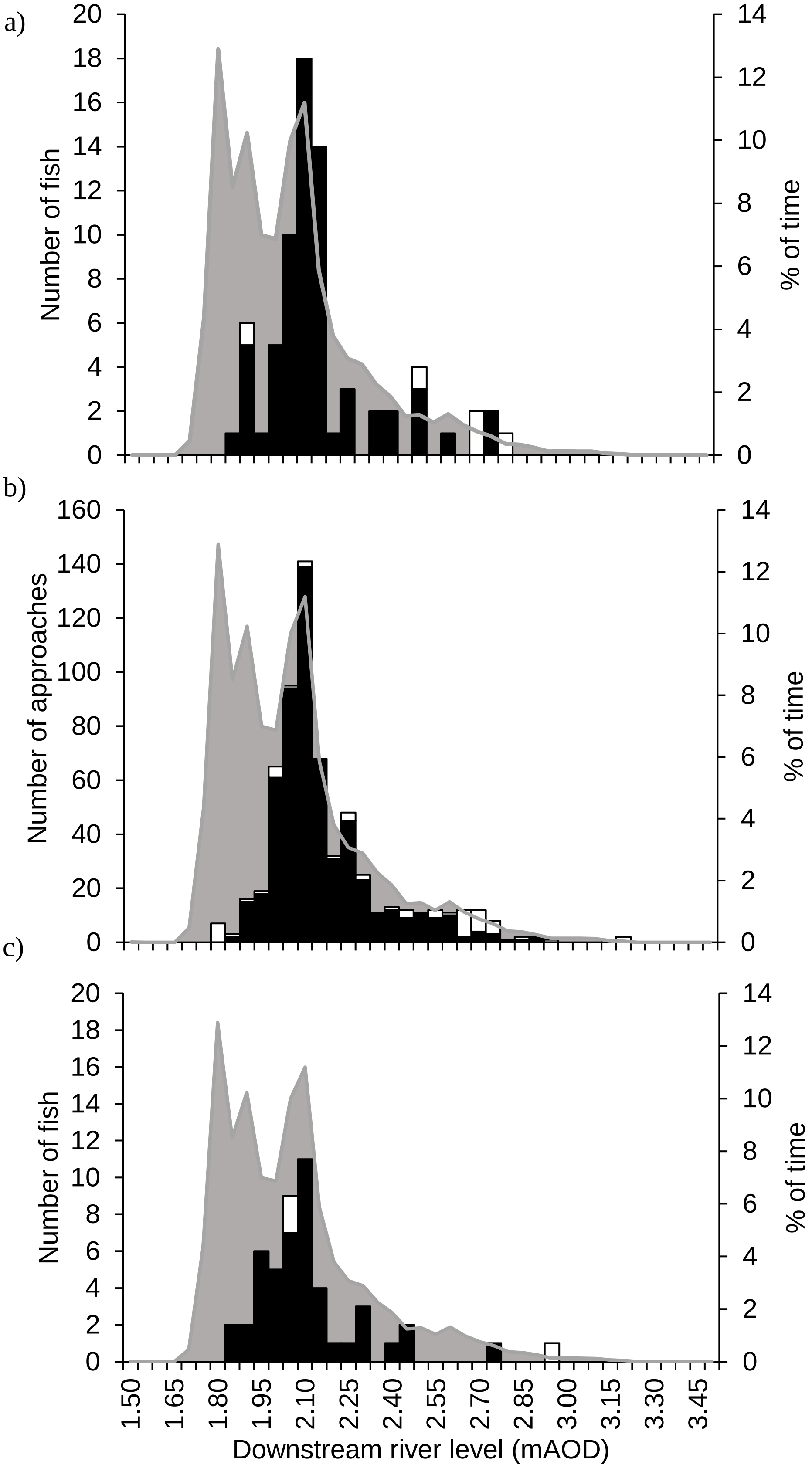


Figure 4: Relationship between downstream river level (mAOD) and first AST/FPS approach (a), subsequent non-passage AST/FPS approaches (b) and FPS passage (c) during periods when the hydropower is on (black) and off (white).

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: $Z = -0.660$, $n = 688$, $P = 0.509$).

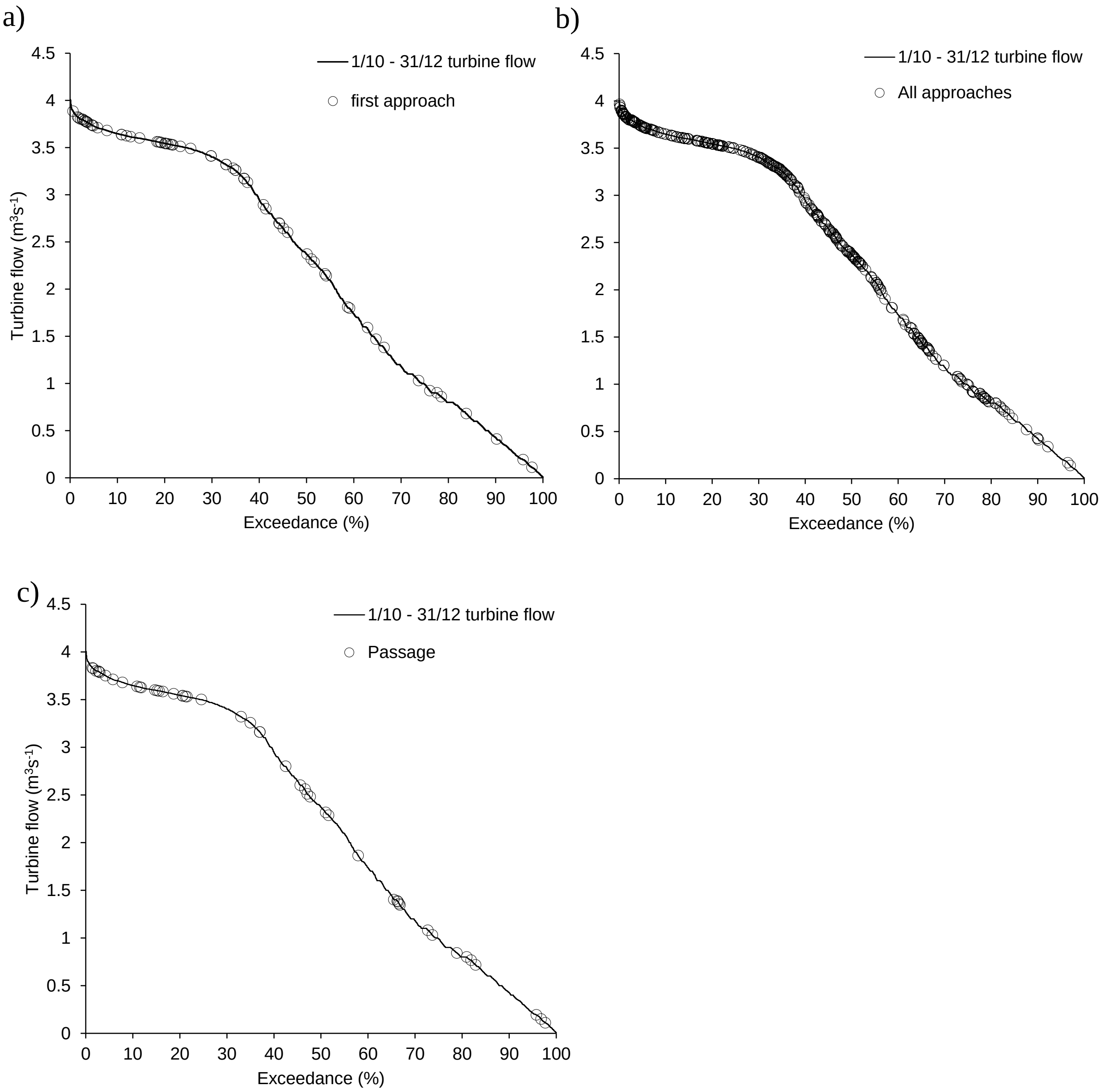


Figure 5: First AST/FPS approaches (a), subsequent non-passage AST/FPS approaches (b) and FPS passages (c) in relation to AST flow exceedance curves during operation (i.e. turbine flow = 0, not plotted).

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 days and five percent took more than one week to be first detected at the weir after release (Fig. 6a). The median *AST/FPS attraction time*, *FPS passage time* and *individual approach duration* 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 – 408.87, *n* = 784), respectively. The median *overall impediment passage time* was 4.02 hr (0.33 – 195.41, *n* = 48) and there was no significant difference between fish that ascended through the FPS (3.34 hr (0.44 – 195.41), *n* = 42) and those that took an alternative route (12.28 hr (0.33 – 86.02), *n* = 6) (Mann Whitney U-test: Z= -0.561, *n* = 48, *P* = 0.594).

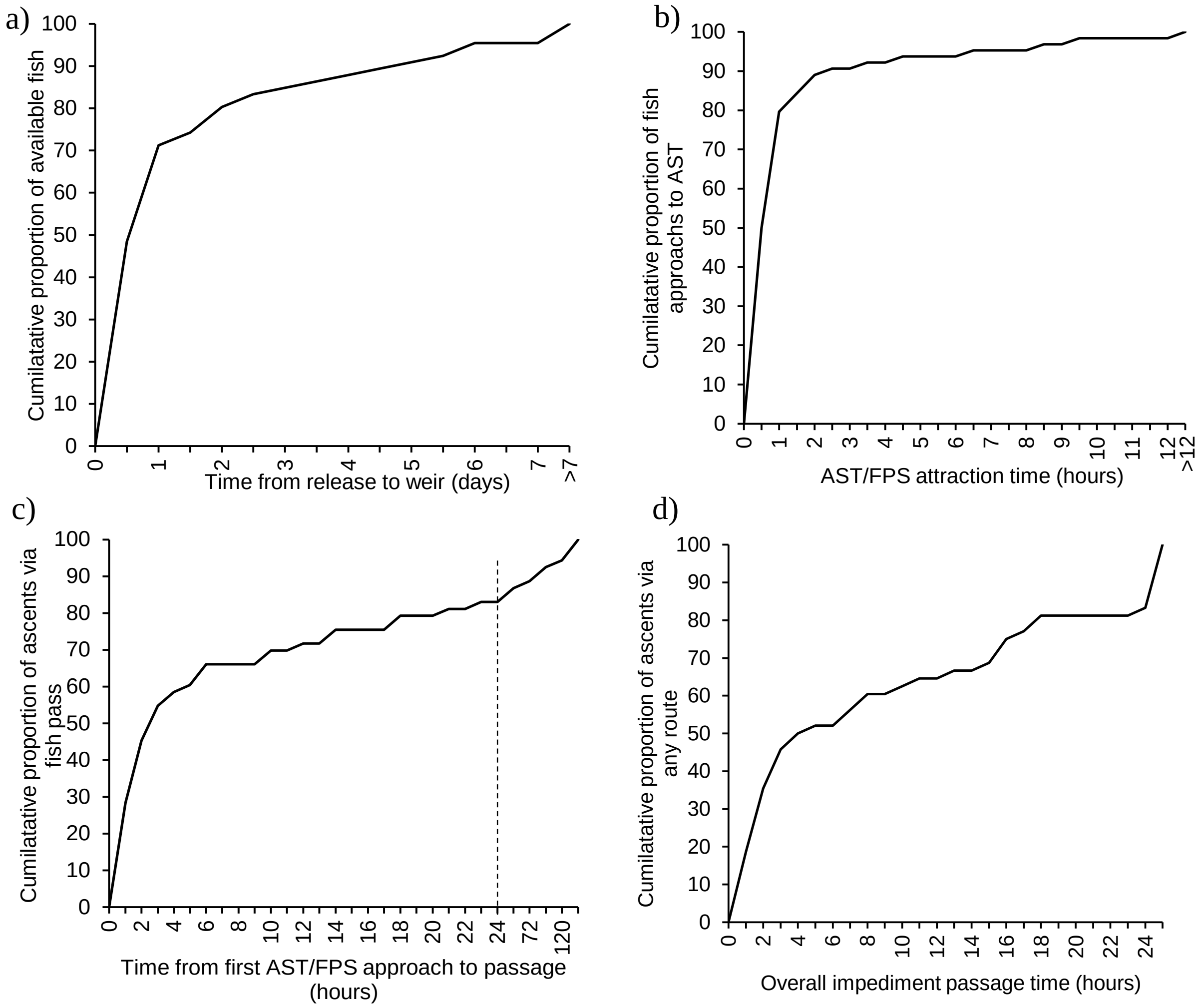


Figure 6: Cumulative proportions (%) for time between a) release and first approach to the weir (days), b) *AST/FPS attraction time* (hours), c) *FPS passage time* (hourly intervals for first day and 24 hour intervals thereafter (dotted line)) and d) *overall impediment passage time* (hours).

Time-to-event analyses

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

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

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

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 these flows were comparable between passage and non-passage approaches to the AST/FPS. Turbine flow was also not a predictor variable and did not have a significant influence on Probability of FPS passage (Model 1), *FPS passage time* (Model 2), FPS passage time remaining after each approach (Model 3) or *individual approach duration* (Model 4). Whilst the *FPS passage efficiency* observed here was below the desirable targets suggested by Lucas and Baras (2001) it was similar to efficiencies for upstream migrating salmonids observed for other pass types (Noonan *et al.* 2012, Bunt *et al*. 2016). Therefore, the performance of the FPS is comparable to other fish passes in general. There is little evidence to suggest how the design could be improved as there is a dearth of evidence for the efficiency of Larinier fish passes for salmonids in general. For example, there were no data for upstream migrating anadromous salmonids at Larinier passes in the recent meta-analysis by Bunt *et al*. (2016). The lack of real-world evidence for the efficiency of Larinier passes, coupled with the performance of the FPS in this study, and the efficiencies of other types of passes worldwide (Bunt *et al*. 2016), highlight how imperative adequate research and monitoring of co-located AST/FPS are. Further research is required to ensure fish passage efficiency objectives are being both appropriately defined and met and to ensure the overall performance of best practice designs and operation for new schemes. The suggestion that higher downstream river level (affected by high tides) had a negative influence on successful passage in this study might suggest that further research is specifically required on the best practice pass designs for tidally influenced conditions and their near-field attractiveness and accessibility when co-located with an AST. One possible mechanism that should be explored is the influence of high tides on the location and extent of attraction plumes from the mouth of the FPS in relation to other competing flows.

Impediment passage efficiency, i.e. the proportion of *available fish* that pass the weir via any route, was 73%. Upstream passage at Ruswarp Weir would need to improve to meet the desirable targets of 90-100% for *impediment passage efficiency* suggested by Lucas and Baras (2001) for passage of diadromous fish at an impediment to maintain healthy populations. Whilst the *FPS* and *impediment passage efficiencies* observed during this study were lower than this desirable target, and therefore may be of concern, the pass performance cannot be attributed to the hydropower scheme and/or to the performance of the FPS *per se*. Furthermore, biotic variables, such as individual motivation (i.e. behaviours related to straying and physiological changes when passing from salt to fresh water) and predation, may have also influenced the movements and fate of fish, thus impacting upon the passage efficiencies both in terms of their measurement and the definition of suitable targets. Fish that did not approach

(36% of all tagged fish) or ascend (27% of tagged fish that approached) Ruswarp Weir during this study may have been predated upon by grey seals (*Halichoerus grypus* (Fabricus)) (e.g. Bendall and Moore, 2008), caught by fishermen (licenced or illegal) in the estuary or may have strayed from other rivers (e.g. Atlantic salmon = 50% (Stewart *et al.*, 2009) and sea trout = >10% (King *et al.*, 2016)). However, the risk of capture by predators or humans, and the prevalence of non-passage behaviours may have been elevated by the presence of Ruswarp Weir and therefore ideally their effect needs to be quantified enabling a complete interpretation of impediment passage efficiencies and the definition of appropriate pass performance targets.

In addition to elevating estuarine predation risk, delay in adult sea trout spawning migration can increase energy expenditure whilst trying to pass the obstruction. For example, Caudill *et al.* (2007) found migrating salmonids that reached spawning grounds on the Columbia River (1300 river km) had shorter passage times than fish that did not reach spawning grounds, with median passage time at individual dams ranging from 0.2 - 2.7 days depending on species and year. The majority (83%) of sea trout passed Ruswarp Weir in less than a day, median passage time was 0.16 days and the longest passage time was eight days. The minor delays observed were considered unlikely to affect migration to spawning grounds, especially given the short length of the River Esk (45 km from source to sea). Indeed, the delay compares favourably with those reported for upstream migrating adult salmonids at weirs (without a low-head hydropower turbines) (Webb, 1990 = 0.6 - 43 days; Gowans *et al.*, 2003 = 1 - 40 days; Newton *et al.*, 2018 = 0.01 - 31 days).

In addition to the co-located fish pass, hands-off-flows (< 0.92 m^3s^{-1}) was another mitigation measure specified in the abstraction licence to protect upstream migrating salmonids at low river levels. No fish approached the impediment while this mitigation measure was in effect. Operational shutdown is an alternative mitigation measure that has been applied when fish migrate at highly predictable times and had been suggested as a management option if the operation of the AST was shown to impact on fish passage at the site. For example, this measure has been used for downstream migrating silver American eel (*Anguilla rostrate* (L.), Smith *et al.*, 2017), silver European eel (*Anguilla anguilla* (L.), Trancart *et al.*, 2013) and Atlantic salmon smolts (Stich *et al.*, 2015), though this could also potentially be applied to upstream migrating fish. While untested during this investigation, information on environmental conditions can be used to identify the potential for implementing operational shutdown at Ruswarp Weir or elsewhere in the future. In this study, sea trout ascended the FPS during all hours of the day and across a wide range of river flows ($Q_{83.7}$ - $Q_{1.8}$), tide heights

($Q_{97.6} – Q_{0.1}$), and downstream river levels ($Q_{82.8} – Q_{1.2}$). Therefore, the range of environmental conditions during upstream migration were too broad to define appropriate periods of targeted hydropower shutdown and their application would in this case be unjustified and lead to a substantial loss of power production. Further, there is a risk that operational shutdown would reduce attraction flow to the AST/FPS and thus potentially reduce overall FPS passage efficiency; which is contrary to the principles of co-locating a fish pass.

Implications of the findings

This investigation identified that a low-head hydropower turbine with a co-located fish pass can attract a high proportion of upstream migrating adult salmonids to the pass, and thus is a useful best-practice mechanism to attract fish to a FPS and potentially facilitate upstream migration of salmonids. However, the FPS and impediment passage efficiencies were below the desirable target suggested for diadromous fishes by Lucas and Baras (2001). Crucially, there was no evidence to suggest AST operation influenced the probability of FPS passage, FPS passage time or approach duration, with prevailing hydrological conditions having an overriding influence. However, FPS passage success did appear to be negatively influenced by high river levels at the entrance to the FSP. As such, it is possible that the efficiency of co-location was determined by the performance of the FPS itself in relation to the complex tidal environment and not by the presence of the hydropower turbine. However, there is no evidence to suggest which aspect of the FPS could be modified to improve performance. Therefore, future research is required to improve understanding of fish pass performance and thus best practice designs, particularly at tidally influenced sites with complex flow environments. A combination of fine-scale fish movement data and hydrological data in the pool surrounding the co-located fish pass and hydropower scheme would help to identify the performance of the pass in terms of near-field attraction and entrance efficiency as well as helping to determine any potential distraction from complex flow environments caused by competing turbine and fish pass flows. Whilst the passage efficiencies in this study were below desirable targets, the influence of predation and straying may have had an unquantified impact on the findings and these natural factors (whilst influenced by the presence of the weir itself) make interpretation and definition of appropriate target passage efficiencies difficult. Therefore, further research is required to establish the effects of predation, exploitation and straying behaviours on fish passage studies and the setting of appropriate targets for passage metrics. Fundamentally, given the results of this study, and the paucity of other well-studied examples, further research is required on upstream migrating adult fish at similar low-head hydropower turbines with co-located fish passes. This is required, along with further studies on Larinier passes in general, to increase our knowledge and understanding of best practice designs for co-location as a mitigation measure and for fish pass designs *per se*. Such evidence would enable an improved understanding of upstream migration and thus more effective fish pass designs, improved best practice mitigation measures and definition of appropriate passage targets for hydropower schemes.

Acknowledgements

The authors wish to thank the Environment Agency (EA) and North York Moors National Park Authority for funding the research and the EA staff for technical support and stakeholder liaison. Many thanks are warmly extended to the various landowners and fishery owners and Esk Energy UK Ltd for access permissions and additional data. The authors gratefully acknowledge the assistance of the staff involved in the fieldwork and particular Natalie Angelopoulos and Ian Wellby for fish tagging. Richard Noble and Ian Cowx gratefully acknowledge the funding of the H2020 FIThydro project (Grant Agreement no. 727830) during preparation of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest and the views in this paper are the views of the authors and not necessarily those of the Environment Agency.

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