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

2014 Second Post-Commissioning dataset

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Report – Ruswarp_20142015

HIFI Final Report

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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 Esk Valley Community Energy Group (EVCEG) in association with the North York Moors National Park (NYMNP) at Ruswarp Weir (tidal limit) on the River Esk in North Yorkshire This became the Whitby Esk Energy Project that was developed by Esk Energy (Yorkshire) Ltd. This installation, 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 in 2011 and 2012) to assess baseline fish passage behaviour. The salmonids tracked in 2014 (16th October to 31st December 2014) constituted the second year of post-commissioning assessment.

In 2014 three salmon and 44 sea trout were tagged with acoustic tags under Home Office licence. Thirty-two sea trout (attraction efficiency = 73%) and two salmon (67%) 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 eight sea trout and one salmon were detected only on mobile hydrophones (particularly in Whitby Marina) and three fish were not recorded anywhere after release. A further two tags were recorded simultaneously on three different hydrophones (Noble's Yard, Whitby and the array) and it was assumed that these tags were inside a seal and that the predation event had actually occurred within the array. For these two fish one was treated as “missing” as it could not be certain when the first predation event occurred whilst the other, was treated as arriving in the array before predation (and thus contributing to attraction and fish pass efficiency metrics), although none of the tracks from these fish were used for further analysis. Twenty-two of the 32 sea trout observed in the array passed the weir; 18 (fish pass efficiency = 56%) via the Larinier fish pass and four via the baulk pass (only one baulk passage was recorded in 2013). 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) and the difference was statistically significant. Overall a much higher proportion (overall passage efficiency = 50% in 2014 and 57% in 2013) of tagged sea trout ascended the weir than in the baseline (35%) and the difference was statistically significant. In 2014 a much larger number of fish than in 2013 did not ascend the weir after being observed in the array (nine sea trout and one salmon) some of these dropped downstream and were last recorded Whitby (*n* = 2) although many were last recorded at Noble's Yard (*n* = 5) or the array (*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 2013/2014 and the baseline. In 2014 the average (median) total time spent in the array by sea trout prior to passage was 26.36 (2.44 – 76.87) minutes (*n* = 18) which was similar to that observed in 2013 and 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 2014 only 11% of sea trout spent less than ten minutes in the array prior to passage via the Larinier pass and 41% of tagged sea trout spent longer than 30 minutes in the array. However, the duration of individual non-passage tracks in 2014 was significantly shorter than in the baseline dataset, i.e. fish briefly visited the array more times in both 2014 and 2013.

In the baseline 70.5% of sea trout passed the weir within one hour of their first detection in the array (including time spent outside of the array) whilst in 2014 this had reduced to 33% and six sea trout (33%) took longer than 12 hours to ascend (similar to 2013). The total time between first detection and passage was significantly longer in 2013 and 2014 than in the baseline. The median time from first detection to passage by sea trout was 3.34 (0.40 – 18.11) hours (n = 18) in 2014 whereas in the baseline 70.2% of fish passed the weir within one hour of arriving in the array.

The ten sea trout that were detected in the array but did not ascend the weir in 2014 spent between 15 and 501 minutes in the array, with five of them spending more than 100 minutes in the array before leaving the array for the final time. Only 14% (n = 3 out of 22) of the sea trout that did pass the weir spent more than 100 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, 2014 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) was used to quantify, visualise and analyse micro-scale behaviours of fish below the fish pass and to enable comparison of fish behaviours between the baseline and post-commissioning. Data from 2014 indicated similar patterns to 2013 and the baseline in that tracks were spread throughout the array. However, data from 2014 and 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 in 2014 and 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 positions of passage tracks being outside this 2m zone. The exception to this were a few tracks of long duration made at high tides (>5.2m at Whitby) when fish were able to spend considerable lengths of time occupying an area immediately in front of the fish pass outfall. In 2014 and 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 appear to occupy this location as much when the hydropower was not operational. It was most apparent at intermediate discharges (flows less than 6.0 m^3s^{-1}, seasonal Q25) and levels of hydropower abstraction (1-3 m^3s^{-1}) but became less distinct at the highest river flows (flows > 10 m^3s^{-1}).

The results presented here and preliminary comparison between 2013/2014 results and 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 an increase in passage efficiency, reduction in fish pass efficiency and the increase in passage delay in the monitoring data for 2013 and 2014 do not necessarily translate to ecologically significant impacts on salmonid migration or population status. Furthermore, the data presented here represent only two of the three years of data collection for the full post-commissioning dataset. Therefore, recommendations for the final year of post-commissioning data collection, and analysis of the full post-implementation dataset against the baseline are presented.

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Contents

Table of tables

Table of figures

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 Esk Valley Community Energy Group (EVCEG) in association with the North York Moors National Park (NYMNP) at Ruswarp Weir (tidal limit) on the River Esk in North Yorkshire This became the Whitby Esk Energy Project that was developed by Esk Energy (Yorkshire) Ltd. This installation, completed in 2012, consists of a single Archimedean screw turbine (diameter = 2.9 m) adjacent to fish pass on the right hand bank. The turbine draws up to 4 m^3s^{-1} and was expected to generate approximately 50 kW of electricity (in practice maximum output has been 43kW). The operating head varies considerably depending on the state of the tide below the weir and the discharge of the river, with a maximum recorded operating head of 1.65m. 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 be used to help formulate and underpin guidance documents such as the Guidance for run-of-river hydropower development (Environment Agency, 2013).

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 second 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 two years post-commissioning of the hydropower turbine.
- To investigate the timing of fish movements and passages in relation to hydrodynamic and environmental cues.
- To make comparisons against the established baseline dataset.
- To make suggestions for future delivery of post-commissioning monitoring.

This report presents the monitoring data collected in Autumn/Winter 2014, the second year since the hydropower scheme has been in commission, and makes comparisons with the first year of post-monitoring and the baseline dataset for sea trout. The report follows the methods and materials described in Walton *et al.* (2012), Noble *et al.* (2013) and Noble *et al.* (2014) 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, namely sea trout (*Salmo trutta trutta* L.) and Atlantic salmon (*Salmo salar* L.), although catches of the latter have declined in the last 40 years whilst those of sea trout have progressively increased (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.

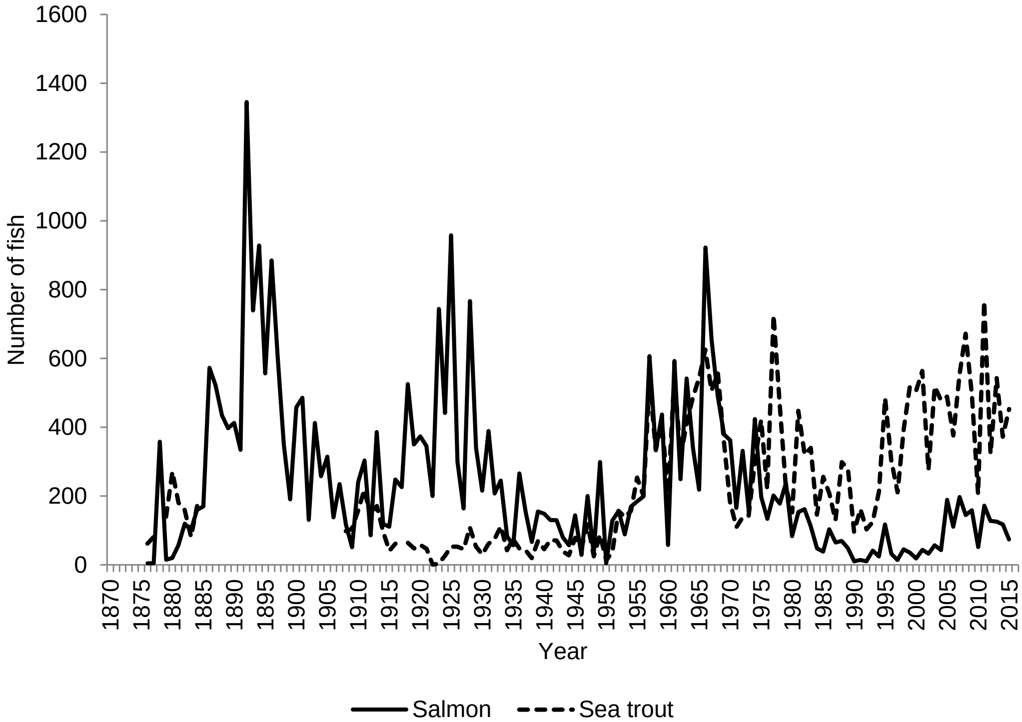


Figure 1. Trends in sea trout and salmon catches in the River Esk, North Yorkshire. Data for 2014 are provisional and the sea trout catches are included in the total for salmon for the period 1885-1902 (I Dolben EA pers. comm.).

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 2014 was identical to 2013 with one hydrophone (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. Since 2013 two changes have been made to the design of the hydropower scheme. Firstly, plastic curtains (see Figure 6) have been added to the outfall (outside of the metal screens) to mitigate for noise disturbance from the turbine and secondly the intake screens were modified on the 15th December 2014 to reduce turbulence at the intake.

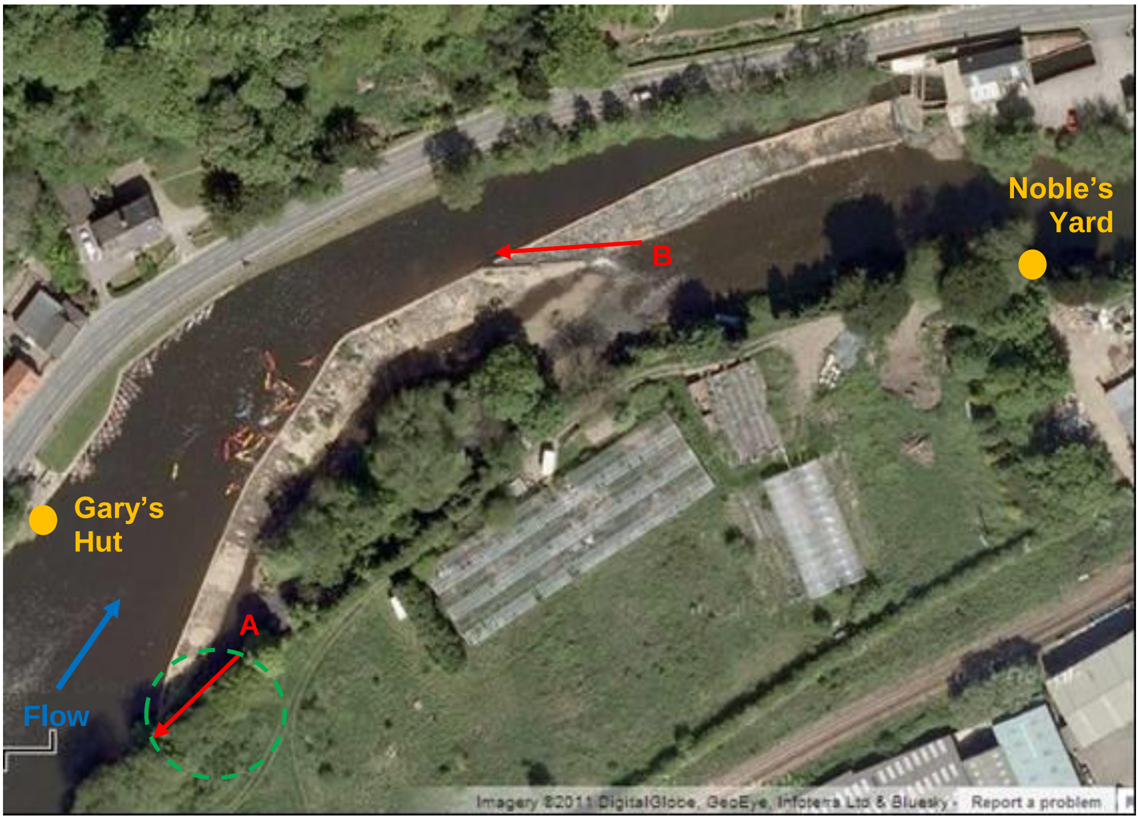


Figure 2. Aerial photograph showing the location of the fish passes (A – pool traverse pass (2011) / Larinier pass (2012 onwards); B – baulk pass) in relation to the weir (kayakers upstream of the weir give an indication of scale). The green circle marks the location of the new hydroelectric turbine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

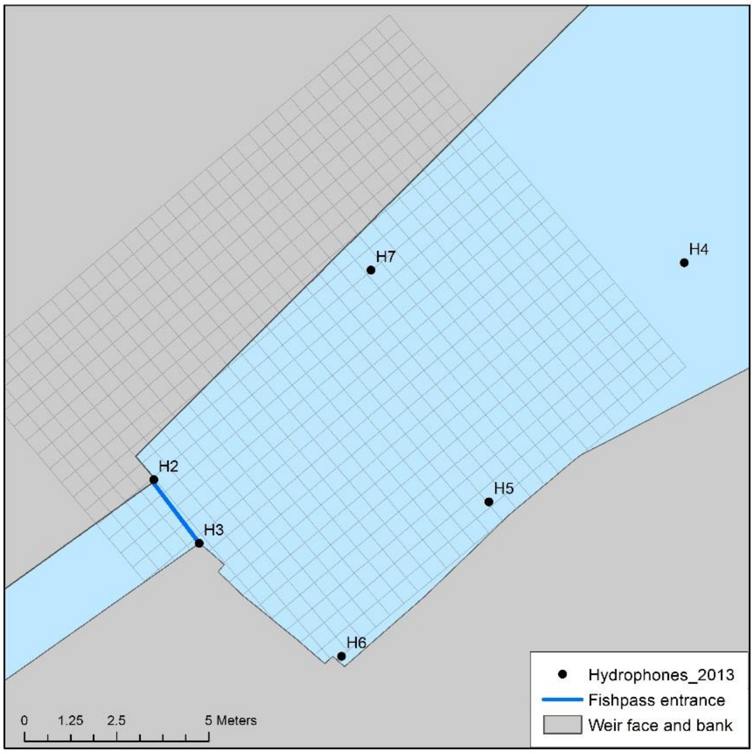


Figure 3. Diagram of the study site showing the positions of 6 of the 8 hydrophones used in the array for 2013 and 2014 (Section 2.3).

Figure 4. View of the Larinier fish pass entrance, hydropower outfall and hydrophones array showing the approximate positions of all 8 hydrophones in 2013 and 2014.

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 (flow 2.09m^{3}s^{-1}).

Figure 6. View of the outfall of the new turbine and hydrophones array in 2014 with the hydropower scheme active under higher flows (36.23 m^{3}s^{-1}). This figure highlights the visually more turbulent plumes of the fish pass, side of fish pass route and the left-hand side of the turbine outfall. The plastic curtains that act as sound baffles on the turbine outfall can also be seen.

2.2 Tagging

Fish were captured downstream of Ruswarp Weir on 16th October and the 4th , 10th & 18th 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. In 2014 a relatively large proportion of sea trout were rejected for tagging due to poor condition (visibly dark and not fresh run) or due to existing injuries (predator damage). Up to 50% of fish caught on the 4th and 10th of November 2014 were rejected. Fewer fish were rejected from the batches on the 16th of October (1 fish) and the 18th of November (2 fish).

Prior to tagging in the field, fish were anaesthetised using MS222 (40 mg L^{-1}). Species, sex, fork length (nearest mm), weight (nearest g) and fat content (hand-held % fat meter) were recorded. Fish were placed ventral side up in a clean V-shaped foam support. Tags were activated (pulse rate ranged from 2500-2822), 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 30-mm long, ventro-lateral incision made with a scalpel, anterior to the muscle bed of the pelvic fins. The incision was closed with an absorbable suture. The procedure lasted approximately 5 minutes. In all cases tag weight did not exceed 2% of the fish body mass (Winter, 1996). Fish were held in a well-aerated 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) (deployed on 10th September 2014 and removed on 19th February 2015). In 2014 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 and 2014 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 and 2014 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. In 2013 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 during the 2013 study to measure tag location accuracy and precision under different flow and tide conditions. During both years the array was visited frequently to inspect for damage (extreme spates posed a constant threat to the array) and remove debris (minimal).

In 2013 and 2014 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. The three mobile hydrophones were initially activated at 14.15 on the 16th of October (prior to release of the first batch of fish). However, a fault in the Noble's Yard hydrophone meant that it was not active until 11.00 on the 17th of October. All three loggers were operative until 10.00 on the 24th of November when the hydrophone at Whitby malfunctioned and then when the hydrophone at Noble's Yard was switched off at 09.00 on the 15th of December 2014 (the last record of a fish here or on the array downstream of the weir was on the 7th of December).

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.

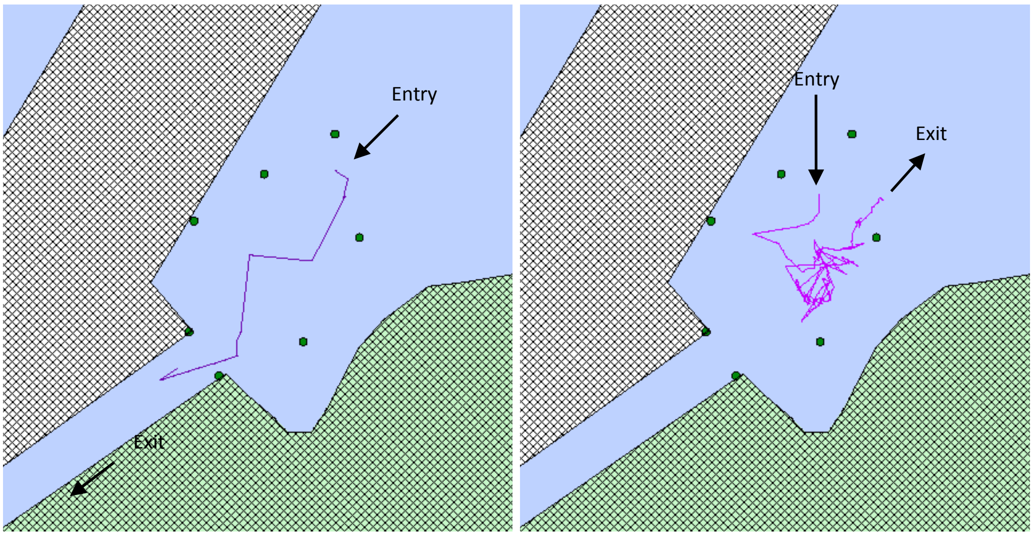


Figure 7. Examples of a passage track (left) and a non-passage track (right) in the array (green circles representing hydrophones).

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 (35.9m^{3}s^{-1}) looking upstream. Arrows represent direction of fish passage (photo taken 3/1/2012 12:00).

In 2011 passage routes were originally divided into “fish pass” and “side of fish pass” routes (Figure 8 and Figure 9) based on a combination of the location of the terminal point of the fish track (nearest to the fish pass or side of fish pass), the time the fish took to ascend (<1-min = fish pass or side of fish pass; >1-min = fish pass) and the flow over the weir at the time of passage (<3 m^{3}s^{-1} = fish pass, >3 m^{3}s^{-1} = fish pass or side of fish pass). Where it was not possible to determine which route was taken as both routes were feasible; these were classified as "pass proximity". In 2012 - 2014 the relocation of H1 into a pool above the Larinier baffles enabled the confirmation of use of the fish pass on all detected ascents of the weir (in fact since 2011 there has been no evidence of tagged fish successfully using the side of fish pass route in preference to the pass itself). In all analysis following the 2012 report (Walton *et al.* 2012) the ascents via the fish pass and via the side of the fish pass have been classified as successful use of the main fish pass structure. That is, any fish that successfully left the array pool by leaving in an upstream direction was determined to have successfully used the fish pass structure, even if it did not traverse the weir within the pass.

Fish tracks were analysed to investigate the following:

- The attraction efficiency – the proportion of tagged fish detected in the array
- The overall passage efficiency – the proportion of tagged fish ascending the weir;
- The fish pass efficiency – the proportion of tagged fish detected in the array that ascended the weir via either the fish pass (Larinier since 2012 or pool-traverse in 2011) or the side-of-fish pass route (i.e. ascended the weir heading upstream from the array pool);
- 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 or upstream mobile hydrophone, 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 or Kruskal-Wallis *K*-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 22.0) with a significance level $\alpha = 0.05$. For all of the key passage rates Chi-squared contingency tests were performed to test for association between the frequency distributions (Yate's corrections were applied where expected frequencies were less than 5).

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 10.2). 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:

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

where Δt is the change in time between points (the time of each step (seconds)), l_p is the length of track in each cell and l_s is the total length of each step. The length of each step within each cell was extracted in ArcGIS by intersecting the polyline fish tracks with the polygon grid. The residence time in each cell was assumed to be proportional to the length of track in each cell, i.e. the fish had constant speed between points. The residence time in each grid cell was assigned a colour ranging from white to red with increasing time (see Figure 11 (left) for example). The colour spectrum was standardised between grids to allow visual comparison. The number of fish to pass through each cell and the average time spent by fish in each cell were pooled for the groups outlined in Section 2.6.1.

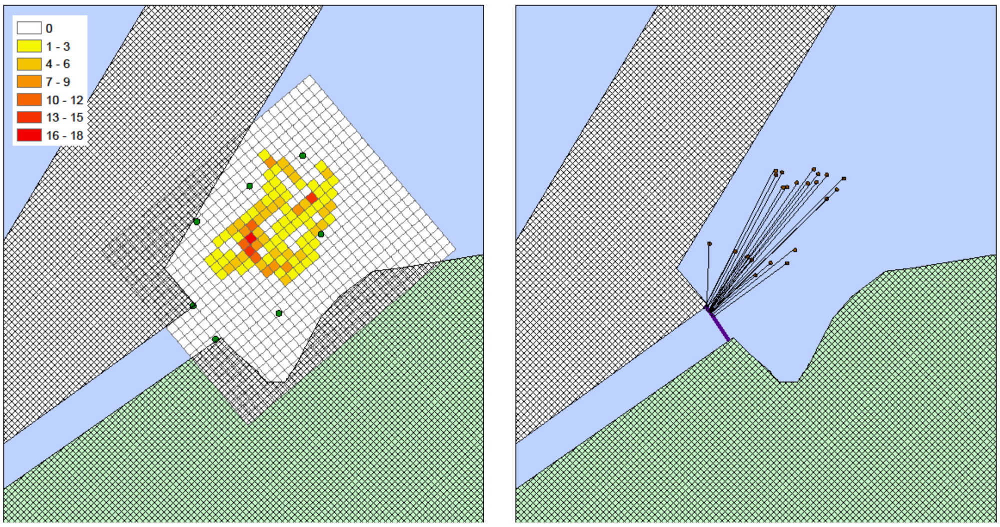


Figure 11. Example residence time (sec) grid, with cells colour coded from white to red with increasing time (left) and a diagrammatic example of proximity analysis (right).

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 Excel™.

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.

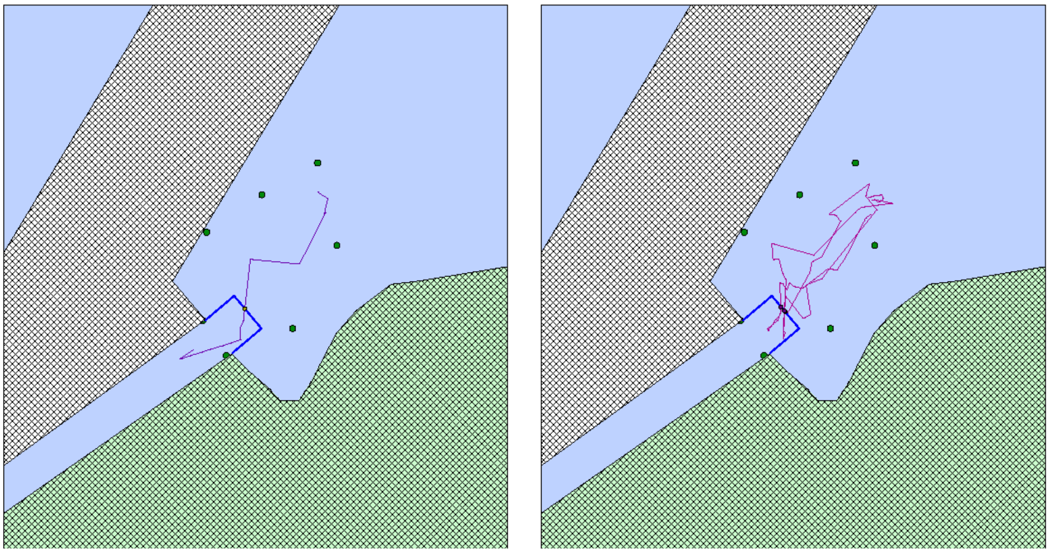


Figure 12. Example of the intersection of a passage (left; nI = 1, nA = 1) and non-passage track (right; nI = 4, nA = 2) with the 2 metre fish pass buffer.

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 (2011 and 2012), where it was previously classified into 3 groups (A, B, C).

2.7 Environmental and hydropower generation data

Flow ($m^3 s^{-1}$) 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 12 August 2014 to 22 February 2015 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 5-min intervals using Admiralty Total Tide software (The United Kingdom Hydrographic Office, Taunton, UK). Daylight timings were obtained online from HM Nautical Almanac Office.

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

2.8 Bathymetry assessment

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

3 Results

3.1 Movements of fish upstream and downstream of Ruswarp Weir

During 2014 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 23 of the 47 tagged fish (49%), ten (43%) of which ascended (or had previously ascended) the weir. Of these ten fish, five went downstream to Whitby prior to ascending, and the other five were detected after ascending the weir but subsequently descended the weir and returned downstream. The hydrophone at Noble's Yard detected 26 of the 47 tagged fish (55%), of which 13 (50%) went on to ascend the weir and one other was later detected after initially ascending the weir (ascended when the mobile hydrophone was faulty). Nine tagged fish (19%) ascended the weir without being detected at Noble's Yard; four of these were not detected as they ascended during a period in which the mobile hydrophone had technical issues (17 hours from first release on 16/10/2014 see Section 2). The other five fish managed to pass the Noble's Yard hydrophone without detection, and ascended either via the baulk or via the Larinier pass. No fish ascended the baulk pass without first having been into the array below the Larinier pass.

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 13 are for first detections only.

3.2 Visits to the array

3.2.1 Fate of tagged fish

During the 2014 post commissioning study three salmon and 44 sea trout were tagged for tracking (Table 1). Of these 44 sea trout, 32 were detected within the hydrophone array, giving an attraction efficiency of 73% (32/44) in 2014. This value is similar to that found in 2013 (67% attraction efficiency) and the average attraction efficiency across 2013 and 2014 was significantly greater than the 35% (17/48) observed in the baseline (χ^2 contingency test, $\chi^2 = 15.37$, *d.f.* = 1, $P < 0.01$). Nine sea trout were detected on a mobile hydrophone downstream of Ruswarp Weir and not seen in the array. Two sea trout and one Atlantic salmon were not detected after release, all three fish were from a batch for which a seal was observed at the release site five minutes after release (J. Dodd (HIFI) & S. McGinty (EA) *pers. obs.*). The fate of these three fish not detected on any hydrophone cannot be determined, although predation is a likely explanation, however returning to sea without detection on the Whitby hydrophone or tag failure cannot be dismissed (Figure 13).

Two tags from batch four, 2738 and 2787, were independently detected on different hydrophones (Whitby, Noble's Yard and the array) until they were last recorded independently on Noble's Yard on the 22/11/2014 and 23/11/2014 respectively (Table 2). Fish 2738 was occasionally seen on Noble's Yard whereas fish 2787 was recorded to travel between Whitby and the array on a tidal cycle. On the morning of 23/11/2014, within the array, detection of these tracks became simultaneous and continued to be so on the mobile hydrophones downstream. Fish 2738 was recorded on H4 of the array from 01:29 of the 23/11/2014 (presumably occupying the channel just downstream of the array towards the right-hand bank) but could not be tracked due to being only detected on one hydrophone. At 02:47 on the 23/11/2014 fish 2787 arrived and was tracked in the array, after which both 2787 and 2738 both left the vicinity of the array together. It was deduced from this information that both fish had been potentially consumed by the same predator (presumably a seal). Following the predation event all the tracks recorded for the pair of tags in the array were of short duration, generally less than 3 minutes long. Although it is unclear which fish was consumed first it is most likely that 2787 was already in the predator by the 23/11/2014 and 2738 was consumed later that morning in the vicinity of the array. In this case one of these fish (2787) has been treated as "missing" with no records (since it is unclear when the first predation event occurred) whilst the second fish (2738) was treated as having reached the array before predation. Given the uncertainty tracks from these fish in the array were not been used in any further behavioural analysis or metrics relating to delay.

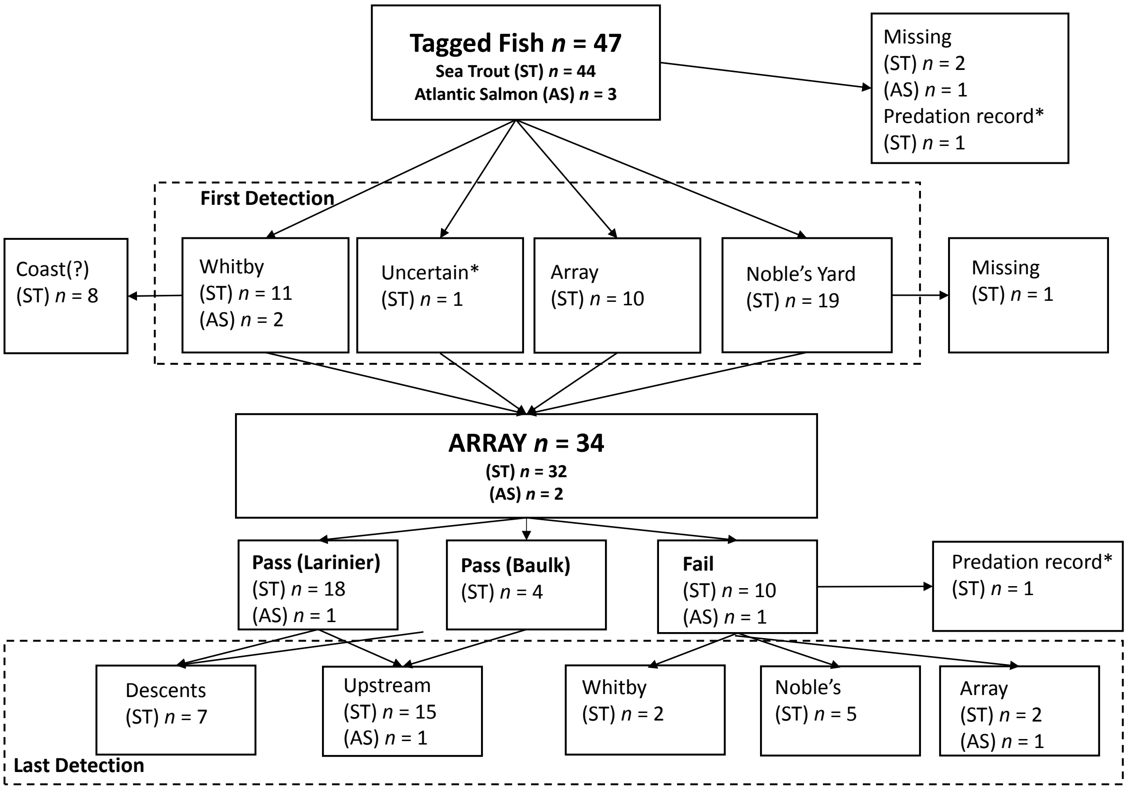


Figure 13 Summary of the fate of tagged fish during 2014 highlighting the detections on each hydrophone system and the passage of fish. * Two sea trout were known to have been consumed by the same predator and this predation event occurred within the vicinity of the array. It is known that at least one of these fish made it to the array before predation but it is uncertain which.

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	2014	Total	2011	2012	2013	2014	Total
n tagged	1	13	1	3	18	38	10	46	44	118
n array (tracked)	1	5	1	2	9	14	3	31[#]	31[#]	79
n array (no passage)	0	1	0	1	2	0	0	5	10	15
n mobile hydrophone only	N/A	N/A	0	0	N/A	N/A	N/A	7	9	16
Tracks										
Non-passage	2	41	0	41	43	23	45	466	446	987
Fish Pass Passage	1	4	1	1	6	14	3	25	18	60
Baulk passage								1	4	1
Downstream Passage					0	1	1	3	11*	16
Second Passage		2			2	1		1	2*	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.
* one fish made a DS passage on 3 occasions (2x over the weir, 1x through the fish pass) all three of its ascents appeared to be via routes other than the Larinier pass (no detections on H1).

Of the nine fish that were only detected on mobile hydrophones (i.e. not detected in the array), eight 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 13).

The records of fish that failed to pass the weir were not evenly distributed between the batches of fish in 2014 (Table 3). In the first three batches approximately 65-70% of sea trout observed in the array would pass the weir via the Larinier pass with around 55-69% of tagged sea trout per batch passing the weir by any route. However, in the fourth batch, released on 18th November, only three of the 13 fish tagged ascended the weir (23%) and only two of the nine fish tracked in the array ascended via the Larinier pass (22%) (Table 3).

Table 2 Illustrative tracks and events on mobile hydrophones to show the sequence of events that lead to the assumed predation event on sea trout 2787 and 2738 (this is an incomplete sequence, events have been left out for illustrative purposes).

Hydrophone	Start time *	Stop time *	2787	2738
Whitby	19/11/2014 19:07:51	19/11/2014 19:53:22	✓	
Noble's	21/11/2014 01:10:59	21/11/2014 01:13:00		✓
Noble's	21/11/2014 01:57:07	21/11/2014 02:08:21	✓	
Array	21/11/2014 03:04:01	21/11/2014 03:04:04	✓	
Noble's	21/11/2014 03:22:38	21/11/2014 03:36:18	✓	
Whitby	21/11/2014 20:03:56	21/11/2014 22:04:08	✓	
Noble's	22/11/2014 02:23:30	22/11/2014 02:24:01	✓	
Array	22/11/2014 03:01:59	22/11/2014 03:04:15	✓	
Noble's	22/11/2014 04:01:48	22/11/2014 04:03:45	✓	
Noble's	22/11/2014 15:13:31	22/11/2014 15:15:07		✓
Noble's	23/11/2014 02:33:32	23/11/2014 02:34:36	✓	
Array	23/11/2014 02:47:29	23/11/2014 02:50:33	✓	#
Array	23/11/2014 03:16:32	23/11/2014 03:18:49	✓	✓
Noble's	23/11/2014 03:39:14	23/11/2014 03:44:29	✓	✓
Array	23/11/2014 03:56:44	23/11/2014 04:04:05	✓	✓
Noble's	23/11/2014 16:26:24	23/11/2014 16:26:35	✓	✓
Array	23/11/2014 16:40:09	23/11/2014 16:44:59	✓	✓
Array	23/11/2014 17:18:30	23/11/2014 17:19:03	✓	✓
Noble's	23/11/2014 17:39:54	23/11/2014 17:41:20	✓	✓
Whitby	24/11/2014 01:56:42	24/11/2014 01:57:18	✓	✓
Noble's	24/11/2014 02:46:30	24/11/2014 02:51:47	✓	✓
Array	24/11/2014 04:27:47	24/11/2014 04:31:29	✓	✓
Noble's	24/11/2014 04:38:39	24/11/2014 04:38:58	✓	✓

✓ Fish tracked in the array or recorded on a mobile hydrophone
* These are the start and stop times of a specific event/track for one of the specific tags – the events for the other tag when co-occurring would be only a few seconds different.
# Tag 2738 was recorded on hydrophone H4 of the array (furthest downstream) continuously from 01:29 on the 23/11/2014 until the records stopped at around the time tag 2787 departed from the array at 02:50 that day, however it could not be tracked as it was recorded on too few hydrophones.
Grey shading indicates tracks where the tags were together and the box indicates when the predation event probably occurred.

Table 3 Batch summary for the fate of tagged fish in 2014 indicating those detected in the array that went on to ascend the Larinier (LFP), the baulk (BFP) or to not ascend the weir (DNP).

Batch	Date	n fish	n mobile only	n Array - LFP	n Array - BFP	n Array - DNP	Total in Array	n 0 Records
1	16/10	13	3	7	2	1	10	0
2	04/11	9	3	4	1	1	6	0
3	10/11	9	1	5	0	2	7	1
4	18/11	13	2	2	1	6	9	2
	Totals	44	9	18	4	10	32	3

Although the condition of the fish of the fourth batch was below average and the lowest observed during the study (Figure 14) there was no significant difference in condition between years (t test: t = 1.592, *d.f.* = 88, p >0.05) or between batches within 2013 (ANOVA $F_{2, 41}$ = 0.510, p >0.05) and 2014 (ANOVA $F_{3, 40}$ = 2.059, p >0.05) (Figure 14).

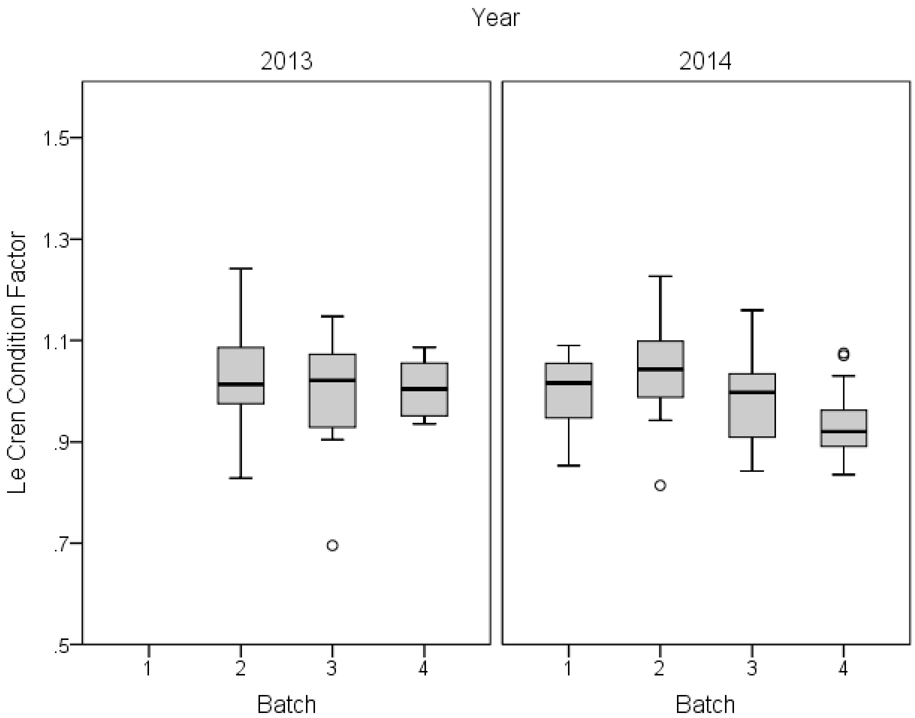


Figure 14 The Le Cren Condition factor for each major batch of sea trout released in 2013 and 2014.

In 2014 fat content was recorded using a digital fat content reader. The proportion of body fat was highest in the first batch in 2014 (16/10/2014) and then lowest in the fourth batch (released on 18/11/2014) (Figure 15). There was a significant difference between the median fat content of the three batches (Kruskal-Wallis *K* = 18.480, *d.f.* = 2, p <0.01) although this difference is most likely due to batch 1 being significantly different from batches three and four (which were very similar).

The general visual condition of fish in batches 2 and 3 in 2014 was worse than in batches 1 and 4. In all batches only fish of suitable condition were selected for tagging and those which were showing predator damage or significant fungal infection were rejected and returned to the river without tagging. No fish were rejected from batch 1, seven fish were rejected from batch 2 (mostly due to fungal infection), eight fish were rejected from batch 3 (fungal infections and clear bite marks) and two fish were rejected from batch 4 (one too small and one with predator damage to the head).

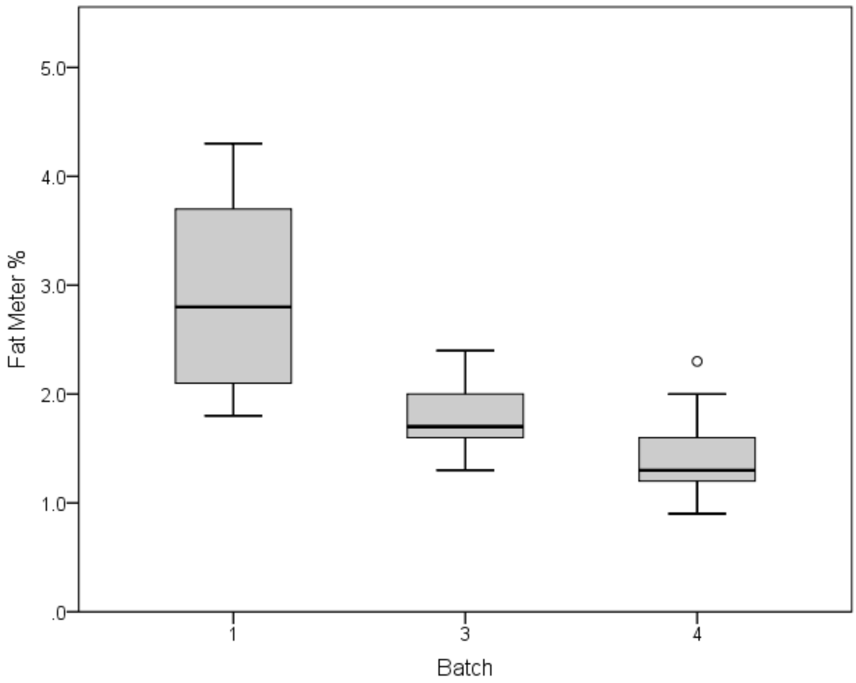


Figure 15 Fat content (% of body weight) assessment of three of the four batches released in 2014 on the following dates: 16/10/2014 (1); 10/11/2014 (3) and 18/11/2014 (4).

3.2.2 Fish passage metrics

Of the 34 fish (32 sea trout and two salmon) detected in the array 23 ascended the weir; 19 ascended via the fish pass and four via another route (assumed to be the baulk pass) (Table 4 and Figure 13). The overall passage efficiency of sea trout in 2014 was 50% (22/44) whilst in the baseline dataset it was approximately 35% for both sea trout (17/48) and salmon (5/14) (Table 3). The average passage efficiency for sea trout across 2013 and 2014 (53%) was significantly greater than the baseline (35%) (χ^2 contingency test, $\chi^2 = 4.030$, *d.f.* = 1, *P* <0.05).

Fish pass efficiency for sea trout was observed to be lower in 2014 (18 of 32, 56%) than in the baseline (17 of 17, 100%) and the average fish pass efficiency across 2013 and 2014 (68%) was significantly lower than in the baseline (χ^2 contingency test with Yate's correction, $\chi^2 = 5.602$, *d.f.* = 1, *P* <0.05).

Batch four in 2014 (released on 18/11/2014) had a very low rate of passage compared to all other batches released in 2013 and 2014, which were themselves very similar to each other (Figure 16). The low proportion of fish in this batch ascending the weir via the Larinier having reached the array influenced the outcome of the statistical significance of the reduction in fish pass efficiency. The fish pass efficiency measured prior to the release of this batch (76%) was not significantly different from the baseline (χ^2 contingency test with Yate's correction, $\chi^2 = 3.350$, *d.f.* = 1, *P* >0.05).

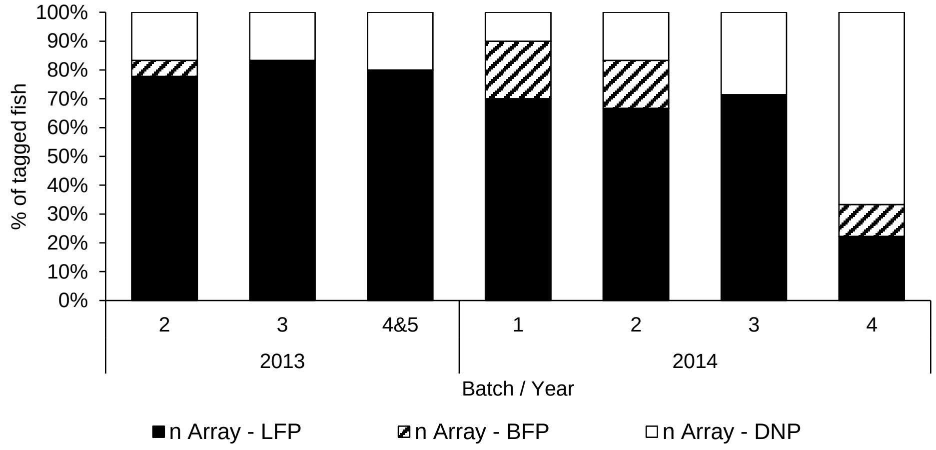


Figure 16 Proportions of fish that entered the array in each major batch in 2013 and 2014 indicating those detected in the array that went on to ascend the Larinier (LFP), the baulk (BFP) or to not ascend the weir (DNP).

3.2.3 Time between release and detection / passage

The time between release and first detection in the array in 2014 (median 0.51, 0.23 – 2.19 days (*n* = 31 – note that this excludes the fish known to have been subject to predation in the array)) was similar to that observed in 2013 (median 0.40, 0.18 – 0.95 days (*n* = 31)). There was no significant difference in the average time between release and first detection of tagged sea trout in 2013 and 2014 (the combined initial post-dataset) compared with the baseline (median 1.01, 0.25 – 9.74 days (*n* = 17)) (Mann Whitney U-test: $Z = -1.276$, $n = 81$, $P > 0.05$) (Figure 17). In 2014 ten of the tagged sea trout passed within one day (< 24 hrs) of release with a further four passing within two days (< 48 hrs). Five of the sea trout took between three and seven days and only one sea trout took more than one week to ascend (32 days) after release (Figure 18). The median time from release to passage via the Larinier fish pass for sea trout in 2014 was 0.96 (0.39 – 2.19, *n* = 18) which was slightly less than the 1.21 (0.85 – 4.81) days in 2013 (*n* = 25). There is no significant difference for the initial post- dataset when compared with 1.02 (0.26 – 15.50) days (*n* = 17) in the baseline dataset (2011 and 2012 combined) (Mann Whitney U-test: $Z = 0.058$, $n = 74$, $P > 0.05$) (Figure 19).

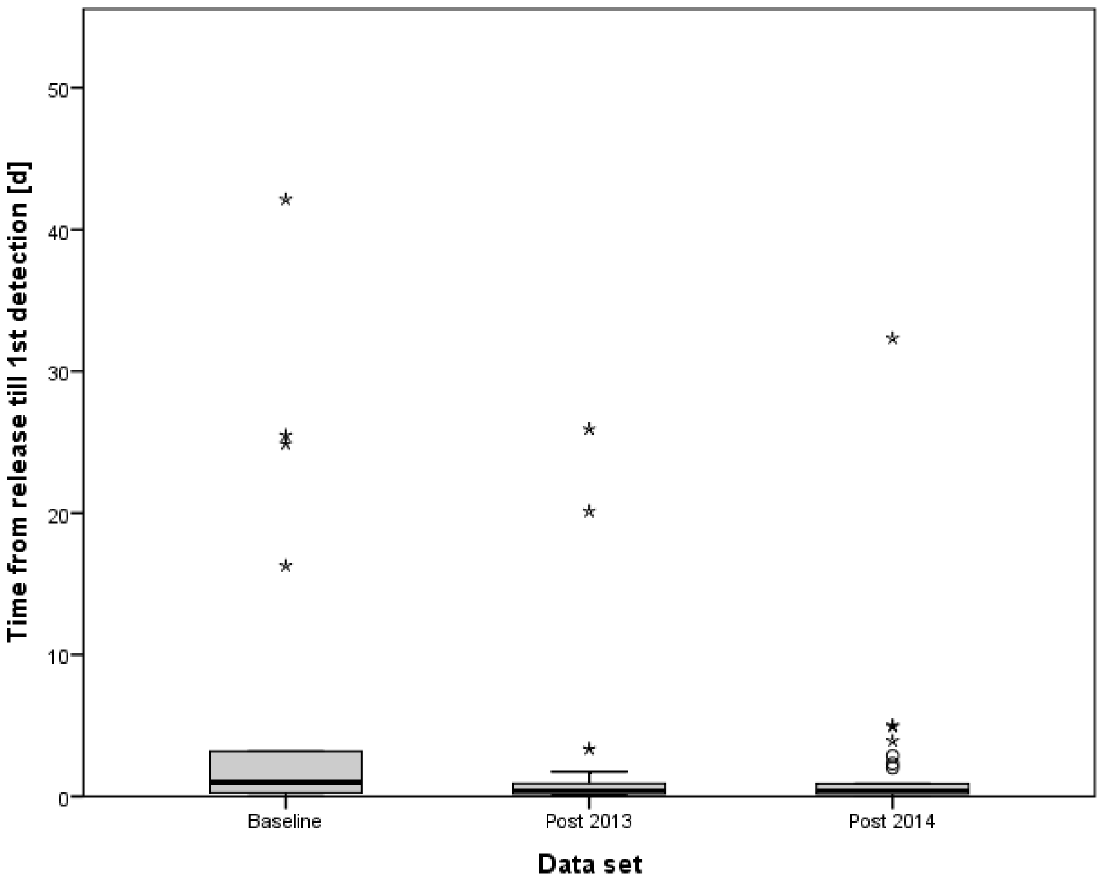


Figure 17 Time from release to detection within the ATS array (days) for tagged sea trout in the baseline dataset (2011 and 2012, *n* = 17) and post dataset (2013 (*n* = 31) and 2014 (*n* = 31).

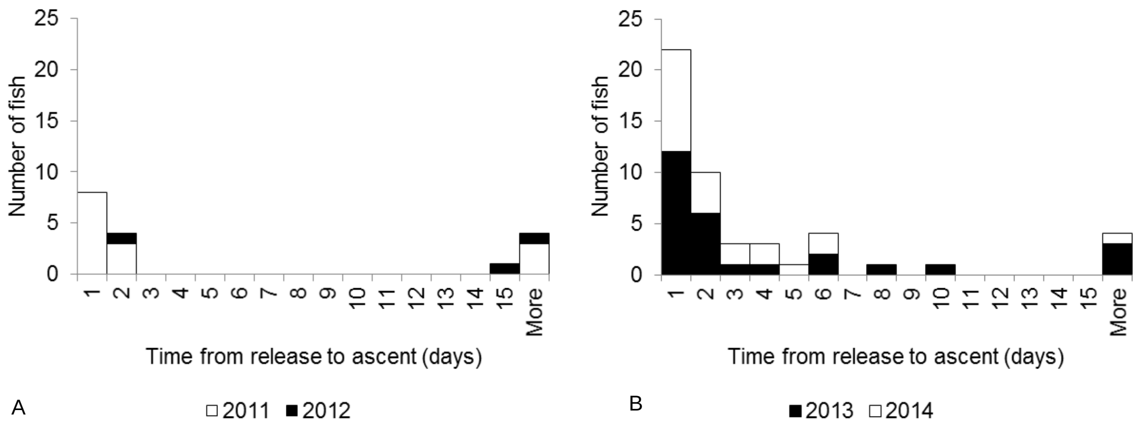


Figure 18. Number of days between release and passage for sea trout in the baseline dataset (A 2011 and 2012, *n* = 17) and in 2013 (B 2013 and 2014, *n* = 49); 1 day = within 24 hours of release.

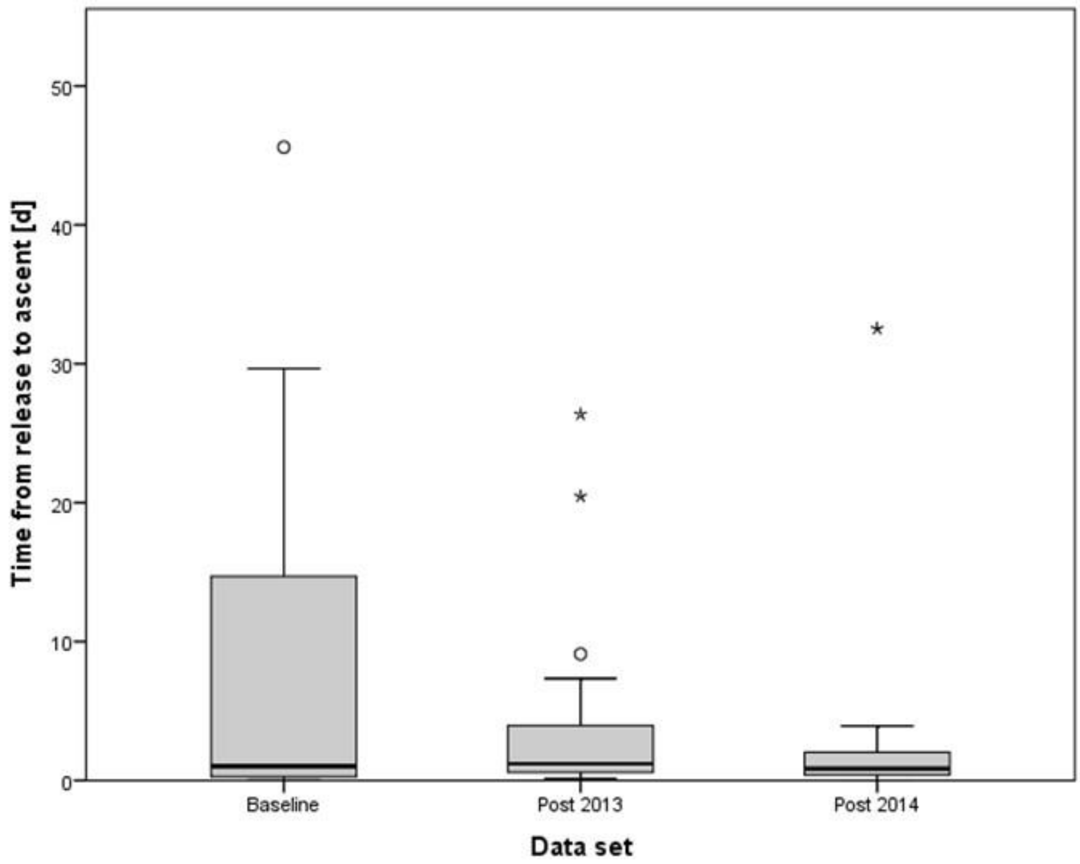


Figure 19 Number of days between release and passage for sea trout in the baseline dataset (2011 and 2012, *n* = 17) and past dataset (2013 and 2014, *n* = 49).

Table 4 Summary statistics for sea trout detected in the ATS array downstream of the Larinier fish pass during 2014 (excluding the two tags known to have been consumed by the same predator).

Passage	Tag No	Size (cm)	Time between release and first detection [d]	Number of tracks in array	Cumulative time in array [min]	Cumulative length of track [m]	Total Time from first detection in array to H8 (or last detection for non-passage) [hrs]	Day / Night passage
Larinier	2500	65	0.35	1	0.37	7.88	0.17	N
	2507	61	0.88	16	69.22	634.26	20.82	D
	2514	50	3.91	1	2.48	25.91	0.13	D
	2521	57	0.12	4	2.10	29.51	5.84	N
	2563	64	0.23	1	0.63	10.12	0.13	N
	2577	52	0.11	7	53.90	1022.20	1.21	N
	2591	56	0.76	12	203.33	1146.80	73.61	D
	2598	50	0.12	13	99.80	775.44	5.35	N
	2612	54	0.19	4	32.08	441.93	13.86	N
	2633	56	0.91	1	10.02	175.76	0.31	N
	2654	55	0.36	7	13.57	171.34	2.93	N
	2668	65	0.27	18	115.27	1046.41	3.75	N
	2689	53	0.34	11	65.78	764.36	22.92	N
	2696	52	0.25	2	20.63	244.17	0.91	N
	2710	47	0.31	7	40.55	405.13	17.21	N
	2731	53	0.74	69	360.70	2080.08	48.70	D
	2794	54	0.61	11	38.50	519.43	1.89	D
	2815	55	0.85	1	14.78	117.65	25.47	D
Baulk	2528	54	0.14	1	0.50	11.23	3.84	
	2542	52	5.01	15	71.62	1097.57	135.93	
	2605	57	0.04	5	27.82	246.78	120.03	
	2780	59	0.49	31	62.63	430.29	98.12	
Non-	2535	53	0.88	23	137.10	1480.08	135.99	
Passage	2661	42	0.38	18	108.05	1049.07	5.23	

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
	2675	48	0.10	13	107.72	1296.13	25.19	
	2703	63	1.57	116	501.27	3769.08	60.48	
	2745	57	0.14	19	200.47	847.44	60.08	
	2752	59	0.08	51	239.46	1858.79	93.59	
	2759	52	2.87	7	49.57	478.94	83.88	
	2766	67	0.20	7	19.60	128.54	1.01	
	2773	50	0.11	5	15.32	193.55	15.14	

3.2.4 Number of visits to the array

In 2014 70% (n = 31) of the sea trout tagged were detected in the array, around twice the return rate observed in the baseline (35%, n = 17) and similar to that found in 2013 (67%, n = 31). In 2014 five sea trout ascended the weir during the first visit to the array, with another six ascending within seven visits. In the baseline dataset, only three of the 17 sea trout (18%) visited the array more than five times before passage (Figure 20). Two sea trout made 116 visits to the array during a four day period in 2014 before one ascended through the fish pass and the other went missing out of the array. Of the ten fish that did not pass the weir at all in 2014, three fish visited the array under eight times while seven fish made more than 10 visits to the array.

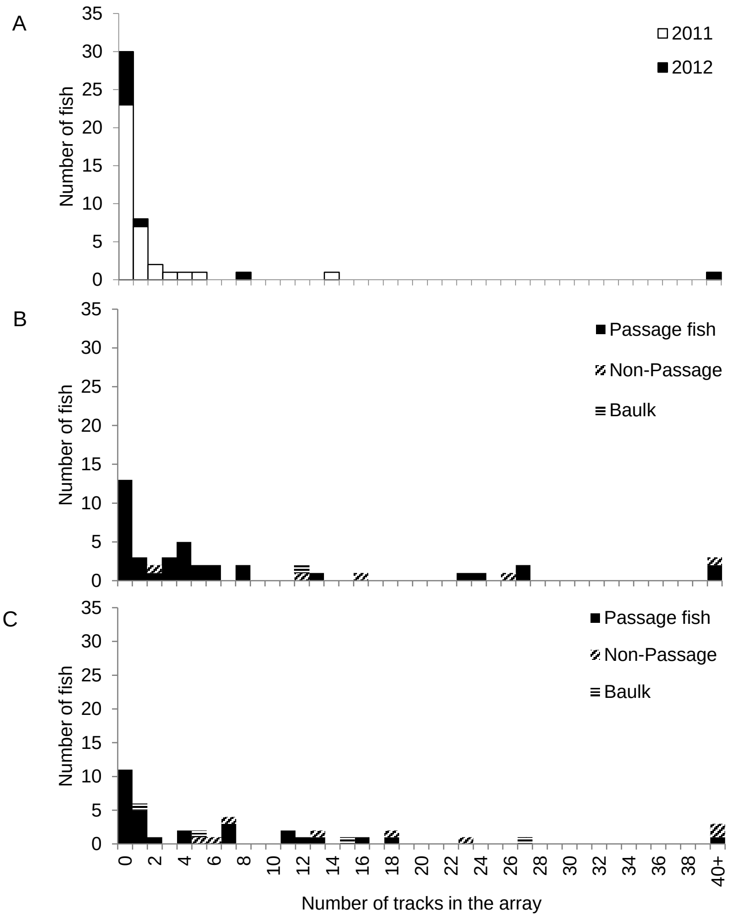


Figure 20. Frequency distribution showing the number of times the hydrophone array was entered by sea trout in A) 2011 and 2012 B) 2013 C) 2014 (0 = number of fish not detected in the array).

3.2.5 Total time in the array

In 2014 the median total time spent in the array by sea trout prior to passage was 26.36 (2.44 – 76.87) minutes (n = 18) and was similar to the times observed in 2013 (24.18, 6.12 – 77.69, n = 25). These were significantly longer than the 5.00 (1.61 – 29.81) minutes (n = 17) in the baseline dataset (Mann Whitney U-test: Z = 2.026, n = 60, 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 2014 only 11% of sea trout (23% of the tagged sea trout that actually ascended the weir) spent less than ten minutes in total within the array prior to passage via the Larinier pass and 41% (n = 18) of tagged sea trout spent longer than 30 minutes in the array. 33 % (*n* = 6) of the 18 fish that spent more than 30 minutes in the array did not pass the weir whilst a further two (11%) ascended by another route (assumed to be the baulk pass) (Figure 21).

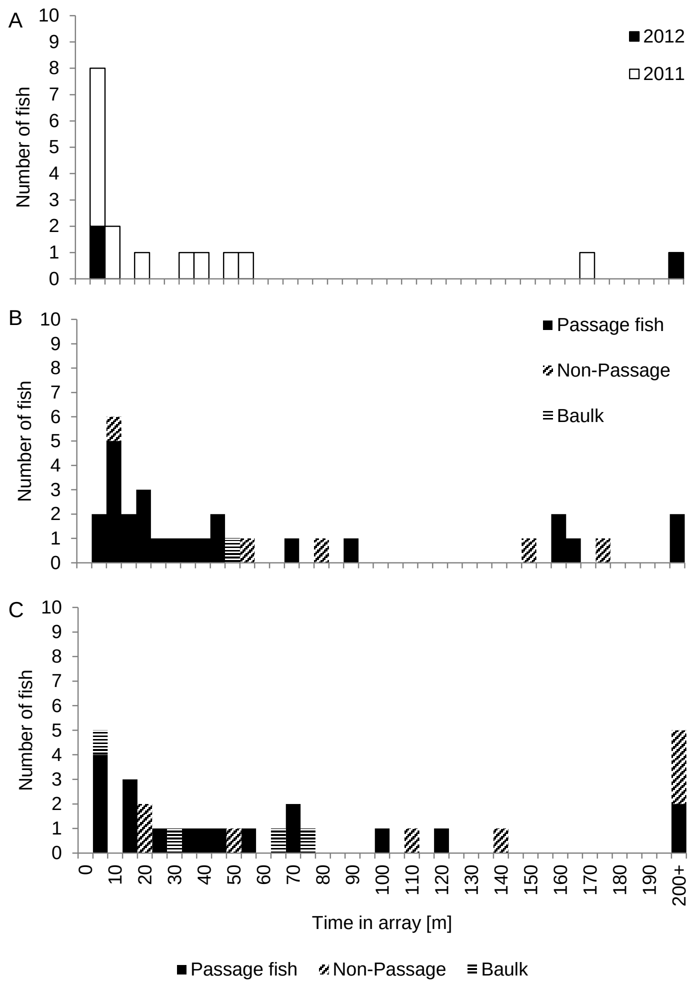


Figure 21 Total time spent in the array prior to passage (sum of all tracks) sea trout in A) 2011 and 2012 B) 2013. C) 2014

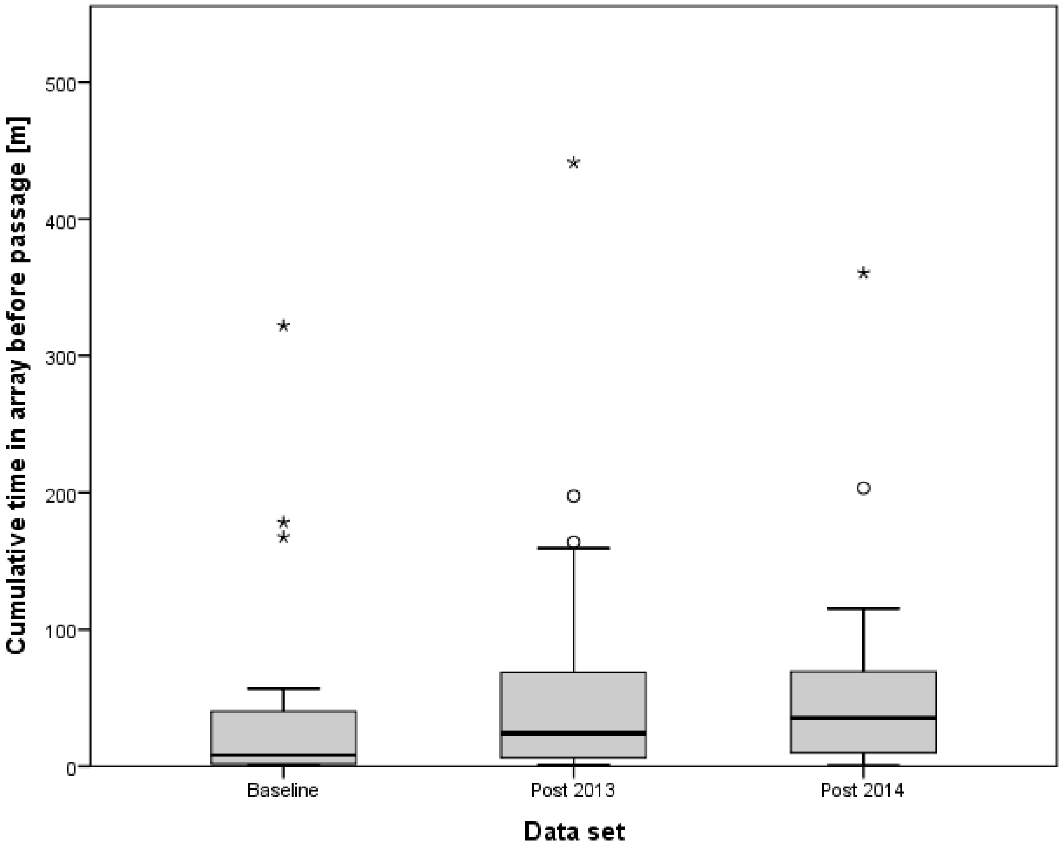
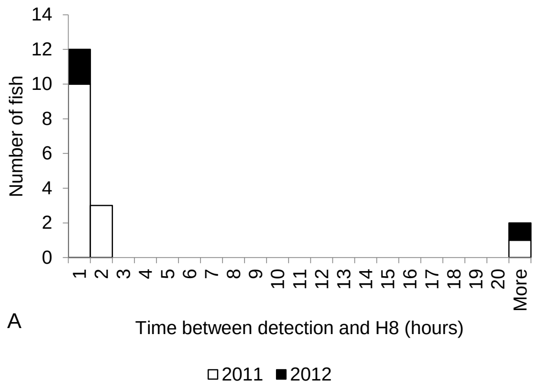


Figure 22 Total time spent within the array (sum of all tracks) prior to passage via the fish pass (minutes) for tagged sea trout in the baseline dataset (2011 and 2012, *n* = 17) and post dataset (2013 *n* = 25, 2014 *n* = 18).

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 2014 only 33% of sea trout passed within one hour of first detection and six sea trout (33%) took longer than 12 hours to ascend (up to 74 hours). The total time between first detection and passage in 2014 (3.34, 0.40 – 18.11 hours, *n* = 18) was slightly longer than in 2013 (2.36, 0.77 – 15.59 hours, *n* = 31). The median time in the initial post- dataset was significantly longer than the baseline (Mann Whitney U-test: *Z* = 2.945, *n* = 60, *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 that took less than 12 hours was 0.17 (0.09 – 0.92) hours in the baseline (*n* = 15) and was significantly longer in the post- dataset (2013 = 1.23, 0.64 – 2.83 hours (*n* = 18) and 2014 = 1.06, 0.20 – 3.55 hours (*n* = 12)) (Mann Whitney U-test: *Z* = 2.961, *n* = 45, *P* <0.01) (Figure 23-25). During this time prior to passage in 2014 the median proportion of time the sea trout spent in the array was 10.3% (4.4 – 41.1) which was similar to that observed in 2013 (8.45%, 3.4 – 38.0) whereas in the baseline they spent a significantly higher proportion of the time in the array (41.0%, 14.5 – 65.9) in the array (Mann Whitney U-test: *Z* = -2.699, *n* = 60, *P* <0.01) (Figure 26).



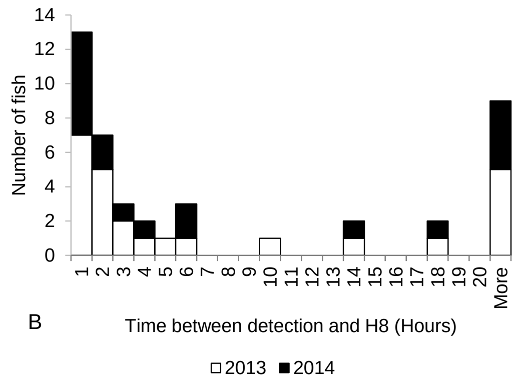


Figure 23. Total time between first arrival in the array and passage (time on H8) for sea trout in A) 2011 and 2012 B) 2013 and 2014

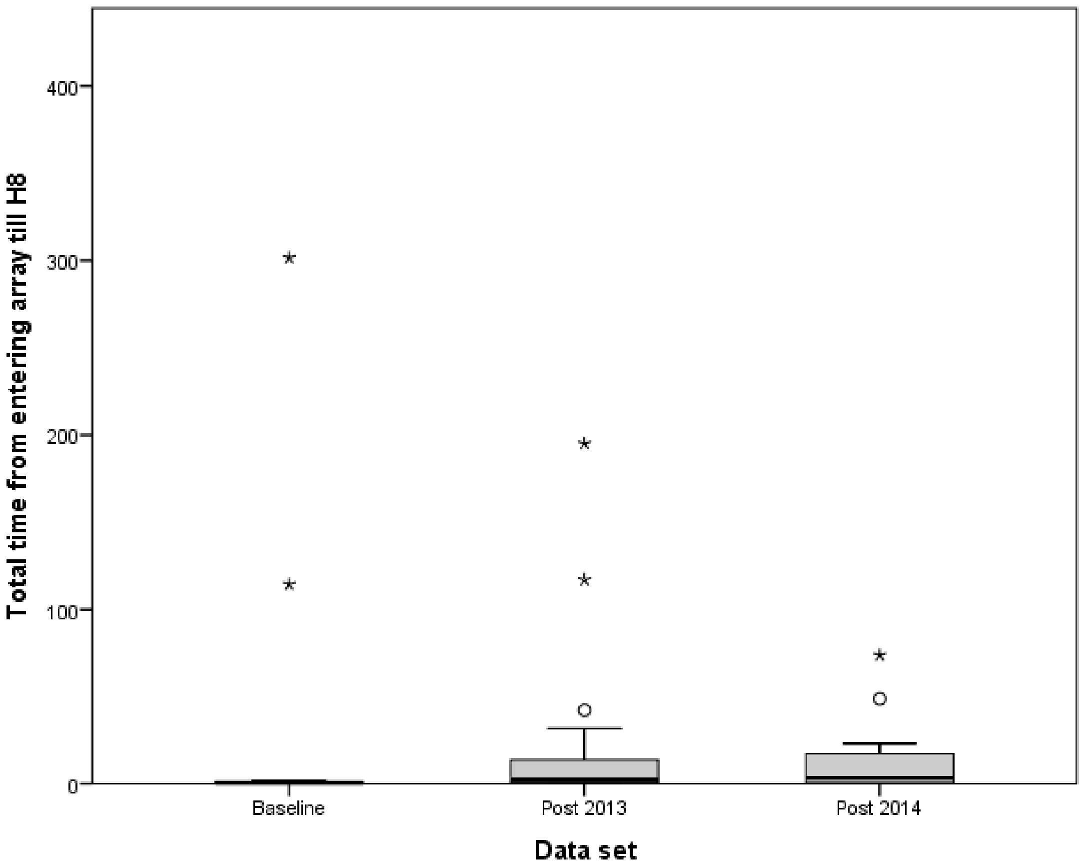


Figure 24 Total time between first detection in the array and final passage for (hours) tagged sea trout in the baseline dataset (2011 and 2012, *n* = 17) and post- dataset(2013 *n* = 25, 2014, *n*= 18).

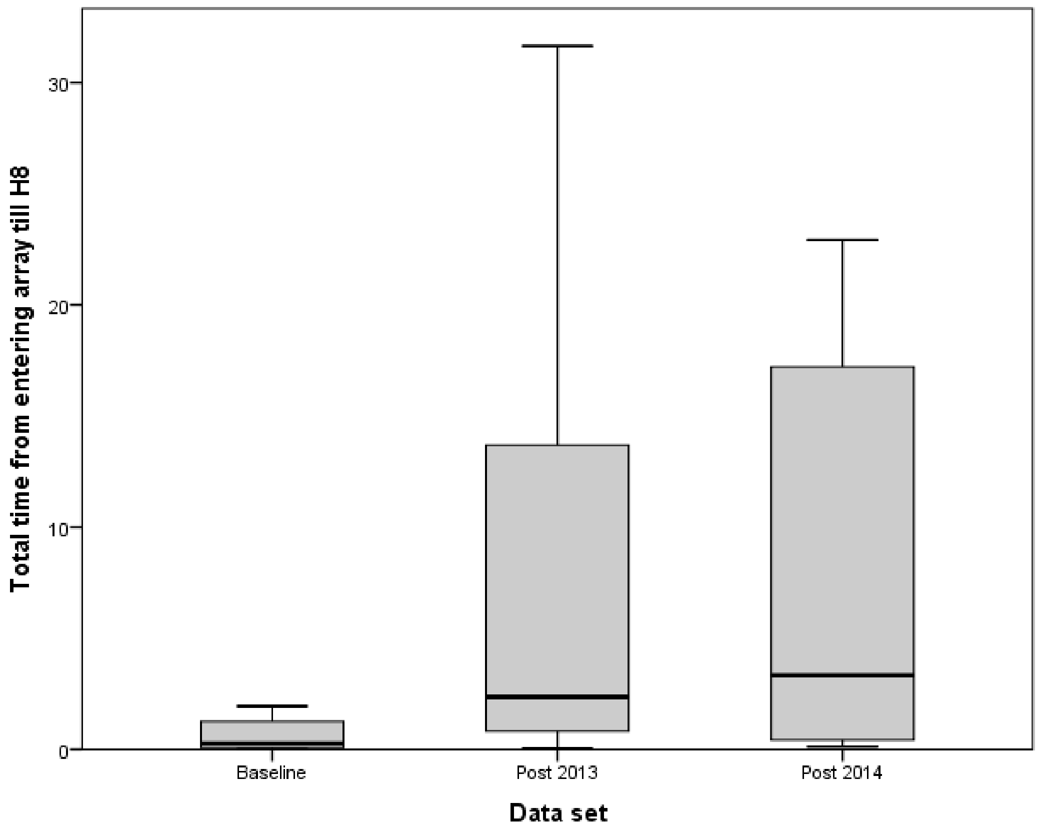


Figure 25 Total time between first detection in the array and final passage (hours) for tagged sea trout in the baseline dataset (2011 and 2012, *n* = 17) and post dataset (2013 *n* = 25, 2014 *n* = 18), focussing on fish that took under 30 hours in total.

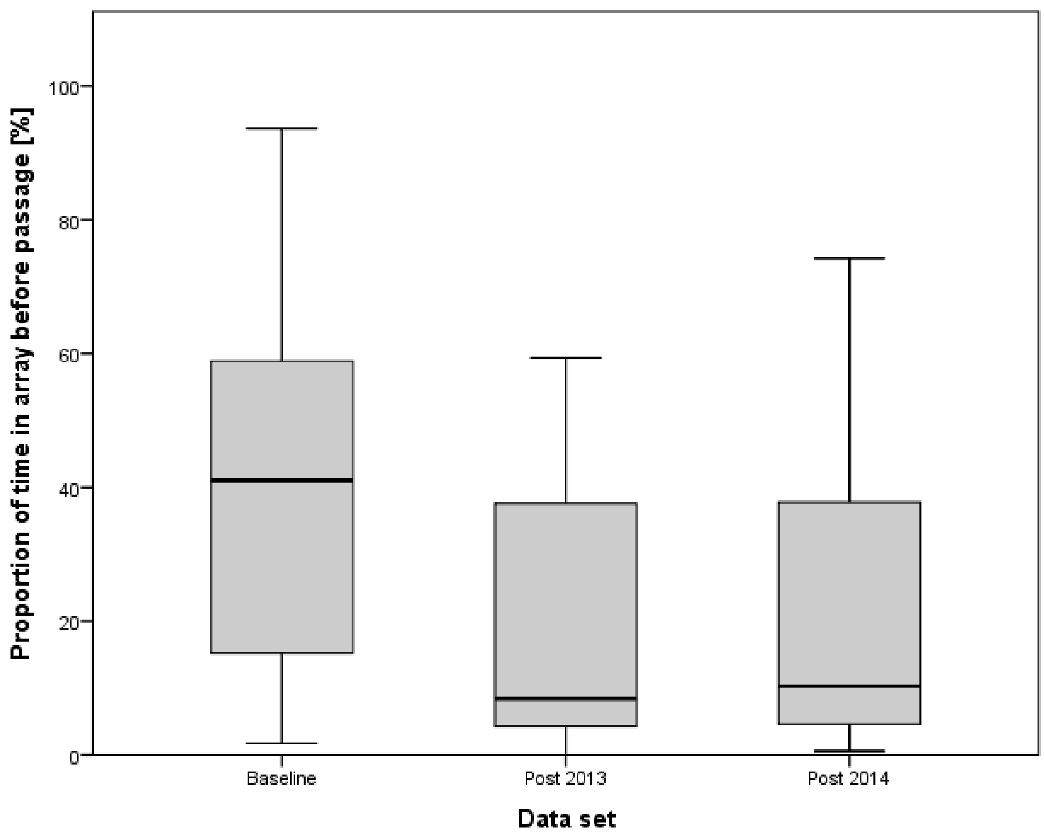


Figure 26 Proportion of time spent within the array between first detection and final passage for tagged sea trout in the baseline dataset (2011 and 2012, *n* = 17) and post dataset (2013 *n* =25, 2014 *n* = 18).

3.2.7 Duration of passage and non-passage tracks

In 2014 18 first passage tracks and 445 non-passage tracks were recorded for sea trout. The median duration (time in the array) of non-passage tracks (2.53, 0.65 – 6.36 minutes (n = 445)) in 2014 was similar to that observed in 2013 (2.18, 0.68 – 5.66 minutes (n = 466)). The non-passage tracks in the initial post- dataset were significantly shorter in duration than in the baseline dataset (4.32, 1.83 – 9.45 minutes (n = 68)) (Mann Whitney U-test: Z = -4.030, n = 977, P <0.01). 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)) or 2014 (4.98, 0.74 – 14.26 (n = 18)) (Mann Whitney U-test: Z = -0.189, n = 60, P >0.05) (Figure 27).

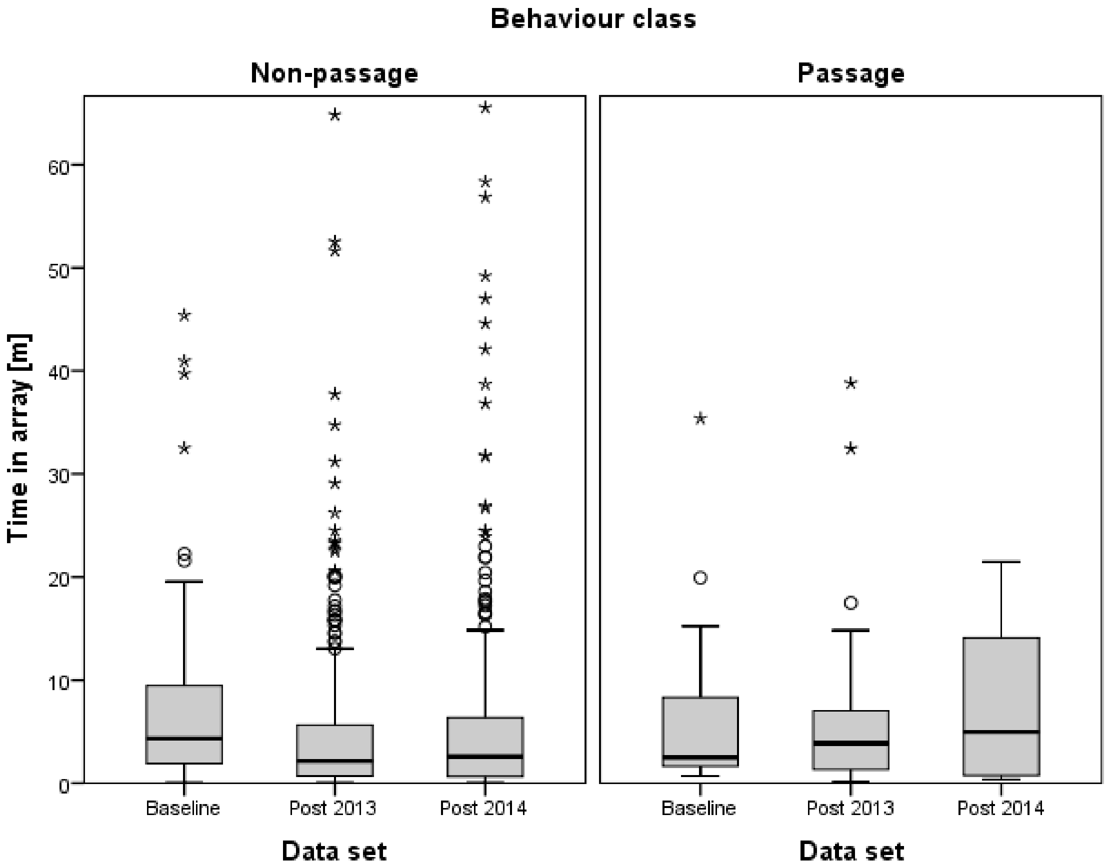


Figure 27. Duration (minutes) of individual array visits in passage (n = 17 [baseline], 2013 n = 25 and 2014 n =18) and non-passage (n = 68 [baseline], 2013 n = 466 and 2014 n = 445) tracks for sea trout.

3.2.8 Ascent route

Of the 22 sea trout ascents over the weir in 2014, 18 used the Larinier fish pass and four were assumed to have used the baulk fish pass (detected on H8 or Gary's Hut hydrophone before (or without) a record on H1). One of the three Atlantic salmon tagged in 2014 used the Larinier fish pass. All four of the fish observed to use the baulk pass had been in the array previously and there was typically around 30 minutes (longest time was 90 minutes) between leaving the array and first being detected above the weir (on H8 or Gary's Hut hydrophone). No fish were recorded to ascend the weir via the side-of-fish pass route (no fish were recorded in H8 before being recorded on H1) and there was typically around 5-10 minutes between detection on H1 (within the Larinier pass) and being detected on H8. In 2014 only one sea trout had a delay from H1 to H8 of <1 minute (four fish observed to be like this in 2013) and this pattern was still concluded to represent passage via the Larinier pass.

3.3 Environmental Influences on timing of movement

3.3.1 Diel variations in fish movements

In 2014 sea trout entered the array 134 times (28%) during the day and 330 times (72%) at night (non-passage and first passage tracks). In 2014 the median time spent in the array in non-passage tracks during the day was 3.62 (1.21 – 8.05) minutes (n = 128) which was slightly longer than the 2.04 (0.48 – 5.61) minutes (n = 174) observed in 2013. Non-passage track duration at night was 1.85 (0.51 – 5.37) minutes (n = 317) and was similar to the 2.21 (0.80 – 5.72) minutes (n = 292) observed in 2013 (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 = -2.108, n = 354, P <0.05) and the night (Mann Whitney U-test: Z = -3.051, n = 622, P <0.01) in the initial post- dataset (2013 and 2014 combined) than in the baseline.

In 2014 six sea trout (33%) ascended the weir for the first time during the day and 12 (67%) ascended during the night, and the average duration of passage tracks during the day (10.06, 3.87 – 18.46 minutes, n = #) was greater than that at night (4.62, 0.65 – 9.46 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 = -0.577, n = 20, P >0.05) and the night (Mann Whitney U-test: Z = 0.076, n = 40, P >0.05) between the initial post- dataset (2013 and 2014 combined) and the baseline.

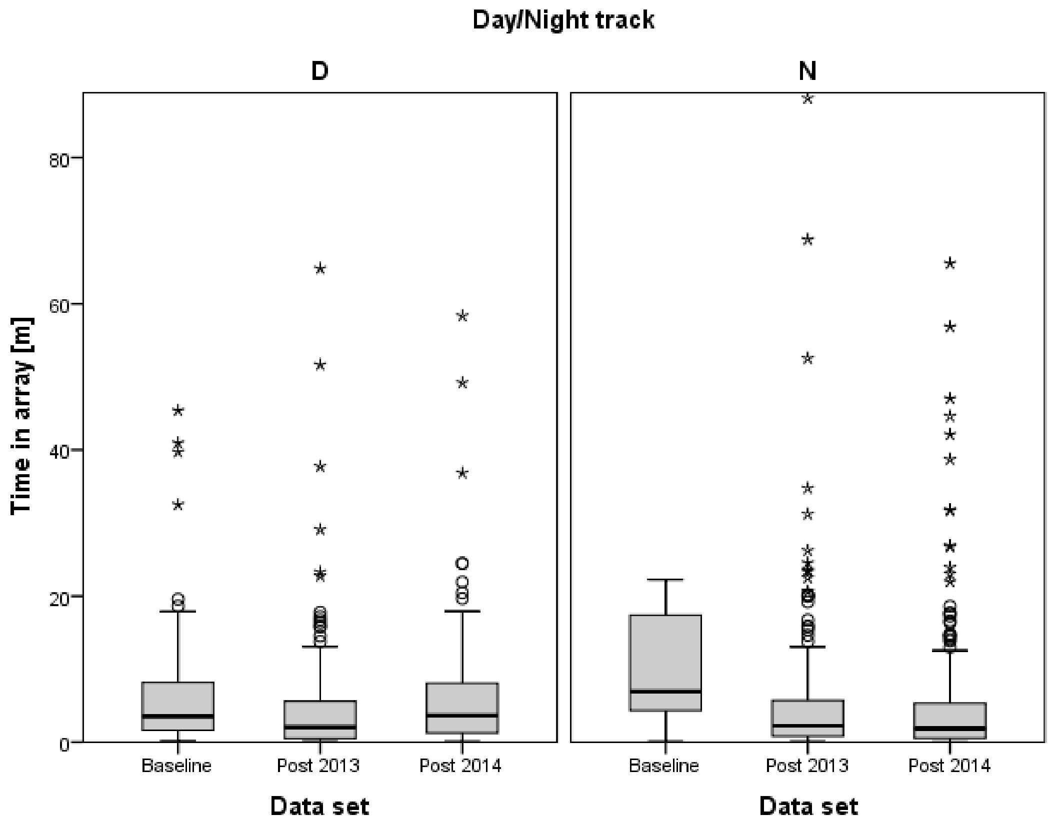


Figure 28. Time spent in the array during non-passage visits of sea trout to the array in the day (D) (*n* = 52 [baseline], 2013 *n*= 174 and 2014 *n* = 128 [post data]] and at night (N) (*n* = 15 [baseline] and 2013 n = 292 and 2014 *n* = 317 [post data])

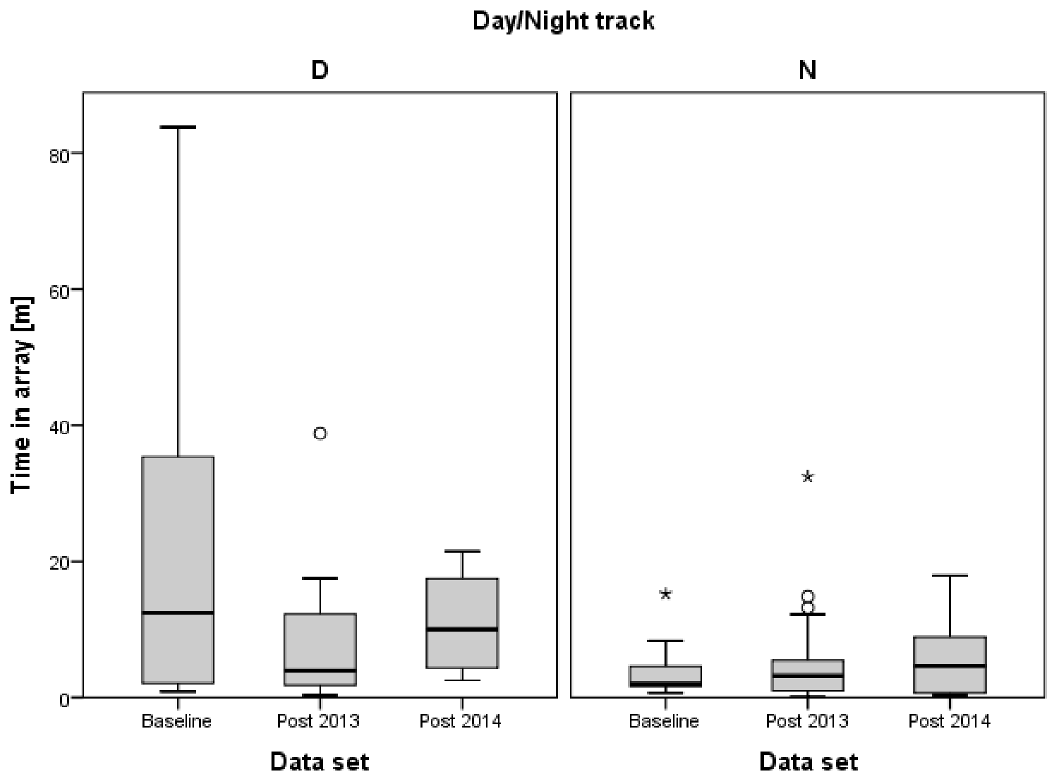


Figure 29. Time spent in the array during passage tracks for sea trout in the day (D) (*n* = 6 [baseline] and 2013 *n* = 8, 2014 *n* = 6 [post data]) and at night (N) (*n* = 11 [baseline] and 2013 *n* = 17, 2014 *n* = 12 [post data]).

3.3.2 Relationship with discharge

In 2014 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. A fish from release two was observed to ascend many days after release following a minor flow peak (early December).

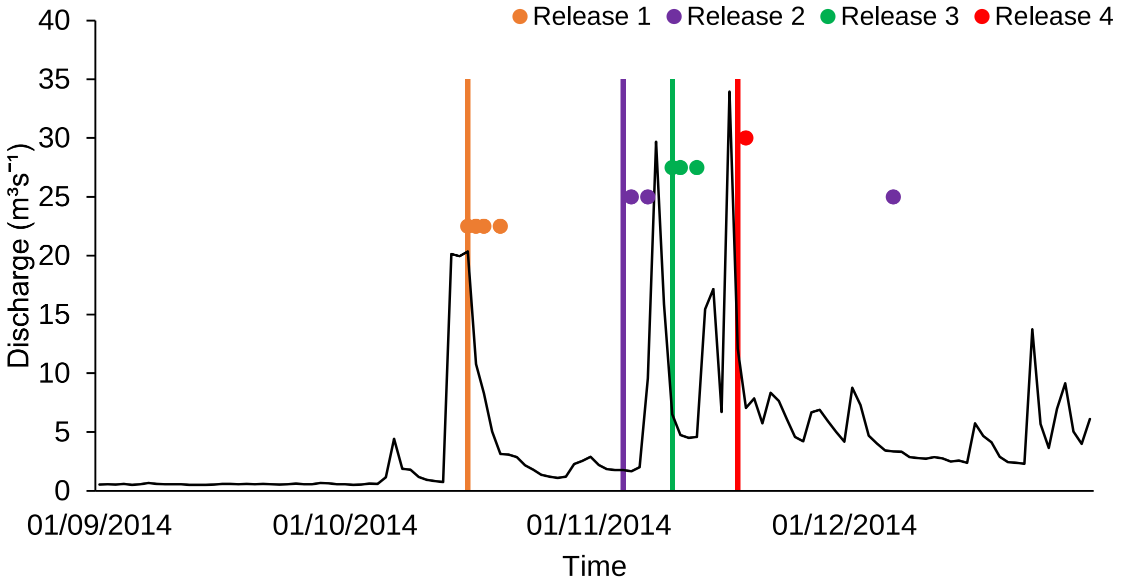


Figure 30. Time series of discharge over the 2014 study period with fish movements represented as points in time. Each point is colour coded according to its release batch. Note: all dots are representative of passage.

2014 was an intermediate year in terms of hydrology being wetter than the dry autumn of 2011 and having only two spates similar to the four >30 cumec events observed in 2012 (Figure 31b). However, 2014 was unusual in that it had a prolonged dry period (September and early October) followed by a series of large spates and a period of flows > 2 cumecs. In 2014 passages of sea trout were observed at discharges between 1.65 and 31.00 cumecs and many of these (seven) were at flows higher than the largest passage flows observed in either 2011 or 2012 (5.52 cumecs). In 2013 and 2014 eight fish were observed to pass at flows >10 cumecs (Figure 31a). Only two fish in 2014 and no fish passages in 2013 were observed at the low flows (<2 cumecs) at which some passages were recorded in 2011 and 2012 (Figures 31 and 32).

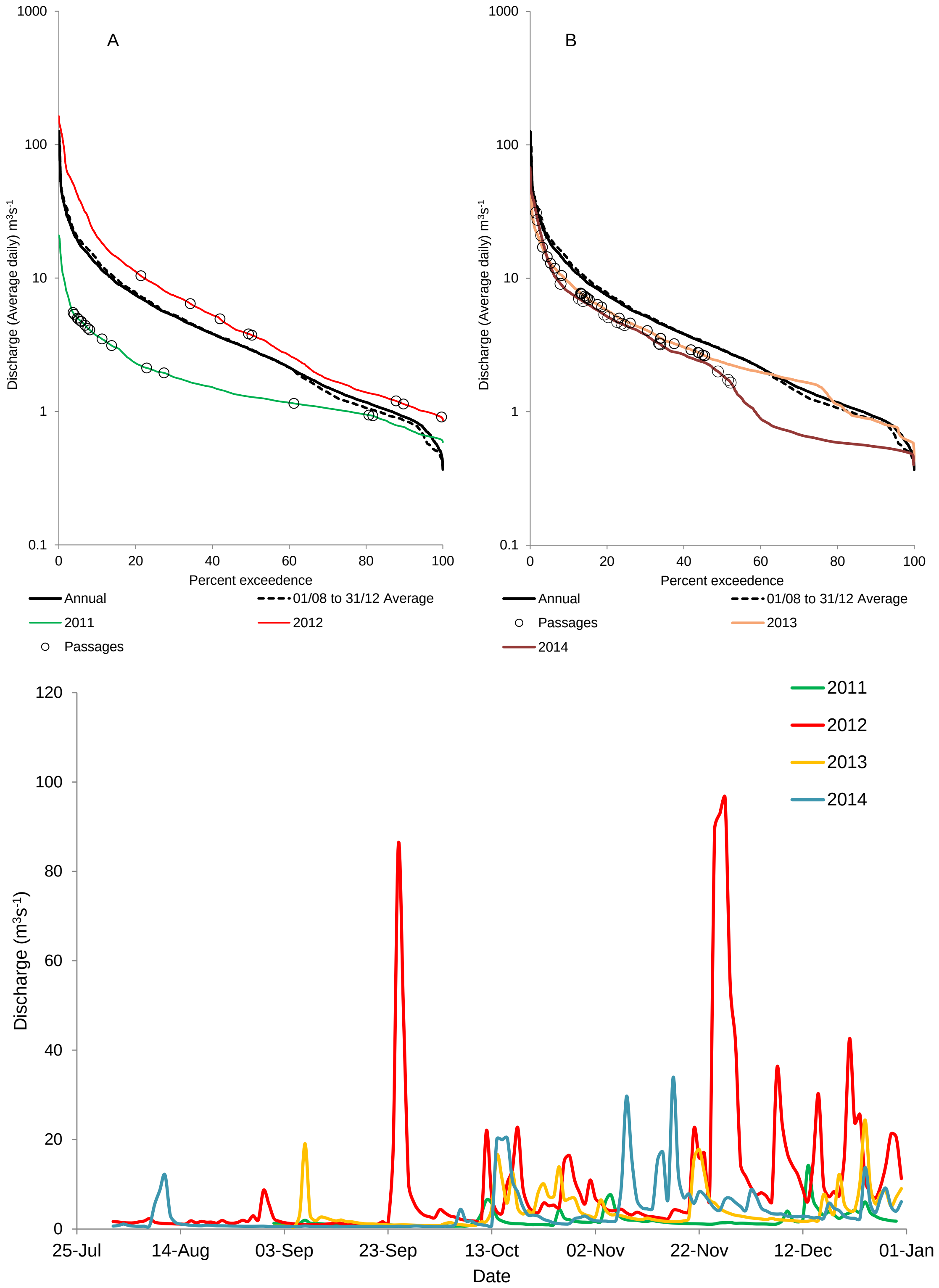


Figure 31. Relationship between sea trout passages and flow exceedance for Pre (A) and Post (B) curves and comparison of the hydrographs over the study period (C).

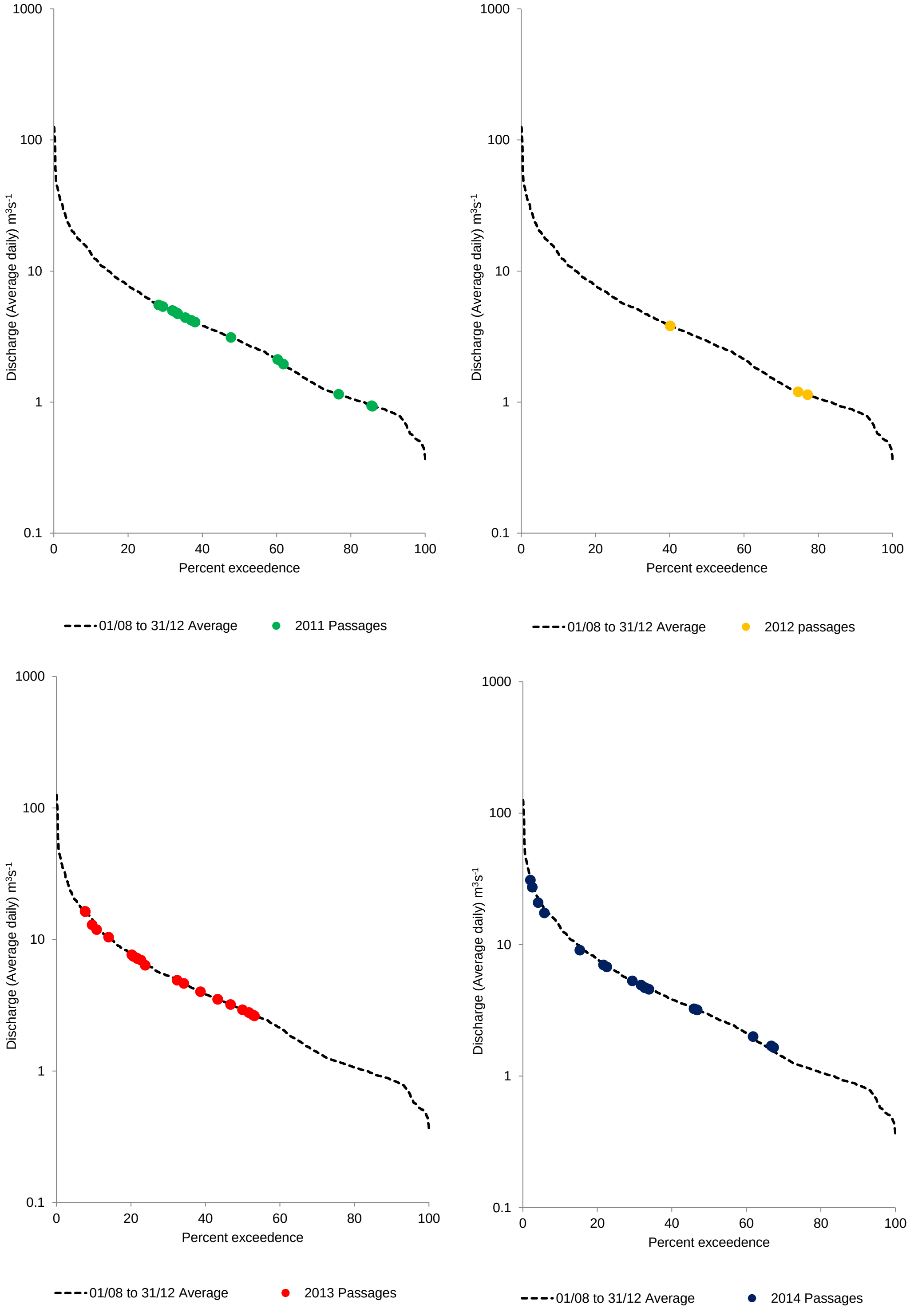


Figure 32 Timing of sea trout passages through the fish passes in 2011 (pool-traverse fish pass)(top left), 2012 (top right), 2013 (bottom left) and 2014 (bottom right)(Larinier fish pass) in respect of discharge ($m^3.s^{-1}$) displayed as a flow exceedence curve for the long term average seasonal (1 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).

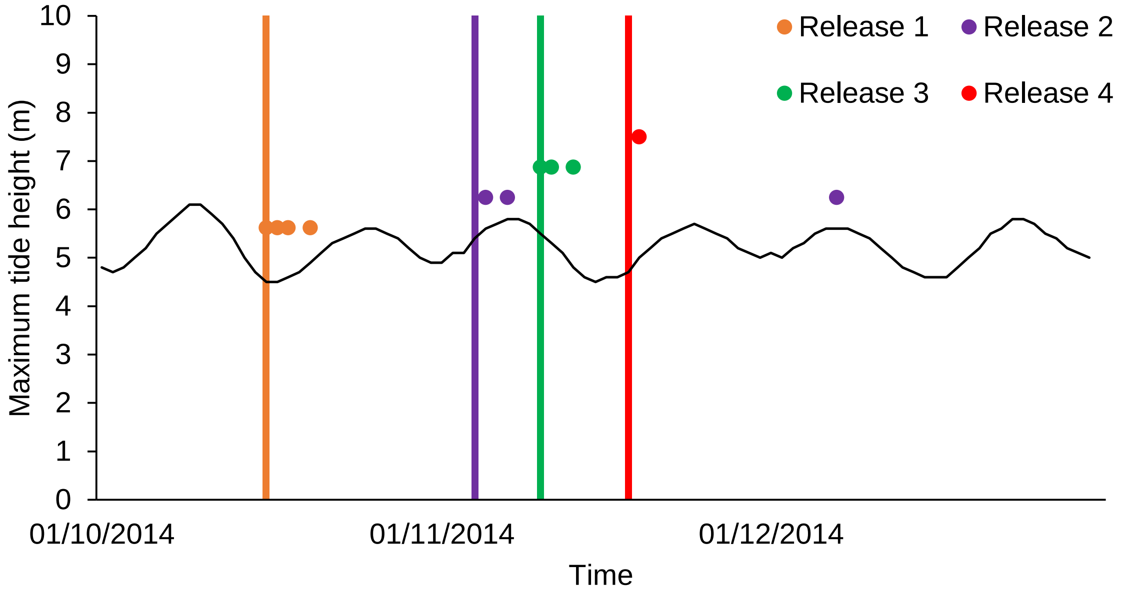


Figure 33. Time series of daily maximum predicted tide heights over the 2014 study period with fish movements represented as points in time. Each point is colour coded according to its release batch.

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, 2013 and 2014. In all datasets the majority of movements occurred around the mid tide (1.5 to 3.0m, 30-70% of tide height). Also in all three periods 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.

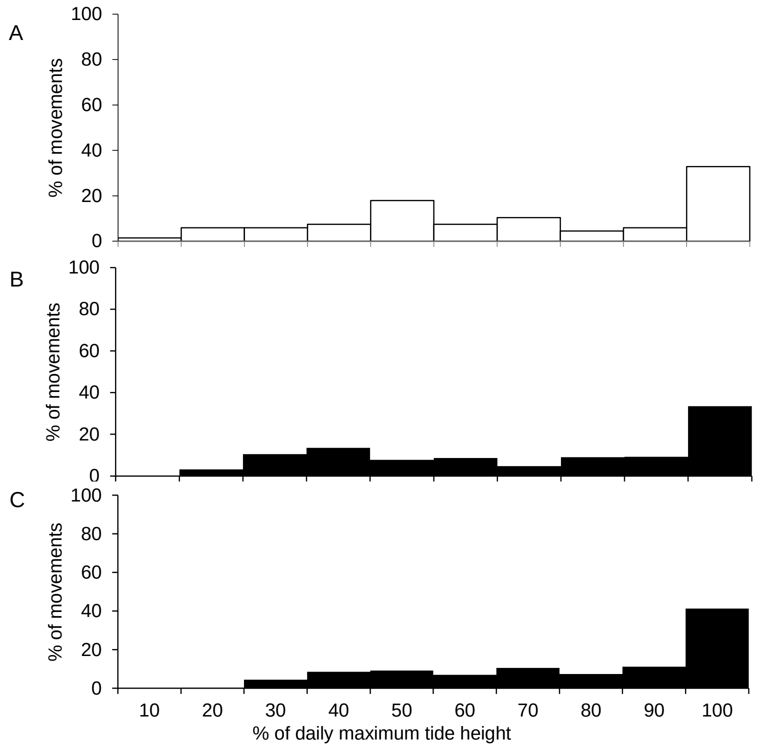


Figure 34. The percentage of non-passage movements versus tide state expressed as the percentage of daily maximum tide height for sea trout. A = Baseline, B = 2013 and C = 2014

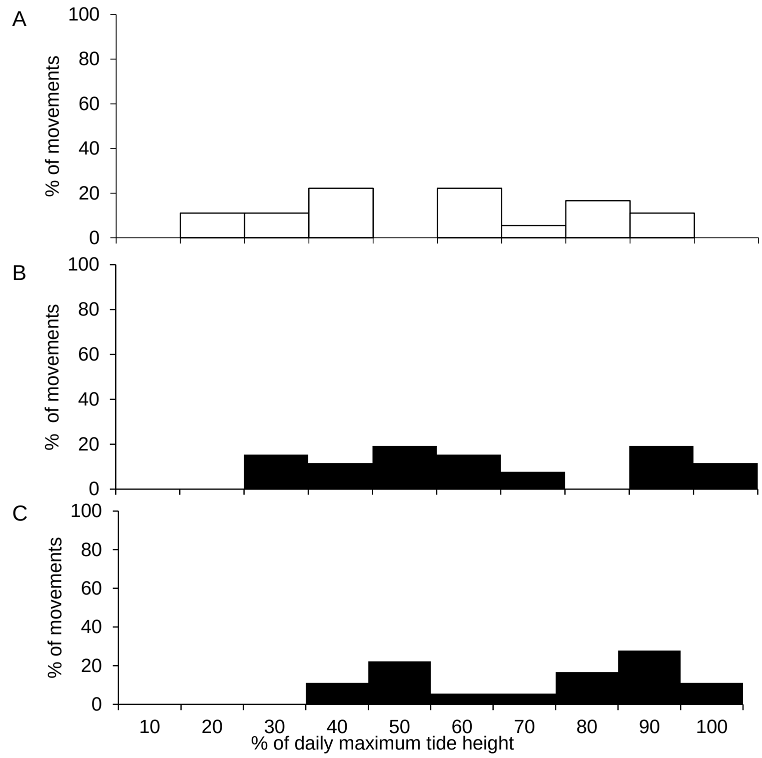


Figure 35. The percentage of passage movements versus tide state expressed as the percentage of daily maximum tide height for sea trout ascending the weir. A = Baseline, B = 2013 and C = 2014

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 > $6m^3s^{-1}$ whilst many sea trout were observed to pass at flows between 6 and $20m^3s^{-1}$ in 2013 and 2014. The pattern was similar for times of first arrival in the array, with no clear pattern in relation to discharge or tide (Figure 37).

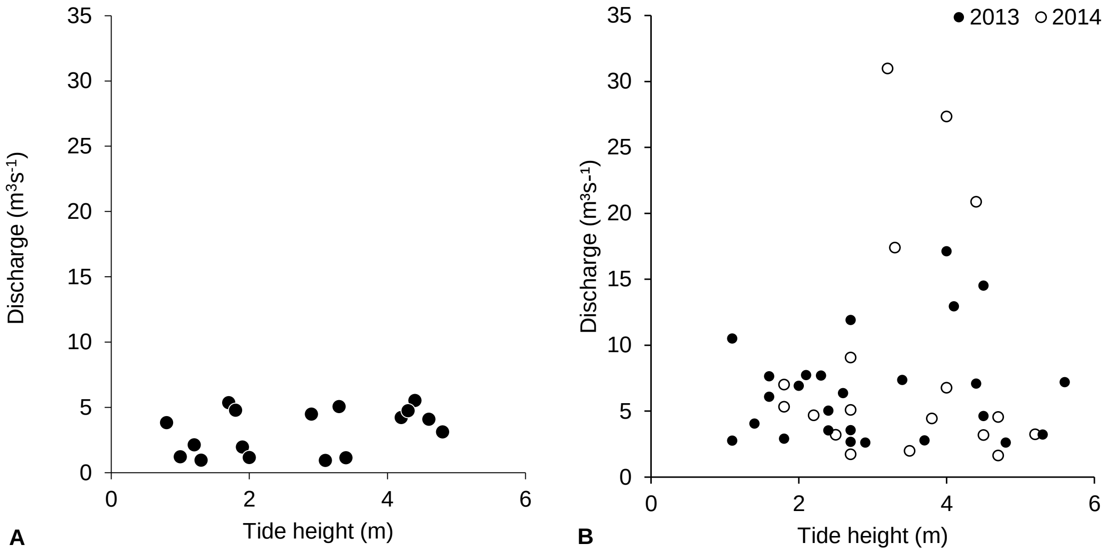


Figure 36. Discharge and tide conditions during passage tracks for sea trout in A) 2011 and 2012 B) 2013 and 2014

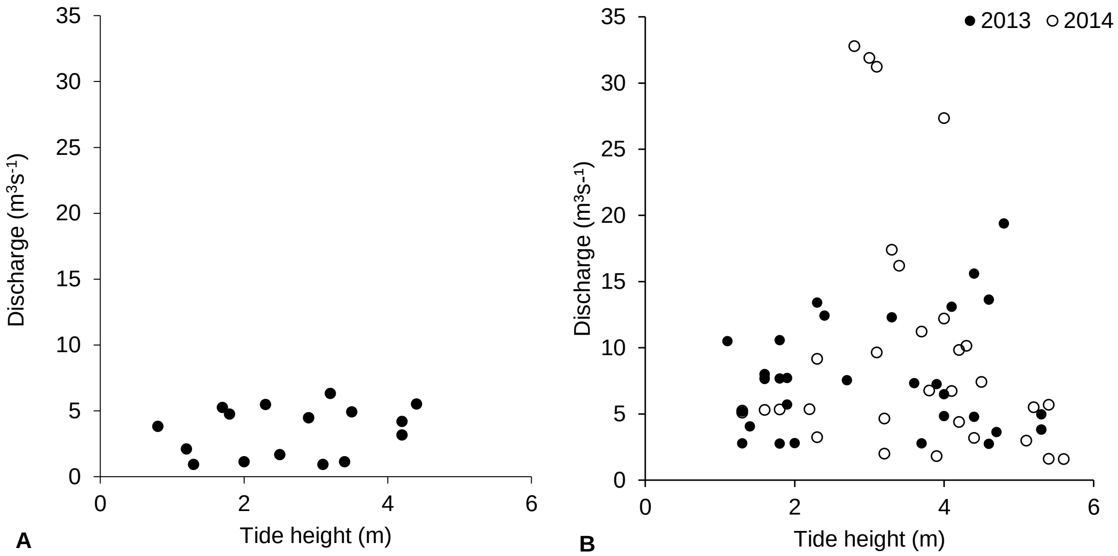


Figure 37. Discharge and tide conditions during first entry into array for sea trout in A) 2011 and 2012 B) 2013 and 2014.

Esk Energy now monitor the pool level downstream of the hydropower scheme (metres above ordnance datum, maOD) and these levels respond to both river discharge and tide height (previously measured as predicted height at Whitby). These data give absolute information as to the discharge conditions in the pool and thus replace the total water index measure (TWI) used in Walton *et al.* 2012 and Noble *et al.* 2013. First arrival and fish passage occur at a range of levels with the majority of passages occurring between 1.85 and 2.10m and the majority of first arrivals between 2.00 and 2.15m (Figure 38).

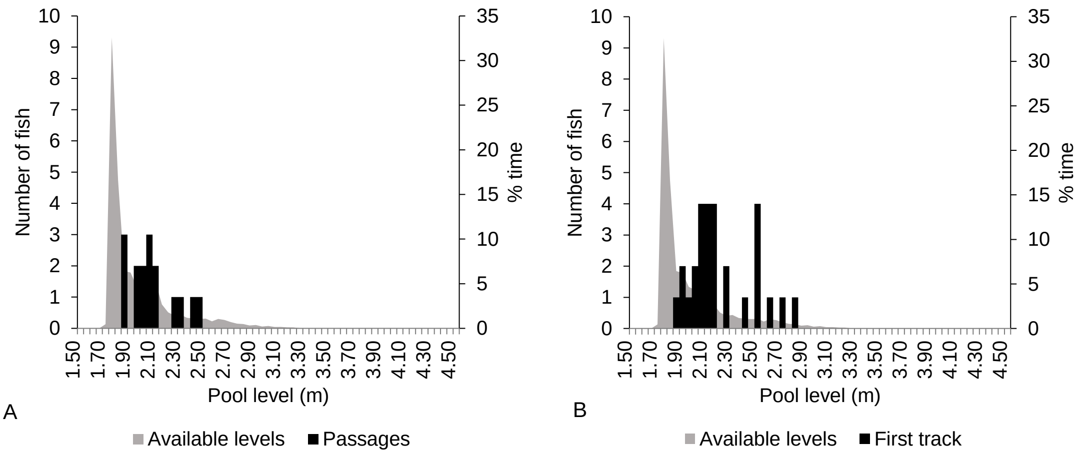


Figure 38. Relationship between A) the timing of passage over the weir and B) first arrival in the pool and the pool level (maOD) (2014).

In 2014 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 = 203) over ebbing tides (n = 147), this is in contrast to the baseline where there was a slight bias towards ebbing tides (n = 34) over flooding tides (n = 24). In all years 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 2014 (median time in array 2.13, 0.57 – 5.12 minutes, n = 147) were on average slightly shorter than those on a flood tide (2.63, 0.72 – 7.22 minutes, n = 203) and the 64 starting at high water slack had an average duration of 1.74 (0.38 – 6.61) minutes. Overall there was little difference in the duration of tracks during different tidal phase in all of the study years and the duration of non-passage tracks were significantly shorter in the initial post-dataset than in the baseline for both ebbing (Mann Whitney U-test: $Z = -2.695$, n = 296, $P < 0.01$) and flooding tides (Mann Whitney U-test: $Z = -3.102$, n = 497, $P < 0.01$).

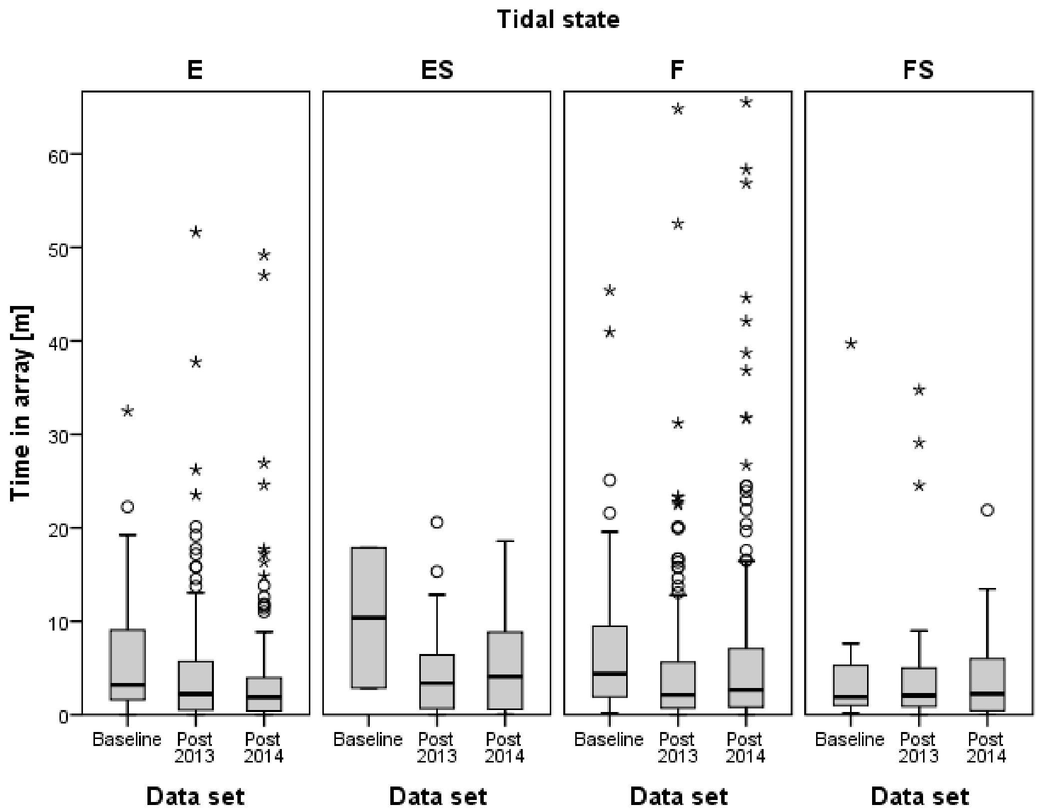


Figure 39. Amount of time spent in the array on non-passage runs of sea trout during ebbing (E; baseline n = 34, 2013 n = 115, 2014 *n* = 147), low water slack (ES; baseline n = 2, 2013 n = 23, 2014 *n* = 30), flooding (F; baseline n = 24, 2013 n = 272, 2014 *n* = 203) and high water slack (FS; baseline n = 1, 2013 n = 56, 2014 *n* = 64) stages of the tide.

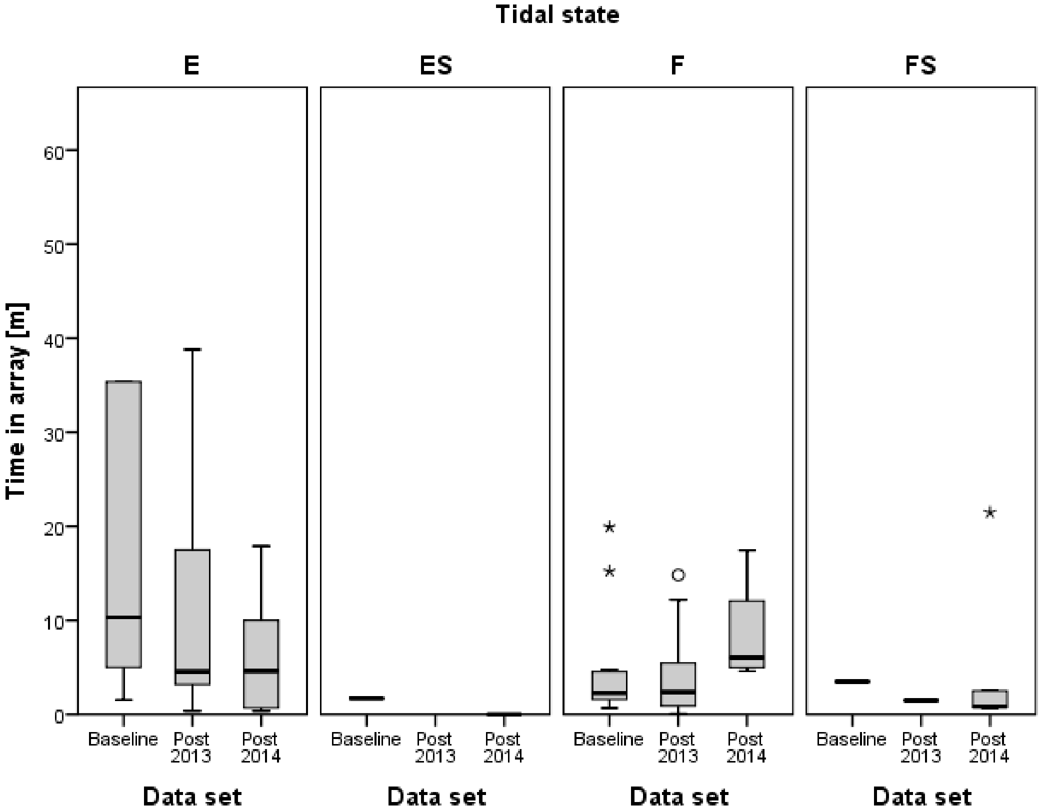


Figure 40. Amount of time spent in the array on passage tracks of sea trout during ebbing (E; baseline n = 5, 2013 n = 10, 2014 *n* = 9), low water slack (ES; baseline n = 1, 2013 n = 0, 2014 *n* = 1), flooding (F; baseline n = 11, 2013 n = 14, 2014 *n* = 4) and high water slack (FS; baseline n = 0, 2013 n = 4) stages of the tide.

In 2014 there was a roughly even split between passage tracks starting on ebbing (n = 8) or flooding (n = 9) tides. 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 in both years (Figure 40). In 2014 passage tracks that started on an ebbing tide (median time in array 4.62, 0.63 – 12.05 minutes) were on average shorter than those on a flood tide (6.02, 4.80 – 14.77 minutes). This pattern was in contrast to both 2013 and the baseline where passage tracks on ebbing tides tended to take longer than on flooding tides. However, there is no significant difference in passage track duration between the initial post- dataset and the baseline for either ebbing tides (Mann Whitney U-test: $Z = -1.102$, n = 24, $P > 0.05$) or flooding tides (Mann Whitney U-test: $Z = 0.225$, n = 29, $P > 0.05$).

3.3.4 Relationship with water temperature

Water temperature declined from around 15-16 °C at the start of September and declined to around 3 °C by mid December. No trends were observed in the movement of fish in relation to temperature over the study period (Figure 41).

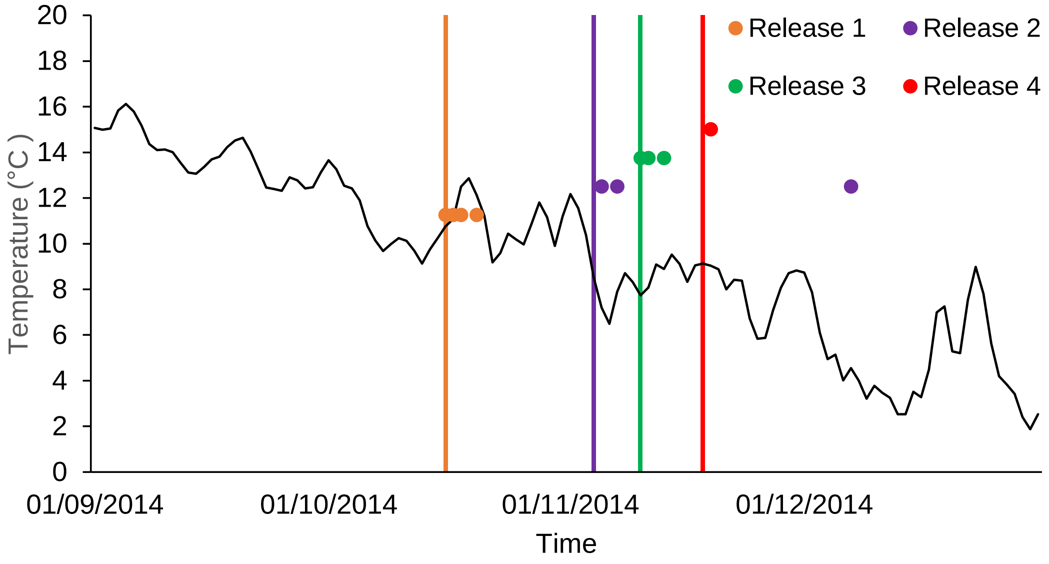


Figure 41. Times series of temperature over the 2014 study period with the passages of fish represented as points in time. Each dot is colour coded according to its release batch, with the release date indicated by the vertical line.

3.3.5 Turbine activity

The hydropower turbine was active for 51% of the time during the study period (1/9/2014 to 31/12/2014) (compared with 58% of the time in 2013) and was operating at near capacity (abstraction of above 3.7 m^3s^{-1}) for <1% of the time (compared with 5.6% of the time in 2013) (Figure 42a). Sea trout were observed to ascend through the fish pass under most conditions, one fish passed whilst the turbine was off and seven fish passing at turbine flows of greater than 3.5 m^3s^{-1} (Figure 42a).

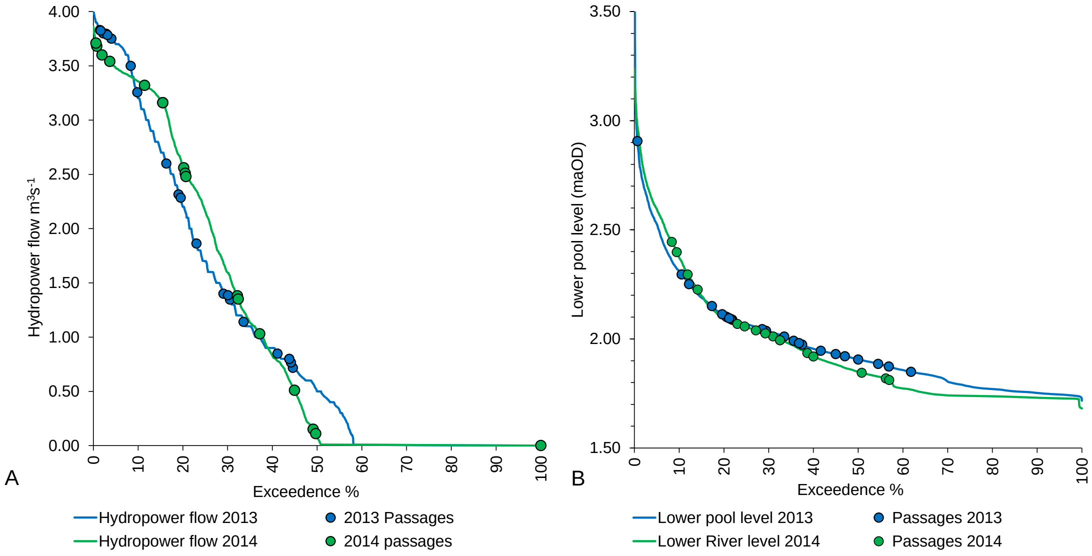


Figure 42 Passages of sea trout (open circles) through the Larinier fish pass plotted against exceedence curves of hydropower flow (A) and level in the pool (B) (exceedence values calculated between 1/9 and 31/12 each year). Note, two sea trout in 2013 and one in 2014 passed when the hydropower flow was zero.

In 2014 the numbers of fish in each batch was spread fairly evenly and the majority of passages followed within the first few days after each release (Figures 43 to 46). The first event was characterised by a large but rapid spate and high flows (>6m^{3}s^{-1} for most of the time) and the turbine running at or near full capacity until the river discharge dropped below 6m^{3}s^{-1} on the third day after the release (Figure 44). The second release was characterised by a period of low flow and little hydropower abstraction until two days after the release when there was a very large spate and the turbine started to work at close to full capacity. The turbine was then inactive at the highest river flows, a large spate peaked around 65 cumecs on the 7th of November. The turbine is turned off either because there is not enough head to extract any energy (spate) or there are high river levels in the downstream pool (tides). There were high tides at Whitby at 16:02 on 7th November and 04:18 on 8th November. These match the peaks in lower river level in Figure 44. The high river flow also contributed to the high water levels in the lower river. (Figure 44). The third and fourth releases were both characterised by prolonged periods of flows around 6 to 10 cumecs, flows at which the hydropower scheme was operating at around full capacity (abstractions >3.5 cumecs) (Figures 46 and 46). It should be noted that very few of the final batch of sea trout actually ascended the weir (Figure 46).

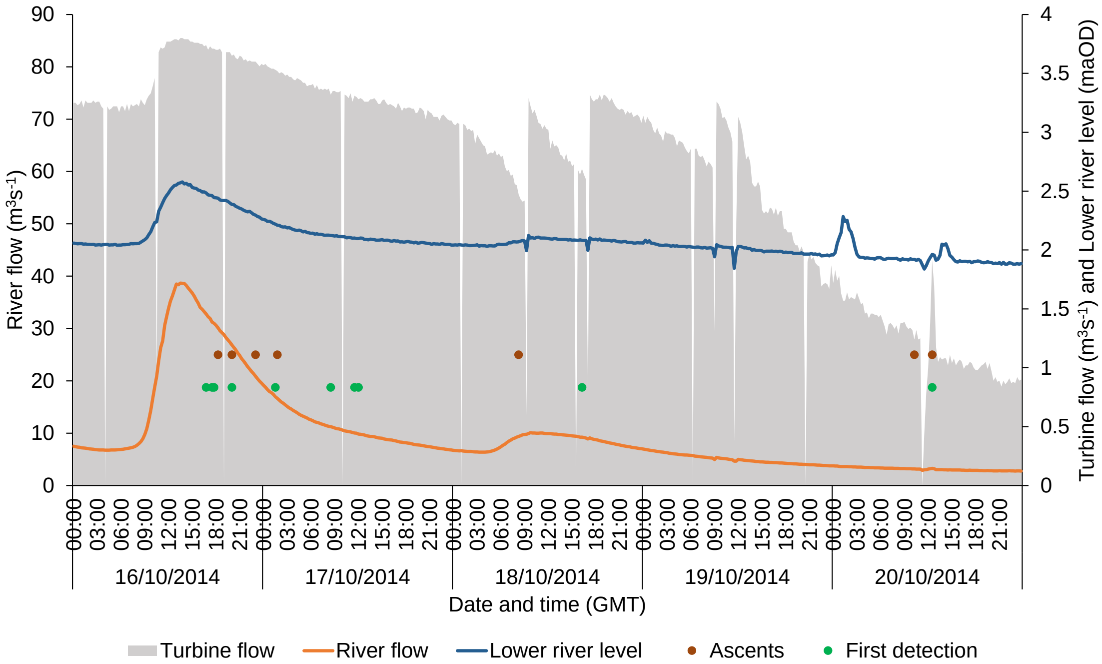


Figure 43 First detection and passage records of sea trout around the 1st tagging event on 16 October 2014 showing river flow, turbine discharge and the river level in the pool.

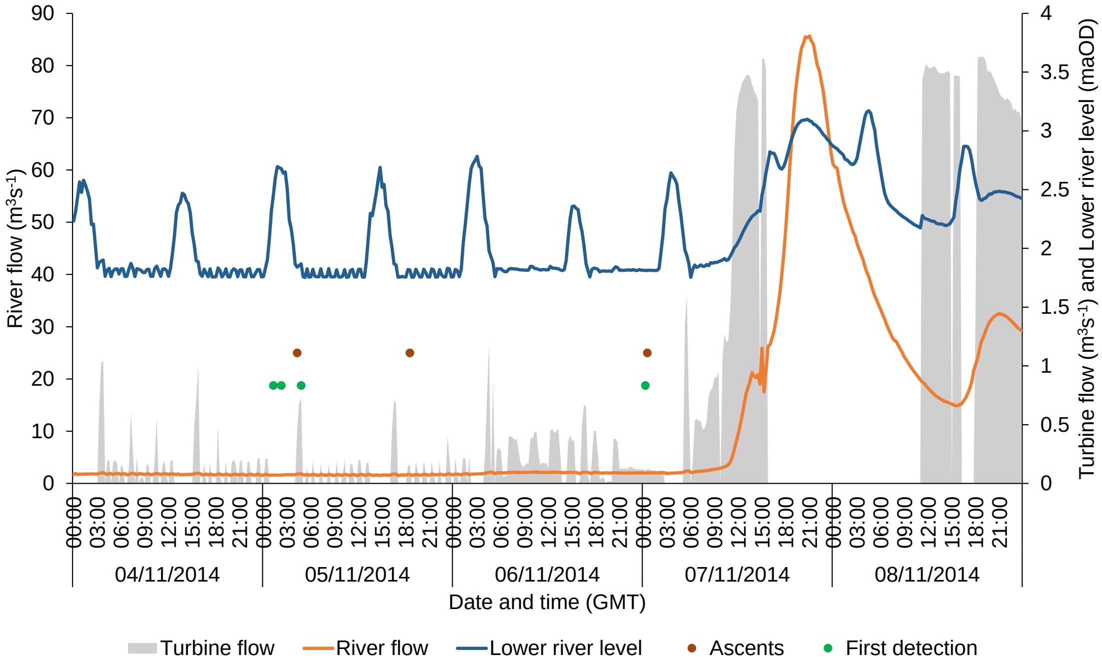


Figure 44 First detection and passage records of sea trout around the 2nd tagging event on 4 November 2014 showing river flow, turbine discharge and the river level in the pool.

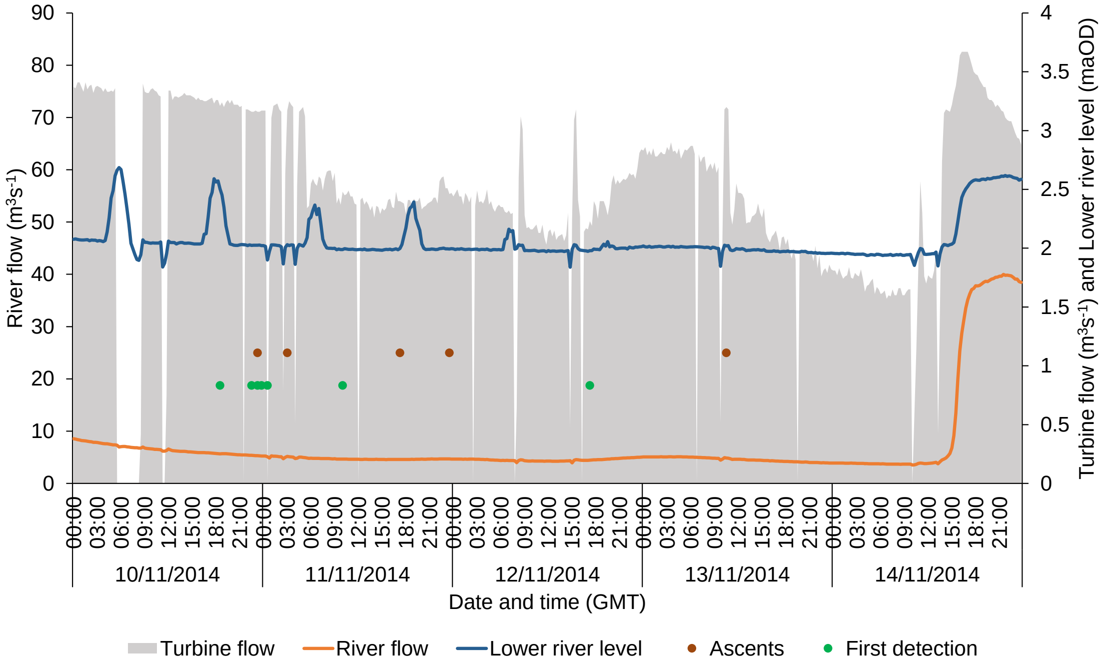


Figure 45 First detection and passage records of sea trout around the 3rd tagging event on 10 November 2014 showing river flow, turbine discharge and the river level in the pool.

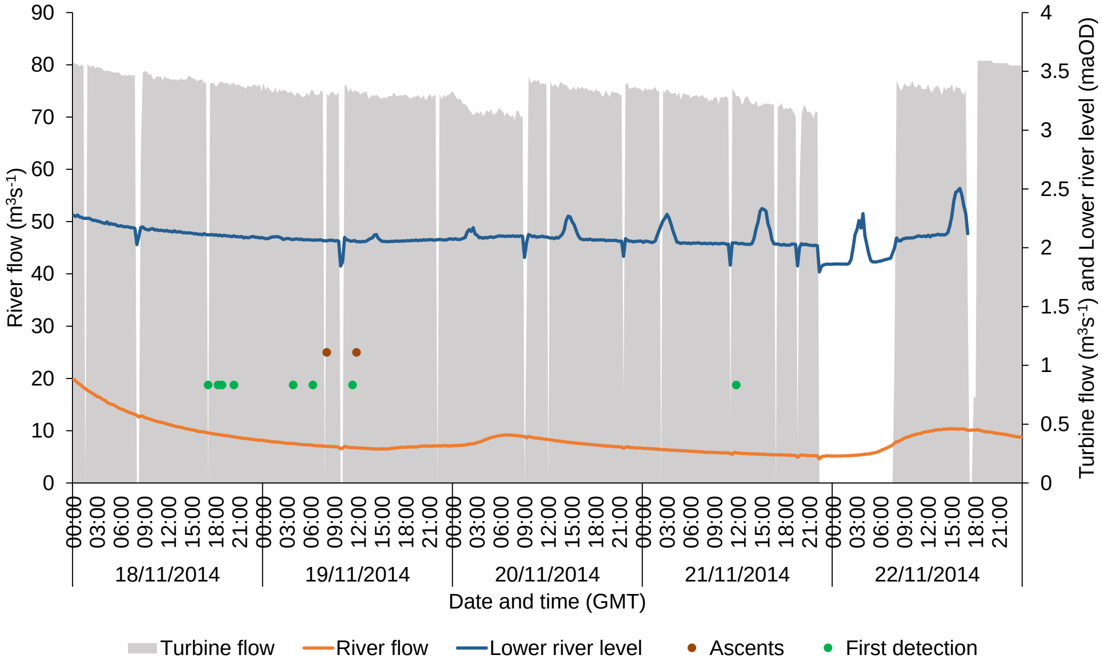


Figure 46 First detection and passage records of sea trout around the 4th tagging event on 18 November 2014 showing river flow, turbine discharge and the river level in the pool.

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 47).

Figure 47. View of the outfall of the new turbine and hydrophones array in 2013 with the hydropower scheme active under higher flows (21.82m^3s^{-1}).

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 both 2013 and 2014 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 48a) 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 and 2014, 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 48b and c). The area approximately 2-3m in front of the fish pass entrance is now relatively shallow (0.5-0.8m) before deepening (1.2-1.4m) at around 4m downstream of the fish pass entrance. In 2014 pool levels were measured with both the fish pass and hydropower turned off, when these were turned on about 15cm of depth was added to parts of the pool.

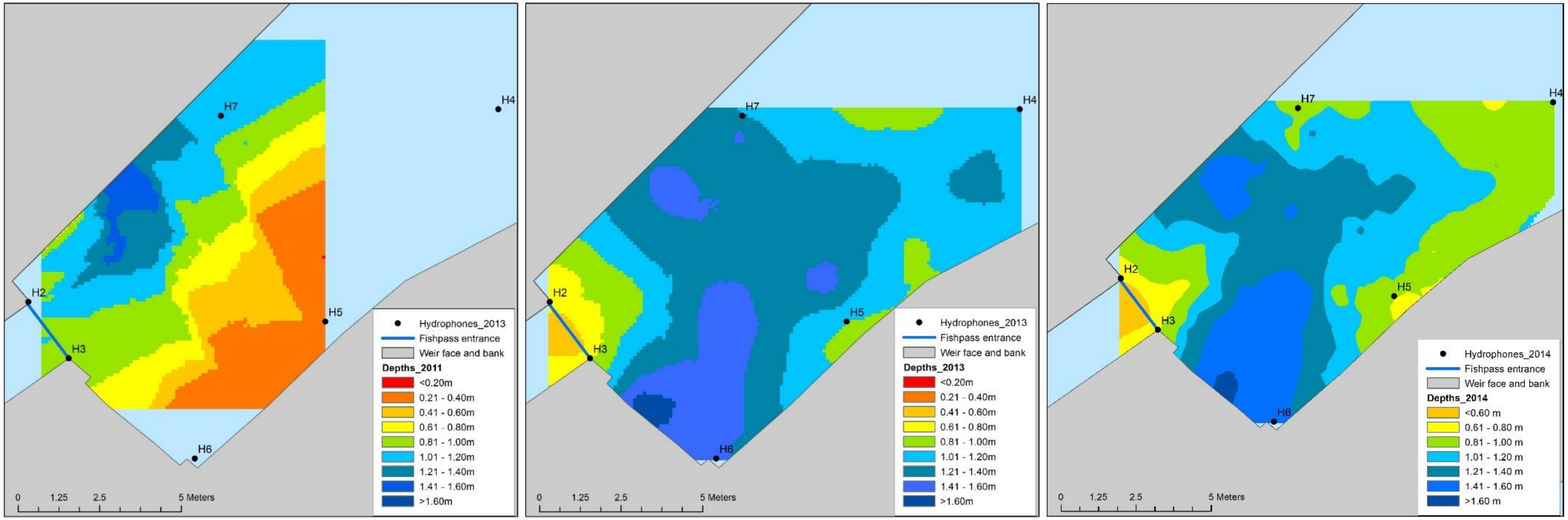


Figure 48 Bathymetry of the pool raster plots calculated by kriging ADCP data in 2011 (left) and manual transect measurement in 2013 (middle) and 2014 (right). Note that these were measured under different flows (and with the hydropower and fish pass turned off in 2014) so the absolute measurements should not be directly compared between years.

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 and 2014 made it increasingly difficult to determine from which direction fish had entered the pool. In 2014 the highest frequency of tracks appeared first in segments A (*n* = 139), towards the weir face at the rear of the pool, and in C and D (*n* = 59 and 66 respectively) at the rear of the pool (Figure 49 and Table 5). The majority of the tracks started in the vicinity of H4 (*n* = 170) and indeed tags were often only detected on H4 before they were detected on enough hydrophones to be triangulated and tracked. A large number of tracks also started (*n* = 52) and terminated (*n* = 77) 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 H6 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. This pattern is very similar to that observed in 2013.

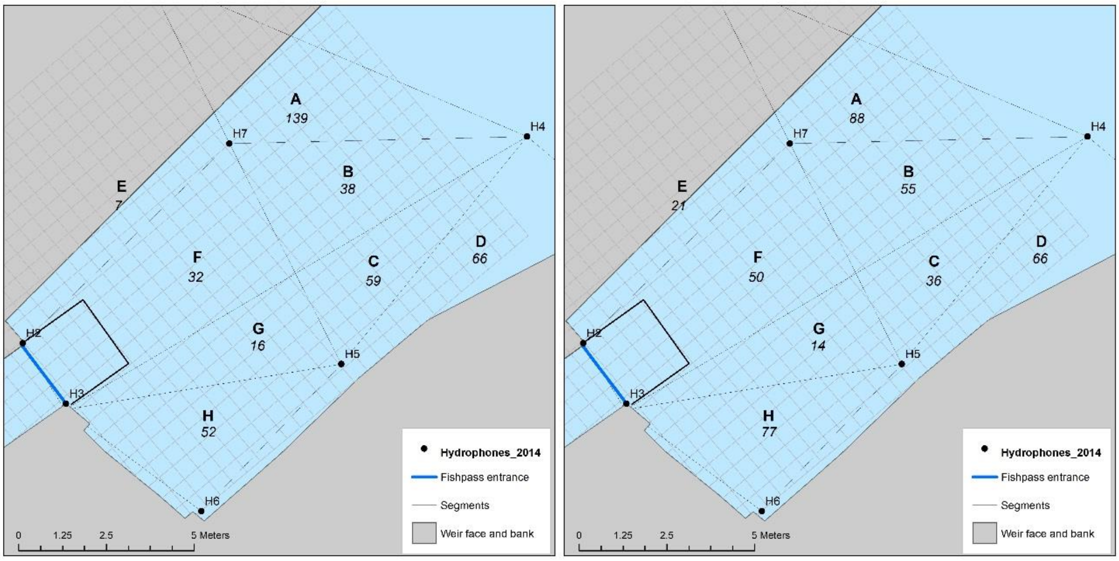


Figure 49. Frequency of start (left) and finish (right) locations of all fish tracks within the array for 2014 in relation to the rear of the grid (A-D) and the front of the grid (E-H)

Table 5. Frequency of start and finish locations of all fish tracks within the array for 2014 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). There were a further 48 tracks which did not start/stop within or clearly enter the array footprint.

	A4	A7	B1	B4	B7	C1	C4	C5	D4	D5
Start of track	80	59	11	10	17	15	23	21	57	9
End of track	54	33	12	20	23	13	14	19	53	13

	E2	E7	F1	F2	F3	F7	G1	G3	G5	H3	H5	H6
Start of track	2	5	7	8	8	9	6	3	7	7	2	50
End of track	8	13	13	10	9	18	5	3	6	6	5	66

3.5.2 Distribution of tracks

In 2014 tracks were again widely distributed throughout the array (Figure 50c) with few cells containing more than 25% of the recorded tracks. The highest density of track records (between 20-50% of tracks) was located in the plumes of the hydropower unlike 2013 when the majority of tracks concentrated around the area between the fish pass and hydropower plumes. The pattern of track distribution in 2014 indicated more of tendency for tracks to pass through locations towards the weir face as observed in the baseline (Figure 50a) although many tracks also passed through the area in front of the outfall, as observed in 2013 (Figure 50b). Residence time was not evenly distributed (Figure 51c) and two hotspots, where a few fish spend a disproportionate amount of their time, were apparent. One was in the cells near the right-hand bank and the outfall of the hydropower turbine, similar to that observed in 2013 (Figure 51b). Additionally one hotspot was observed in front of the fish pass plume, similar to that observed in the baseline (Figure 51a). However, interrogation of the track data indicated that the hotspot in front of the fish pass was caused by track 18 of sea trout 2745 that was around 2.5 hours long and occurred on a high spring tide (>5.2m at Whitby). The fish spent around 30 minutes holding station within one 50cm square cell alone in front of the fish pass (Figure 51d). In contrast the hotspot in front of the hydropower turbine, near H6, was formed by 81 different tracks, 24 of which spent >30 seconds in this location (up to a maximum of 396 seconds). The highest frequency of tag detections were detected within 4.0 - 6.0 m of the fish pass in 2014 (Figure 52). A higher proportion of tag detections were located within <2m of the fish pass than observed in 2013 (Figure 52). However, the generally low rate of detections rates within 2m of the fish pass entrance across 2013 and 2014 in comparison with the baseline may result from reduced frequency of fish using/traversing this area or due to decreased efficiency of tag detection, both related to the shallow and turbulent nature of the area in 2013 and 2014. Indeed the higher detection rates in 2014 generally relate to tracks formed at high tide when the turbulence is reduced.

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

Passage tracks (Figure 53a) were seemingly more widely spread than non-passage tracks (Figure 53b) in 2014, however this may be an artefact of the low numbers of passage tracks. In non-passage tracks a higher proportion of tracks were focussed towards the left-hand side of the pool, immediately downstream of the fish pass outfall. This is in contrast to the pattern observed in 2013 where they were more focussed towards the right-hand side of the pool. 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), the rear of the array in-line with the fish pass and in the zone towards the side-of-fish pass route (Figure 54a). In non-passage tracks hotspots in front of the hydropower screen and the fish pass entrance were apparent (Figure 54b). Again the hotspot in front of the fish pass mouth appears to have resulted from the track of one fish. The general patterns of tag detection proximity in relation to the fish pass entrance were similar between passage (Figure 55) and non-passage tracks (Figure 56) with high numbers of pings recorded around 3-6m 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 2014. The detections observed within 2m during non-passage tracks are related to the unusually long track recorded for fish 2745, formed over 2.5 hours at high tide.

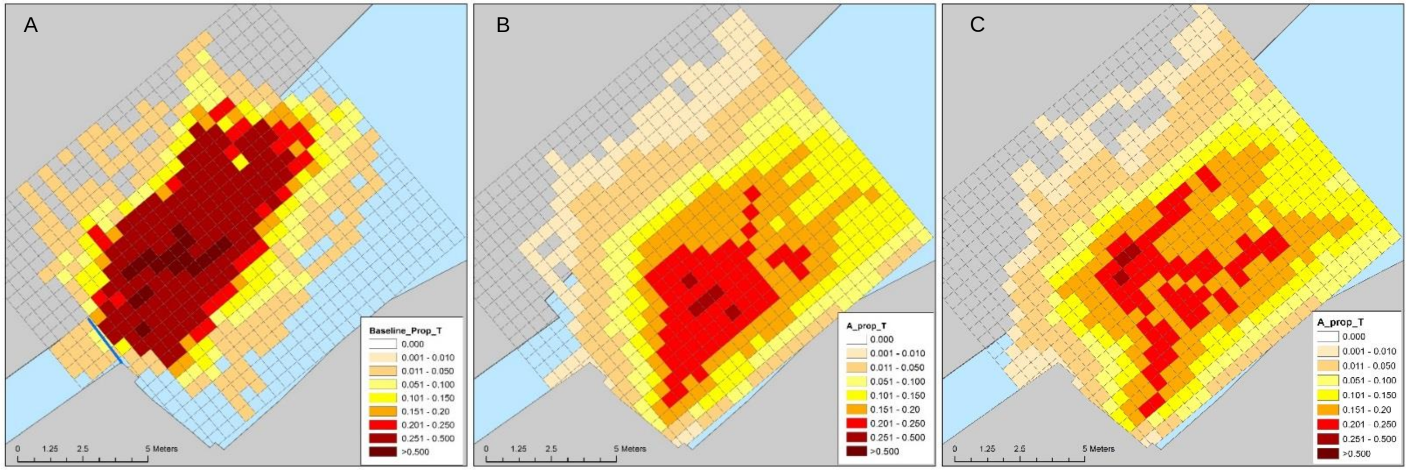


Figure 50. All sea trout tracks combined: proportion of tracks to pass through each grid cell in the baseline (A), 2013 (B) and in 2014 (C). Note that there were far fewer tracks overall in the baseline.

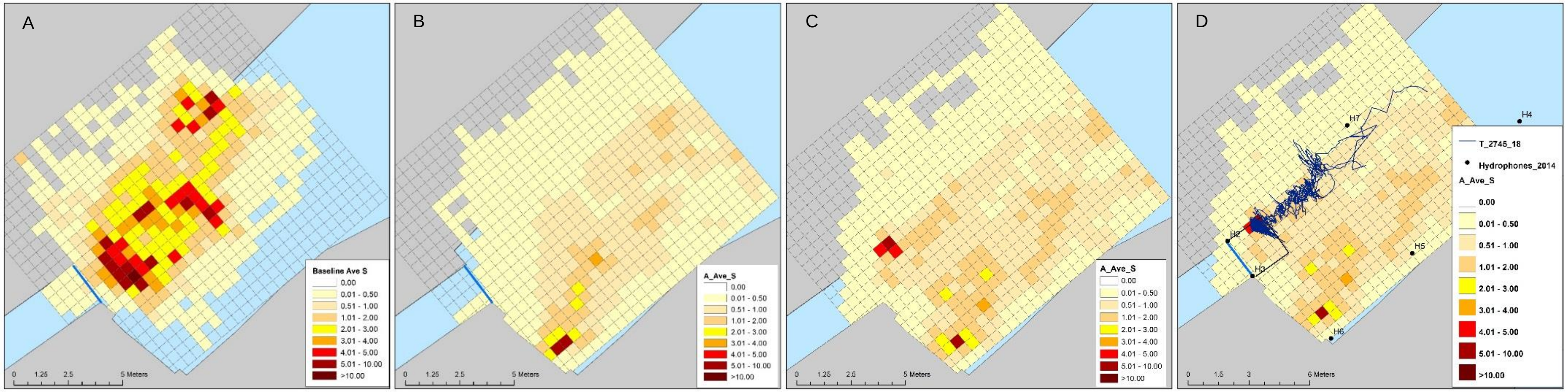


Figure 51. All sea trout tracks combined: average time (seconds) spent by sea trout in each grid cell in the baseline (A), 2013 (B) and in 2014 (C) – the influence of track 2745_18 on the hotspot in front of the fish pass outfall is shown in (D).

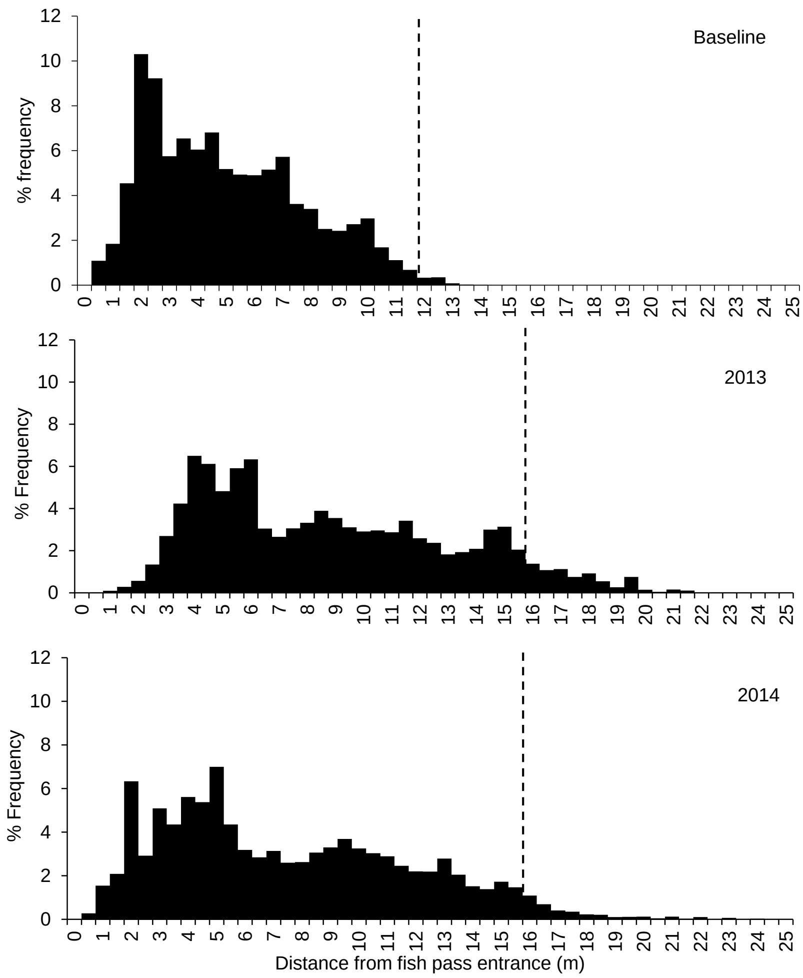


Figure 52. Numbers of tag detections in the array against distance from the entrance to the fish pass (m) as a percentage of the total number of tag detections recorded in 2014, 2013 and the baseline. Dashed lines indicate the approximate extent of the furthest hydrophone from the fish pass in each dataset.

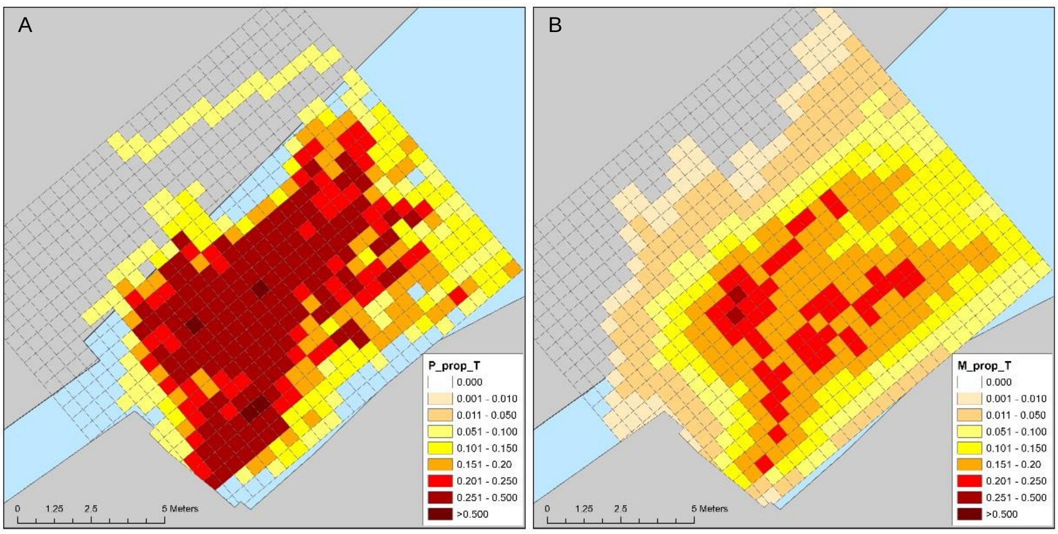


Figure 53. Proportion of sea trout tracks to pass through each grid cell during passage (left) and non-passage (right) visits to the array in 2014.

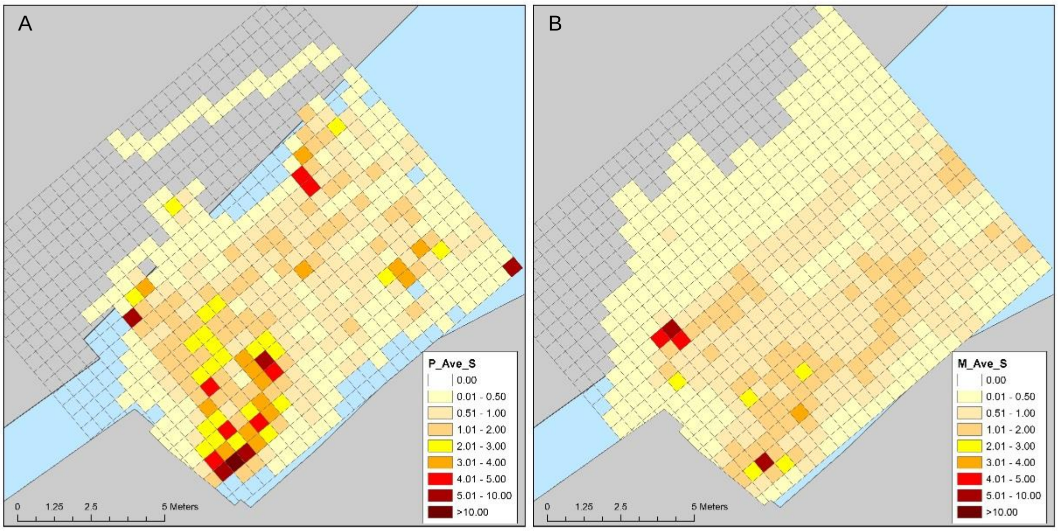


Figure 54. Average time (seconds) spent in each grid cell by sea trout during passage (left) and non-passage (right) visits to the array in 2014.

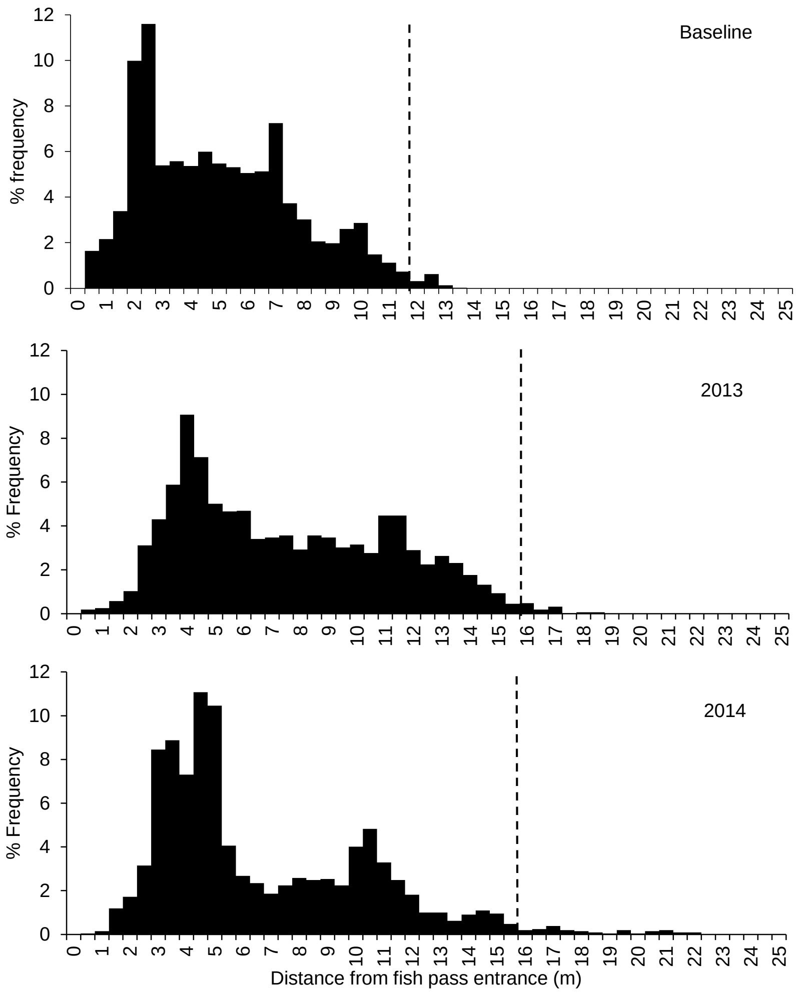


Figure 55. Numbers of tag detections in the array as a percentage of the total number of tag detections recorded in sea trout passage tracks, against distance from the entrance to the fish pass. Dashed lines indicate the approximate extent of the furthest hydrophone from the fish pass.

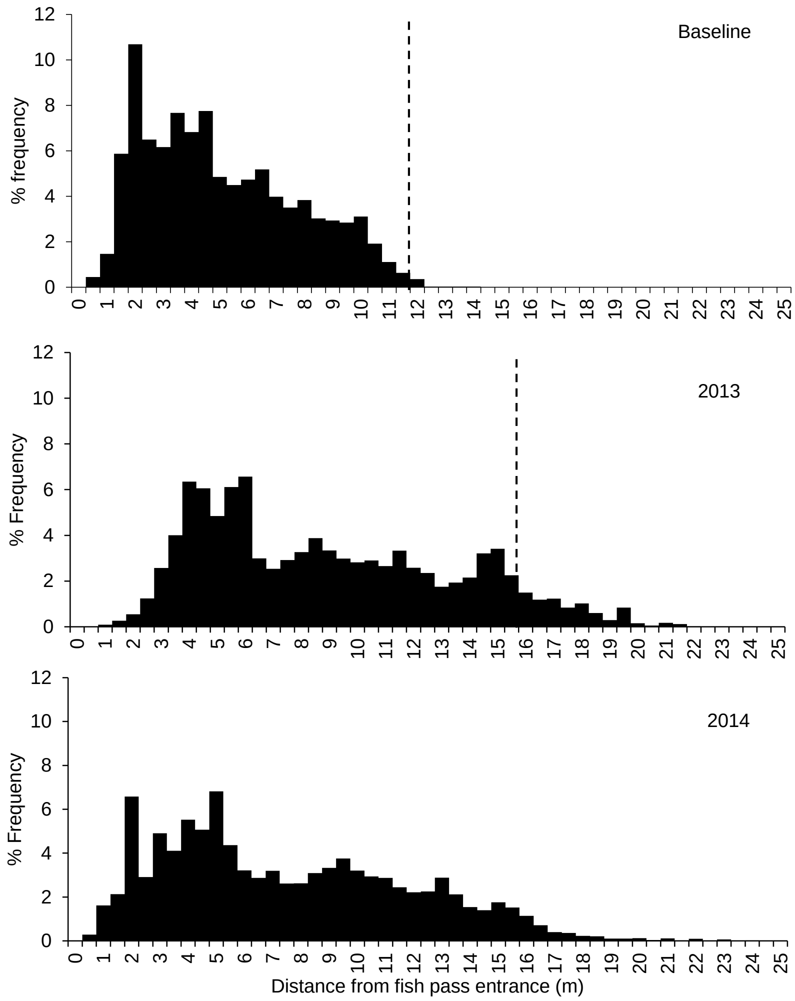


Figure 56. Numbers of tag detections in the array as a percentage of the total number of tag detections recorded in sea trout non passage tracks, against distance from the entrance to the fish pass. Dashed lines indicate the approximate extent of the furthest hydrophone from the fish pass.

3.5.4 Diel variations in spatio-temporal distribution within the array

In 2014 there appeared to be a discernible difference in the distribution of tracks and the proportion of time spent within the array during the day and at night (Figures 57 and 58). During the day tracks occurred more frequently towards the middle of the pool / right-hand bank rather than near the weir face, whereas during the night tracks were most frequent in the fish pass plume. Also in both cases hotspots in average time spent in cells were apparent in front of the hydropower screens near the right-hand bank. However, during the day more hotspots were observed in the deepest parts of the pool in front of the hydropower outfall. The hotspot formed in front of the fish pass at night was again due to the unusually long track formed by 2745. The frequency of tag detections decreased with distance above a 4.0 m proximity from the fish pass entrance during the day (Figure 59) but was highest at 2m during the night (again probably related to one track from 2745) (Figure 60). In both cases another key location was suggested at 8-9m from the fish pass entrance.

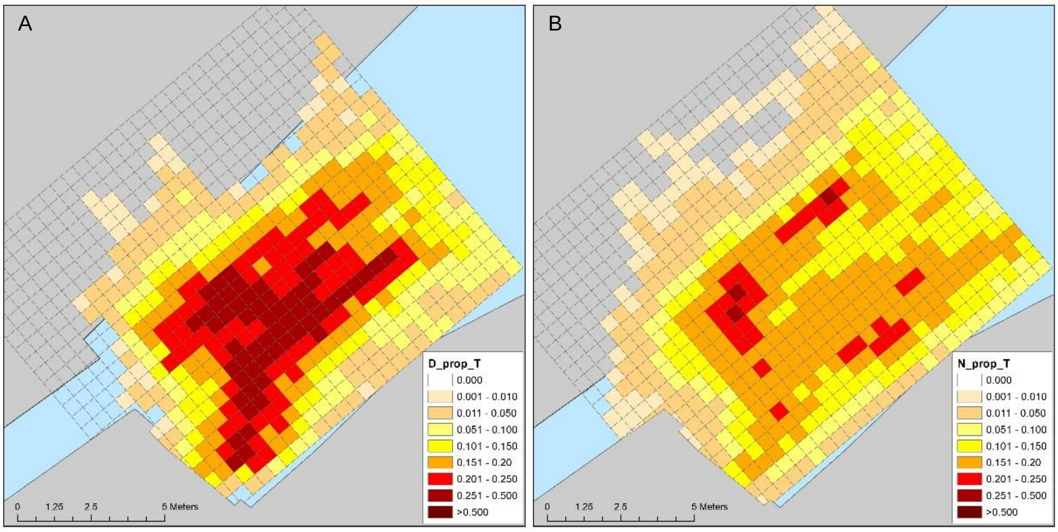


Figure 57. Proportion of sea trout tracks to pass through each grid cell (standardised by number of tracks in each group) during the day (left) and at night (right) in 2014.

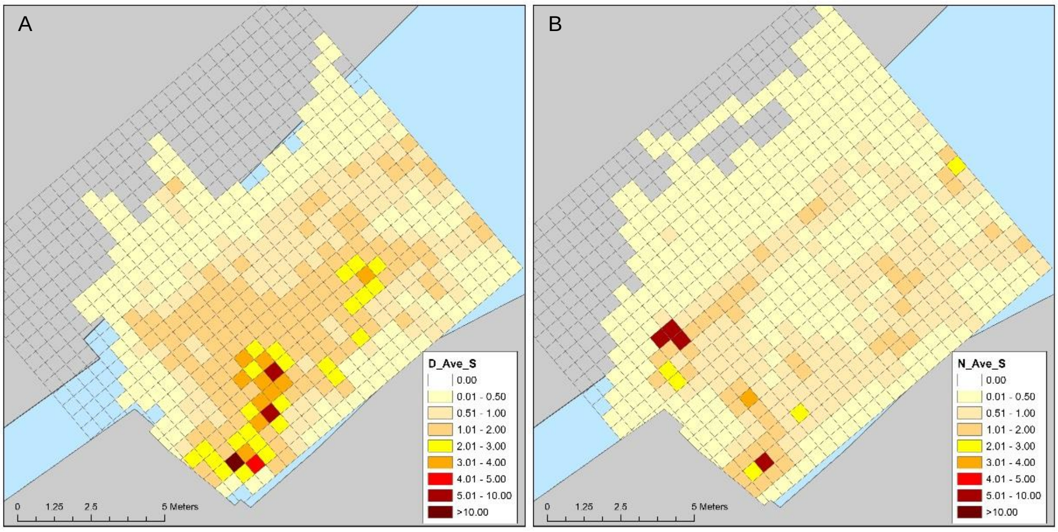


Figure 58. Average time (seconds) spent in each grid cell by sea trout during the day (left) and at night (right) in 2014.

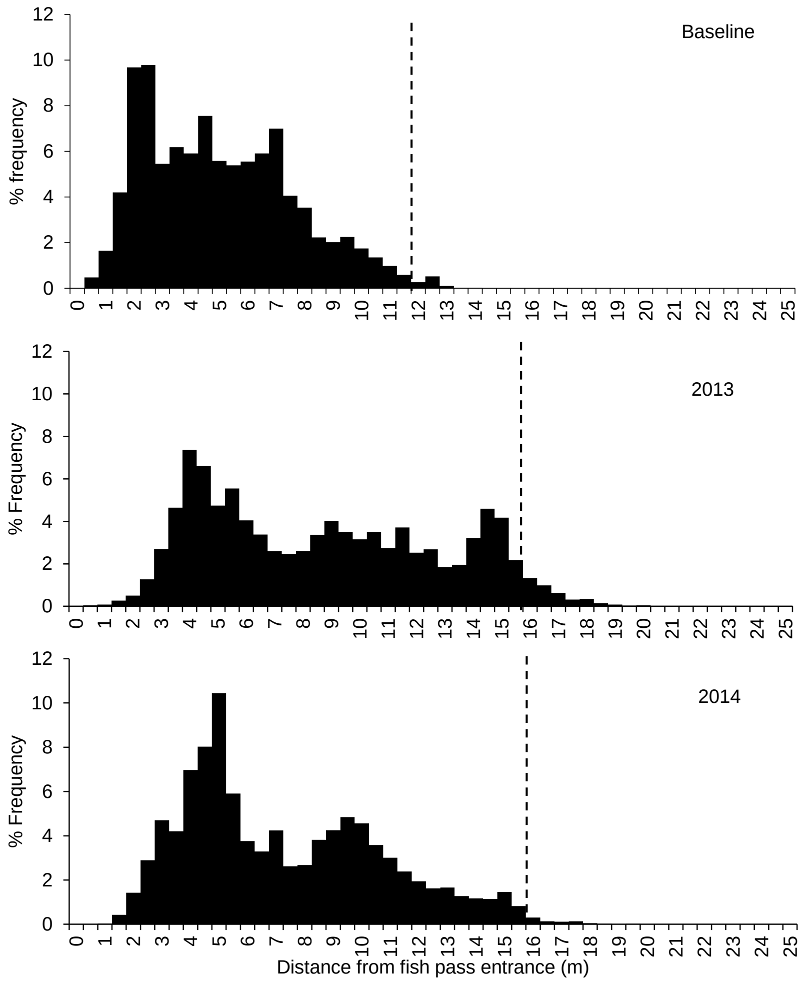


Figure 59. Numbers of tag detections in the array as a percentage of the total number of tag detections recorded during the day, against distance from the entrance to the fish pass. Dashed lines indicate the approximate extent of the furthest hydrophone from the fish pass.

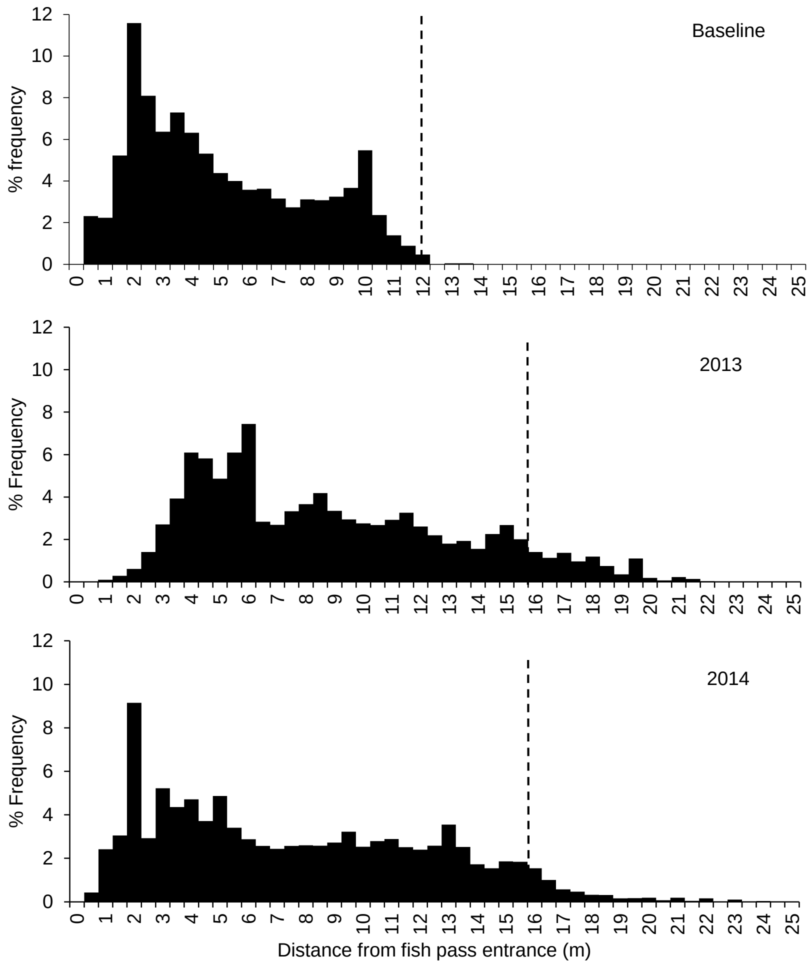


Figure 60. Numbers of tag detections in the array as a percentage of the total number of tag detections recorded during the night, against distance from the entrance to the fish pass. Dashed lines indicate the approximate extent of the furthest hydrophone from the fish pass.

3.5.5 Tide state and spatio-temporal distribution within the array

Little discernible difference in patterns was observed between track locations at different tidal states (Figure 61), except for the tracks (n = 68) made during high-water slacks (Figure 61d) when tracks seem to congregate towards the rear of the array. There was also little discernible difference in residence time during the different tidal states, with hotspots of track occurrence and residence located at the front of the hydropower screens, near the right-hand side of the pool (Figure 62), this was especially apparent at high-water slack (Figure 62d).

Trends in the frequency of tag detections with distance from the fish pass entrance were similar between different tide states, 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 3.0 – 5.0 m proximity. The high frequency of tag detections for ebbing tides around 2m from the fish pass was again due to the track formed by 2745 (Figures 63 to 65).

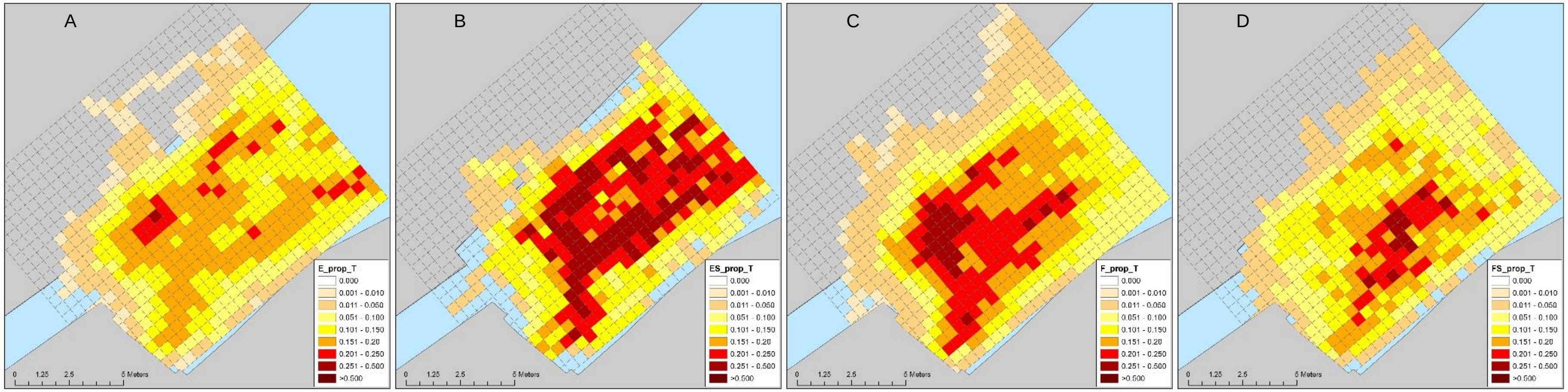


Figure 61. Counts of sea trout tracks to pass through each grid cell (standardised by the number of tracks in each group) recorded during an ebbing (left), ebb slack, flooding and flood slack (right) tide in 2014.

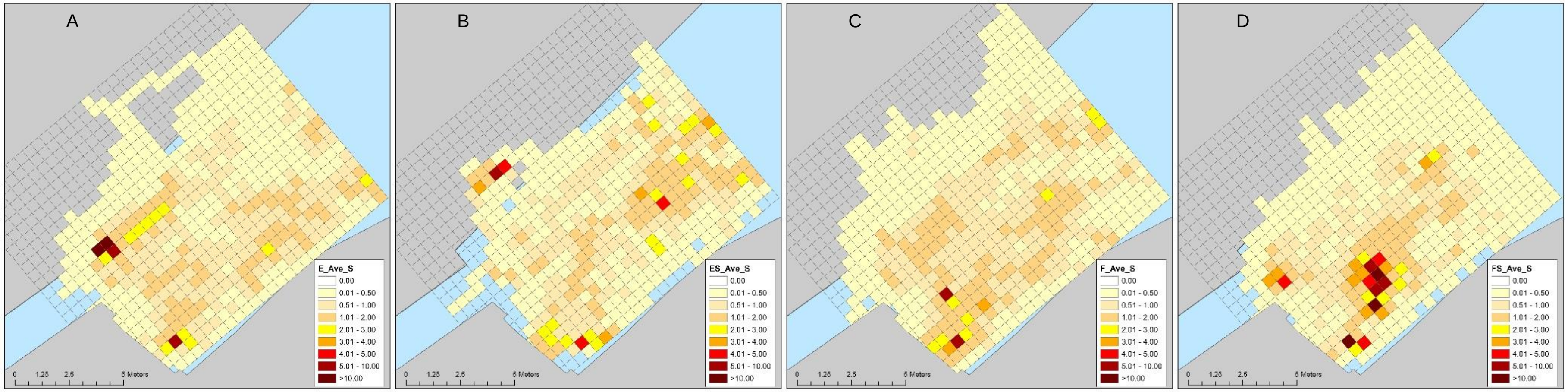


Figure 62. Average time (seconds) spent in each grid cell in sea trout tracks recorded during an ebbing (left), ebb slack, flooding and flood slack (right) tide in 2014.

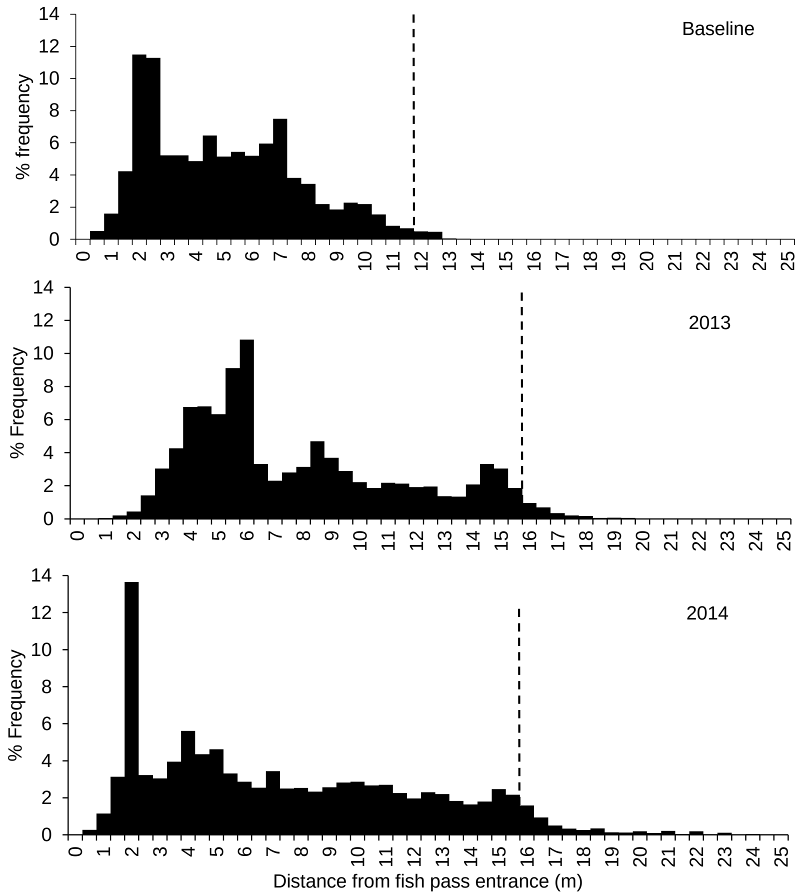


Figure 63. Numbers of tag detections in the array as a percentage of the total number of tag detections recorded during ebbing tides, against distance from the entrance to the fish pass.

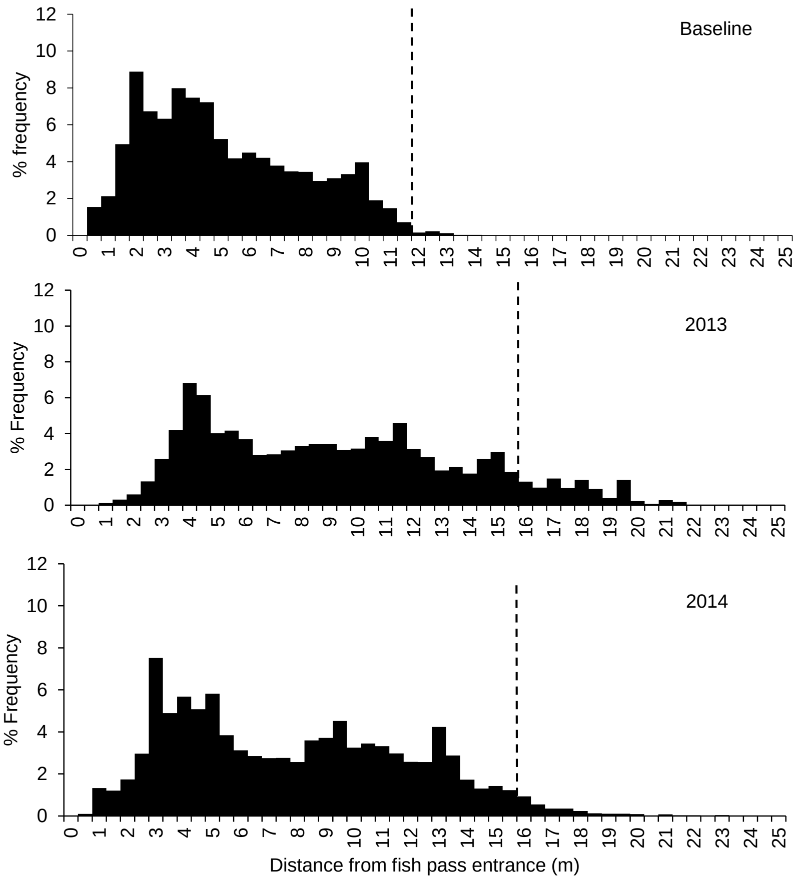


Figure 64. Numbers of tag detections in the array as a percentage of the total number of tag detections recorded during flooding tides, against distance from the entrance to the fish pass.

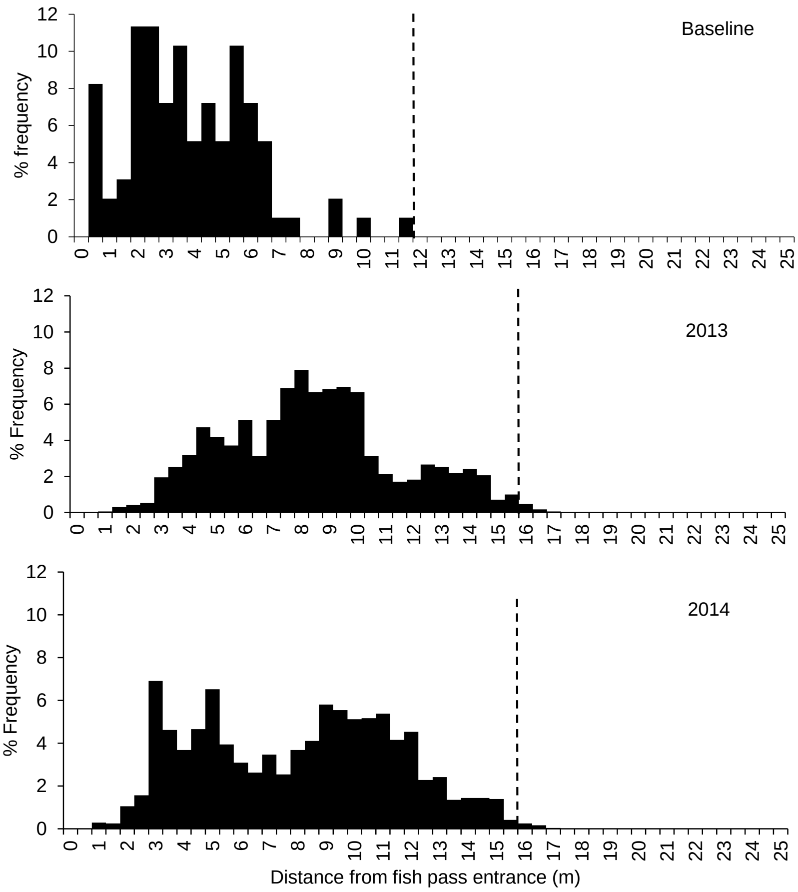


Figure 65. Numbers of tag detections in the array as a percentage of the total number of tag detections recorded during ebb low water, against distance from the entrance to the fish pass.

3.5.6 Discharge and hydropower turbine operation

Hydropower turbine operation data were occasionally not available during 2014; no turbine operation data were available for five sea trout tracks, all of which were non-passage tracks. In 2014 the majority of sea trout tracks were recorded whilst the hydropower turbine was active; 26 (7%) of the 386 tracks (with associated turbine operation data) occurred when the turbine was not operating. Fish tracks were recorded across the full range of turbine abstractions (maximum recorded was 3.74, which although below the theoretical max of 4 cumecs was only just below the largest abstraction recorded during 2014). When the turbine was inactive no real hotspots of occupation were observed, with areas of slightly high periods of occupation occurring in line with the weir face and the fish pass outfall (Figure 66a). 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 >3m^{3}s^{-1}) (Figure 66e). Hotspots in residence time were observed at most river flows, and hot spots in front of the hydropower outfall were most apparent at river flows between the long term seasonal Q_{25} and Q_{50} (≈ 2.9 - 6.3 m^{3}s^{-1}) and were less apparent at flows less than or greater than this and were absent at flows greater than the seasonal Q_{10} (≈ 13.6 m^{3}s^{-1}) (Figure 67a-d). When periods of turbine operation with abstractions > 2 m^{3}s^{-1} were considered in isolation, the hotspots in front of the turbine outfall were most apparent at river discharges <6.0 m^{3}s^{-1} and were not present at river discharges > 10.0 m^{3}s^{-1} (Figure 68 a-c).

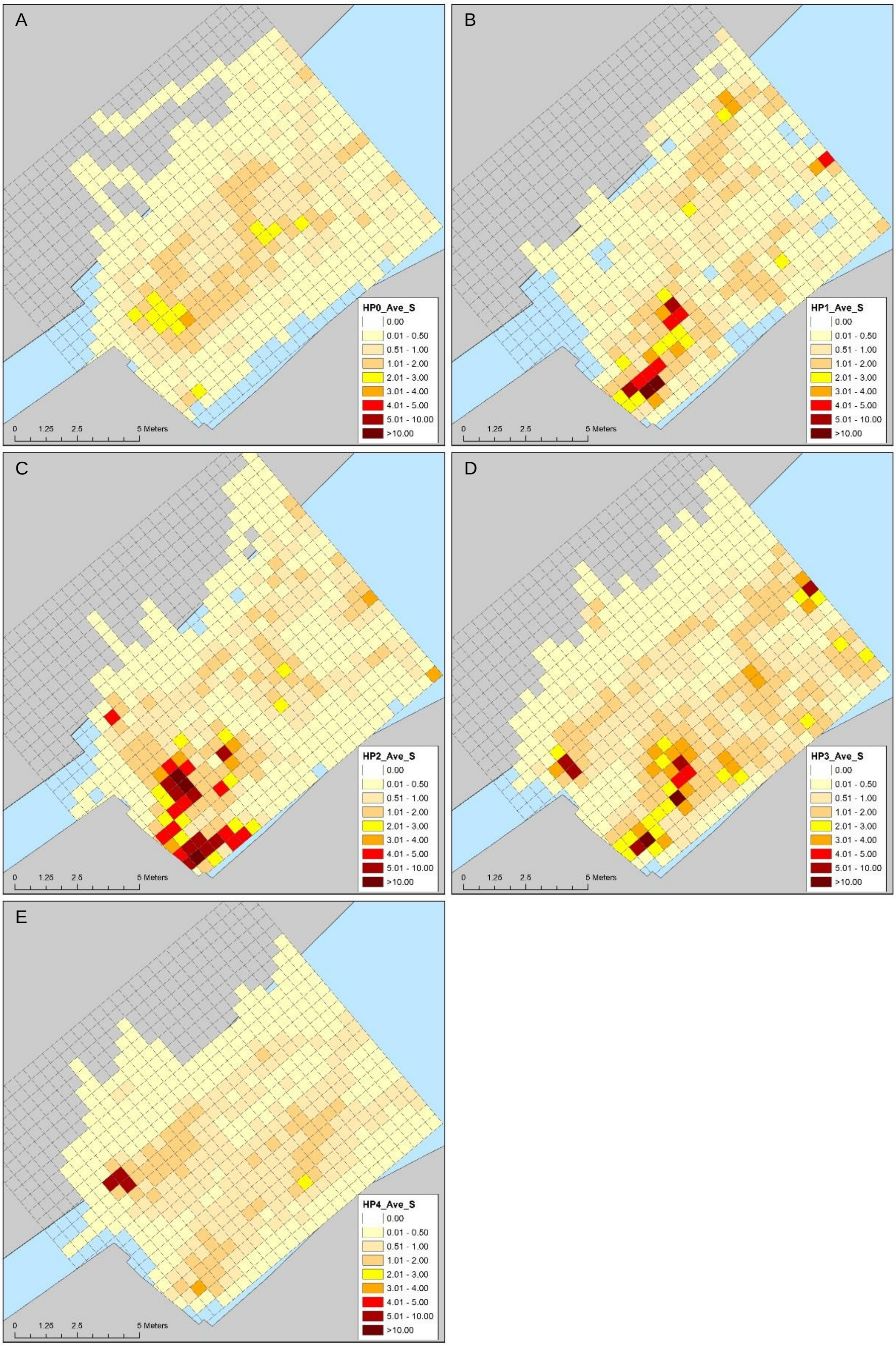


Figure 66. Average time (seconds) spent in each cell by sea trout recorded during five classes of hydropower flows (0.0 (HP0, *n* = 26), 0.1-1.0 (HP1, *n* = 13), 1.1-2.0 (HP2, *n* = 30), 2.1-3.0 (HP3, *n* = 89) and 3.1-4.0 (HP4, *n* = 228) cumecs).

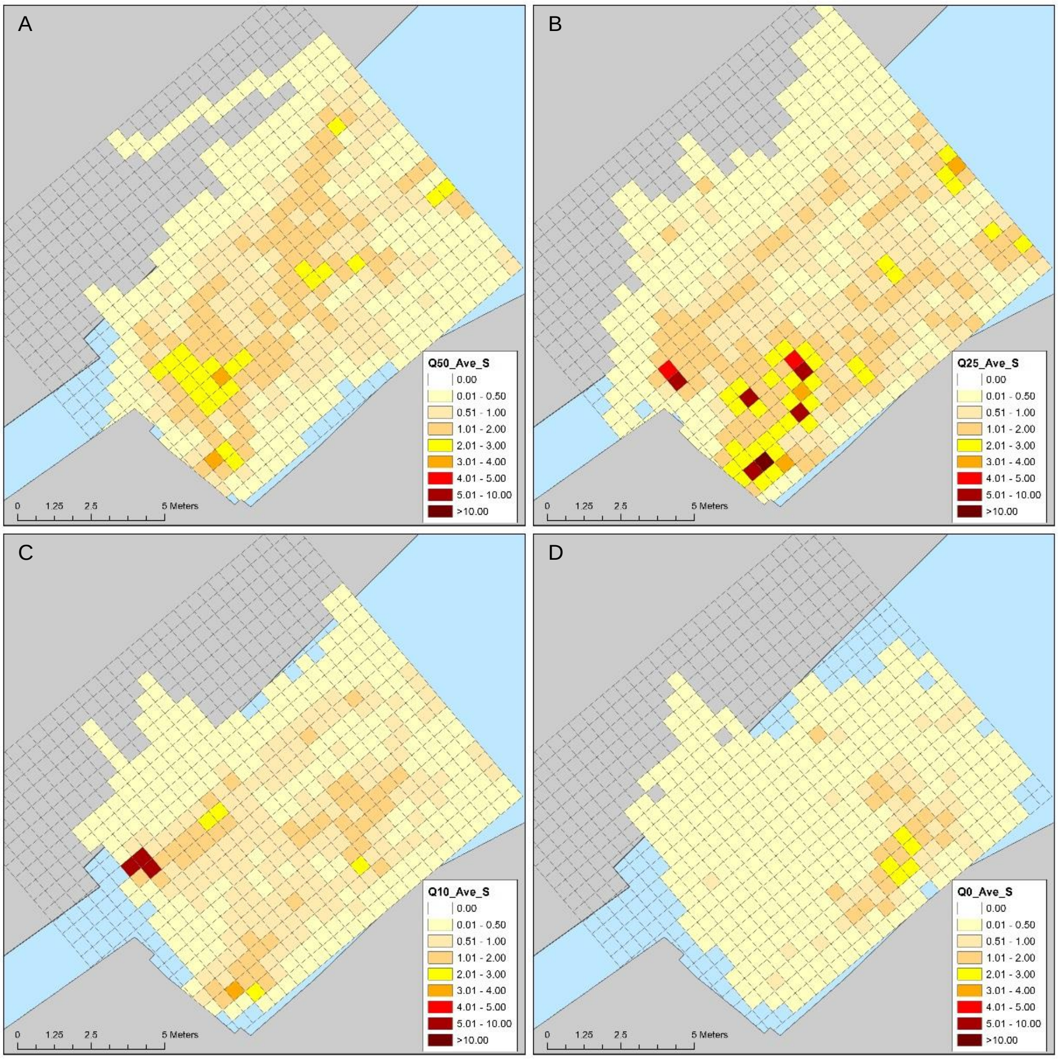


Figure 67. Average time (seconds) spent in each cell by sea trout recorded during four classes of river discharge – Q100 to Q50 (Q50, *n* = 23), Q51-Q25 (Q25, *n* = 151), Q24-Q10 (Q10, *n* = 140) and Q9 to Q0 (Q0, *n* = 77) based on the long-term average seasonal hydrograph for the period 1/8 to 31/12 2000 to 2012.

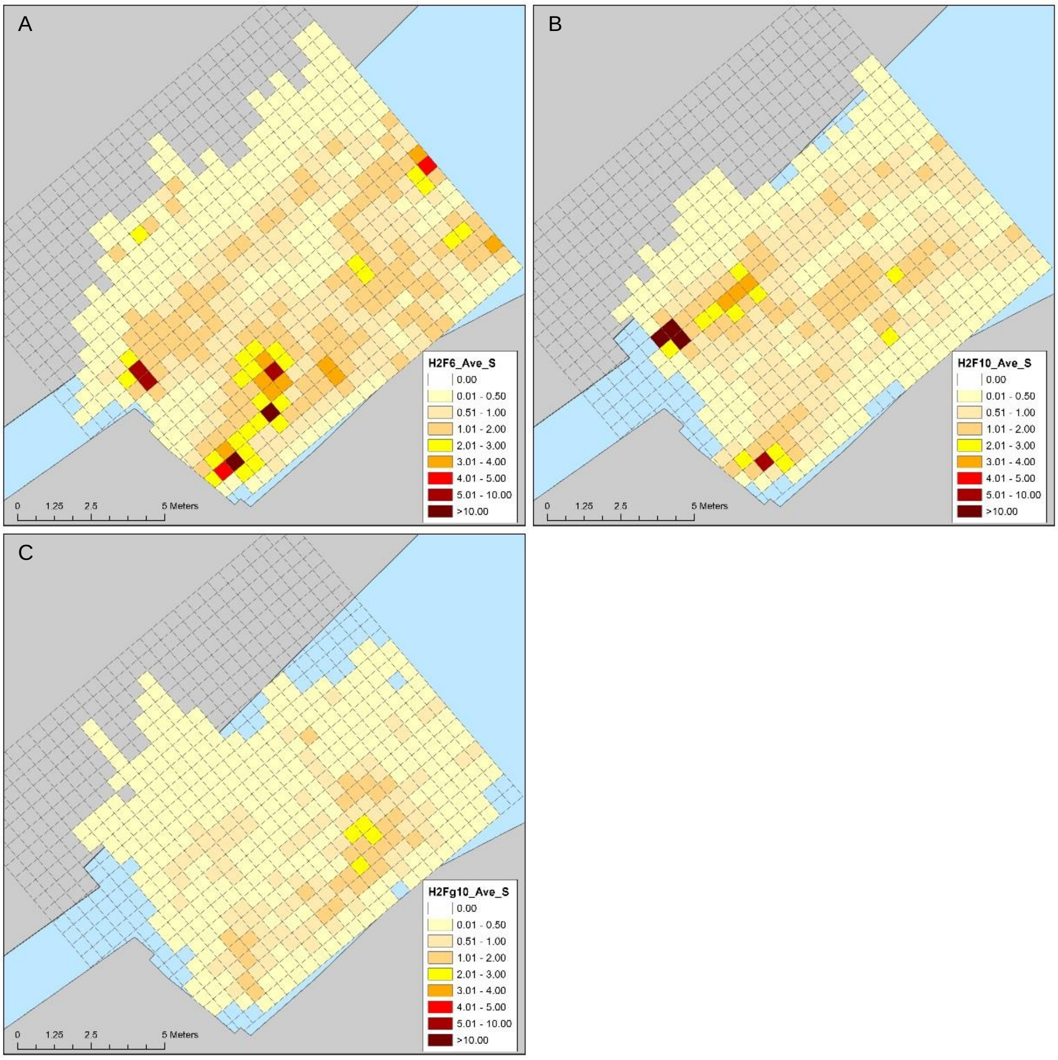


Figure 68. Average time (seconds) spent in each cell by sea trout recorded when the hydropower flows were > 2 cumecs and the river flows of < 6 cumecs (A, n = 110), 6.01 – 10.00 cumecs (B, n = 111) and >10.00 cumecs (C, n = 96) in 2014.

3.5.7 Fish passage approach

Although more approaches were recorded in 2014 (n = 446, range 0 – 132 per track [463 tracks]) than in 2013 (n = 108, range 0 – 13 per track [489 tracks]), relatively fewer fish were recorded within 2m of the Larinier pass entrance than during the baseline; both non-passage (Mann Whitney U-test: Z = -2.815, n = 977, P <0.01) and passage tracks (Mann Whitney U-test: Z = -4.101, n = 60, P <0.01) contained significantly fewer approaches than in the baseline (n = 211, range 0 – 82 per track [85 tracks]). Although 446 approaches were recorded across all tracks in 2014 at an average of 0.96 approaches per track, one track contained 132 approaches, with the fish milling at high tide around the entrance to the fish pass. If this fish is excluded the other sea trout approached the fish pass on average 0.68 times per track compared with an average of 2.44 per track for sea trout in the baseline (maximum 66 approaches in a single track). In 2014 many passage tracks (route confirmed by H1 in the fish pass) were last located more than 2m from the pass entrance and 9 of the 18 passage tracks actually contained no records of the fish within the 2m boundary of the fish pass entrance. In summary, most fish now 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. The exception to this is fish tracks made during high tides where the plume of high velocity aerated water from the fish pass is reduced and fish are both able to occupy this area for prolonged periods and are also more easily tracked. 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 18th October 2014 to 31st December 2014, the second year of monitoring since the commissioning of the Ruswarp Weir low-head hydropower scheme. These data are analysed in comparison with data from 2013 (Noble *et al.* 2014) and the established baseline (Noble *et al.* 2013) as the next 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 still 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 micro-scale 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 4.4% of the time (in this case when the turbine abstraction was >3.5 cumecs). The hydropower turbine was not operational for 57.5% of the study period. In the other 39% of the time the flow down the fish pass constituted more than 28% 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 (see Noble *et al.* 2014). When the hydropower was operational the weir appeared to overtop at a river discharge of around 6 m^3s^{-1} (reflecting the balance of up to $4m^3s^{-1}$ through the turbine, a minimum of $1m^3s^{-1}$ down the Larinier and around 0.5 m^3s^{-1} down the baulk pass). It is therefore inferred that previously the water flowing through the hydropower scheme (up to $4m^3s^{-1}$) 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 $6m^3s^{-1}$. During spring tides the hydropower was not operational (due to reduced head) and the weir over-topped at lower flows, presumably because 4 m^3s^{-1} passed over the weir rather than through the turbine. The turbine was seemingly not always affected by neap tides, and was only inactive when river flows were high enough to increase the lower river level to the turbine trip point. Typically the turbine is likely to go off if high tide is above about 5.4 m above Whitby datum but this also depends on river flow. The turbine trips if lower river level above 2.796 mAOD (local). The result of this is that the weir would have been overtopped for less time than previously (before commissioning of the hydropower) which may influence the availability and attractiveness of the alternative passage routes (fish pass, side of fish pass, baulk pass and overtopping weir face at high tides). Interpreting how these multifaceted alterations to hydrological conditions local to Ruswarp Weir may affect upstream migrating adult salmonids is problematic since there are no generic models for the relationship between fish pass efficiency and fish pass hydraulics. Therefore, potential impacts of these hydraulic changes on sea trout migration behaviour cannot be inferred directly from the hydraulic changes themselves and need to be directly measured from any changes in the migration behaviour of sea trout and the efficiency of the existing fish passage facilities over Ruswarp Weir.

Walton *et al.* (2012) suggested a number of potential impacts (amended here) that the hydropower development on Ruswarp Weir, which included changing the fish pass from 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 m^3s^{-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 m^3s^{-1} volumetric flow) may distract fish from finding the fish pass entrance (rated at a minimum volumetric flow of 1 m^3s^{-1}), with fish being attracted to the turbine discharge (impacting on fish attraction to the entrance of fish pass). This could result in fewer fish finding / entering the fish pass or being delayed in their migration. However, it should be noted that volumetric flows may not be directly related to the relative water velocities from the two structures and that relative linear velocities may be the most important feature for attraction. EA guidelines and the Ruswarp abstraction licence states that the turbine linear velocity rates should be $\leq$ 1.0ms^{-1} whereas the Larinier pass should be $\geq$ 1.5ms^{-1} (M. Ford *pers. comm.*). As such whilst the turbine may have a larger volumetric flow at times (up to four times larger) it may not be the most attractive flow.

- 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 determined to have ascended via the side of the fish pass in 2012, 2013 or 2014, numerous untagged fish were observed (both successfully and unsuccessfully) attempting to ascend the weir via this route in both 2013 and 2014.

Changes to the hydrological conditions at Ruswarp Weir and geomorphological attributes of the pool downstream of the fish pass and hydropower development could translate into a change in the overall passability of the weir (hereafter referred to as overall passage efficiency). Specifically, the overall passage efficiency was defined as the proportion of potential migrants (all tagged fish) which successfully ascend the weir. 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 2014 and 2013 datasets 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 2014 and initial post- dataset

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 50% (22 / 44) in 2014 and 56% (26 / 46) in 2013; around 60% greater than in the baseline (35%, 17/48), This observed difference between the baseline (35%) and the initial post- dataset (average of 53%) was 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 and 2014 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 hydrophones can be used to evaluate potential levels of predation/tag loss/failure. Of the 13 tags not detected in the array in 2014, three were not detected at all after release and nine were only detected on the mobile hydrophones (i.e. not in the hydrophone array). One tag (either 2738 or 2787) was also consumed by a predator, potentially before being subsequently detected on the mobile hydrophones and the array. Two of the three tags that were never detected were from batch three (released 10/11/13) when a seal was spotted feeding at the release site (S. McGinty EA *pers. comm.*). The inference here is that a proportion (unknown but potentially large) of tag disappearances from the release site (those never detected again) may be attributable to predation of tagged fish soon after release (See Figure 13 in Section 3.2.1).

Of the 34 tags detected in the array, ten were not detected to ascend the weir, of which two returned to Whitby whilst five were last located at Noble's Yard. A further tag from batch four was identified to have reached the array independently but soon after its records became concomitant with those of another tag and were both subsequently detected on the hydrophone at Noble's Yard, Whitby and the array at exactly the same times around high and low tides. It was assumed that both of these tagged fish had been consumed, probably by a seal, the first at some unknown time after release and the other at a known time within the vicinity of the array. 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) (4 of 47, 9%) 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 14 of 47, 30%) (See Figure 17 in Section 3.1.2). These figures are similar to those seen in 2013 although fewer fish went missing completely in 2014. 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 “rogue” seals that have specialised in feeding in tidal waters rather than on the main coast. Graham *et al.* (2011) identified that “rogue” seal in rivers fed more often on adult salmonids 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 seals on tagged sea trout may have been in the region of 47% of tagged fish within the first 2.5 days after release. In relation to this, Stansbury *et al.* (2015) have recently shown that Vemco acoustic tags operating at 69 kHz may act as an attractant for foraging seals indicating that predation rates of tagged fish in some trials may be higher than that for untagged fish. However, the HTi used for that study operated at 307 kHz which is not audible by seals so the predation rates inferred in this study will not be affected by this reported “dinner bell” effect.

Secondly, of the 43 fish detected on all hydrophones, 29 were first detected at Noble’s Yard or the array whilst 13 (28% of fish) moved downstream to Whitby after release (similar to 2013); eight of these fish did not return to the river whilst all but one fish 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, five were last observed at Noble’s Yard and two were last observed at Whitby (again similar to 2013). A further four fish that that failed to ascend the weir were last recorded in the array (including the fish known to have been eaten). Given these figures it is possible to estimate a minimum 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; 10 of 47, 21% (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 give an indication of the fates of tagged fish in 2013/2014 and perhaps give an indication of the potential relative influences of mortality/tag failure and motivation/straying on the data in 2013 and 2014, these data cannot explain the large difference in overall passage efficiency between the baseline and current post-commissioning dataset (which itself was highly consistent between 2013 and 2014). 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 2014 three salmon and 44 sea trout were tagged for tracking. Of these 44 sea trout, 32 (73%) were detected within the hydrophone array (including one known to have been subject to predation in the array), and a further 9 (20%) were only detected on one or more of the three mobile hydrophones (mostly at Whitby). This gives a measured attraction efficiency of 73% in 2014 (32/44) which was similar to the 67% in 2013 (31/46). This was a significantly higher return rate of the tagged fish (70% in the array on average in 2013 and 2014) 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 100% increase in attraction efficiency for sea trout between the baseline and the initial post-commissioning dataset (2013 and 2014 combined), a change that was highly statistically significant.

It is unclear why the detection rates in the array in 2013 and 2014 were 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 2014 (n = 20; 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 (it should be noted that Noble's Yard did not operate as successfully in 2014 as in 2013 and actually missed a number of fish approaching the weir). Furthermore, only one fish was observed to do the same in 2013. This would suggest that the main factors limiting fish finding the fish pass in 2014 and 2013 were the motivations and / or ability of fish to reach the weir, rather than factors once the weir was 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 has altered the distribution of flows across the weir face and the area immediately downstream of the weir. When the hydropower scheme is operating and river flows are <$6m^3s^{-1}$ 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 $6m^3s^{-1}$, up to 4 m^3s^{-1} of the discharge would have been dispersed across the weir face prior to the hydropower development. It is possible that prior to commissioning of the hydropower scheme that the baulk pass was the most attractive flow plume under a wider range of flows that in the last two years and that in previous years fish spent more time exploring this pass without being attracted to the main fish pass pool. However, it is impossible to determine whether any changes between 2011/2012 and 2013/2014 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 and 2014 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 2013/2014 and the baseline. Certainly the general hydrological conditions were very different between the four years (2011 was very dry and low flows, 2012 was very wet and 2013/2014 somewhere just below the average for the river, although 2014 also had a prolonged period of low flows) 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 two years of data.

4.2.4 Fish pass efficiency

Eighteen of the 32 tagged sea trout and one of the three tagged salmon in 2014 were detected in the hydrophone array downstream of the fish pass and ascended via the fish pass; giving sea trout fish pass efficiency = 56% in 2014 which was appreciably lower than the 81% observed in 2013. In addition, four 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 be lower in 2013 and 2014 (68% on average across the two years) than in the baseline (100%; 17/17). This difference was statistically significant. This suggests that whilst a larger proportion of tagged fish found the fish pass in 2014 and 2013 (see Section 4.2.2), a significant proportion of these migrating fish were unsuccessful in using the fish pass (also observed to a lesser extent in 2013); a feature not previously observed in the baseline (except for one salmon in 2012). However, it should be noted that it is the contribution of the final batch of fish released on 18/11/2014, where only two of the ten sea trout that reached the array subsequently ascended via the Larinier pass, which ensured this result to be statistically significant. It is not clear why this batch had an unusually low passage efficiency (22% - whereas all previous batches in 2013 and 2014 had a similar fish pass efficiency of around 66-80%). Although the fish in this last batch appeared to have a below average condition this was not significantly different from all other batches including those in 2013. The fates of the unsuccessful fish in this last batch would suggest that were subject to higher rates of mortality/predation within the vicinity of the weir. It is not clear why this might be the case, however, four of the fish that failed to ascend via the Larinier spent over 60 hours each within the vicinity of the weir which may have exposed them to a higher risk of predation. It does not explain why they were unable or unwilling to ascend via the Larinier despite spending around 100 minutes each on average in the array.

This 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 (Armstrong *et al*. 2010) states targets of a minimum fish pass efficiency of 80% for adult returning migratory salmonids (unless there is significant spawning habitat downstream), although with a 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 and 2014 is below that aimed for by the EA. Despite this, the 69% average passage efficiency for sea trout across 2013 and 2014 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 the fish pass efficiency measured in 2014 (58%) is below these previously reported values. There were considerable differences between the conditions observed for the majority of the baseline, the 2013 and 2014 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 reduction in efficiency was a feature of overriding hydrological conditions, a result of the different fish pass design, a result of the activity of the hydropower scheme an unknown temporary blockage to the fish pass or increased levels of predation of fish below the weir. However, it should be noted that the overall results from 2013 and 2014 were remarkably similar in terms of attraction efficiency and fish behaviour so this lower fish pass efficiency may be a consistent feature of the new pass/hydropower complex.

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 2013/2014 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 2013/2014 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 (only observed in 2013 and 2014).
3. Fish that dropped back downstream for an appreciable amount of time before re-ascending the river under spate conditions and passing the weir with only a short delay.
4. Fish that went back to the coast and were not detected again (only possible to detect from 2013 onwards).

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

Such variability in the motivation to migrate, and success of ascent of individual fish has been noted in other studies. It can be related to the motivation of individuals and the conditions under which the movements are taken (particularly the discharge acting as a stimulus). Gowans *et al.* (1999) identified similar classes of behaviour in successfully migrating salmon at Pitlochry fish ladder (single visit and successful ascent; two or more visits to Pitlochry dam separated by <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) and the longest delay from release to first detection in 2014 was only 5 days. The flows in 2011 (the majority of the baseline) were far lower than in 2013 and 2014 indicating that this class of migration behaviour is positively associated by low flow conditions reducing the stimuli for, or ability of, fish to ascend the river.

In 2014 and 2013 the average cumulative time spent in the array by sea trout prior to passage (combined duration of all tracks) was significantly longer than in the baseline dataset. However, the duration of individual non-passage tracks in 2014 and 2013 was significantly shorter than tracks in the baseline dataset. There was no significant difference in the average duration of passage tracks in the baseline dataset and in the initial post- dataset (2013 and 2014 combined). 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 (26% of sea trout) and 2014 (11% of sea trout) fewer fish spent less than ten minutes in total within the array prior to passage via the Larinier pass and a higher proportion of tagged sea trout spent longer than 30 minutes in the array before either ascending or dropping back downstream (64% in 2013 and 41% in 2014). In the baseline 70.5% of sea trout passed the weir within one hour of their first detection in the array whilst in 2013 and 2014 only 32% and 33% of sea trout respectively passed within one hour of first detection and in 2013 seven sea trout (28%) and 2014 six sea trout (33%) took longer than 12 hours to ascend. The total time between first detection and passage was significantly longer in both 2014 and 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, 1.23 (0.64 – 2.83) hours in 2013 and 1.06 (0.20 – 3.55) hours in 2014. During this time prior to passage in 2013 and 2014 sea trout spent significantly lower proportion of the time in the array compared to the baseline. This indicates that in 2014 and 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 hydrophones indicated that the behaviour of fish that exhibited prolonged behaviours after being detected in the array included both movements to/from the pool to the area around the downstream end of the weir (Noble's Yard) and occasionally movements to/from Whitby harbour associated with the tidal cycle.

Whilst the average time taken to pass the weir was significantly longer in both 2014 and 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) although none of these structures were at the head of the tide. 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 potentially 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) and 2014 (higher flows but also with a prolonged dry period) 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 (median delay of 2.36 hours (0.77 – 15.59) from first arrival in the array) and 2014 (median delay of 3.34 hours (0.40 – 18.11) (up from 0.27 hours (0.09 – 1.41) in the baseline) would significantly affect the success of the overall migration to spawning grounds. The impact of delay on the success of migration can be considered as both (1) an increased energetic cost of delay and energy expenditure during ascent against a finite energy resource (as adult salmonids do not feed in freshwater) and (2) an increase in predation risk whilst holding below structures. The length of delays observed in 2013/2014 (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 2013/2014 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 in 2013 and 4 of 14 in 2014) occurred in the tidal river prior to the fish reaching the weir. However, in 2014 nine fish reached the weir (8 got into the array) but went missing without ascending or being detected back in Whitby. So whilst the majority of predation may occur in the lower river, some level of predation is now known to occur around the weir and in the fish pass pool. As such it would appear that increased delays at the weir may increase the risk of predation, although further study would be required to determine this quantitatively.

4.2.6 Micro-scale behaviour of migrating sea trout

Spatial data of fish behaviour within the pool were broadly similar in 2013, 2014 and in the baseline, in that tracks were spread throughout the array. However, there were also some subtle differences between years. In 2013 and 2014 the data indicate a potential bias towards the right-hand bank in front of the hydropower outfall and away from the fish pass entrance and weir face. Analysis of the average duration of time spent within each cell indicated hotspots in use of the pool immediately in front of the hydropower outfall 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 and 2014 (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 $<6m^3s^{-1}$, i.e. when the weir was not over-topping and the discharge from the hydropower scheme (0.1 to 3 m^3s^{-1}) was up to 3 times the discharge from the fish pass ($\sim 1m^3s^{-1}$). This propensity to occupy the area downstream of the hydropower turbine was less apparent when the turbine was off, the weir was overtopping and particularly at the highest flows. This could suggest that the discharge from the turbine may be attracting fish (either by distracting them from the fish pass plume whilst seeking a passage route or as a preference of attractive flows suitable for refuge) 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 $1m^3s^{-1}$). Once the weir overtops and water is flowing down the side of the fish pass the relative influence of the two flows changed. Distraction caused by turbine outfalls has been observed elsewhere, albeit for very large scale hydro schemes with potentially large distances between the turbine outfall and the attraction flows from fish passes. For example, Lundqvist *et al.* (2008) identified that during periods of high turbine discharge and low bypass flow, fish were attracted from a bypass channel (towards the turbine outfall), delaying the upstream migration of salmon on the River Umealven in Sweden, where in this case the turbine and fish pass are many kilometres apart. Whilst this is an example of a much larger system with a distinct turbine outlet versus bypass channel entrance it appears that, despite their immediate proximity and high ratio (worst case scenario of 1:4), 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 potentially less turbulent parts of the pool (visually appears to be less turbulent with assumed lower flow velocities, although this would need to be confirmed with 3D assessment of flows using an ADCP), and as such, the hotspot may represent a location of refuge and resting rather than distraction. 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 – one fish appeared to do this three times in 2014) are apparent. Given this it may be that the pool downstream of the fish pass provides a habitat that is suitable for resting and maintaining energy reserves before further ascent of the river. It may be particularly important given that Ruswarp represents the transition from brackish to freshwater conditions.

This shift in track distribution also included a reduced proportion of detections of fish within 2m of the mouth of the fish pass and reflected in reduced detections of approaches to within 2m of the fish pass entrance compared with the baseline. Although due to some unusually long tracks made at high tides this detection rate within 2m of the fish pass entrance was actually higher in 2014 than in 2013. 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 of Noble et al. (2014) for summary of a study using beacon tags to identify variable tracking efficiency under different conditions and in different parts of the pool) and probably less attractive for prolonged occupation (apart from at high spring tides when the turbulent plume from the fish pass is reduced). 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 less appropriate to the data from 2013 and 2014. Indeed nine of the 18 passage tracks in 2014 were not detected within the 2m approach zone of the fish pass prior to ascent (both due to potential changes in approach behaviours and the ability to track fish in this area). As such metrics like "fish pass approach" will need to be re-defined in a final analysis 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 2014 and the comparison with 2013 and the baseline raised four key conclusions:

(1) The proportion of tagged fish that successfully passed the weir (passage efficiency) was greater in the current post-commissioning dataset than in the baseline dataset and this difference was statistically significant (Section 3.2.2).

(2) The proportion of tagged sea trout entering the array (attraction efficiency) was significantly higher in the current post-commissioning (Section 3.2.1)

(3) The fish pass efficiency of sea trout detected in the array reduced from 100% in the baseline to 81% in 2013 and to 58% in 2014 (an average of 69% for the current post-commissioning dataset) and this difference was statistically significant (Section 3.2.2).

(4) The delay between arrival in the pool and eventual passage was, whilst statistically significantly greater in the current post-commissioning dataset 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, particularly as predation (presumably seal) has been demonstrated to occur within, or in close proximity to, the pool.

(5) 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 <$6m^3s^{-1}$, when the weir was not overtopping and the turbine abstraction was <$3m^3s^{-1}$. 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 2013/2014 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 still too early to determine whether the observations in 2013/2014 can be attributed to the activity of the hydropower scheme. Despite this, there is very clear similarity in the coarse scale behaviour data between 2013 and 2014 (and also between 2011 and 2012). This suggests that patterns observed in each year of the study can be analysed in relation to the hydropower operation and the changes to the fish pass/pool. 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 and 2014. A further year's study is however required to validate these changes and whether there 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 be the motivation to migrate (related to time of year and river flows), the condition of the fish and the predation/mortality rates linked to delayed migration in the estuary. The batch-by-batch analysis for 2013 and 2014 certainly indicates that the final batch in 2014 exhibited an unusually low overall passage rate and, although there was no significant difference, the last batch in 2014 had the lowest average condition (although they did have a significantly lower fat content than previous batches in 2014 – it is unknown whether this was a typical pattern for late season fish). However, this batch were visually fresher and seemingly in better condition than previous batches in 2013 where up to 50% of the fish caught were rejected for tagging due to poor condition or visible injuries. It is likely that this last batch may have had a reduced propensity or ability to migrate and quite possibly were subject to higher rates of predation. 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.

4.4 Future delivery

Although the 2014 season yielded data for more fish and tracks than expected prior to 2013 and the trends between 2013 and 2014 were actually remarkably consistent for some metrics, the potential differences observed between the 2014, 2013 and the baseline data (in particular the impact of the final batch of fish released in 2014 on the statistical significance of the change in fish pass efficiency) indicated that the study needs to continue for at least one more season (the original study design anticipated three years post monitoring of which 2014 was the second). This is particularly important to ascertain whether the variability of hydrological conditions and predation risk between study years is the overriding factor explaining the differences observed, in particular the changes in fish pass efficiency.

The monitoring undertaken from 2011 to 2014 has developed a tagging and tracking protocol, particularly with the use of the three mobile hydrophones in 2013 and, that has generated highly successful returns of tagged fish and good resolution tracking data to explain observed behaviours. Further tracking in 2015 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 (although it should be noted that conditions were not conducive to fish migration for long periods in the early phase of the 2014 study window). 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 2014, 2013 and the baseline (October to November).

Whilst the data from 2013 and 2014 suggest that the mobile hydrophone at Gary's Hut may in most cases have been superfluous to the H8 hydrophone 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 post-commissioning 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 post-commissioning 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.

Appendix 1

Summary of fish tagged in 2014

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

Batch	Tag	Species	Sex	Length (mm)	Weight (kg)	Fat meter %	Date of release	Time of release
4	2780	Sea Trout	M	590	1.825	1.60	18/11/2014	15:00:00
	2787	Sea Trout	F	530	1.425	1.10	18/11/2014	15:00:00
	2794	Sea Trout	F	540	1.500	1.30	18/11/2014	15:00:00
	2801	Sea Trout	F	570	1.700	1.20	18/11/2014	15:00:00
	2808	Sea Trout	F	440	0.875	2.00	18/11/2014	15:00:00
	2815	Sea Trout	M	555	1.550	1.20	18/11/2014	15:00:00
	2822	Sea Trout	F	535	1.275	1.10	18/11/2014	15:00:00

Summary of fish tagged in 2013

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

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

Summary of fish tagged in 2012

Fish #	Tag Period (msec)	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

Appendix 2

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

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

Appendix 3

Summary of fish passage data in 2011, 2012 and 2013

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

Passage	Tag No	Size (cm)	Time between release and first detection [d]	Number of tracks in array	Cumulative time in array [min]	Cumulative length of track [m]	Total Time from first detection in array to H8 (or last detection for non-passage) [hrs]	Day / Night passage
Larinier	2500	57.0	20.1	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	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
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	-

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 in array (ms^{-1})	Time from release to passage (days)	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} passage)	St		-	3	00:44:28	384.12	0.14	1.83	FP	D
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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