



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

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Report – XXXXXX/R (project code number)

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Executive summary

An opportunity to improve understanding of the potential impacts of low head hydropower schemes on migratory salmonids arose on a scheme proposed by the North York Moors National Park (NYMNP) in association with the Esk Valley Energy Group (EVEG) at Ruswarp weir on the River Esk in North Yorkshire. This proposed installation consists of a single Archimedean screw turbine (diameter = 2.9 m) adjacent to fish pass on the right hand bank. The intake for the screw would be located just upstream of the fish pass exit and the outflow located adjacent to the fish pass entrance. The micro-behaviour of upstream migrating salmonids in relation to hydrodynamic and environmental cues that attract and guide fish at fish passes was investigated (11 October 2011 – 12 January 2012) using an acoustic tag tracking system.

Fifteen (14 sea trout and 1 salmon) of the 39 tagged fish were detected in the hydrophone array (38%) positioned downstream of the fish pass entrance. Twelve fish ascended the weir within three days of release and four fish did so within 6 hours (mean \pm C.L. (days) = 6.3 ± 6.1 , compared to 4.4 ± 5.2 in 2010). All fish detected in the array successfully ascended the weir. The majority of the detected fish (75%) ascended the weir via the fish pass, but some fish ascended via the side of the fish pass during elevated river levels. No tagged fish used the baulk route to ascend the weir in 2011, compared to 4 out of 9 ascents (44%) in 2010. Seven fish entered the array only once before ascending, and all but one fish entered the array less than five times. Nine fish ascended shortly after entry into the array (<10 min) and all but two fish ascended in under 3 hours spent within the array. Fish movements were more prevalent at times of elevated flow, at night, on spring tides (although fish tagging was focused around spring tides) and on a flooding tide (movements were focussed around the 50th percentile of daily tide height).

A grid based approach (0.5 x 0.5 m cells; track count and residence time), proximity analysis (frequency of tag echoes) and approach analysis (2 m buffer; count and time) was used in this study to quantify, visualise and standardise micro-scale behaviours of fish below the fish pass and to enable comparison with future scenarios. When all tracks were overlaid in the current study, most cells within the grid were intersected by at least one track and the area within the array was well covered by multiple tracks. No favoured route or preference for one side of the array was apparent from this grid. The sum of all time intervals in each grid cell revealed that fish spend large periods of time at the entrance to the fish pass, although time was also spent throughout the pool. In passage and non-passage runs the concentration of high time values was focussed directly at the entrance of the fish pass with little time spent elsewhere. Fish from most groups (i.e. passage, non-passage, day, night, ebbing tide and ebbing/flooding tide) were generally found in close proximity to the fish pass (frequency of tag echoes and residence time). The average residence time and the number of approaches within a 2-m radius of the pass entrance was not statistically different between groups (i.e. passage vs non passage, day vs night and ebbing vs ebbing/flooding vs flooding tides), and can be pooled in future analyses (giving 87.3 ± 43.0 seconds per fish track, and 7.8 ± 5.6 per fish track respectively).

Recommendations for future study include the continuation and development of the grid based micro-scale behaviour analysis used in this study, and widening the study to incorporate the behaviour of downstream moving fish (using acoustics tags), including smolts, and an overarching assessment of the fish migration and recruitment in the River Esk catchment. A review of the necessary considerations for the post-installation survey design is also provided to ensure the successful continuation of this investigation.

Acknowledgements

The authors wish to thank Dr. Jon Hateley, Phil Young and Jim Gregory (Environment Agency; EA) for technical support and managerial input and advice. Andy Delaney (EA) is recognised for sharing his intimate knowledge of the River Esk to the benefit of the project. Many thanks are warmly extended to the various landowners and fishery owners for access and permissions. The authors gratefully acknowledge the assistance of Andrew Delaney, Phil Young, Darren Rollins and Shaun McGinty (EA) in electric fishing surveys, Andy Hindes, Chris Gardener (EA) and Ian Welby (BlueRoof) for tagging fish, and Natalie Angelopolous, Matt Styles and Marie Taylor (HIFI) during Acoustic Doppler Current Profile surveys.

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1 Introduction

1.1 Background

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

With concerns over climate change, rivers worldwide are becoming increasingly exploited for hydropower (Jansson, 2002; Murchie et al., 2008). Although the harnessing of energy from water discharge and conversion to electrical power did not begin until the mid 19th Century (Poff & Hart, 2002), it is now considered the most important renewable electricity source worldwide (Bratrich et al., 2004), accounting for 19% of the world's electricity (Paish, 2002). This capture of energy from rivers is in line with regional policy objectives (e.g. EU Renewable Energy Directive 2001/77/EF) and hydropower is considered to be the most reliable and cost effective renewable energy source (Bruno, 2008), and often presented as a clean (Rosenberg et al., 1995), 'green' energy source with no negative impacts on the environment (Bratrich et al., 2004).

In the past few years there has been a resurgence of interest in hydropower as a direct consequence of the UK Government's commitment to renewable energy and associated financial incentives. The majority of new schemes are run-of-river, which have no significant storage of water, the turbine only making use of the available flow at the site. These generally require an impounding structure and the passing the water through a turbine, sometimes involving the diversion of water through a secondary channel or pipeline and returning it to the main river downstream of the weir. The view that hydropower has no negative impacts on the environment, has been challenged by numerous authors who consider the impacts on fisheries and biota as significant. Unfortunately, research on the impacts of hydropower schemes on fish populations is mainly restricted to larger schemes, and little work has been carried out to investigate the impact of small-scale schemes on fisheries or river ecosystems.

An opportunity to improve understanding of the potential impacts of low head hydropower schemes on migratory salmonids arose on a scheme proposed by the North York Moors National Park (NYMNP) in association with the Esk Valley Energy Group (EVEG) at Ruswarp weir on the River Esk in North Yorkshire. This proposed installation consists of a single Archimedean screw turbine (diameter = 2.9 m) adjacent to fish pass on the right hand bank. The turbine would draw up to $4 \text{ m}^3\text{s}^{-1}$ and generate approximately 50 kW of electricity. The operating head varies considerably from 1.6 m to 2 m depending on the state of the tide below the weir. The intake for the screw would be 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 current fish pass will be replaced as it is believed to be suboptimal (the pass is 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 fish passage facility 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 Hydropower Good Practice Guidelines (GPG).

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

1.3 Objectives

The objective of this report is to provide baseline 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 ensure appropriate mitigation measures are installed with the hydropower scheme to maintain or improve passage efficiency in the future. Specifically the objectives are:

- To establish a baseline for fish micro-behaviour around the existing fish passage facilities so that any adverse effects the hydropower scheme may have can be mitigated effectively and ensure that fish passage is optimised. Passage success/failure analysis will be used to assess the efficacy of the current fish pass.
- To investigate the timing of fish movements and ascents in relation to hydrodynamic and environmental cues.

2 Materials and methods

2.1 Study site

The Yorkshire River Esk flows approximately 45 km from its source upstream of Westerdale on the North York Moors to its mouth on the North Sea coast in the harbour town of Whitby. The Esk supports important migratory salmonid populations, especially sea trout (*Salmo trutta*) and Atlantic salmon (*Salmon salar*), 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.

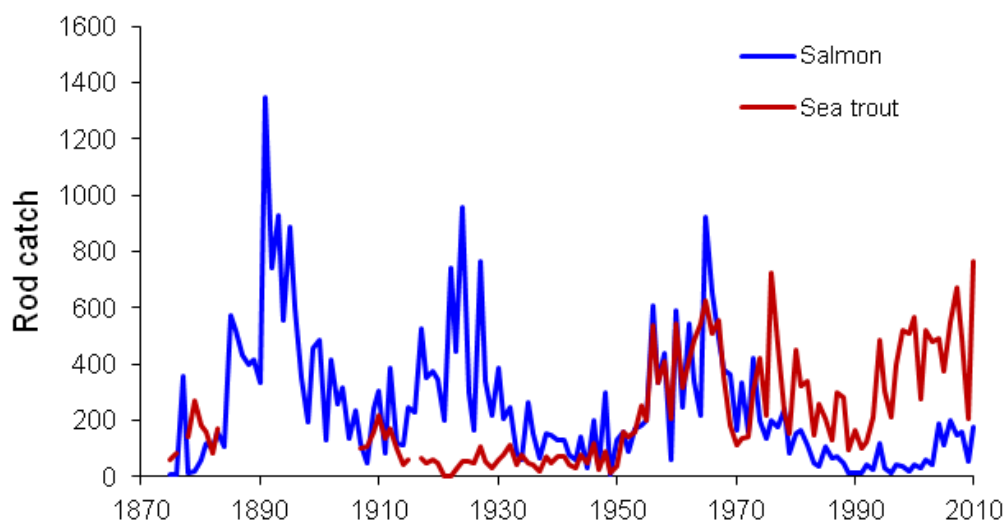


Figure 1. Trends in sea trout and salmon catches in the River Esk, North Yorkshire.

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 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 catchment generally consists of sparsely populated, open moorland with little pressure from industrial or urban development (Figure 5b). The moorland streams that feed the Esk are affected by natural "flushes" of acidity, as well as iron run-off from natural ironstone strata and old mineral workings, making some of these becks an ochreous-orange colour after periods of rainfall. The geology of the catchment is dominated by rocks from the Jurassic period, mostly lower oolite and lias with low permeability (Figure 5c).



Figure 2. Aerial photograph showing the location of the fish passes (A – pool traverse pass; 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 proposed hydroelectric turbine and the focus of this study (Figure 3).

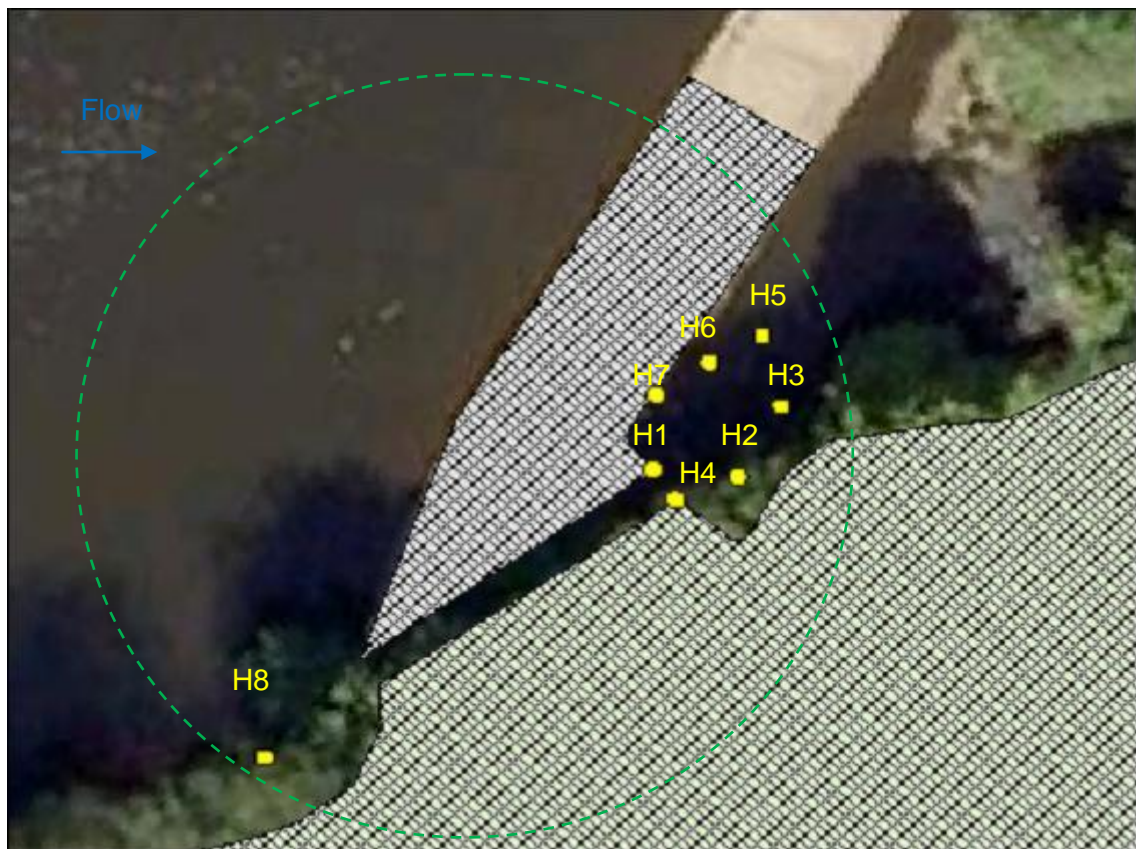


Figure 3. Diagram of the study site showing the positions of all 8 hydrophones (Section 2.3).



Figure 4. View of the array showing the approximate positions of all 8 hydrophones.

2.2 Tagging

Fish were captured downstream of Ruswarp Weir on 11, 12, 24 and 25 October 2011 using pulsed DC (50 Hz) electric fishing equipment from a boat (Electracatch control box, 6 V single anode with Honda 7.5 kVA generator). Prior to tagging in the field, fish were anaesthetised using benzocaine dissolved in solution of acetone (carrier to enable dissolution with water; 40 mg L⁻¹). Species, sex and fork length (nearest 0.5 cm) were recorded.

Fish were placed ventral side up in a clean V-shaped foam support. Tags were activated (pulse rate ranged from 2514-2794 ms), 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 (46-mm long x 14-mm diameter, 4.5-g weight in air, expected life of 90 days, 307 kHz, Hydroacoustic Technology Inc, Seattle, USA) were inserted into the body cavity of all but one fish through a 30-mm long, ventro-lateral incision made with a scalpel, anterior to the muscle bed of the pelvic fins. A model 795LX acoustic tag (66-mm long x 14-mm diameter, 13.0 g weight in air, expected life of 180 days, 307 kHz, Hydroacoustic Technology Inc, Seattle, USA) was inserted into the largest sea trout (70-cm) in a similar way, through a 50-mm long ventro-lateral incision. The incision was closed with an absorbable suture and treated with a skin adhesive powder (Orahesive, ConvaTec Limited, Deeside, UK). The procedure lasted approximately 5 minutes. In all cases tag weight did not exceed 2 % of the fish body mass (Winter, 1996). Fish were held in a well-aerated observation tank until they regained balance and were actively swimming, before returning them to the river, at a suitable site for release (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.

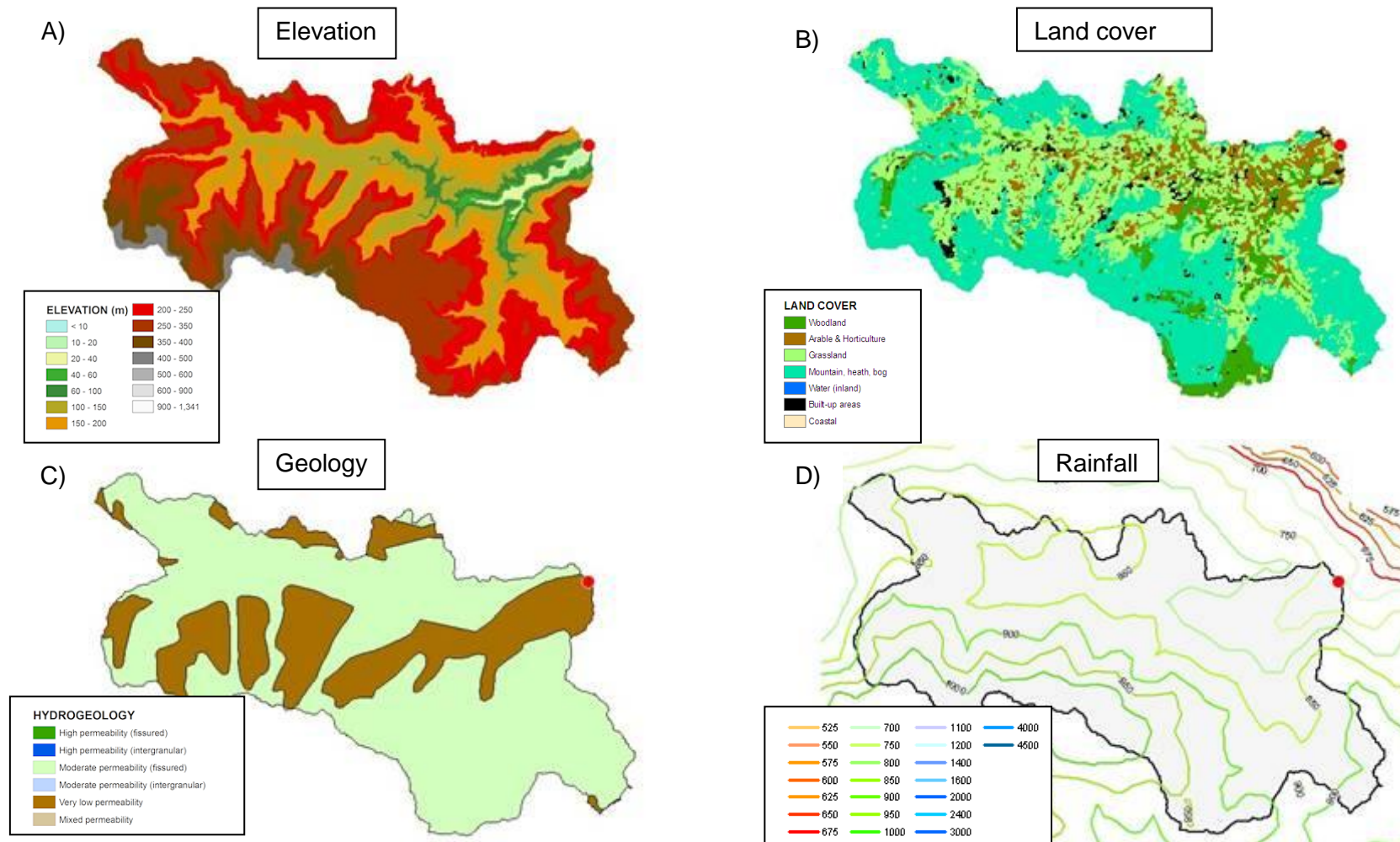


Figure 5. Plan form maps of catchment characteristics (elevation, landcover, geology and rainfall (mm)) for the Esk catchment (<http://data.ecn.ac.uk/sites/ecnsites.asp?site=R02>).

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), 11 October 2011 – 12 January 2012. Seven hydrophones (H1-H7) were arranged as an array downstream of the fish pass and a single hydrophone (H8) upstream of the fish pass (Figure 3 and Figure 4). The relative position of each hydrophone in the array was determined by measuring the pair-wise distance to two locations with known grid references (walls of fish pass entrance). The sub-metre 2D position of fish within the array was triangulated using the arrival times of tag pulses at each hydrophone using Hydroacoustic Technologies Inc. proprietary software. H8 was used to indicate when a fish had ascended, but could not indicate a fish's position. Tag detection data (identity, date, time and location) were recorded using HTI Acoustic Tag software (Hydroacoustic Technology Inc, Seattle, USA) and stored on a portable laptop computer. Throughout the study, the effectiveness of the array and H8 (detection range = full river width) were periodically tested using a Model 795LG tag drawn through the river to reflect all possible routes and behaviours of fish. The test tag also verified that battery life spanned the duration of the experiment. The array was visited daily to inspect for damage (none) and remove debris (minimal). The array was not operating between 25 - 26 November and 31 December - 2 January because of power outages, but this was not considered critical as all fish recorded had passed the array before this time.

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 as a proportion of the total number observed in the array was used to quantify the permeability of the weir to fish.

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 enters the array and terminate when the array is exited via an upstream route (Figure 6 left). Non-passage tracks were defined as tracks that start when the array is entered and terminate when the fish leaves the array via a downstream route (Figure 6 right). Time in the array was defined as the time between the first detection and the last detection on hydrophones 1 to 7.

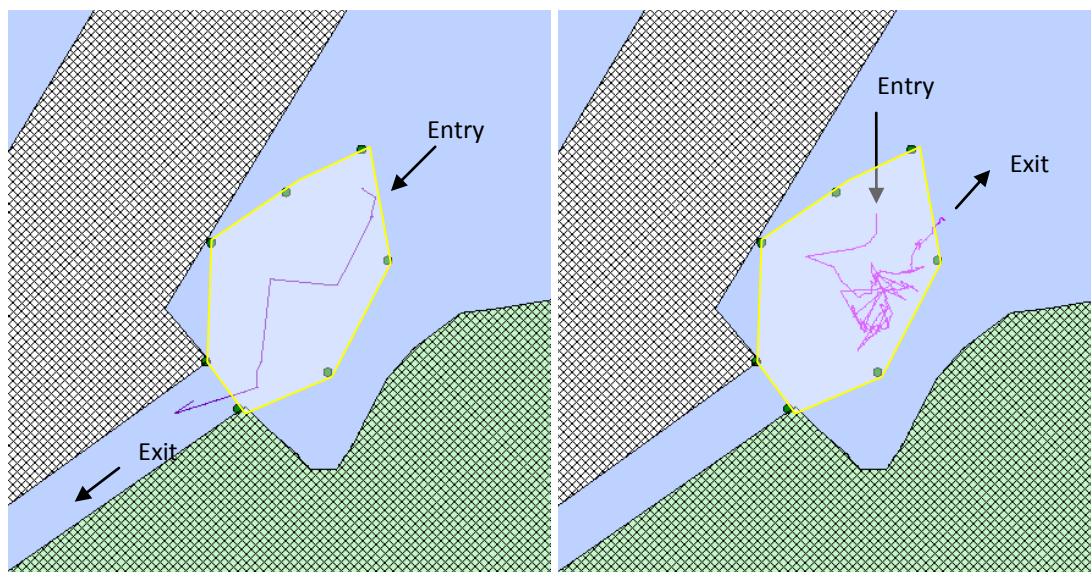


Figure 6. Examples of a passage track (left) and a non-passage track (right) in the array (yellow polygon).

Passage routes were divided into fish pass and side of fish pass routes (Figure 7 and Figure 8) 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 ($<3 \text{ m}^3\text{s}^{-1}$ = fish pass, $>3 \text{ m}^3\text{s}^{-1}$ = fish pass or side of fish pass). In two cases it was not possible to determine which route was taken as both routes were feasible; these were classified as "pass proximity".



Figure 7. Fish pass and side of fish pass ascent routes in low flows ($1.47 \text{ m}^3 \text{ s}^{-1}$) looking downstream. Arrows represent direction of fish passage (photo taken 31/10/2011 17:42).



Figure 8. Fish pass and side of fish pass ascent routes in high flows ($35.9 \text{ m}^3 \text{ s}^{-1}$) looking upstream. Arrows represent direction of fish passage (photo taken 3/1/2012 12:00).

Fish tracks were analysed to investigate the following:

- delay between release and fish passage (see Section 3.1);
- number of times the array was entered (see Section 3.1);
- duration of array visits – passage/non-passage (see Section 3.1);
- total time taken from entering array to leaving fish pass/side of fish pass (detection on H8) (see Section 3.1);
- the proportion of fish ascending via the fish pass, side of the fish pass or the baulk fish pass (see Section 3.2);
- diel timing of movements (see Section 3.3);
- the influence of fish size on movement (see Section 3.4); and
- the duration and timing of array visits related to the following environmental variables (discharge, tide state, total water index and temperature) (see Section 3.5).

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 Mann-Whitney *U*-tests were performed. Relationships between variables were assessed using Pearson's correlations. All statistics were carried out in SPSS (version 17.0) with a significance level $\alpha = 0.05$.

2.6 Micro-scale behaviour analysis

2.6.1 Initial processing

Triangulated positions of tag pulses/echoes produced by the HTI software were plotted as points in ArcGIS (ESRI ArcMAP version 9.3). Hawth's tools (Beyer, 2004) were used to connect points in chronological order to produce a continuous fish track made up of individual polyline "steps" (Figure 9). The length (distance between consecutive points; m) and bearing (azimuth) 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}). Please note bearing is not representative of orientation, rather fish movement as the fish may be orientated upstream whilst drifting downstream with the flow. Bearings were pooled in the groups listed below and displayed in rose diagrams (Rozeta version 2.0). The groups below were also used in all other 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; and
- ebbing tide versus ebbing/flooding tide versus flooding tide



Figure 9. 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 (t_p) 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 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 10 (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.

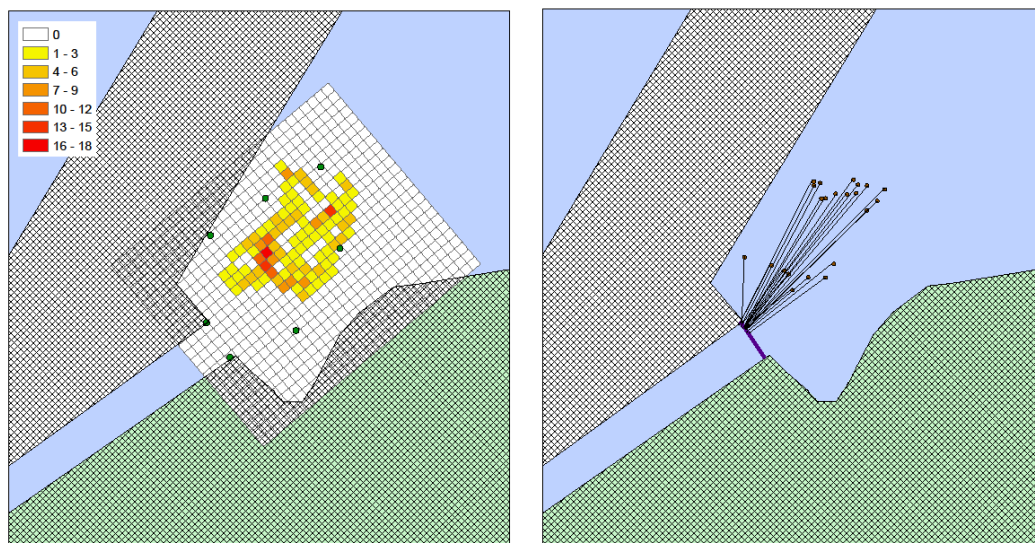


Figure 10. Example residence time (sec) grid, with cells colour coded from white to red with increasing time (left) and a diagrammatic example of proximity analysis (right).

2.6.3 Proximity analysis

The proximity of tag echoes (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 10 (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

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 11) and the number of approaches this represented in passage runs was calculated by:

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

and for non-passage runs by;

$$nA = nl / 2$$

where nA is the number of approaches and nl 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.

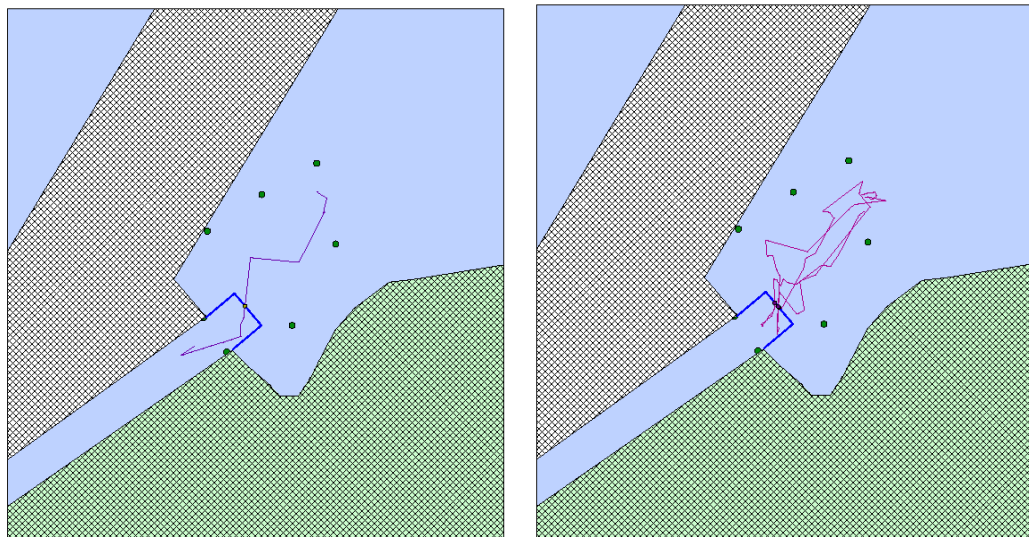


Figure 11. Example of the intersection of a passage (left; $nl = 1$, $nA = 1$) and non-passage track (right; $nl = 4$, $nA = 2$) with the 2 metre fish pass buffer.

2.6.5 Array entry

The movements of all fish tracks into the array were classified into 3 groups (A, B, C) according to the location of the first recorded echo(s) between hydrophones 6, 5, 3 and 2. Entry between 6 and 5 = A, 5 and 3 = B, and 3 and 2 = C. In cases where it was not possible to determine the point of entry accurately, tracks were classified as "indeterminate".

2.7 Environmental data

Flow ($\text{m}^3 \text{s}^{-1}$) was measured at 15-min intervals at the Briggswath gauging weir (NZ 866 081). Water temperature was recorded from 31 October 2011 to 16 January 2012 at 15-min intervals using a 2 tg-4100 logger (Tinytalk, Orion Instruments, Chichester, UK). Temperature data before 31 October 2011 were modelled using the relationship between the River Esk and the River Tyne (Table 1). Tide data were obtained at 15-min intervals using Admiralty Total Tide software (The United Kingdom Hydrographic Office, Taunton, UK). The movement of fish downstream of the weir may be facilitated by a combination of the freshwater discharge and tidal inputs. Actual discharge data were not available for Ruswarp Weir, so a Total Water Index (TWI) was calculated by adding discharge at the gauging weir and tide height to determine the relative quantity of water downstream of the weir.

Table 1. Linear regression relationships between water temperature in the rivers Esk and Tyne.

Linear regression	P	r^2	n
Esk = Tyne $(-1.195)+1.199$	<0.001	0.94	5905

2.8 Hydraulic assessment

A flow velocity profile within the array was obtained at low flows (mean daily discharge = $1.36 \text{ m}^3 \text{s}^{-1}$) using a Teledyne™ RDI StreamPro Acoustic Doppler Current Profiler (ADCP) along five transects (Figure 12 and Figure 13). Hydraulic surveys using the ADCP were not possible at flows higher than those surveyed as turbulence within the pool disrupted the ADCP accuracy. Turbulence at the entrance to the fish pass (transect 0; Figure 12) was too great for the ADCP to obtain meaningful readings during this study. Multiple passes along transects 1-4 were pooled and geo-referenced in arcGIS. Data from these transects were spatially interpolated to give an approximate distribution of flow velocities throughout the array. Ordinary kriging using the Matern (K-Bessel) model was used for spatial interpolation. The variogram was estimated using a lag size of 0.5001 and 12 lags, with the models (nugget effect = 0.0247, spherical component (partial sill) = 0.0308, and range = 3.582), fitted using the Geostatistical Analyst within ArcGIS™.

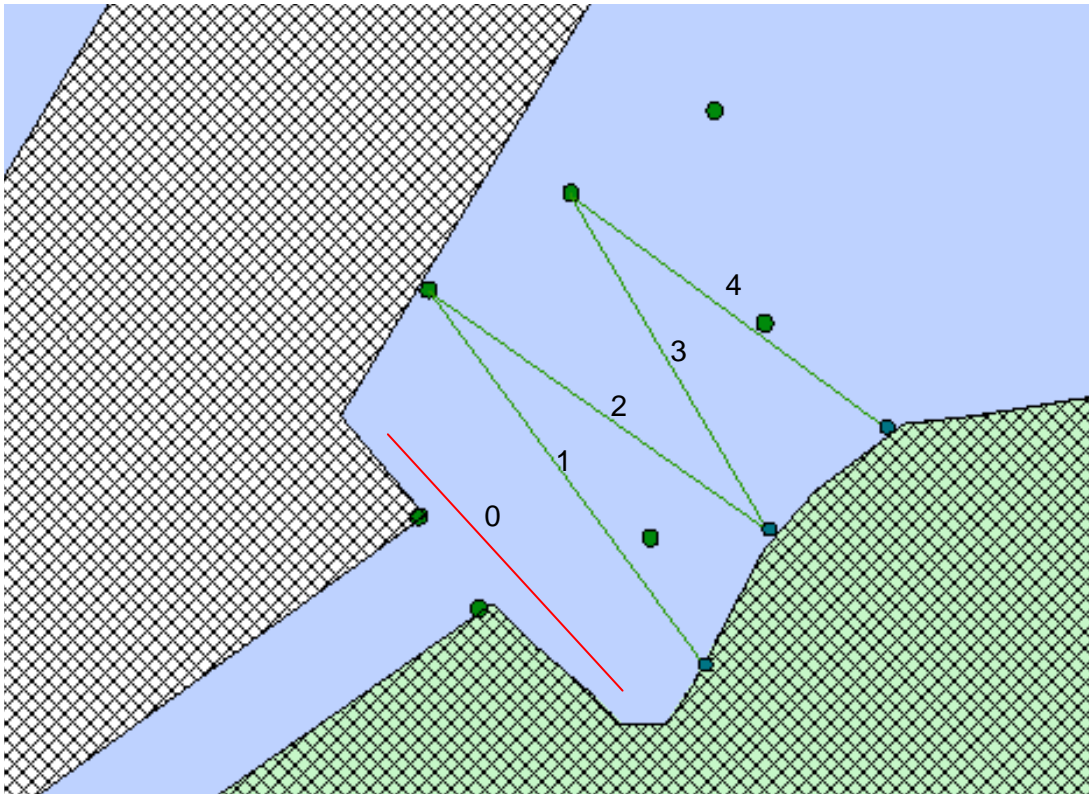


Figure 12. Flow velocity profiling transect locations (0-4).



Figure 13. ADCP in operation on transect 4 within the array.

3 Results

3.1 Visits to the array

Of the 39 fish tagged, 15 fish (14 sea trout and 1 salmon; 37%) were detected in the hydrophone array (Table 2). All fish detected in the array went on to ascend the weir, including one sea trout that ascended the weir twice. Four sea trout ascended the weir on the day of release, with one fish doing so within 20 minutes. The majority of fish ascended the weir within three days of release (Figure 14), while three others ascended the weir 17, 30 and 42 days after release (mean \pm C.L.; days = 6.3 ± 6.1 , compared to 4.4 ± 5.2 in 2010).

Seven sea trout ascended the weir on their first visit to the array, while two did so on the second visit, three during the third and one during the fourth (Figure 15). The total time from entering the array and ascending was generally less than 2 hours (Figure 16). The smallest sea trout tagged (38 cm) was observed in the array on 14 separate occasions over a period of five days (114 h) before ascending the weir. The only tagged salmon that ascended the weir did so during its second visit to the array, 13 h after its first detection. The weir ascent track was significantly shorter duration for fish that entered the array more than once, than the tracks that ended with the fish leaving the array via another route, i.e. downstream (Mann Whitney U-test: $Z = -2.21$, $n = 16$, $P = 0.027$) (Figure 17).

3.2 Ascent route

Of the 15 sea trout ascents over the weir, 12 opted to use the fish pass and two used the side of the fish pass during elevated river levels (note this route was dry at normal levels). No fish were observed to use the baulk fish pass (detected only on H8).

3.3 Diel variations in fish movements

Fish entered the array 20 times during the day and 20 times at night. The time fish spent in the array was not significantly different (independent samples t-test, $t(23) = -1.31$, $P > 0.05$), between day (8.31 ± 5.72 min) and night (24.82 ± 18.86 min) during non-passage visits to the array (Figure 18). More fish ascended the weir at night ($n = 10$) than during the day ($n = 6$). Again, although the difference was not significant (independent samples t-test, $t(14) = -1.55$, $P > 0.05$), fish spent a longer duration in the array during the day (18.83 ± 25.71 minutes) than at night (3.70 ± 2.86 minutes) during passage visits (Figure 19).

3.4 The influence of fish size on movement

The number of array visits, the time fish spent in the array on passage runs, the total time from entering the array to ascending the weir were all significantly negatively correlated to fish size (Pearson correlation: $n = 16$, $r = -0.713$, $P = 0.002$; $n = 16$, $r = -0.751$, $P = 0.001$; $n = 16$, $r = -0.722$, $P = 0.001$, respectively), i.e. smaller fish visited the array more frequently, spent longer in the pool on passage runs and took longer to ascend after their initial entry into the array.

Table 2. Summary of movement characteristics of fish that ascended Ruswarp weir. (FP = fish pass, FPS = fish pass side, FPP = fish pass proximity)

Tag (tag period; ms)	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 ascent (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 ascent)	St		-	2	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

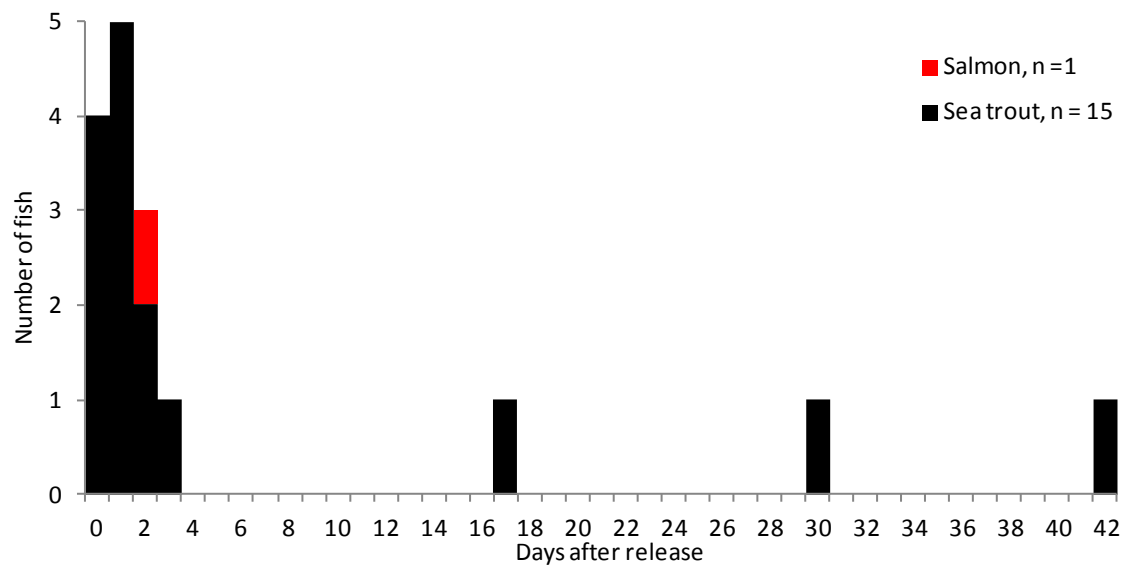


Figure 14. Number of days between release and passage. 0 = day of release.

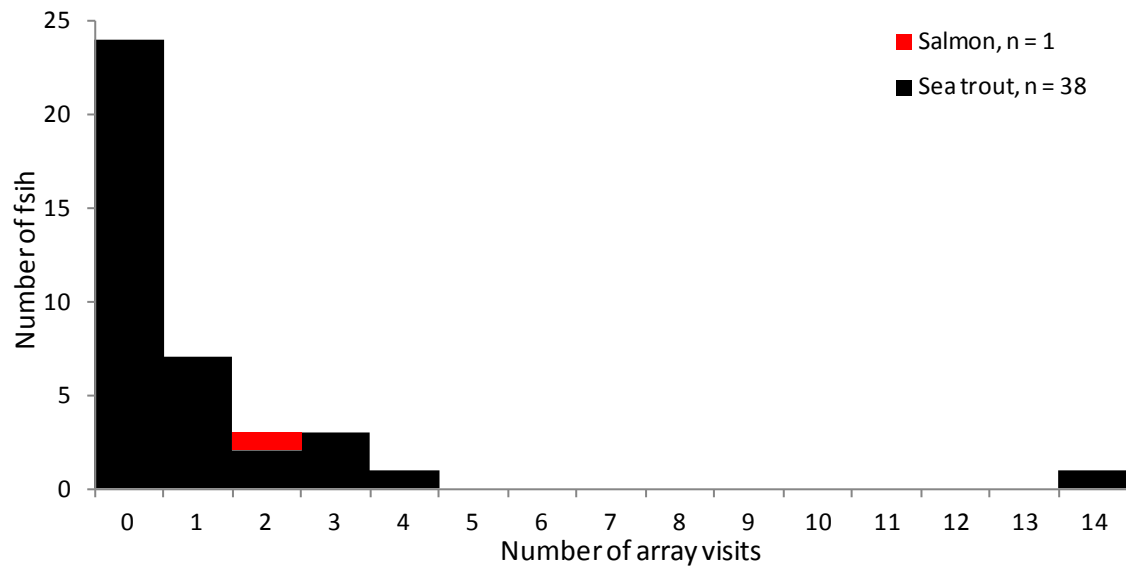


Figure 15. Frequency distribution showing the number of times the hydrophone array was entered by fish. 0 = no entry.

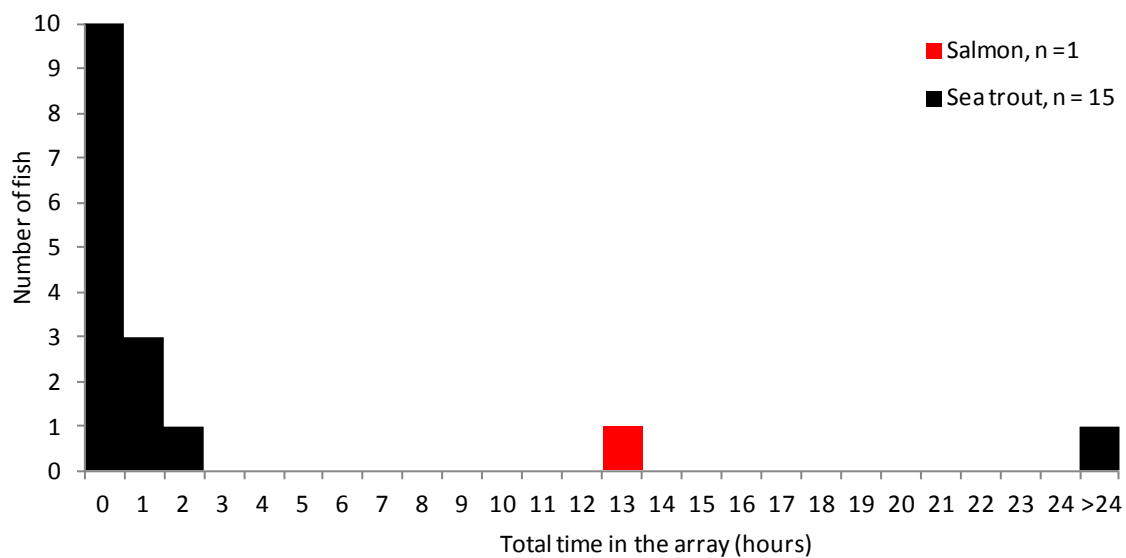


Figure 16. Total time from entering array to passage (sum of all tracks). 0 = day of release.

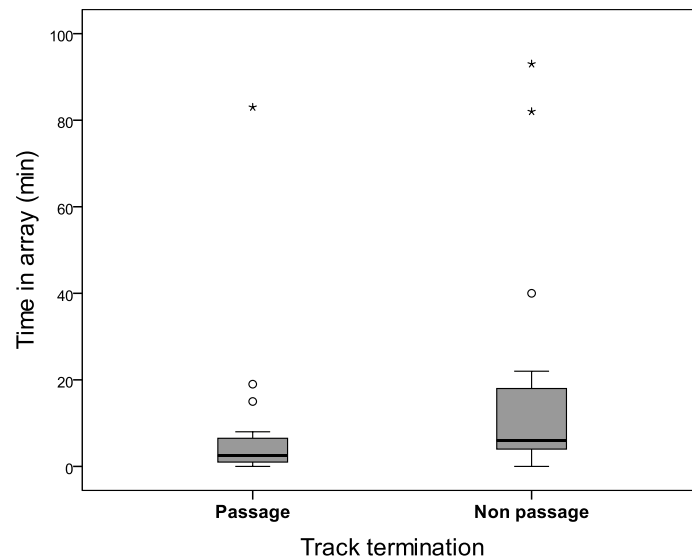


Figure 17. Duration of individual array visits in passage (n = 16) and non passage (n = 24) runs.

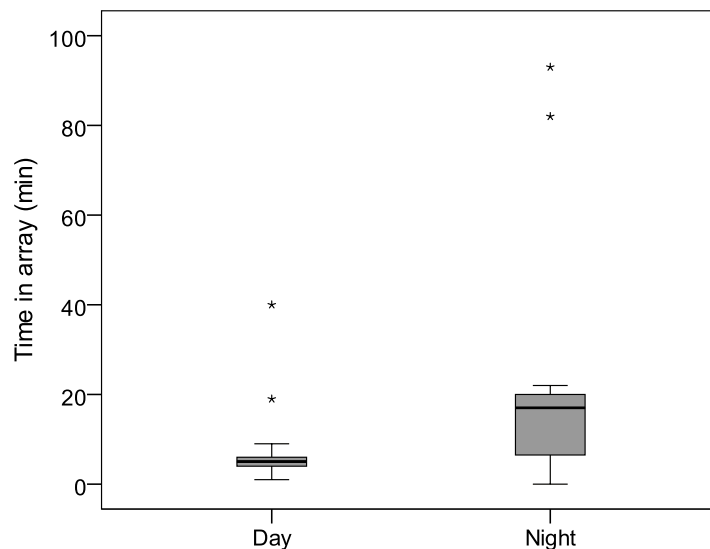


Figure 18. Box plot showing the relative time spent in the array during non-passage visits to the array in the day (n = 14) and at night (n = 10).

3.5 Environmental influences on timing of movement

Fish were generally observed to move at periods of elevated flow (Figure 20 and Figure 21), but these periods of high flow followed shortly after releases so in the majority of cases it was not possible to discern whether fish movements occurred as a consequence of release or in response to a specific flow event. Irrespective, a sea trout from release 1 (tag 2563) was observed to move 16 days after release (thus seemingly independent of its release) and coincided with a moderate flow peak (26-27 Oct). Similarly, a fish from release 2 (tag 2717) was observed in the array (but did not ascend) 25 days after release following a major flow peak (5-6 Nov). This fish, together with another from release 2 (tag 2640; ascent 42 days after release) did not ascend at times of elevated flow but their ascents may be linked to tidal phase (29 and 42 days after release; Figure 22). Indeed, fish were generally observed to move at the peak of spring tides (Figure 22), although spring tides coincided with the release times in most observations. In those fish where movement was independent of release time (tags 2563, 2717 and 2640) ascents coincided with spring tides.

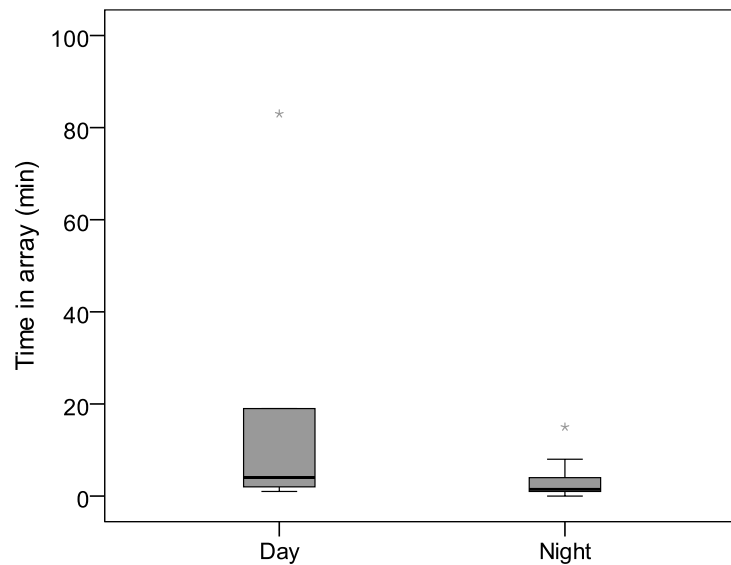


Figure 19. Box plot showing the relative time spent in the array during passage runs in the day ($n = 6$) and at night ($n = 10$).

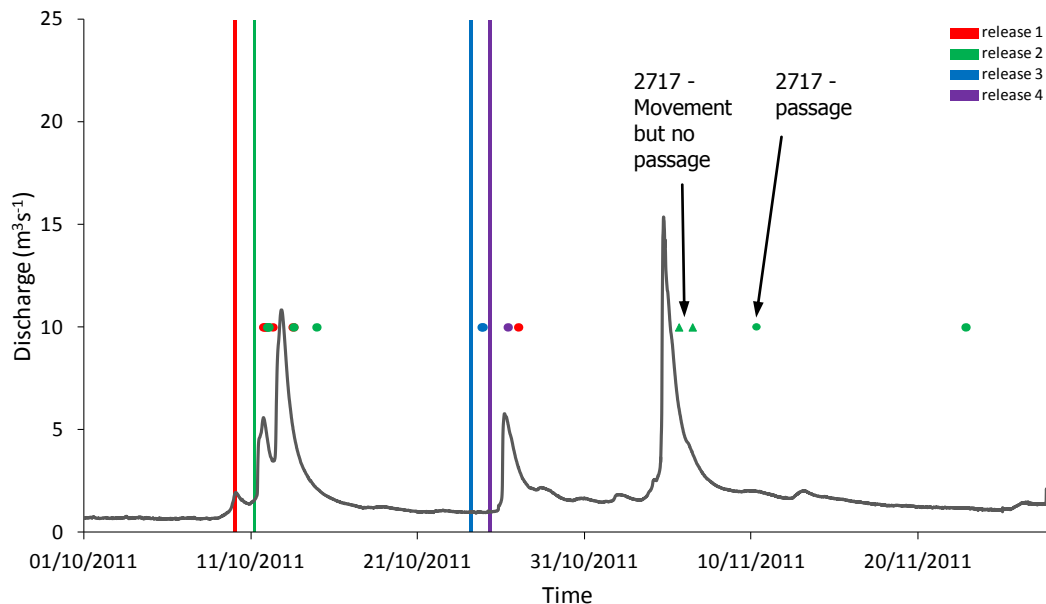


Figure 20. Time series of discharge over the study period with fish movements represented as points in time. Each point is colour coded according to its release batch. Note: all dots are representative of passage with the exception of the triangular points representing tag no. 2717 labelled in the diagram. This movement was independent of the fish's subsequent passage (also labelled).

There was no discernible trend in the timing of fish movements within the array relative to tide height that day for non-passage (Figure 23) and passage movements (Figure 24), but there was a peak around the 50th percentile for all movements combined. Fish were generally observed to ascend the fish pass on a flood tide ($n = 10$), although four fish ascended on an ebbing tide and two fish were observed to ascend on the slack phase of the tide between ebbing and flooding, but not between flooding and ebbing tides. The state of the tide (ebbing or flooding) did not significantly influence the time fish spent in the array (ANOVA: F^2 , 13 = 1.65, $P = 0.23$) (Figure 25).

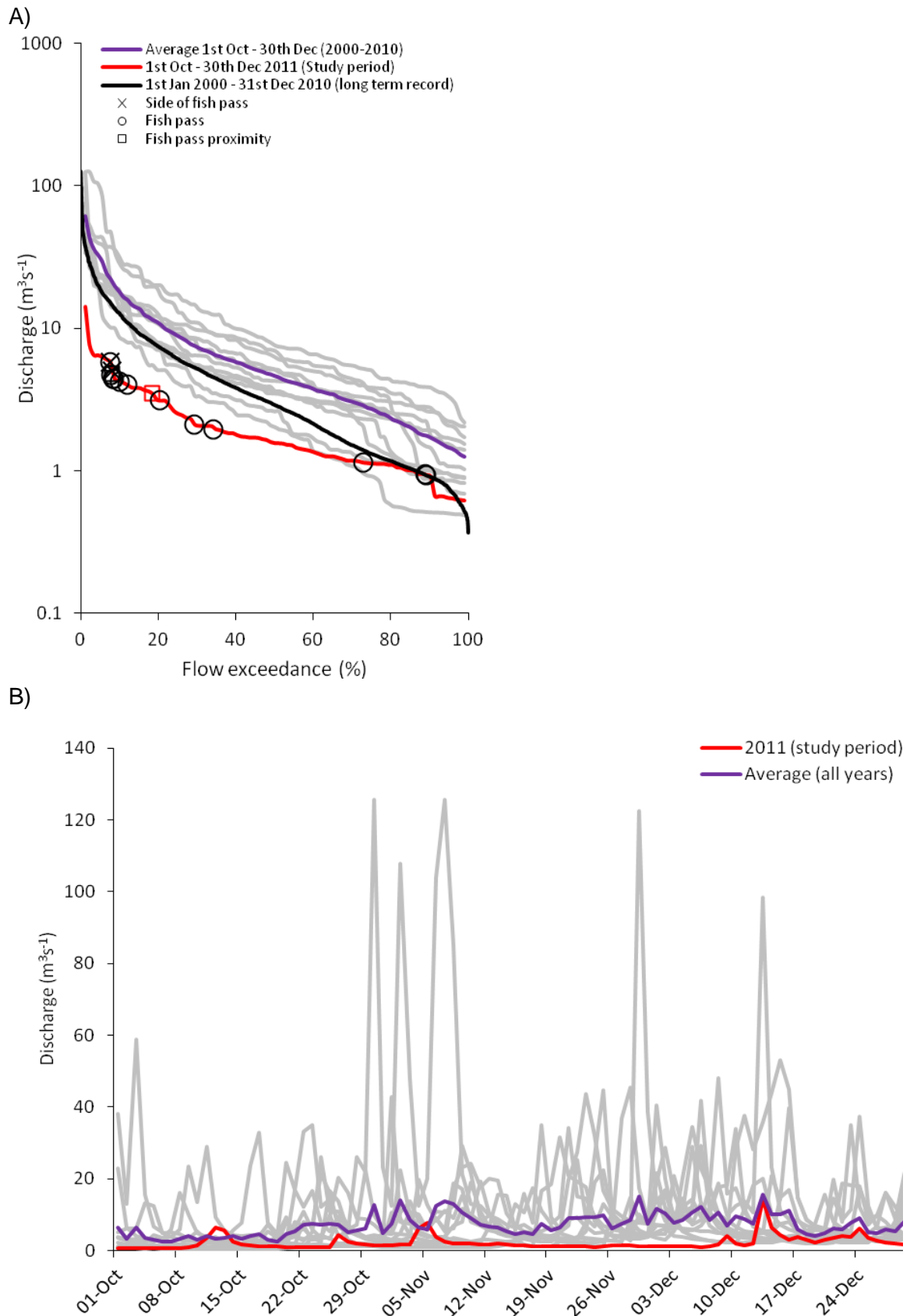


Figure 21. A) Flow exceedance curves for the study period (red), the same period in other years (grey) and the period average over all years (purple). The timing of passages in relation to exceedance probability and their ascent route is indicated. B) Comparison of the hydrograph over the study period (red) with the same period in other years (grey) and the period average over all years (purple).

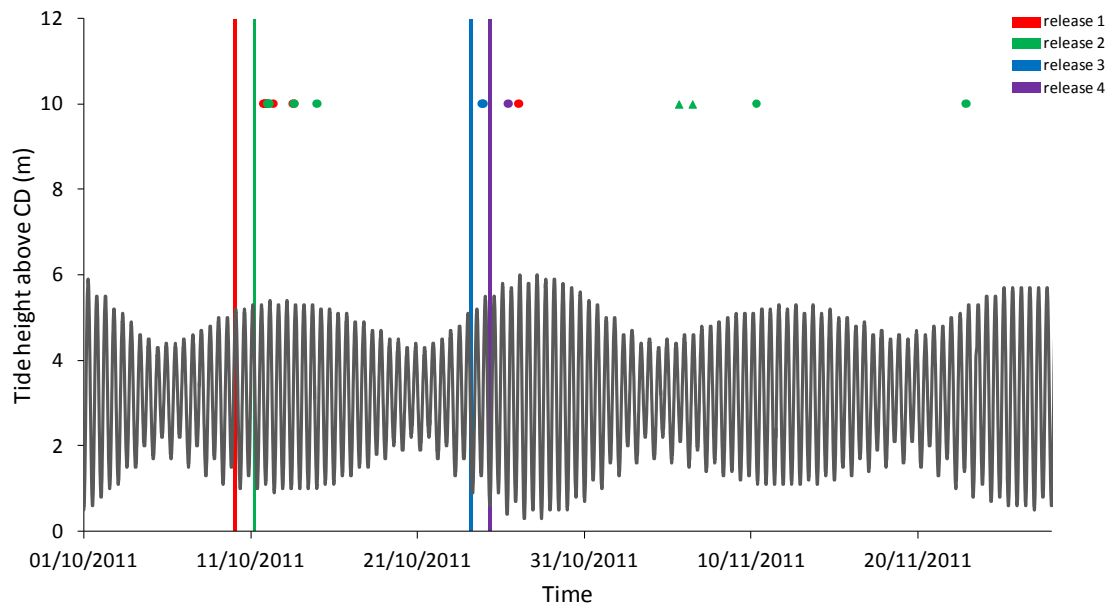


Figure 22. Time series of tides over the study period with fish movements represented as points in time. Each point is colour coded according to its release batch.

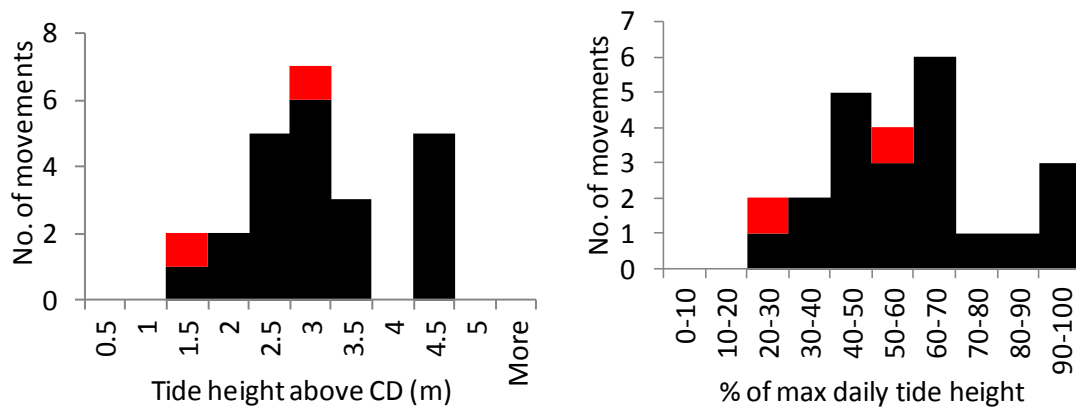


Figure 23.a) Number of fish that entered the array during non-passage movements in relation to tide height and b) to the proportion of maximum tide height on the day of fish movement.

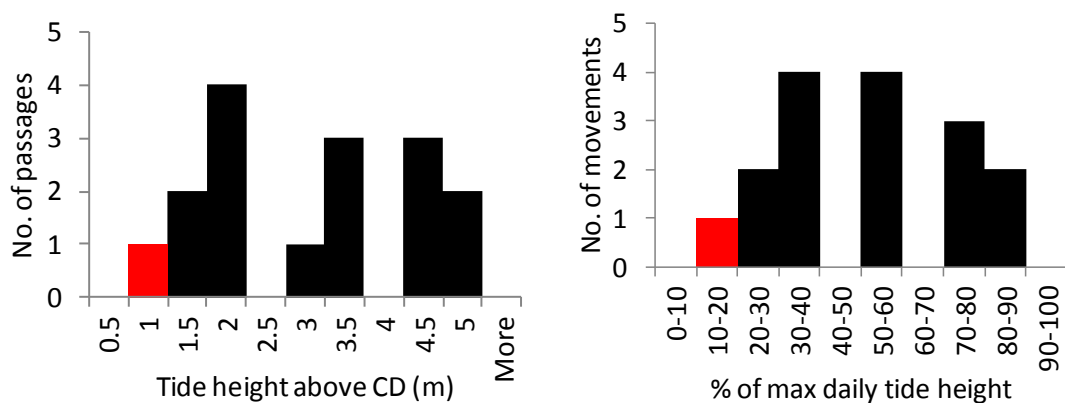


Figure 24.a) Number of fish that ascended the weir in relation to tide height and b) to the proportion of maximum tide height on the day of fish movement.

More fish were observed milling on an ebbing tide during non-passage runs than a flooding tide, but the time they spent in the array was not statistically different ($t(21) = -0.36$, $P > 0.05$) (Figure 26). The ebbing/ flooding group could not be compared statistically as it only contained a single case.

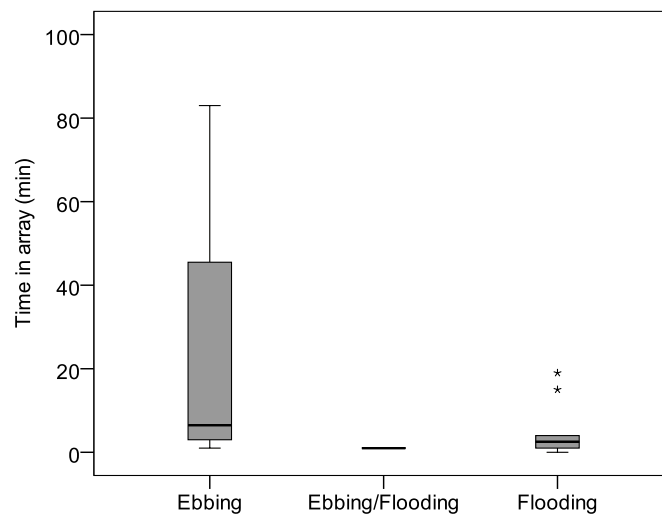


Figure 25. Amount of time spent in the array on passage runs during ebbing (n = 4), ebbing/flooding (n = 2) and flooding (n = 10) stages of the tide.

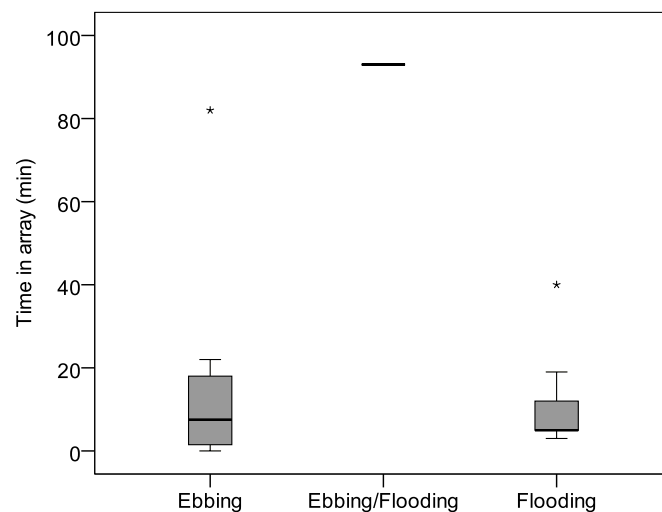


Figure 26. Amount of time spent in the array on non-passage runs during ebbing (n = 12), ebbing/flooding (n = 1) and flooding (n = 11) stages of the tide.

The timings of first detection of fish in the array were related to TWI to determine if there is a threshold below which upstream migration of fish from the estuary may be inhibited because of lack of suitable water depths. The timing of first detections of fish in the array generally occurred when the TWI was high but as previously mentioned these movements also generally coincide with fish releases (Figure 27). Eleven fish first arrived in the array at TWIs higher than 7, suggesting higher water volumes may be preferential for movement, but four fish ascended the weir at values below this range (Figure 28). Indeed, the lowest TWI value a fish was recorded entering the array was 2.24. TWIs below 2.24 occurred less than 2.37% of the time (Figure 27) suggesting that water depths in the area encompassed by the array were sufficient for fish to have access to the fish pass for 97.6% of the time, thus fish can access the fish pass even under periods of low flows in the driest years.

No obvious trends were observed in the movement of fish in relation to temperature over the study period (Figure 29).

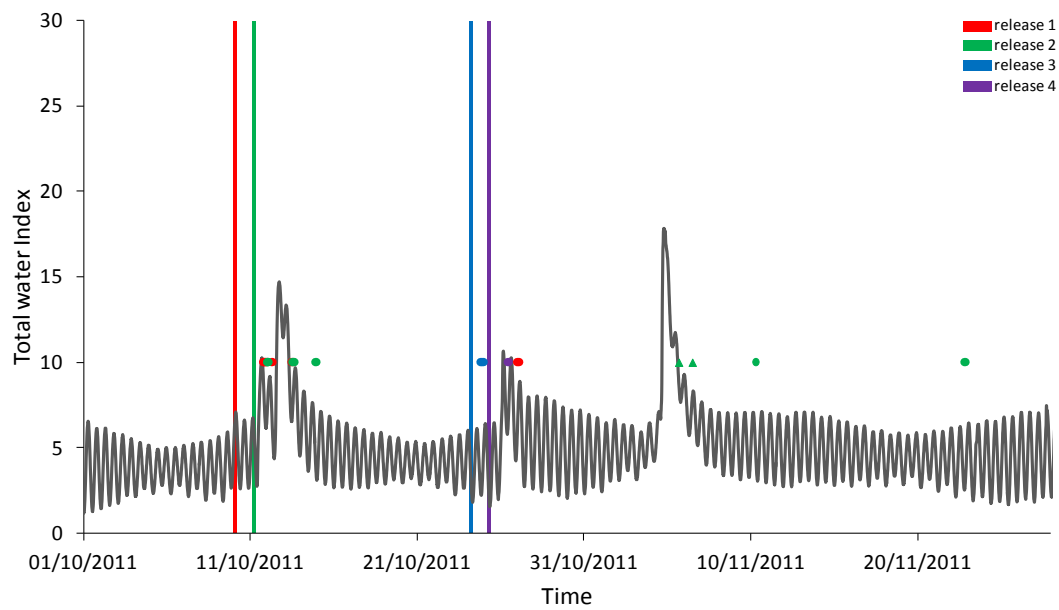


Figure 27. Time series of total water index (tide + discharge) over the study period with fish movements represented as points in time. Each point is colour coded according to its release batch.

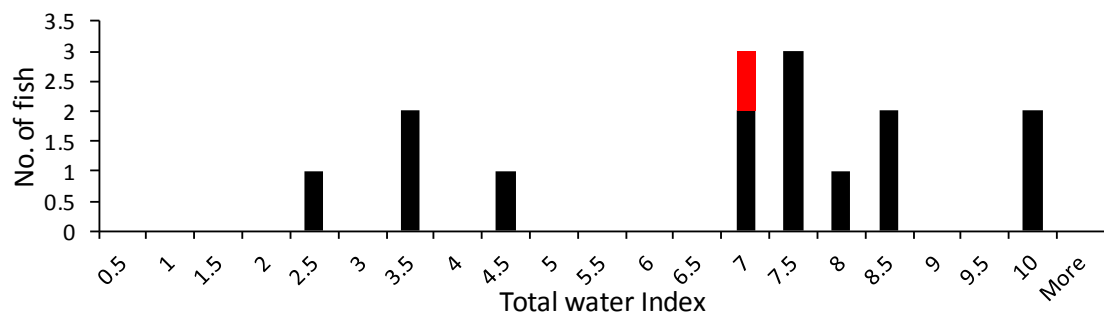


Figure 28. Timing of first recorded tracks of all 15 fish in relation to TWI.

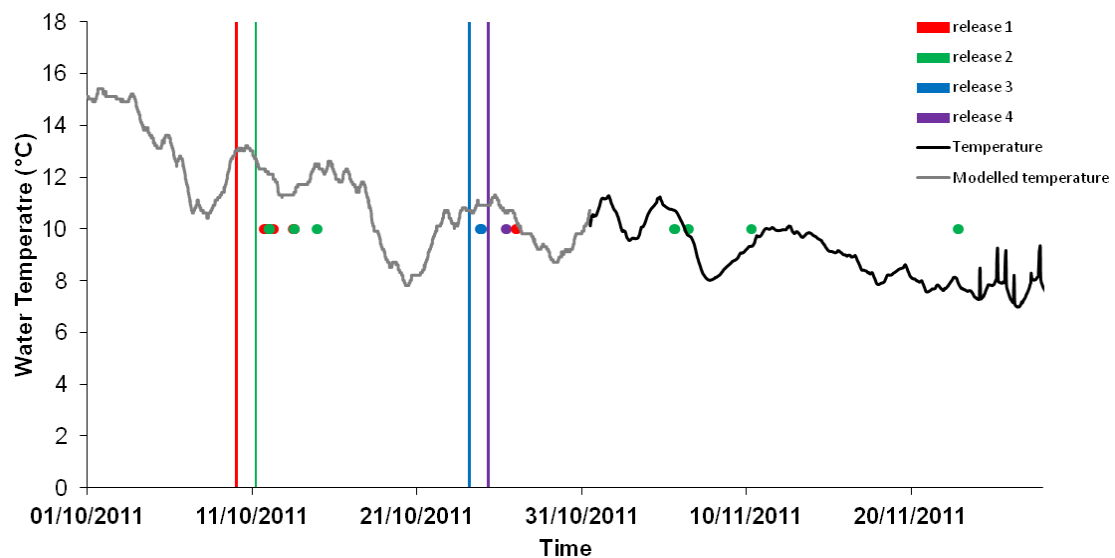


Figure 29. Times series of temperature over the study period with the movements of fish represented as points in time. Each dot is colour coded according to its release batch.

3.6 Hydraulic conditions within the array

Hydraulic surveys using an ADCP along four transects in the hydrophone array (Figure 30) were interpolated to produce a “flow map” of the pool (Figure 31). Flow velocities ranged from 0 to 1.5 ms^{-1} and the fastest flows were found near the entrance to the fish pass at the top of the water column. Below this area of fast water was an area of slacker water which might be used as a flow refuge by fish. This could explain high residence times in this area (see Section 3.7).

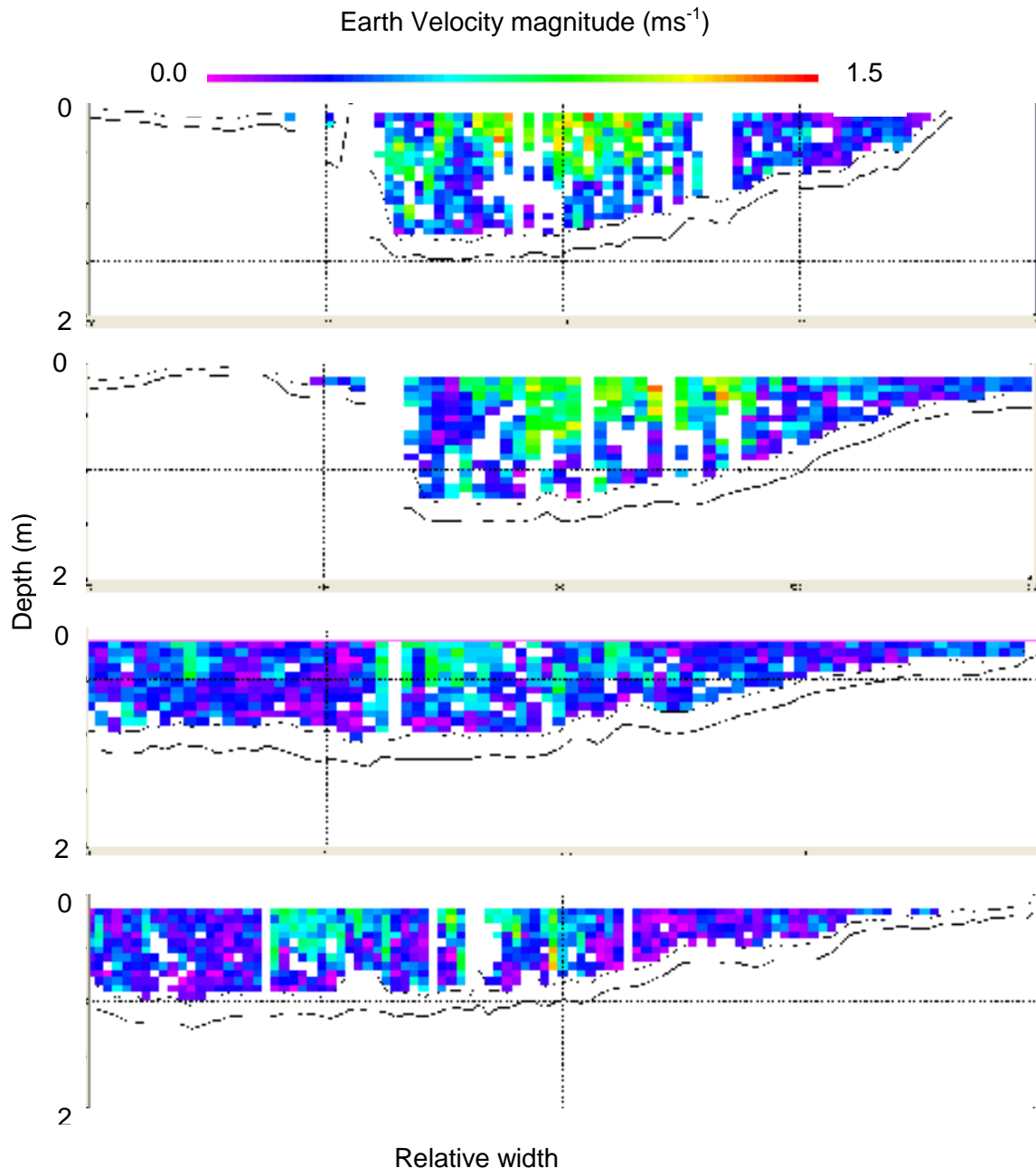


Figure 30. Cross sectional flow profiles of ADCP transects 1-4 (Figure 12)

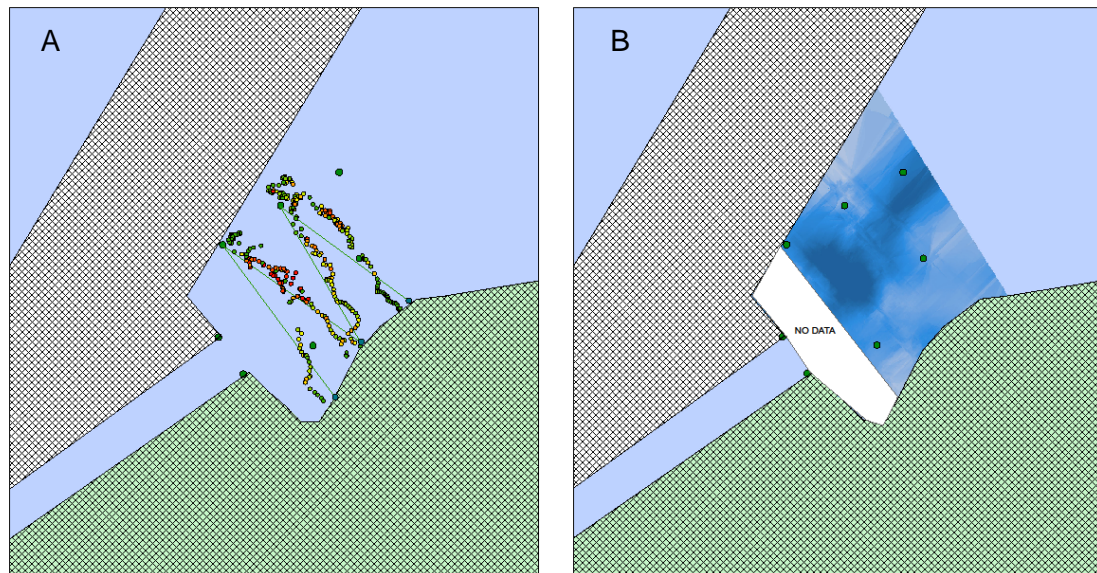


Figure 31. a) Example of depth averaged transects taken using the ADCP and b) the interpolated output of all data (darker blue corresponds to higher flow). Note: no adequate data was obtained near the fish pass due to turbulent flows.

3.7 Quantitative analysis of micro scale fish behaviour within the array

3.7.1 All tracks

Although track counts were evenly distributed throughout the array (Figure 32), residence time was not evenly distributed. Hotspots, where fish spend a disproportionate amount of their time, were apparent at the entrance to the fish pass and to a lesser extent at the back of the pool (Figure 33). The highest frequency of tag echoes were detected within 2-3 m of the fish pass (Figure 34). The average (\pm C.L.) number of approaches to the fish pass (within 2 m distance from the entrance) was 7.8 ± 5.6 per fish track, and fish spent an average of 87.3 ± 48.0 sec within this area during each fish track.

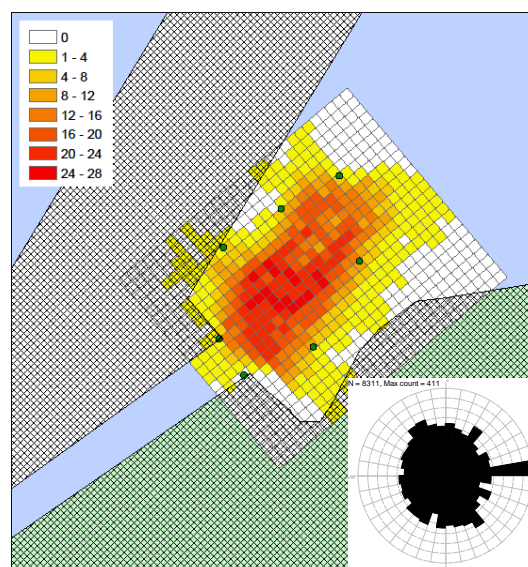


Figure 32. All tracks combined: count of tracks to pass through each grid cell.

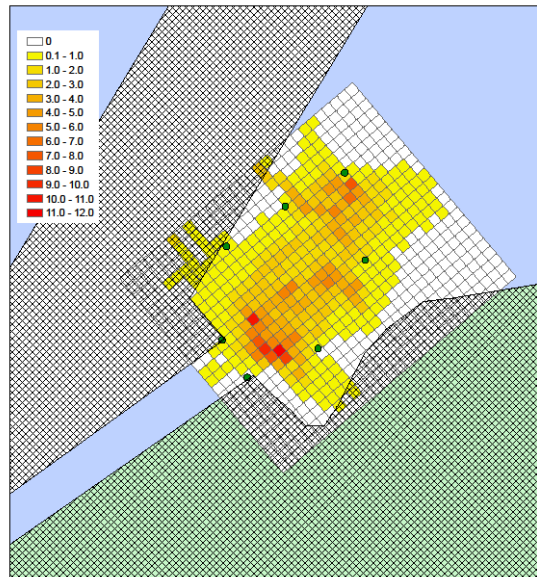


Figure 33. Average time (sec) spent in each grid cell by all fish that entered the array (all tracks combined).

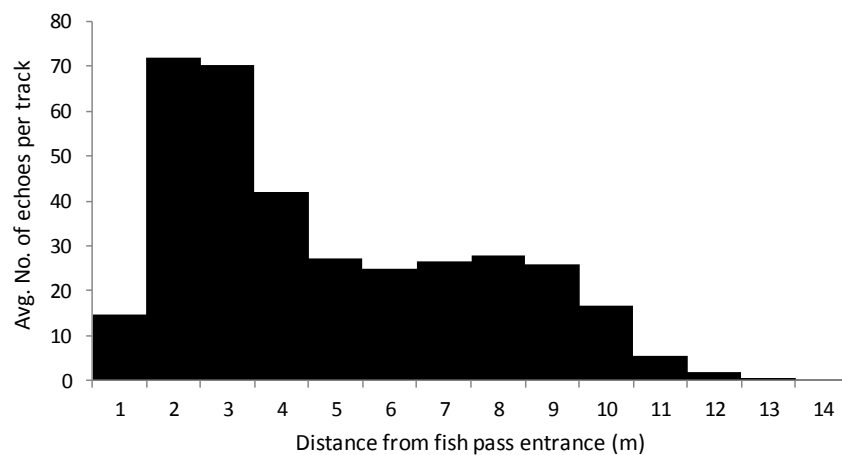


Figure 34. Average number of tag echoes detected in the array (per fish track) against distance from the entrance to the fish pass (m).

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

On average a greater number of tracks were recorded nearer the fish pass in passage tracks than during non-passage tracks (Figure 35), but there were no obvious differences in residence time within the array (Figure 36). The general patterns of tag echo proximity in relation to the fish pass entrance were similar between passage and non-passage tracks, however a much greater number of tag echoes was detected per track in the immediate vicinity of the fish pass (<3-m radius) in non-passage tracks. In addition, the highest frequency of tag echoes recorded was at a closer proximity to the fish pass entrance in non-passage tracks (1-2 m) than in passage tracks (2-3 m).

The average number of approaches to the fish pass (within 2 m distance from the entrance) was not significantly different ($t(38) = 1.09$, $P = 0.281$) between passage (8.06) and non-passage (7.54) tracks. Average time spent within a 2-m radius of the fish pass was not significantly different ($t(38) = 0.66$, $P = 0.481$) between passage (78.8 sec) and non-passage visits (93.0 sec).

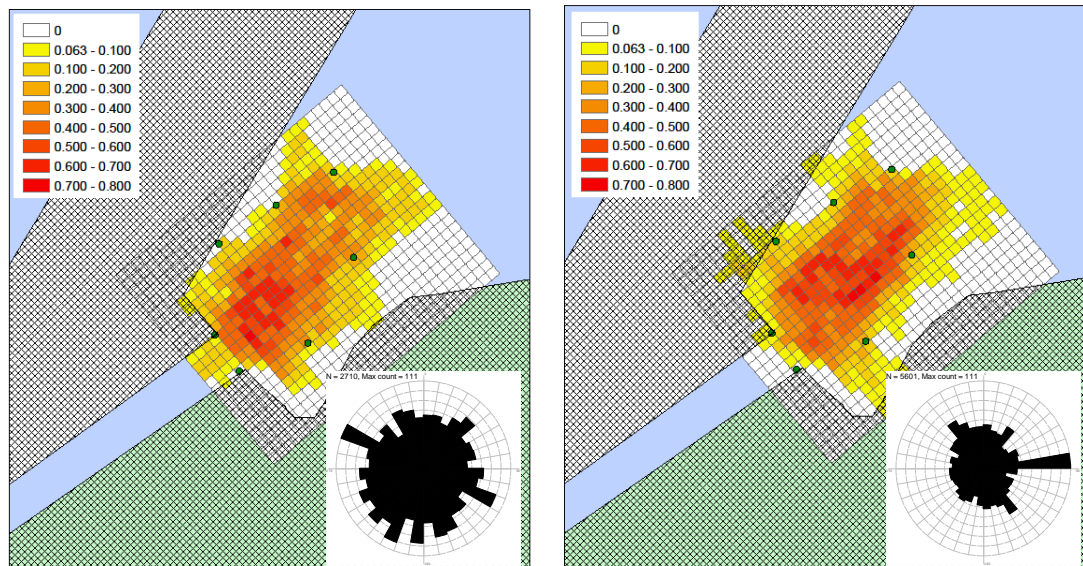


Figure 35. Count of tracks to pass through each grid cell (standardised by number of tracks in each group) during passage (left) and non-passage (right) visits to the array.

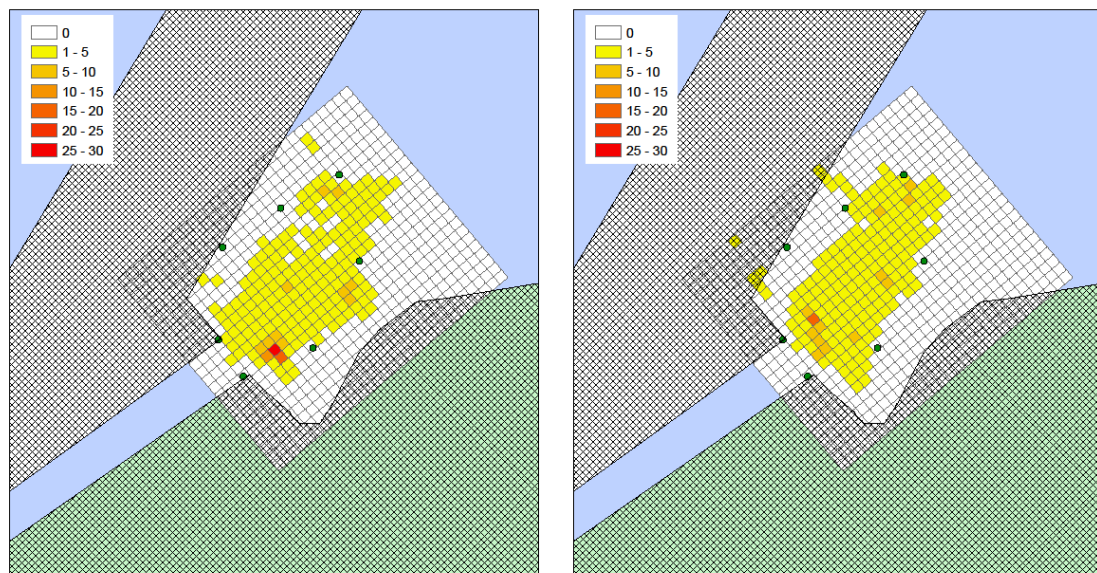


Figure 36. Average time (sec) spent in each grid cell by fish during passage (left) and non-passage (right) visits to the array.

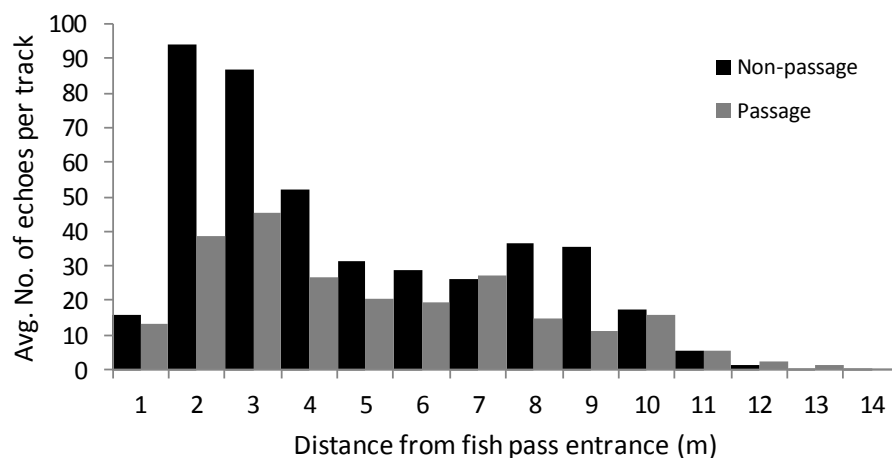


Figure 37. Average number of tag echoes (per fish track) detected in the array in passage and non-passage runs, against distance from the entrance to the fish pass.

3.7.3 Diel variations in spatio-temporal distribution within the array

There was little difference in the distribution of average track counts within the array during the day and at night (Figure 38). However, a difference was apparent in the time distributions as a hotspot was found at the entrance to the fish pass during tracks made during the day that was not defined in tracks made at night (Figure 39). The frequency of tag echoes decreased with distance above a 1 m proximity from the fish pass entrance during the day. This trend is also seen in tracks made during the night but it is less well defined and night time tracks generally have higher frequencies of tag echoes, especially at the extremes of the scale along the x-axis (2-4 m, 8-10 m). In both day and night tracks the highest tag echo frequencies were within a 1-2 m proximity of the fish pass (Figure 40). There was no significant difference between the average number of approaches made during the day (6.15) and the number made at night (9.35) ($t(38) = -0.90$, $P = 0.370$). In addition, there was no significant difference in the time fish spent within 2 m of the fish pass during the day (137.0 sec per fish track) and during the night (73.9 sec per fish track) ($t(38) = 0.19$, $P = 0.985$).

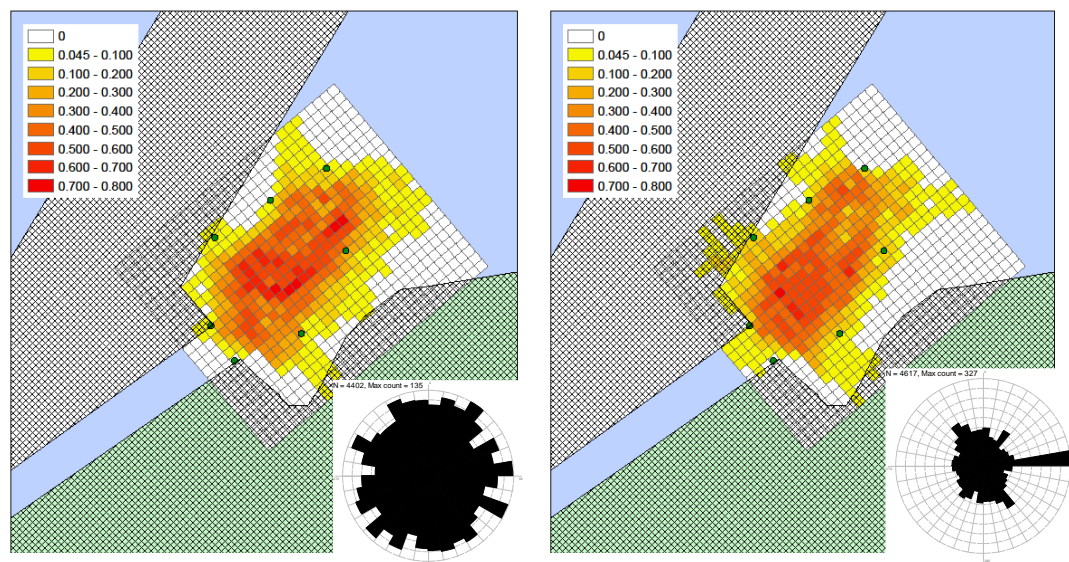


Figure 38. Count of tracks to pass through each grid cell (standardised by number of tracks in each group) during the day (left) and at night (right).

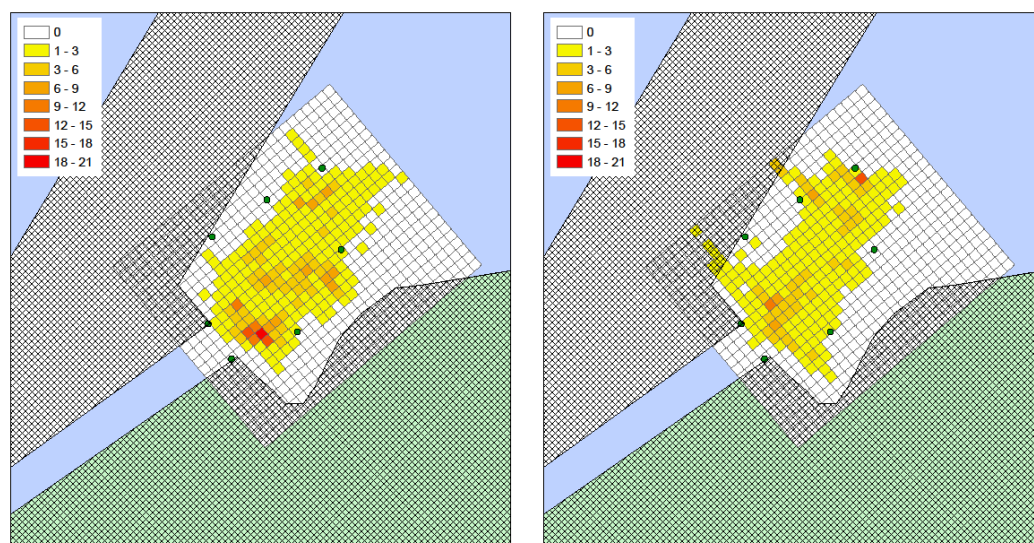


Figure 39. Average time (sec) spent in each grid cell by fish during the day (left) and at night (right).

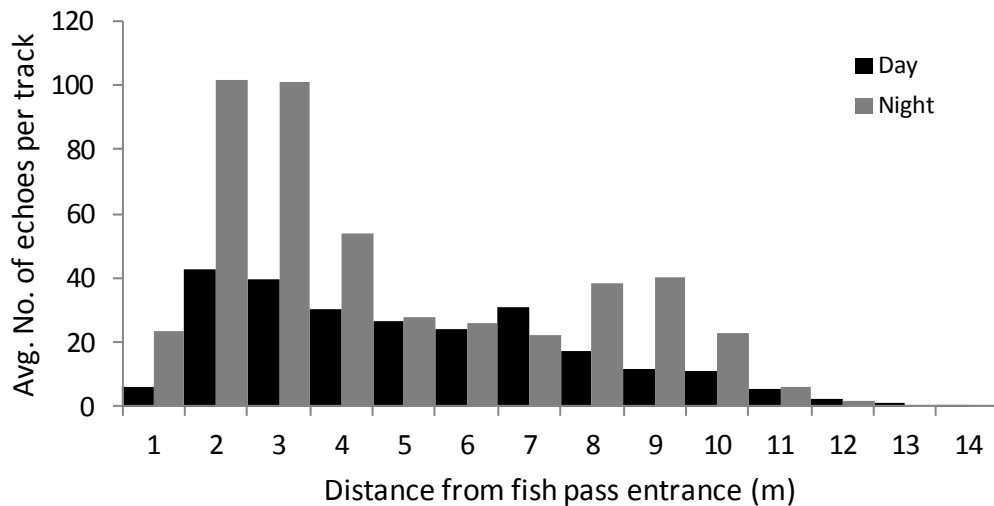


Figure 40. Average number of tag echoes (per fish track) detected in the array during the day and at night, against distance from the entrance to the fish pass.

3.7.4 Tide state and spatio-temporal distribution within the array

Hotspots of track counts were observed towards the back of the array during an ebbing tide (Figure 41: left) but residence time was highest near the fish pass (Figure 42: left). In contrast hotspots of track counts during ebbing/flooding and flooding tides were located at the front of the array, near the fish pass entrance along with residence time hotspots (Figure 41 and Figure 42: middle & right). The average count values observed in the ebbing/flooding group (Figure 41: middle) were heavily influenced by a low number of tracks and one track with high residence times in grid cells (track 2549, 1 of 3 milling).

Trends in the frequency of tag echoes with distance from the fish pass entrance were similar between groups, with frequencies generally decreasing with distance from the fish pass (above a distance of 1 m). Frequencies of tag echoes were unusually high in the ebbing/ flooding group due to the influence of one track with high residence times (as previously mentioned). The highest frequencies of tag echoes were recorded at 1 – 2 m proximity in ebbing and flooding groups and 2 - 3 m in the ebbing/ flooding group (Figure 43).

Fish made an average of 7.3 approaches per fish track during ebbing tides, 35.3 approaches during ebbing/flooding tides and 4.19 approaches during flooding tides. There was no statistically significant differences between approaches (Kruskal-Wallis test: $\chi^2 = 2.38$, d.f. = 2, $P = 0.305$). Fish spent an average of 105.9 sec within 2 m of the fish pass during ebbing tides compared with 194.3 sec during ebbing/ flooding tides and 57.9 sec during flooding tides. Average residence times within the vicinity of the fish pass were not significantly different (Kruskal-Wallis test: $\chi^2 = 1.53$, d.f. = 2, $P = 0.47$).

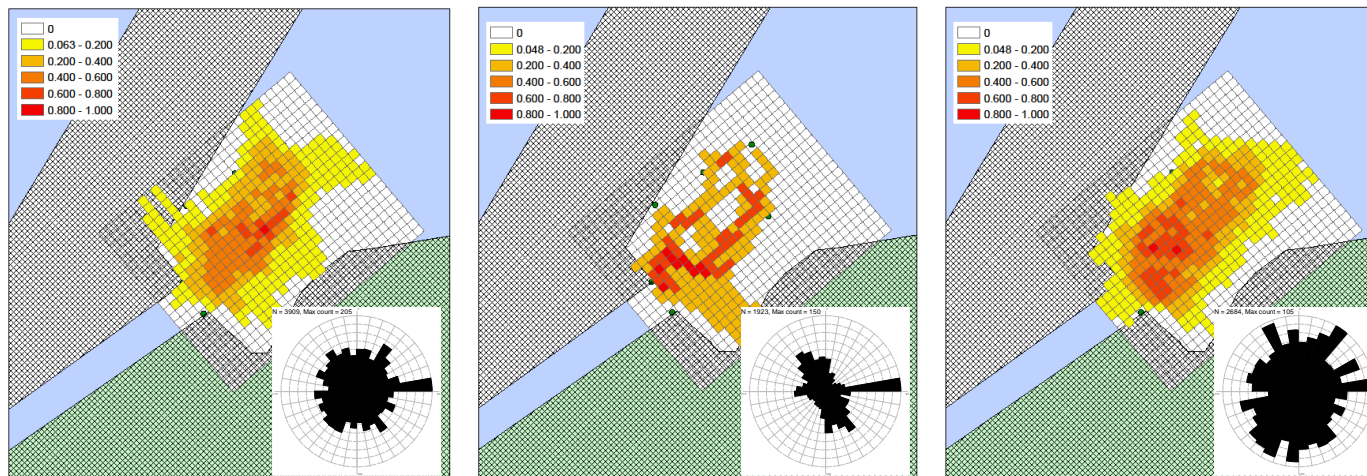


Figure 41. Counts of tracks to pass through each grid cell (standardised by the number of tracks in each group) recorded during an ebbing (left), ebbing/flooding (middle) and a flooding (right) tide.

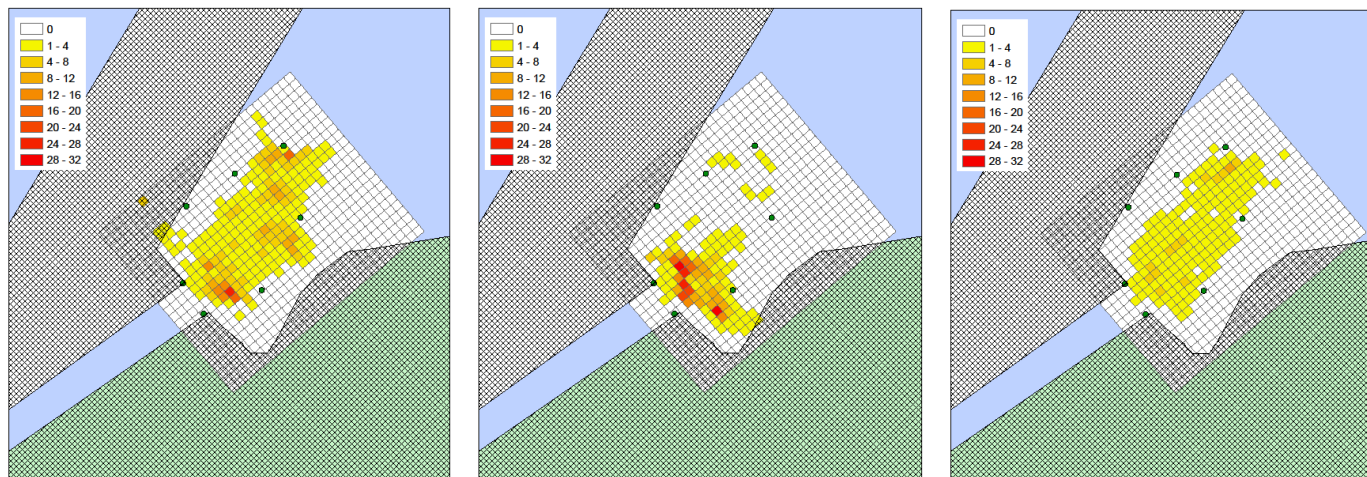


Figure 42. Time spent in each grid cell (standardised by number of fish tracks in each group) in tracks recorded during an ebbing (left), ebbing/flooding (middle) and a flooding (right) tide.

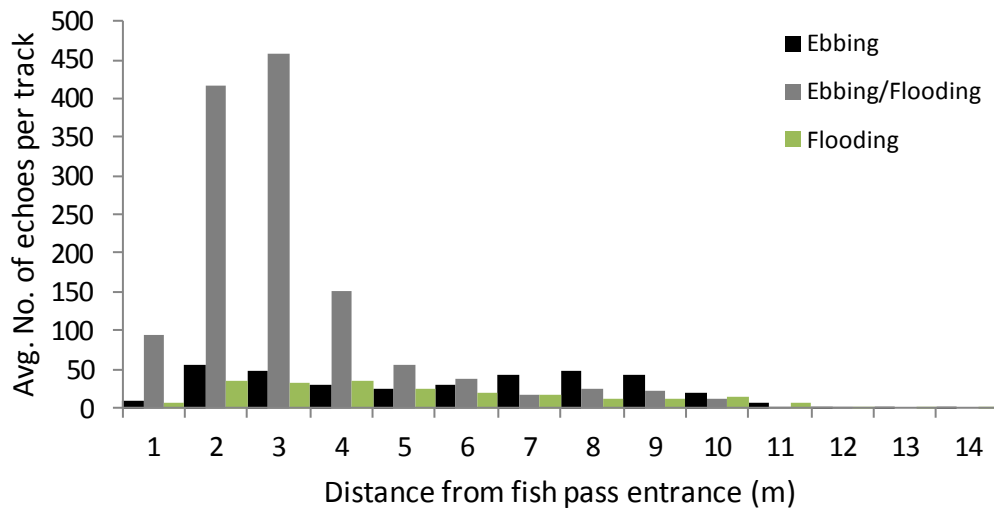


Figure 43. Average number of tag echoes (per fish track) detected in the array in at different tide states, against distance from the entrance to the fish pass.

3.7.5 Array entry

The predominant route for entry into the array between hydrophones 5 and 3, with 17 first tag echoes recorded between these points. Route A (between hydrophones 5 and 6) was the second most used route, with 15 entries observed. One entry was observed by route C and the entry of 7 tracks were indeterminate.

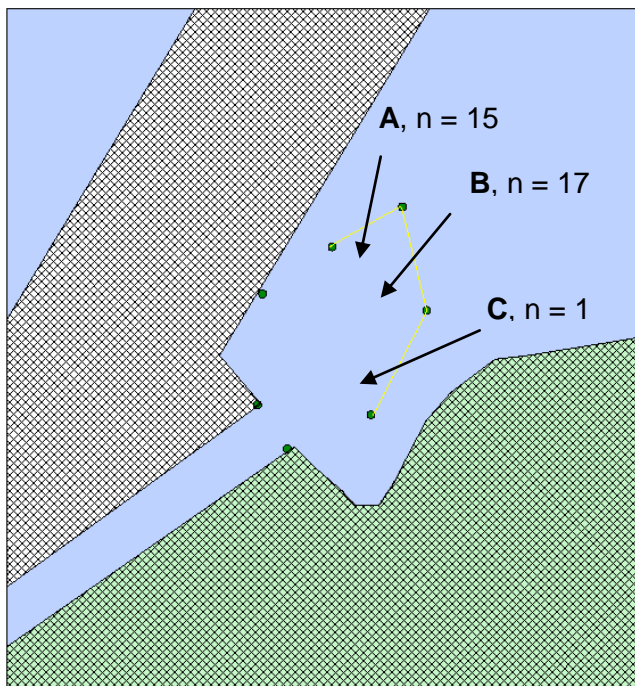


Figure 44. Analysis of all fish tracks that enter the array by routes A, B and C. Note: the entry of 7 tracks could not be determined.

4 Discussion

4.1 Overview study findings

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 was provided. This includes establishing a baseline for fish micro-behaviour around the existing fish passage facilities so that any effects of the hydropower scheme can be determined and where possible mitigation measures proposed to ensure that upstream fish passage is not compromised.

Fifteen of the tagged fish were detected in the array (38%), which is comparable with other studies of returning salmonids (e.g. Bendall & Moore, 2008 = 37%). Tagged fish not detected in the array may have died (including predation, e.g. seals and cormorants), expelled the tag, ascended other local rivers (e.g. Stewart et al., 2009 = 50%), returned to sea for the study period or the tag may have failed (technical fault or battery expiration). It must be noted that the study period was short (11 October 2011 – 12 January 2012) and towards the end of the upstream migration period, that effectively ends around November in most UK rivers (Crisp, 2000). Unfortunately, flow conditions in the River Esk vary dramatically both intra- and inter-annually (Figure 21), inevitably influencing the timing of upstream migration of salmonids. Indeed, as a result of unseasonably low discharges and drought conditions in late 2011 unusually low numbers of fish were reported in the river over the study period (A. Delaney pers. comm.).

Of the fish detected in the array, most (80%) ascended within 48 hours of release and four fish did so within 6 hours, highlighting that upstream migration was not compromised by the tagging procedure. All fish detected in the array successfully ascended the weir, giving 100% passage efficiency over the weir. The majority of fish (75%) ascended the weir via the fish pass, but some fish ascended via the side of the fish pass during elevated river levels (Section 3.5). No fish were observed to ascend the weir via the baulk fish pass, but passages via this route have been recorded in past studies (see Appendix 2). Seven fish entered the array only once before ascending, and all but one fish entered the array less than five times. Nine fish ascended shortly after entry into the array (<10 min) and all but two fish ascended in under 3 hours. Fish movements were more prevalent at times of elevated flow, at night, on spring tides (although fish tagging was focused around spring tides) and on a flooding tide (movements were focussed around the 50th percentile of daily tide height).

River flow is known to be an important influence, and perhaps the dominant extrinsic influence, affecting the willingness of salmonids to move upstream (Huntsman, 1948; Smith et al., 1994; Smith & Smith, 1997). The upstream movements of salmon are well documented and usually precede or follow spate conditions (Lamond, 1916; Huntsman, 1948; Stuart, 1957; Alabaster, 1970; Hellawell et al., 1974). The movements of sea trout are less well documented but they generally move over a wider range of flows than salmon (Baxter, 1961; Le Cren, 1985) and move at lower flows more readily, especially at night (Banks, 1969). Fish in the Yorkshire Esk were also observed to move at periods of elevated flow, although a statistical relationship could not be established due to the overlap of the high flows and time the tagged fish were released.

Little literature exists on the influence of tide on the movements of sea trout during upstream migration but considerable work has been carried out on salmon. Salmon move through estuaries towards the river on flood tides (Stasko, 1975; Brawn, 1982; Potter et al., 1992; Priede et al., 1988), but there appear to be differences between

ivers regarding the predominant range of tidal phase associated with river entry by salmon (Hayes, 1953; Priede et al., 1988). Indeed, salmon enter some rivers at all stages of the tidal cycle (Potter, 1988; Webb, 1989; Potter et al., 1992). During the course of this investigation the majority of fish entered the array and subsequently ascended on a flooding tide, but some fish movements were observed at other tide phases. It seems counter-intuitive that a fish would choose to move on an ebbing tide as this requires greater energy expenditure. Similarly, fish moved on the slack between an ebbing and flooding tide but not between a flooding and ebbing tide. This is also counter-intuitive as water levels would be higher on the latter, facilitating more efficient passage. However, currents in the estuary are unlikely to be strong enough to impede the progress of adult salmonids at any phase of the tidal cycle, although they may influence the rate of progress upstream. The greater seaward current during the ebb tide perhaps provides homing sea trout and salmon with rheotactic or olfactory cues that encourage upstream movement (Smith & Smith, 1997).

When all tracks were overlaid in the current study, most cells within the grid are intersected by at least one track and the area within the array is well covered by multiple tracks. No favoured route or preference for one side of the array was apparent from this grid. The sum of all time intervals in each grid cell revealed that fish spend more of their time at the entrance to the fish pass although time was also spent throughout the pool. In passage and non-passage runs the concentration of high time values was focussed at the entrance of the fish pass with little time spent elsewhere.

Fish from most groups (i.e. passage, non-passage, day, night, ebbing tide and ebbing/flooding tide) were generally found in close proximity to the fish pass (frequency of tag echoes and residence time). The residence time within a 2 m radius and the number of approaches to the fish pass was not statistically different between groups (i.e. passage vs non passage, day vs night and ebbing vs ebbing/flooding vs flooding tides). Therefore data from all tracks can be pooled for future analysis.

One sea trout made 14 approaches to the array and fish pass during the period of study before finally ascending the pass. This fish was the smallest fish tagged and it is possible smaller individuals are less committed and physiologically able to negotiate the flows in the weir, although this could not be confirmed from the present study.

4.2 Potential impacts of the hydropower development on upstream fish migration

The potential hydrological impacts of the hydropower development were previously considered in Kibel & Coe (2009). Specifically, the volume of water in the pass would form approximately 6-10% of the maximum turbine take of 4 cumecs (Mike Ford, pers. comm.), well above the minimum suggested value of 5% (Kibel & Coe, 2009). Interpreting how the hydrological impacts of the hydropower development will affect migratory salmonids in the River Esk catchment is problematic because no definitive hydraulic models linking fish passage to hydraulic conditions in the fish pass exist. Despite this, the hydropower development on Ruswarp Weir will have a number of potential impacts on fish upstream migration behaviour. Channel engineering downstream of the hydropower installation combined with increased discharges at the southern end of the weir may improve access to the fish pass. Despite this, the following list, although not exhaustive, identifies the possible ways fish passage rates at Ruswarp Weir could be compromised:

- Flows from the Archimedes screw may distract fish (fish attraction to the entrance of fish passes is impacted).

- Passage efficiency may change as a result of the installation of the new Larinier fish pass.
- Flow diverted through the Archimedes screw may remove valuable water from fish pass (although distraction should be minimal in this case because of the close proximity of the pass and turbine outfall).
- The route up the side of the fish pass will change / not exist with the new design of the fish pass infrastructure (e.g. installation of the new elver pass).

4.3 Recommendations for future study

4.3.1 Micro scale analysis

The grid approach used in this study allows for behaviours below the fish pass to be quantified, visualised and standardised between fish to enable comparison with future scenarios. Any shift in the spatio-temporal distribution of activity in the future, will be apparent through comparison of similar grids produced post-installation with the baseline grids demonstrated in this study. Changes representative of behavioural shifts are likely to manifest themselves as a concentration of high time values (hotspots) around areas where fish were not previously observed. For example, the flow through the turbine may create an attraction flow that could result in fish orientating themselves towards the turbine outfall, thus modifying their previously observed behaviour. Equally, the flow through the turbine, or any other by-product of turbine operation (e.g. noise), may perturb fish and their distribution within the pool would change, with hotspots appearing further away from the fish pass/turbine. It must, however, be borne in mind that the current study was carried out under abnormally low flow conditions and it is unsure whether the distribution of movements across the grid presented truly represent the situation under more normal autumn flow conditions.

4.3.2 Downstream movements (kelts and smolts)

The importance of the fish pass as a route for downstream migration should not be overlooked. Given the abundance of sea trout in the system, which are known for their multiple spawning migrations (more so than salmon which suffer from very high post-spawning mortality in the river) adequate provision for efficient downstream passage needs to be assured. From previous fish sampling on the Esk and subsequent fish scale age analysis found 30% of sea trout were multi-sea winter fish (A. Delaney pers. comm.). This highlights that a large proportion of the population within the river make repeated ascents/ descents over the weir. Only two downstream movements through the fish pass were observed over the period, possibly because the study duration was short and downstream passage outside of the fish pass could not be determined.

Furthermore, it is likely fish will pass through the turbine on their downstream migration. It is likely that more fish will pass through the turbine than any other route, as the ratio of fish passing through the turbine to fish passing through other by-pass channels (i.e. the adjacent fish pass) is related to the ratio of flow through each route and is not to behavioural selection (Kibel et al., 2009). In an assessment of the impact of an Archimedes screw turbine on the downstream passage of salmonids, Kibel (2007) found no damage to any trout (size range 8 to 63 cm) in over 1000 passages of fish through the turbine, across a range of operating speeds up to a maximum of 31 rpm. Smolts passing naturally through the turbine also suffered minimal damage with light, recoverable scale loss observed in a few individuals. Minimal damage was also found for eels (Kibel & Coe, 2008), coarse fish (Kibel et al., 2009) and lampreys (Lucas & Bracken, 2010). However, the intensity of injury and mortality depends of the design

and operation of the hydropower scheme (Robson et al., 2011) and previous investigations do not account for long-term post-passage mortality. Indeed, it is suggested that the sub-lethal effects of passage through a turbine (e.g. pressure changes, disorientation) could result in long-term, discrete damage to fish or modification of their behaviour so as to limit their life expectancy (e.g. make them vulnerable to predation) (Robson et al., 2011). However, little evidence exists on the behaviour of fish following their descent through Archimedes screws. The use of acoustics tags in the future has the advantage of allowing the observation of fish behaviour after their passage through the turbine providing valuable information of national and international significance. This will, however, require further monitoring of the downstream movement of fish and tagging of the smolt life stage to gain any meaningful data.

4.3.3 Catchment-wide migration

Further to a focused investigation into fish behaviour immediately downstream of Ruswarp Weir, future studies should cover wider spatial and temporal scales. To improve the spatial scale of future studies, a hydrophone should be placed in the fish pass (definitive identification of ascent route) and hydrophones should be placed approximately 1-2 km downstream of Ruswarp weir to help elucidate the fate of fish that do not enter the array and thus establish the general weir approach behaviour outside of the array. The migration of fish upstream of Ruswarp Weir should also be studied, including the influence of other barriers to longitudinal connectivity (e.g. Sleights) and the identification of key spawning tributaries and reaches using mobile hydrophones. This would be particularly important to detect different spawning habitat preferences of the now more prolific sea trout over the once dominant salmon, and test if this may be a contributory factor to the collapse of pearl mussel recruitment in the Esk in recent years (see below). In addition, the influence of catchment processes on spatial variations in habitat quality parameters should be analysed in relation to salmonid recruitment. Electric fishing surveys should be combined with a comprehensive assessment of physical and topographical variables to characterise habitat quality (e.g. water quality, flow conditions, sediment dynamics and interstitial habitat) to evaluate the suitability of each reach in terms of juvenile salmon and trout abundances. Ideally, three years of electric fishing is needed to account for natural variability in salmonid recruitment.

Salmon stocks have declined over the last 30-40 years in the Esk, although sea trout stocks have increased (Figure 1). The potential relationship between the species' population shifts has not been investigated, so the cause(s) for the temporal variations in migratory salmonid stocks remains unknown. To improve the temporal scale of future studies, a comprehensive assessment of migratory salmonid stock dynamics should be performed using where possible adult fish counter and rod catch records, and juvenile distribution and density data (national monitoring survey data; EA National Fish Population Database). The assessment should also include the influence of climate change on salmonid stock dynamics, including the effect of temporal variability in temperature influencing timing of spawning and in rainfall patterns during periods of salmonid migration by examining river discharge patterns (Sleights 1970-1997; Briggswath 2000-2010) and Met Office rainfall data (pre 1970 and gaps) as a surrogate of river discharge. In addition, the impact of temporally variable migratory salmonids stocks on freshwater pearl mussel (*Margaritifera margaritifera*; FPM) population(s) and recruitment dynamics should also be tested; one of the critical stages in the life cycle of FPM larvae (glochidia) infecting the gill filaments of young (particularly ages 0+ and 1+) salmon and trout. A catchment wide assessment would radically advance understanding of migratory salmonid and FPM population dynamics and linkages to chronic and/or acute factors causing the decline in both salmon and FPM, and thus effectively target measures for conservation.

4.4 Future delivery

Once the Archimedes screw turbine has been installed, the behaviour of upstream migrating salmonids will be investigated. A number of systems of work are available to the EA to deliver the aims and objectives of any future work effectively. These range from the EA taking sole responsibility of management and delivery of the project to complete assignment of the project to a contractor. Alternatively, a collaborative partnership option could be pursued to enable key roles and responsibilities to be allocated to the appropriate partner, thus maximising respective contributions to the project. For example, overall project leadership and technical steer can be provided by the EA, while daily project management, technical assistance and operational support can be provided by the contractor. Collaboration also permits the exchange of knowledge and expertise to improve project outputs. Collaboration with an academic institution would enable a dedicated graduate student to support fieldwork, augment scientific rigour and dedicate the necessary time to the extensive data analysis required; a task which may not be possible for EA staff, given time constraints, or be cost effective for a senior consultant. Indeed, data processing was the most time consuming and difficult aspect of this investigation as it required novel and bespoke methodologies across HTI software, Access, Excel (including VBA macros) and arcGIS. Notwithstanding, the project should be ably supported by experienced senior staff who will oversee the work, especially of a more technical nature.

Contractors were employed by the EA to co-ordinate and manage the pre-installation phase (2011), including daily supervision of the HTI Acoustic Tracking System (ATS), collection and analysis of acoustic data files and delivery of this report, i.e. draw conclusions of local and national relevance. It is recommended that this is the minimum level of duties passed to the collaborator during the post-installation phase. Indeed, other responsibilities could be passed to a collaborator including the capture and tagging of fish - provided the staff are trained to electric fish and possess the Home Office licences to perform surgery on fish. Such delegation would enable tagging events to be more reactive to prevailing environmental conditions and overcome the logistical constraints encountered during 2011, i.e. EA staff responsible for tagging having to perform a six-hour commute to Ruswarp Weir. Conversely, a greater contribution from the EA hydrology team is recommended to ensure suitable hydraulic monitoring equipment (i.e. an ADCP) is used effectively and efficiently. Flow velocities within the pool undoubtedly dictate the fidelity of fish to certain areas within the array. The link between hydraulics and residence time need to be better understood to optimise attraction to fish passes in future installations (nationally).

A fundamental requirement of any future work is to ensure the continual and optimised operation of the HTI ATS. One option that could be pursued is the use of remote desktop technology, allowing the array to be monitored and data downloaded from an offsite location. This approach should not completely replace the physical on site monitoring, which is needed to ensure the ATS is secure and hydrophones and cables are clear of debris and safe from damage. It is therefore recommended that the site will be closely supervised during the critical migration periods (certainly the first 3-4 days after tagging) by an individual residing close to the site. At other times, remote monitoring combined with weekly site visits should suffice, provided security concerns (door quality), power supply reliability (installation of UPS and / or back-up generator) and electronic equipment protection (bespoke undercover shelf) at the pumping station are addressed. The site should also be visited after periods of elevated flow to remove debris (identified by daily river level reports) and prior to periods of extreme flow to salvage equipment (identified by river level SMS alerts (provide a 2 hour equipment recovery window)). Notwithstanding this, river levels below the SMS trigger observed during 2011 were deemed too dangerous to permit entry to recover the hydrophone array, thus minimising the likelihood of salvaging the equipment during more extreme

events. Cost savings associated with remote monitoring would permit the tracking period to be extended to maximise the chances of detecting fish movements. For example, a large run of fish may have occurred prior to the 2011 study period (A. Delaney pers. comm.) and therefore it is recommended that tagging should be initiated earlier in 2012. Consequently, the merits of remote monitoring far outweigh the disadvantages associated with an unmanned site. In this context, it should be noted that the array setup in 2011 was very different to that in 2010 when the array was washed out, and the likelihood of wash out is greatly reduced.

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Glossary

ADCP: An Acoustic Doppler Current Profiler (ADCP or ADP) is a sonar that attempts to produce 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 echoes (see tag echoes).

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 echoes: A acoustic pulse emitted from a tag which has been assigned a 2D position by HTI software.

Tag period: The time between tag echoes (tag echoes). 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.

TWI: Total Water Index; Calculated by adding discharge at the gauging weir and tide height to determine the relative quantity of water downstream of the weir.

Appendix 1

Summary of fish tagged in 2011

Date tagged	Species	Sex	Length (cm)	Tag period
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 Fish
1015	St	47.0	20/07/2010 18:00:00	15/08/2010 05:39:41	25.29	Pass
2116	Sa	51.5	27/09/2010 18:00:00	30/09/2010 14:38:07	2.51	Baulk Fish
2179	St	69.0	27/09/2010 18:00:00	29/09/2010 02:17:54	1.20	Pass
			27/09/2010 18:00:00	30/09/2010 09:41:01	2.39	Fish Pass
			28/09/2010 18:00:00	29/09/2010 02:48:18	0.22	Fish Pass
2228	Sa	61.5	28/09/2010 18:00:00	29/09/2010 00:39:30	0.16	Pass
2235	Sa	66.0	28/09/2010 18:00:00	29/09/2010 06:44:21	0.31	Baulk Fish
2242	Sa	66.2	28/09/2010 18:00:00	03/10/2010 00:15:51	4.15	Pass
2284	Sa	74.7	28/09/2010 18:00:00			Baulk

Appendix 3

All recorded tracks during the study grouped by fish (tag number).

2703

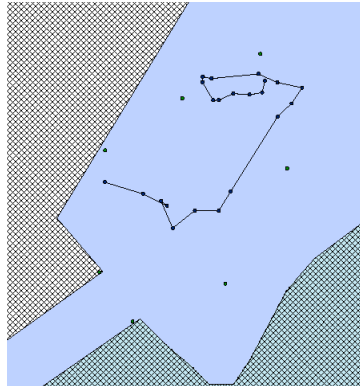


Figure A: 1. Tag 2703 1 of 3 passage.

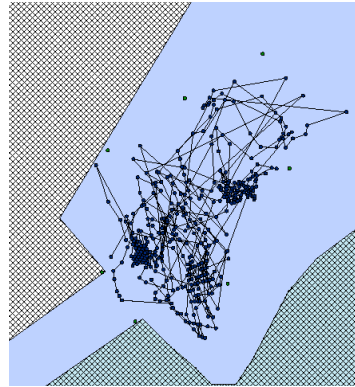


Figure A: 2. Tag 2703 2 of 3 non-passage.

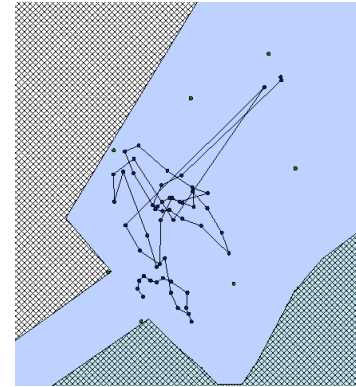


Figure A: 3. Tag 2703 3 of 3 passage.

2514

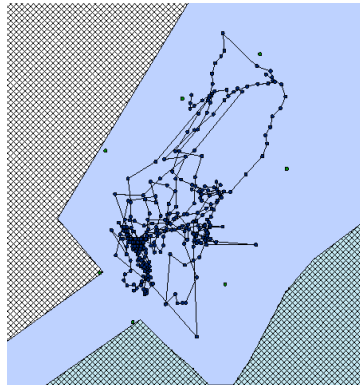


Figure A: 4. Tag 2514 1 of 3 non-passage.

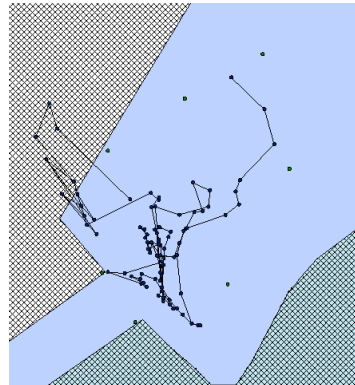


Figure A: 5. Tag 2514 2 of 3 non-passage.

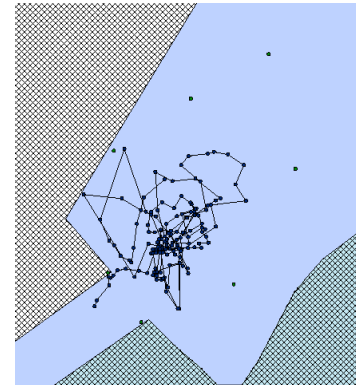


Figure A: 6. Tag 2514 3 of 3 passage.

2549

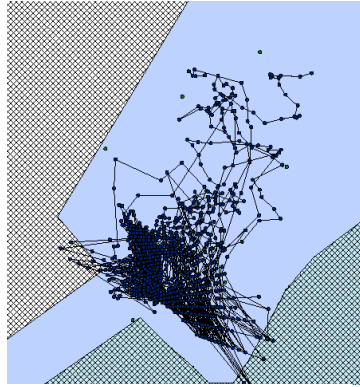


Figure A: 7. Tag 2549 1 of 3 non-passage.

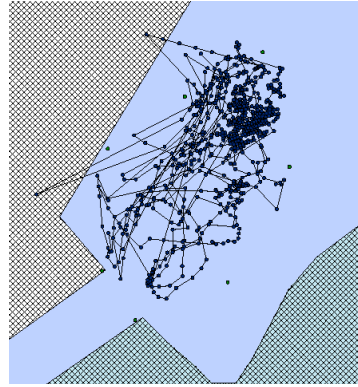


Figure A: 8. Tag 2549 2 of 3 non-passage.

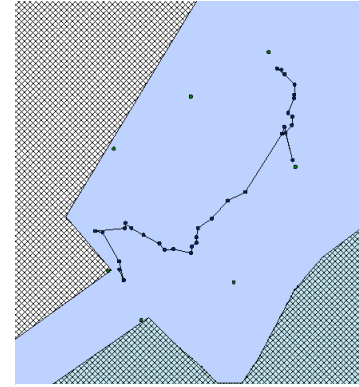


Figure A: 9. Tag 2549 3 of 3 passage.

2633

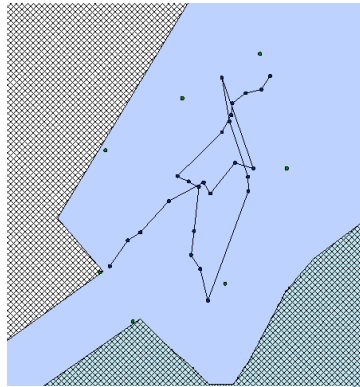


Figure A: 10. Tag 2633 1 of 1 passage.

2591

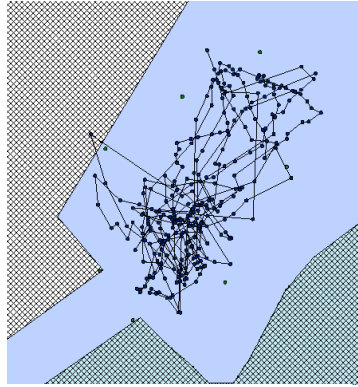


Figure A: 11. Tag 2591 1 of 2 non-passage.

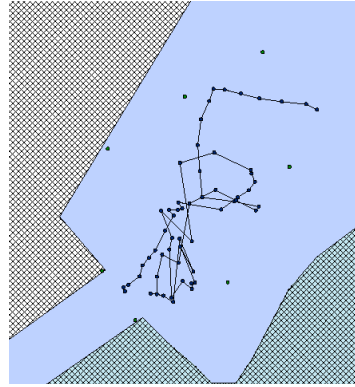


Figure A: 12. Tag 2591 2 of 2 passage.

2710

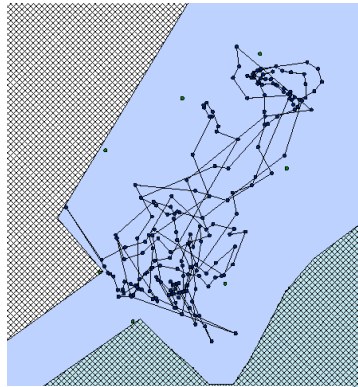
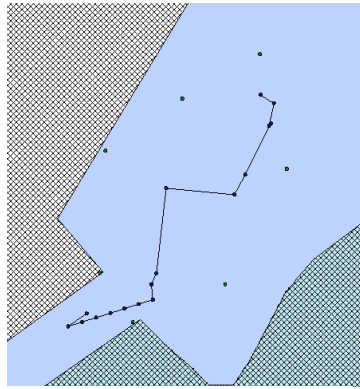


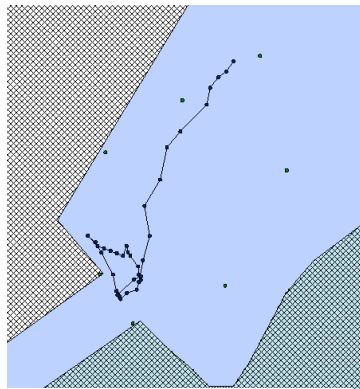
Figure A: 13. Tag 2710 1 of 1 passage.

2577



**Figure A: 14. Tag 2577 1 of 1
passage.**

2661



**Figure A: 15. Tag 2661 1 of 1
passage.**

2647

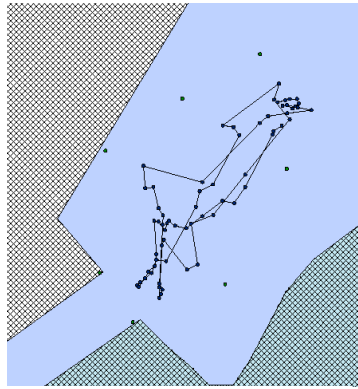


Figure A: 16. Tag 2647 1 of 2 non-passage.

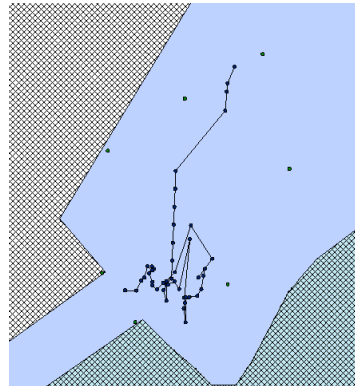


Figure A: 17. Tag 2647 2 of 2 passage.

2773

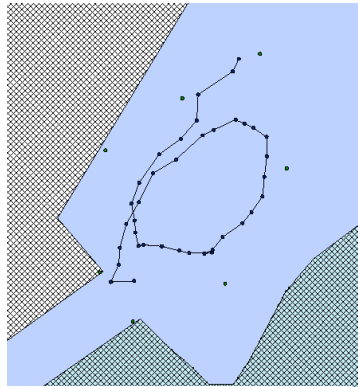


Figure A: 18. Tag 2773 1 of 1 passage.

2745

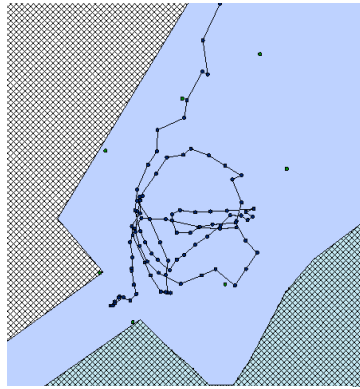


Figure A: 19. Tag 2745 1 of 1 passage.

2794



Figure A: 20. Tag 2794 1 of 4 non-passage.

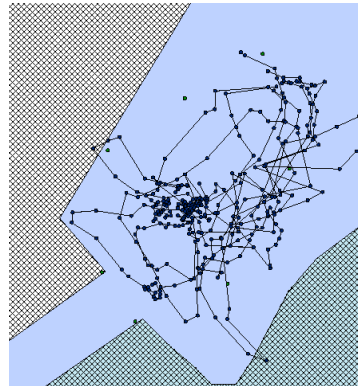


Figure A: 21. Tag 2794 2 of 4 non-passage.

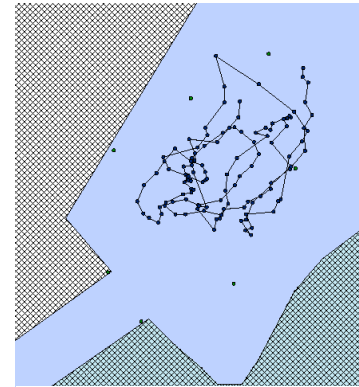


Figure A: 22. Tag 2794 3 of 4 non-passage.

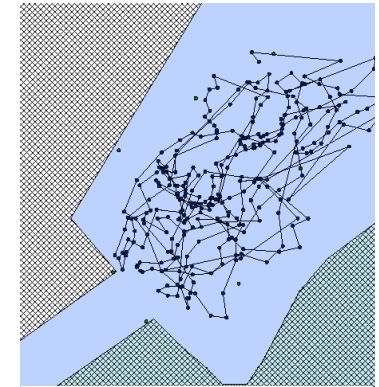


Figure A: 23. Tag 2794 4 of 4 non-passage.

2563

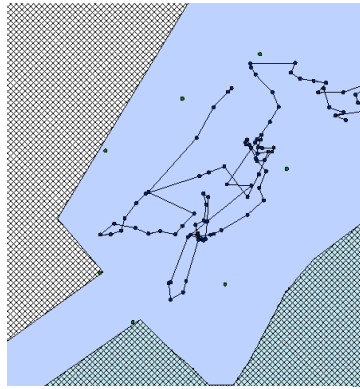


Figure A: 24. Tag 2563 1 of 2 non-passage.

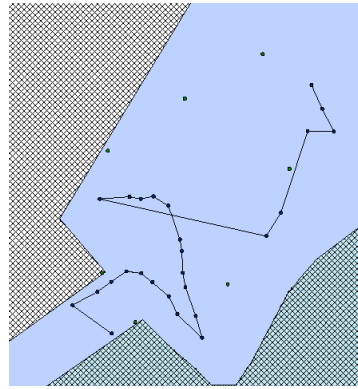


Figure A: 25. Tag 2563 2 of 2 non-passage.

2717

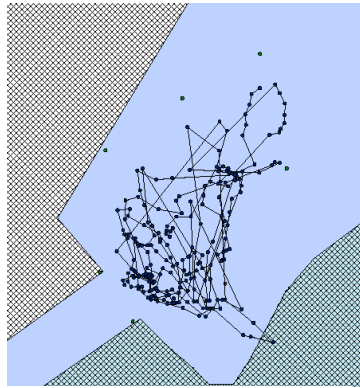


Figure A: 26. Tag 2717 1 of 14 non-passage.

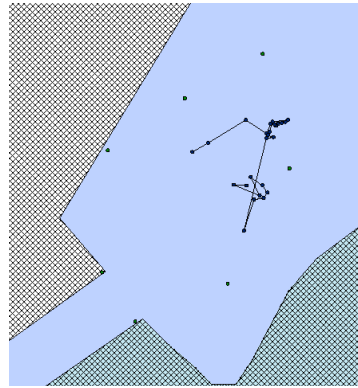


Figure A: 27. Tag 2717 2 of 14 non-passage.

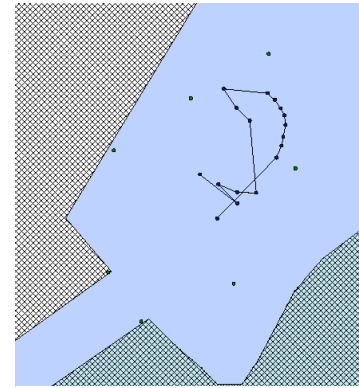


Figure A: 28. Tag 2717 3 of 14 non-passage.

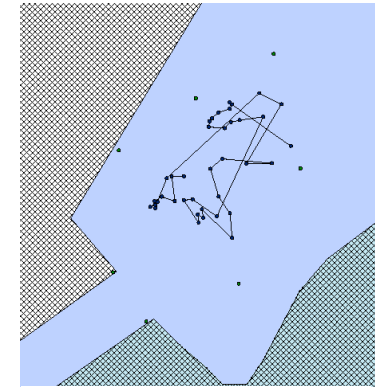


Figure A: 29. Tag 2717 4 of 14 non-passage.

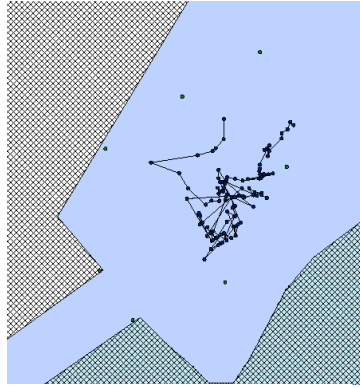


Figure A: 30. Tag 2717 5 of 14 non-passage.

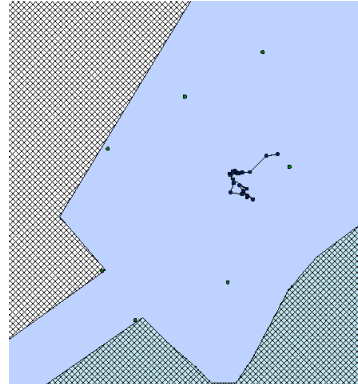


Figure A: 31.Tag 2717 6 of 14 non-passage.

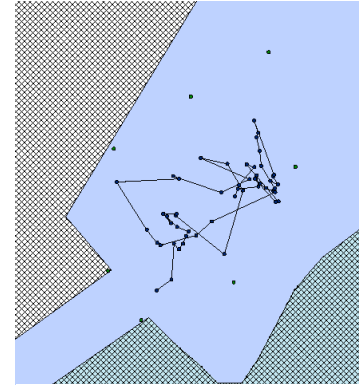


Figure A: 32. Tag 2717 7 of 14 non-passage.

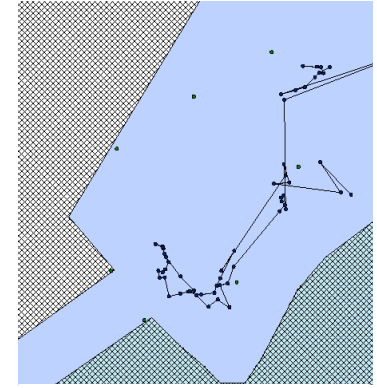


Figure A: 33.Tag 2717 8 of 14 non-passage.

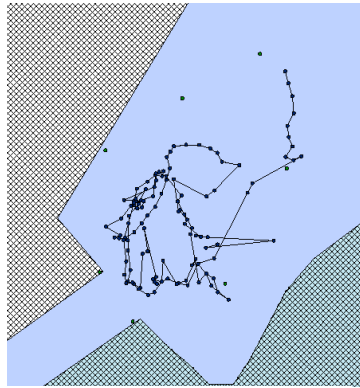


Figure A: 34. Tag 2717 9 of 14 non-passage.

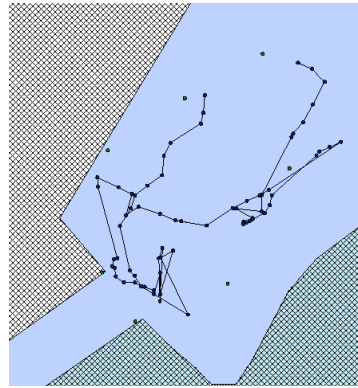


Figure A: 35. Tag 2717 10 of 14 non-passage.

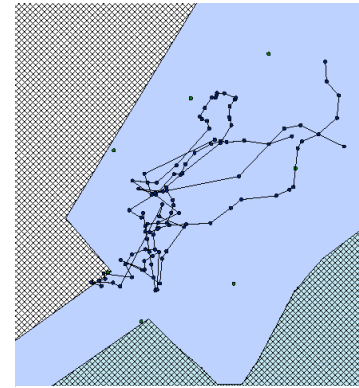


Figure A: 36. Tag 2717 11 of 14 non-passage.

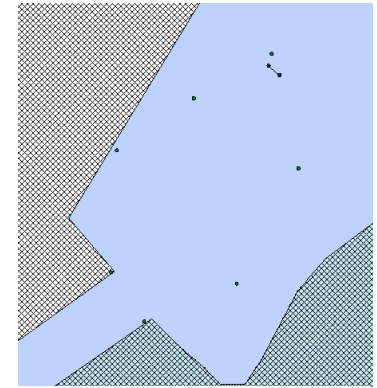


Figure A: 37. Tag 2717 12 of 14 non-passage.

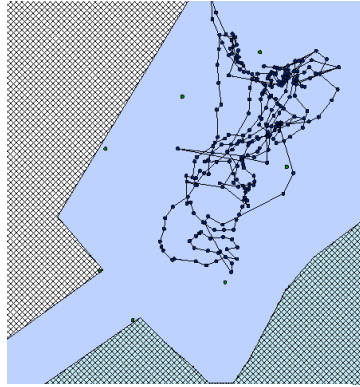


Figure A: 38. Tag 2717 13 of 14 non-passage.

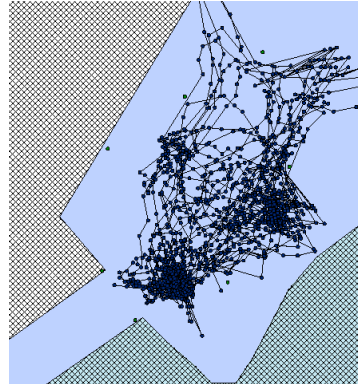


Figure A: 39. Tag 2717 14 of 14 passage.

2640

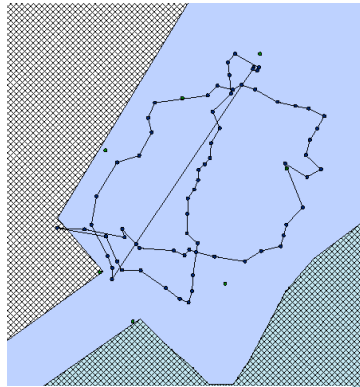


Figure A: 40. Tag 2640 1 of 1 passage

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