



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

2013 Initial Post-Commissioning dataset

R.A.A. Noble, J.R. Dodd, J.D. Bolland, S.E. Walton and I.G. Cowx Report – Ruswarp_2013

HIFI Final Report, 10 June 2014

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Published by:
Environment Agency
Coverdale House, Aviator Court, Amy Johnson Way,
Clifton Moor, York, YO30 4GZ
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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 by the North York Moors National Park (NYMNP) in association with the Esk Valley Energy Group (EVEG) at Ruswarp Weir (tidal limit) on the River Esk in North Yorkshire. This installation, constructed in 2012, consists of a single Archimedean screw turbine (diameter = 2.9 m) adjacent to a Larinier fish pass on the right hand bank. The intake for the screw is located immediately upstream of the fish pass exit and the outflow located adjacent to the fish pass entrance. 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 using an acoustic tracking system. Salmon and sea trout were tracked prior to commissioning and completion of the hydropower scheme (upstream of the weir by the EA in 2010 and in the pool downstream of the weir 11 October 2011 – 12 January 2012 and 20 August 2012 – 12 December 2012) to assess baseline fish passage behaviour. The salmonids tracked in 2013 (23 September to December) constituted the first year of post-commissioning assessment. In 2013 (only) mobile hydrophones were located in Whitby Marina and immediately downstream of the weir to investigate movements through the estuary and approaches to the weir.

In 2013 one salmon and 46 sea trout were tagged (in 2013 salmon were not specifically targeted given the relatively low numbers recorded in the baseline surveys). Thirty-one sea trout (68%) and one salmon (100%) were detected in the hydrophone array in the pool downstream of the fish pass entrance; a return rate that was approximately double that observed in the baseline studies. A further seven sea trout were detected only on mobile hydrophones (particularly in Whitby Marina) and six fish were not recorded anywhere after release. A further two tags were recorded simultaneously on three different hydrophones (Whitby, Noble's Yard and the array) and it was assumed that these tags were inside a seal. In 2013 27 passage tracks (including one salmon and one second passage by a sea trout) and 466 non-passage tracks were recorded in 2013. Twenty-six of the 31 sea trout observed in the array passed the weir; 25 (fish pass efficiency = 81%) via the Larinier fish pass and one via the baulk pass (the first recorded use of the baulk by tagged fish since 2010). This fish pass efficiency, for fish observed in the array, was lower than the 100% passage rate observed for sea trout in the baseline (17/17) although the difference was not statistically significant. Overall a much higher proportion (passage efficiency = 53%) of tagged sea trout ascended the weir via the fish pass than in the baseline (35%) although again the difference was not statistically significant. The five remaining fish observed in the array that did not ascend the weir dropped downstream and were either last recorded Whitby (n = 2) or were last recorded at Noble's Yard (n = 3).

There were significant differences observed in the number of times individual fish were recorded in the array, the duration of visits to the array and the time from first arrival in the array to passage between 2013 and the baseline. In 2013 the average (median) total time spent in the array by sea trout prior to passage was 24.18 (6.13 – 77.69) minutes (n = 25) which was significantly longer than the 5.00 (1.61 – 29.81) minutes (n = 17) in the baseline dataset. In the baseline 65% of sea trout (n = 11) spent less than a total of ten minutes in the array prior to passage with only 24% (n = 4) spending longer than 30 minutes. In 2013 only 26% of sea trout (32% of the tagged sea trout that actually ascended) spent less than ten minutes in the array prior to passage via the Larinier pass and 64% of tagged sea trout (n = 20) spent longer than 30 minutes in the array. However, the duration of individual non-passage tracks in 2013 was significantly shorter than in the baseline dataset, i.e. fish briefly visited the array more times in 2013.

In the baseline 70.5% of sea trout passed the weir within one hour of their first detection in the array (including time when the fish was outside of the array) whilst in 2013 this had reduced to 32% and seven sea trout (28%) took longer than 12 hours to ascend. The total time between first detection and passage was significantly longer in 2013 than in the baseline. When excluding fish that took longer than 12 hours to ascend (equivalent to more than one tidal cycle) the median time from first detection to passage by sea trout was 0.17 (0.09 – 0.92) hours in the baseline (n = 15) and 1.23 (0.64 – 2.83) hours (n = 18) in 2013.

The five fish that were detected in the array but did not ascend the weir spent between 7 and 171 minutes in the array, with three of them spending more than 75 minutes in the array before leaving the array for the final time. Only 25% (n = 5) of the sea trout that did pass the weir spent more than 75 minutes in the array before passage. 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. Overall no significant difference was observed in the time from release to passage between the sea trout tracked in 2013 and the baseline.

A grid based approach (0.5 x 0.5 m cells; track count and residence time), proximity analysis (frequency of tag detections) and approach analysis (2 m buffer; count and time) was used to quantify, visualise and standardise micro-scale behaviours of fish below the fish pass and to enable comparison of fish behaviours between the baseline and post-commissioning. Data from 2013 indicated similar patterns to the baseline in that tracks were spread throughout the array. However, data from 2013 indicate a potential bias towards the right-hand bank (looking downstream) away from the fish pass entrance and towards the hydropower outfall. This shift in track distribution was also reflected in a reduction of recorded approaches to within 2m of the fish pass entrance, and a reduced proportion of time spent within 2m, in 2013 compared with the baseline. The nature of the 2m approach zone for the fish pass changed considerably after the installation of the Larinier pass (now much shallower with greatly aerated water) which probably made the location less appealing for sea trout to occupy for extended periods of time. The changes in the pool conditions also made tracking of fish in this location more difficult; with many the final triangulated position of many passage tracks being outside this 2m zone. Furthermore, in 2013 analysis of the average duration of time spent within each cell indicated hotspots immediately in front of the hydropower outfall screens in the vicinity of the right-hand bank. Although changes in the bathymetry (depth) of the pool mean that this location is now the deepest part of the pool (whereas it was shallow margins in 2011) fish did not occupy this location when the hydropower was not operational. It was most apparent at intermediate discharges (flows less than 6.3 m³s⁻¹, seasonal Q25) and levels of hydropower abstraction (1-3 m³s⁻¹) but became less distinct at the highest river flows (flows > 13 m³s⁻¹, seasonal Q10).

The results presented here and preliminary comparison with the baseline, are discussed to evaluate the potential implications of the differences observed in attraction efficiency, passage efficiency, passage duration and passage behaviour for migrating salmonids in the River Esk. The report highlights that potential increase in passage efficiency, reduction in fish pass efficiency and statistically significant increase in passage delay in the monitoring data for 2013 do not necessarily translate to ecologically significant impacts on salmonid migration or population status. Indeed the aim of the ATS study was addressed at the former aspect and not the latter. Furthermore, the data presented here represent only one year of study and only the first year of data collection for the full post-commissioning dataset. Therefore, recommendations for future study, and analysis of the full post-implementation dataset against the baseline are presented.

Acknowledgements

The authors wish to thank Dr Jon Hateley, Mark Reid, Phil Young and Jim Gregory (Environment Agency; EA) for technical support and managerial input and advice. Andy Delaney (EA) is recognised for sharing his intimate knowledge of the River Esk to the benefit of the project. Many thanks are warmly extended to the various landowners and fishery owners for access and permissions. The authors gratefully acknowledge the assistance of Andrew Delaney and Shaun McGinty (EA) in electric fishing surveys in 2013; Andy Hindes (FishTrack Ltd), Ian Wellby (BlueRoof) and Dr Natalie Angelopoulos (HIFI) as NACWOs during tagging fish. The authors also thank Dr Jon Harvey for help during electric fishing surveys and the tagging.

The authors would also like to thank the stakeholders from Esk Energy, YERT and North York Moors National Park for their comments on the draft report.

All tagging was undertaken under Home Office Licence (PPL 80/2411) and full ethical review by The University of Hull.

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1 Introduction

1.1 Background

Rivers provide an array of ecosystem services, including provision of biodiversity, attenuation of flood waters, abstraction, recreation, production of power, food and other marketable goods (Millennium Ecosystem Assessment, 2005; Cowx *et al.*, 2011). As a consequence, rivers have been widely altered by a suite of interacting activities, including effluent discharge, dam building, habitat alteration and water abstraction (Baron *et al.*, 2002; Nilsson *et al.*, 2005).

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 did not begin until the mid 19th Century (Poff & Hart, 2002), it 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 2001/77/EF) 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).

In the past decade 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 the 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. 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.

An opportunity to improve understanding of the potential impacts of low head hydropower schemes on migratory salmonids arose on a scheme proposed by the North York Moors National Park (NYMNP) in association with the Esk Valley Energy Group (EVEG) at Ruswarp weir on the River Esk in North Yorkshire. This installation, completed in 2012, consists of a single Archimedean screw turbine (diameter = 2.9 m) adjacent to fish pass on the right hand bank. The turbine draws up to 4 m³s⁻¹ and generates approximately 50 kW of electricity. The operating head varies considerably from 1.6 m to 2 m depending on the state of the tide below the weir. 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) guidelines relating to hydropower schemes. The pool-traverse fish pass was replaced by a new Larinier fish pass in 2012 (during construction of the hydropower scheme) as the old pass was believed to be suboptimal (the pass was over-energised at high flows (Kibel & Coe, 2009)).

1.2 Aims

The overall aim of this study is 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. The work will used to help formulate and underpin guidance documents such as the Hydropower Good Practice Guidelines (GPG).

A secondary aim is 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 report is to review the first year of post-commissioning monitoring data and provide information on 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 hydropower scheme. The specific objectives for this reports are therefore:

- To analyse sea trout migration in the first year post-commissioning of the hydropower turbine.
- To investigate the timing of fish movements and passages in relation to hydrodynamic and environmental cues.
- To make preliminary comparisons against the established baseline.
- To make suggestions for future delivery of post-commissioning monitoring.

This report presents the monitoring data collected in Autumn/Winter 2013, the first year since the hydropower scheme has been in commission, and makes initial comparisons with the baseline dataset for sea trout. The report follows the methods and materials described in Walton *et al.* (2012) and Noble *et al.* (2013) and draws comparison with the baseline dataset described in Noble *et al.* (2013). The data collected during the whole project will be used to ensure that, if needed, appropriate mitigation measures are installed to maintain or improve passage efficiency in the future.

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, especially 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 (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.

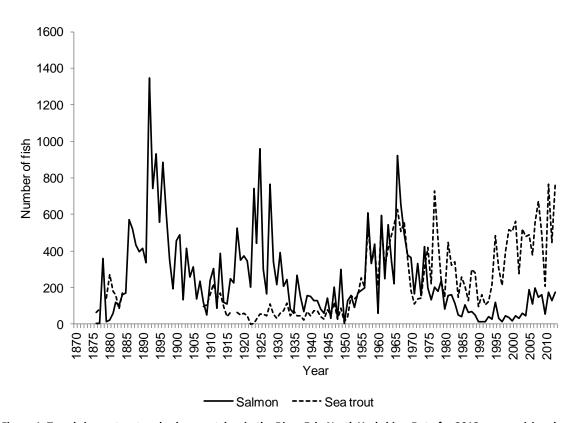


Figure 1. Trends in sea trout and salmon catches in the River Esk, North Yorkshire. Data for 2012 are provisional and the sea trout catches are included in the total for salmon for the period 1885-1902 (I Dolben EA pers. comm.).

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 pool and traverse 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 represents the study site in this investigation. An array of 8 hydrophones was installed to monitor the progress of upstream migrating salmonids (Figure 3 and Figure 4). The configuration of the array in 2013 was similar to 2012 with

one of the hydrophones (H1) within a pool above the baffles in the new Larinier fish pass to confirm fish movement through the pass and one above the weir (H8) to confirm ascent.

The original pool-traverse 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.

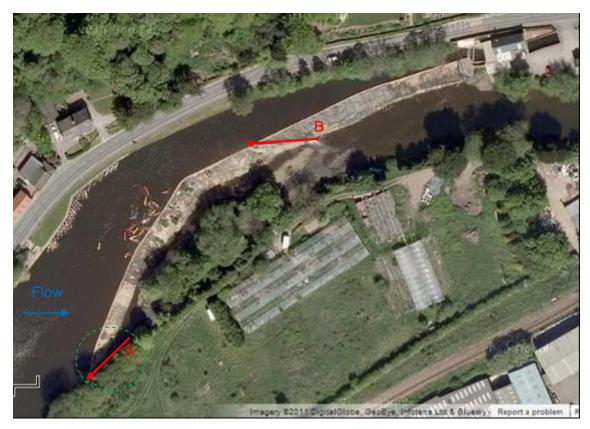


Figure 2. Aerial photograph showing the location of the fish passes (A – pool traverse pass (2011) / Larinier pass (2012 & 2013); B – baulk pass) in relation to the weir (kayakers upstream of the weir give an indication of scale). The green circle marks the location of the new hydroelectric turbine and the focus of this study.

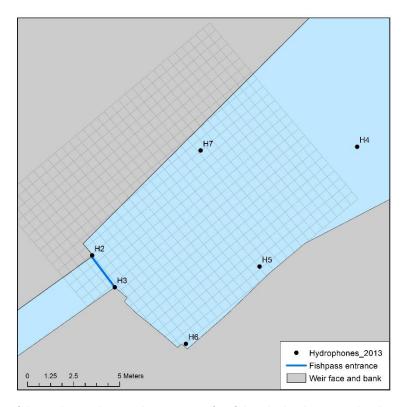


Figure 3. Diagram of the study site showing the positions of 6 of the 8 hydrophones used in the array for 2013 (Section 2.3).



Figure 4. View of the Larinier fish pass entrance, hydropower outfall and hydrophones array showing the approximate positions of all 8 hydrophones in 2013.



Figure 5. View of the new Larinier fish pass entrance, outfall of the new turbine and hydrophones array in 2013 with the hydropower scheme inactive.



Figure 6. View of the outfall of the new turbine and hydrophones array in 2013 with the hydropower scheme active under higher flows. This figure highlights the visually more turbulent plumes of the fish pass and the left-hand side of the turbine outfall.

2.2 Tagging

Fish were captured downstream of Ruswarp Weir on 23rd September, 15th October, 1st, 18th & 22nd November (Appendix 1) 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. Prior to tagging in the field, fish were anaesthetised using MS222 (40 mg L⁻¹). Species, sex and fork length (nearest mm) were recorded.

Fish were placed ventral side up in a clean V-shaped foam support. Tags were activated (pulse rate ranged from 2500-2829 excluding 2815), tested with a hand held detector (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 30mm 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 and treated with a skin adhesive powder (Orahesive, ConvaTec Limited, Deeside, UK). 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 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), 23 September 2013 -27 February 2014. In 2013 six hydrophones (H2-H7) were arranged as an array downstream of the fish pass, a single hydrophone (H1) was positioned within the fish pass and a single hydrophone (H8) upstream of the fish pass (Figure 3 and Figure 4). Changes in the pool following construction work meant that the footprint of the array in 2013 was different to the footprint in both 2011 and 2012. 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. In 2013 H1 was used to indicate when a tagged fish had actually traversed the weir through the fish pass and H8 was used to indicate when a fish had ascended, but neither could indicate a fish's position. 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. During the study, the effectiveness of the array and H1/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. Fixed location tags were also deployed in the array to measure tag location accuracy and precision under different flow and tide conditions. The array was visited frequently to inspect for damage (extreme spates posed a constant threat to the array) and remove debris (minimal).

In 2013 (only) three Model 300 mobile hydrophones were also 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 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 installed prior to 2013, 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 is 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 effectiveness 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 fish pass as a proportion of the total number observed in the array was used to quantify the permeability of the weir to fish – the fish pass efficiency. Given that the Larinier pass is not the only route over the weir, a further metric of "overall passage efficiency" is calculated as the proportion of all tagged fish that successfully pass the weir.

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. A minimum gap of 2 minutes was used to determine separation of tracks, although in general the gaps were longer than this. The tracks observed over the period were broadly 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 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 and was not detected on H1 or H8 immediately 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.

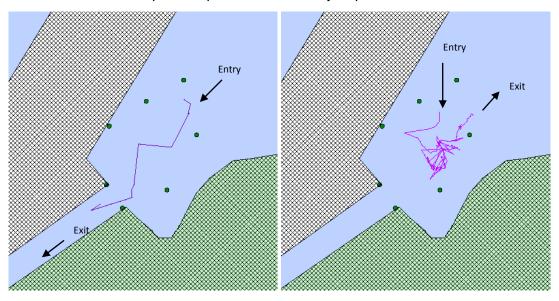


Figure 7. Examples of a passage track (left) and a non-passage track (right) in the array (green circles representing hydrophones).



Figure 8. Larinier fish pass and side-of-fish-pass ascent routes, looking downstream. 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 (35.9m³s⁻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 m³s⁻¹ = fish pass, >3 m³s⁻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 and 2013 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.

Fish tracks were analysed to investigate the following:

- The overall passage efficiency (proportion of tagged fish ascending the weir);
- The fish pass efficiency (proportion of tagged fish detected in the array that ascended the weir via the Larinier pass);
- delay between release and first detection in the array (days) (see Section 3.2);
- delay between first detection in the array and passage (detection on H8, hours) (see Section 3.2);
- delay between release and fish passage (days) (see Section 3.2);
- number of times the array was entered (see Section 3.2);
- duration (minutes) of array visits passage/non-passage (see Section 3.2);
- 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 (see Section 3.2.8);
- diel timing of movements (see Section 3.3.14) with daylight data obtained from HM Nautical Almanac Office online:
- the duration and timing of array visits related to the following environmental variables (discharge, tide state and temperature) (see Section 3.3).
- the influence of hydropower turbine activity on fish behaviour and passage (see Section 3.5.4).

2.5 Statistical analysis

Raw and \log_{10} transformed data were tested for normality using the Kolmogorov Smirnov test. In samples that conformed to a normal distribution, means were compared using independent samples *t*-tests. Where data failed to meet assumptions of normality non-parametric Mann-Whitney *U*-tests were performed to compare medians. In all cases where non-parametric tests are performed medians are reported with interquartile ranges (25%-75%). Relationships between variables were assessed using Pearson's correlations. All statistics were carried out in IBM SPSS Statistics (version 20.0) with a significance level $\alpha = 0.05$.

2.6 Micro-scale behaviour analysis

2.6.1 Initial processing

Triangulated positions of tag pulses/pings produced by the HTI software were plotted as points in ArcGIS (ESRI ArcGIS version 10). 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; ms⁻¹). The groups below were used in all micro-scale analyses (excluding array entry (Section 2.6.5) where only "all tracks" were analysed):

- all tracks;
- passage versus non-passage;
- day versus night;
- ebbing tide versus ebbing/flooding tide versus flooding tide; and
- classes of river discharge (measured at Briggswath) and classes of turbine generation activity.



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

2.6.2 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:

$$t_p = (\Delta t \times I_p) / I_s$$

where Δt is the change in time between points (the time of each step (seconds)), $I_{\rm p}$ is the length of track in each cell and $I_{\rm s}$ 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 spent by fish in each cell were pooled for the groups outlined in Section 2.6.1.

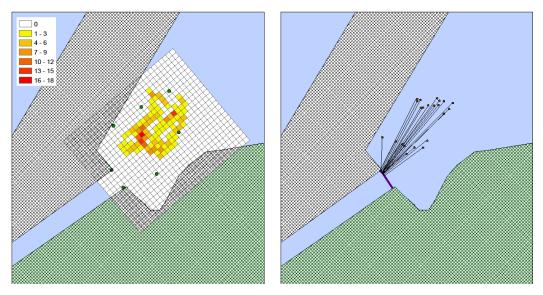


Figure 11. Example residence time (sec) grid, with cells colour coded from white to red with increasing time (left) and a diagrammatic example of proximity analysis (right).

2.6.3 Proximity analysis

The proximity of tag detections (plotted as points) to the entrance of the fish pass (plotted as a polyline) was calculated in ArcGIS, using the near function, which calculates the shortest distance between a point and a polyline (see Figure 11 (right) for example). The near distances of points in tracks were pooled into groups (see Section 2.6.1) standardised by the number of tracks in each group and plotted as histograms in MS ExcelTM.

2.6.4 Fish pass approaches

In 2011 a fish movement to within a 2 m distance from the fish pass was considered indicative of an approach towards the fish pass. The number of times a fish approached the fish pass was calculated by drawing a buffer the width of the fish pass (2.25 m) 2 m from the entrance. The total number of times a fish track intersected this buffer was determined in ArcGIS (Figure 12) and the number of approaches this represented in passage runs was calculated by:

$$nA = (nI + 1) / 2$$

and for non-passage runs by;

$$nA = nI/2$$

where *nA* is the number of approaches and *nI* is the total number of buffer intersects. The total number of approaches was calculated for each group (see section 2.6.1) and standardised by the number of fish tracks in each group. The amount of time fish spent within this 2-m buffer for each group (as above) was calculated by summing the residence time values of the grid cells that lie within it; these values were standardised by the number of fish tracks within each group.

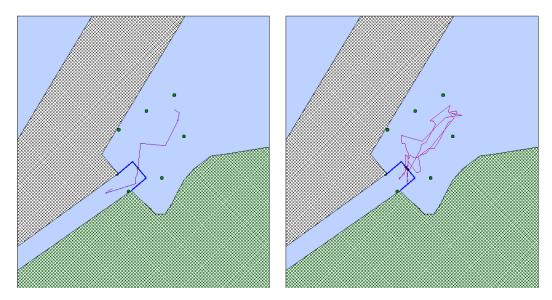


Figure 12. Example of the intersection of a passage (left; nI = 1, nA = 1) and non-passage track (right; nI = 4, nA = 2) with the 2 metre fish pass buffer.

2.6.5 Array entry/exit

The first and last detections of each fish track were classified into 22 groups according to the location they were first/last detected (inside the array) or position they entered/exited the array (outside the array). The array was split into 8 subsections (A-H) by plotting lines between hydrophones creating 4 sections front and back of the array. Each track was then classified by which section it was first detected in and by which hydrophone it was closest to in that section. This method of classification generated 22 different categories. This method of classification was changed from previous years, where it was classified into 3 groups (A, B, C), due to the increased number of tracks observed and the increased variability in initial track detections.

2.7 Environmental and hydropower generation data

Flow (m³ s⁻¹) was measured at 15-min intervals at the EA Briggswath gauging weir (NZ 866 081). Water temperature in the pool downstream of the fish pass was recorded from 23 September 2013 to 27 February 2014 at 15-min intervals using a 2 tg-4100 temperature logger (Tinytalk, Orion Instruments, Chichester, UK). Predicted tide data for Whitby harbour were obtained at 15-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 (m³.s⁻¹), level upstream of the intake (maOD) and level in the pool downstream (maOD).

2.8 Bathymetry assessment

In 2011 a flow velocity profile within the array was obtained at low flows (mean daily discharge = 1.36 m³ 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 2013 so the

depth of the pool was measured manually at 50cm intervals along transects between each pair of hydrophones which formed the array. Point depth data from the ADCP in 2011 and transects in 2013 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

During 2013 (although not in 2011 or 2012) the movements of fish through the tidal reaches and immediately upstream of Ruswarp Weir were monitored using mobile hydrophones (Section 2.3). A hydrophone at Whitby Marina detected 20 of the 47 tagged fish (42%), ten (50%) of which ascended (or had previously ascended) the weir. Of these ten fish, six (60%) went downstream to Whitby prior to ascending, and the other four (40%) were detected after ascending the weir but subsequently descending the weir and returning downstream. The hydrophone at Noble's Yard detected 31 of the 47 tagged fish (66%), of which 24 (77%) went on to ascend the weir. Three tagged fish (6%) ascended the weir without being detected at Noble's Yard; two of these were not detected as they ascended before the hydrophone was installed at Noble's Yard (15/10/2013 - the deployment of Noble's Yard was delayed due to a technical fault) whilst the third was observed to ascend via the Larinier pass (23/10/13; 38 days after the hydrophone was installed). Note the number of detections presented above include both first detections and detections on hydrophones after being detected elsewhere, whereas the data summarised in Figure 16 are for first detections only.

Sixteen fish made movements between the array and Noble's Yard (downstream end of the weir) more than once before either ascending or being detected later on the hydrophone at Whitby. Three examples of behaviours are shown here for fish 2738 (indicating a repeat visit to the array and time spent at Noble's Yard, Figure 13), 2640 (frequent movement up and down the weir seemingly related to tides, Figure 14) and 2549 (movement between the array and Whitby seemingly related to the tidal cycle, Figure 15). In general the eleven fish that spent more than three hours between first arrival in the array and passage made movements between the hydrophone array and the downstream end of the weir (detected on Noble's Yard hydrophone).

Fish 2549 was observed to move between the array and Whitby harbour on multiple occasions over a period of 12 days (Figure 15). This fish was usually detected on the Noble's Yard hydrophone at the peak of high tide and then detected in the harbour during low tidal periods.

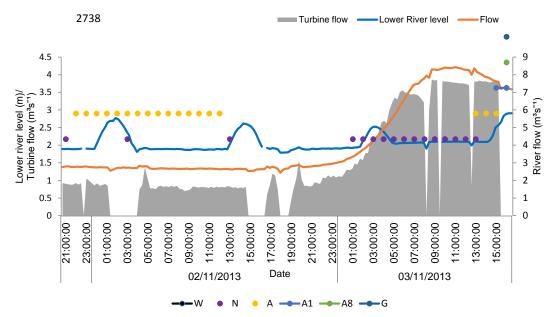


Figure 13. Detections of fish 2738 movements at each of the hydrophones (Whitby W; Noble's Yard N, Array A; and above the weir A8 and Gary's Hut G) with river/turbine flows and lower river levels.

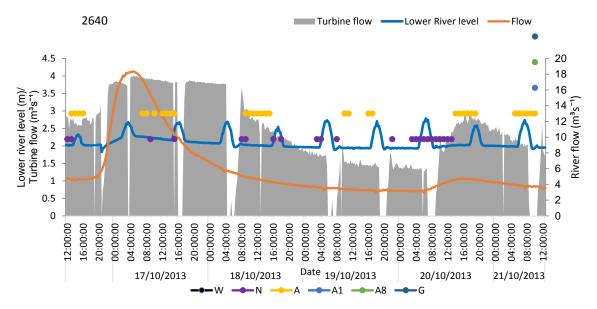


Figure 14. Detections of fish 2640 movements at each of the hydrophones (Whitby W; Noble's Yard N, Array A; and above the weir A8 and Gary's Hut G) with river/turbine flows and lower river levels

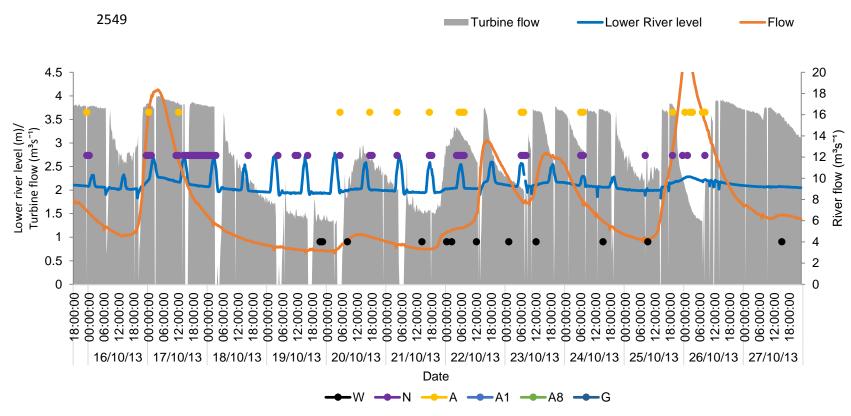


Figure 15. Detections of fish 2549 movements at each of the hydrophones (Whitby W; Noble's Yard N, Array A; and above the weir A8 and Gary's Hut G) with river/turbine flows and lower river levels

3.2 Visits to the array

3.2.1 Fate of tagged fish

During the 2013 post commissioning study 1 salmon and 46 sea trout were tagged for tracking (Table 1). Of these 46 sea trout, 31 were detected within the hydrophone array, giving an attraction efficiency of 67% (31/46) in 2013 that was significantly greater than the 35% (17/48) observed in the baseline (χ^2 contingency test, χ^2 = 9.61, d.f. = 1, P <0.01). A further 7 (15%) were detected on a mobile hydrophone downstream of Ruswarp Weir. Six fish were not detected after release and four of these fish were from the third batch of fish tagged in 2013, which were released 1/11/13 and three seals were observed at the release site (S. McGinty (EA) *pers. comm.*). A further two tags from batch three were subsequently detected on hydrophones at Whitby, Noble's Yard and in the array at exactly the same times, neither of these fish passed the weir so it was deduced that both of these fish (and the tags) were consumed by a seal. The fate of the other tagged fish (4) not detected on any hydrophone cannot be deduced, with predation a likely explanation, although returning to sea without detection on the Whitby hydrophone cannot be dismissed Figure 16).

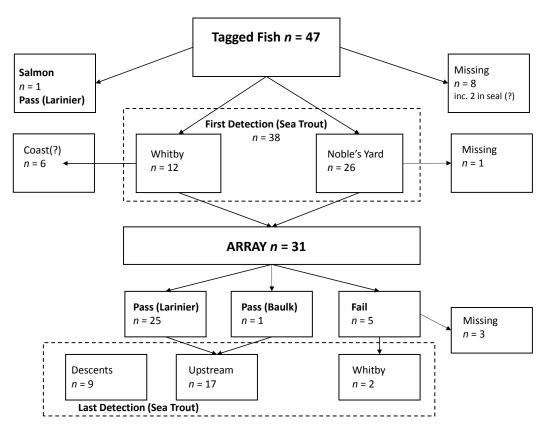


Figure 16 Summary of the fate of tagged fish during 2013 highlighting the detections on each hydrophone system and the passage of fish.

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			
Year	2011	2012	2013	Total	2011	2012	2013	Total
n tagged	1	13	1	15	38	10	46	74
n array mobile	1	5	1	7	14	3	31#	48
hydrophone	N/A	N/A	0	N/A	N/A	N/A	7	7
Tracks								
Non-passage	2	41	0	43	23	45	466	534
Passage	1	4	1	6	14	3	25	43
Baulk passage							1	1
DS Passage				0	1	1	3	5
Second Passage		2		2	1		1	2
Total Tracks	3	47	1	51	39	49	497	585

[#] 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

Of the seven fish that were only detected on mobile hydrophones (i.e. not detected in the array), six of them were only detected on the Whitby Marina mobile hydrophone, and thus returned to sea. The other fish was only detected on Noble's Yard, and the final fate could not be determined (Figure 16).

3.2.2 Fish passage metrics

Of the 32 fish (31 sea trout and one salmon) detected in the array downstream 27 (87%) ascended the weir; 26 (84%) ascended via the fish pass and one via another route (assumed to be the baulk pass) (Table 1 and Figure 16). The overall passage efficiency of sea trout in 2013 was 57% (26/46) whilst in the baseline dataset it was approximately 35% for both sea trout (17/48) and salmon (5/14) (Table 2); although this difference was not statistically significant (χ^2 contingency test with Yate's correction, $\chi^2 = 2.683$, d.f. = 1, P > 0.05). Fish pass efficiency for sea trout was observed to be lower in 2013 (25 of 31, 81%) than in the baseline (17 of 17, 100%) although this difference was not statistically significant (χ^2 contingency test with Yate's correction, $\chi^2 = 2.199$, d.f. = 1, P > 0.05).

3.2.3 Time between release and detection / passage

There was no significant difference in the average time between release and first detection of tagged sea trout in the array in 2013 (median 0.40, 0.18 – 0.95 days (n = 31)) compared with the baseline (median 1.01, 0.25 – 9.74 days (n = 17)) (Mann Whitney U-test: Z = -1.710, n = 50, P >0.05) (Figure 17). In 2013 twelve of the tagged sea trout passed within one day (< 24 hrs) of release with a further six passing within two days (< 48 hrs). Four of the sea trout took between three and seven days and five sea trout took more than one week to ascend with three taking considerably longer (over 14 days) to ascend the weir after release (Figure 18). The median time from release to passage via the Larinier fish pass for sea trout was 1.21 (0.85 – 4.81) days in 2013 (median and interquartile range, n = 25) compared with 1.02 (0.26 – 15.50) days (n = 17) in the baseline dataset (2011 and 2012 combined) although the difference was not significant (Mann Whitney U-test: Z = 0.192, n = 42, P >0.05) (Figure 19).

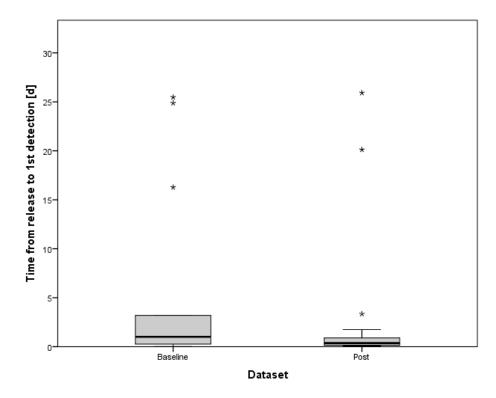


Figure 17 Time from release to detection within the ATS array (days) for tagged sea trout in the baseline dataset (2011 and 2012, n = 17) and in 2013 (n = 25).

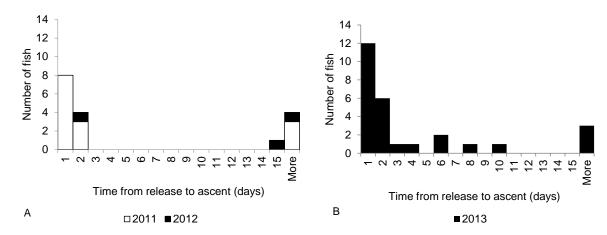


Figure 18. Number of days between release and passage for sea trout in the baseline dataset (A 2011 and 2012, n = 17) and in 2013 (B n = 25); 1 day = within 24 hours of release.

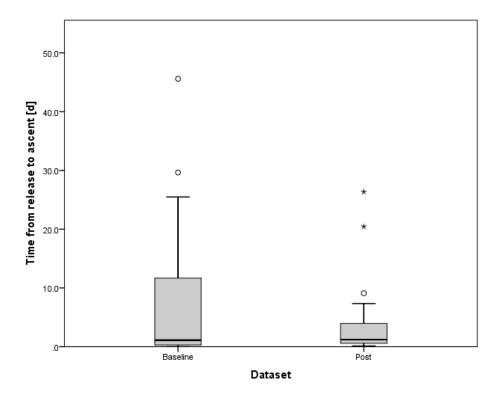


Figure 19 Number of days between release and passage for sea trout in the baseline dataset (2011 and 2012, n = 17) and in 2013 (n = 25).

Table 2 Summary statistics for sea trout detected in the ATS array downstream of the Larinier fish pass during 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	4	6.07	54.48	2.36	N
	2507	53.5	25.9	1	1.33	12.81	0.20	N
	2521	58.0	1.3	4	6.18	77.31	0.63	N
	2563	65.0	0.1	64	197.55	1519.11	134.14	D
	2577	52.0	0.2	6	24.18	292.86	17.50	D
	2584	51.0	0.1	3	15.88	185.77	1.24	N
	2591	55.0	0.2	4	38.27	356.67	1.21	N
	2598	66.0	0.1	4	14.88	186.22	0.65	N
	2605	52.0	0.7	8	41.93	488.39	1.35	D
	2626	63.0	0.1	1	0.92	14.10	0.03	N
	2633	48.0	0.1	6	32.23	291.43	3.09	N
	2640	54.0	0.8	72	441.37	3463.53	116.96	D
	2647	54.0	0.1	3	25.93	166.38	0.73	N
	2654	55.0	0.1	27	68.70	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	42	5.05	56.59	0.23	N
	2710	54.0	1.1	20	19.23	222.12	0.81	N
	2738	46.0	0.2	23	163.83	1894.22	42.14	D
	2745	51.0	0.9	27	158.20	732.97	4.07	N
	2794	52.0	1.2	14	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	5	5.12	84.32	1.37	D
	2829	59.0	0.3	4	15.50	116.85	2.75	N
Baulk	2542	59.0	0.4	12	45.42	714.78	7.24	-
Non-	2514	64.0	0.5	16	75.43	742.13	30.91	-
Passage	2549	53.0	0.2	47	149.53	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	26	170.78	1112.42	162.40	-

3.2.4 Number of visits to the array

In 2013 67% (n = 31) of the sea trout tagged were detected in the array, around twice the return rate observed in the baseline (35%, n = 17). In 2013 three of the sea trout ascended the weir during the first visit to the array, with another eleven ascending within five visits. In the baseline dataset only three of the 17 sea trout (18%) visited the array more than five times before passage (Figure 20). One sea trout made 64 visits to the array during a six day period in 2013 before ascending through the fish pass. Of the five fish that did not pass the weir at all, one fish visited the array twice while four fish made more than 10 visits to the array.

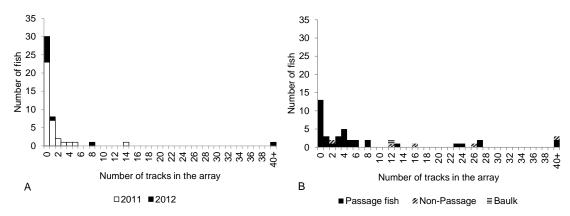


Figure 20. Frequency distribution showing the number of times the hydrophone array was entered by sea trout in A) 2011 and 2012 B) 2013 (0 = number of fish not detected at all in the array).

3.2.5 Total time in the array

In 2013 the median total time spent in the array by sea trout prior to passage was 24.18 (6.13 – 77.69) minutes (n = 25) which was significantly longer than the 5.00 (1.61 – 29.81) minutes (n = 17) in the baseline dataset (Mann Whitney U-test: Z = 2.037, n = 42, P <0.05) (Figure 21). In the baseline 65% of fish spent less than ten minutes in the array prior to passage with only 24% spending longer than 30 minutes. In 2013 only 26% of sea trout (32% of the tagged sea trout that actually ascended) spent less than ten minutes in total within the array prior to passage via the Larinier pass and 64% of tagged sea trout spent longer than 30 minutes in the array. 25 % (n = 4) of the fish that spent more than 30 minutes in the array did not pass the weir (Figure 21).

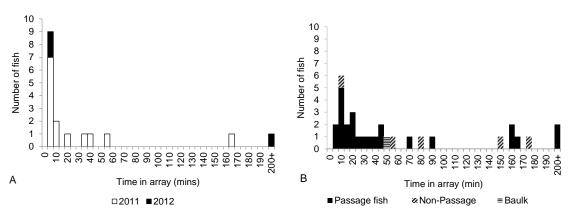


Figure 21 Total time spent in the array prior to passage (sum of all tracks) sea trout in A) 2011 and 2012 B) 2013.

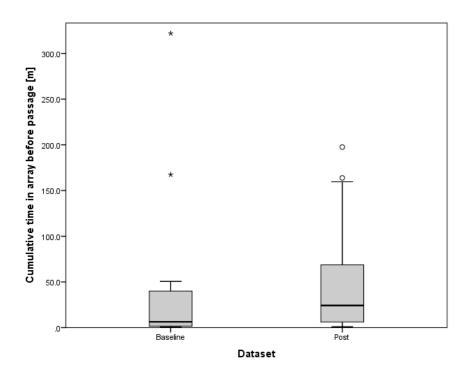


Figure 22 Total time spent within the array (sum of all tracks) prior to passage (minutes) for tagged sea trout in the baseline dataset (2011 and 2012, n = 17) and in 2013 (n = 25).

3.2.6 Time between detection and passage

In the baseline 70.5% of sea trout (n = 12) passed the weir within one hour of their first detection in the array although two fish passed the weir 114 and 301 hours after their first detection. In 2013 only 32% of sea trout passed within one hour of first detection and seven sea trout (28%) took longer than 12 hours to ascend (up to 195 hours). The total time between first detection and passage was significantly longer in 2013 than in the baseline (Mann Whitney U-test: Z = 2.755, n = 42, P <0.01). When excluding fish that took longer than 12 hours to ascend (more than one tidal cycle) the median time from first detection to passage by sea trout was 0.17 (0.09 – 0.92) hours in the baseline (n = 15) and in 2013 was also significantly longer at 1.23 (0.64 – 2.83) hours (n = 18) (Mann Whitney U-test: Z = -2.820, n = 33, P <0.01) (Figure 23-25). During this time prior to passage in 2013 sea trout spent an average of 19.3% (\pm 30.3) of the time within the array whereas in the baseline they spent a significantly higher proportion of the time in the array (40.8% \pm 19.6%) in the array (Mann Whitney U-test: Z = 2.755, n = 42, P <0.05) (Figure 26).

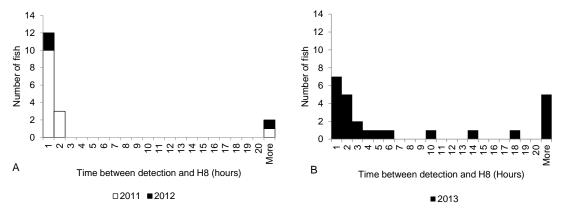


Figure 23. Total time between first arrival in the array and passage (time on H8) for sea trout in A) 2011 and 2012 B) 2013

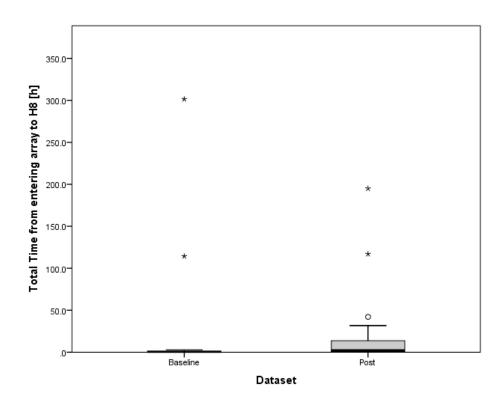


Figure 24 Total time between first detection in the array and final passage for (hours) tagged sea trout in the baseline dataset (2011 and 2012, n = 17) and in 2013 (n = 25).

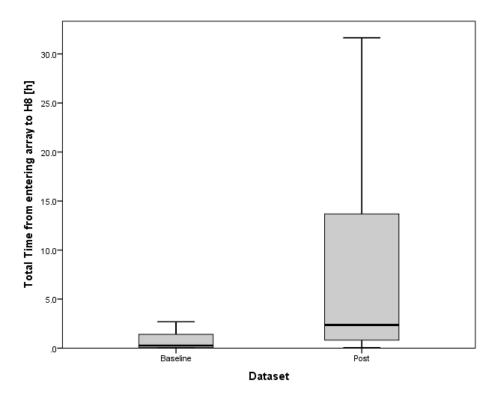


Figure 25 Total time between first detection in the array and final passage (hours) for tagged sea trout in the baseline dataset (2011 and 2012, n = 17) and in 2013 (n = 25), focusing on fish that took under 30 hours in total.

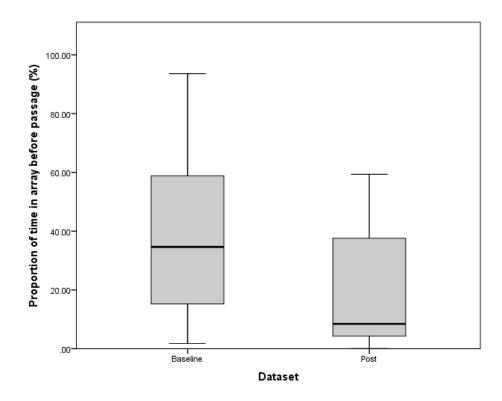


Figure 26 Proportion of time spent within the array between first detection and final passage for tagged sea trout in the baseline dataset (2011 and 2012, n = 17) and in 2013 (n = 25).

3.2.7 Time in array during passage and non-passage tracks

In 2013 27 passage tracks, including a fish ascending the fish pass for a second time, and 466 non-passage tracks were recorded for sea trout. The median time in the array during non-passage tracks (2.18, 0.68-5.66 minutes (n=466)) was significantly shorter than in the baseline dataset (4.32, 1.83-9.45 minutes (n=68)) (Mann Whitney U-test: Z=-4.211, n=534, P<0.05). The median duration of passage tracks in the baseline (2.50, 1.61-11.78 minutes (n=17)) was not significantly different from the duration of passage tracks in 2013 (3.85, 1.16-9.62 minutes (n=25)) (Mann Whitney U-test: Z=-0.397, n=42, P>0.05) (Figure 27).

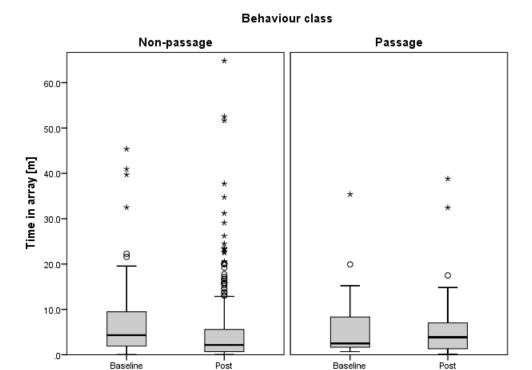


Figure 27. Duration (minutes) of individual array visits in passage (n = 17 [baseline] and 25 [2013]) and non-passage (n = 68 [baseline] and 466 [2013]) tracks for sea trout.

Dataset

3.2.8 Ascent route

Of the 27 sea trout ascents over the weir in 2013, 26 used the Larinier fish pass (including one second passage) and one used the baulk fish pass (detected on H8 before H1 (situated inside the fish pass)). This is the first recorded use of the baulk pass by tagged fish since 2010 (EA initial monitoring data). The one Atlantic salmon tracked in 2013 used the Larinier fish pass.

3.3 Influences on timing of movement

Dataset

3.3.1 Diel variations in fish movements

In 2013 sea trout entered the array 182 times (37%) during the day and 309 times (63%) at night (non-passage and first passage tracks). In 2013 the median time spent in the array in non-passage tracks during the day was 2.04 (0.48 – 5.61) minutes (n = 174) and 2.21 (0.80 – 5.72) minutes (n = 292) at night (Figure 28). In the baseline sea trout non-passage track duration was 3.53 (1.60 – 8.44) minutes (n = 52) during the day and 6.95 (2.80 – 17.58) minutes (n = 15) during the night. The duration of non-passage tracks was significantly shorter during both the day (Mann Whitney U-test: Z = -3.104, n = 226, P < 0.01) and the night (Mann Whitney U-test: Z = -2.959, n = 307, P < 0.01) in 2013 than in the baseline.

In 2013 eight sea trout (32%) ascended the weir for the first time during the day and 17 (68%) ascended during the night, and the average duration of passage tracks during the day (3.93, 1.65 - 14.88 minutes, n = 8) was greater than that at night (3.20, 0.95 - 8.84 minutes) (Figure 28). In the baseline the average passage time during the day

(12.47, 1.78 – 47.49 minutes, n = 6) was greater than that at night (1.97, 1.55 – 4.75 minutes, n = 11) (Figure 29). The duration of passage tracks was not significantly different during both the day (Mann Whitney U-test: Z = -0.775, n = 14, P >0.05) and the night (Mann Whitney U-test: Z = 0.071, n = 28, P >0.05) between 2013 and the baseline.

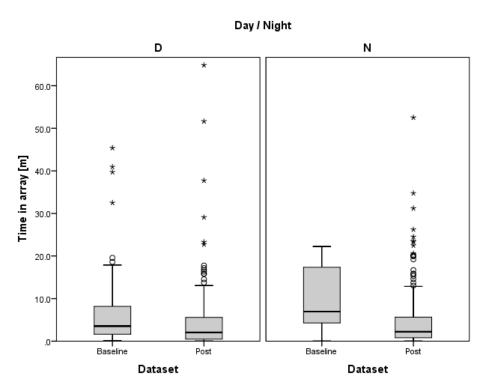


Figure 28. Time spent in the array during non-passage visits of sea trout to the array in the day (D) (n = 52 [baseline]) and at night (N) (n = 15 [baseline]) and 292 [2013]).

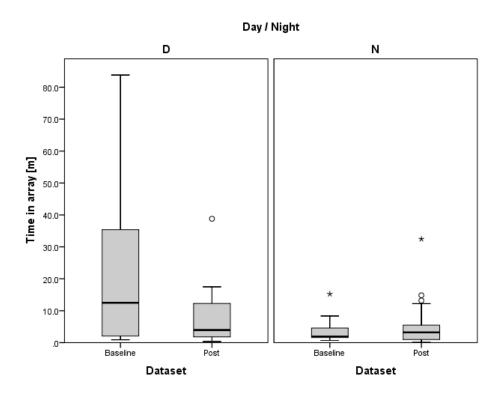


Figure 29. Time spent in the array during passage tracks for sea trout in the day (D) (n = 6 [baseline] and 8 [2013]) and at night (N) (n = 11 [baseline] and 17 [2013]).

3.3.2 Relationship with discharge

In 2013 fish were generally observed to move at periods of elevated flow (Figure 30 and Figure 31). However, 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. Irrespective, both sea trout from release one (tag 2500 and 2507) were observed to move many days after release (thus seemingly independent of its release) and coincided with the first spate (15-16 Oct) following their release. Both of these fish were also detected in Whitby as they returned to the river during the spate. Similarly, a fish from release two was observed to ascend many days after release following a minor flow peak (early Nov) that coincided with batch three.

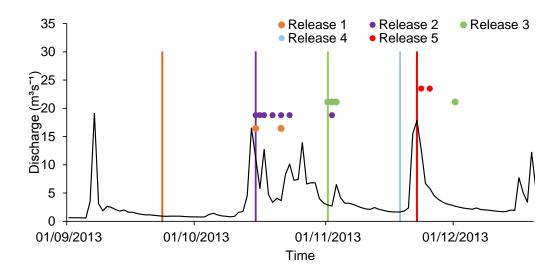


Figure 30. Time series of discharge over the 2013 study period with fish movements represented as points in time. Each point is colour coded according to its release batch. Note: all dots are representative of passage.

2013 was an intermediate year in terms of hydrology being wetter than the dry autumn of 2011 but having no spates similar to the four >30 cumec events observed in 2012 (Figure 31b). Despite this passage of sea trout in 2013 were observed at discharges higher than those of either 2011 or 2012 with a number of passages recorded at flows >10 cumecs (Figure 31a). No fish passages were observed in 2013 at the low flows at which some passages were recorded in 2011 and 2012 (Figures 31 and 32). In 2013 no passages were recorded at flows lower than the long-term seasonal Q50 (Figure 32).

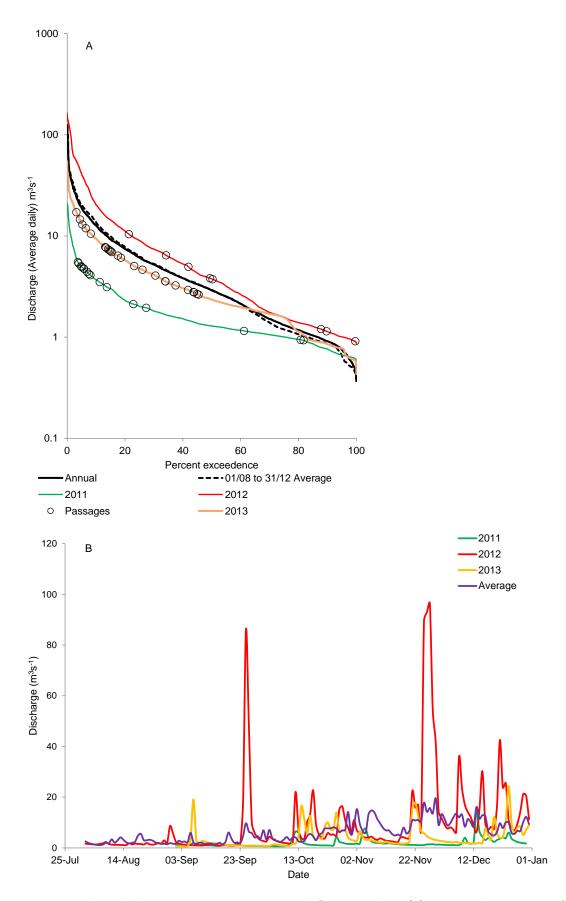


Figure 31. Relationship between sea trout passages and flow exceedence (A) curves and comparison of the hydrographs over the study period (B).

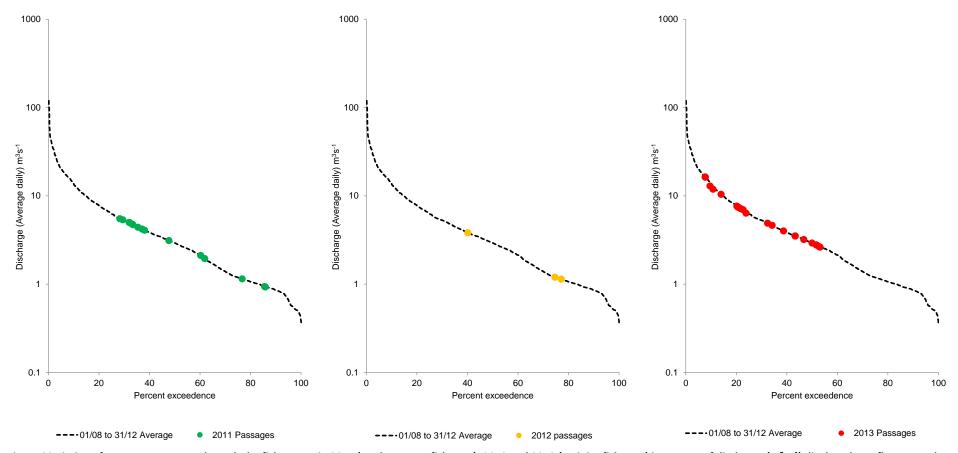


Figure 32 Timing of sea trout passages through the fish passes in 2011 (pool-traverse fish pass), 2012 and 2013 (Larinier fish pass) in respect of discharge (m³.s⁻¹) displayed as a flow exceedence curve for the long term average seasonal (1 Aug to 31 Dec) flows.

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

Although many fish passages seems to coincide with periods of spring tides (Figure 33) this pattern also matches the periods of spates observed (and also to some extent the sampling regime used).

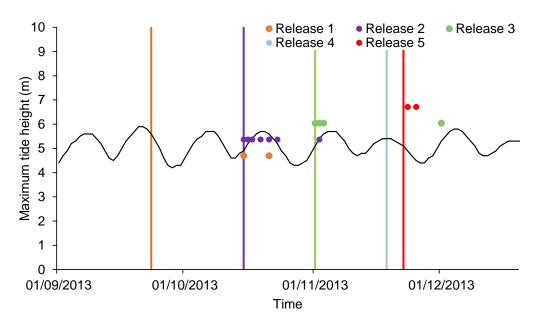


Figure 33. Time series of daily maximum predicted tide heights over the 2013 study period with fish movements represented as points in time. Each point is colour coded according to its release batch.

The pattern of non-passage movements of sea trout in relation to absolute and relative tide height appeared to be broadly similar in the baseline and 2013. In both datasets the majority of movements occurred around the mid tide (1.5 to 3.0m, 30-70% of tide height). Also in both 2013 and the baseline a high proportion of non-passage tracks started around high tide (tide height >5.0m and 90-100% of the daily maximum height) (Figure 34). Passage tracks occurred at most states of tide except for the very lowest tide heights (Figure 35). The level of water in the pool downstream of the fish pass is not affected by tidal water at this level.

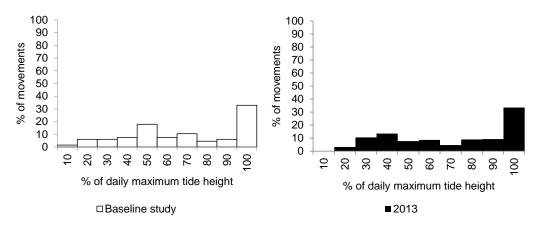


Figure 34. The percentage of non-passage movements versus tide state expressed as the percentage of daily maximum tide height for sea trout.

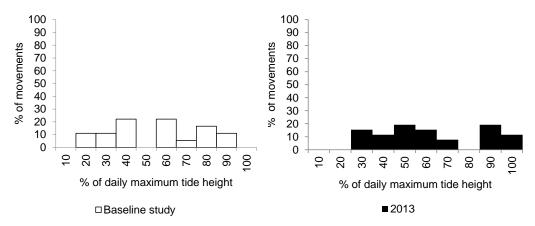


Figure 35. The percentage of passage movements versus tide state expressed as the percentage of daily maximum tide height for sea trout ascending the weir.

There was no clear pattern in first entry to the array or passage (Figure 36) 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 > 6m³s⁻¹ whilst many sea trout were observed to pass at flows between 6 and 15m³s⁻¹ in 2013. The pattern was similar for times of first arrival in the array, with no clear pattern in relation to discharge or tide (Figure 37).

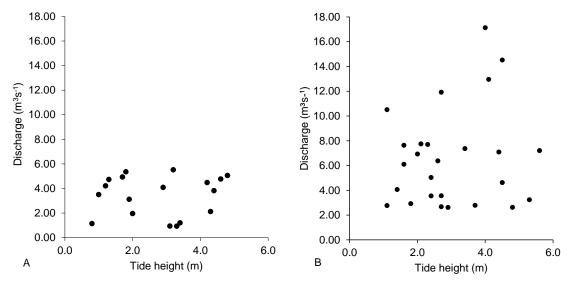


Figure 36. Discharge and tide conditions during passage tracks for sea trout in A) 2011 and 2012 B) 2013

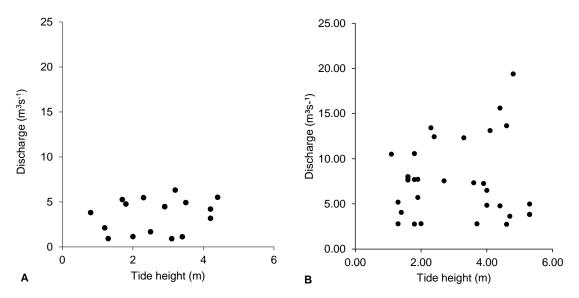


Figure 37. Discharge and tide conditions during first entry into array for sea trout in A) 2011 and 2012 B) 2013.

Esk Energy now monitor the pool level downstream of the hydropower scheme (metres above ordnance datum) 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 2.0 and 2.10m and the majority of first arrivals between 2.05 and 2.15m (Figure 38).

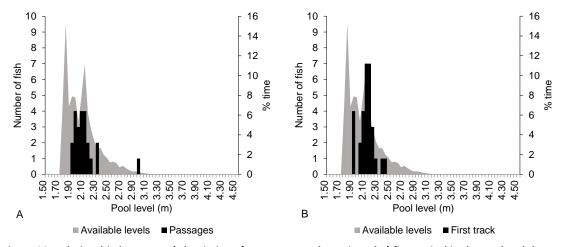


Figure 38. Relationship between A) the timing of passage over the weir and B) first arrival in the pool and the pool level (maOD) (2013).

In 2013 sea trout were observed to enter the array during non-passage tracks on all states of the tide with a tendency to favour flooding tides (n = 272) over ebbing tides (n = 115), this is in contrast to the baseline where there was a slight bias towards ebbing tides (n = 34) over flooding tides (n = 24). In both datasets tracks were also observed to start around low water and high water slacks although the numbers were far fewer (Figure 39). Non-passage tracks that started on an ebbing tide in 2013 (median time in array 2.23, 0.53 - 6.08 minutes, n = 115) were on average slightly longer than those on a flood tide (2.15, 0.70 - 5.69 minutes, n = 272) and the 56 starting at high water slack had an average duration of 2.05 (0.89 - 5.05) minutes. The duration of non-passage tracks were significantly longer in 2013 than in the baseline for both ebbing (Mann Whitney U-test: Z = -2.402, n = 149, P < 0.05) and flooding tides (Mann Whitney U-test: Z = -3.408, n = 296, P < 0.01).

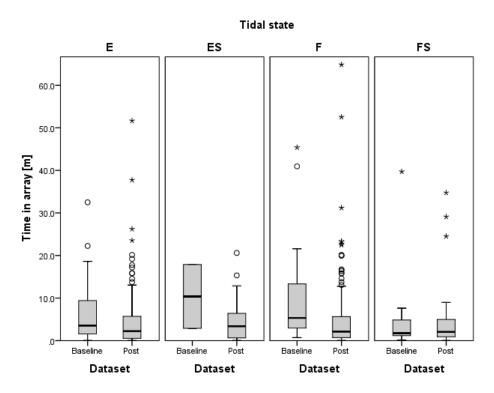


Figure 39. Amount of time spent in the array on non-passage runs of sea trout during ebbing (E; baseline n = 34, 2013 n = 115), low water slack (ES; baseline n = 2, 2013 n = 23), flooding (F; baseline n = 24, 2013 n = 272) and high water slack (FS; baseline n = 1, 2013 n = 56) stages of the tide.

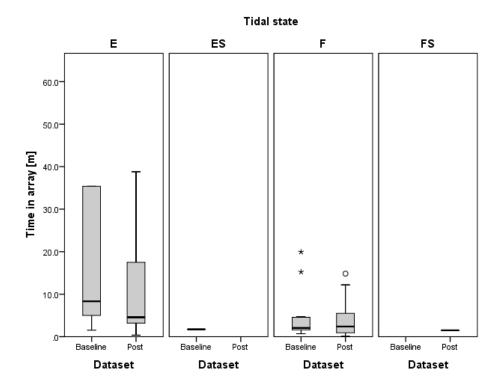


Figure 40. Amount of time spent in the array on passage tracks of sea trout during ebbing (E; baseline n = 5, 2013 n = 10), low water slack (ES; baseline n = 1, 2013 n = 0), flooding (F; baseline n = 11, 2013 n = 14) and high water slack (FS; baseline n = 0, 2013 n = 1) stages of the tide.

In 2013 the majority of passage tracks for sea trout were observed to start on flooding (n = 14) rather than ebbing tides (n = 10), with only one passage occurring around high water slack (Figure 40). Passage tracks that started on an ebbing tide (median time in array 4.57, 2.92 - 21.24 minutes) were on average longer than those on a flood tide (2.38, 0.74 - 5.87 minutes). This pattern was similar to that observed in the baseline dataset.

3.3.4 Relationship with water temperature

No trends were observed in the movement of fish in relation to temperature over the study period (Figure 41).

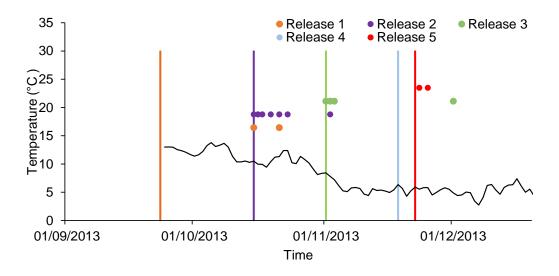


Figure 41. Times series of temperature over the 2013 study period with the passages of fish represented as points in time. Each dot is colour coded according to its release batch, with the release date indicated by the vertical line.

3.3.5 Turbine activity

The hydropower turbine was active for 67% of the time during the study period (1/9/2013 to 14/2/2014) and was operating at near capacity (abstraction of above 3.7 m³s⁻¹) for 24.7% of the time, and at capacity of 4m³s⁻¹ for 5.5% of the time (Figure 42a). Sea trout were observed to ascend through the fish pass under most conditions, two fish passed whilst the turbine was off and eight fish passing at flows of greater than 3.7 m³s⁻¹ (Figure 42a). Turbine activity (both abstraction and RPM) was related to river flow (Figure 43b) and the river level below the turbine. Turbine activity increased with increasing flow up to a discharge of 6m³s⁻¹ when it reached full capacity (4m³s⁻¹ licensed abstraction in addition to the approximate ratings of 1m³s⁻¹ for the fish pass and 0.5m³s⁻¹ for the baulk pass). The water level in the pool downstream of the fish pass was influenced both by river flow (Figure 42a) and tide height (Figures 44 and 45 show the tidal influence during spring tides, whilst tidal influence appeared to be reduced under neap tides). The relationship between downstream river level and discharge was two-staged with a change at around 6m³s⁻¹ (gauged flow at Briggswath, Figure 43a), presumably linked to when the river level was sufficient to significantly overtop the weir crest rather than the majority of the flow passing through the turbine and the fish passes. Turbine activity was reduced or stopped under high tide conditions of spring tides when the operational head difference was reduced (Figures 44 and 45).

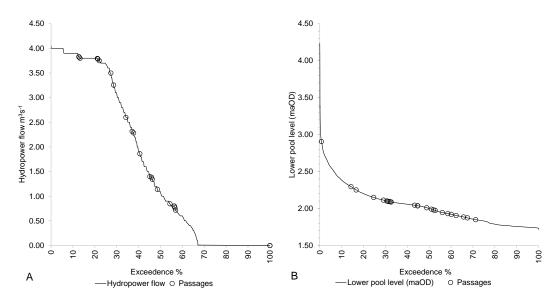


Figure 42 Passages of sea trout (open circles) through the Larinier fish pass plotted against exceedence curves of hydropower flow (A) and level in the pool (B). Note, only two sea trout fish passed when the hydropower flow was zero.

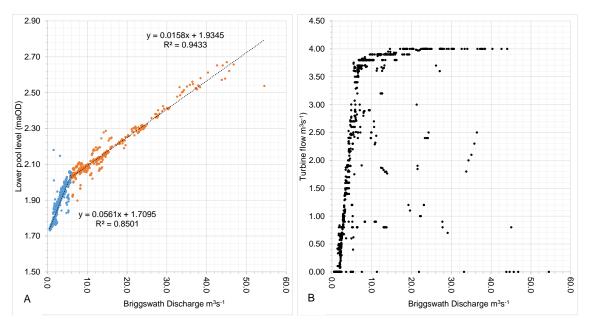


Figure 43 relationship between river discharge and pool level at low tide conditions (A, where blue dots are flows <6m³s⁻¹ and orange dots are flows >6m³s⁻¹) and river discharge and hydropower discharge under predicted low tide conditions (B).

Seventeen of the 25 sea trout observed to pass the weir via the Larinier pass did so over two periods of around 48 hours. Twelve sea trout passed during the period 15-17th of October, associated with a spate flow on the 14th and a release of tagged fish on the 15th (one fish tagged in the previous batch also ascended at this time) (Figure 44). A further five fish ascended during the period 1-3rd November, in relation to a tagging event on the 1st of November (Figure 45). The first event was characterised by high flows (>6m³s⁻¹ for most of the time) and the turbine running at or near full capacity apart from periods of high tide and as the river discharge dropped below 6m³s⁻¹ on the afternoon of the 16th and again on the 18th (Figure 44). The movements of fish between the 1st and 3rd of November followed a release of tagged fish on the 1st. At this time the

river was dropping following a spate on the 29th of October and the turbine was operating at a low capacity (<1.5 m³s⁻¹ abstraction) and the river flow was <4m³s⁻¹ until another spate on the 3rd of November (Figure 45).

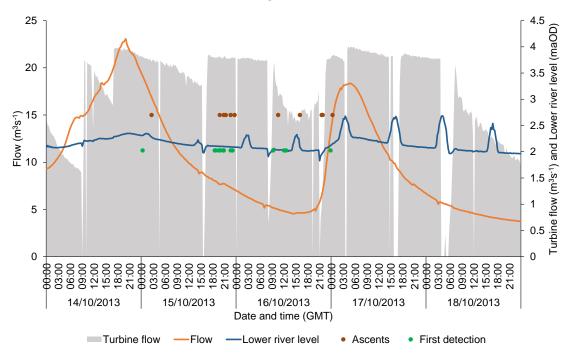


Figure 44 First detection and passage records of sea trout around the tagging event on 15 October 2013 showing river flow, turbine discharge and the river level in the pool (movements in the early hours of 15/10/2012 are a fish tagged on the previous tagging event).

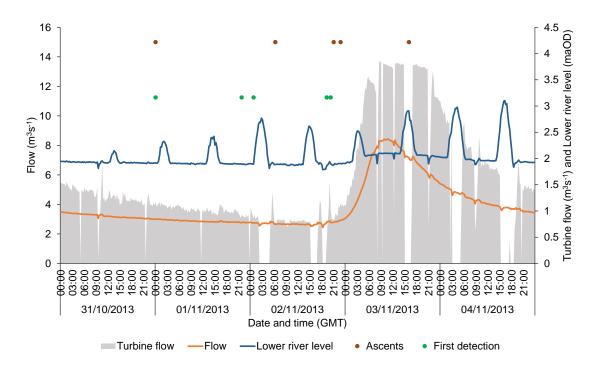


Figure 45 First detection and passage records of sea trout around the tagging event on 1 November 2013 showing river flow, turbine discharge and the river level in the pool (movements in the early hours of 1/11/2012 are a fish tagged on a previous tagging event).

3.4 Bathymetry of the pool

When the hydropower scheme was operational the pool is 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 are areas of visually less turbulent water between these two plumes and between the hydropower plume and the reinforced right-hand bank (Figure 46).



Figure 46. View of the outfall of the new turbine and hydrophones array in 2013 with the hydropower scheme active under higher flows.

The bathymetry (depth) of the pool downstream of the pool-traverse fish pass entrance was measured prior to construction of the hydropower scheme and the Larinier pass using an ADCP in 2011 and manually in 2013 after the hydropower scheme had been commissioned. Although the absolute depths recorded were similar (0.15 to 1.70m) they cannot be directly compared between years due to differences in discharge at the times of measurement, the depth profile of the pool has changed considerably. In 2011 (Figure 47a) the pool was relatively deep (≈ 1m) up to the entrance of the pool-traverse fish pass, with the deepest section (1.4-1.5m) approximately 3m downstream and in line with the discharge plume. In 2013, following construction of the hydropower scheme, change of the fish pass from a pool-traverse to a Larinier and reinforcement of the right hand bank (looking downstream) the deepest section of the pool (1.4-1.7m) was towards the right-hand bank and in front of the hydropower outfall screens (Figure 47b). The area approximately 2-3m in front of the fish pass entrance is now relatively shallow (0.5-0.8m) before deepening (1.2-1.3m) at around 4m downstream of the fish pass entrance.

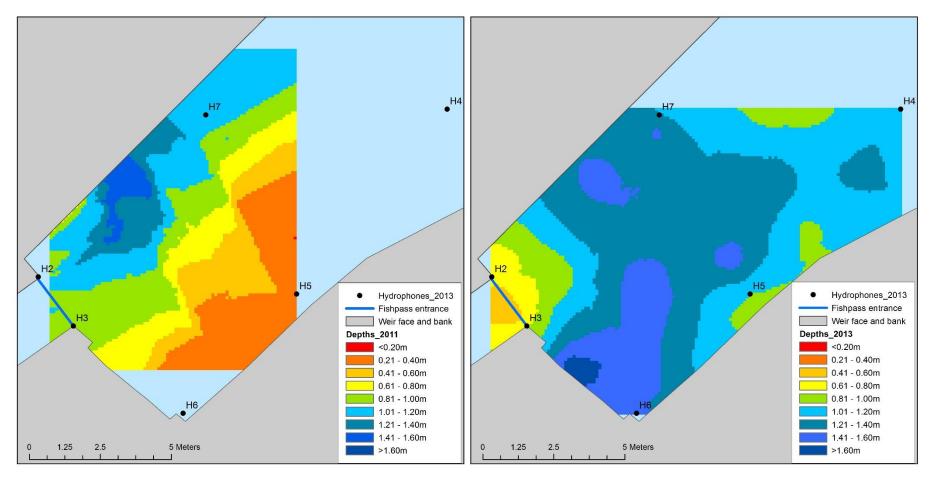


Figure 47 Bathymetry of the pool raster plots calculated by kriging ADCP data in 2011 (left) and manual transect measurement in 2013 (right). Note that these were measured under different flows so the absolute measurements should not be directly compared between years.

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

3.5.1 Array entry

The diversity of fish behaviours recorded in 2013 made it increasingly difficult to determine from which direction fish had entered the pool. The highest frequency of tracks appeared first in segments A (n = 119) and B (n = 81), towards the weir face and at the rear of the pool (Figure 48 and Table 3). A large number of tracks also started (n = 69) and terminated (n = 85) in segment H which related to the zone immediately downstream of the hydropower outfall screens and right-hand bank. A large proportion of these tracks related to only a few fish that spent prolonged periods in this area, in the immediate vicinity of Hydrophone 6 and the screens, and which were sporadically "lost" from the tracking system. It is likely that many of these "new" tracks were all part of one behavioural event rather than multiple visits to the pool.

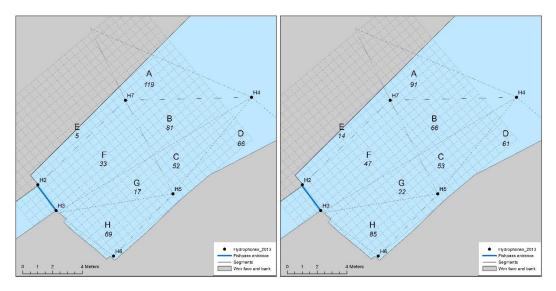


Figure 48. Frequency of start (left) and finish (right) locations of all fish tracks within the array for 2013 in relation to the rear of the grid (A-D) and the front of the grid (E-H)

Table 3. Frequency of start and finish locations of all fish tracks within the array for 2013 in relation to the rear of the grid (A-D) and the front of the grid (E-H) and in relation to the nearest hydrophone (2-7).

		A4	A7	B1	B4	B7	C1	C4	C5	D4	D5
Start track	of	69	50	10	33	38	21	21	10	52	14
End track	of	46	45	12	27	27	21	27	5	52	9

	E2	E7	F1	F2	F3	F7	G1	G3	G5	НЗ	H5	H6
Start of track	2	3	13	3	7	10	10	4	3	3	3	63
End of track	6	8	11	14	3	19	5	8	9	6	8	71

3.5.2 Distribution of tracks

In 2013 tracks were widely distributed throughout the array (Figure 49) 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 between the plumes of the hydropower and fish pass outfalls. The pattern of track distribution indicated a tendency for more tracks to pass through locations towards the right-hand side of the pool rather than nearer the weir face as observed in the baseline (Figure 49a). Residence time was not evenly distributed (Figure 50b) and a hotspot, where a few fish spend a disproportionate amount of their time, was apparent in the cells near the right-hand bank and the outfall of the hydropower turbine. This is in contrast with the baseline where hotspots were observed in front of the fish pass plume (Figure 50a). The highest frequency of tag detections were detected within 4.0 - 6.0 m of the fish pass in 2013 (Figure 51). A far lower proportion of tag detections were located <2m of the fish pass as observed in the baseline (Figure 51). The low rate of detections within 2m of the fish pass entrance 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 in 2013.

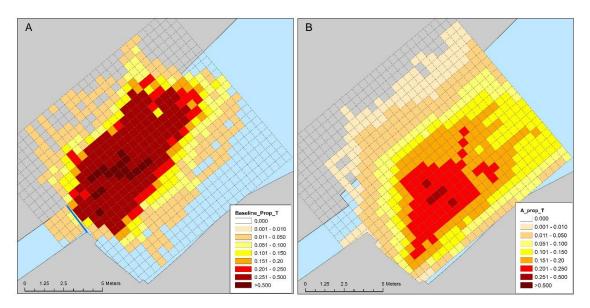


Figure 49. All sea trout tracks combined: proportion of tracks to pass through each grid cell in the baseline (left) and in 2013 (right). Note that there were far fewer tracks overall in the baseline.

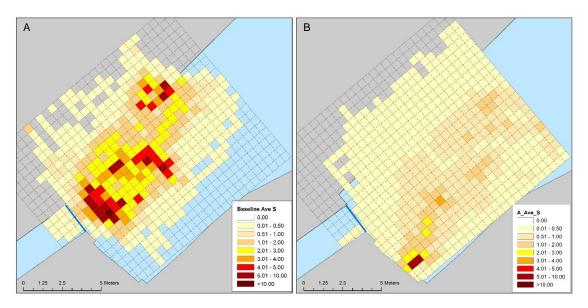


Figure 50. All sea trout tracks combined: average time spent by sea trout in each grid cell in the baseline (left) and in 2013 (right).

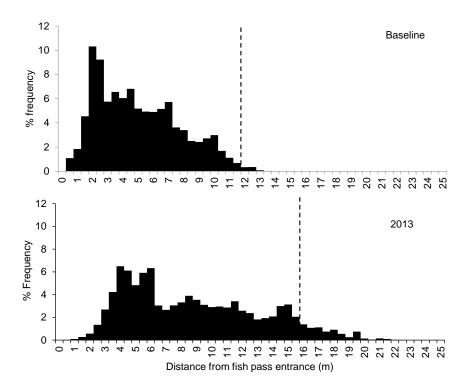


Figure 51. Numbers of tag detections in the array against distance from the entrance to the fish pass (m) as a percentage of the total number of tag detections recorded in 2013 and the baseline. Dashed lines indicate the approximate extent of the furthest hydrophone from the fish pass in each dataset.

3.5.3 Passage versus non passage spatio-temporal distribution within the array

On average a greater proportion of tracks were recorded nearer the fish pass in passage tracks (Figure 52a) than during non-passage tracks (Figure 52b), with more than 50% of passage tracks passing through cells approximately 4m immediately

downstream of the fish pass entrance. In non-passage tracks a higher proportion of tracks were focussed towards the right-hand side of the pool, immediately downstream of the hydropower outfall. In passage tracks differences in average residence time within the array highlighted hot spots occurring around the hydropower outfall (near the screen and right-hand bank) and the rear of the array in-line with the fish pass (Figure 53a). In non-passage tracks only the hotspot in front of the hydropower screen was apparent (Figure 53b). The general patterns of tag detection proximity in relation to the fish pass entrance were similar between passage (Figure 54) and non-passage tracks (Figure 55) with high numbers of pings recorded around 3-4m from the fish pass entrance. For both types of track relatively few tag detections were recorded within 2m of the fish pass entrance. The low rate of detections within 2m of the fish pass entrance 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 in 2013.

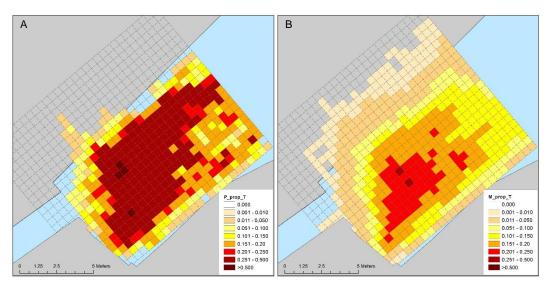


Figure 52. Proportion of sea trout tracks to pass through each grid cell during passage (left) and non-passage (right) visits to the array.

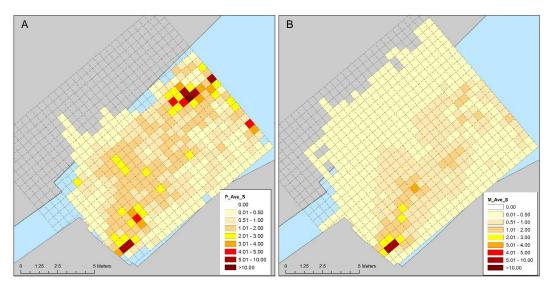


Figure 53. Average time (seconds) spent in each grid cell by sea trout during passage (left) and non-passage (right) visits to the array.

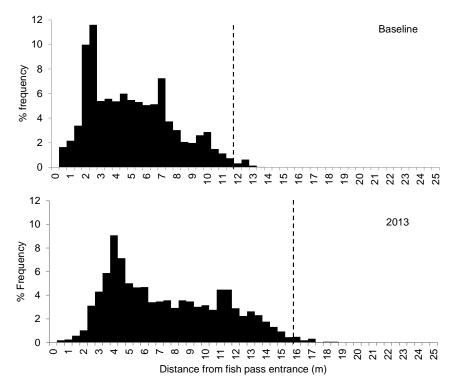


Figure 54. Numbers of tag detections in the array as a percentage of the total number of tag detections recorded in sea trout passage tracks, against distance from the entrance to the fish pass. Dashed lines indicate the approximate extent of the furthest hydrophone from the fish pass.

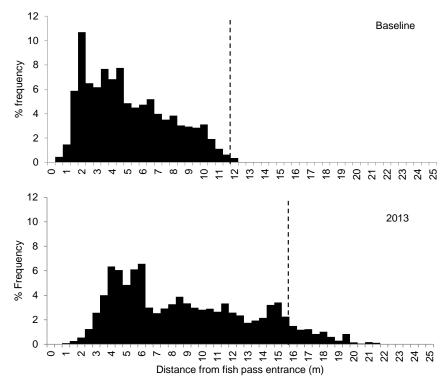


Figure 55. Numbers of tag detections in the array as a percentage of the total number of tag detections recorded in sea trout non passage tracks, against distance from the entrance to the fish pass. Dashed lines indicate the approximate extent of the furthest hydrophone from the fish pass.

3.5.4 Diel variations in spatio-temporal distribution within the array

There was no discernible difference in the distribution of tracks or the proportion of time spent within the array during the day and at night (Figures 56 and 57). In both cases tracks occurred more frequently towards the middle of the pool / right-hand bank rather than near the weir face. Also in both cases hotspots in average time spent in cells were apparent in front of the hydropower screens near the right-hand bank. The frequency of tag detections decreased with distance above a 4.0 m proximity from the fish pass entrance during both the day (Figure 58) and night (Figure 59). In both cases a number of different key locations were suggested at 8-9m and 14-15m from the fish pass entrance.

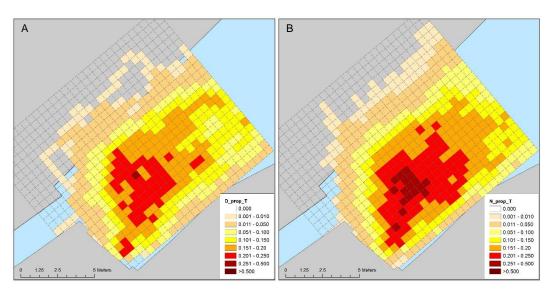


Figure 56. Proportion of sea trout tracks to pass through each grid cell (standardised by number of tracks in each group) during the day (left) and at night (right) in 2013.

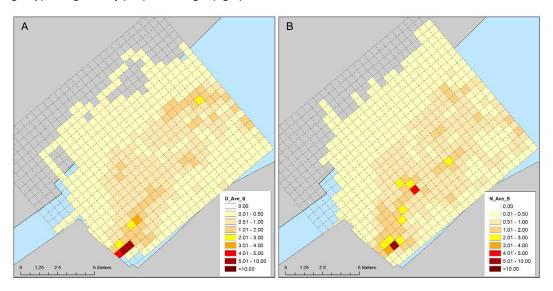


Figure 57. Average time (seconds) spent in each grid cell by sea trout during the day (left) and at night (right) in 2013.

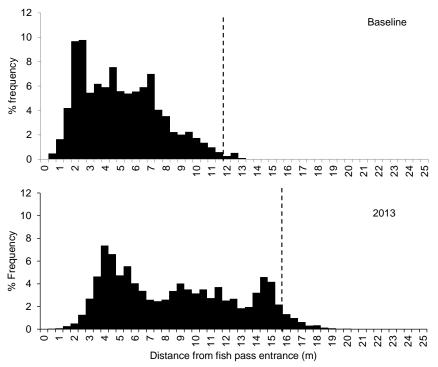


Figure 58. Numbers of tag detections in the array as a percentage of the total number of tag detections recorded during the day, against distance from the entrance to the fish pass. Dashed lines indicate the approximate extent of the furthest hydrophone from the fish pass.

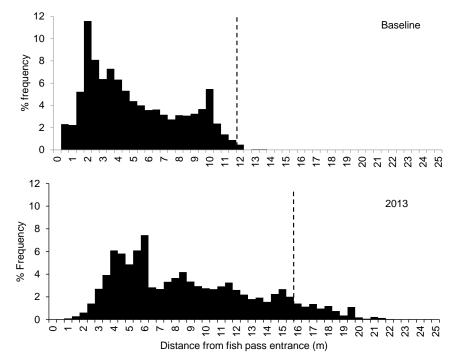


Figure 59. Numbers of tag detections in the array as a percentage of the total number of tag detections recorded during the night, against distance from the entrance to the fish pass. Dashed lines indicate the approximate extent of the furthest hydrophone from the fish pass.

3.5.5 Tide state and spatio-temporal distribution within the array

No discernible difference in patterns was observed between track locations at different tidal states (Figure 60). There was also little discernible difference in residence time

during the different tidal states, although fish present during ebb slack appeared to spend more time towards the rear of the pool (Figure 61). In other tidal states a hotspots of track occurrence and residence were located at the front of the hydropower screens, near the right-hand side of the pool (Figure 61).

Trends in the frequency of tag detections with distance from the fish pass entrance were similar between ebbing and flooding tides, with frequencies generally decreasing with distance from the fish pass (above a distance of 6 m). The highest frequencies of tag detections were recorded at 4.0-5.0 m proximity in flooding tides with tracks on ebbing tides occupying locations around 5.0-6.0 m from the fish pass a slightly higher proportion of the time (Figures 62 to 64).

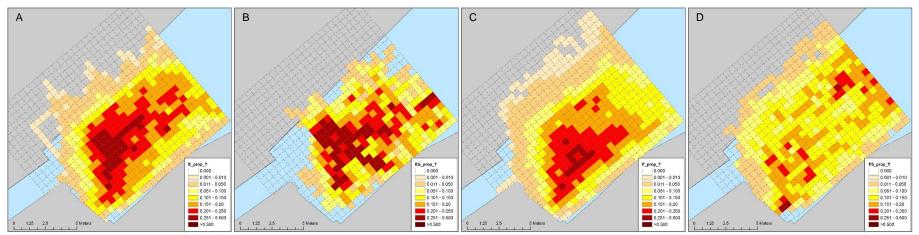


Figure 60. Counts of sea trout tracks to pass through each grid cell (standardised by the number of tracks in each group) recorded during an ebbing (left), ebb slack, flooding and flood slack (right) tide.

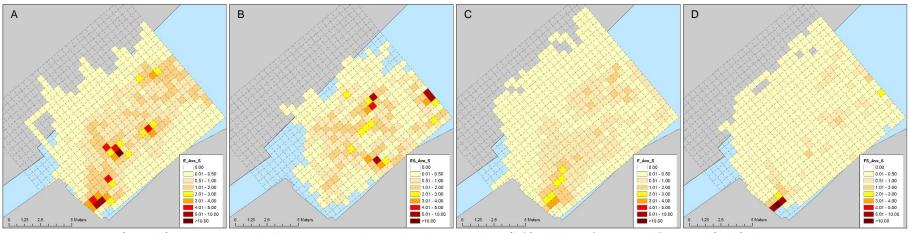


Figure 61. Average time (seconds) spent in each grid cell in sea trout tracks recorded during an ebbing (left), ebb slack, flooding and flood slack (right) tide.

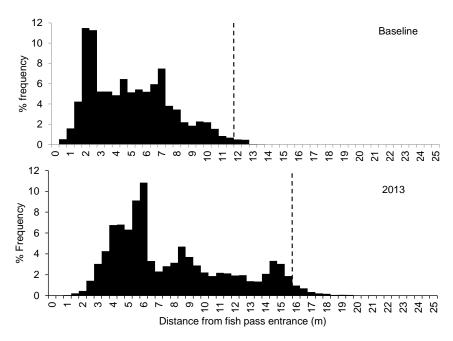


Figure 62. Numbers of tag detections in the array as a percentage of the total number of tag detections recorded during ebbing tides, against distance from the entrance to the fish pass.

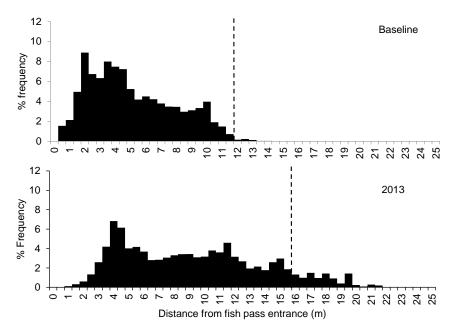


Figure 63. Numbers of tag detections in the array as a percentage of the total number of tag detections recorded during flooding tides, against distance from the entrance to the fish pass.

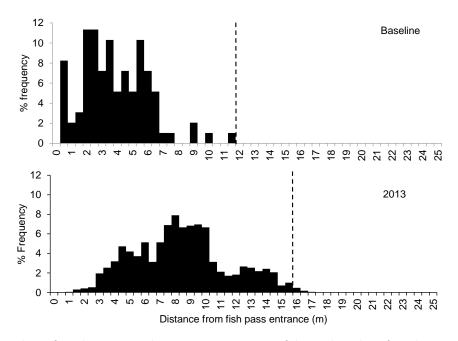


Figure 64. Numbers of tag detections in the array as a percentage of the total number of tag detections recorded during ebb low water, against distance from the entrance to the fish pass.

3.5.6 Discharge and hydropower turbine operation

Hydropower turbine operation data were occasionally not available; no turbine operation data was available for 14 sea trout tracks, including two passage tracks. In 2013 the majority of sea trout tracks were recorded whilst the hydropower turbine was active; 52 (11%) of the 480 tracks (with associated turbine operation data) occurred when the turbine was not operating. Fish tracks were recorded across the full range of turbine speeds (minimum 400rpm up to around 1800rpm). The only residence time hotspot when the turbine was inactive was towards the rear of the array near the weir face (Figure 65a). 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 >3m³s⁻¹) (Figure 65e). Hotspots in residence time were observed at most river flows lower than the long term seasonal Q25 (≈ 6.3 m³s⁻¹) and were less apparent at flows greater than this and were absent at flows greater than Q10 (≈ 13.6 m³s⁻¹) (Figure 66a-d).

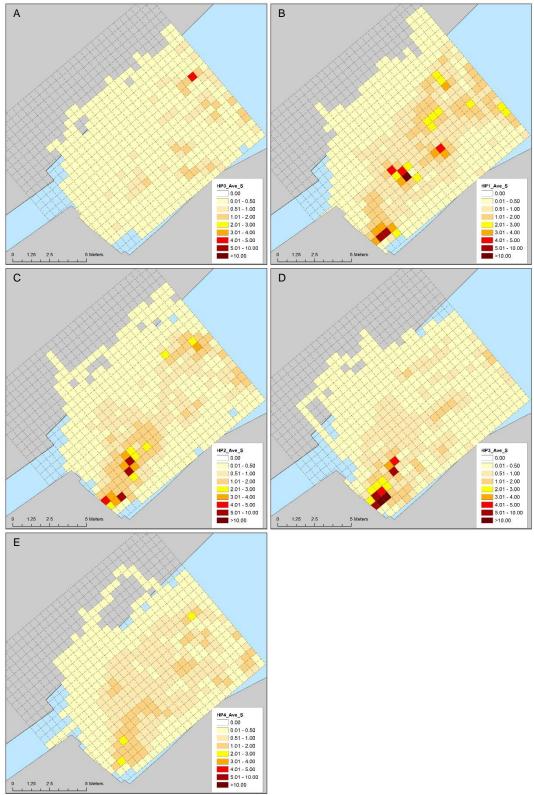


Figure 65. Average time spent in each cell by sea trout recorded during five classes of hydropower flows (0.0 (HP0, n = 52), 0.1-1.0 (HP1, n = 109), 1.1-2.0 (HP2, n = 57), 2.1-3.0 (HP3, n = 107) and 3.1-4.0 (HP4, n = 155) cumecs).

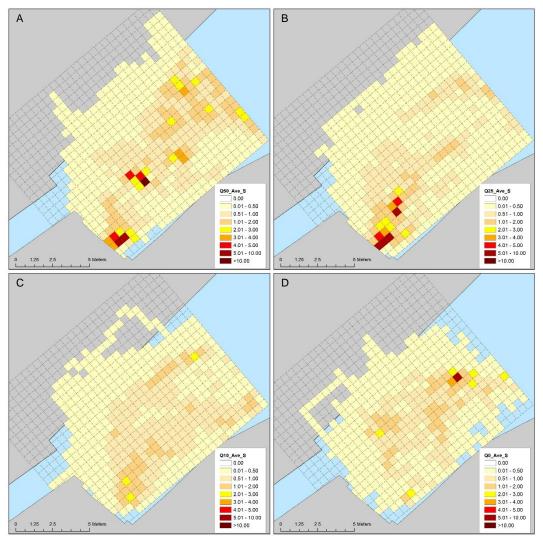


Figure 66. Average time spent in each cell by sea trout recorded during four classes of river discharge – Q100 to Q50 (Q50, n = 127), Q51-Q25 (Q25, n = 167), Q24-Q10 (Q10, n = 156) and Q9 to Q0 (Q0, n = 45) based on the long-term average seasonal hydrograph for the period 1/8 to 31/12 2000 to 2012.

3.5.7 Fish passage approach

In 2013 relatively few fish were recorded within 2m of the Larinier pass entrance; both non-passage (Mann Whitney U-test: Z = -4.200, n = 534, P < 0.01) and passage tracks (Mann Whitney U-test: Z = -3.924, n = 42, P < 0.01) contained significantly fewer approaches in 2013 than in the baseline. Only 110 approaches were recorded across all tracks in 2013 at an average of 0.22 approaches per track (maximum of 13 approaches in a single track), compared with an average of 2.44 per track for sea trout in the baseline (maximum 66 approaches in a single track). In fact many passage tracks (route confirmed by H1 in the fish pass) were last located more than 2m from the pass entrance. In summary, fish don't appear to occupy or traverse this area prior to ascent and move through it quickly during passage tracks. This can probably be attributed to the pool immediately downstream of the fish pass being far shallower than during the baseline (see Section 3.6) and associated changes in hydraulics. Additionally the changes in hydraulics have potentially reduced the efficiency of tag detection within this zone. Regardless, approach analysis, as defined by this 2m buffer, is no longer a useful metric to describe approaches to the fish pass or attempts to pass.

4 Discussion

4.1 Potential impacts of the hydropower development on upstream fish migration

This report summarises and analyses the fish tracking data from 24th September 2013 to 14th February 2014, the first year of monitoring since the commissioning of the Ruswarp Weir low-head hydropower scheme. These data are analysed in comparison with the established baseline (Noble et al. 2013) as the first step towards 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. This report should be viewed as an initial analysis of post-commissioning data and not a final analysis of the influence of the Ruswarp Weir hydropower scheme on sea trout migration. The discussion section here summarises the key findings for fish passage efficiency, the duration of migratory behaviours prior to fish passage and the microscale behaviours of sea trout in hydrophone array downstream of the fish pass and hydropower scheme. These initial findings are reviewed in the light of existing knowledge of sea trout migration to determine whether there may be any early indications of ecologically significant changes to migration behaviour and fish passage in the River Esk.

The potential hydrological impacts of the hydropower development were previously considered in Kibel & Coe (2009). Specifically, that the lowest flow of water in the fish pass (1 cumec) would form a minimum of 25% of the maximum turbine take of 4 cumecs (Mike Ford, pers. comm.), well above the minimum suggested value of 5% (Kibel & Coe, 2009). Analysis of the hydrology and hydropower operation data from 2013 indicated that this scenario occurred approximately 20% of the time. The hydropower turbine was not operational for 23% of the study period. In the other 57% of the time the flow down the fish pass constituted more than 25% of the hydropower discharge. 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. When the hydropower was operational the weir appeared to overtop at a river discharge of around 6 m³s⁻¹ (reflecting the balance of up to 4m³s⁻¹ through the turbine, a minimum of 1m³s⁻¹ down the Larinier and around 0.5 m³s⁻¹ down the baulk pass). It is therefore inferred that previously the water flowing thought the hydropower scheme (up to 4m³s⁻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 6m3s-1. During spring tides the hydropower was not operational (due to reduced head) and the weir over-topped at lower flows, presumably because 4 m³s⁻¹ passed over the weir rather than through the turbine. The turbine was seemingly not always affected by neap tides although it is not clear at which specific tide height the effect starts. The result of this is that the weir would have been overtopped for less time than previously 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 impacts (amended here) that the hydropower development on Ruswarp Weir, which included changing the fish pass from pool-traverse to a Larinier, could have on upstream migration behaviour of fish:

- Channel engineering downstream of the hydropower installation combined with increased discharges at the upstream end of the weir (up to approximately 5 m³s⁻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 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 m³s⁻¹) may distract fish from finding the fish pass entrance (rated at a minimum flow of 1 m³s⁻¹), with fish being attracted to the turbine discharge (fish attraction to the entrance of fish pass is impacted). Fewer fish find / enter the fish pass or are delayed in the migration.
- Flow diverted through the Archimedes screw may remove valuable water from the fish pass reducing the attractiveness of the pass and potentially the functioning of the pass for migrating fish. This is not likely now with the control over discharge rating through the new Larinier pass.
- The route up the side of the fish pass is changed (in terms of availability and attractiveness) with 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, the efficiency of the route or the duration for which this route was available. Whilst no tagged fish were observed to pass via the side of the fish pass in 2012 or 2013, numerous untagged fish were observed (both successfully and unsuccessfully) attempting to ascend the weir via this route in 2013.

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 passage efficiency). Specifically, the overall passage efficiency was defined as the proportion of potential migrants (all tagged fish) which successfully ascend the weir. This overall metric was also separated into two distinct aspects; the ability of fish to find the entrance to the pass (attraction efficiency) and the passability of the fish pass (fish pass efficiency). 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 2013 dataset 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 Observations in 2013

4.2.1 Overall passage efficiency

The overall passage efficiency for sea trout, i.e. the proportion of potential migrants (all tagged fish) which successfully ascended the weir (see Section 4.1) was 56% (26 / 46), and around 60% greater than in the baseline (35%, 17/48), although this observed difference was not statistically significant. This observed difference in passage efficiency is difficult to explain given the lack of data for the fate of fish not observed in the array during the baseline. However, analysis of the fates of unsuccessful migrants during 2013 may be used to evaluate potential fates of those fish that did not pass the weir (Section 4.2.2).

4.2.2 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 (including predation, e.g. seals and cormorants), expelled the tag, ascending other local rivers (e.g. Stewart *et al.* 2009 = 50%), return to sea for the study period or tag failure (technical fault or battery expiration). 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 and the fate of tagged fish to be elucidated.

Firstly, the data from the mobile loggers can be used to evaluate potential levels of predation/tag loss/failure. Of the 13 tags not detected in the array in 2013, six were not detected at all after release and seven were only detected on the mobile loggers (i.e. not in the hydrophone array). Four of the six tags that were never detected were from batch three (released 1/11/13) when up to three seals were spotted at the release site (S. McGinty EA *pers. comm.*). The inference here is that the majority of tag disappearances from the release site (those never detected again) may be attributable to predation of tagged fish soon after release (See Figure 17 in Section 3.1.2).

Of the 33 tags detected in the array, seven were not detected to ascend the weir, of which two returned to Whitby whilst three were last located at Noble's Yard. A further two tags from batch three were subsequently identified on loggers at Whitby, Noble's Yard and in the array at exactly the same times and for the same duration, neither of these tags were detected to pass the weir so it was assumed that both of these tagged fish had been consumed, probably by a seal soon after release. 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 be eaten) (8 of 47, 17%) 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 11 of 47, 23%) (See Figure 17 in Section 3.1.2). These potential levels of predation and mortality indicate that predation of fish in the upper estuary may be a significant factor in the success of fish passage. The seals observed in the lower River Esk are probably a low number of seals that have specialised in feeding in tidal waters rather than on the main coast. Graham et al. (2011) identified that "roque" seal in rivers fed more often on adult salmonids that 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 seal on tagged sea trout may have been in the region of 47% of tagged fish within the first 2.5 days after release.

Secondly, of the 41 fish detected on all loggers, 27 were first detected at Noble's Yard whilst 14 (30% of fish) moved downstream to Whitby after release; six of these fish did not return to the river whilst the rest were subsequently detected in the array. 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, six were last observed at Noble's Yard and two were last observed at Whitby. Given these figures it is possible to estimate a minimum estimate 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; 8 of 47, 17% (6 went out to Whitby without re-ascending whilst two returned but then left to Whitby without ascending) (See Figure 17 in Section 3.1.2). 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.

Although these figures given an indication of the fates of tagged in 2013 and perhaps give an indication of the potential relative influences of mortality/tag failure and motivation/straying on the data in 2013, these data cannot explain the large difference in overall passage efficiency between the baseline and 2013. 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, further data would be required to determine how variable migration behaviour and predation levels may be between years in relation to hydrological conditions before this could be used to explain differences in detection of tagged fish in each year.

4.2.3 Fish tracking and detections – fish pass attractiveness

In 2013 one salmon and 46 sea trout were tagged for tracking. Of these 46 trout, 31 (67%) were detected within the hydrophone array, and a further 7 (15%) were only detected on a one or more of the three mobile hydrophones. This gives a measured attraction efficiency of 67% in 2013 (31/46). This was a significantly higher return rate on the tagged fish (67% in the array and 82% overall) 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 indicates that there was potentially a 91% increase in attraction efficiency between the baseline and 2013.

It is unclear why the detection rates in the array in 2013 were virtually double those from 2011 and 2012. Of all the tagged fish detected on the mobile hydrophone (see Section 4.2.4) at Noble's Yard in 2013 (n = 32; not in situ in 2011 or 2012) only one was 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 in 2013 were the motivations and / or ability of fish to reach the weir, rather than factors once the weir is encountered. The operation of the hydropower scheme will not have altered the conditions in the tidal reaches of river further downstream of the weir (in that the total discharge does not alter 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). However, flow and level data suggest that the operation of the hydropower scheme have 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 <6m³s⁻¹ the majority of discharge will pass through the fish pass and hydropower scheme, with little or no water overtopping the weir face, which may potentially have made the fish pass pool more attractive/approachable under a wider range of flows. Indeed, at a total river flow of 6m³s⁻¹ up to 4 m³s⁻¹ of the discharge would have been dispersed across the weir face prior to the hydropower development. It is impossible to determine whether any changes between 2011/2012 and 2013 in attraction efficiency might relate to changes in the probability of a fish reaching the weir or changes in the ability of fish finding the fish pass once the weir is reached. However, the fates of unsuccessful migrants in 2013 would suggest the former to be more likely than the latter (i.e. nearly all fish that found the weir were shown to find the fish pass pool). It is therefore possible that it was the general conditions in the river and/or different levels of predation, tag loss and/or tag failure that may account for differences in the attraction efficiency observed between 2013 and the baseline. Certainly the general hydrological conditions were very different between the three years (2011 was very dry and low flows, 2012 was very wet and 2013 somewhere just below the average for the river) and this alone may have affected the migratory behaviour and success of migration in each year. As such it is critical that judgments on the passage efficiency, fish pass efficiency and attraction efficiency with the hydropower scheme active are not based solely on one year of data.

4.2.4 Fish pass efficiency

Twenty five of the 31 tagged sea trout and the only tagged salmon in 2013 were detected in the hydrophone array downstream of the fish pass and ascended via the fish pass; giving sea trout fish pass efficiency = 81%. In addition, one of the sea trout detected in the array ascended via another route (assumed to be the baulk pass) (see Section 4.2.1). As described in section 4.1, the fish pass efficiency was defined as the proportion of tagged fish detected in the array that ascended via the fish pass. Consequently fish pass efficiency for sea trout was observed to lower in 2013 (81%) than in the baseline (100%; 17/17) although this difference was not statistically significant. This suggests that whilst a larger proportion of tagged fish found the fish pass in 2013 (see Section 4.2.2), a proportion of these migrating fish were unsuccessful in using the fish pass, a feature not previously observed (except for one salmon in the baseline in 2012).

This potential reduction in fish pass efficiency is of concern, especially considering that it has been suggested that a successful upstream passage facility should pass more than 95% of the migrating adult fish (Ferguson *et al.* 2002). Furthermore, the EA fish pass manual states targets of a minimum fish pass efficiency of 80% for adult returning migratory salmonids (unless there is significant spawning habitat downstream), although with minimum target level of 90% if the pass is downstream of spawning habitat and multiple barriers are present on the system. Therefore, the measured fish pass efficiency in 2013 is below that aimed for by the EA. Despite this, the 81% passage efficiency for sea trout is within the range of observations in other studies. 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%. However, it should

be noted that there are considerable differences between the conditions observed for the majority of the baseline and the 2013 dataset. In particular the design of the pass was changed in 2012 and the prevailing river levels were very different between each study year. As such it is currently too early to determine if this potential reduction in efficiency was a feature of overriding hydrological conditions, a result of the different fish pass design or a result of the activity of the hydropower scheme.

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 in 2013 and the baseline there were differences observed in the number of tracks in the pool, the duration of tracks in the pool and the time from first arrival in the pool to final passage. In both the baseline and the data from 2013 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 (<48hrs) 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 (in 2013 only).
- 3. Fish that dropped back downstream for an appreciable amount of time (up to 25 days) 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 in 2013).

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 stimuli). 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 <24hrs; multiple visits separated by >24hrs) 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 31 (6%) in 2013 (and both of these fish were from batch one, caught and released under low flows). The flows in 2011 (the majority of the baseline) were far lower than in 2013 indicating that this class of migration behaviour is positively associated by low flow conditions reducing the stimuli for fish to ascend the river.

In 2013 the average total time spent in the array by sea trout prior to passage was significantly longer than in the baseline dataset. However, the duration of individual non-passage tracks in 2013 was significantly shorter than in the baseline dataset. There was no significant difference in the average duration of passage tracks in the baseline dataset and in 2013. 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. In 2013 only 26% of sea trout (32% of the tagged sea trout that actually ascended)

spent less than ten minutes in total within the array prior to passage via the Larinier pass and 64% of tagged sea trout spent longer than 30 minutes in the array before either ascending or dropping back downstream. In the baseline 70.5% of sea trout passed the weir within one hour of their first detection in the array whilst in 2013 only 32% of sea trout passed within one hour of first detection and seven sea trout (28%) took longer than 12 hours to ascend. The total time between first detection and passage was significantly longer in 2013 than in the baseline. When excluding fish that took longer than 12 hours to ascend (more than one tidal cycle) the median time from first detection to ascent by sea trout was 0.17 (0.09 - 0.92) hours in the baseline and 1.23 (0.64 – 2.83) hours in 2013. During this time prior to passage in 2013 sea trout spent significantly lower proportion of the time in the array compared to the baseline. This indicates that in 2013 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 loggers 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 in 2013 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). The change in the delay observed here is relatively small with few fish taking more than a day to pass after first arrival. It is difficult to determine whether the longer ascent time has any relation to the activity of the hydropower potential distracting fish from finding or accessing the fish pass (Section 4.2.5). The overall discharge conditions between the majority of the baseline (lower than average flows in 2011) to 2013 (higher flows) 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.

Although 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, it is difficult to determine whether the delays observed in 2013 (a change in the median delay of 0.17 to 1.23 hours from first arrival in the array) 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 in 2013 (a matter of hours for successful migrants) are probably 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 the risk of predation is less easy to evaluate. The majority of possible predation identified in the 2013 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 (8 of 12 missing fish) occurred in the tidal river prior to the fish reaching the weir. However, four fish reached the weir (3 got into the array) but went missing without ascending. So whilst the majority of predation may occur in the lower river, some levels of predation could 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.

4.2.6 Micro-scale behaviour of migrating sea trout

Spatial data of fish behaviour within the pool from 2013 indicated similar patterns to the baseline in that tracks were spread throughout the array. However, data from 2013 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 screens 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 in 2013 (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 <6m³s⁻¹, i.e. when the weir was not over-topping and the discharge from the hydropower scheme (0.1 to 3 m³s⁻¹) was up to 3 times the discharge from the fish pass (~1m³s⁻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 distracting fish from the fish pass plume at flows 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 1m³s⁻¹). Once the weir overtops and appreciable water is flowing down the side of the fish pass the relative influence of the two flows changed. This potential situation has been observed elsewhere for large scale hydro schemes. 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. Whilst this is an example of a much larger system with a distinct turbine outlet versus bypass channel entrance it appears that turbulence from the turbines at Ruswarp may be distracting sea trout from the Larinier plume. However, given that 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 visually less turbulent parts of the pool (and assumed lower flow velocities), and as such, the hotspot may represent a location of refuge and resting rather than distraction (although ADCP studies of flows in the pool would be needed to determine if this is an area of lower flow). This study has 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) 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.

This shift in track distribution also included a reduced proportion of detections of within 2m of the mouth of the fish pass and reflected in reduced detections of approaches to within 2m of the fish pass entrance in 2013 compared with the baseline. The nature of the 2m approach zone of the fish pass changed considerably after the installation of the Larinier pass. Whereas previously this area was the deepest part of the pool this area is now much shallower with greatly aerated water due to the Larinier plume which made tracking of fish in this location difficult (see Appendix 4 for summary of a study using beacon tags which identifies variable tracking efficiency under different conditions and in different parts of the pool) and probably less attractive for prolonged occupation. These conditions also potentially mean that the "approach" to the fish pass could be considered to extend further into the pool than before. This, combined with difference in tracking efficiencies, means that the definition of the fish pass approach

metric from the baseline dataset is not appropriate to the data from 2013 (both due to potential changes in approach behaviours and the ability to track fish in this area). As such metrics like "fish pass approach" may need to be re-defined to allow comparison of approach behaviours between the baseline data and the post-commissioning dataset.

4.3 Interim conclusions and recommendations

The data from tracking sea trout during 2013 raised four key conclusions:

- (1) The proportion of tagged fish that successfully passed the weir (passage efficiency) was greater in 2013 than in the baseline dataset although the difference was not statistically significant (Section 4.2.1).
- (2) The fish pass efficiency of sea trout detected in the array reduced from 100% in the baseline to 81% in 2013 although the difference was not statistically significant (Section 4.2.4).
- (3) The delay between arrival in the pool and eventual passage was, whilst statistically significantly greater in 2013 than in the baseline, probably of little energetic consequence given the overall scale and duration of the sea trout migration (Section 4.2.5). However, it is possible that this delay may have consequences for successful passage in relation to potential increased risk of predation before passage.
- (4) There is 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 <6m³s⁻¹, when the weir was not overtopping and the turbine abstraction was <3m³s⁻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 or being distracted from the fish pass plume by the outfall from the hydropower screw (Section 4.2.6).

Given that the differences in behaviour observed between the baseline and the data from 2013 are confounded by the change in the design in the fish pass, the changed bathymetry of the pool and different hydrological conditions in each year it is too early to determine whether the observations in 2013 can be attributed to the activity of the hydropower scheme. The observed reduction in fish pass efficiency of fish tracked in the pool is offset by the observed increase in overall passage success of all fish in 2013, although further years study are required to determine if this is a verifiable and an ecologically important change in fish pass efficiency. One of the major factors that may influence the passage efficiency in any year may the motivation to migrate (related to time of year and river flows) and the predation/mortality rates linked to delayed migration in the estuary. Further studies into the predation by seals on the Esk would be required to identify if this is a significant factor in tagged sea trout failing to ascend the weir. Additionally, an ADCP study of the hydrology of the pool needs to be undertaken to assess the distribution of water velocities and related that to the occupation of the pool by sea trout.

4.4 Future delivery

Although the 2013 season yielded data for more fish and tracks than expected the potential differences observed between the 2013 data and the baseline study indicated that the study needs to continue for at least one more season (the original study design anticipated three years post monitoring of which 2013 was the first). This is particularly important to ascertain whether the variability of hydrological conditions between study

years is the overriding factor explaining the differences observed. It is also recommended that the EA undertake an ADCP study of the fish pass pool to determine the distribution of flow velocities between the fish pass plume and the outfall of the hydropower scheme.

The monitoring undertaken from 2011 to 2013 has developed a tagging and tracking protocol, particularly with the use of the three mobile hydrophones in 2013, that has generated highly successful returns of tagged fish and good resolution tracking data to explain observed behaviours. Further tracking in 2014 should follow the protocol developed by HIFI of working around high tides and reactive tagging following spate events (at levels where wading is possible), to optimise chances of catching fish and to rationalise costs. However, as previously stated this work can only be taken under flow conditions where this is safe to do so (ideally with levels lower around 0.70-0.90m on the Briggswath gauge and on the falling limb of a spate). Ideally the tracking array and mobile hydrophones should be installed and operational from early August and thus enable study of spates in late summer early autumn that have been missed in previous years (in 2013 due to it only being possible to deploy the array once on site bank reinforcement had been finished by contractors). However, whilst data concerning migrations at this time will be of interest and of use for assessing efficiency of the fish pass, effort should not be diluted from ensuring that sufficient data are collected for migration during time periods comparable with 2013 and the baseline (October to November).

Whilst the data from 2013 suggest that the mobile logger at Gary's Hut may have been superfluous to the H8 logger in terms of detecting fish ascending the river via a route other than the Larinier pass (indeed no data from Gary's Hut have been reported here) the overlap between Gary's Hut and H8 this does provide a level of redundancy that would protect against data loss due to a prolonged power cut to the mains operated ATS system. As such, whilst it would be interesting to collect data pertaining to some other aspect of migration behaviour (arrival at Sleights or movement through some other point of the estuary) the mobile hydrophone should remain at Gary's Hut to ensure fish passages are detected from all routes and under all conditions. Additionally, given the variables that change/have changed during the course of the study (seasonal flow, the fish pass design, the hydropower scheme, the nature of the pool etc.) it would be beneficial to avoid changing any element of the study until the post-commissioning monitoring is complete.

The changes observed in the geomorphological and hydraulic conditions of the fish pass pool, in relation to the behaviours of migrating sea trout have indicated that some metrics defined during the baseline may now not be appropriate for analysing the postcommissioning dataset, or may need redefining to enable direct comparison between years. For example in 2011, when the fish pass was of a pool-traverse design, fish pass approaches were defined as movements to within 2m of the fish pass entrance. Since the introduction of the Larinier pass the new hydraulic conditions mean it is difficult to track fish in this area and additional fish spend less time in the area and enter/traverse it less often. Furthermore, many passage tracks were last detected outside of the 2m zone. Given the new conditions a new definition of a fish pass approach may need to be defined (for example it could now be defined as entry into the fish pass plume, which extends up to 5m into the pool along the weir face) to enable potential changes in behaviours to be measured between the baseline and post commissioning dataset. The final comparison of the baseline with the complete postcommissioning dataset will need to review all of the metrics proposed in baseline reports to determine their efficacy.

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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.

Approach: A section of a fish track was classified as an approach if a 2m buffer around the entrance of the fish pass was intersected by that track section.

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.

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 an orange to red appearance indicating the cells high time value.

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.

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	М	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	М	560	2.175	15/10/2013	17:45
	2542	Sea Trout	М	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	М	620	2.307	15/10/2013	17:45
	2577	Sea Trout	F	520	1.375	15/10/2013	17:45
	2584	Sea Trout	М	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	М	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	М	480	1.100	15/10/2013	17:45
	2640	Sea Trout	М	540	1.300	15/10/2013	17:45
	2647	Sea Trout	М	540	1.450	15/10/2013	17:45
	2654	Sea Trout	М	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	М	520	0.975	01/11/2013	16:40
	2689	Sea Trout	М	620	2.150	01/11/2013	16:40
	2696	Salmon	F	640	2.750	01/11/2013	16:40
	2703	Sea Trout	М	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	М	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	М	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

Batch	Tag	Species	Sex	Length (mm)	Weight (kg)	Date of release	Time of release
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
	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	М	590	2.225	22/11/2013	14:00

Summary of fish tagged in 2012

Fish #	Tag (msec)	Period	Length (mm)	Species	Sex	Capture date and time
1	2500		527	Sea trout	male	20/08/2012 19:00
2	2507		490	Sea trout	male	20/08/2012 19:00
3	2514		610	Salmon	male	20/08/2012 19:00
4	2521		548	Salmon	male	20/08/2012 19:00
5	2528		553	Salmon	male	20/08/2012 19:00
6	2535		515	Sea trout	male	21/08/2012 06:00
7	2542		616	Sea trout	female	18/09/2012 18:00
8	2549		589	Salmon	male	18/09/2012 18:00
9	2556		538	Sea trout	male	19/09/2012 18:00
10	2563		463	Sea trout	female	19/09/2012 18:00
11	2570		588	Sea trout	male	19/09/2012 18:00
12	2577		607	Salmon	female	19/09/2012 18:00
13	2584		477	Sea trout	male	19/09/2012 18:00
14	2591		815	Sea trout	male	19/09/2012 18:00
15	2598		483	Sea trout	male	19/09/2012 18:00
16	2605		638	Salmon	male	27/09/2012 16:00
17	2612		807	Salmon	male	27/09/2012 16:00
18	2619		608	Salmon	male	28/09/2012 12:00
19	2626		670	Salmon	male	28/09/2012 12:00
20	2633		735	Salmon	female	28/09/2012 12:00
21	2640		657	Salmon	female	28/09/2012 15:00
22	2647		640	Salmon	male	28/09/2012 15:00
23	2654		703	Salmon	female	28/09/2012 16:00

Summary of fish tagged in 2011

Date tagged	Species	Sex	Length (cm)	Tag period (msec)
10 Oct	Sea trout	Male	56.0	2514
	Sea trout/salmon	Male	59.5	2521
	Sea trout	Female	61.0	2528
	Sea trout	Male	64.0	2535
	Sea trout	Female	49.0	2542
	Salmon	Male	60.0	2549
	Sea trout	Female	60.0	2556
	Sea trout	Male	64.0	2563
	Sea trout	Female	59.5	2570
11 Oct	Sea trout	Male	64.0	2577
	Sea trout	Male	57.5	2584
	Sea trout	Male	59.5	2591
	Sea trout	Male	63.0	2605
	Sea trout	Male	53.0	2626
	Sea trout	Male	48.0	2633
	Sea trout	Male	58.0	2640
	Sea trout	Female	52.5	2647
	Sea trout	Male	61.0	2654
	Sea trout	Female	57.0	2661
	Sea trout	Male	53.0	2668
	Sea trout	Male	55.5	2675
	Sea trout	Male	56.0	2682
	Sea trout	Female	49.5	2689
	Sea trout	Female	57.0	2696
	Sea trout	Male	59.0	2703
	Sea trout	Male	54.5	2710
	Sea trout	Female	38.0	2717
	Sea trout	Male	70.0	2738
	Sea trout	Female	59.5	2724
	Sea trout	Male	64.0	2731
24 Oct	Sea trout	Female	52.5	2738
	Sea trout	Female	65.5	2745
	Sea trout	Female	59.0	2766
	Sea trout	Male	54.0	2773
	Sea trout	Female	58.0	2780
	Sea trout	Female	56.5	2787
25 Oct	Sea trout	Female	46.0	2752
	Sea trout	Male	59.0	2759
	Sea trout	Female	55.5	2794

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

BEACON TAG STUDY

Eight tags were fixed to weighted lines and left in the array for 3 weeks following the completion of the tracking study to evaluate the precision and performance of the ATS array (Figure A). The "tracks" from these tags were analysed for precision in location and consistency in detection.

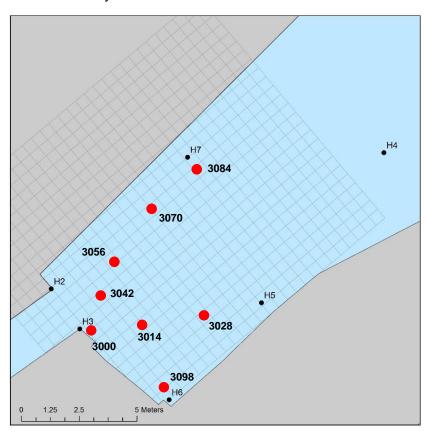


Figure A - Approximate locations of eight tags positioned as beacon tags to assess the precision and performance of the ATS under different flow and tide conditions. Tags 3042 and 3056 were located within the plume from the fish pass and 3014 was located in the main plume of visually more turbulent water from the hydropower turbine.

The tracks were analysed from a range of different hours during the period representing different flow, tide and generation conditions (six scenarios shown in Tables A and B). The analysis indicated that under some of the scenarios consistency of tag detection was compromised as some tags were received consistently by less than 3 hydrophones. More analysis is required for this dataset to fully evaluate the precision and consistency of locations, in particular for tag 3042 which was within the 2m approach to the fish pass and was not consistently detected.

Table A – Six different hour file scenarios studied for precision and consistency of tag detection in the array

Scenario	Turbine	Date	Hour	River Flow (m ³ s ⁻¹)	Tide height (m)
1	On	18/02/2014	06:00	9.63	5.2
2	On	26/02/2014	00:00	4.24	4.7
3	Off	13/02/2014	03:00	62.91	4.8
4	On	12/02/2014	07:00	10.4	2.1
5	On	26/02/2014	08:00	3.9	1.9
6	On	18/02/2014	18:00	8.9	5.4

Table B – Summary of the consistency of tag detections on the 6 hydrophones of the array in the six different hour file scenarios. The numbers represent the number of hydrophones on which "full" detection and "partial" detection (includes those hydrophones with full detection) for the hour was observed. A minimum of 3 hydrophone is required for triangulation – cases where less than 3 hydrophones had full or partial detection of tags are highlighted.

		Scenario													
Tag	1		2		3		4		5		6				
	Full	Partial	Full	Partial	Full	Partial	Full	Partial	Full	Partial	Full	Partial			
3000	2	4	6	6	4	5	2	3	4	6	4	6			
3014	3	6	5	6	4	4	3	3	5	5	6	6			
3028	4	6	4	6	4	4	2	3	3	5	5	6			
3042	2	5	4	6	4	4	1	2	3	6	5	6			
3056	4	6	5	6	4	4	2	4	5	6	6	6			
3070	4	5	6	6	4	5	3	4	6	6	5	6			
3084	2	3	3	5	0	0	2	3	3	4	4	5			
3098	4	5	4	5	4	5	2	3	2	4	5	6			

Summary of fish passage data in the baseline 2011 and 2012

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

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 array (ms ⁻¹)	in Time release passage (days)	from to	Route taken	Day / night
2703	St	59.0	0.01	1	00:05:00	18.73	0.06	0.02		FPS	D
2703 (2 nd	St		-	3	00:44:28	384.12	0.14	1.83		FP	D
passage) `											
2514	St	56.0	1.04	3	00:08:20	319.52	0.64	1.08		FP	N
2549	Sa	60.0	1.08	3	02:56:20	1250.76	0.12	2.42		FPP	D
2633	St	48.0	0.21	1	00:01:40	30.74	0.31	0.21		FPP	N
2591	St	59.5	0.25	2	00:19:39	276.15	0.23	0.33		FP	N
2710	St	54.5	0.25	1	00:15:14	166.52	0.18	0.25		FP	N
2577	St	64.0	0.29	1	00:00:41	15.69	0.38	0.29		FP	N
2661	St	57.0	3.17	1	00:01:33	18.02	0.19	3.17		FP	N
2647	St	52.5	1.79	2	00:07:40	76.57	0.17	1.83		FP	D
2773	St	54.0	0.10	1	00:01:43	27.73	0.27	0.13		FP	N
2745	St	65.5	0.21	1	00:04:24	56.67	0.21	0.21		FP	N
2794	St	55.5	0.71	4	00:50:33	537.40	0.18	0.71		FPS	D
2563	St	64.0	16.25	2	00:09:14	94.23	0.17	16.29		FP	N
2717	St	38.0	29.54	14	02:47:25	1374.02	0.14	29.62		FP	D
2640	St	58.0	42.08	1	00:04:45	109.37	0.38	42.08		FP	N

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