Investigating Fish Passage: Acoustic Fish Tracking Project – Yorkshire Esk, Ruswarp

Final Report

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Report – Ruswarp_2016

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Executive summary

An opportunity to improve understanding of the potential impacts of low head hydropower schemes on migratory salmonids arose on a scheme proposed for Ruswarp Weir (the tidal limit) on the River Esk in North Yorkshire. This installation, constructed in 2012, consists of a single Archimedean screw turbine co-located with a refitted fish pass. Prior to 2012 the main fish pass was a step-pool design; as part of the redevelopment of the site this was refitted as a Larinier pass following best practice guidance. The micro-scale behaviour of upstream migrating salmonids in relation to hydrodynamic and environmental cues that attract and guide fish at fish passes was investigated between 2010 and 2015 using an acoustic tracking study to identify any impact of the hydropower scheme on fish passage through the site and to obtain evidence to improve best practice guidance for co-location of turbines with fish passes. The analysis of the tracking data for sea trout post-commissioning and the comparison with the baseline identified five key results:

The proportion of tagged sea trout that successfully passed the weir (*overall passage efficiency*) varied markedly between years and the average overall passage efficiency post-commissioning (47%) was not significantly different from the baseline (35%). The post-commissioning study identified that 73% of the sea trout that returned to the weir after tagging successfully ascended via any route.

The proportion of tagged sea trout entering the array (*attraction efficiency*) was significantly higher post-commissioning (62%) than in the baseline (35%) although this too varied markedly between years. In all years of the post-commissioning dataset the vast majority of sea trout that approached the weir were attracted to the co-located Larinier pass (96%).

The *fish pass efficiency* of the main fish pass structure reduced significantly from 100% in the baseline to 67% post-commissioning for tagged sea trout detected in the array (although this varied from 56% in 2014 to 81% in 2013). The main fish pass changed from the step-pool pass in 2011 to the Larinier pass in 2012, prior to the commissioning of the turbine, adding a confounding factor to the baseline.

The delay between arrival in the fish pass pool and eventual passage was, whilst statistically significantly greater post-commissioning (median 2.69 [0.79 – 17.28] hours) than during the baseline (median 0.28 [0.09 – 1.41] hours), was not of energetic consequence given the overall scale and duration of the sea trout migration. It is possible that this delay may have unknown consequences for successful passage through altering motivation to migrate or predation risk.

There was some evidence of attraction of fish to the area in front of the hydropower outfall screens, which was most apparent when the turbine was active at river flows <6.28 $m^3 s^{-1}$, when the weir was not overtopping and the turbine abstraction was >0 $m^3 s^{-1}$ and <3 $m^3 s^{-1}$. However, this area is also the deepest part of the pool so it was difficult to determine if the sea trout were seeking refuge in deep water, being distracted from finding the fish pass plume by the outfall from the hydropower screw or utilising this area of the pool during their approach to the fish pass entrance.

The comparable overall passage efficiencies pre- and post-commissioning indicate that overall passage through the site has been maintained. However, the relatively low pass efficiency observed for the Larinier pass may be of concern and mitigation measures to improve the pass efficiency could be addressed. There is no evidence that the variability and changes in these passage metrics were related to the activity of the hydropower scheme.

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1 Introduction

1.1 Background

With concerns over climate change, rivers worldwide are becoming increasingly exploited for hydropower (Jansson, 2002; Murchie *et al.*, 2008). Although the harnessing of energy from water discharge and conversion to electrical power began in the mid 19th Century (Poff & Hart, 2002), it is making a resurgence and is now considered the most important renewable electricity source worldwide (Bratrich *et al.*, 2004), accounting for 19% of the world's electricity (Paish, 2002). This capture of energy from rivers is in line with regional policy objectives (e.g. EU Renewable Energy Directive 2009/28/EC) and hydropower is considered to be the most reliable and cost effective renewable energy source (Bruno, 2008), and often presented as a clean (Rosenberg *et al.*, 1995), 'green' energy source with no negative impacts on the environment (Bratrich *et al.*, 2004). Indeed, the European Renewable Energy Directive (2009/28/EC) set out mandatory targets to have member states achieve 20% total energy consumption from a renewable source by 2020.

In the past twenty years there has been a resurgence of interest in hydropower as a direct consequence of the UK Government's commitment to renewable energy and associated financial incentives. The majority of new schemes are run-of-river, which have no significant storage of water, the turbine only making use of the available flow at the site. These generally require an impounding structure and the passing of water through a turbine, sometimes involving the diversion of water through a secondary channel or pipeline and returning it to the main river downstream of the weir. The view that hydropower has no negative impacts on the environment, has been challenged by numerous authors who consider the impacts on fisheries and biota as significant. Robson *et al*. (2011) presented a comprehensive literature review of the potential impacts of run-of-river hydropower schemes on fish populations in the UK. Unfortunately, research on the impacts of hydropower schemes on fish populations is mainly restricted to larger schemes, and little work has been carried out to investigate the impact of small-scale schemes on fisheries or river ecosystems (Bilotta *et al*. 2016). However, Robson *et al.* (2011) concluded that the potential impacts observed for large schemes (e.g. impeded migration, loss of habitat, altered flow regimes, entrainment of fish with subsequent damage/mortality and potential cumulative impacts of multiple schemes) were all still applicable to small-scale hydropower schemes.

To mitigate these potential impacts development of small scale hydropower in England is regulated through the Environment Agency (EA), with developers required to follow best-practice guidance (Environment Agency, 2016). Developments are regulated through the EA granting appropriate water resources licences (abstraction and impoundment) under the Water Resources Act (1991), flood defence consents and where applicable fish pass approvals. Developers must prepare an environmental report which addresses management of flows and abstraction, fish passage solutions, methods of fish screening and assessment of the scheme in the context of protecting the ecological status of the waterbody on which it is situated under the European Water Framework Directive 2000/60/EC. In particular developers must address fish passage at the site and the EA require developers to install a fish pass and appropriate flow management on rivers where upstream or downstream fish passage may be made worse by the scheme or where improved fish passage is needed to fulfil the requirements of legislation such as the Salmon and Freshwater Fisheries Act (SAFFA, 1975) and the Eels (England and Wales) Regulations (2009). Where there is existing provision for fish passage, approved or otherwise, any hydropower development must maintain the effectiveness and efficiency of the pass or passage through the site. When existing fish passes are to be used, but are known to be inefficient, the EA shall expect developers to address opportunities for improving fish passage. Where a new fish pass is required, or an existing pass requires modification, the design and associated flow requirements must be approved by the Environment Agency following the statutory requirements of the SAFFA (1975), the Eels (England and Wales) Regulations (2009), the Environment Act (1995) and the WFD. As part of the EA guidance (Environment Agency, 2016) it is suggested that any new low-head hydropower scheme situated on a weir should be co-located with a fish pass such that the discharge from the turbine enhances fish passage through the site by enhancing attraction to and accessibility to the fish pass.

An opportunity to improve understanding of the potential impacts of low head hydropower schemes on migratory salmonids and the efficacy of co-locating turbine outfalls with fish passes arose on a scheme proposed by the Esk Valley Community Energy Group (EVCEG) in association with the North York Moors National Park (NYMNP) at Ruswarp Weir (tidal limit) on the River Esk in North Yorkshire. This became the Whitby Esk Energy Project that was developed by Esk Energy (Yorkshire) Ltd*.* This installation, completed in 2012, consists of a single Archimedean screw turbine (diameter = 2.9 m) adjacent to a fish pass on the right hand bank. The turbine draws up to 4 $m^3 s^{-1}$ and was expected to generate approximately 50 kW of electricity (in practice maximum output has been 43 kW). The operating head varies considerably depending on the state of the tide below the weir and the discharge of the river, with a maximum recorded operating head of 1.65 m. The intake for the screw is located just upstream of the fish pass exit and the outflow located adjacent to the fish pass entrance. This is in accordance with the Environment Agency (EA) guidance relating to hydropower schemes (Environment Agency, 2016). A step-pool fish pass was replaced by a new Larinier fish pass in 2012 (during construction of the hydropower scheme) as the old pass was assessed to be suboptimal (the pass was over-energised at high flows and the approach channel too shallow (Kibel & Coe, 2009)).

1.2 Aims

The overall aim of this study was to investigate the behaviour of upstream migrating salmonids at a hydropower scheme that includes a co-located fish passage facility, to identify any impact of the hydropower scheme on fish passage and to help address one of the "evidence gaps" in knowledge about migratory behaviour of adult upstream migrating salmonids; specifically real world evidence pertaining to the efficacy of co-locating a hydropower turbine with a fish pass and fish passage performance at weirs on the head of tide. The work will be used to help formulate and underpin guidance documents such as the guidance for run-of-river hydropower development (Environment Agency, 2016).

A secondary aim was to investigate fish micro-behaviour in relation to hydrodynamic, hydraulic and environmental cues that attract and guide fish at fish passes to improve best practice guidance on fish pass design by optimising fish attraction to the entrance of fish passes and improving fish passage rates.

1.3 Objectives

The objective of this study was to analyse the behaviour of migratory salmonids in the River Esk around Ruswarp Weir; including the timing of their movements and their interaction with the weir and fish pass(es) to assess whether any changes have occurred due to the operation of the new hydropower scheme. Furthermore, the data collected during the project are to be used to identify whether any mitigation measures are required to maintain or improve passage efficiency in the future. The specific objectives for this report are therefore:

- To analyse sea trout migration and passage over Ruswarp Weir in the three years post-commissioning of the hydropower turbine.
- To investigate the timing of sea trout movements and passages in relation to hydrodynamic and environmental cues.
- To make comparisons against the established baseline dataset.
- To determine whether there is any evidence that the hydropower scheme has affected the passage of sea trout at Ruswarp Weir.
- To, if needed, identify appropriate mitigation measures to maintain or improve passage efficiency in the future.

This report collates the monitoring data collected between 2013 and 2015, and makes comparisons with the baseline dataset collected between 2011 and 2012. The report follows the methods and materials described in Walton *et al.* (2012) and Noble *et al.* (2013, 2014 and 2015) and draws comparison with the baseline dataset described in Noble *et al.* (2013).

2 Materials and methods

2.1 Study site

The Yorkshire River Esk flows approximately 45 km from its source upstream of Westerdale on the North York Moors to its mouth on the North Sea coast in the harbour town of Whitby. The Esk supports important migratory salmonid populations, namely sea trout (*Salmo trutta trutta* L.) and Atlantic salmon (*Salmo salar* L.), although catches of the latter have declined in the last 40 years whilst those of sea trout have progressively increased until recent years (Figure 1). The river also supports a population of freshwater pearl mussel (*Margaritifera margaritifera*), a species that is highly dependent on a healthy population of salmonids to complete its lifecycle. The upstream migration of adult salmonids is impeded by a number of weirs constructed to divert water through mills, of which Ruswarp weir is the first on the system and sits at the head of tide.

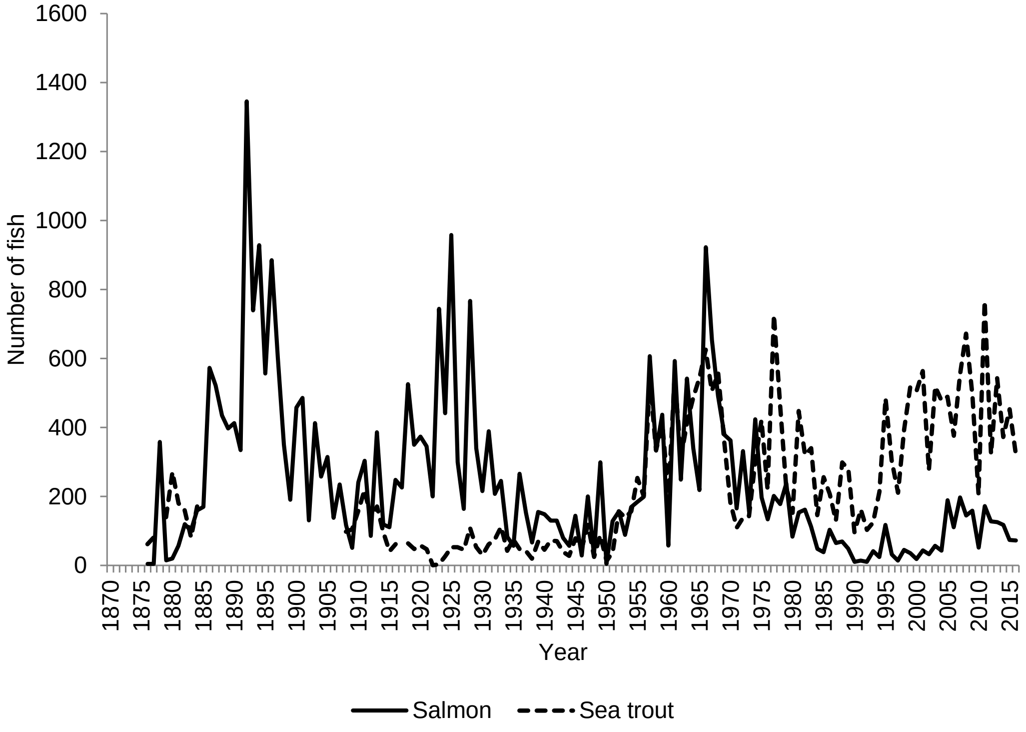

Figure 1. Trends in sea trout and salmon rod catches in the River Esk, North Yorkshire. Sea trout catches are included in the total for salmon for the period 1885-1902 (I Dolben EA pers. comm.).

The tidally influenced reach of the Esk extends from Whitby to the weir at Ruswarp (NGR NZ 804053; weir length: 270 m and width: 10 m). There are no significant barriers to fish movement below Ruswarp weir, although movement may be restricted at low tide because of insufficient water depths over gravel bars. There are two fish passes that facilitate upstream migration; a step-pool pass on the southern bank (replaced by a Larinier pass in 2012) and a diagonal baulk in the centre of the weir (Figure 2). The former was the focus in this investigation.

The original step-pool fish pass was replaced with a Larinier baffle pass during summer 2012 (Figures 5 and 6) at the same time as the hydropower turbine was installed and commissioned. Since 2013 two changes have been made to the design of the hydropower scheme. Firstly, plastic curtains (see Figure 6) have been added to the outfall (outside of the metal screens) to mitigate for noise disturbance from the turbine and secondly the intake screens were modified on the 15th December 2014 to reduce turbulence at the intake.

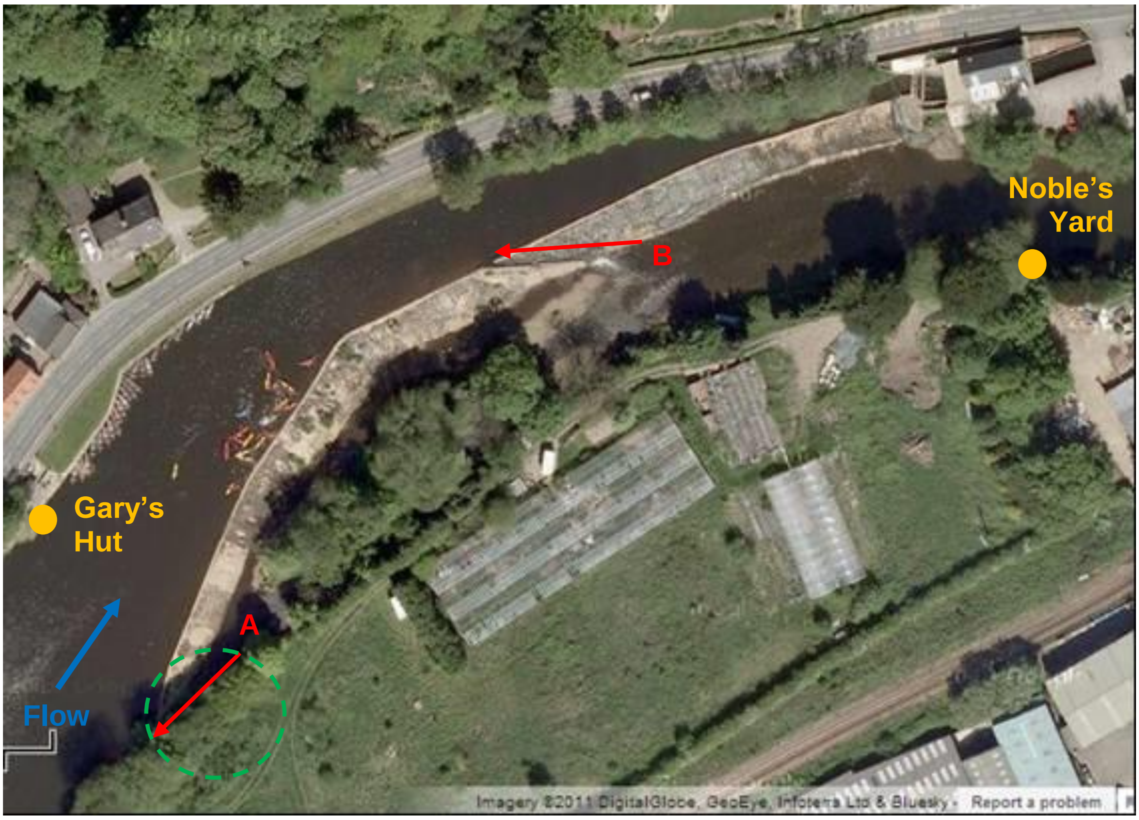

Figure 2. Aerial photograph showing the location of the fish passes (A – step-pool pass (2011) / Larinier pass (2012 onwards); B – baulk pass) in relation to the weir (kayakers upstream of the weir give an indication of scale). The green circle marks the location of the new hydroelectric turbine and the focus of this study and the two orange dots indicate the mobile hydrophone locations of Gary's Hut and Noble's Yard.

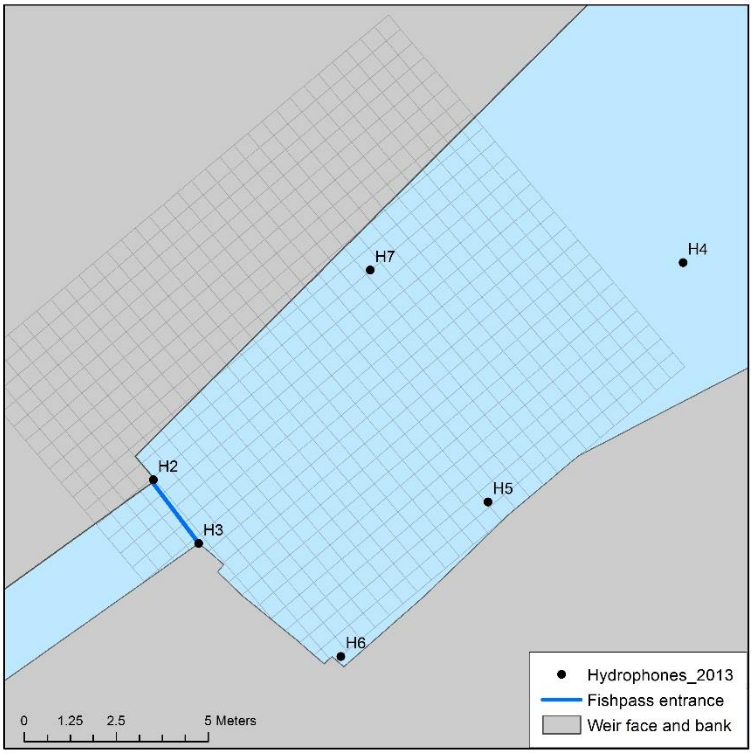

Figure 3. Diagram of the study site showing the positions of 6 of the 8 hydrophones used in the array for 2013, 2014 and 2015 (Section 2.3).

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2.2 Tagging

In all years sea trout and salmon were captured in batches downstream of Ruswarp Weir using pulsed DC (50 Hz) electric fishing equipment whilst wading at low tide or from a boat at high tide (EasyFisher control box with fully adjustable settings, single anode with Honda 2.5 kVA generator). The condition of all fish caught was screened to ensure they were suitable for tagging, fish which were deemed unsuitable were held in tanks before being released back into the river untagged. In late 2014 and during 2015 there was concern over disease, fungal infection and condition of fish in the catchment. During this period a number of sea trout were rejected for tagging due to poor condition (visibly dark and not fresh run), due to existing injuries (predator damage) or levels of fungal infection that might compromise the condition of fish during tagging and recovery (see Appendix 1 for examples).

Prior to tagging in the field, fish were anaesthetised using MS222 (40 mg L^{-1}). Species, sex, fork length (nearest mm), weight (nearest g) and fat content (hand-held % fat meter, Distell Model - FM 692) were recorded. Fish were placed ventral side up in a clean V-shaped foam support. Tags were activated and checked (pulse rate ranged from 2500-2822 msec.), 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, sterilised with alcohol and rinsed with distilled water prior to use. 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 inserted into the body cavity of fish deemed fit to tag 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. The procedure lasted approximately 5 minutes. In all cases tag weight did not exceed 2% of the fish body mass (Winter, 1996). Fish were held in a well-aerated and oxygenated observation tank until they regained balance and were actively swimming, before returning them to the river, at a suitable site for release (Viaduct slipway, NZ 896 096, approximately 1 km downstream). All fish were treated in compliance with the UK Animals (Scientific Procedures) Act 1986; Home Office licence number PPL 80/2411.

2.3 Acoustic tracking system

Fish tracking was performed using an acoustic tag tracking system (Model 290 acoustic tag receiver, Hydroacoustic Technology Inc., Seattle, USA). An array of 8 hydrophones was installed to monitor the progress of upstream migrating salmonids (Figure 3 and Figure 4). Changes in the pool following construction work meant that the footprint of the array in 2013, 2014 and 2015 was different to the footprint in both 2011 and 2012. In the post-construction years (2012 onwards) the configuration of the array included one hydrophone (H1) within a pool above the baffles in the new Larinier fish pass to confirm fish movement through the pass. In all years one hydrophone (H8) was located above the weir to confirm ascent. (Figure 3 and Figure 4). The relative position of each hydrophone in the array was determined by measuring the pair-wise distance to two locations with known grid references (walls of fish pass entrance). The sub-metre 2D position of fish within the array was triangulated using the arrival times of tag pulses at each hydrophone using Hydroacoustic Technologies Inc. proprietary software. Tag detection data (identity, date, time and location) were recorded using HTi AcousticTag software (Hydroacoustic Technology Inc., Seattle, USA) and stored on a portable laptop computer. The effectiveness of the array and H1/H8 (H8 detection range = full river width) were tested using a Model 795LG tag drawn through the river to reflect possible routes and behaviours of fish. During all years the array was visited frequently to inspect for damage (extreme spates posed a constant threat to the array) and remove debris.

From 2013 onwards three Model 300 mobile hydrophones were also successfully installed along the river in attempt to ascertain the general behaviour of fish outside of the hydrophone array. The most downstream hydrophone was located on a jetty in Whitby harbour (Whitby Marina), the second was located on the right-hand bank 300m downstream of the fish pass, opposite the downstream end of the weir (Noble's Yard) and the third was located on the left-hand bank upstream of the weir (Gary's Hut) to monitor any fish which ascend via the baulk pass. Mobile hydrophones were not successfully installed prior to 2013 (due to technological problems), and thus the behaviour of tagged fish outside of the hydrophone array during the baseline study were unknown. The mobile hydrophones were only capable of detecting when a tagged fish was in the vicinity, i.e. they were not capable of fine-scale location. In addition, the detection range of these hydrophones will vary with river depth (tide and freshwater influence) but detection efficiency under high flows could not be verified during the study for health and safety reasons.

2.4 Output processing and data analysis

The proportion of fish that successfully ascend a fish pass is a simple but effective measure of fish pass performance (Roscoe & Hinch, 2010). The number of fish that ascended the weir via the main fish pass structure, as a proportion of the total number observed in the array, was used to quantify the performance of the main pass – the "***fish pass efficiency***". Given that the Larinier pass is not the only route over the weir, a further metric of "***overall passage efficiency***" was calculated as the proportion of all tagged fish that successfully passed the weir to determine the permeability of the weir to fish.

Time-stamped location data for each fish recorded in the array were separated into individual tracks (separate behavioural events in the array) on the basis of time between records. In general a minimum gap of 2 minutes was used to determine separation of tracks, in most cases the gaps between tracks were appreciably longer than this. However, since there were some occasions where triangulation of fish in the array was not possible but records on individual hydrophones identified that the fish had not exited the array, tracks were only split where the records for the hydrophones confirmed that the fish had exited the array. Where the records from individual hydrophones confirmed that the fish was still in the array during these gaps then the separate tracks were joined into single continuous events for the analysis. The tracks observed over the period were classified into passage and non-passage tracks, where passage tracks were defined as tracks that start when a fish was detected in the array and terminates with the fish exiting the array via an upstream passage route (determined by immediate subsequent detection on H1 and H8) (Figure 7 left). Non-passage tracks were defined as tracks that started when the fish was detected in the array, and terminate when the fish left the array in a downstream direction or was not detected on H1 or H8 immediately (less than 1 minute after leaving the array) (Figure 7 right). Time in the array was defined as the time between the first position plot detection and the last position plot detection on hydrophones 2 to 7.

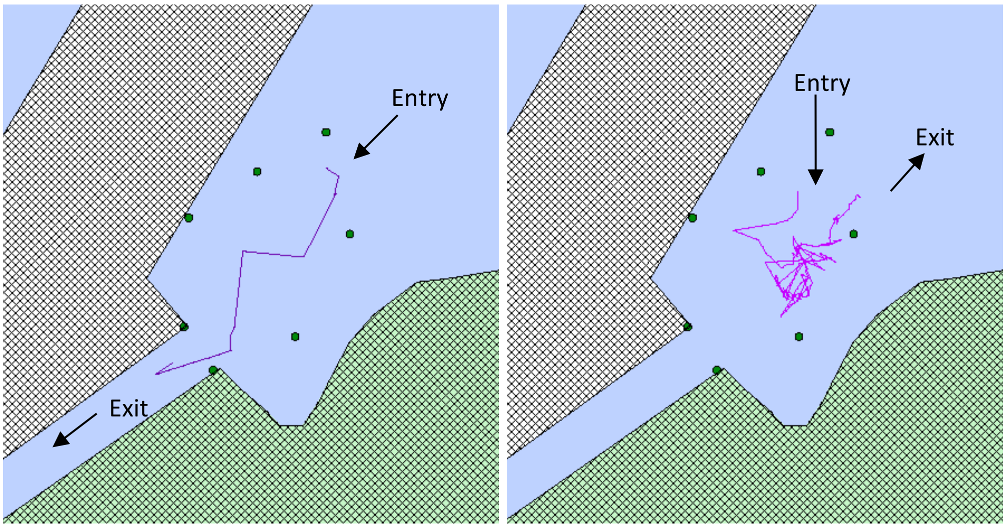

Figure 7. Examples of a passage track (left) and a non-passage track (right) in the array (green circles representing hydrophones).

Figure 8. Larinier fish pass and side-of-fish-pass ascent routes, looking downstream at high flows (21.44 $m^3 s^{-1}$). Arrows represent direction of fish passage (photo taken 22-11-2013 13:10).

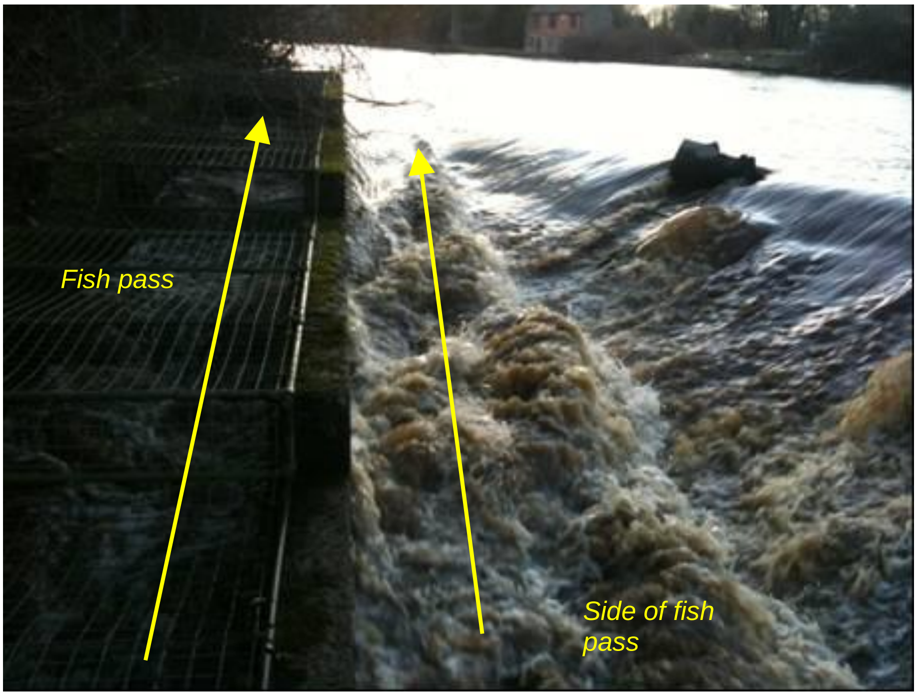

Figure 9. Old fish pass and side of fish pass ascent routes in high flows (35.9m^{3}s^{-1}) looking upstream. Arrows represent direction of fish passage (photo taken 3/1/2012 12:00).

In 2011 passage routes were originally divided into "fish pass" and "side of fish pass" routes (Figure 8 and Figure 9) based on a combination of the location of the terminal point of the fish track (nearest to the fish pass or side of fish pass), the time the fish took to ascend (<1-min = fish pass or side of fish pass; >1-min = fish pass) and the flow over the weir at the time of passage (<3 m^3 s^{-1} = fish pass, >3 m^3 s^{-1} = fish pass or side of fish pass). Where it was not possible to determine which route was taken as both routes were feasible; these were classified as "pass proximity". In 2012 - 2015 the relocation of H1 into a pool above the Larinier baffles enabled the confirmation of use of the fish pass on all detected ascents of the weir. In all analysis following the 2012 report (Walton *et al.* 2012) the ascents via the fish pass and via the side of the fish pass have been classified as successful use of the main fish pass structure. That is, any fish that successfully left the array pool by leaving in an upstream direction was determined to have successfully used the fish pass structure, even if it did not traverse the weir within the pass itself.

Fish tracks were analysed to investigate the following metrics:

- The ***attraction efficiency*** – the proportion of potential migrants (all tagged fish) detected in the array. A further, refined, estimate of attraction efficiency was calculated for the post-commissioning data as the proportion of tagged fish returning to the weir that entered the array. This refined metric could not be calculated for, or tested against, the baseline as it was not possible to identify in the baseline how many sea trout returned to the weir without finding the array (the Noble's Yard logger was not present in the baseline).

- The ***overall passage efficiency*** – the proportion of potential migrants (in this case defined as all tagged fish) ascending the weir via any route (fish pass, side of fish pass, baulk pass or ascent via the weir face at high flows). A further, refined, estimate of overall passage efficiency was calculated for the post-commissioning data as the proportion of tagged fish returning to the weir that successfully ascended the weir. As above this refined metric could not be calculated for, or tested against, the baseline as it was not possible to identify in the baseline how many sea trout returned to the weir without finding the array (the Noble's Yard logger was not present in the baseline).

- The ***fish pass efficiency*** – the proportion of tagged fish detected in the array that ascended the weir via either the fish pass (Larinier since 2012 or step-pool in 2011) or the side-of-fish pass route (i.e. ascended the weir heading upstream from the array pool utilising the structure of the main fish pass).
- Delay between release and first detection in the array (days).
- Delay between first detection in the array and passage (passage time defined as first detection on H8 or Gary's Hut mobile hydrophone) (hours).
- Delay between release and fish passage (days).
- Number of times the array was entered.
- Duration (minutes) of individual array visits.
- Cumulative time (minutes) and cumulative track length (m) in the array before passage.
- The proportion of fish ascending via the fish pass, side of the fish pass or the baulk fish pass.

These metrics were related to a range of environmental variables (discharge, tide state and temperature) and post-commissioning the hydropower turbine activity (measured as abstraction volume).

2.5 Micro-scale behaviour analysis

2.5.1 Track processing

Triangulated positions of tag pulses/pings produced by the HTI software were plotted as points in ArcGIS (ESRI ArcGIS version 10.3). Point location data were connected in chronological order using Geospatial Modelling Environment tracking tools to produce a continuous fish track made up of individual polyline "steps" (Figure 10). The length (distance between consecutive points; m) of each step was extracted, as well as the total track length (sum of all step lengths; m) and the average speed of each fish track (total track length divided by total time of the track; m s^{-1}).

Figure 10. Digitised site layout (left) and an example fish track (right) plotted as polyline steps (green lines) between time stamped points (purple dots).

2.5.2 Time grids

To enable direct quantitative comparison of time distribution between tracks within the array, a polygon grid of 0.5 x 0.5 m cells (750) that covered the entire array was plotted. Residence time (tp) for each cell was calculated using:

$$t_p = (\Delta t \times l_p) / l_s$$

where Δt is the change in time between points (the time of each step (seconds)), l_p is the length of track in each cell and l_s is the total length of each step. The length of each step within each cell was extracted in ArcGIS by intersecting the polyline fish tracks with the polygon grid. The residence time in each cell was assumed to be proportional to the length of track in each cell, i.e. the fish had constant speed between points. The residence time in each grid cell was assigned a colour ranging from white to red with increasing time (see Figure 11 (left) for example). The colour spectrum was standardised between grids to allow visual comparison. The number of fish to pass through each cell and the average time (geometric mean of log occupancy time per cell) spent by fish in each cell were pooled for the groups outlined in Section 2.5.1.

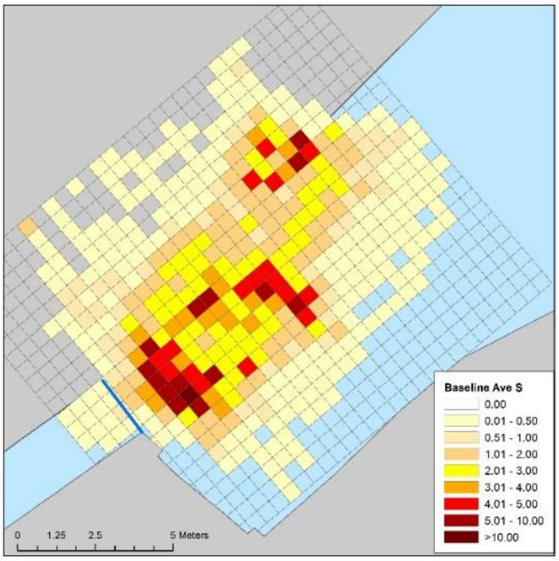

Figure 11. Example residence time (seconds) grid, with cells colour coded from white to red with increasing average time.

2.6 Statistical analysis

All data were prepared, presented and analysed in Microsoft Excel and IBM SPSS Statistics (version 24.0). The following statistical and graphical methods were used to report and analyse specific metrics.

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% [25-41% CI, α=0.05]. The Bayes Credible Interval is the most appropriate confidence interval for proportion data and the credible interval has a 95% probability of containing the true proportion (with the credible interval being dependent on the sample size and being bounded in the range 0 to 100%). All passage metrics were tested between periods using the Chi-square contingency test for association between the frequency distributions (Yate's corrections were applied where expected frequencies were less than 5). This test reports the χ^2 contingency test statistic and whether the test result is insignificant P >0.05, significant P <0.05 or highly significant P <0.01.

All metrics related to the duration and number of tracks and the delay to passage were tested for normality using the Kolmogorov Smirnov test. In all cases the distribution of data were not normal and exhibited a negative skew; the majority of data points were of a low value with only a few very large values. As all data failed to meet assumptions of normality non-parametric Mann-Whitney *U*-tests (two-tailed) were performed to compare medians between groups. Where non-parametric tests are performed medians are reported with interquartile ranges (25^{th} % and 75^{th} %, a range containing 50% of the observed values). Median data and their distributions were graphically represented as frequency distribution plots and box and whisker plots. Box and whisker plots represent the median value, the interquartile range (the box) and the whiskers which represent 1.5x the interquartile range above and below the median.

2.7 Environmental and hydropower generation data

Flow (m^3 s^{-1}) was measured at 15-min intervals at the EA Briggswath gauging station (NZ 873 082) located 1.6 km upstream of Ruswarp weir. Water temperature in the pool downstream of the fish pass was recorded using a 2 tg-4100 temperature logger (Tinytalk, Orion Instruments, Chichester, UK). Predicted tide data for Whitby harbour were obtained at 5-min intervals using Admiralty Total Tide software (The United Kingdom Hydrographic Office, Taunton, UK). Daylight timings were obtained online from HM Nautical Almanac Office.

Esk Energy supplied 15-min interval flow and generation data for the Ruswarp hydropower scheme. These data included turbine speed (rpm), flow through the turbine (m^3 s^{-1}), level upstream of the intake (maOD) and level in the pool downstream (maOD). In this case maOD is metres above a local variant of reference ordnance datum specified by the Environment Agency.

2.8 Bathymetry assessment

In 2011 a flow velocity profile within the array was obtained at low flows (mean daily discharge = 1.36 m^3 s^{-1}) using a Teledyne™ RDI StreamPro Acoustic Doppler Current Profiler (ADCP) along five transects (See Walton *et al.* 2012 and Noble *et al.* 2013). This also generated a bathymetry profile for the pool downstream of the fish pass (see Noble *et al.* 2013 for methods). An ADCP was not available for use in the post-commissioning study so the depth of the pool was measured manually at 50 cm intervals along transects between each pair of hydrophones which formed the array. Point depth data from the ADCP in 2011 and transects in 2013 and 2014 were geo-referenced in ArcGIS 10 and data kriging (interpolation and smoothing) was used to generate bathymetry raster plots of pool depths and profile.

3 Results

3.1 Movements of fish upstream and downstream of Ruswarp Weir

Over the course of the study 179 sea trout and 19 salmon were tagged and tracked in the tideway of the Esk below Ruswarp Weir (Table 1). Tracking data were used to determine the passage route and migratory behaviour of the fish (Table 1) in the baseline (Figure 12) and the post-commissioning period (Figure 13).

In the baseline six of the fourteen tagged salmon approached the fish pass (attraction efficiency = 43% [21-67% CI] and five of these used the fish pass (fish pass efficiency = 83% [47-99% CI]) (Figure 12). The overall passage efficiency for salmon in the baseline was 38% [16-62% CI] (*n* = 5/14). Post commissioning three of the five tagged salmon approached the fish pass (attraction efficiency = 60% [24-90% CI]) with two of these ascending the pass (fish pass efficiency = 67% [23-96% CI]) (Figure 13). The overall passage efficiency for salmon post-commissioning was 40% [12-78% CI] (*n* = 2/5). Due to the low numbers of salmon caught no statistical comparisons can be made for this species so all further analyses are confined to the observations for sea trout.

In the post-commissioning period (2013 to 2015) seventy-two of the tagged sea trout (55% [46-63% CI]) were first detected at Ruswarp weir after tagging (either the array or Noble's Yard hydrophone). Only one sea trout ascended the weir (presumably via the baulk pass) without first having been into the array below the Larinier pass.

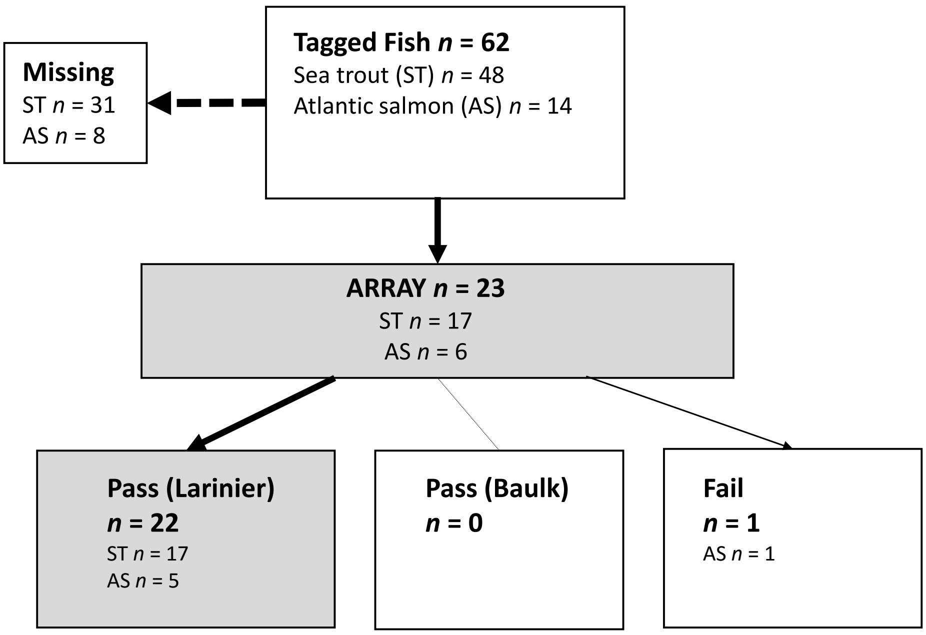

Figure 12. Summary of the fate of tagged fish during the baseline study (2011-2012) highlighting the detections on the ATS array and the passage of fish.

Table 1. Summary of the numbers of fish tagged, detected and their movement characteristics at Ruswarp weir through the study period.

Species	Salmon						Sea Trout					
Study	Baseline		Post Commissioning				Baseline		Post Commissioning			
Year	2011	2012	2013	2014	2015	Total	2011	2012	2013	2014	2015	Total
Fish												
n tagged	1	13	1	3	1	19	38	10	46	44	41	179
n array (tracked)	1	5	1	2	0	9	14	3	31[#]	31[#]	18	97
n array (no passage)	0	1	0	1	0	2	0	0	5	10	7	22
n mobile hydrophone only	N/A	N/A	0	0	1	1	N/A	N/A	7	9	18	34
Tracks												
Non-passage	4	40	8	26	0	78	26	39	298	313	121	797
Fish Pass Passage	1	4	1	1	0	7	14	3	25	18	11	71
Baulk passage									1	4	2	7
Downstream Passage							1	1	3	11*	6	22
Second Passage		2				2	1		1	2*		4
Total Tracks	5	46	9	27	0	87	42	43	328	348	140	901

* one fish made a downstream passage on 3 occasions (2x over the weir, 1x through the fish pass) all three of its ascents appeared to be via routes other than the Larinier pass (no detections on H1).
[#] two further tags were detected in the array but it was determined from mobile hydrophone data that these fish had been consumed soon after release, presumably by a seal.

In the post-commissioning period the movements of sea trout through the tidal reaches and immediately upstream of Ruswarp Weir were monitored using mobile hydrophones (Section 2.3). The hydrophone at Whitby Marina detected 43 tagged sea trout that initially moved downstream after tagging (33% [25-41% CI]) (Table 2). Twelve of the sea trout (28% [16-42% CI]) initially detected in Whitby then went on to re-ascend the river to Ruswarp. The proportion of sea trout first descending to Whitby after tagging was similar in 2013 (26%) and 2014 (25%) but was much higher in 2015 (49%). The proportion of fish that then re-ascended the tideway to Ruswarp varied greatly between years, with only 15% of the sea trout that descended to Whitby in 2015 returning to the weir (27% in 2014 and 50% in 2013). During the course of the post-commissioning study, a number of sea trout were inferred from tracking data to undertake movements ascending/descending the Esk tideway between Ruswarp and Whitby on flooding/ebbing tides respectively.

Table 2.Summary of the sea trout first detected at Whitby Harbour after release and the number which then returned upstream to be detected at Ruswarp weir. Percent values are presented with 95% Bayes Credible Intervals.

	Year		
Behaviour/Detections	2013	2014	2015
n sea trout tagged	46	44	41
n sea trout not detected			
n First detected in Whitby	12	11	20
% of tagged sea trout	26% [61-40%]	25% [15-40%]	49% [34-64%]
n later detected at Ruswarp	6	3	3
% re-ascending river	50% [25-75%]	27% [10-57%]	15% [5-36%]
n later detected in array	6	3	2
n later detected at Noble's Yard only	0	0	1

During the post-commissioning study four fish were assumed to have been predated upon, presumably by seals. This was determined from tracking records in 2013 and 2014 when two tags were repeatedly detected simultaneously and on multiple hydrophones and had identical tracks simultaneously within the array. During the 2014 study one of the predation events appeared to have occurred within the vicinity of the array. In this case both tags associated with the predation event had been seen independently within the array prior to a record of those tags entering the array independently but thereafter having identical tracking records. As it could not be determined which of these tags was predated first (one was assumed to be in the predator before arrival in the array), only one of these fish has been included within attraction analysis and fish pass efficiency. The other three fish have been treated as missing.

In 2015, towards the end of the study (8/12/2015), an attempt was made to locate missing tags using a boat-based mobile-hydrophone survey in the tideway. Only three of the missing tags from 2015 were detected. One tag was located 400 m downstream of the release location, and the other two tags were located between 300 – 400 m upstream from the release location (an area downstream of Glen Esk Caravan Park).

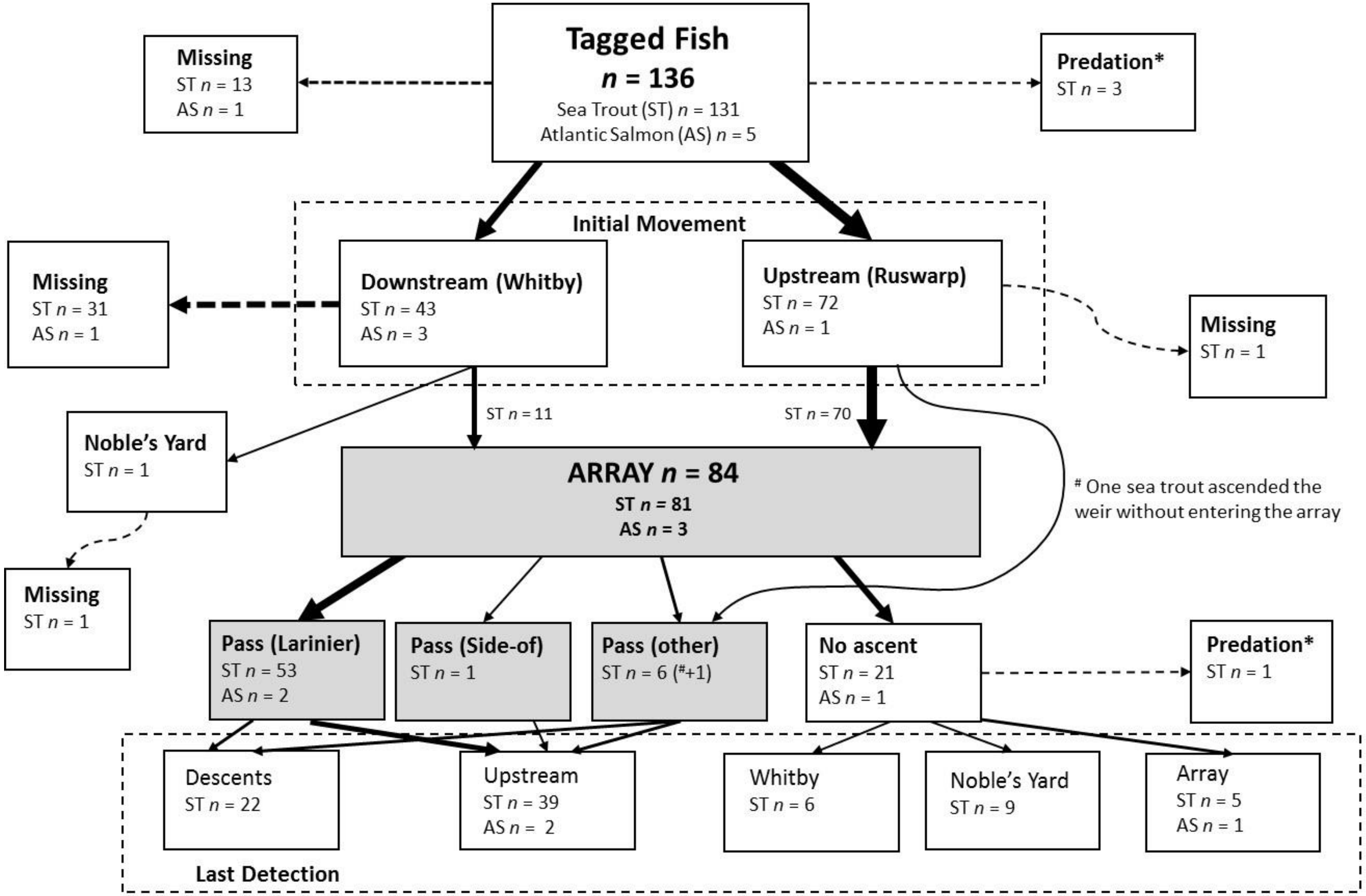

Figure 13. Summary of the fate of tagged fish during the post-commissioning study (2013-2015) highlighting the detections on each hydrophone system and the passage of fish. * Two sea trout were known to have been consumed by the same predator and this predation event occurred within the vicinity of the array. It is known that at least one of these fish made it to the array before predation but it is uncertain which.

3.2 Passage metrics

3.2.1 Detections in the array (*attraction efficiency*)

During the post commissioning study 131 sea trout were tagged for tracking (Table 1). Of these 131 sea trout, 81 were detected within the hydrophone array, giving an attraction efficiency of 62% (53-70% CI, *n* = 81/131). The measured attraction efficiency was lower in 2015 (44% [30-59% CI]) than in 2014 (73% [59-84% CI]) and 2013 (67% [53-80% CI]). The average attraction efficiency across the post-commissioning study (62% [53-70% CI, *n* = 81/131]) was significantly greater than the 35% (23-49% CI, *n* = 17/48) observed in the baseline (χ^2 contingency test, $\chi^2 = 9.894$, *d.f.* = 1, *P* <0.01).

Of the 131 sea trout tagged 84 (64% [56-72% CI]) reached the weir (detected in the array or Noble's yard). Of the sea trout that reached the weir, 81 (96% [91-99% CI]) were detected in the array and this varied little between years (95% in 2015 and 97% in 2013 and 2014).

Table 3. Summary tagging and passage metrics for sea trout in the two years of baseline data (2011 and 2012) and three years of post-commissioning (2013-2015) tracking of fish passage at Ruswarp Weir.

	Baseline			Post-commissioning			
Metric	2011	2012	**Total**	2013	2014	2015	**Total**
n tagged	38	10	48	46	44	41	131
n detected on ATS array	14	3	17	31	32	18	81
Attraction efficiency	**37%**	**30%**	**35%**	**67%**	**73%**	**44%**	**62%**
95% CI	(23-52)	(9-59)	(23-49)	(53-80)	(59-84)	(30-59)	(53-70)
n ascending weir	14	3	17	26	22	13	61
Overall passage rate	**37%**	**30%**	**35%**	**57%**	**50%**	**32%**	**47%**
95% CI	(23-52)	(9-59)	(23-49)	(42-70)	(36-64)	(19-46)	(38-55)
n using main fish pass	14	3	17	25	18	11	54
Fish pass efficiency	**100%**	**100%**	**100%**	**81%**	**56%**	**61%**	**67%**
95% CI	(82-100)	(47-100)	(85-100)	(65-92)	(39-72)	(39-80)	(56-76)

The proportion of tagged fish detected after release varied little between different batches and years. All but one batch had detection rates between 75 and 100% with the exception being the batch released on 01/11/2013 when four tags from this batch (46%) were never detected after release. Immediately after the release of this batch three seals were observed within the vicinity of the release site (S. McGinty (EA) *pers. comm.*).

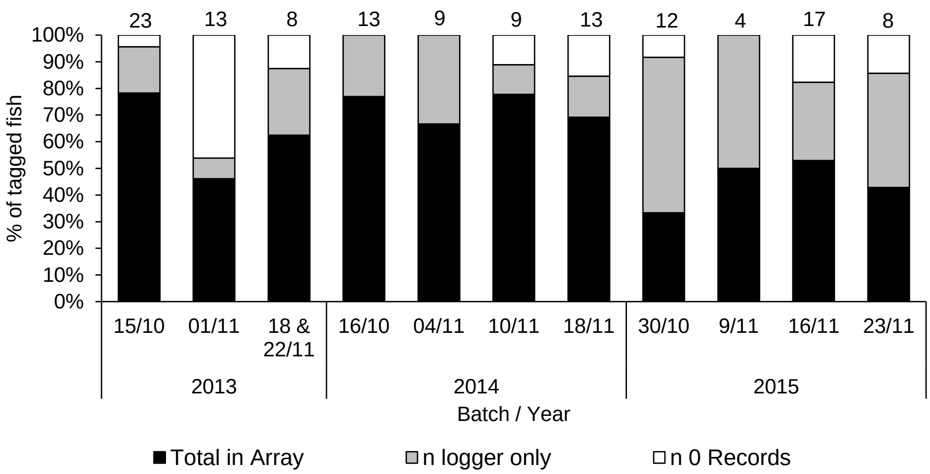

Figure 15. Proportion of fish that entered the array within each major post-commissioning study batch indicating those detected in the array, those not detected or those only detected on a mobile hydrophone. Batch date and number of fish are indicated.

3.2.2 Overall passage efficiency and ascent route

Of the 81 sea trout detected in the array 60 ascended the weir; 53 ascended via the fish pass, one via the side of the fish pass and six via another route (assumed to be the baulk pass) (Table 4 and Figure 13). One further fish ascended the weir without ever having been into the array giving a total of 61 sea trout ascending the weir.

The ***overall passage efficiency*** of sea trout in the post commissioning period, as defined as the proportion of tagged fish ascending the weir, was 47% (38-55% CI, *n* = 61/131) whilst in the baseline dataset it was 35% for sea trout (23-49% CI, *n* = 17/48) and salmon (5/14) (Table 3). There was no significant difference in the overall passage efficiency for sea trout in the post commissioning period compared with the baseline (χ^2 contingency test, χ^2 = 1.776, *d.f.* = 1, *P* >0.05). Furthermore this metric varied considerably during the post-commissioning period between 32% (19-46% CI) in 2015 and 57% (42-70% CI) in 2013. Of all the sea trout that were detected to reach the weir after tagging in the post-commissioning study 73% (62-81% CI, n = 61/84) successfully ascended via any route. This varied between 67% in 2014, 68% in 2015 and 81% in 2013.

Of the 61 sea trout ascents over the weir between 2013 and 2015 seven were assumed to have used the baulk fish pass (detected on H8 or Gary's Hut hydrophone before (or without) a record on H1). Six of these seven sea trout had been in the array previously and there was typically around 30 minutes (longest time was 152 minutes) between leaving the array and first being detected above the weir (on H8 or Gary's Hut hydrophone). Only one sea trout was recorded to ascend the weir via the side-of-fish pass route (recorded on H8 before being recorded on H1) and there was typically around 5-10 minutes between detection on H1 (within the Larinier pass) and being detected on H8.

The records of fish that failed to pass the weir were not evenly distributed between post-commissioning batches of fish. The majority of large batches (≥ 8 sea trout per batch) had approximately 50-83% of sea trout observed in the array pass the weir via the Larinier pass, (Figure 14). However, the last batch in both 2014 (n = 13) and 2015 (n = 8) had low rates of sea trout seen in the array pass through the Larinier pass (23% and 0% retrospectively).

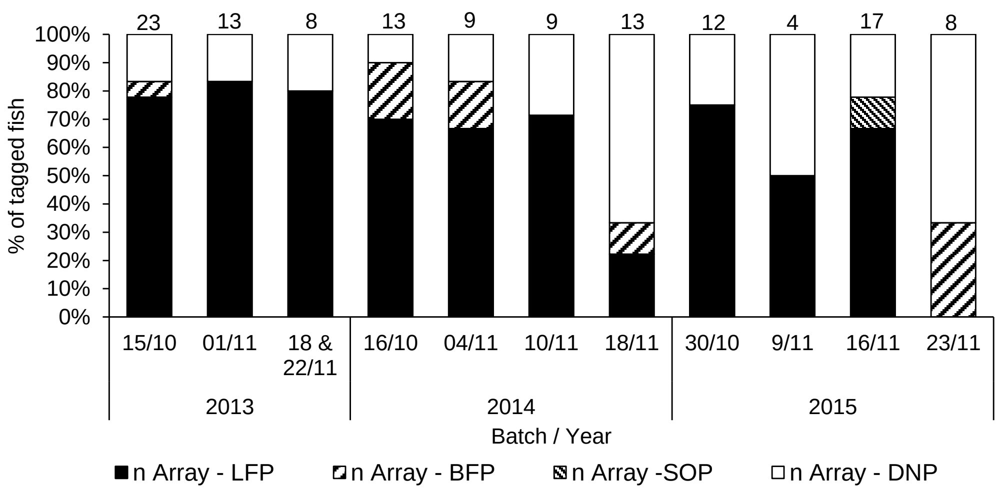

Figure 14. Proportion of fish that entered the array within each major post-commissioning study batch indicating those detected in the array that went on to ascend the Larinier (LFP), the baulk (BFP), side of fish pass (SOP) or to not ascend the weir (DNP). Batch date and number of fish are indicated.

3.2.3 Fish pass efficiency

The ***fish pass efficiency*** for sea trout was observed to be lower in the post commissioning period (67% [56-76% CI, n = 54/81) than in the baseline (100% [85-100% CI, n = 17/17]) and this reduction was significant (χ^2 contingency test with Yate's correction, $\chi^2 = 6.241$, *d.f.* = 1, *P* <0.05). In the post-commissioning period the observed fish pass efficiency ranged from 56% (39-72% CI) in 2014 to 81% (65-92% CI) in 2013.

In 2011 (baseline) 14/14 (100% [82-100% CI]) sea trout successfully used the step-pool fish pass structure to ascend the weir. Some of these fish were deemed to have potentially used the side of the fish pass to ascend the weir at higher flows. In 2012, 3/3 sea trout were successful in ascending the weir via the Larinier pass and 4/5 (80% [41-98% CI]) salmon were successful in ascending the Larinier pass.

3.2.4 Time between release and detection / passage

During the post-commissioning study, the median time between release and first detection was 0.37 days (0.14 – 0.87, *n* = 80 – note that this excludes the fish known to have been subject to predation in the array), compared to the median duration of 1.00 day for the baseline (0.25 – 9.73 days, *n* = 17). There was no significant difference in the average time between release and first detection of tagged sea trout in post commissioning compared with the baseline (Mann Whitney U-test: *Z* = -1.963, *n* = 97, *P* >0.05).

In the post-commissioning study twenty-nine of the tagged sea trout passed within one day (< 24 hrs) of release with a further eleven passing within two days (< 48 hrs). Sixteen of the sea trout took between three and seven days and five sea trout took more than one week to ascend after release (Figure 17b). The median time from release to passage via the Larinier fish pass for sea trout post-commissioning was 1.04 (0.47 – 2.61, *n* = 53) which was similar to the 1.02 (0.26 – 15.50) days (*n* = 17) in the baseline dataset (Mann Whitney U-test: *Z* = 0.062, *n* = 71, *P* >0.05) (Figure 18).

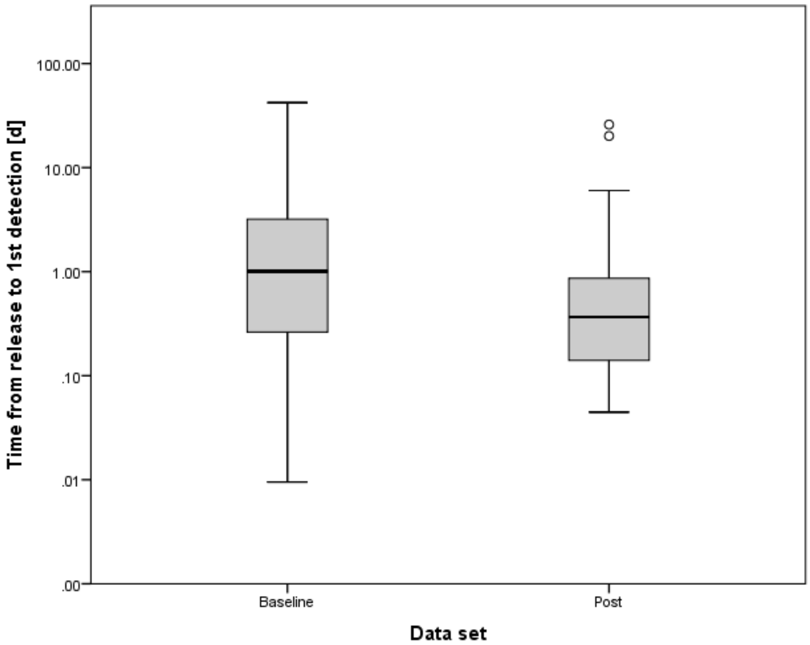

Figure 16. Time from release to detection within the ATS array (days) for tagged sea trout in the baseline dataset (2011 and 2012, *n* = 17) and post commissioning dataset (2013 (*n* = 31), 2014 (*n* = 31) and 2015 (*n* = 18)). Box plots show median (black bar), interquartile range (50% of observations within the grey box), whiskers encompass the values that are no greater or less than 1.5x the interquartile range and circles represent outliers between 1.5x and 3x the interquartile range.

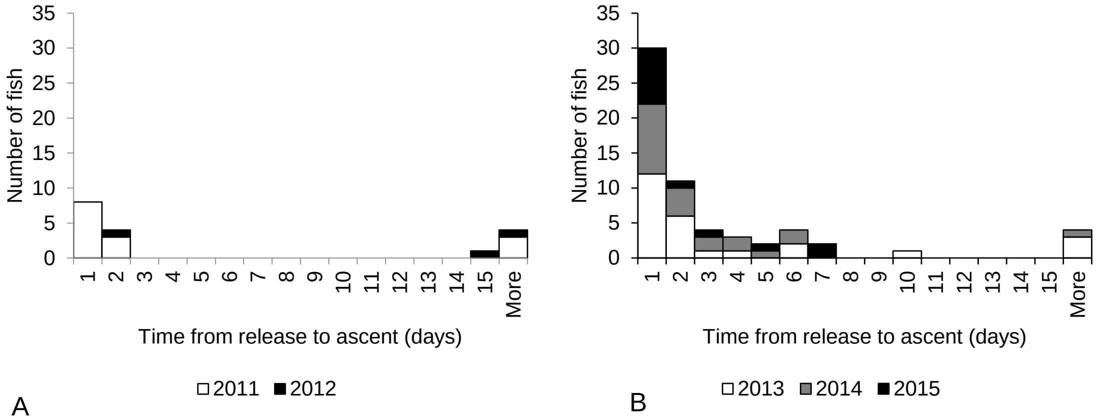

Figure 17. Number of days between release and passage for sea trout in the baseline dataset (A 2011 and 2012, *n* = 17) and in post-commissioning (B 2013, 2014 & 2015 *n* = 61); 1 day = within 24 hours of release.

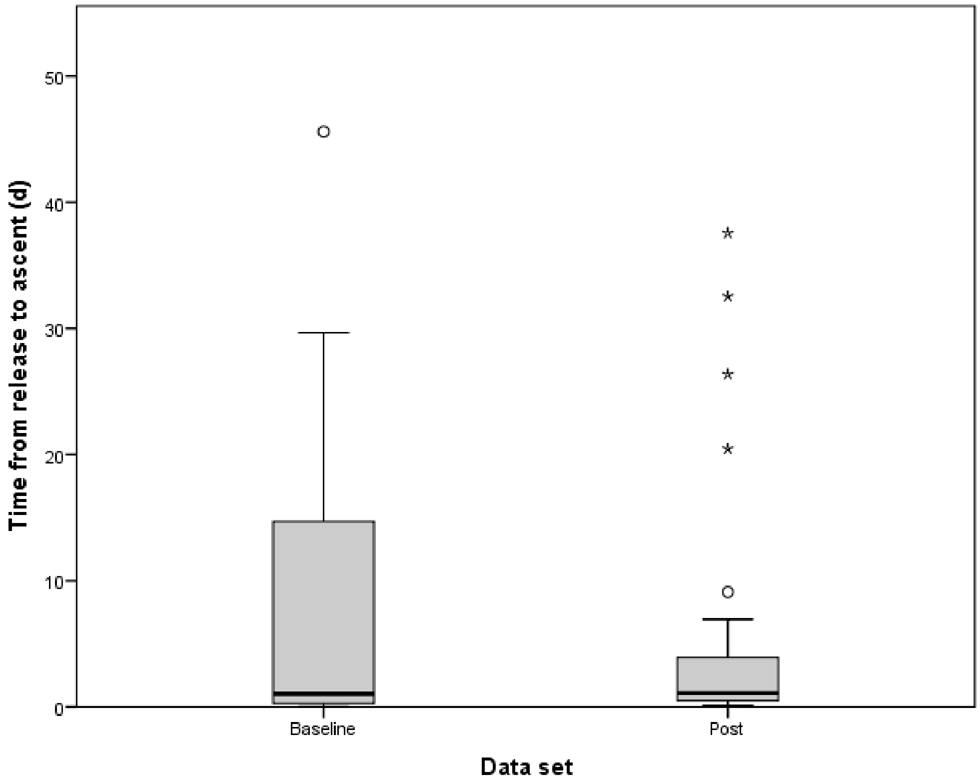

Figure 18. Number of days between release and passage for sea trout in the baseline dataset (2011 and 2012, *n* = 17) and post dataset (2013, 2014 and 2015 *n* = 61). Data indicated by * are extreme values > 3x the interquartile range.

3.2.5 Number of visits to the array

During the post-commissioning study 62% (*n* = 81) of the sea trout tagged were detected in the array, just under twice the return rate observed in the baseline (35%, *n* = 17). Only eleven sea trout ascended the weir during their first visit to the array, a further twenty-four ascended within seven visits. In the baseline dataset, only two of the 17 sea trout (12% [2-32% CI]) visited the array more than five times before passage (Figure 19a) whereas in the post-commissioning study 22 sea trout (41% [28-54% CI]) had more than five visits before passage. This difference was statistically significant (χ^2 contingency test, $\chi^2 = 4.851$, *d.f.* = 1, *P* <0.05).

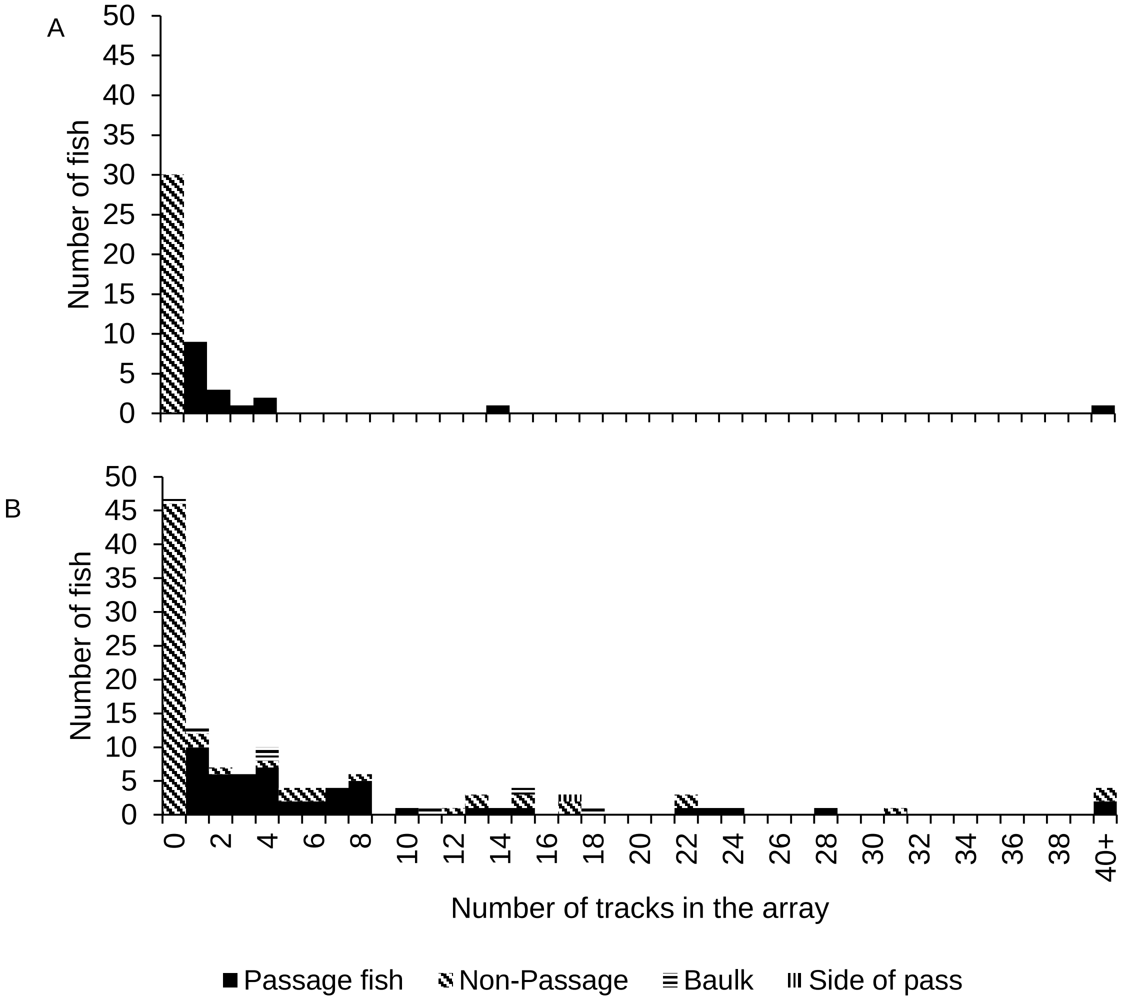

Figure 19. Frequency distribution showing the number of times the hydrophone array was entered by sea trout in A) 2011 and 2012 B) 2013, 2014 and 2015 (0 = number of fish not detected in the array).

3.2.6 Time in the array

There were differences observed in both the duration of visits to the array and the total time spent in the array from first arrival in the array to passage between the post-commissioning study and the baseline. The average duration of individual tracks in the array was similar between the baseline (median 3.58 minutes [1.58 – 9.50]) and the post-commissioning study (median 2.87 minutes [0.84 – 8.24]) (Figure 20) (Mann Whitney U-test: *Z* = -1.894, *n* = 856, *P* >0.05). There was an increase in the average (median and interquartile range) total time spent in the array by sea trout prior to passage between the baseline (4.75 (1.54 – 27.79) minutes (*n* = 17)) and post-commissioning dataset (23.59 (8.04 – 70.95) minutes (*n* = 54)) and this difference was significant (Mann Whitney U-test: *Z* = 2.237, *n* = 71, *P* <0.05). In the baseline 65% of tagged sea trout (42-84% CI, *n* = 11/17) spent less than a total of ten minutes in the array prior to passage via the main fish pass, whereas after commissioning this reduced to 28% (17-40% CI, *n* = 15/54) and this change was highly significant (χ^2 contingency test, $\chi^2 = 7.597$, *d.f.* = 1, *P* <0.01) (Figure 21).

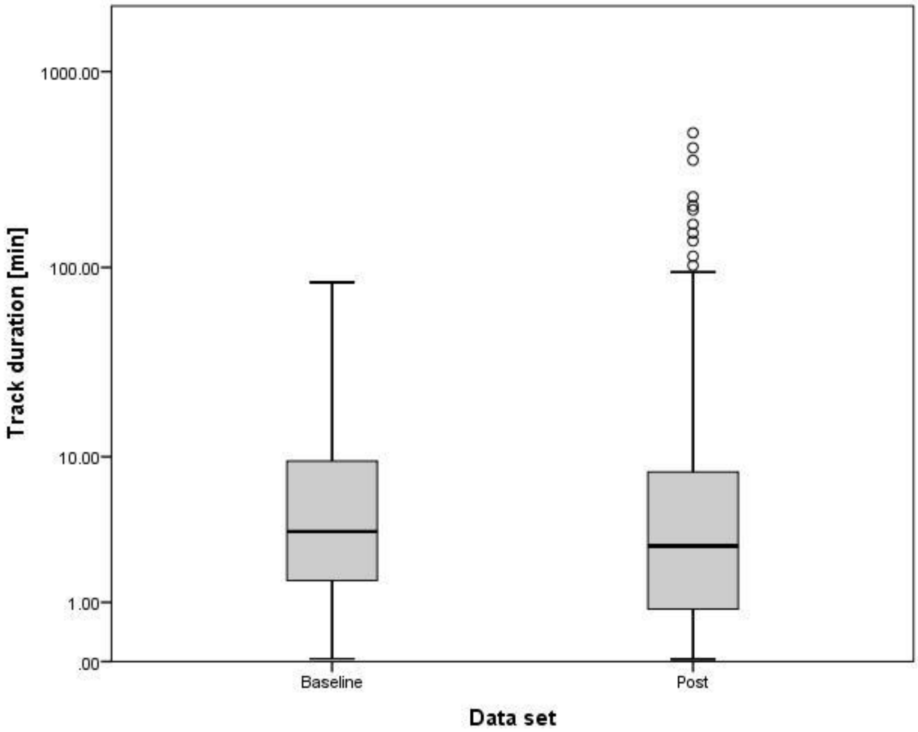

Figure 20. Duration (minutes) of individual tracks within the array (minutes) for baseline and post-commissioning.

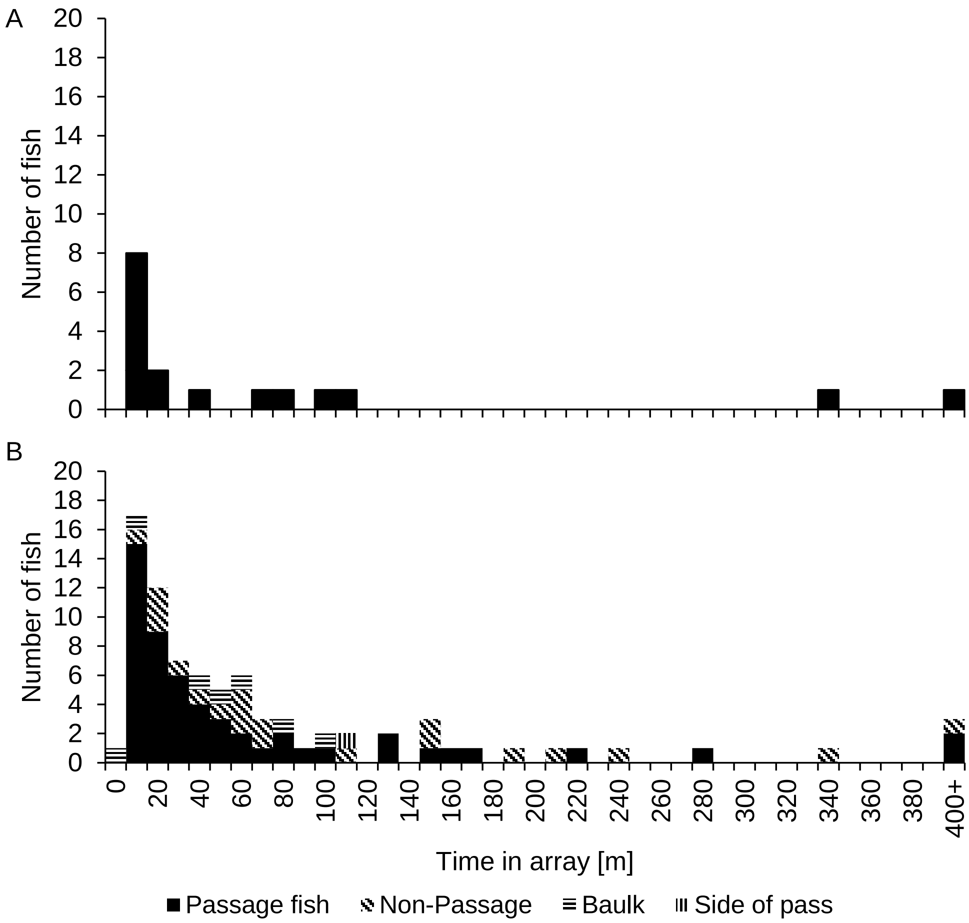

Figure 21. Total time spent in the array prior to passage (sum of all tracks) sea trout in A) 2011 and 2012 B) 2013, 2014 and 2015

The 27 sea trout that were detected in the array but did not ascend the weir via the Larinier pass in the post-commissioning study each spent between 1 and 805 minutes in total in the array; with eight of them (30% [15-48% CI]) spending more than 100 minutes in the array before leaving the array for the final time. Mobile hydrophone data also indicated that delayed fish often moved in and out of the array following first detection. This included movements to and from the area around the downstream end of the weir (Noble's Yard) and occasionally movements to and from Whitby harbour.

Sea trout that failed to use the Larinier post-commissioning tended to have spent slightly longer in the array before the last detection with a median time in the array of 62.4 minutes (22.2 – 165.7) compared with 48.7 minutes (23.5 – 77.9) for sea trout that went on to use the baulk and the 23.59 minutes (8.04 – 70.95) for sea trout that passed via the Larinier (Figure 22) although the difference was not statistically significant (Kruskal Wallis test: K = 5.056, n = 81, $d.f.$ = 2, P > 0.05).

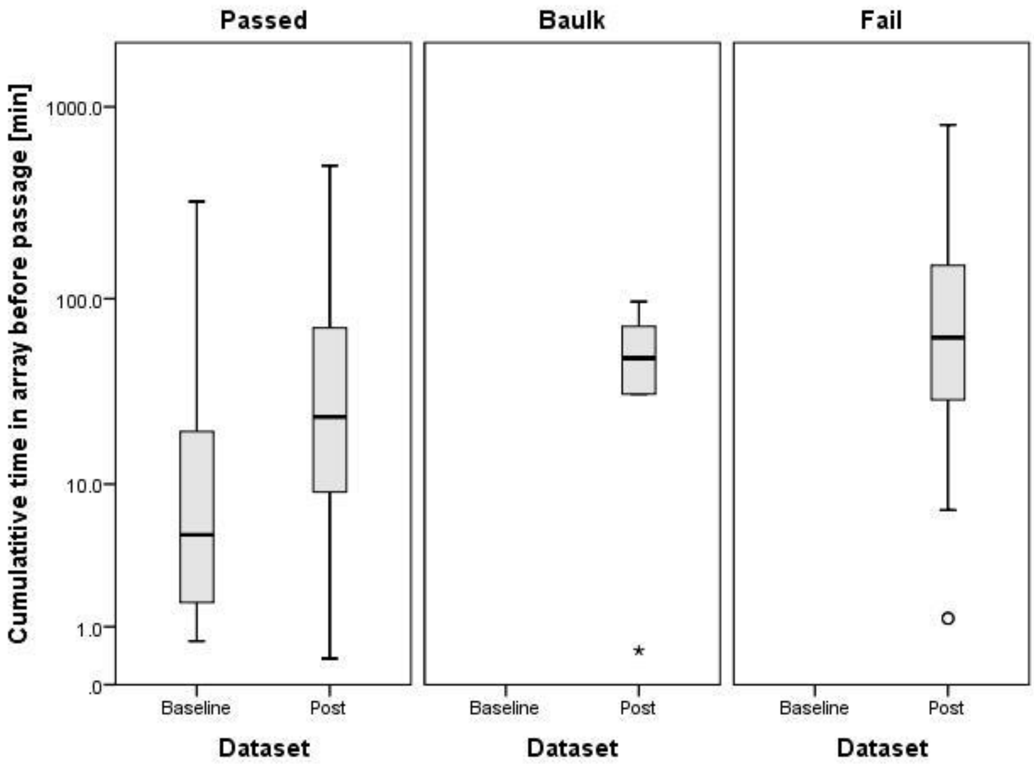

Figure 22. Total time spent within the array (sum of all tracks) prior to passage via the fish pass (minutes) for tagged sea trout in the baseline dataset (*n* = 17) and post-commissioning passage (*n* = 54), baulk (*n* = 6) and non-passage (*n* = 21).

3.2.7 Time between first detection in the array and passage

In the baseline 71% (48-88% CI, n = 12/17) of sea trout passed the weir within one hour of their first detection in the array (including time spent outside of the array) whilst in the post-commissioning dataset this reduced to 28% (17-40% CI, n = 15/54) and this change was highly significant (χ^2 contingency test, χ^2 = 10.055, $d.f.$ = 1, P <0.01). Furthermore, in the post-commissioning period 16 sea trout (30% [19-42% CI]) took longer than 12 hours to ascend (Figure 23). The median time from first detection to passage by sea trout was 2.69 (0.79 – 17.28) hours (n = 54) in the post-commissioning dataset which was significantly longer than the median passage delay in the baseline of 0.28 (0.09 – 1.41) hours after first arrival in the array (Mann Whitney U-test: Z = 3.153, n = 71, P

<0.01) (Figure 24). Sea trout which failed to use the Larinier spent significantly longer in the vicinity of the weir before either using the baulk pass (9.19 [0.76 – 186.6] hours) or until their last detection in the array before dropping back downstream or being lost from the study (34.68 [5.75 – 78.30] hours) compared with the sea trout that passed the weir (2.59 [0.61 – 18.11] hours) (Kruskal Wallis test: K = 11.183, n = 80, $d.f.$ = 2, P <0.01) (Figure 25).

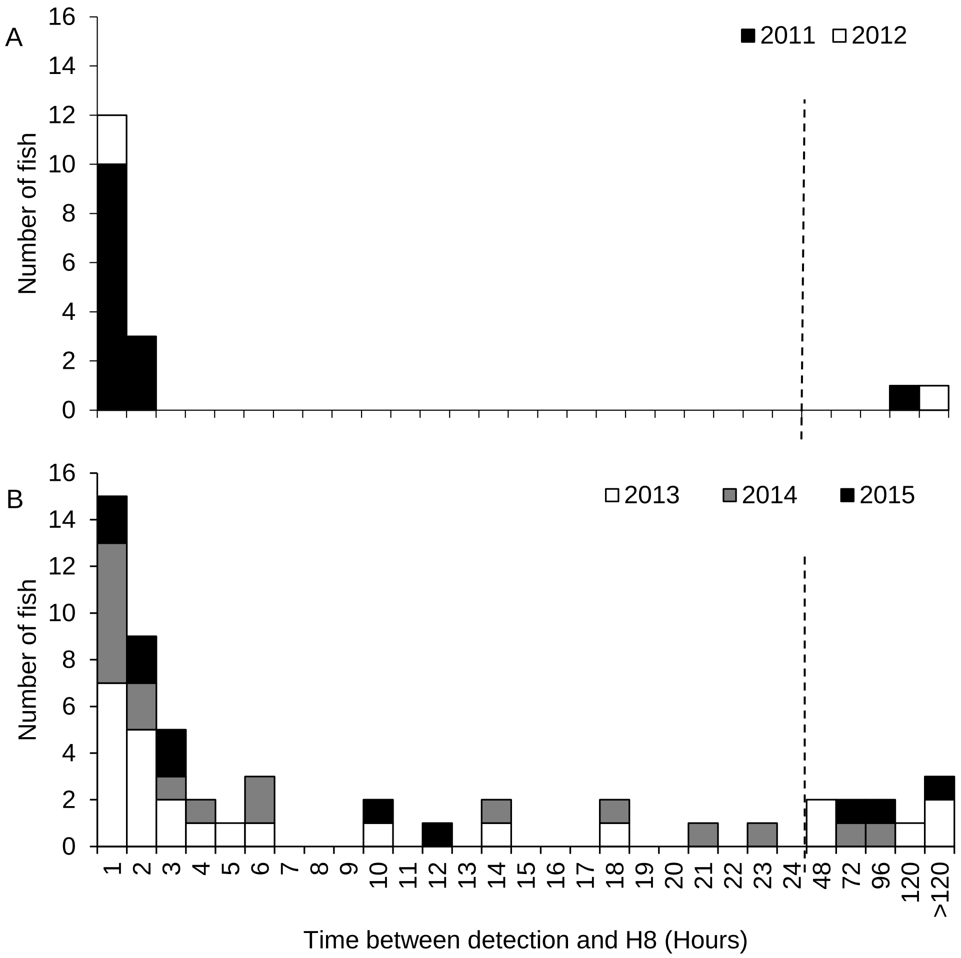

Figure 23. Total time between first arrival in the array and passage (time on H8) for sea trout in A) 2011 and 2012 B) 2013, 2014 and 2015 (dotted line represents change in time intervals after the first 24 hours)

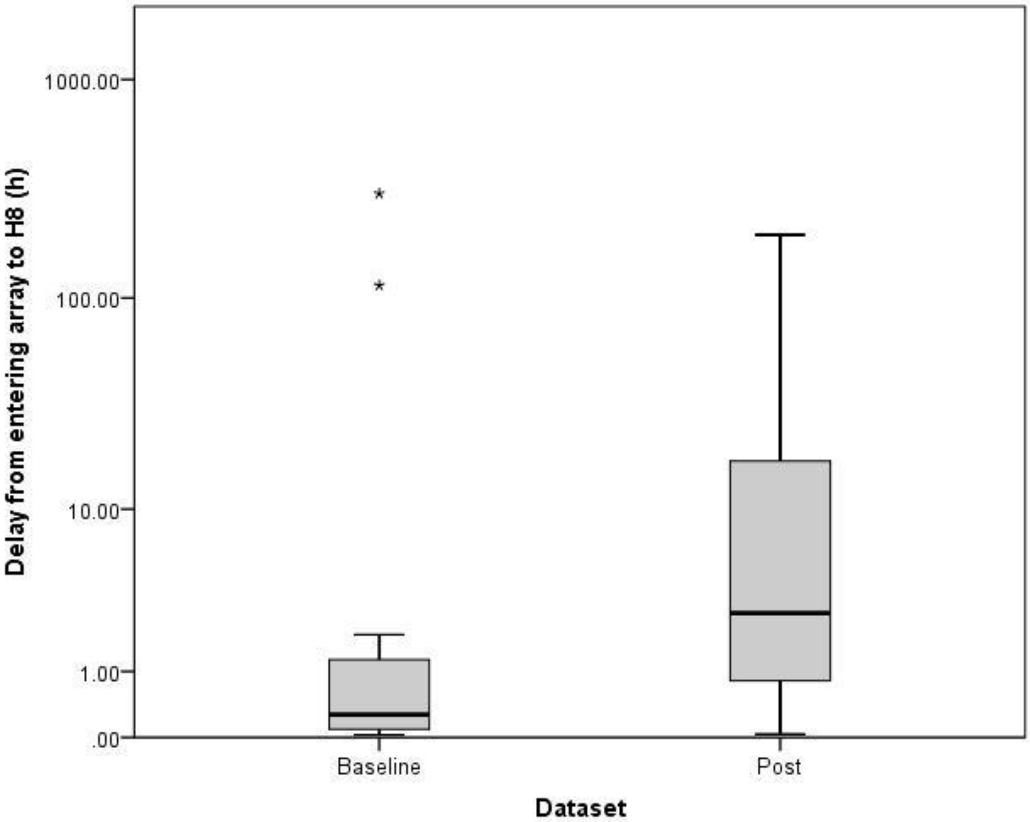

Figure 24. Total time between first detection in the array and final passage for (hours) tagged sea trout in the baseline dataset (2011 and 2012, *n* = 17) and post-commissioning dataset (2013 *n* = 25; 2014, *n*= 18; 2015, *n* = 11).

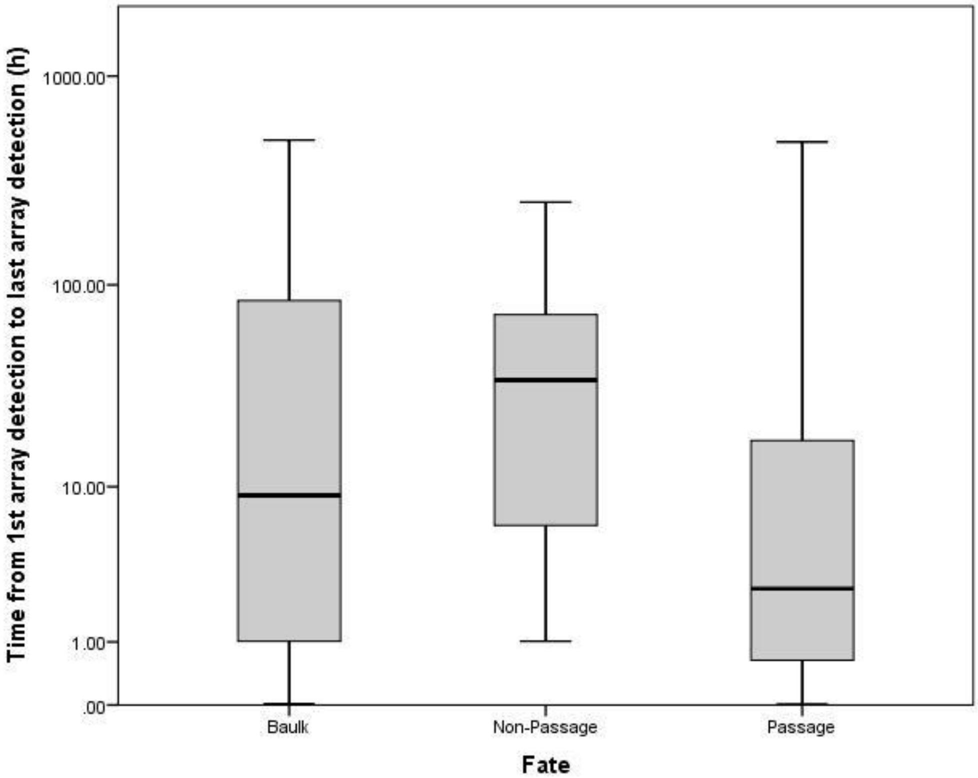

Figure 25. Total time from first detection in the array prior to final departure from the array prior to passage via the fish pass/baulk or leaving the array for the last time (hours) for tagged sea trout in the post-commissioning study (Baulk *n* = 6, Non-passage *n* = 20, Passage *n* = 54).

3.2.8 Fate of fish that did not ascend

Of the 23 sea trout that were detected at Ruswarp but did not ascend the weir during the post-commissioning study, 21 (91%) are known to have reached the array. One of these fish is assumed to have been predated upon within the vicinity of the array during the 2014 study. One fish that failed to reach the array was detected over 12 consecutive days on the Noble's Yard logger for between 15 to 24 hours each day. Seventeen sea trout that reached the weir were last detected downstream; 11 at Noble's Yard (one of which was never detected in the array) and six at Whitby harbour. There were five sea trout that were last detected leaving the array after spending a period of 1-4 days in the vicinity of the weir. None of these fish were subsequently detected moving downstream on either Noble's Yard or Whitby.

3.3 Environmental Influences on timing of movement

3.3.1 Relationship with discharge

There was marked differences in the river discharge between the five study years (Figures 26a, 26b and Table 4). In most years flows were generally low during August and early autumn spates occurred in early September. The lowest flows were experienced during 2011 when very few spates >6 $m^3 s^{-1}$ were observed. 2012 was a wet year and included the two highest spates observed during the study and during the October and November of that year flows were above 15 $m^3 s^{-1}$ for an appreciable time (27% of the time in November 2012). 2014 was an intermediate year in terms of hydrology being wetter than the dry autumn of 2011 and having only two spates similar to the four >30 $m^3 s^{-1}$ events observed in 2012 (Figure 26). 2013 was unusual in that it had a prolonged dry period (September and early October) followed by a series of large spates and a period of flows > 2 $m^3 s^{-1}$. 2015 was also a wet autumn with flows during November being greater than 6 $m^3 s^{-1}$ for 63% of the time (Table 4).

Table 4. Summary metrics of hydrological records during the tracking periods in September, October and November of the years since 2011 comprising the baseline and post-commissioning.

					% of days in discharge category				
Year	Month	Min $m^3 s^{-1}$	Max $m^3 s^{-1}$	Q50 $m^3 s^{-1}$	< 1 $m^3 s^{-1}$	1-2 $m^3 s^{-1}$	2-6 $m^3 s^{-1}$	6-15 $m^3 s^{-1}$	>1 $m^3 s^{-1}$
2011	Oct	0.94	10.82	1.50	14	55	27	5	0
	Nov	0.96	15.36	1.48	0	83	10	7	0
2012	Sep	0.86	141.40	1.20	27	47	13	3	10
	Oct	1.64	38.60	4.62	0	13	55	19	13
	Nov	2.23	163.60	4.35	0	0	60	13	27
2013	Sep	0.76	0.96	0.88	100	0	0	0	0
	Oct	0.73	23.07	4.06	23	16	26	32	3
	Nov	1.53	28.04	2.87	0	20	63	10	7
2014	Oct	1.05	38.67	2.64	0	31	50	13	6
	Nov	1.65	67.41	5.69	0	13	33	37	17
2015	Oct	4.99	21.40	7.81	0	0	0	100	0
	Nov	1.76	38.90	7.36	0	7	30	53	10

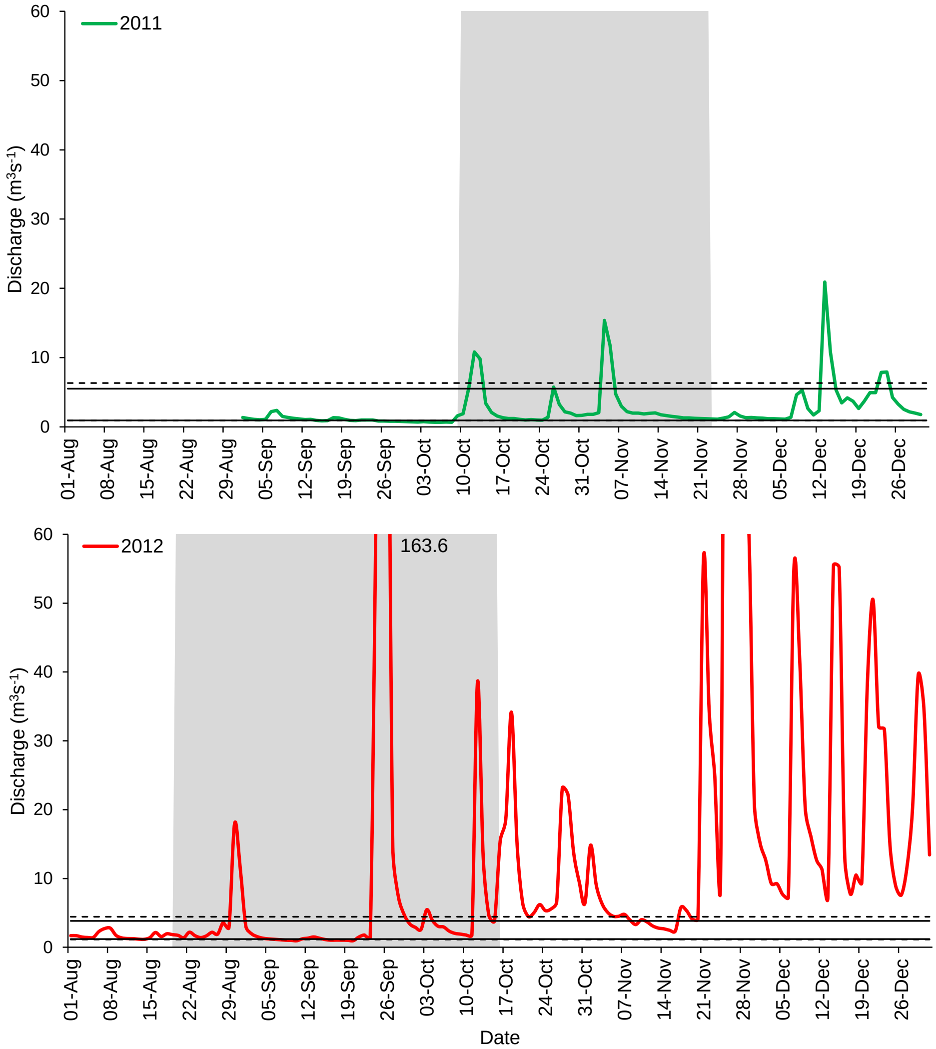

Figure 26a. Hydrographs for discharge (m³ s⁻¹) in the River Esk measured at the EA gauging station at Briggswath during the autumn of 2011 and 2012. Shaded areas indicate the period of the tracking studies in each year from the date of first release to the last track in the array (excluding descents). The solid horizontal lines represent the highest and lowest discharge for recorded passage in each year and the dashed horizontal lines represent the highest and lowest recorded discharge whilst fish were in the array.

Analysis of the tracking data and the hydrographs from Briggswath indicate that the flows experienced by sea trout whilst occupying the pool downstream of the fish pass and the flows on which they were able to ascend the fish pass were determined by the range of flows occurring in each year. In all years sea trout were able to ascend the pass utilising the majority of flows they experienced with passage not observed at only the lowest of flows and largest flows observed each year. For example sea trout were not observed to pass at flows higher than 5.52 $m^3 s^{-1}$ in 2011, flows only exceeded for 7 days during the tracking period in this year (Figure 26a). Despite the larger spates observed in 2012 all sea trout passages were observed at flows <4 $m^3 s^{-1}$ in this year. Over the course of the post-commissioning study the sea trout were exposed to a wider range of flows more frequently during the tracking period which was reflected in the highest and lowest flows associated with successful passages in each of the 3 years (Figure 26b). The lowest flow associated with a successful passage post-commissioning was 1.65 $m^3 s^{-1}$ in 2014, and average daily flows in the river were only lower than this for about 11% of the entire tracking periods in 2013, 2014 and 2015.

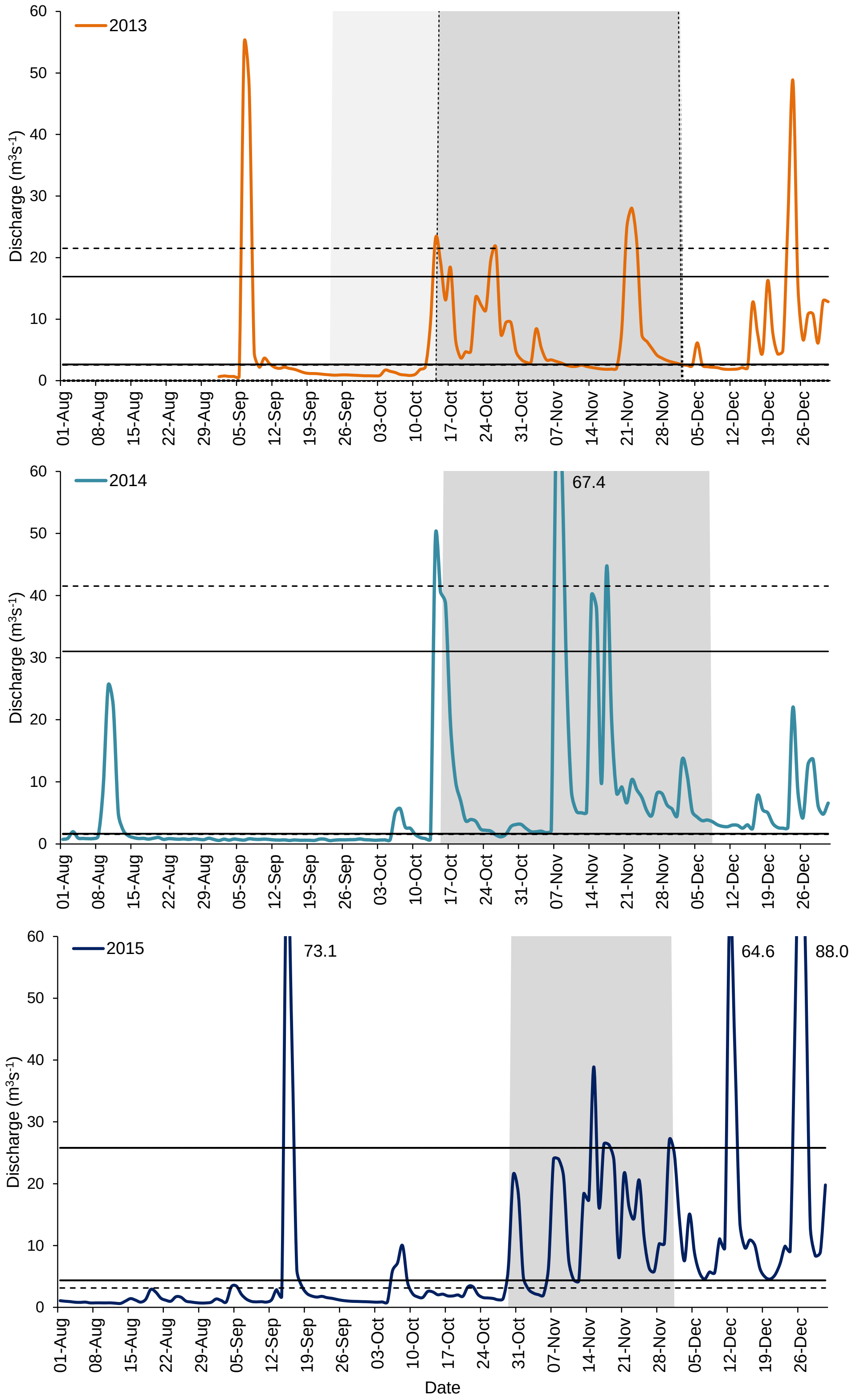

Figure 26b. Hydrographs for discharge ($m^3 s^{-1}$) in the River Esk measured at the EA gauging station at Briggswath during the autumn of 2013, 2014 and 2015. Shaded areas indicate the period of the tracking studies in each year from the date of first release to the last track in the array (excluding descents). In 2013 only 2 fish were released before the 15th of October (represented by the lightly shaded area) but these two fish only passed on the 15/10/13. The solid horizontal lines represent the highest and lowest discharge for recorded passage in each year and the dashed horizontal lines represent the highest and lowest recorded discharge whilst fish were in the array.

During the tracking period in 2013 to 2015 sea trout were generally observed to ascend at times of elevated flow (Figure 27b). However, capture and releases of the tagged fish also deliberately coincided with these periods of high flow, or followed shortly after, so in the majority of cases it was not possible to discern whether fish movements occurred as a consequence of release or in response to a specific flow event. Post-commissioning passages of sea trout were observed at discharges between 1.65 and 31.00 $m^3 s^{-1}$, with passages over the baulk up to 31.00 $m^3 s^{-1}$. Many of these (29) were at flows higher than the largest passage flows observed in either 2011 or 2012 (5.52 $m^3 s^{-1}$). Post-commissioning 10 fish were observed to pass the Larinier at flows >10 $m^3 s^{-1}$ (Figure 27) and five of the seven baulk passages were observed at flows above this level (Figure 28). Post-commissioning only two sea trout were observed to pass the Larinier at low flows (<2 $m^3 s^{-1}$) at which some passages were recorded in 2011 and 2012 (Figures 27 and 28) although flows below this level, which occurred for 35% of the time during the baseline tracking study, were only available for 18% of the tracking periods between 2013 and 2015.

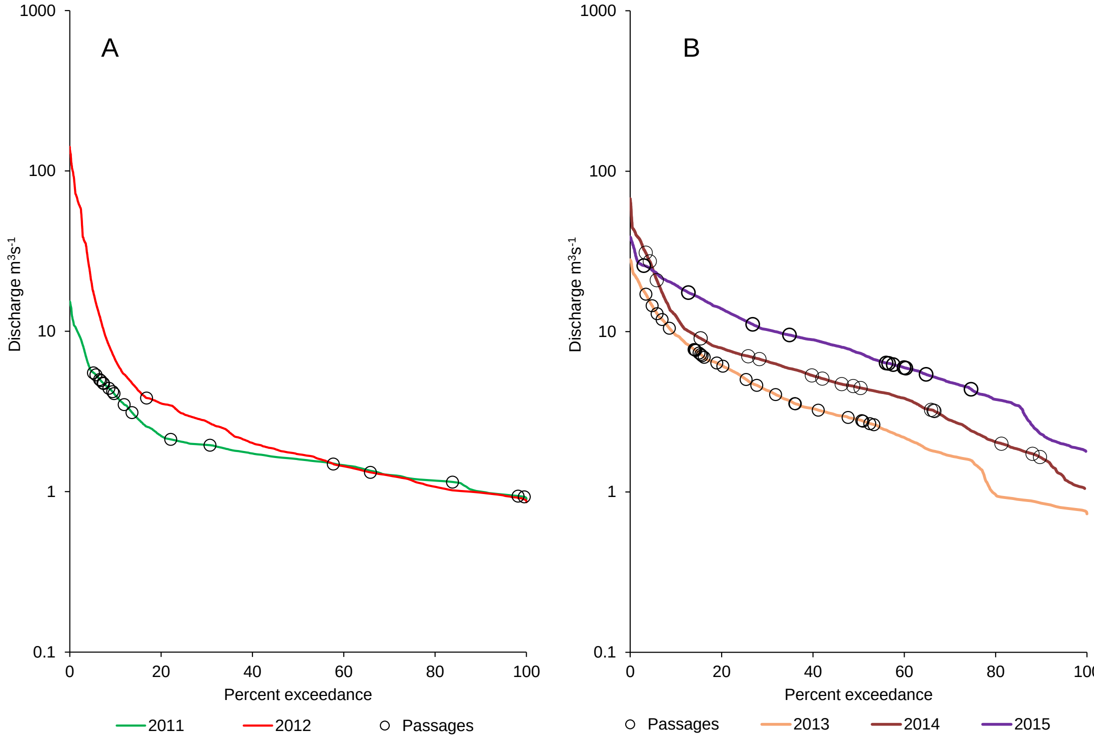

Figure 27. Relationship between sea trout passages and percent exceedance flow duration curves in each study period for Pre- (A) and Post-commissioning (B). The flow duration curves for each year represent the flows that occurred between the first release of tagged fish and the last recorded track in the array (excluding descending fish) in each year.

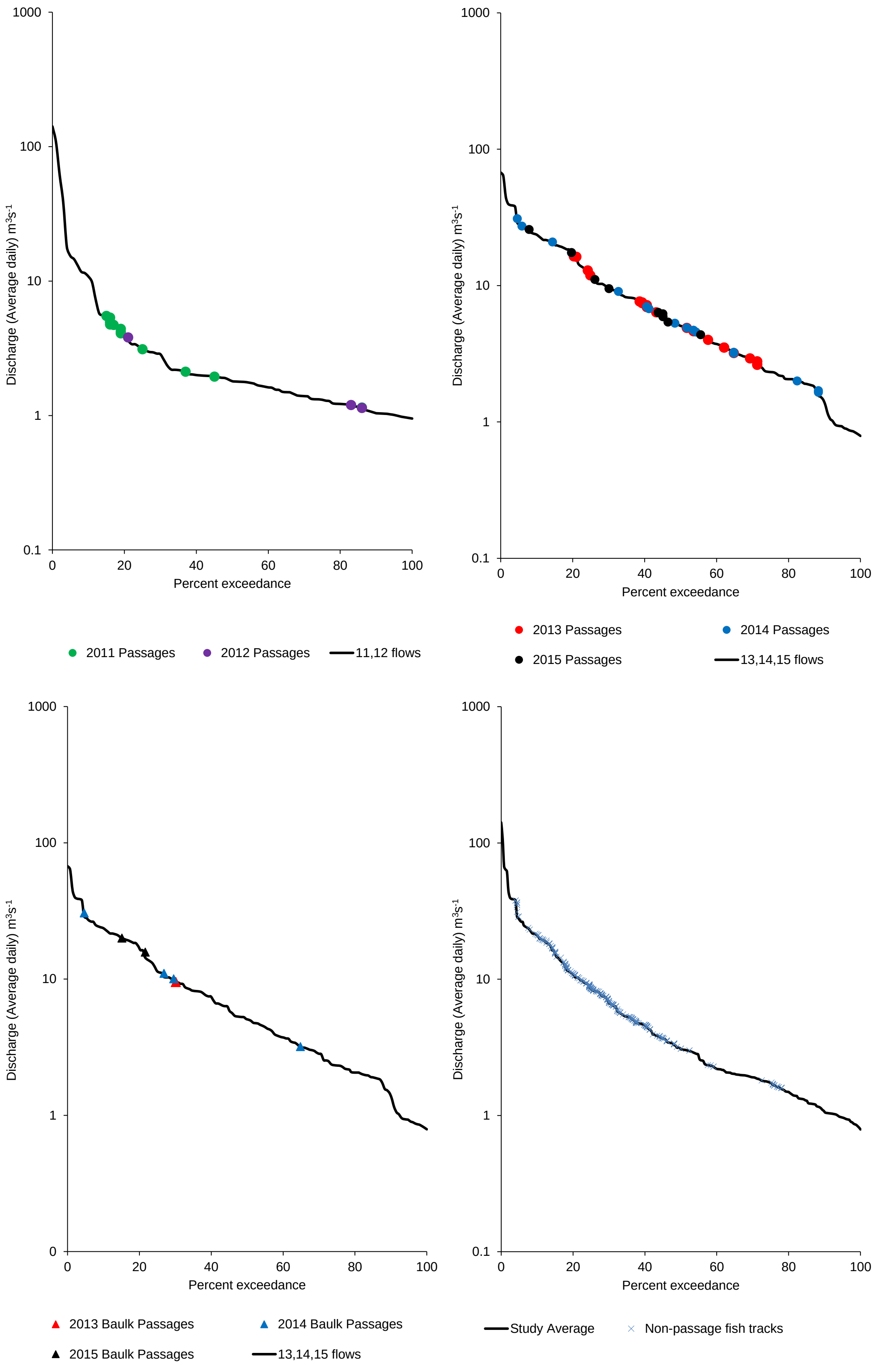

Figure 28. Timing of sea trout passages through the fish passes in the baseline data set (top left), the post-commissioning study (top right), post commissioning baulk passages (bottom left) and tracks in the array from non-passage fish post-commissioning in respect of discharge ($m^3 s^{-1}$ - displayed as a summary flow exceedance curve for flows across the tracking periods in the baseline [2011 and 2012] and post-commissioning [2013, 2014 and 2015] with the tracking period comprising the time between first release and last detection in the array in each year.

3.3.2 Relationship with tide and water level in the fish-pass pool

There was no clear pattern in first entry to the array or passage (Figure 29) when discharge and tide were considered together. Sea trout were observed to pass under a range of tide heights and discharges. The passage activity in the baseline was restricted by the range of flows available during that time (particularly in the dry autumn of 2011). In the baseline no passage tracks were observed at discharges > 6m^3 s^{-1} whilst many sea trout were observed to pass at flows between 6 and 30m^3 s^{-1} in the post-commissioning years. The pattern was similar for times of first arrival in the array, with no clear pattern in relation to discharge or tide (Figure 30).

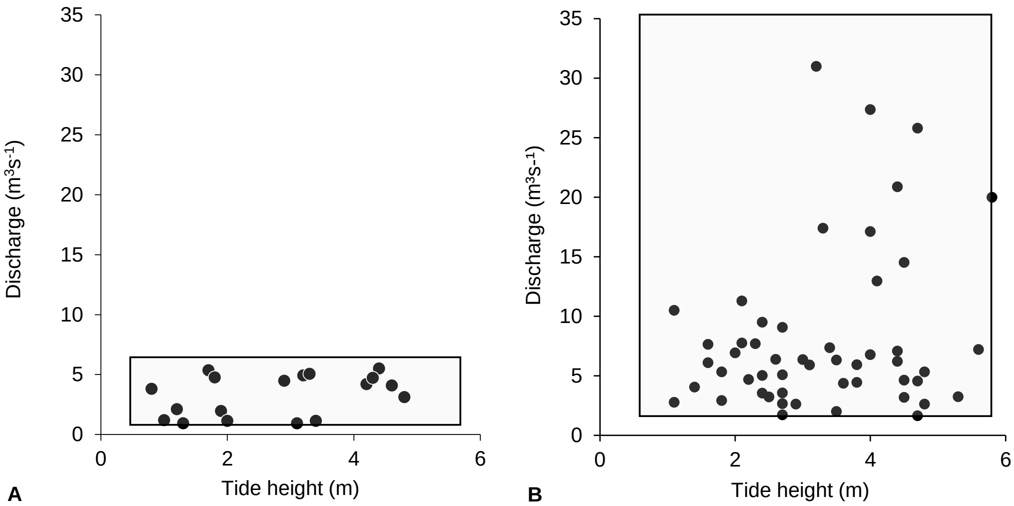

Figure 29. Discharge and tide conditions during passage tracks for sea trout in A) baseline B) post-commissioning. The grey boundary box indicates the range of flows and tides experienced by sea trout whilst in the array.

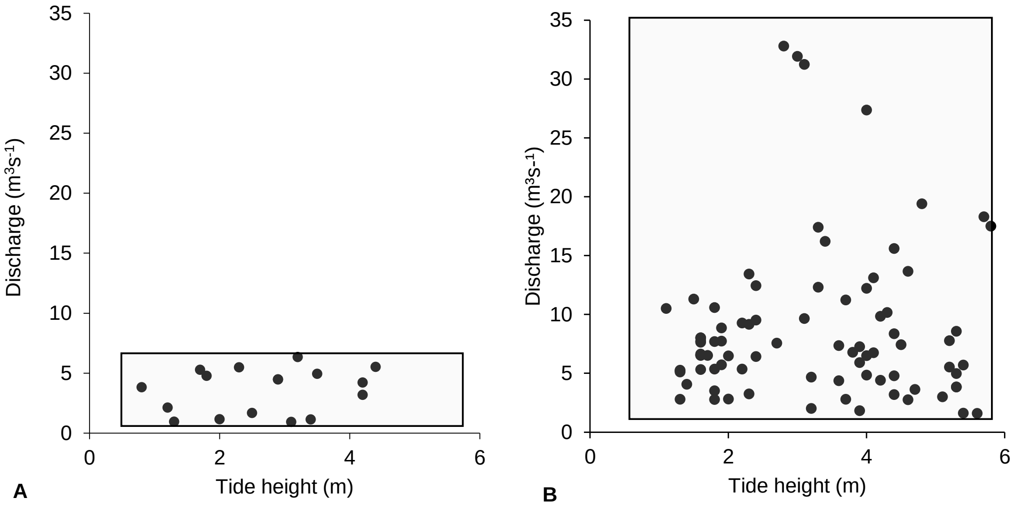

Figure 30. Discharge and tide conditions during first entry into array for sea trout in A) baseline B) post-commissioning. The grey boundary box indicates the range of flows and tides experienced by sea trout whilst in the array.

Esk Energy now monitor the pool level downstream of the hydropower scheme (metres above ordnance datum, maOD) and these levels respond to both river discharge and tide height (previously measured as predicted height at Whitby). These data give absolute information as to the discharge conditions in the pool and thus replace the total water index measure (TWI) used in Walton *et al.* 2012 and Noble *et al.* 2013. First arrival and fish passage occur at a range of levels with the majority of passages occurring between 1.85 and 2.10 m and the majority of first arrivals between 2.00 and 2.15 m (Figure 31).

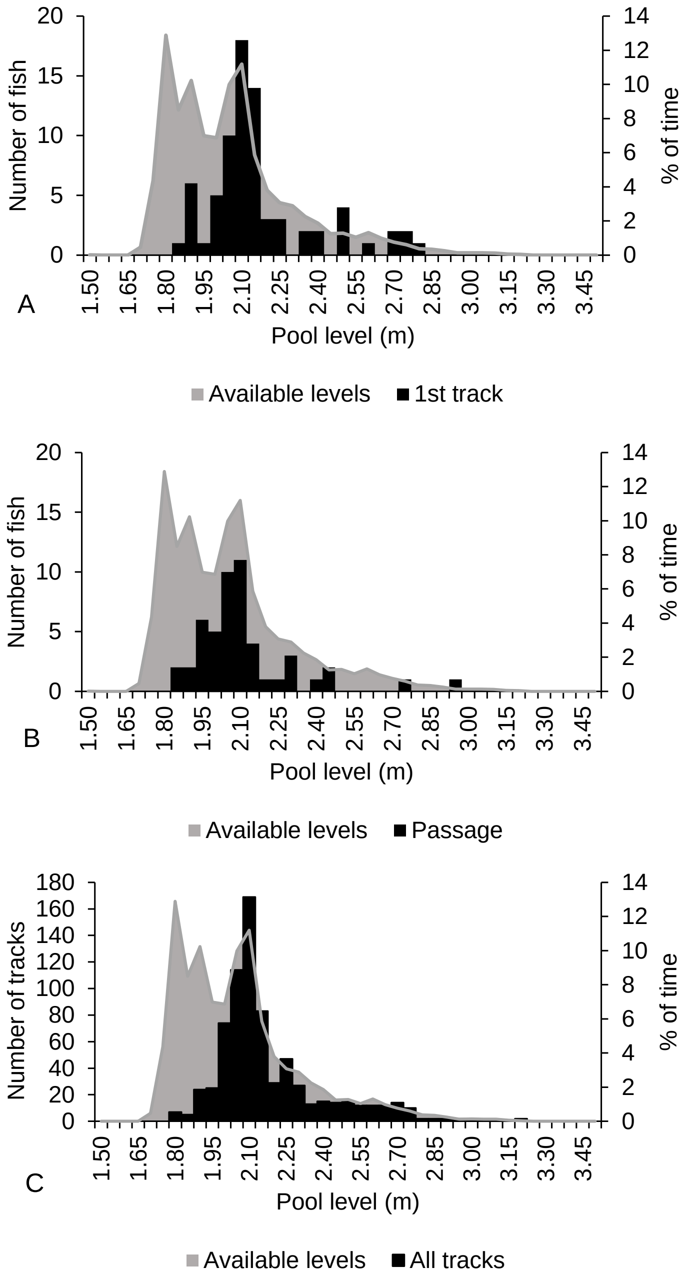

Figure 31. Relationship between A) the timing of passage over the weir, B) first arrival in the pool and C) all tracks in the array and the pool levels that occurred during the tracking period only (maOD) (Post commissioning data set).

3.3.3 Turbine activity

The hydropower turbine was active for 62.5% of the time during the post commissioning study (considered to be 1st September – 31st December in each study year) and was operating at near capacity (abstraction of above 3.5 $m^3 s^{-1}$) for 19.8% of the time (Figure 32a). In each year of the post-commissioning study the turbine was active for different proportions of the tracking period (as defined from the first date of a release in each year to 31st December). The turbine was active for 64% of the time whilst tracking in 2013, 78% in 2014 and 97% in 2015. The turbine was operating at >3.5 $m^3 s^{-1}$ for 10% of the tracking period in 2013, 5% in 2014 and 52% in 2015. Sea trout were observed to ascend through the fish pass under most conditions. However, in 2015, 10/11 (91%) of the sea trout ascended the pass whilst turbine flows were greater than 3.5 $m^3 s^{-1}$ (Figure 32a). Only three sea trout passed when the hydropower scheme was inactive; two in 2013 and one in 2014.

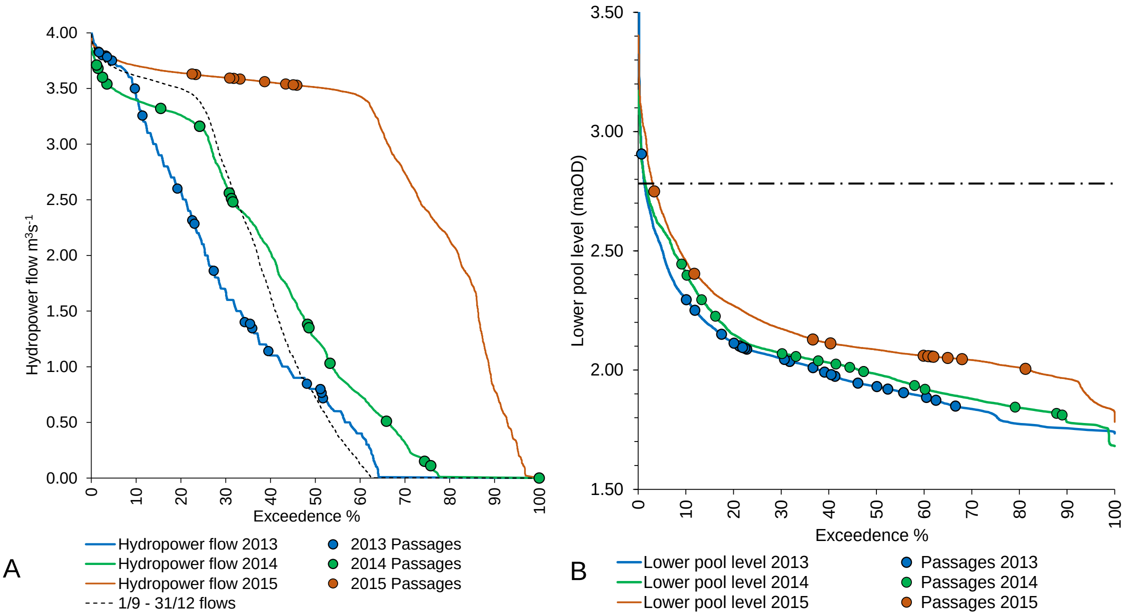

Figure 32. Passages of sea trout (circles) through the Larinier fish pass plotted against exceedance curves of hydropower flow (A) and level in the pool (B) (exceedance values calculated between study years 1st release and 31/12 each year). Note, two sea trout in 2013 and one in 2014 passed when the hydropower flow was zero. The dashed line in (A) represents the abstraction exceedence curve for the 3 years of post-commissioning study for the period of 1st September to 31st December. The dashed line in B indicates the pool level at which the hydropower scheme automatically shuts off.

3.4 Bathymetry of the pool

When the hydropower scheme was operational the pool was characterised by a pair of well oxygenated plumes of turbulent water originating from the fish pass and from the left-hand side (looking downstream) of the hydropower outfall. There were areas of visually less turbulent water between these two plumes and between the hydropower plume and the reinforced right-hand bank (Figure 33).

The bathymetry (depth) of the pool downstream of the step-pool fish pass entrance was measured prior to construction of the hydropower scheme and the Larinier pass using an ADCP in 2011 and manually in both 2013 and 2014 after the hydropower scheme had been commissioned. Although the absolute depths recorded were similar (0.15 to 1.70 m) they cannot be directly compared between years due to differences in discharge at the times of measurement. The depth profile of the pool, the spatial distribution of shallow and deep areas, changed considerably after construction of the hydropower scheme. In 2011 (Figure 34a) the pool was relatively deep (≈ 1 m) up to the entrance of the step-pool fish pass, with the deepest section (1.4-1.5 m) approximately 3m downstream and in line with the discharge plume. In 2013 and 2014, following construction of the hydropower scheme, change of the fish pass from a step-pool to a Larinier and reinforcement of the right hand bank (looking downstream) the deepest section of the pool (1.4-1.7 m) was towards the right-hand bank and in front of the hydropower outfall screens (Figure 34b). The area approximately 2-3 m in front of the fish pass entrance is now relatively shallow (0.5-0.8 m) before deepening (1.2-1.4 m) at around 4 m downstream of the fish pass entrance. In 2014 pool levels were measured with both the fish pass and hydropower turned off, when these were turned on about 15 cm of depth was added to parts of the pool.

Figure 33. View of the outfall of the new turbine and hydrophones array in 2013 with the hydropower scheme active under higher flows (21.82$m^3 s^{-1}$).

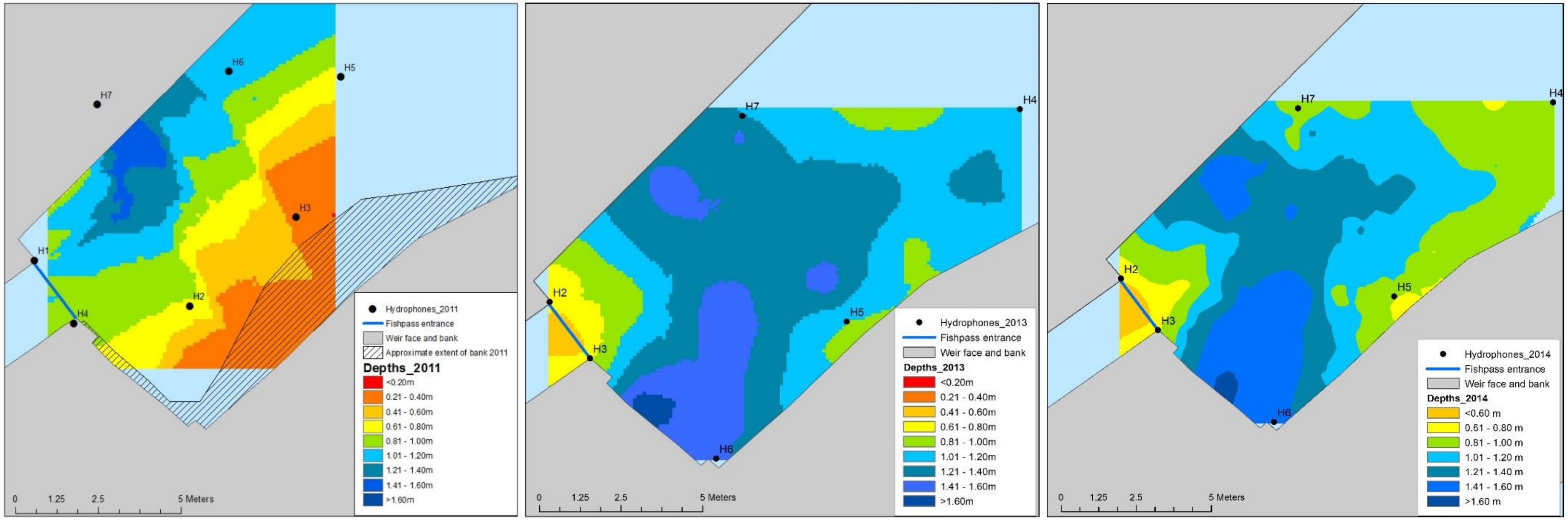

Figure 34 Bathymetry of the pool raster plots calculated by kriging ADCP data in 2011 (left) and manual transect measurement in 2013 (middle) and 2014 (right). Note that these were measured under different flows (and with the hydropower and fish pass turned off in 2014) so the absolute measurements should not be directly compared between years. The shaded area on the right-hand bank in 2011 marks the approximate location of the bank before construction of the hydropower turbine, it should be noted that this was originally a gently sloping gravel bank, where the depth of water would have been shallow except for periods of high tide.

3.5 Quantitative analysis of micro scale sea trout behaviour within the array

3.5.1 Distribution of tracks

Post-commissioning tracks were widely distributed throughout the array (Figure 35b) with few cells containing more than 25% of the recorded tracks. The highest density of track records (between 20-50% of tracks) was located in the fish pass and hydropower plumes. The pattern of track distribution post-commissioning indicated more of a tendency for tracks to pass through locations in the centre of the pool, which was similar to that observed in the baseline (Figure 35a) although in the baseline the centre, and deepest part of the pool, was located in front of the fish pass entrance and towards the weir face (Figure 35a).

Residence time was not evenly distributed in either the baseline (Figure 36a) or during the post-commissioning period (Figure 36b) and hotspots, where a few fish spend a disproportionate amount of their time, were apparent. In the baseline the hotspots were in the vicinity of the entrance to the fish pass (Figure 36a) whereas post-commissioning a hotspot was located near the right-hand bank and immediately in front of the outfall of the hydropower turbine (Figure 36b). Post-commissioning another hotspot was observed in front of the fish pass plume, similar to that observed in the baseline (Figure 36b). The generally low rate of detections rates within 2 m of the fish pass entrance post-commissioning in comparison with the baseline may result from reduced frequency of fish using/traversing this area or due to decreased efficiency of tag detection, both related to the shallow and turbulent nature of the area post-commissioning.

3.5.2 Discharge and hydropower turbine operation

Post-commissioning the majority of sea trout tracks were recorded whilst the hydropower turbine was active; only 44 (6%) of the 674 tracks (with associated turbine operation data) occurred when the turbine was not operating. Fish tracks were recorded across the full range of turbine abstractions (maximum recorded was 3.96, which although below the theoretical max of 4 $m^3 s^{-1}$ was only just below the largest abstraction recorded during 2014). When the turbine was inactive no real hotspots of occupation were observed, with areas of slightly high periods of occupation occurring in line with the weir face and the fish pass outfall (Figure 37a). When the turbine was active hotspots, in terms of residence time, were observed in front of the hydropower screen near the right hand bank, although these were less apparent for tracks that occurred at the highest levels of turbine activity (abstractions >3$m^3 s^{-1}$) (Figure 37e). Hotspots in residence time were observed at most river flows, and hot spots in front of the hydropower outfall were most apparent at river flows between the long term seasonal Q_{25} and Q_{50} (≈ 2.9 - 6.28 $m^3 s^{-1}$) and were less apparent at flows less than or greater than this and were absent at flows greater than the seasonal Q_{10} (≈ 13.6 $m^3 s^{-1}$) (Figure 38a-d). When periods of turbine operation with abstractions > 2 $m^3 s^{-1}$ were considered in isolation, the hotspots in front of the turbine outfall were most apparent at river discharges <6.0 $m^3 s^{-1}$ and were not present at river discharges > 13.6 $m^3 s^{-1}$ (Figure 38 a-c).

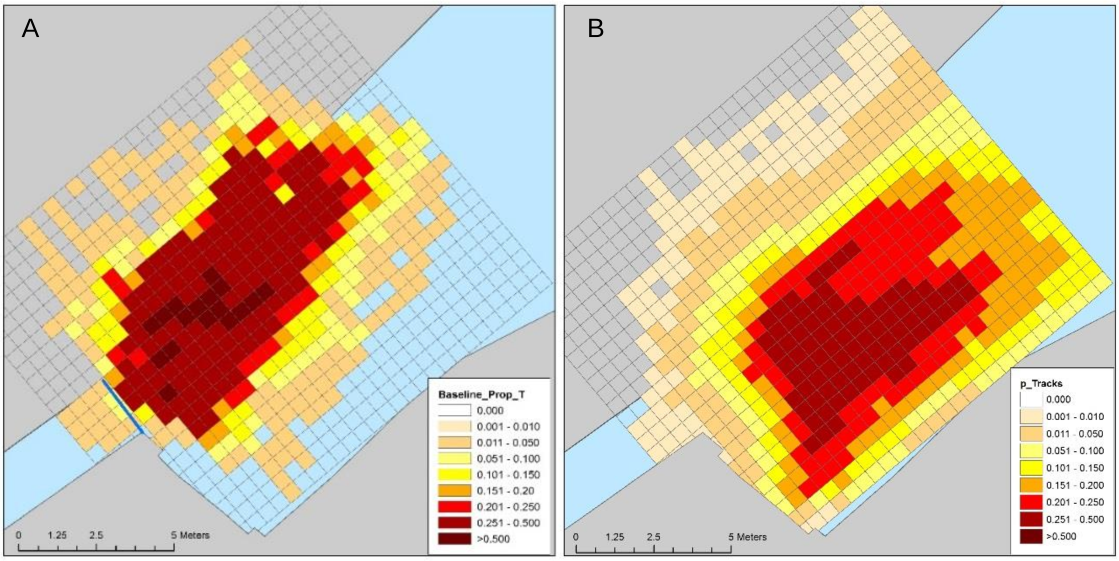

Figure 35. All sea trout tracks combined: proportion of tracks to pass through each grid cell in the baseline (A) and post-commissioning period (B). Note that there were far fewer tracks overall in the baseline.

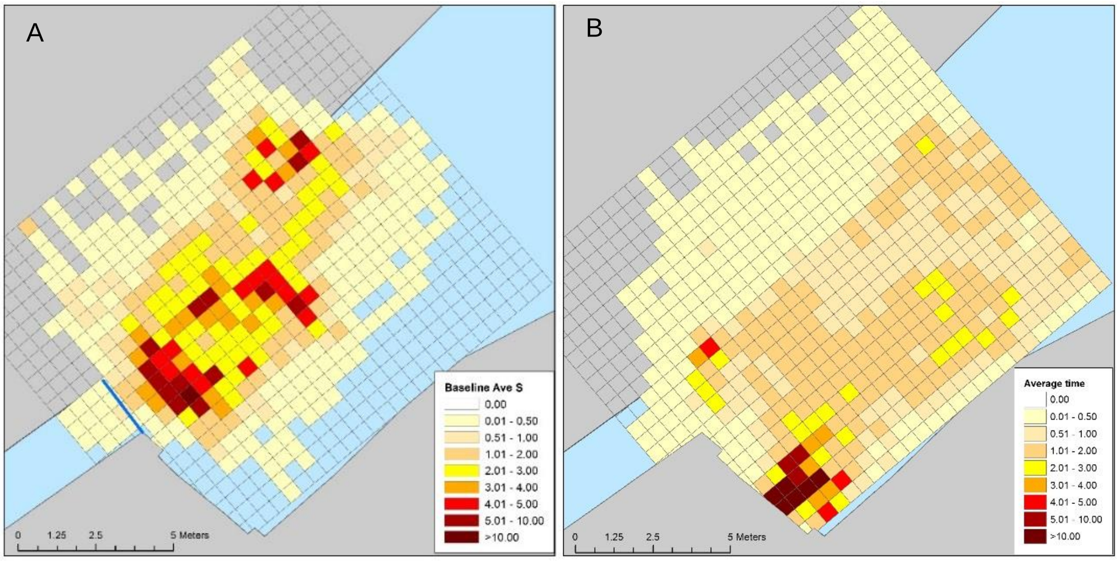

Figure 36. All sea trout tracks combined: average time (seconds) spent by sea trout in each grid cell in the baseline (A) and post commissioning period (B).

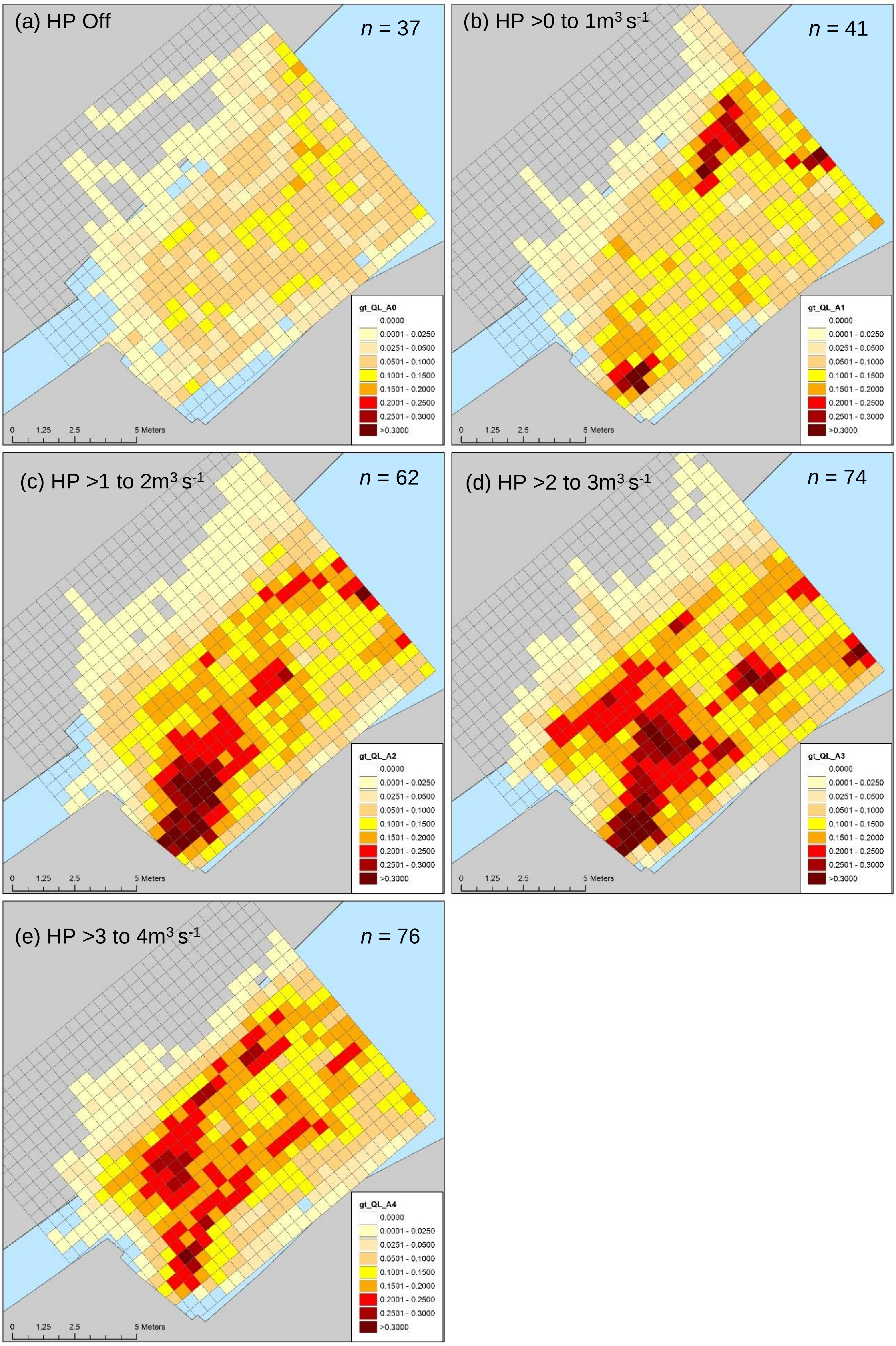

Figure 37. Spatial occupancy (average residency time (geometric mean) in seconds) of the pool downstream of the fish pass and hydropower outfalls by sea trout at five different turbine discharges (HP) when the river flow was < Q25 (6.28 $m^3 s^{-1}$), approximately equivalent to levels that do not overtop the weir when the turbine is active (n = number of individual fish tracks).

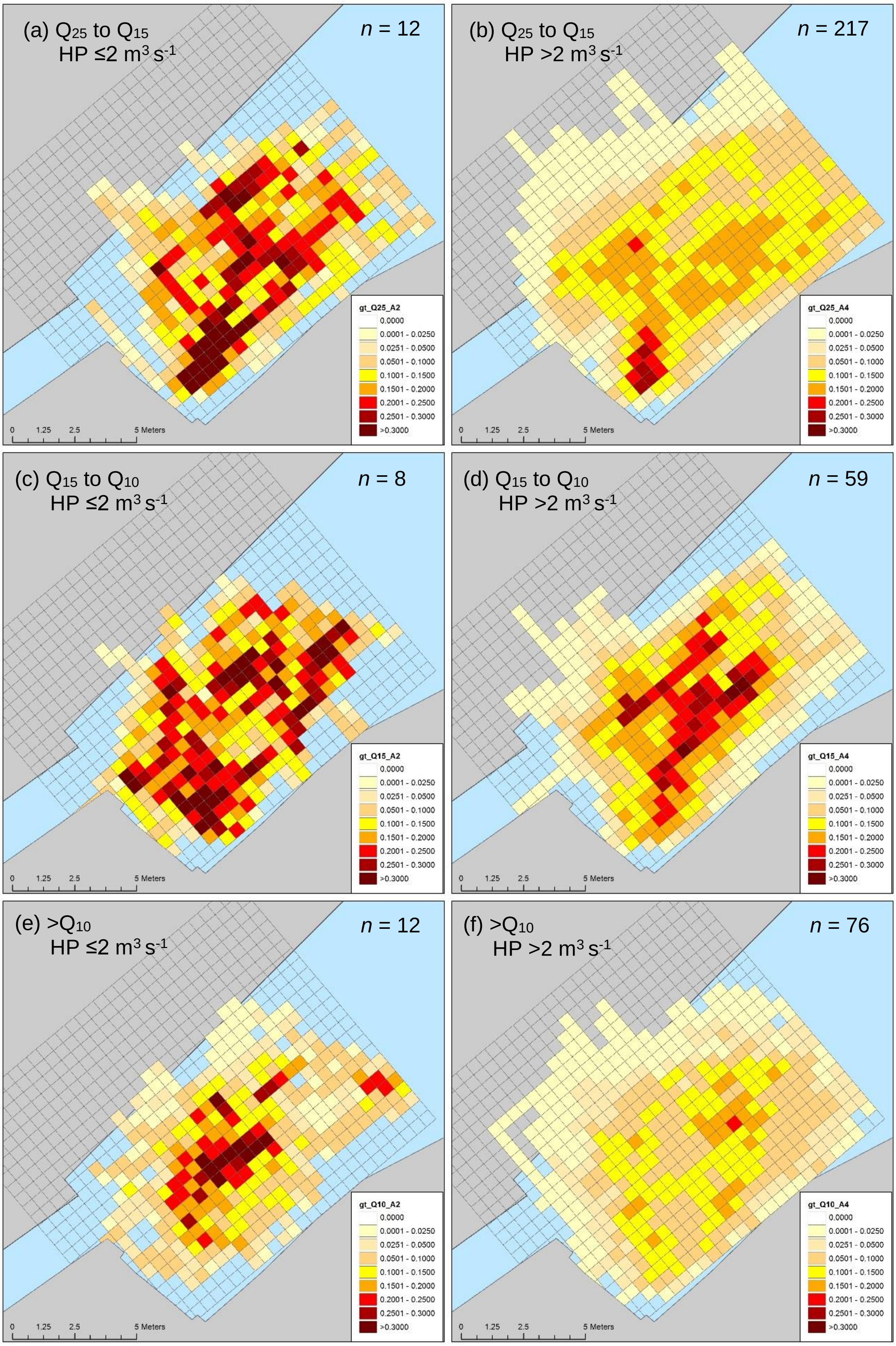

Figure 38. Spatial occupancy (average residency time (geometric mean) in seconds) of the pool downstream of the fish pass and hydropower outfalls by sea trout at three classes of river flows and two levels of turbine discharge (HP) when the river flow was > Q25 (6.28 $m^3 s^{-1}$), approximately equivalent to periods when the weir was over-topping (n = number of individual fish tracks).

4 Discussion

4.1 Potential impacts of the hydropower development on upstream fish migration

This report analyses the fish tracking data collected during post commissioning of the Ruswarp Weir low-head hydropower scheme between 2013 and 2015. These data are analysed in comparison with data from the established baseline (Noble *et al.* 2013) as a robust assessment of the behaviour of upstream migrating salmonids in the River Yorkshire Esk, including analysis of the timing of fish movements and ascents in relation to hydrodynamic and environmental cues and the operation of the hydropower scheme. The discussion here summarises the key findings for fish passage over the weir, fish passage efficiency of the new Larinier pass, the duration of migratory behaviours prior to fish passage and the micro-scale behaviours of sea trout in the hydrophone array downstream of the fish pass and hydropower scheme. These findings are reviewed in the light of existing knowledge of sea trout migration to determine whether there is any evidence of ecologically significant changes to migration behaviour and fish passage in the River Esk that can be related to the operation of the hydropower scheme.

The potential hydrological impacts of the hydropower development at Ruswarp were previously considered in Kibel & Coe (2009). Specifically, that the lowest flow of water in the fish pass (1 $m^3 s^{-1}$) would form a minimum of 25% of the maximum turbine take of 4 $m^3 s^{-1}$ (Mike Ford, pers. comm.), well above the minimum suggested value of 5% (Kibel & Coe, 2009) and the 5-10% of the maximum turbine flow required by EA guidance. Analysis of the hydrology and hydropower operation data post-commissioning indicated that this scenario occurred approximately 19.8% of the time (in this case inferred when the turbine abstraction was >3.5 $m^3 s^{-1}$ and assuming that the fish pass always operated at 1 $m^3 s^{-1}$). The hydropower turbine was not operational for 37.5% of the study period. In the other 57.3% of the time the flow down the fish pass constituted more than 25% of the hydropower discharge (inferred assuming the fish pass always had a flow ≥ 1 $m^3 s^{-1}$). The hydropower monitoring data (pool levels and hydropower flow) also indicated that the operation of the hydropower affected the flow at which the weir crest was overtopped (see Noble *et al.* 2014). When the hydropower was operating at full capacity the weir appeared to overtop at a river discharge of around 6 $m^3 s^{-1}$ (reflecting the balance of up to 4 $m^3 s^{-1}$ through the turbine, a minimum of 1$m^3 s^{-1}$ down the Larinier and around 0.5 $m^3 s^{-1}$ down the baulk pass). It is therefore inferred that previously the water flowing through the hydropower scheme (up to 4$m^3 s^{-1}$) would have been available to spill over the whole weir face and as such the weir would have spilt at some (unknown) flow lower than 6$m^3 s^{-1}$. During spring tides the hydropower was not operational (due to reduced head) and the weir over-topped at lower flows, presumably because up to 4 $m^3 s^{-1}$ passed over the weir rather than through the turbine, with a portion of this extra water going through the two fish passes. The turbine was usually not affected by neap tides, being inactive only when river flows were high enough to increase the lower river level to the point at which the turbine automatically shuts off. Typically the turbine is likely to go off if high tide is above about 5.4 m above Whitby datum but this also depends on river flow. The turbine automatically shuts off if lower river level goes above 2.796 mAOD (local). The result of this is that the weir would have been overtopped for less time than previously (before commissioning of the hydropower) which may influence the availability and attractiveness of the alternative passage routes (fish pass, side of fish pass, baulk pass and overtopping weir face at high tides). Interpreting how these multifaceted alterations to hydrological conditions local to Ruswarp Weir may affect upstream migrating adult salmonids is problematic since there are no generic models for the relationship between fish pass efficiency and fish pass hydraulics. Therefore, potential impacts of these hydraulic changes on sea trout migration behaviour cannot be inferred directly from the hydraulic changes themselves and need to be directly measured from any changes in the migration behaviour of sea trout and the efficiency of the existing fish passage facilities over Ruswarp Weir.

Walton *et al.* (2012) suggested a number of potential impacts (amended here) that the hydropower development on Ruswarp Weir, which included changing the fish pass from step-pool to a Larinier, could have on upstream migration behaviour and passage success of salmonids:

- Channel engineering downstream of the hydropower installation combined with increased discharges at the upstream end of the weir (up to approximately 5 $m^3\,s^{-1}$ discharge through the fish pass pool before the weir overtops) may improve access to the fish pass (the fish pass pool could become more attractive or accessible to fish).

- Channel engineering downstream of the hydropower installation may alter the habitat of the pool and influence the use of habitat in the pool by fish, potentially altering the attractiveness or accessibility of the fish pass entrance to migrating fish.

- Flows from the Archimedes screw (up to 4 $m^3\,s^{-1}$ volumetric flow) may distract fish from finding the fish pass entrance (rated at a minimum volumetric flow of 1 $m^3\,s^{-1}$), with fish being attracted to the turbine discharge (impacting on fish attraction to the entrance of fish pass). This could result in fewer fish finding / entering the fish pass or being delayed in their migration. However, it should be noted that volumetric flows may not be directly related to the relative water velocities from the two structures and that relative linear velocities may be the most important feature for attraction. EA guidance (Environment Agency, 2016), and the Ruswarp abstraction licence, state that the turbine linear velocity rates should be $<= 1.0\ m\,s^{-1}$ whereas the Larinier pass should be $>= 1.5\ m\,s^{-1}$ (M. Ford *pers. comm.*). As such whilst the turbine may have a larger volumetric flow at times (up to four times larger) it may not have the highest flow velocities and may not be the most attractive flow.

- The route up the side of the fish pass has changed in terms of availability and attractiveness. The operation of the hydropower affecting the conditions under which the weir overtops and the amount of water flowing through this route affecting the attractiveness of the route. In turn this affects the attractiveness of the route, the efficiency of the route and the duration for which this route was available. Furthermore, an eel pass was installed in 2012 in this side-of-fish-pass route. This was subsequently removed (later in 2012) as it altered the hydraulics and availability of this route. Later on a depression in the weir crest at the top of this route was also filled in which may have also altered the hydraulics of this route. In the baseline the tracks suggested that two of the 14 sea trout tracked in 2011 may have used the side of the fish pass route rather than the step-pool pass (Walton *et al.* 2012), whilst only one tagged fish was determined to have ascended via the side of the fish pass since 2012 (observed in 2015). Since numerous untagged fish were seen (both successfully and unsuccessfully) attempting to ascend the weir via this route in all years these data would not suggest that there has been any change in the efficacy of this route.

Changes to the hydrological conditions at Ruswarp Weir and geomorphological attributes of the pool downstream of the fish pass and hydropower development could translate into a change in the overall passability of the weir (hereafter referred to as overall passage efficiency). Specifically, the overall passage efficiency was defined as the proportion of potential migrants (all tagged fish) which successfully ascend the weir. The three components that contribute to this overall metric are; the ability of fish to find the entrance to the pass (attraction efficiency), the passability of the fish pass (fish pass efficiency) and the ability of fish to pass the weir via alternative routes. Attraction efficiency was defined as the proportion of all the tagged fish that were detected in the hydrophone array, while fish pass efficiency was defined as the proportion of tagged fish detected in the hydrophone array that ascend via the fish pass. In addition, the behaviour of the fish have been evaluated to see if there is any initial evidence of delayed passage or distraction to migration behaviour that could be attributed to the hydropower development, including the modified fish pass and downstream pool, or the operation of the hydropower scheme.

The following section reviews the results for these three metrics in the post-commissioning period and the baseline and interprets the differences in the light of the observed fish behaviours that contributed to them and evidence from other studies.

4.2 Evaluation of results

4.2.1 Overall passage efficiency

The overall passage efficiency for sea trout, i.e. the proportion of potential migrants (all tagged sea trout) which successfully ascended the weir (see Section 4.1) was 57% (26/46) in 2013, 50% (22/44) in 2014 and 32% (13/41) in 2015; an average of 47% ([38-55% CI], *n* = 61/131) for the post-commissioning dataset. This was not significantly different (P >0.05) from the 35% [23-49% CI], *n* = 17/48) observed in the baseline.

The observed annual variability in overall passage efficiency is difficult to explain given the lack of data for the behaviour and fate of fish not observed in the array during the baseline. However, analysis of the tracking data for unsuccessful migrants during the post-commissioning study, particularly those that descended to Whitby without returning to Ruswarp Weir, may be used to evaluate potential fates of those fish that did not pass the weir (Section 4.2.4). In this context it is apparent that the largest single influence on the overall passage efficiency metric in each year was the propensity of tagged fish to return to the weir after tagging rather than descending to Whitby without re-ascending to the weir.

Post-commissioning only 7 (11%) of the 61 sea trout that passed the weir used a route other than the main fish pass structure (it was assumed that these fish used the baulk pass). No sea trout were observed to use a route other than the main fish pass to ascend the weir during the baseline (2011 and 2012) and only one of the three sea trout passages recorded in 2010 was via the baulk pass (Appendix 3). This indicates that consistently the majority of fish tend to pass the weir using the main fish pass structure, although the numbers of fish using alternative routes does vary between years. It is possible that the baulk pass (or other alternative routes) may become more attractive or accessible under certain conditions, certainly all but one of the baulk passages recorded post-commissioning occurred at flows greater than 9.5 $m^3 s^{-1}$, suggesting that the baulk passage route may be utilised more effectively at higher flows.

Given the large influence that fish which did not re-ascend the river after tagging had on this metric a refined metric for overall passage efficiency, the proportion of sea trout that returned to the weir after tagging (a more refined assessment of “potential migrants”) that went on to pass the weir, was estimated as 73% during the post-commissioning period. However, this refined metric cannot be calculated for the baseline so no determination can be made whether this refined metric would have been different in the baseline.

4.2.2 Fish pass attractiveness and accessibility

Five salmon and 131 sea trout were tagged for tracking post-commissioning. Of these 81 sea trout (62%) were detected within the hydrophone array (including one known to have been subject to predation in the array), and a further 45 (34%) were only detected on one or more of the three mobile hydrophones (mostly at Whitby). The measured attraction efficiency was 73% in 2014 (32/44) which was similar to the 67% in 2013 (31/46), although this was lower in 2015 (44%, 18/41). This was a higher return rate of the tagged fish (62% in the array on average post-commissioning) in relation to the return rates observed over two years in the baseline dataset (attraction efficiencies of 35% for sea trout and 43% for salmon) and relatively higher than the detection rates reported in other studies of returning salmonids (e.g. Bendall & Moore, 2008 = 37%). This highly statistically significant (p <0.01) increase in the measured return rate of tagged fish to the array indicates that there was potentially an increase in attractiveness or accessibility of the fish pass between the baseline and the post- commissioning dataset.

It is unclear why the detection rates in the array post-commissioning were higher than those from 2011 and 2012 (twice as high in both 2013 and 2014 but only slightly higher in 2015). Of all the tagged fish detected on the mobile hydrophone (see Section 3.2.1) at Noble's Yard post-commissioning (n = 84) only three were not subsequently detected in the hydrophone array, *i.e.* nearly all the fish that reached the weir successfully found the fish pass pool. This would suggest that the main factors limiting fish finding the fish pass post-commissioning were the motivations and/or ability of fish to return to the weir after tagging, rather than factors once the weir was encountered. Certainly the data pertaining to the proportion of sea trout that descended to Whitby without subsequently returning to Ruswarp Weir would indicate that it was the variability in this behaviour between years that had most influence over the attraction efficiency and overall passage efficiency metrics in each year of the post-commissioning period.

The operation of the hydropower scheme will not have altered the conditions in the tidal reaches of river further downstream of the weir. The total discharge is not altered by the hydropower abstraction and, as such once passed the weir, flow in the river immediately downstream of the weir will be the same irrespective of the distribution of the flow between the hydropower turbine, fish passes and over the weir crest. So it is unlikely that the changes to the distribution of flows following the construction of the hydropower scheme had any influence on the propensity of fish to descend to Whitby without returning to the weir after tagging.

Flow and level data show that the operation of the hydropower scheme has altered the distribution of flows across the weir face and the area immediately downstream of the weir. When the hydropower scheme is operating and river flows are <6 $m^3 s^{-1}$ the majority of discharge will pass through the fish pass and hydropower scheme, with little or no water overtopping the weir face. Furthermore, when the weir is not over topping the majority of the discharge now flows between the island and the right-hand bank immediately downstream of the turbine. This may potentially have made the fish pass pool more attractive/approachable under a wider range of flows. Indeed, at a total river flow of 6 $m^3 s^{-1}$, approximately 4 $m^3 s^{-1}$ of the discharge would have been dispersed across the weir face and down the two fish passes prior to the hydropower development. Fundamentally, this is the concept behind the co-location of the turbine outfall with the attraction flow from the fish pass; utilising the flows from the turbine to make the fish pass more attractive and/or accessible under a wider range of flows. In the post-commissioning period 96% of tagged sea trout that reached the weir were able to find the fish pass pool successfully (an estimate of near-field attraction) suggesting that co-location of the pass with the turbine makes the pass highly attractive and easily accessible. However, given that there are no data from the baseline regarding fish that reached the weir without finding the main fish pass (the mobile hydrophones did not work during the baseline) it is not possible to state whether co-location has made the main fish pass more or less attractive/accessible than during the baseline. It is possible that prior to commissioning of the hydropower scheme the main fish pass was less attractive/accessible under certain flows. If this was the case then it could be assumed that the baulk pass may have been the most attractive flow plume under a wider range of flows during the baseline, particularly as this would be the first concentration of high velocity/turbulent flow encountered by fish approaching the weir. If this were the case then it could by proposed that in previous years fish may have spent more time exploring the baulk pass without being attracted to the main fish pass pool. However, there were no baulk passages recorded during 2011 and 2012 and it is not possible to determine whether there were any fish that reached the weir in this period but did not find the main fish pass. Therefore, it is impossible to determine whether the changes in measured attraction efficiency between 2011/2012 and post-commissioning relate to changes in the in the ability of fish finding the fish pass once the weir is reached over and above the changes in the proportion of tagged fish returning to the weir. However, the fates of unsuccessful migrants post-commissioning would suggest the latter to be a stronger influence than the former (*i.e.* nearly all fish that returned to the weir post-commissioning were shown to find the fish pass pool). It is therefore probable that it was the general conditions in the river and/or different levels of mortality, tag loss and/or tag failure, migration motivation or straying that accounts for the variability in the attraction efficiency and overall passage efficiency observed over the post-commissioning and baseline periods. Notwithstanding, the high proportion of fish that entered the array having returned to the weir in the post-commissioning period suggests that co-location of the turbine with the attraction flow from the fish pass is beneficial for the attractiveness and accessibility of the fish pass.

4.2.3 Fish pass efficiency

Eighty-one of the 131 tagged sea trout and three of the five tagged salmon post-commissioning were detected in the hydrophone array downstream of the fish pass and 54 of these sea trout ascended via the fish pass; giving sea trout fish pass efficiency of 67% in this period which was significantly lower ($p < 0.05$) than the 100% observed in the baseline. Additionally, six of the sea trout detected in the array ascended via another route (assumed to be the baulk pass) (see Section 4.2.1). This suggests that whilst a larger proportion of tagged fish found the fish pass in 2013 to 2015 (see Section 4.2.2), a significant proportion of these migrating fish were unsuccessful in using the main fish pass; a feature not previously observed in the baseline (except for one salmon in 2012). Fish pass efficiency varied between years in post-commissioning period. Whilst most batches of sea trout exhibited pass efficiencies of 67 to 83% three batches had efficiencies of ≤50%. Two of these batches were the final batches of fish released in 2014 and 2015, where only 2/10 and 0/3, respectively, of the sea trout that reached the array subsequently ascended via the Larinier pass. It is not clear why these batches had an unusually low passage efficiency (22% and 0%). The fates of the unsuccessful fish in these last batches would suggest that they were subject to higher rates of mortality/predation within the vicinity of the weir and the tideway (see section 4.2.4). It is not clear why this might be the case, however, 8 of the 26 sea trout that failed to ascend via the Larinier pass (including fish that then used the baulk pass) spent over 72 hours each within the vicinity of the weir which may have exposed them to a higher risk of predation. It does not explain why they were unable or unwilling to ascend via the Larinier despite spending around 100 minutes each on average in the array.

There is a dearth of evidence for the efficiency of Larinier passes for salmonids in the published literature (e.g. there were no data for Larinier passes and salmonids in the recent meta-analysis by Bunt *et al*. 2012), and the 67% average fish pass efficiency for sea trout post-commissioning is at the lower end of the range of observations in other studies of other types of fish passes (Table 5). In the example from the UK Gowans *et al.* (2003) recorded passage efficiencies in the range of 63.2 to 91.7% for salmon at a series of barriers on the River Connon in Scotland. In that study three of the six barriers studied had passage efficiencies of around 60-68%. Although the efficiency observed at Ruswarp is similar to this it could be considered suboptimal given the location of Ruswarp Weir at the head of the tide.

Table 5. Examples of fish pass efficiencies for salmonids in different types of fish passes reported in grey and published literature.

Source	Species	Type of Fish pass	Attraction efficiency	Passage efficiency
Aarestrup *et al*, 2003	Sea trout	Nature-like bypass	60%	91%
Lundqvist *et al,* 2008*	Atlantic salmon	Bypass channel and fish ladder	-	0-47 %
Calles & Greenberg, 2009**	Sea trout	Nature-like bypass	81 – 89 %	95 – 97 %
Karlsson 2013	Atlantic salmon	Fish ladder	-	78%
Gowans *et al.* 2003#	Atlantic salmon	Fish ladder and Borland fish lift	-	63 – 92%
Clifton-Dey (in Armstrong *et al.* 2010)	Atlantic salmon	Various (21 sites River Thames)	-	65-100%
Chanseau *et al.* (1999)	Atlantic salmon	Various (31 sites Pau River, France)	-	35-100%
P Gough (in Armstrong *et al.* 2010)	Atlantic salmon	Denil	-	25-39%
Pon *et al.* 2006	Sockeye salmon	Vertical slot	76%	100%
	Pink salmon	Vertical slot	22%	100%
	Sockeye salmon	Vertical slot	-	60%

* multiple year study of one pass
** different passes over a two year study
# different passes

There were considerable differences between the conditions observed between years in the baseline and the post-commissioning dataset. In particular, the design of the pass was changed in 2012 and the prevailing river levels were different between each study year. Insufficient sea trout were tracked in 2012 to make a judgement about fish pass efficiency of the Larinier for sea trout in the year after construction, but before operation of the hydropower scheme (a strategic decision was made by the project board at the request of the stakeholder group to invest the effort and tags in 2012 in attempting to strengthen the baseline for salmon). However, if the data for both sea trout and salmon tracked in 2012 are combined the fish pass efficiency of the Larinier in 2012 was estimated to be 88% (7/8 salmonids successfully ascended). Therefore, it is possible that the change in the fish pass design itself may have influenced the pass efficiency. However, it cannot be conclusively determined if the reduction in fish pass efficiency post-commissioning was a feature of the different fish pass design, a result of the activity of the hydropower scheme, unknown temporary blockages to the fish pass at specific times, an increase in levels of predation of fish below the weir or the prevailing hydrological conditions in each period. Notwithstanding, the observed reduction in fish pass efficiency is of concern, especially considering that it has been suggested that a successful upstream passage facility for salmonids should pass more than 95% of the migrating adult fish (Ferguson *et al.* 2002). The average 67% fish pass efficiency observed at Ruswarp is certainly appreciably below this aspirational 95% level. There was also considerable temporal variation between years in the Ruswarp study and it should be noted that the fish pass efficiency measured in 2014 (56%) is below many of the reported values for other passes (Table 5). This is also of concern given that the Larinier pass is the main fish pass on the first upstream barrier on the Esk and is also located at the head of tide.

Whilst the EA fish pass manual (Armstrong *et al*. 2010 – now updated and hosted by the Institute of Fisheries Management) identifies that "there is a legal duty under Section 9(1) of SAFFA, 1975, for fish passes for migratory salmonids to be maintained in an efficient state" it does not state a target for a minimum fish pass efficiency that would be considered efficient. All fish pass approvals under the legislation require that a pass is "efficient in all respects and for all purposes…. to the Agency's satisfaction". Whilst the manual does not identify a specific satisfactory efficiency for salmonids, it does identify that any fish pass should generally aim to achieve at least 90% *availability* during the required period of operation. Passage data from Ruswarp indicate that this target for pass availability was met during the tracking period studied, with fish able to use the pass under the majority of flows encountered.

4.2.4 Fate of tagged fish that did not pass the weir

Tagged fish not detected in the array may have had a number of fates including:

- death as a result of predation (e.g. seals and cormorants), post-tagging mortality or exploitation (both legal and illegal);
- ascending other local rivers (straying);
- return to sea for the study period;
- tag loss or tag failure[1].

Whilst no data were available to evaluate these potential fates in the baseline dataset, mobile hydrophones at Whitby (detecting downstream movement after release) and Noble's Yard (confirming arrival at the weir) enabled the movements of fish through the estuary to be studied post-commissioning and the potential fate of tagged fish to be elucidated.

Firstly, the data from the mobile hydrophones can be used to evaluate potential levels of predation/tag loss/failure/exploitation. Of the 50 tagged sea trout not detected in the array post-commissioning, 13 were not detected at all after release and 37 were only detected on the mobile hydrophones (i.e. not in the hydrophone array). Four tags (two in 2013 and two in 2014) were also concluded to have been consumed by a predator, potentially before being subsequently detected on the mobile hydrophones and the array. One of these tags in 2014 was identified to have reached the array but soon after its records became concomitant with those of another tag and were both subsequently detected on the hydrophone at Noble's Yard, Whitby and the array at exactly the same times around high and low tides. It was assumed that both of these tagged fish had been consumed, probably by a seal, the first at some unknown time after release and the other at a known time within the vicinity of the array. Two of the three tags that were never detected in 2013 were from batch three (released 01/11/13) when seals were spotted feeding at the release site (S. McGinty EA *pers. comm.*). Furthermore, of the 81 tagged sea trout detected in the array, 21 were not detected to ascend the weir; six of which returned to Whitby, nine were last located at Noble's Yard and five last recorded in the array.

The inference here is that a proportion (unknown but potentially large) of these tag disappearances (both those never detected again after release and tag disappearances after detection within the tideway) may be attributable to predation or exploitation of tagged fish after release (See Figure 13 in Section 3.2.1). Therefore, mortality/tag failure prior to reaching the weir could be estimated as the proportion of tagged fish that were not detected again after release (or assumed to have been eaten) (17 of 131, 13% [8-19% CI]) or a combination of those plus fish that were detected but did not ascend the weir and were not detected to return to Whitby (total of 33 of 131, 25% [18-33% CI]) (See Figure 13 in Section 3.2.1).

[1] A potential failure rate of 5% has been suggested by Dr Jon Hateley (EA) based on previous experience and this was not challenged by HTi. This estimate also includes all failures prior to tagging which would have been screened out in the course of this study. Hence, the likely failure rate during this study would been appreciably <5% of tags.

These potential levels of predation/mortality indicate that loss of fish in the tideway may be a significant factor in the success of fish passage. Sources of mortality may include predation, legal exploitation in the coastal fishery and potentially unpermitted/illegal exploitation in the tideway.

The seals observed in the lower River Esk are probably a low number of “rogue” seals that have specialised in feeding in tidal waters rather than on the main coast. Graham *et al.* (2011) identified that “rogue” seal in rivers fed more often on adult salmonids than similar seals in coastal areas, with harbour seals being present throughout the year and grey seals often entering rivers of the Moray Firth more frequently during winter months (November to February); although it was often only a very small number of seals present. Observations by Carter *et al.* (2001) and Butler *et al.* (2006) have shown that predation on salmonids by seals in rivers is variable seasonally and between rivers, with Carter *et al.* (2001) providing minimum estimates in the region of couple of hundred fish per year on the River Don and 500-1000 fish per year in the River Dee (sampled in the mid 1990s). The impact of seal predation is difficult to determine but bioenergetics modelling by Butler *et al.* (2006) suggested that seal predation may have less than 1% impact on the overall run (measured by changes to modelled rod catches) but that may increase in small rivers (17% increase in modelled rod catches) where a low number of rogue seal may have a greater impact on a smaller population. However, in telemetry studies on the River Tees Bendall & Moore (2008) showed that predation by seals on tagged sea trout may have been in the region of 47% of tagged fish within the first 2.5 days after release. In relation to this, Stansbury *et al.* (2015) have recently shown that Vemco acoustic tags operating at 69 kHz may act as an attractant for foraging seals indicating that predation rates of tagged fish in some trials may be higher than that for untagged fish. However, the HTi tag used for this study operated at 307 kHz which is not audible by seals so the predation rates inferred in this study will not be affected by this reported “dinner bell” effect.

Secondly, of the 115 sea trout detected on any hydrophones, 73 were first detected at Noble’s Yard or the array whilst 43 (33% of sea trout) moved downstream to Whitby after release. Of the 43 sea trout first detected in Whitby only 12 were subsequently detected at Ruswarp Weir (11 in the array and one at Noble’s Yard only). The mobile hydrophones also gave increased resolution concerning the last known locations of fish. Of the fish which were detected near, but did not ascend, the weir, 11 were last observed at Noble’s Yard and six were last observed at Whitby. A further 5 fish that failed to ascend the weir were last recorded in the array (including the fish known to have been eaten). Given these figures it is possible to estimate a minimum level of potential straying behaviour (fish that chose not to ascend). Straying could be estimated as the proportion of tagged fish that returned to Whitby after tagging without first ascending the weir; 37 of 131, 28% (21-36% CI) (See Figure 13 in Section 3.2.1). Stewart *et al.* (2009) recorded 50% of tagged salmon dropping out of a river and ascending other adjacent rivers whilst King (2016) reported >10% of sea trout caught entering the River Tamar were strays from other adjacent rivers). These data also suggest that an appreciable proportion of sea trout observed in the estuary (even right up to the tidal limit) may not have the same motivation to migrate as others, and thus may exhibit different behaviours. However, these figures could also be influenced by mortality/exploitation (both legal and illegal) off the coast or in the tideway.

Although these figures give an indication of the fates of tagged fish between 2013 and 2015 and perhaps give an indication of the potential relative influences of mortality (natural and fishery)/tag failure and motivation/straying on the data in that period, it is difficult to explain the variability in attraction efficiency and overall passage efficiency between the years of the baseline and the post- commissioning dataset (which were fairly similar in 2013 and 2014 but lower in 2015). It is possible that levels of predation and migration motivation may be linked to the different hydrological conditions in each year and these translated to the stimuli to migrate, the ability to access the weir and the levels of mortality of fish holding in the estuary under low flows. For example, the low flows in 2011 may have resulted in reduced stimuli to migrate and increased risks of migration if fish were being held up in the lower estuary due to low flows. However, conditions in 2015, a period of relatively high flows, when these metrics were similar to those observed in the second year of the baseline (2012), indicate that there may be other unknown factors at play other than river flows influencing the upstream movement of tagged sea trout in each year. Furthermore, during periods of high flow the proportional contribution of discharge from the turbine and the Larinier pass to the overall flow over the weir will be reduced and as such attraction flows to the fish pass would be less focussed during these periods.

4.2.5 Duration and timing of fish passages

Although no significant difference was observed in the time from release to passage between the sea trout tracked post-commissioning and the baseline there were differences observed in the number of tracks in the pool, the duration of tracks in the pool and the delay from first arrival in the pool to final passage. In both the baseline and the data from 2013 to 2015 four main types of migration behaviour were observed:

1. Fish that migrated upstream quickly, and ascended the weir with a short delay, within 24-48 hrs of release.
2. Fish that approached the weir quickly (<48 hrs) but were then delayed below the weir, often for over 24 hours, making multiple visits to the array before either passing the weir or dropping back downstream/going missing (only observed post-commissioning).
3. Fish that dropped back downstream for an appreciable amount of time before re-ascending the river under spate conditions and passing the weir with only a short delay.
4. Fish that went back to the coast and were not detected again (only possible to detect from 2013 onwards).

In addition to this the post-commissioning period also saw a greater number of fish that went missing after being detected in the array but then subsequently failed to ascend the weir (mostly 2014), potentially suggesting an increase in predation/mortality within the vicinity of the weir in this period.

Such variability in the motivation to migrate, and success of ascent of individual fish has been noted in other studies. It can be related to the motivation of individuals and the conditions under which the movements are taken (particularly the discharge acting as a stimulus). Gowans *et al.* (1999) identified similar classes of behaviour in successfully migrating salmon at Pitlochry fish ladder (single visit and successful ascent; two or more visits to Pitlochry dam separated by <24 hrs; multiple visits separated by >24 hrs) although they did not find any relationship between behaviour class and fish size and date of release to suggest that it might be related to swimming ability or motivation to migrate. Lundqvist *et al.* (2008) related similar classes of observed behaviour in migrating salmon around a large scale hydropower turbine outfall and bypass channel (enter and ascend bypass channel quickly; enter bypass and hold position for relatively long periods; attracted to turbine outfall and move up/downstream depending on turbine flows) to the relative flows between the turbine and bypass channel. This indicates that migratory behaviour is probably primarily related to river discharge as a stimulus to migrate. Four of the 17 baseline sea trout (24%) that entered the array arrived after waiting more than 14 days after release to migrate whereas this figure was only 2 out of 81 (2.5%) in the post-commissioning period (both of these fish were from a single batch, caught and released under low flows in September 2013) and the longest delay from release to first detection in the array post-commissioning was 26 days. The flows in 2011 (the majority of the baseline) were far lower than in all other study years indicating that this class of migration behaviour is positively associated with low flow conditions reducing the stimuli for, or ability of, fish to ascend the river.

Post-commissioning the average cumulative time spent in the array by sea trout prior to passage (combined duration of all tracks) was significantly longer than in the baseline dataset. However, the duration of individual non-passage tracks post-commissioning was significantly shorter than tracks in the baseline dataset. There was no significant difference in the average duration of passage tracks in the baseline dataset and in the post-commissioning dataset. In the baseline 65% of sea trout spent less than ten minutes in the array prior to passage with only 24% spending longer than 30 minutes. Post-commissioning fewer fish (15/54 = 28%) spent less than ten minutes in total within the array prior to passage via the Larinier pass and a higher proportion of tagged sea trout spent longer than 30 minutes in the array before either ascending or dropping back downstream (44/81 = 54%). In the baseline 71% of sea trout passed the weir within one hour of their first detection in the array whilst post-commissioning only 28% of sea trout passed within one hour of first detection and 30% of sea trout took longer than 12 hours to ascend. The total time between first detection and passage was significantly longer post-commissioning than in the baseline. During this time prior to passage post-commissioning sea trout spent a lower proportion of the time in the array compared to the baseline. This indicates that post-commissioning, although sea trout generally took longer to pass the weir via the Larinier pass and spent longer in the pool, they spent proportionately less time in the pool than fish observed in the baseline. Analysis of the data from mobile hydrophones indicated that the behaviour of fish that exhibited prolonged behaviours after being detected in the array included both movements to/from the pool to the area around the downstream end of the weir (Noble's Yard) and occasionally movements to/from Whitby harbour associated with the tidal cycle.

Whilst the average time taken to pass the weir was significantly longer post-commissioning than in the baseline, this was only by a matter of hours. Previous studies in other rivers have detected periods of delay of many days before entry into fish passes (0.6 to 43 days, Webb 1990; up to 14 days, Laine 1995; 1 to 40 days Gowans *et al.* 2003; median passage times 0.2 to 2.7 days Caudill *et al.* 2007) although none of these structures were at the head of the tide. Caudill *et al.* (2007) identified that successfully migrating salmonids (those detected to reach spawning grounds) had consistently shorter passage times at individual dams and through a multi-dam reach of the lower Columbia River. Furthermore, using the study on the River Pau (Chanseau, Croze & Larinier, 1999) the EA Fish Pass Manual identified that:

"the fish passes that were determined to be 100% efficient were characteristically those that caused delays to passage of no more than two weeks, while those with efficiencies less than 100% were characterised by significant numbers of fish being delayed for periods longer than this. Those fishways that were efficient were also those that cause the least delay, and there was an inverse relationship between the two factors" (Armstrong *et al.* 2010).

Therefore, delays in fish passage and pass efficiency are inextricably linked with long delays associated with low efficiency passes. Therefore, increased delay below the weir may have consequences for the passage success of fish approaching the weir. It is difficult to determine whether the delays observed in 2013 (median delay of 2.36 hours [0.77 – 15.59] from first arrival in the array), 2014 (median delay of 3.34 hours [0.40 – 18.11]) and 2015 (median delay of 2.63 hours [1.18 – 49.88]) (up from 0.28 hours [0.09 – 1.41] in the baseline) would significantly affect the success of the overall migration to spawning grounds. The impact of delay on the success of migration can be considered as both (1) an increased energetic cost of delay and energy expenditure during ascent against a finite energy resource (as adult salmonids do not feed in freshwater) and (2) an increase in predation risk whilst holding below structures. The length of delays observed post-commissioning (a matter of hours for successful migrants) are relatively small with few fish taking more than a day to pass after first arrival and hence is unlikely to be detrimental to the overall timing of migration of fish up the Esk (The EA fish pass manual highlights that in France fish passes with delays of up to 2 weeks are considered acceptable provided the pass is 80% efficient (Armstrong et al. 2010)). The delays observed at Ruswarp are not of energetic significance given the duration of the overall migration to the spawning grounds of the River Esk; a journey potentially taking weeks or months without feeding. However, the potential impact of such delays on subsequent successful passage or the risk of predation below the weir is less easy to evaluate. The majority of possible predation identified in the post-commissioning data could be attributable to the seals that are known to occupy the tidal River Esk, and which do approach Ruswarp Weir at high tide and have been shown to enter the fish pass pool. Most of the possible cases of predation (3 of the 4 fish inferred to be predated post-commissioning) occurred in the tidal river prior to the fish reaching the weir. However, in this period 17 tagged fish reached the weir (15 got into the array) but went missing without ascending or being detected back in Whitby. So whilst the majority of predation may occur in the lower river, some level of predation is now known to occur around the weir and in the fish pass pool. As such it would appear that increased delays at the weir may increase the risk of predation, although further study would be required to determine this quantitatively.

It is difficult to determine whether the longer ascent time has any relation to the activity of the hydropower potentially distracting fish from finding or accessing the fish pass (Section 4.2.5). The overall variation in discharge conditions between the different years of the study will probably have contributed to the difference in migration times since it has been observed in other studies that ascents can be delayed under higher flows. Caudill *et al.* (2007) suggested that slower passage at higher flows probably reflected decreased ground speed of swimming fish through higher velocity water and an increase in the searching time required to find fish way entrances in a more turbulent environment. As such it is possible that the delays observed in each period were just a function of the prevailing river flows and associated hydraulic conditions experienced in each year.

4.2.6 Micro-scale behaviour of migrating sea trout

Spatial data of fish behaviour within the pool exhibited similarities between post-commissioning and the baseline (see Noble *et al.* 2013), in that tracks were spread throughout the array. However, there were also some notable differences between periods. Post-commissioning the data indicate a potential bias towards the right-hand bank in front of the hydropower outfall and away from the fish pass entrance and weir face. Analysis of the average duration of time spent within each cell indicated hotspots in use of the pool immediately in front of the hydropower outfall screen in the vicinity of the right-hand bank. Although changes in the bathymetry (depth) of the pool mean that this location was the deepest part of the pool from 2012 onwards (whereas it was shallow margins in 2011) the hotspot of attraction to this area in front of the hydropower screens was most prevalent when the hydropower was active and the discharge in the river was <6.28 $m^3 s^{-1}$, *i.e.* when the weir was not over-topping and the discharge from the hydropower scheme (0.1 to 3 $m^3 s^{-1}$) was up to 3 times the discharge from the fish pass (~1 $m^3 s^{-1}$). This propensity to occupy the area downstream of the hydropower turbine was less apparent when the turbine was off, the weir was overtopping and particularly at the highest flows. This could suggest that the discharge from the turbine may be attracting fish (either by distracting them from the fish pass plume whilst seeking a passage route, as a preference of attractive flows suitable for refuge or as part of their approach to the Larinier pass) where the discharge is similar or exceeds the rating of the fish pass (in that the fish pass is designed to operate with a protected minimum flow of 1 $m^3 s^{-1}$). Once the weir overtops and water is flowing down the side of the fish pass the relative influence of the two flows changed.

Distraction caused by turbine outfalls has been observed elsewhere, albeit for very large scale hydro schemes with potentially large distances between the turbine outfall and the attraction flows from fish passes. For example, Lundqvist *et al.* (2008) identified that during periods of high turbine discharge and low bypass flow, fish were attracted from a bypass channel (towards the turbine outfall), delaying the upstream migration of salmon on the River Umealven in Sweden, where in this case the turbine and fish pass are many kilometres apart. Whilst this is an example of a much larger system with a distinct turbine outlet versus bypass channel entrance it has also been shown that even in small scale systems competing flows and turbulence may affect route choice, even within a fish-way with alternative routes (Lindberg *et al.* 2016). It appears that, despite their immediate proximity and high ratio (worst case scenario of 1:4), turbulence from the turbine at Ruswarp may be distracting sea trout from the Larinier plume and delaying their ascent. Whilst it is generally accepted that migrating salmonids are attracted to high velocity plumes or follow the main current when migrating (Stuart 1962) it has also been seen that migratory fish may also follow routes of low velocity or low resistance to reduce resistance and swimming effort (McElroy *et al.* 2012; Lindberg *et al.* 2016). If the right-hand side of the screen (facing downstream) has the lowest velocities and the turbulence represents an upstream backwash then, if sea trout do attempt to find paths of low velocities to conserve energy, this may draw them away from the Larinier plume. However, if the majority of the discharge of the hydropower turbine is assumed to be on the left-hand side of the screen (facing downstream) the area of the hotspot is actually in one of the deeper and potentially less turbulent parts of the pool (visually appears to be less turbulent with assumed lower flow velocities, although this would need to be confirmed with 3D assessment of flows using an ADCP), the hotspot may alternatively represent a location of refuge and resting rather than attraction to a low velocity route.

This study has also shown (as indeed have previous studies) that salmonid migrations are not purely linear from sea to spawning grounds and some level of resting and yo-yo migration (dropping back down stream before re-ascending – one fish appeared to do this three times in 2014) are apparent. Given this it may be that the pool downstream of the fish pass provides a habitat that is suitable for resting and maintaining energy reserves before further ascent of the river. It may be particularly important given that Ruswarp represents the transition from brackish to freshwater conditions.

4.3 Conclusions

The analysis of the tracking data post-commissioning and the comparison with the baseline identified five key results:

(1) The proportion of tagged fish that successfully passed the weir (overall passage efficiency) varied markedly between years in the post-commissioning period and the average overall passage efficiency across this period was not significantly different from the baseline (Section 3.2.3). Evidence from the mobile hydrophones suggested that the single largest influence on this metric each year was the proportion of tagged fish that did not re-ascend the river after tagging. One of the major factors that may influence the passage efficiency in any year may be the motivation to migrate (related to time of year and river flows), the condition of the fish and the mortality rates linked to delayed migration in the estuary. The batch-by-batch analysis during the post-commissioning study indicates that the final batches in both 2014 and 2015 exhibited an unusually low overall passage rate. It is possible that these later batches may have had a reduced propensity or ability to migrate and were possibly subject to higher rates of predation or other causes of mortality. The post-commissioning study identified that 73% of the sea trout that returned to the weir after tagging successfully ascended via any route.

(2) The proportion of tagged sea trout entering the array (attraction efficiency) was significantly higher post-commissioning although this too varied markedly between years post-commissioning (Section 3.2.1). In all years of the post-commissioning dataset the vast majority of sea trout that approached the weir were attracted to the fish pass (96%). Hence, the major influence over the attraction efficiency as described here was the propensity of sea trout to successfully re-ascend the tideway after tagging (in particular the proportion of those that initially dropped back downstream to Whitby Harbour that subsequently returned to the weir).

(3) The fish pass efficiency of sea trout detected in the array using the main fish pass structure reduced significantly from 100% in the baseline to 67% post-commissioning (although this varied from 56% in 2014 to 81% in 2013) (Section 3.2.3). The main fish pass changed from the step-pool pass in 2011 to the Larinier pass in 2012 adding a confounding factor to the baseline. The evidence for the efficiency of the Larinier pass before the hydropower turbine was commissioned is limited by the small sample size of sea trout in 2012; although 100% of the tagged sea trout (3/3) observed in the array passed successfully. In 2012 one of the 5 tagged salmon observed in the array was the first fish that failed to use the main fish pass structure having reached entered the pool.

(4) The delay between arrival in the fish pass pool and eventual passage was, whilst statistically significantly greater post-commissioning than during the baseline, is not of energetic consequence given the overall scale and duration of the sea trout migration (Section 3.2.7 & 4.2.5). It is possible that this delay may have unknown consequences for successful passage in relation reducing the motivation to pass or to potential increased risk of predation before passage, particularly as predation (presumably by seals) has been demonstrated to occur within, or in close proximity to, the pool. However, there is no evidence with which to quantify any change in the risk.

(5) There is some evidence of attraction of fish to the area in front of the hydropower outfall screen, which was most apparent when the turbine was active at river flows <6.28 $m^3 s^{-1}$, when the weir was not overtopping and the turbine abstraction was >0 and <3 $m^3 s^{-1}$. However, this area is also the deepest part of the pool so it is difficult to determine if the sea trout were seeking refuge in deep water, being distracted from finding the fish pass plume by the outfall from the hydropower screw or utilising this area of the pool during their approach to the fish pass entrance (Section 3.5.2 & 4.2.6).

Given the variation in the coarse scale behaviour data and passage metrics between the years post-commissioning and in the baseline (although passage metrics in 2011 and 2012 were very similar to each other) it is difficult to determine whether the significant changes observed during the study (listed above) can be attributed to the activity of the hydropower scheme. The changes in behaviour observed between the baseline and the post-commissioning data are also confounded by the change in the design in the fish pass in 2012, the changed bathymetry of the pool, the different hydrological conditions in each year and the inability to determine in the baseline whether any tagged fish returned to the weir without finding the main fish pass. The main aim of this study was to identify whether the installation and operation of the new hydropower scheme at Ruswarp (including the change in fish pass design) had any impact on fish passage over Ruswarp Weir. The EA Guidance for hydropower development (Environment Agency, 2016) states that:

"Where there is existing provision for fish passage, approved or otherwise, any hydropower development must maintain the effectiveness and efficiency of the pass or passage through the site. When existing fish passes are to be used, but are known to be inefficient, we shall expect developers to address the opportunities for improving fish passes".

Notwithstanding the history of the development at Ruswarp and the complexity of ownership and responsibility for the main fish pass and weir, to address whether the development as a whole has failed to maintain passage through the site a number of questions need to be answered.

(1) *Has overall passage efficiency been maintained?* Tracking data show that overall passage rates varied greatly between years and there was no significant difference between before and after commissioning of the turbine. The major factor influencing the proportion of tagged fish passing the weir post-commissioning was the propensity of fish to return to the weir in each year. In the post-commissioning period 73% of tagged sea trout that returned to the weir succeeded ascending the weir; although it is not possible to determine if this was better or worse than during the baseline. Therefore, there is no evidence to suggest that the hydropower development has resulted in a reduction in the effectiveness or efficiency of passage through the site.

(2) *Has the effectiveness and efficiency of the main fish pass reduced or been improved following the installation of the Larinier and the commissioning of the turbine?* The decision to replace the step-pool pass with the Larinier pass was taken following best practice guidance and following expert judgement that the old pass was inefficient and over-energised. The measured efficiency of the Larinier pass post-commissioning was significantly lower than the measured efficiency of the step-pool pass prior to construction of the hydropower scheme. However, there is very little evidence to confirm the efficiency of the new Larinier pass in 2012 prior to commissioning of the hydropower turbine. The limited evidence from 2012 would suggest that the Larinier pass was not 100% efficient at this stage. Therefore, although the fish pass efficiency was significantly lower and the delay to passage was significantly longer post-commissioning there is no evidence that this is directly attributable to the activity of the hydropower scheme rather than the change in the design of the pass.

(3) *Has co-location of the pass with the turbine improved passage over the weir?* Tracking evidence showed that 96% of tagged sea trout that returned to the weir in the post-commissioning period entered the fish pass pool indicating that this area is highly attractive to migrating salmonids. However, although the proportion of tagged fish that approached the fish pass was larger post-commissioning than in the baseline, it was highly variable between years and was highly influenced by the propensity of tagged fish to return to the weir post tagging. Since it was not possible to identify in the baseline fish which returned to the weir without finding the pool below the main fish pass it is not possible to determine whether this area is now more or less attractive/accessible than it was before. However, there is no evidence to suggest that this area has become unattractive or inaccessible under any conditions.

(4) *Can any of the changes in passage behaviour be attributed to the activity of the turbine?* There is no evidence to suggest that any of the changes and variability in the passage metrics and the delay in passage through the main fish pass can be solely attributed to the activity of the hydropower turbine. Whilst the spatial behaviour of sea trout in the pool downstream of the turbine/fish pass exhibited some propensity to occupy an area in front of the turbine outfall when the turbine was active the cause of this behaviour cannot be isolated from other changes to the habitat of the pool and the change in the type of fish pass that would have altered how the fish used the pool and how they approach the fish pass.

Finally, the comparable overall passage efficiencies pre- and post-commissioning indicate that overall passage through the site has been maintained since the observed reduction in the efficiency of the main fish pass was offset by the statistically significant improvement in the attraction efficiency to the fish pass. There is no evidence that the variability and changes in these passage metrics are related to the activity of the hydropower scheme.

4.4 Recommendations

Although there is no evidence that shows that the hydropower scheme at Ruswarp has reduced overall passage at the site, the relatively low efficiency of the Larinier pass may still be of concern and measures could be identified to attempt to improve this in the future.

Firstly, it would be sensible to ensure that the hydropower scheme and fish pass in their current state are operating within their design criteria, in particular that the velocity of the outfalls are meeting the guidance set down by the EA in the abstraction licence. Therefore, it is recommended that the EA repeats and documents the permitting audits for the turbine and fish pass outfalls using ADCP to ensure the hydraulics of the pool and exit velocities are compliant with the design and permitted operating regime. This auditing of flow velocities in the pool, and the hydraulic data collected, might also enable further analyses of the fine-scale fish tracking data in relation to their behaviours and occupancy of the pool that were outside the scope of the original project.

Secondly, it is recommended that specialists review the design and characteristics of the Larinier pass to both ensure it is operating as originally designed and also that its design still matches the best practice design for Larinier passes, which may have evolved and improved with new experience gained since the installation of the pass. It is also recommended that fish pass design specialists are also consulted as to whether there are any improvements that could be made to improve the performance of the pass. However, it is recognised that the fish pass at Ruswarp does not fall within the responsibility of the hydro operator. Responsibility for the pass technically lies with the weir owner. As the weir owner is now a 'shell company' and thus has no liabilities that can be enforced, the EA have made an exception and agreed to maintain the fish pass but with no legal responsibility for it. As such any future improvements would need to be developed by the local stakeholders.

Data collected by the study and the experience gained during the project have highlighted the important influence of fish migration behaviour in the tideway on the metrics of passage and the proportion of tagged fish passing the weir. Fundamentally, the lack of data for the behaviour of tagged fish outside the array in the baseline was one of the major limits in interpreting the differences observed between the baseline and post-commissioning period. It was also the main reason that no conclusion could be drawn as to whether co-location of the turbine outfall with the fish pass had actually improved accessibility/attractiveness to the pass. Therefore, it is recommended that in any future research addressing fish passage and fish pass performance that the studies ensure that both the study design and the technology used allows for detection of the number of fish approaching the obstacle, accounting for tagged fish that may not attempt to re-ascend a river after tagging and cannot be considered to contribute to metrics of attraction and passage efficiency.

This study was unique in its context, inception and level of investment and as a result has collected data that few other research projects have been able to do in relation to fish passage studies at small-scale hydropower schemes. Therefore, the Agency should ensure that the experiences of the project, the data collected and the lessons learned are incorporated into future guidance in respect to hydropower development and fish pass design and approval. The performance of a fish pass will always be context specific, however it would be useful if the general guidance for fish pass approval in association with hydropower development could be more specific on what levels of fish pass performance, in what circumstances, would be considered efficient in all respects and for all purpose to the Agency's satisfaction. Whilst it is recognised that without appropriate monitoring it would be impossible to determine whether a pass was meeting specific passage targets, without this "satisfactory" fish pass performance will always be subjective and a matter of debate. This would promote transparency in decision making and also standardisation of the design and approval process.

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Glossary

ADCP: An Acoustic Doppler Current Profiler (ADCP or ADP) is a sonar that produces a record of water current velocities for a range of depths.

ArcGIS (GIS): ArcGIS is a suite consisting of a group of geographic information system (GIS) software products produced by Esri.

Array: The arrangement of hydrophones below the fish pass.

CI: The confidence interval of an estimate. In the case of proportions this is the Bayes 95% Credible Interval.

EA: Environment Agency

Grid cell (cell): 0.5 m by 0.5m area within the grid. A value of residence time was calculated for each grid cell.

Grid: Two dimensional grid dividing the array into 0.5 m by 0.5 m grid cells (see grid cells) for residence time analysis (see residence time).

Hotspot: Area where fish spend a disproportionate amount of their time, represented by a group of cells within the grid with a relatively high average occupancy time.

HTi: Hydroacoustic technology Inc.

Hydrophone: A device for the detection and monitoring of tag pulses (see tag pulses).

Non-passage tracks: tracks that start when the array is entered and terminate when the fish leaves the array by a route other than the fish pass (usually exited from the downstream side of the array).

Passage tracks: tracks that start when a fish enters the array and terminate when the array is exited via the fish pass.

Polyline: A continuous line produced in GIS, composed of one or more line segments.

Residence time: the time spent, by fish, in each grid cell within the array.

Tag pulses: An acoustic pulse emitted from a tag which has been assigned a 2D position by HTI software.

Tag period: The time between tag pulses. This is unique to each fish in the study and can therefore be used to identify individual fish.

Tag: A small (sound-emitting) device that allows the detection and/or remote tracking of fish.

Appendix 1

Examples of fish that were rejected from tagging due to poor condition

Sea trout which had lost vision in one of its eyes and was rejected from tagging.

Sea trout with open wound predation marks that were rejected for tagging.


Sea trout that was highly coloured had a wide spread of fungus on the body that was rejected from tagging.

Appendix 2

Summary tagging, passage and delay metrics for tagged sea trout that passed Ruswarp Weir via the main fish pass in the five years of the study (2011-2015).

	Baseline			Post-commissioning			
Metric	**2011**	**2012**	**Total**	**2013**	**2014**	**2015**	**Total**
n tagged	38	10	48	46	44	41	131
n detected on ATS array	14	3	17	31	32	18	81
Attraction efficiency	**37%**	**30%**	**35%**	**67%**	**73%**	**44%**	**62%**
95% Bayes CI	(23-52)	(9-59)	(23-49)	(53-80)	(59-84)	(30-59)	(53-70)
n ascending weir	14	3	17	26	22	13	61
Overall passage rate	**37%**	**30%**	**35%**	**57%**	**50%**	**32%**	**47%**
95% Bayes CI	(23-52)	(9-59)	(23-49)	(42-70)	(36-64)	(19-46)	(38-55)
n using main fish pass	14	3	17	25	18	11	54
Fish pass efficiency	**100%**	**100%**	**100%**	**81%**	**56%**	**61%**	**67%**
95% Bayes CI	(82-100)	(47-100)	(85-100)	(65-92)	(39-72)	(39-80)	(56-76)
***n* sea trout with >5 tracks prior to passage via main fish pass**	1	1	2	9	9	4	22
%	**7%**	**33%**	**12%**	**36%**	**50%**	**36%**	**41%**
95% Bayes CI	(0-28)	(4-77)	(2-32)	(20-55)	(29-71)	(14-64)	(28-54)
Median track duration (m)	**4.75**	**2.62**	**3.58**	**2.72**	**3.12**	**3.07**	**2.87**
Interquartile rage	1.65-12.64	1.55-8.91	1.58-9.50	0.88-7.52	0.75-9.58	0.87-7.35	0.84-8.24
Mean track duration (m)	9.40	7.74	8.56	10.13	10.08	9.75	10.05
Median cumulative time in array before passage via main fish pass (m)	**5.54**	**1.55**	**4.75**	**23.15**	**26.36**	**30.95**	**23.60**
Interquartile range	1.55-23.74	NA	1.54-27.79	5.10-57.18	2.44-85.82	13.07-98.27	8.04-70.95
Mean cumulative time in array (m)	23.00	108.36	38.07	47.58	72.90	74.72	61.55
***n* sea trout with cumulative time in array <10 minutes prior to passage via main fish pass**	9	2	11	8	5	2	15
%	**64%**	**67%**	**65%**	**32%**	**28%**	**18%**	**28%**
95% Bayes CI	(40-85)	(23-96)	(42-84)	(16-51)	(11-50)	(4-45)	(17-48)
Median time from 1st detection to passage via main fish pass (h)	**0.23**	**0.31**	**0.28**	**2.36**	**3.34**	**2.63**	**2.69**
Interquartile range	0.08-1.34	NA	0.09-1.41	0.77-15.60	0.39-18.11	1.19-49.88	0.79-17.28
Mean time from 1st detection to passage via main fish pass(h)	8.67	100.66	24.91	23.32	12.23	26.61	20.29
***n* sea trout with delay <1hr from 1st detection to passage via main fish pass**	10	2	12	7	6	2	15
%	**71%**	**67%**	**71%**	**28%**	**33%**	**18%**	**28%**
95% Bayes CI	(47-90)	(28-96)	(48-88)	(13-47)	(15-55)	(4-45)	(17-40)

Appendix 3

Summary of fish tagged during the project

Summary of fish tagged in 2015

Batch	Tag	Species	Sex	Length (mm)	Weight (kg)	Fat meter %	Date of release	Time of release
1	2500	Sea Trout	F	625	-	2.20	30/10/2015	15:30:00
	2507	Sea Trout	M	580	-	2.10	30/10/2015	15:30:00
	2514	Sea Trout	M	675	-	5.10	30/10/2015	15:30:00
	2521	Sea Trout	F	535	-	2.30	30/10/2015	15:30:00
	2528	Sea Trout	F	560	-	2.20	30/10/2015	15:30:00
	2535	Sea Trout	F	625	-	3.00	30/10/2015	15:30:00
	2542	Sea Trout	F	560	-	3.40	30/10/2015	15:30:00
	2549	Sea Trout	F	610	-	4.10	30/10/2015	15:30:00
	2556	Sea Trout	M	650	-	3.50	30/10/2015	15:30:00
	2563	Sea Trout	F	585	-	2.20	30/10/2015	15:30:00
	2570	Sea Trout	F	560	-	4.30	30/10/2015	15:30:00
	2577	Sea Trout	F	580	-	2.10	30/10/2015	15:30:00
2	2584	Sea Trout	F	675	2.825	2.80	09/11/2015	17:00:00
	2591	Sea Trout	F	630	2.650	3.90	09/11/2015	17:00:00
	2598	Sea Trout	F	715	4.300	1.90	09/11/2015	17:00:00
	2605	Salmon	F	635	2.325	1.70	09/11/2015	17:00:00
	2612	Sea Trout	M	670	2.850	2.60	09/11/2015	17:00:00
3	2619	Sea Trout	F	660	2.775	1.90	16/11/2015	16:10:00
	2626	Sea Trout	-	480	0.950	1.30	16/11/2015	16:10:00
	2633	Sea Trout	F	535	1.625	1.20	16/11/2015	16:10:00
	2640	Sea Trout	M	640	2.600	1.80	16/11/2015	16:10:00
	2647	Sea Trout	M	715	3.550	3.30	16/11/2015	16:10:00
	2654	Sea Trout	F	570	1.775	1.30	16/11/2015	16:10:00
	2661	Sea Trout	M	575	-	3.70	16/11/2015	16:10:00
	2668	Sea Trout	F	575	1.975	2.00	16/11/2015	16:10:00
	2675	Sea Trout	M	565	1.950	2.40	16/11/2015	16:10:00
	2682	Sea Trout	M	575	2.100	2.50	16/11/2015	16:10:00
	2689	Sea Trout	M	605	2.500	2.60	16/11/2015	16:10:00
	2696	Sea Trout	M	650	2.725	2.30	16/11/2015	16:10:00
	2703	Sea Trout	F	595	1.800	1.80	16/11/2015	16:10:00
	2710	Sea Trout	M	610	2.800	1.50	16/11/2015	16:10:00
	2717	Sea Trout	F	645	2.925	4.80	16/11/2015	16:10:00
	2724	Sea Trout	M	490	1.175	1.60	16/11/2015	16:10:00
	2731	Sea Trout	M	600	2.125	1.80	16/11/2015	16:10:00
4	2738	Sea Trout	M	580	1.725	1.90	23/11/2015	15:35:00
	2745	Sea Trout	M	625	2.425	2.30	23/11/2015	15:35:00
	2752	Sea Trout	F	590	2.025	1.60	23/11/2015	15:35:00
	2759	Sea Trout	F	600	2.000	1.70	23/11/2015	15:35:00
	2766	Sea Trout	F	640	2.575	1.80	23/11/2015	15:35:00
	2773	Sea Trout	F	620	2.475	1.60	23/11/2015	15:35:00
	2780	Sea Trout	M	535	1.400	1.20	23/11/2015	15:35:00
	2787	Sea Trout	F	570	1.675	1.30	23/11/2015	15:35:00

Summary of fish tagged in 2014

Batch	Tag	Species	Sex	Length (mm)	Weight (kg)	Fat meter %	Date of release	Time of release
1	2500	Sea Trout	M	650	2.950	1.90	16/10/2014	14:15:00
	2507	Sea Trout	M	610	2.325	2.80	16/10/2014	14:15:00
	2514	Sea Trout	F	500	1.250	2.30	16/10/2014	14:15:00
	2521	Sea Trout	M	570	1.575	3.70	16/10/2014	14:15:00
	2528	Sea Trout	F	540	1.450	3.50	16/10/2014	14:15:00
	2535	Sea Trout	F	530	1.550	2.20	16/10/2014	14:15:00
	2542	Sea Trout	F	520	1.425	3.70	16/10/2014	14:15:00
	2549	Sea Trout	F	570	1.750	1.80	16/10/2014	14:15:00
	2556	Salmon	M	560	1.525	2.40	16/10/2014	14:15:00
	2563	Sea Trout	F	640	2.850	4.00	16/10/2014	14:15:00
	2570	Sea Trout	M	500	1.200	4.30	16/10/2014	14:15:00
	2577	Sea Trout	F	520	1.300	1.80	16/10/2014	14:15:00
	2584	Sea Trout	F	550	1.750	3.60	16/10/2014	14:15:00
	2591	Sea Trout	F	560	1.850	2.10	16/10/2014	14:15:00
2	2598	Sea Trout	F	500	1.300	1.60	04/11/2014	16:25:00
	2605	Sea Trout	F	570	1.825	1.40	04/11/2014	16:25:00
	2612	Sea Trout	F	540	1.700	2.20	04/11/2014	16:25:00
	2619	Sea Trout	F	500	1.175	_	04/11/2014	16:25:00
	2626	Salmon	M	490	1.150	_	04/11/2014	16:25:00
	2633	Sea Trout	F	560	1.425	_	04/11/2014	16:25:00
	2640	Sea Trout	F	390	0.725	_	04/11/2014	16:25:00
	2647	Sea Trout	M	590	2.250	_	04/11/2014	16:25:00
	2654	Sea Trout	M	550	1.875	_	04/11/2014	16:25:00
	2661	Sea Trout	F	420	0.750	_	04/11/2014	16:25:00
3	2668	Sea Trout	F	650	2.950	1.30	10/11/2014	16:00:00
	2675	Sea Trout	F	480	1.100	1.50	10/11/2014	16:00:00
	2682	Salmon	M	730	3.825	1.30	10/11/2014	16:00:00
	2689	Sea Trout	F	530	1.350	1.60	10/11/2014	16:00:00
	2696	Sea Trout	F	520	1.225	1.70	10/11/2014	16:00:00
	2703	Sea Trout	M	630	2.500	2.40	10/11/2014	16:00:00
	2710	Sea Trout	F	470	1.200	2.20	10/11/2014	16:00:00
	2717	Sea Trout	F	520	1.450	1.80	10/11/2014	16:00:00
	2724	Sea Trout	M	610	2.250	1.70	10/11/2014	16:00:00
	2731	Sea Trout	M	530	1.250	2.00	10/11/2014	16:00:00
4	2738	Sea Trout	F	500	1.200	1.30	18/11/2014	15:00:00
	2745	Sea Trout	F	565	1.925	1.60	18/11/2014	15:00:00
	2752	Sea Trout	M	590	1.750	1.90	18/11/2014	15:00:00
	2759	Sea Trout	F	520	1.250	0.90	18/11/2014	15:00:00
	2766	Sea Trout	F	670	2.725	2.30	18/11/2014	15:00:00
	2773	Sea Trout	F	495	1.300	1.20	18/11/2014	15:00:00
	2780	Sea Trout	M	590	1.825	1.60	18/11/2014	15:00:00
	2787	Sea Trout	F	530	1.425	1.10	18/11/2014	15:00:00
	2794	Sea Trout	F	540	1.500	1.30	18/11/2014	15:00:00
	2801	Sea Trout	F	570	1.700	1.20	18/11/2014	15:00:00

Batch	Tag	Species	Sex	Length (mm)	Weight (kg)	Fat meter %	Date of release	Time of release
	2808	Sea Trout	F	440	0.875	2.00	18/11/2014	15:00:00
	2815	Sea Trout	M	555	1.550	1.20	18/11/2014	15:00:00
	2822	Sea Trout	F	535	1.275	1.10	18/11/2014	15:00:00

Summary of fish tagged in 2013

Batch	Tag	Species	Sex	Length (mm)	Weight (kg)	Date of release	Time of release
1	2500	Sea Trout	F	570	2.375	24/09/2013	16:45
	2507	Sea Trout	F	535	1.500	24/09/2013	16:45
2	2514	Sea Trout	M	640	2.600	15/10/2013	17:45
	2521	Sea Trout	F	580	2.025	15/10/2013	17:45
	2528	Sea Trout	F	560	1.775	15/10/2013	17:45
	2535	Sea Trout	M	560	2.175	15/10/2013	17:45
	2542	Sea Trout	M	590	2.175	15/10/2013	17:45
	2549	Sea Trout	F	530	1.525	15/10/2013	17:45
	2556	Sea Trout	F	490	1.275	15/10/2013	17:45
	2563	Sea Trout	F	650	3.075	15/10/2013	17:45
	2570	Sea Trout	M	620	2.307	15/10/2013	17:45
	2577	Sea Trout	F	520	1.375	15/10/2013	17:45
	2584	Sea Trout	M	510	1.275	15/10/2013	17:45
	2591	Sea Trout	F	550	2.000	15/10/2013	17:45
	2598	Sea Trout	F	660	3.300	15/10/2013	17:45
	2605	Sea Trout	M	520	1.600	15/10/2013	17:45
	2612	Sea Trout	F	530	1.500	15/10/2013	17:45
	2619	Sea Trout	F	540	1.550	15/10/2013	17:45
	2626	Sea Trout	F	630	2.200	15/10/2013	17:45
	2633	Sea Trout	M	480	1.100	15/10/2013	17:45
	2640	Sea Trout	M	540	1.300	15/10/2013	17:45
	2647	Sea Trout	M	540	1.450	15/10/2013	17:45
	2654	Sea Trout	M	550	1.800	15/10/2013	17:45
	2661	Sea Trout	F	450	0.875	15/10/2013	17:45
	2668	Sea Trout	F	420	0.750	15/10/2013	17:45
3	2675	Sea Trout	F	500	1.250	01/11/2013	16:40
	2682	Sea Trout	M	520	0.975	01/11/2013	16:40
	2689	Sea Trout	M	620	2.150	01/11/2013	16:40
	2696	Salmon	F	640	2.750	01/11/2013	16:40
	2703	Sea Trout	M	590	2.350	01/11/2013	16:40
	2710	Sea Trout	F	540	1.650	01/11/2013	16:40
	2717	Sea Trout	F	580	2.125	01/11/2013	16:40
	2724	Sea Trout	F	545	1.500	01/11/2013	16:40
	2731	Sea Trout	M	680	3.350	01/11/2013	16:40
	2738	Sea Trout	F	460	0.950	01/11/2013	16:40
	2745	Sea Trout	F	510	1.225	01/11/2013	16:40
	2752	Sea Trout	F	530	1.600	01/11/2013	16:40
	2759	Sea Trout	M	620	2.550	01/11/2013	16:40
	2766	Sea Trout	F	360	0.475	01/11/2013	16:40
4	2773	Sea Trout	F	450	0.850	18/11/2013	16:00
	2780	Sea Trout	F	520	1.350	18/11/2013	16:00
5	2787	Sea Trout	F	470	1.000	22/11/2013	14:00
	2794	Sea Trout	F	520	1.475	22/11/2013	14:00

Batch	Tag	Species	Sex	Length (mm)	Weight (kg)	Date of release	Time of release
5	2801	Sea Trout	F	740	3.800	22/11/2013	14:00
	2808	Sea Trout	F	510	1.400	22/11/2013	14:00
	2822	Sea Trout	F	480	1.150	22/11/2013	14:00
	2829	Sea Trout	M	590	2.225	22/11/2013	14:00

Summary of fish tagged in 2012

Batch	Tag	Species	Sex	Length (mm)	Date of release	Time of release
1	2500	Sea trout	M	527	20/08/2012	20:30:00
	2507	Sea trout	M	490	20/08/2012	20:30:00
	2514	Salmon	M	610	20/08/2012	20:30:00
	2521	Salmon	M	548	20/08/2012	20:30:00
	2528	Salmon	M	553	21/08/2012	11:30:00
	2535	Sea trout	M	515	21/08/2012	11:30:00
2	2542	Sea trout	F	616	19/09/2012	14:30:00
	2549	Salmon	M	589	19/09/2012	14:30:00
	2556	Sea trout	M	538	20/09/2012	12:00:00
	2563	Sea trout	F	463	20/09/2012	12:00:00
	2570	Sea trout	M	588	20/09/2012	12:00:00
	2577	Salmon	F	607	20/09/2012	12:00:00
	2584	Sea trout	M	477	20/09/2012	12:00:00
	2591	Sea trout	M	815	20/09/2012	12:00:00
	2598	Sea trout	M	483	20/09/2012	12:00:00
3	2605	Salmon	M	638	28/09/2012	17:30:00
	2612	Salmon	M	807	28/09/2012	17:30:00
	2619	Salmon	M	608	28/09/2012	17:30:00
	2626	Salmon	M	670	28/09/2012	17:30:00
	2633	Salmon	F	735	28/09/2012	17:30:00
	2640	Salmon	F	657	28/09/2012	17:30:00
	2647	Salmon	M	640	28/09/2012	17:30:00
	2654	Salmon	F	703	28/09/2012	17:30:00

Summary of fish tagged in 2011

Batch	Tag	Species	Sex	Fish length (mm)	Date of release	Time of release
1	2514	Sea Trout	M	560	10/10/2011	18:15:00
	2521		M	595	10/10/2011	18:15:00
	2528	Sea Trout	F	610	10/10/2011	18:15:00
	2535	Sea Trout	M	640	10/10/2011	18:15:00
	2542	Sea Trout	F	490	10/10/2011	18:15:00
	2549	Salmon	M	600	10/10/2011	18:15:00
	2556	Sea Trout	F	600	10/10/2011	18:15:00
	2563	Sea Trout	M	640	10/10/2011	18:15:00
	2570	Sea Trout	F	595	10/10/2011	18:15:00
	2577	Sea Trout	M	640	11/10/2011	18:00:00
	2584	Sea Trout	M	575	11/10/2011	18:00:00
	2591	Sea Trout	M	595	11/10/2011	18:00:00
	2605	Sea Trout	M	630	11/10/2011	18:00:00
	2626	Sea Trout	M	530	11/10/2011	18:00:00
	2633	Sea Trout	M	480	11/10/2011	18:00:00
	2640	Sea Trout	M	580	11/10/2011	18:00:00
	2647	Sea Trout	F	525	11/10/2011	18:00:00
	2654	Sea Trout	M	610	11/10/2011	18:00:00
	2661	Sea Trout	F	570	11/10/2011	18:00:00
	2668	Sea Trout	M	530	11/10/2011	18:00:00
	2675	Sea Trout	M	555	11/10/2011	18:00:00
	2682	Sea Trout	M	560	11/10/2011	18:00:00
	2689	Sea Trout	F	495	11/10/2011	18:00:00
	2696	Sea Trout	F	570	11/10/2011	18:00:00
	2703	Sea Trout	M	590	11/10/2011	18:00:00
	2710	Sea Trout	M	545	11/10/2011	18:00:00
	2717	Sea Trout	F	380	11/10/2011	18:00:00
	2738	Sea Trout	M	700	11/10/2011	18:00:00
	2724	Sea Trout	F	595	11/10/2011	18:00:00
1	2731	Sea Trout	M	640	11/10/2011	18:00:00
2	2738	Sea Trout	F	525	24/10/2011	17:00:00
	2745	Sea Trout	F	655	24/10/2011	17:00:00
	2766	Sea Trout	F	590	24/10/2011	17:00:00
	2773	Sea Trout	M	540	24/10/2011	17:00:00
	2780	Sea Trout	F	580	24/10/2011	17:00:00
	2787	Sea Trout	F	565	24/10/2011	17:00:00
	2752	Sea Trout	F	460	25/10/2011	16:30:00
	2759	Sea Trout	M	590	25/10/2011	16:30:00
	2794	Sea Trout	F	555	25/10/2011	16:30:00

Appendix 4

Data from a previous tracking study (July-September 2010) carried out by the Environment Agency.

Tag	Species	Size (cm)	Release time	Passage time	Time from release to ascent (days)	Route taken
1010	St	50.2	20/07/2010 18:00:00	24/07/2010 03:41:09	3.24	Baulk
1015	St	47.0	20/07/2010 18:00:00	15/08/2010 05:39:41	25.29	Fish Pass
2116	Sa	51.5	27/09/2010 18:00:00	30/09/2010 14:38:07	2.51	Baulk
2179	St	69.0	27/09/2010 18:00:00	29/09/2010 02:17:54	1.20	Fish Pass
			27/09/2010 18:00:00	30/09/2010 09:41:01	2.39	Fish Pass
2228	Sa	61.5	28/09/2010 18:00:00	29/09/2010 02:48:18	0.22	Fish Pass
2235	Sa	66.0	28/09/2010 18:00:00	29/09/2010 00:39:30	0.16	Baulk
2242	Sa	66.2	28/09/2010 18:00:00	29/09/2010 06:44:21	0.31	Fish Pass
2284	Sa	74.7	28/09/2010 18:00:00	03/10/2010 00:15:51	4.15	Baulk

Appendix 5

Summary of fish passage data in 2011, 2012, 2013, 2014 and 2015

Summary statistics for sea trout detected in the ATS array downstream of the Larinier fish pass during 2015.

Passage	Tag No	Size (mm)	Time between release and first detection [d]	Number of tracks in array	Cumulative time in array [min]	Cumulative length of track [m]	Total Time from first detection in array to H8 (or last detection for non-passage) [hrs]	Day / Night passage
Larinier	2507	580	1.94	3	428.65	830.23	120:11:50	D
	2563	585	0.09	1	15.93	58.67	1:11:19	N
	2570	560	1.52	1	1.80	35.49	0:10:24	N
	2584	675	0.09	1	9.00	25.45	0:15:32	N
	2640	640	0.73	5	13.07	97.34	1:16:50	D
	2647	715	0.42	6	98.27	473.34	9:07:28	D
	2654	570	0.37	3	35.12	158.02	2:35:03	N
	2661	575	0.39	8	17.83	155.68	2:37:53	N
	2724	490	5.59	4	53.35	142.06	11:44:30	N
	2731	600	0.09	15	30.95	374.20	49:52:39	N
Side of Pass	2619	660	0.35	17	117.90	716.08	93:38:29	N
Baulk	2745	625	0.23	4	52.42	142.02	11:08:07	
Non-Passage	2521	535	0.11	8	30.38	327.71	38:26:21	
	2598	715	0.11	15	50.90	260.42	7:19:36	
	2633	535	0.45	17	45.47	264.79	61:33:51	
	2675	565	0.40	6	70.00	417.90	3:46:48	
	2759	600	4.52	13	202.42	1156.76	50:34:26	
	2773	620	6.01	5	13.67	78.80	14:11:45	

Summary statistics for sea trout detected in the ATS array downstream of the Larinier fish pass during 2014 (excluding the two tags known to have been consumed by the same predator).

Passage	Tag No	Size (cm)	Time between release and first detection [d]	Number of tracks in array	Cumulative time in array [min]	Cumulative length of track [m]	Total Time from first detection in array to H8 (or last detection for non-passage) [hrs]	Day / Night passage
Larinier	2500	65	0.35	1	0.37	7.88	0.17	N
	2507	61	0.88	14	73.23	634.26	20.82	D
	2514	50	3.91	1	2.49	25.91	0.13	D
	2521	57	0.12	4	2.09	29.51	5.84	N
	2563	64	0.23	1	0.63	10.12	0.13	N
	2577	52	0.11	3	2.27	1022.20	1.21	N
	2591	56	0.76	8	214.98	1146.80	73.61	D
	2598	50	0.12	7	123.60	775.44	5.35	N
	2612	54	0.19	4	32.08	441.93	13.86	N
	2633	56	0.91	1	10.02	175.76	0.31	N
	2654	55	0.36	7	13.57	171.34	2.93	N
	2668	65	0.27	8	148.87	1046.41	3.75	N
	2689	53	0.34	10	70.18	764.36	22.92	N
	2696	52	0.25	2	20.63	244.17	0.91	N
	2710	47	0.31	6	43.03	405.13	17.21	N
	2731	53	0.74	44	493.27	2080.08	48.70	D
	2794	54	0.61	8	46.18	519.43	1.89	D
	2815	55	0.85	1	14.78	117.65	25.47	D
Baulk	2528	54	0.14	1	0.50	11.23	3.84	
	2542	52	5.01	15	71.62	1097.57	135.93	
	2605	57	0.04	4	31.25	246.78	120.03	
	2780	59	0.49	18	96.60	430.29	98.12	
Non-Passage	2535	53	0.88	22	141.15	1480.08	135.99	
	2661	42	0.38	17	108.05	1049.07	5.23	
	2675	48	0.10	13	107.72	1296.13	25.19	

Passage	Tag No	Size (cm)	Time between release and first detection [d]	Number of tracks in array	Cumulative time in array [min]	Cumulative length of track [m]	Total Time from first detection in array to H8 (or last detection for non-passage) [hrs]	Day / Night passage
	2703	63	1.57	50	804.55	3769.08	60.48	
	2745	57	0.14	15	233.97	847.44	60.08	
	2752	59	0.08	31	332.15	1858.79	93.59	
	2759	52	2.87	6	52.97	478.94	83.88	
	2766	67	0.20	4	29.15	128.54	1.01	
	2773	50	0.11	5	15.32	193.55	15.14	

Summary of movement characteristics of fish that ascended Ruswarp weir in 2013

Passage	Tag No	Size (cm)	Time between release and first detection [d]	Number of tracks in array	Cumulative time in array [min]	Cumulative length of track [m]	Total Time from first detection in array to H8 (or last detection for non-passage) [hrs]	Day / Night passage
Larinier	2500	57.0	20.1	3	4.90	54.48	2.36	N
	2507	53.5	25.9	1	1.33	12.81	0.20	N
	2521	58.0	1.3	2	1.77	77.31	0.63	N
	2563	65.0	0.1	42	125.85	1519.11	134.14	D
	2577	52.0	0.2	4	23.15	292.86	17.50	D
	2584	51.0	0.1	2	0.55	185.77	1.24	N
	2591	55.0	0.2	3	25.68	356.67	1.21	N
	2598	66.0	0.1	4	14.88	186.22	0.65	N
	2605	52.0	0.7	7	37.75	488.39	1.35	D
	2633	48.0	0.1	5	20.42	291.43	3.09	N
	2640	54.0	0.8	28	275.58	3463.53	116.96	D
	2647	54.0	0.1	3	25.93	166.38	0.73	N
	2654	55.0	0.1	22	60.17	602.52	25.91	N
	2661	45.0	0.8	4	11.62	131.29	9.95	N
	2668	42.0	3.3	8	41.02	382.68	13.69	D
	2689	62.0	0.3	24	86.68	891.29	5.90	N
	2703	59.0	0.3	1	5.05	56.59	0.23	N
	2710	54.0	1.1	2	10.13	222.12	0.81	N
	2738	46.0	0.2	23	163.83	1894.22	42.14	D
	2745	51.0	0.9	7	54.20	732.97	4.07	N
	2794	52.0	1.2	13	159.57	1305.90	195.03	N
	2801	74.0	0.4	2	5.15	62.32	1.02	D
	2808	51.0	0.6	4	9.28	84.32	1.37	D
	2829	59.0	0.3	2	24.05	116.85	2.75	N
Baulk	2542	59.0	0.4	11	48.12	714.78	7.24	-
Non-Passage	2514	64.0	0.5	12	86.90	742.13	30.91	-
	2549	53.0	0.2	45	155.70	2555.09	249.72	-
	2556	49.0	1.8	12	50.28	411.57	3.45	-
	2752	53.0	0.9	2	7.07	37.82	2.60	-
	2822	48.0	0.6	22	182.28	1112.42	162.40	-

Summary of movement characteristics of fish that ascended Ruswarp weir in 2012. (FP = fish pass, FPS = fish pass side, FPP = fish pass proximity)

Fish	Species	Size (mm)	Behaviour class	Time from release to 1st detection [d]	Number of tracks in array	Total time in array [min]	Total distance in array [m]	Time from release to passage [d]	Route taken	Day / Night track
2500	ST	527	Passage	2.13	40	322.00	2767.24	14.70	FP	D
2549	Sa	589	Passage	0.62	12	56.68	672.25	1.40	FP	N
2584	ST	477	Passage	1.01	1	1.55	29.48	1.02	FP	D
2584	ST	477	DS Passage		8*					N
2626	Sa	670	Passage	0.97	2	8.78	87.69	0.99	FP	D
2626	Sa	670	Second Passage		4*	2.15	57.53	14.83	FP	D
2647	Sa	640	Passage	0.16	4	15.78	218.57	0.34	FP	N
2647	Sa	640	Second Passage		5*	0.53	12.23		FP	D
2556	ST	538	Passage	25.47	1	1.53	20.75	25.48	FP	N
2633	Sa	735	Passage	0.20	3	6.98	104.93	0.23	FP	N
2528	Sa	553	Non-Passage	0.29	23	149.22	1177.73			

NOTE – Salmon 2528 had 23 tracks within the array over a 6hr period on 21/08/2012 but was not recorded to ascend via the fish pass

* Total number of tracks recorded for the fish including non-passage prior to passage, passages, descents, non-passage tracks after descent and second passages

Summary of movement characteristics of fish that ascended Ruswarp weir in 2011. (FP = fish pass, FPS = fish pass side, FPP = fish pass proximity)

Fish	Species	Size (cm)	Time from release to first detection in array (days)	Number of array visits	Total time in array (mins)	Total distance in array (m)	Speed in array (m s^{-1})	Time from release to passage (days)	Route taken	Day / night
2703	ST	59	0.01	1	5.00	18.73	0.06	0.02	FPS	D
2703 (2nd passage)	ST		-	3	44.47	384.12	0.14	1.83	FP	D
2514	ST	56	1.04	3	8.33	319.52	0.64	1.08	FP	N
2549	AS	60	1.08	3	176.33	1250.76	0.12	2.42	FPP	D
2633	ST	48	0.21	1	1.67	30.74	0.31	0.21	FPP	N
2591	ST	59.5	0.25	2	19.65	276.15	0.23	0.33	FP	N
2710	ST	54.5	0.25	1	15.23	166.52	0.18	0.25	FP	N
2577	ST	64	0.29	1	0.68	15.69	0.38	0.29	FP	N
2661	ST	57	3.17	1	1.55	18.02	0.19	3.17	FP	N
2647	ST	52.5	1.79	2	7.67	76.57	0.17	1.83	FP	D
2773	ST	54	0.1	1	1.72	27.73	0.27	0.13	FP	N
2745	ST	65.5	0.21	1	4.40	56.67	0.21	0.21	FP	N
2794	ST	55.5	0.71	4	50.55	537.40	0.18	0.71	FPS	D
2563	ST	64	16.25	2	9.23	94.23	0.17	16.29	FP	N
2717	ST	38	29.54	14	167.42	1374.02	0.14	29.62	FP	D
2640	ST	58	42.08	1	4.75	109.37	0.38	42.08	FP	N

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