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

2012 Extended baseline dataset

R.A.A. Noble, T. Coddington, S.E. Walton, J.D. Bolland and I.G. Cowx

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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 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 is 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 and 20 August – 12 December 2013) using an acoustic tag tracking system.

Over the two years 14 salmon and 48 sea trout were tagged (13 of the salmon were tagged in 2012 following a disproportionate sampling effort to catch them). Twenty-three (17 sea trout and 6 salmon) of the 62 tagged fish were detected (35% of sea trout and 43% of salmon) in the hydrophone array positioned downstream of the fish pass entrance. Three of the tagged salmon passed the weir within one day of release, with one passing within 6 hours. The remainder both passed within three days. Eight of the sea trout passed within one day of release with a further four passing within two days. However, five sea trout took considerably longer (over 14 days) to ascend the weir after tagging. The average time from release to ascent for salmon was 3.37 ± 5.67 days (Mean ± SD) and was 7.87 ± 13.25 for sea trout (compared to 6.3 ± 6.1 in 2011 alone and 4.4 ± 5.2 in 2010). All but one fish (one salmon in 2012) detected in the array successfully ascended the weir. In 2011 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. In 2012 all the detected fish known to have passed their weir moved via the fish pass. No tagged fish were observed to use the baulk route to ascend the weir in 2011 or 2012, compared to 4 out of 9 ascents (44%) in 2010. Despite all fish passing through the fish pass being detected on hydrophone H8, it is unclear whether this was performing adequately under all flow conditions to detect ascents via the baulk pass. Four of the salmon made between 3 and 5 visits to the array before ascending the fish pass, with the other two detected fish making 12 and 23 visits. Eight of the sea trout ascended the weir during the first visit to the array, with another five ascending within five visits. One sea trout in 2011 made 14 visits to the array over a period of five days and in 2012 one sea trout made 40 visits to the array over a period of thirteen days prior to ascent. The majority of sea trout 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. Excluding these two outliers the average time from first detection to ascent by sea trout was 0.51 ± 0.62 hours. The average time from first detection to ascent by salmon was 5.48 ± 7.57 hours.

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. The sum of all time intervals in each grid cell revealed that sea trout 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. Sea trout tracks 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 for sea trout was not statistically

different between groups (i.e. passage vs. non passage, day vs. night and ebbing vs. ebbing/flooding vs. flooding tides), and sea trout tracks can be pooled in future analyses (giving 87.3 ± 43.0 seconds per fish track, and 7.8 ± 5.6 per fish track respectively). When all tracks from salmon (2011 and 2012) 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 low numbers of salmon (and hence salmon tracks) available limited the analysis and interpretation of these data. However, the proximity analysis of echo locations during different phases of the tide did indicate potential bimodality in distribution and also differences in relation to high and low water slack conditions. It is unclear whether this pattern is accurate or an artefact of the low number of salmon available to study.

Recommendations for future study, and analysis of the post-implementation data against the baseline, include the continuation and development of the grid based micro-scale behaviour analysis, 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. Given the low numbers of salmon available to this study, and the disproportionately high effort required to get a statistically valid sample size, it is recommended that sea trout should be the focus of the assessment and that data for salmon are used as a supplement to the main study to provide an insight into fish behaviour around the turbine and fish pass.

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All tagging was undertaken under Home Office Licence.

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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 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 would draw up to 4 m^3s^{-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 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 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 fish passage facility to help address one of the “evidence gaps” in knowledge about migratory behaviour of adult upstream migrating salmonids. The work will used to help formulate and underpin guidance documents such as the Hydropower Good Practice Guidelines (GPG).

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

1.3 Objectives

The objective of this report is to 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.

This report presents the extended baseline dataset for sea trout and provides an analysis of the limited salmon tracking combining data collected in 2012 and 2013. The report extends and refines the material presented in Walton (2012).

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 (*Salmo 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.

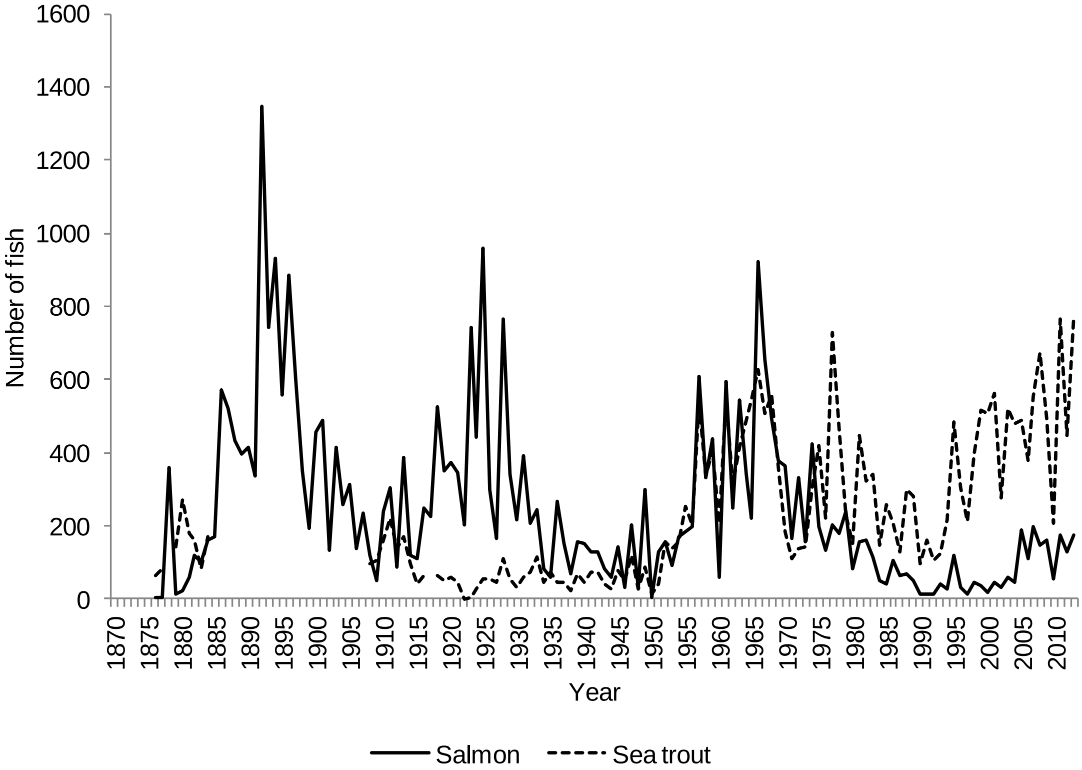


Figure 1. Trends in sea trout and salmon catches in the River Esk, North Yorkshire. Data for 2012 are provisional and the sea trout catches are included in the total for salmon for the period 1885-1902 (I Dolben pers. comm.).

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 (2012 Figure 3 and 2011 Figure 4). The configuration of the array was changed in 2012 to reposition one of the hydrophones (H1) within a pool above the baffles in the new Larinier fish pass to confirm fish movement through the pass.

The catchment generally consists of sparsely populated, open moorland with little pressure from industrial or urban development (Figure 7b). 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 7c).

The original pool-traverse fish pass was replaced with a Larinier baffle pass during summer 2012 at the same time as the hydropower turbine was installed and commissioned. Therefore, the 2012 data collected reflected both conditions for a new design of fish pass and the potential effects of construction. Additionally, an elver pass was installed alongside the fish pass, although this was eventually removed later in the year (end of November/early December 2012) (see Appendix 2 for time line).

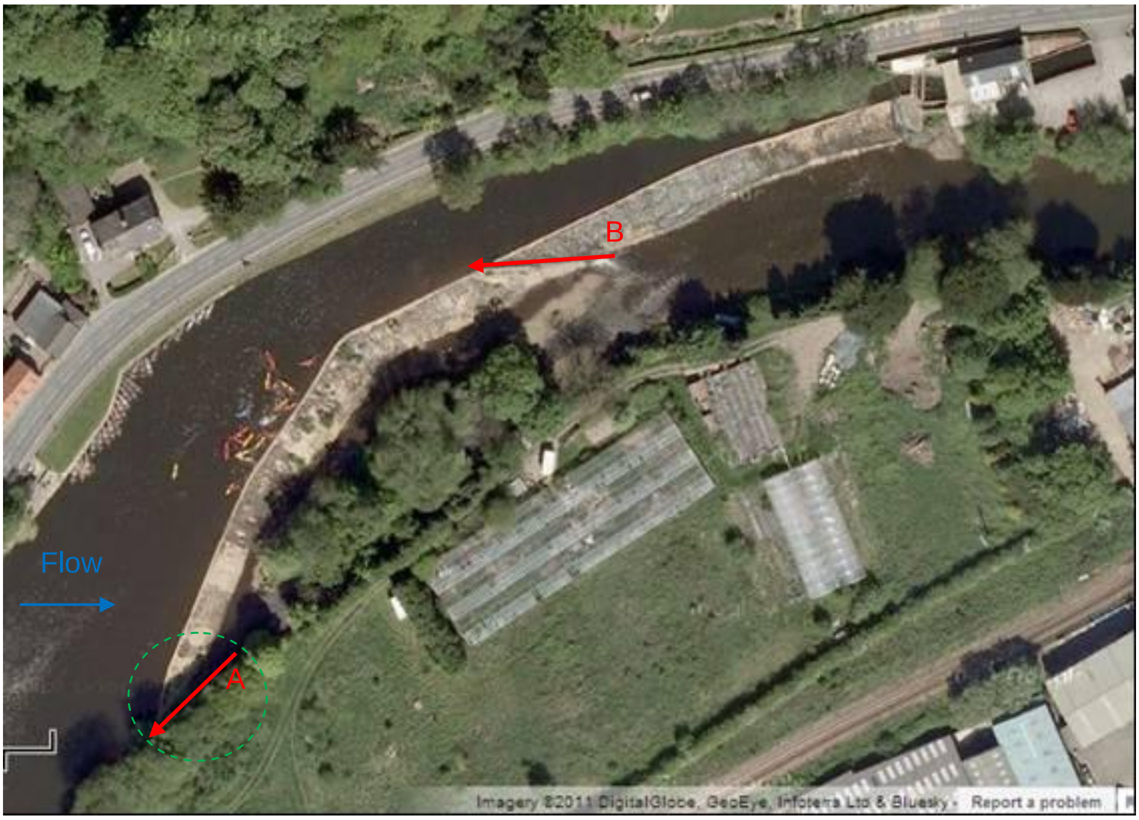


Figure 2. Aerial photograph showing the location of the fish passes (A – pool traverse pass (2011) / Larinier pass (2012); B – baulk pass) in relation to the weir (kayakers upstream of the weir give an indication of scale). The green circle marks the location of the new hydroelectric turbine and the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

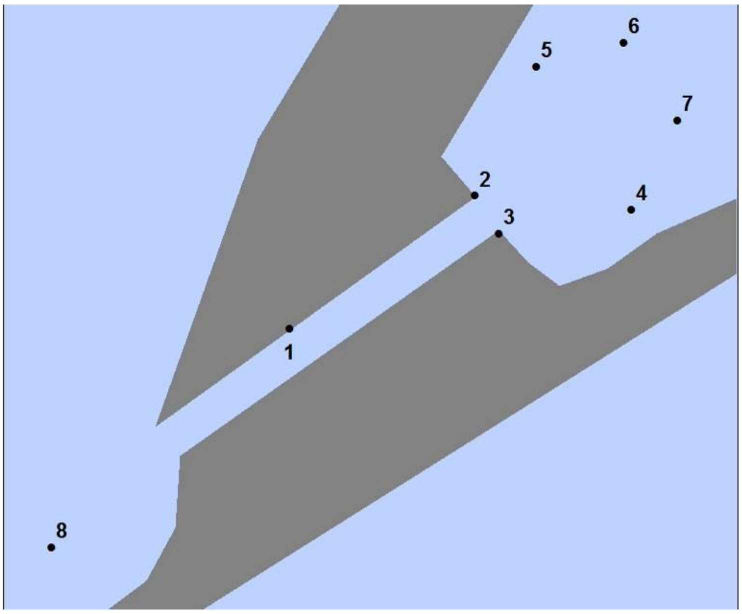


Figure 3. Diagram of the study site showing the positions of all 8 hydrophones used in the array for 2012 (Section 2.3).

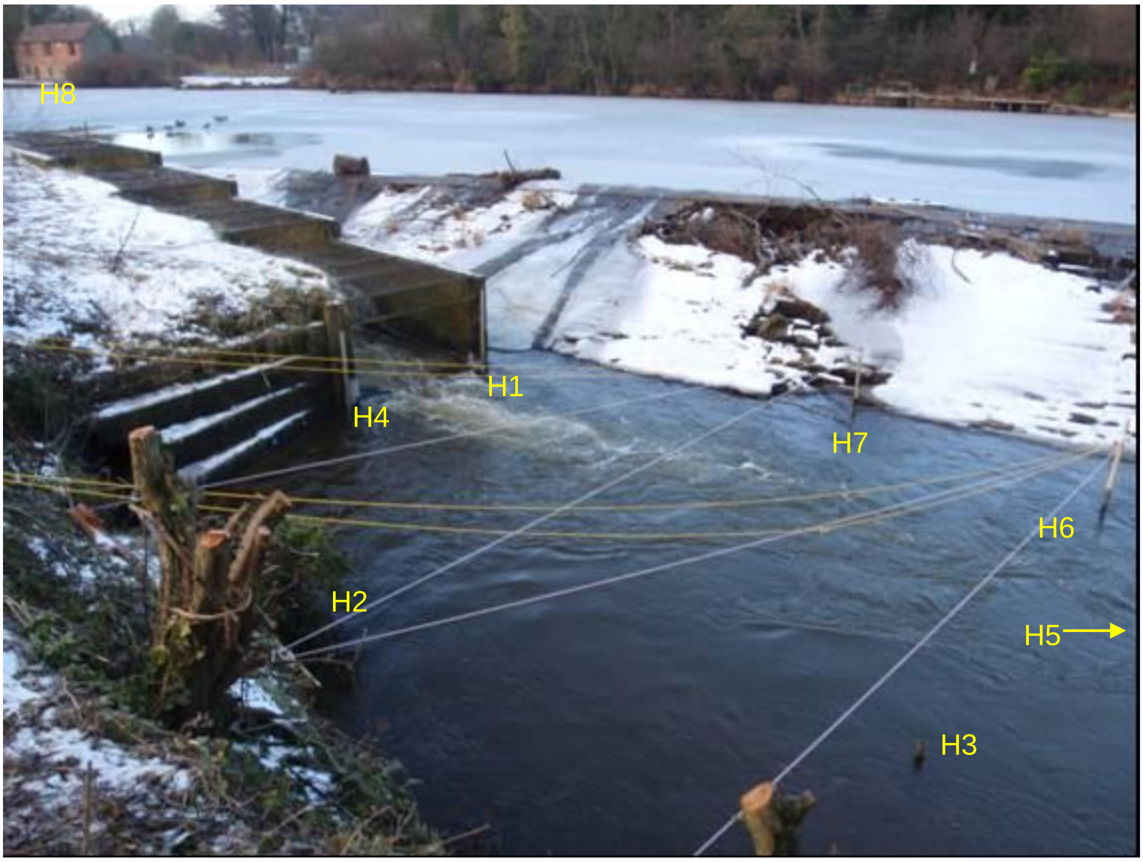


Figure 4. View of the old pool-traverse fish pass entrance and hydrophones array showing the approximate positions of all 8 hydrophones in 2011.

Figure 5. View of the new Larinier fish pass entrance, outfall of the new turbine and hydrophones array in 2012.

Figure 6. View of the outfall of the new turbine and hydrophones array in 2012.

2.2 Tagging

Fish were captured downstream of Ruswarp Weir on 11, 12, 24 and 25 October 2011 and 20/21 August, 18/19 September and 27/28 September 2012 (Appendix 1) using pulsed DC (50 Hz) electric fishing equipment from a boat (Electracatch control box, 6 V single anode with Honda 7.5 kVA generator or EasyFisher control box with fully adjustable settings). Prior to tagging in the field, fish were anaesthetised using MS222 (40 mg L^{-1}). Species, sex and fork length (nearest mm) were recorded.

Fish were placed ventral side up in a clean V-shaped foam support. Tags were activated (pulse rate ranged from 2514-2794 ms in 2011 and 2500-2654 ms in 2012), 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 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. In 2011 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.

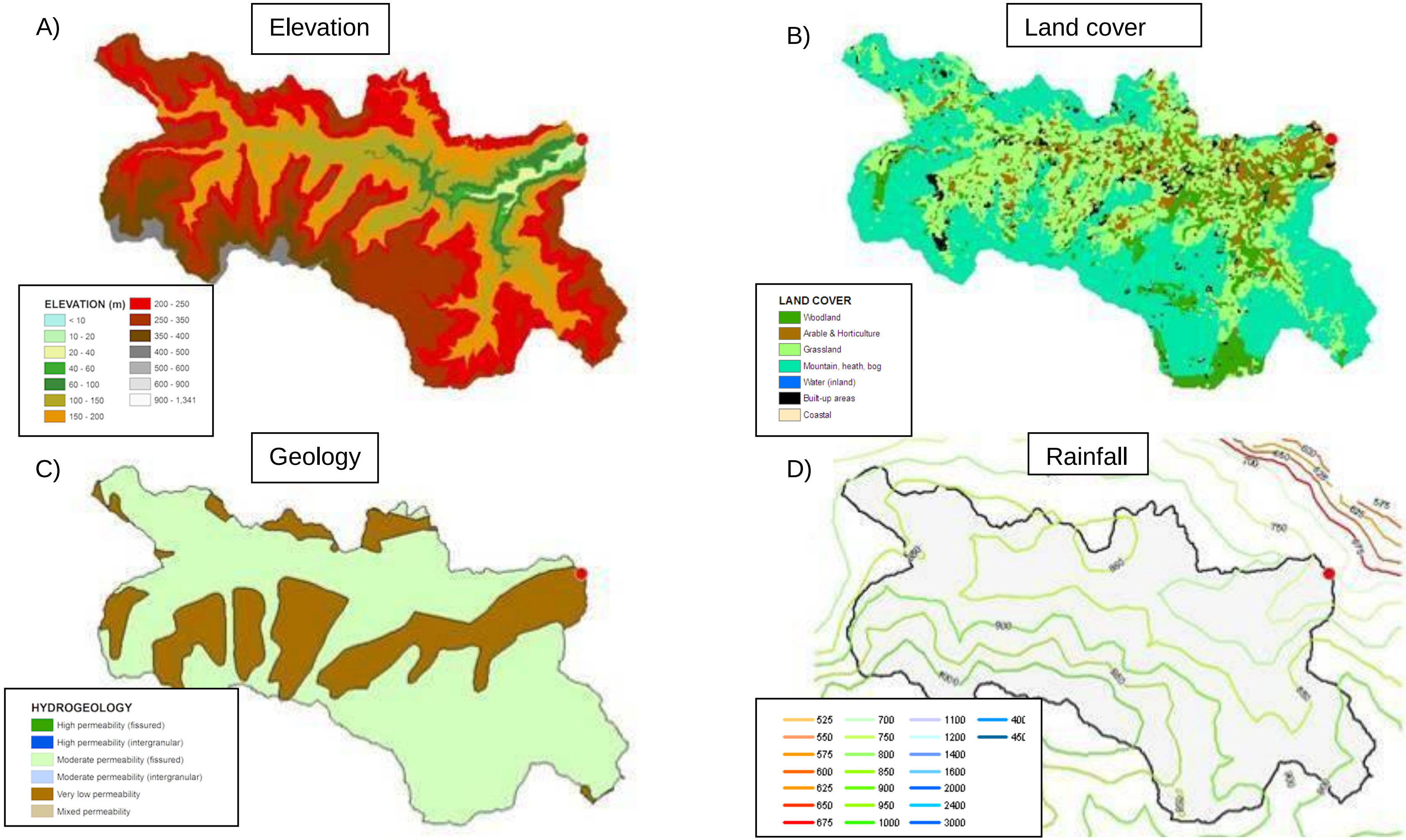


Figure 7. Plan form maps of catchment characteristics (elevation, land cover, geology and rainfall (mm)) for the Esk catchment (http://data.ecn.ac.uk/sites/ecnsites.asp?site=R02).

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 and 20 August 2012 - 12 December 2012. In 2012 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). Construction work during 2012 also meant that the hydrophone array was positioned differently than in 2011 meaning that it had a slightly different footprint in each year. 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 2012 H1 was also 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 Acoustic Tag software (Hydroacoustic Technology Inc, Seattle, USA) and stored on a portable laptop computer. In 2012 two mobile data loggers were also installed downstream of Ruswarp to attempt to ascertain behaviour of fish that were not detected on the weir. Unfortunately, neither of these was functional due to developmental issues that could not be addressed by the manufacturer. Throughout the study, the effectiveness of the array and H1/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 frequently to inspect for damage (extreme spates and the construction work posed a constant threat to the array) and remove debris (minimal). In 2011 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. In 2012 the array had a number of short periods where it was not operating due to power outages but again this was not considered critical.

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.

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 enters the array and terminate when the array is exited via an upstream route (Figure 8 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 8 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.

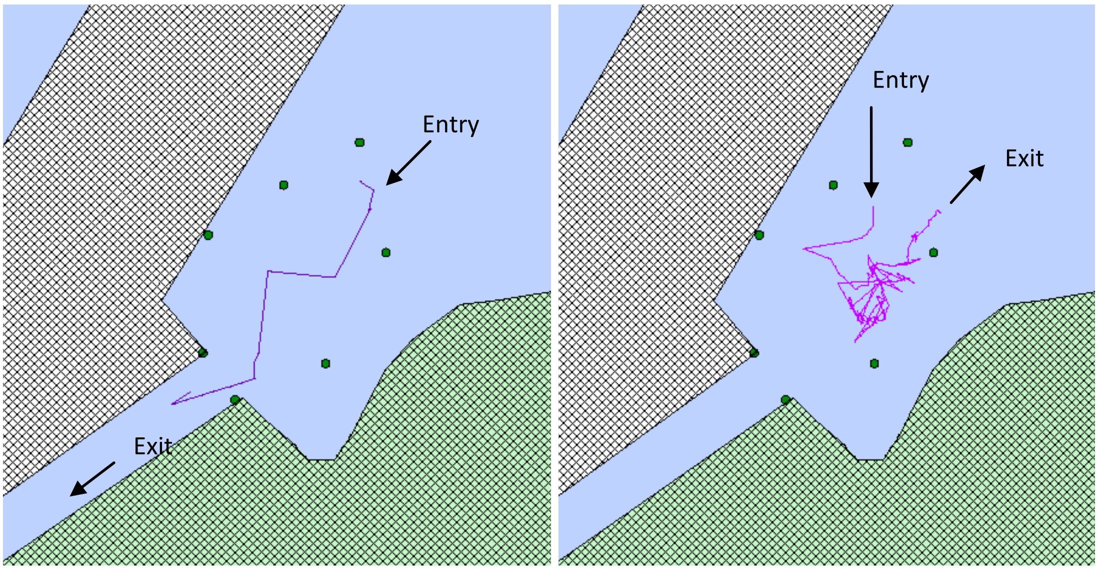


Figure 8. Examples of a passage track (left) and a non-passage track (right) in the array (yellow polygon).

In 2011 passage routes were divided into “fish pass” and “side of fish pass” routes (Figure 9 and Figure 10) 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^3s^{-1} = fish pass, >3 m^3s^{-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". In 2012 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.

Figure 9. Old fish pass and side of fish pass ascent routes in low flows (1.47m^3s^{-1}) looking downstream. Arrows represent direction of fish passage (photo taken 31/10/2011 17:42).

Figure 10. 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).

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 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 IBM SPSS Statistics (version 19.0) 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 10). Point location data were connected in chronological order using ArcMAP tracking tools to produce a continuous fish track made up of individual polyline "steps" (Figure 11). 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}). 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; and
- ebbing tide versus ebbing/flooding tide versus flooding tide

Figure 11. 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 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 12 (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.

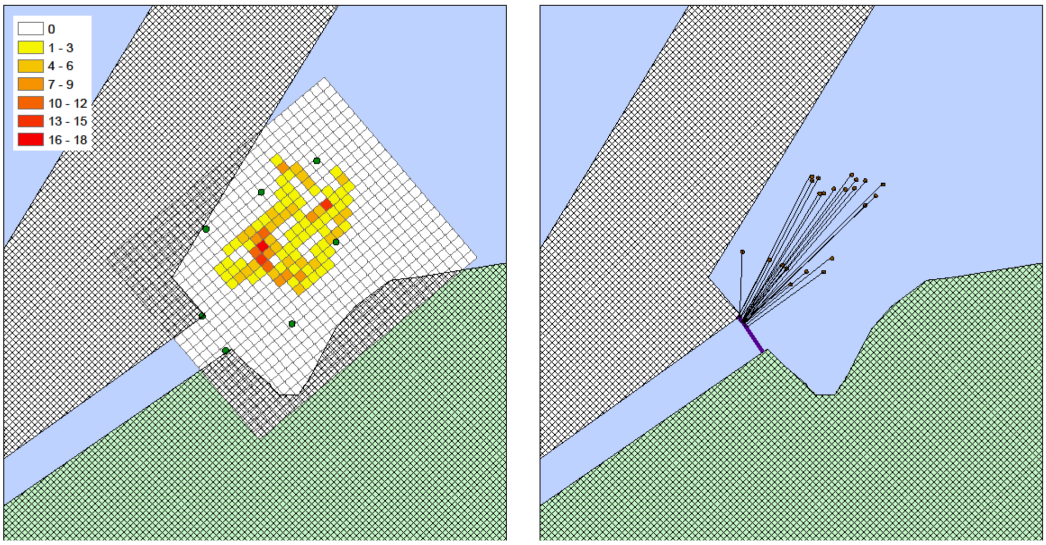


Figure 12. Example residence time (sec) grid, with cells colour coded from white to red with increasing time (left) and a diagrammatic example of proximity analysis (right).

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 12 (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 13) 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.

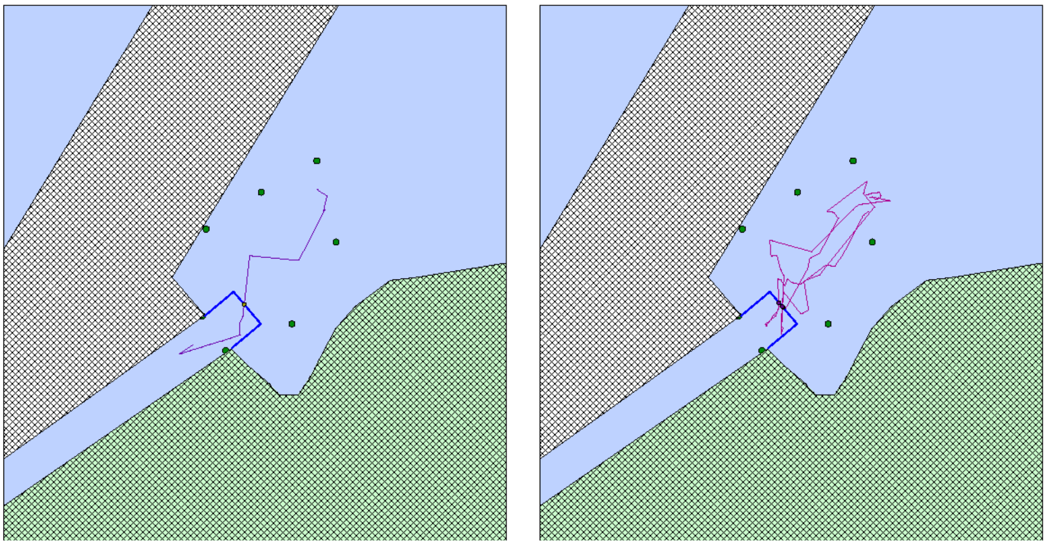


Figure 13. Example of the intersection of a passage (left; *nI* = 1, *nA* = 1) and non-passage track (right; *nI* = 4, *nA* = 2) with the 2 metre fish pass buffer.

2.6.5 Array entry

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). This was determined by entry points between hydrophones. Although specific hydrophone positions were different between 2011 and 2012 the classes of entry point were consistent. Entry was classified as (A) from a position towards the left hand bank (between H6 and H5 in 2011 and 2012), (B) from downstream (between H5 and H3 in 2011 and between H6 and H7 in 2012) and (C) from a position towards the right hand bank (between H3 and H2 in 2011 and between H7 and H4 in 2012. In cases where it was not possible to determine the point of entry accurately, tracks were classified as "indeterminate".

2.7 Environmental data

Flow ($m^3 s^{-1}$) 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 and 31st August 2012 to 30th November 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). Temperature data were not logged from 30th November 2012 to the removal of the array in that year as the logger had become displaced by the extreme flows during this period. 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 lows flows (mean daily discharge = 1.36 $m^3 s^{-1}$) using a Teledyne™ RDI StreamPro Acoustic Doppler Current Profiler (ADCP) along five transects (Figure 14 and Figure 15). 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 14) 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 still) = 0.0308, and range = 3.582), fitted using the Geostatistical Analyst within ArcGIS™.

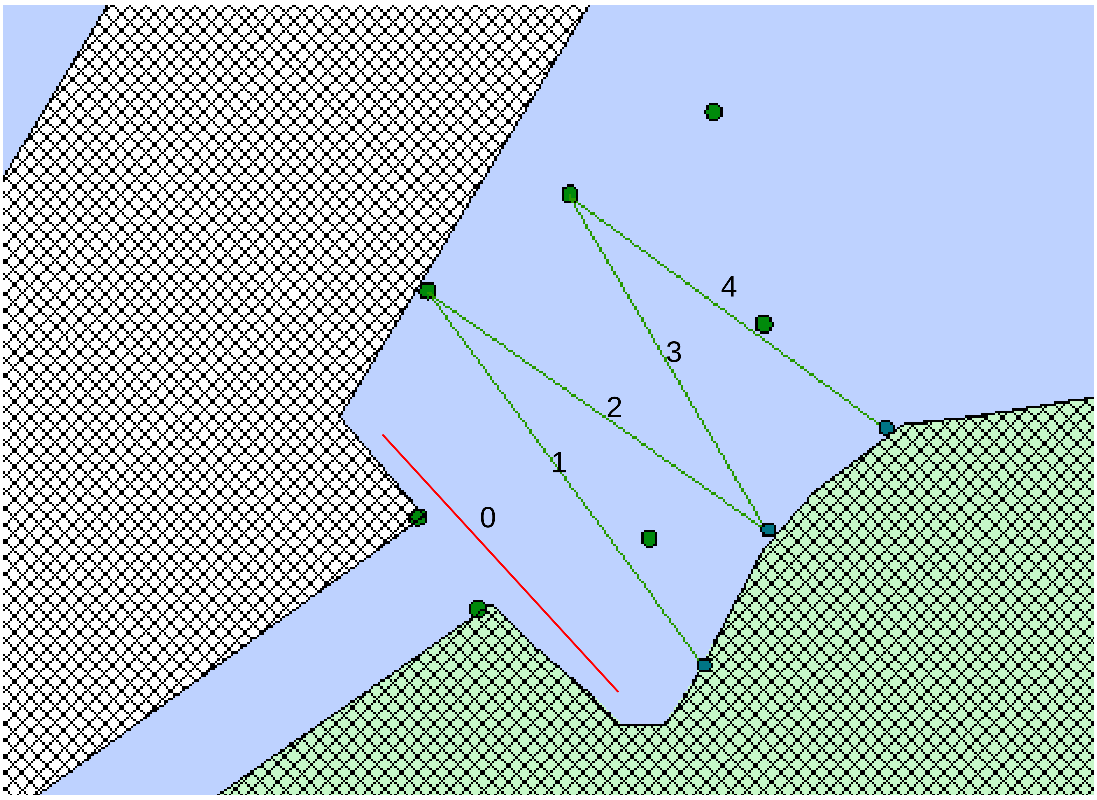


Figure 14. Flow velocity profiling transect locations (0-4).

Figure 15. ADCP in operation on transect 4 within the array.

3 Results

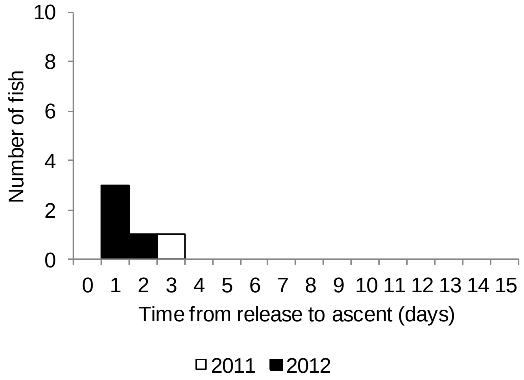
3.1 Visits to the array

Over both years comprising the pre-implementation study 14 salmon and 48 sea trout were tagged for tracking (Table 2). Of these 13 of the salmon were tagged in 2012 following a disproportionally high sampling effort to obtain them (during the same surveys around 100 sea trout were captured). Of the tagged fish 6 salmon (43%) and 17 sea trout (35%) were detected within the hydrophone array. Five of the salmon and all of the sea trout were observed to pass the weir. Of these two sea trout were also observed to descend via the fish pass some time after their initial upstream migration. Additionally in 2012 two salmon were observed to pass the weir for a second time a considerable period after their initial passage (around 3 weeks).

Table 2. Summary of the numbers of fish tagged, detected and their movement characteristics at Ruswarp weir in 2011 and 2012.

Species	Salmon			Sea Trout		
Year	2011	2012	Total	2011	2012	Total
n tagged	1	13	14	38	10	48
n detected	1	5	6	14	3	17
Tracks						
Non-passage	2	41	43	23	45	68
Passage	1	4	5	14	3	17
DS Passage			0	1	1	2
Second Ascent		2	2	1		1
Total Tracks	3	47	50	39	49	88

Three of the tagged salmon passed the weir within one day of release, with one passing within 6 hours (Tables 3 & 4). The remainder both passed within three days (Figure 16). Eight of the sea trout passed within one day of release with a further four passing within two days. However, five sea trout took considerably longer (over 14 days) to ascend the weir after tagging. The average time from release to ascent for salmon was 3.37 ± 5.67 days (Mean ± SD) and was 7.87 ± 13.25 for sea trout (compared to 6.3 ± 6.1 in 2011 alone and 4.4 ± 5.2 in 2010) (Figure 16).



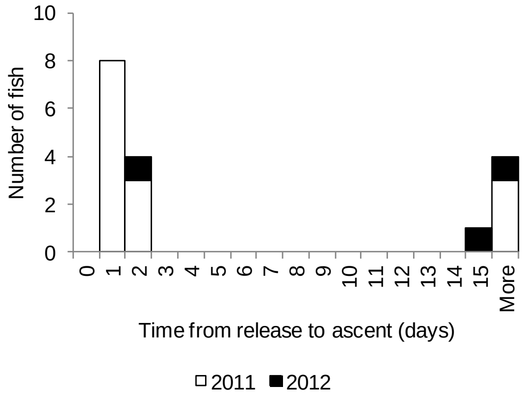


Figure 16. Number of days between release and passage for (a) salmon and (b) sea trout in 2011 and 2012. 1 = within one day of release.

Table 3. 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 ascent [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 Ascent		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 Ascent		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, ascents, descents, non-passage tracks after descent and second ascents

Table 4. 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 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 (2nd ascent)	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

Four of the salmon made between 3 and 5 visits to the array before ascending the fish pass, with the other three detected fish making 8, 12 and 23 visits (some of which included reappearance in the array after initial passage) (Figure 17). Eight of the sea trout ascended the weir during the first visit to the array, with another five ascending within five visits. One sea trout in 2011 made 14 visits to the array over a period of five days and in 2012 one sea trout made 40 visits to the array over a period of thirteen days prior to ascent. In all of the 23 fish tracked across the two years only four fish exhibited more than four tracks in the array prior to first passage (or not passing) through the fish pass.

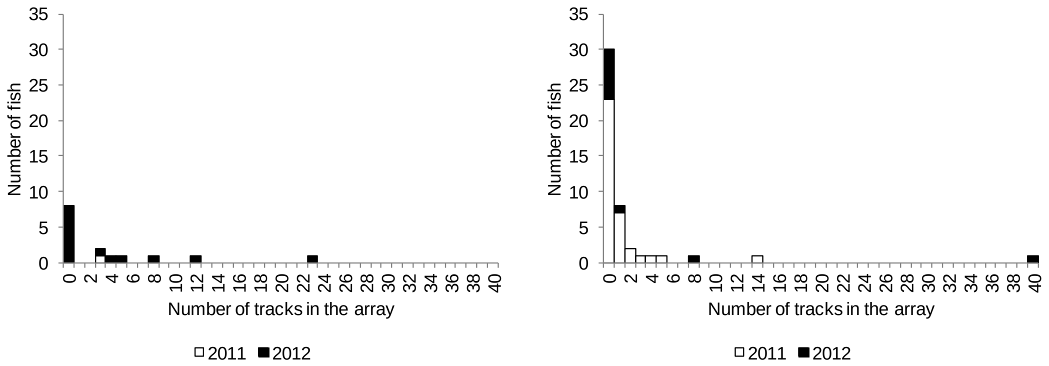


Figure 17. Frequency distribution showing the number of times the hydrophone array was entered by (a) salmon and (b) sea trout in 2011 and 2012. 0 = no entry.

The average total time spent in the array by salmon prior to passage was 38.46 ± 64.58 minutes, and sea trout spent an average of 39.87 ± 80.80 minutes within the array (Figure 18). The greater variance and standard deviation for sea trout reflect the few fish that spent a disproportionally long time within the array over a large number of visits. Most sea trout spent less than five minutes in total within the array prior to passage whereas all of the salmon spent over five minutes within the array before passing the weir.

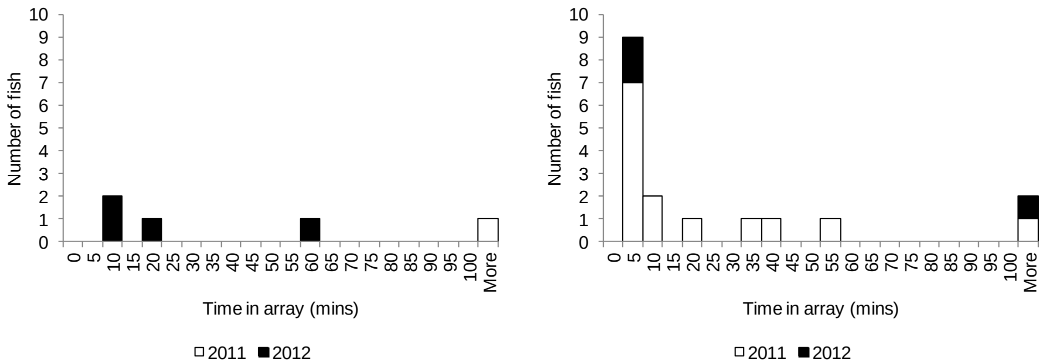


Figure 18 Total time spent in the array prior to passage (sum of all tracks) for (a) salmon and (b) sea trout in 2011 and 2012.

The majority of sea trout 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. Excluding these two outliers the average time from first detection to ascent by sea trout was 0.51 ± 0.62 hours. The average time from first detection to ascent by salmon was 5.48 ± 7.57 hours (Figure 19).

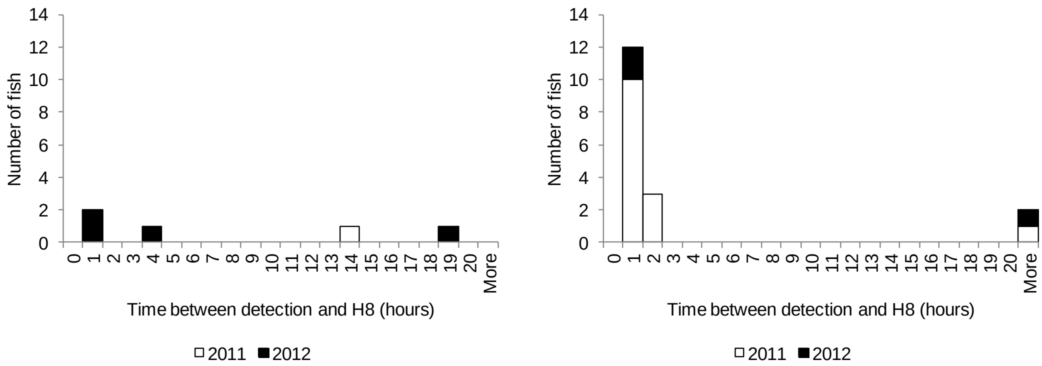


Figure 19. Total time between first arrival in the array and passage (time on H8) for (a) salmon and (b) sea trout in 2011 and 2012.

Overall seven passage tracks and 43 non-passage tracks were recorded for salmon. The average time in the array during non-passage tracks was 9.16 ± 18.61 minutes and 4.79 ± 4.22 minutes in passage tracks (Figure 20). The average time in the array on the passage tracks of the two salmon detected ascending the weir for the second time in 2012 was 0.36 ± 0.25 minutes. The difference in times between passage and non-passage runs for salmon was not significant (Mann Whitney U-test: Z = -0.881, n = 50, P >0.05).

Overall 17 passage tracks and 67 non-passage tracks were recorded for sea trout. The average time in the array during non-passage tracks was 8.05 ± 9.96 minutes and 11.26 ± 20.79 minutes in passage tracks (Figure 21). The time in the array on the passage track of the one sea trout detected ascending the weir for the second time in 2012 was 3.52 minutes. The difference in times between passage and non-passage runs for sea trout was not significant (Mann Whitney U-test: Z = -0.597, n = 85, P >0.05).

3.2 Ascent route

Of the 15 sea trout ascents over the weir in 2011, 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). All tagged fish that were detected to pass the weir in 2012 did so via the fish pass (detected on H1). No fish were observed to use the baulk fish pass (detected only on H8).

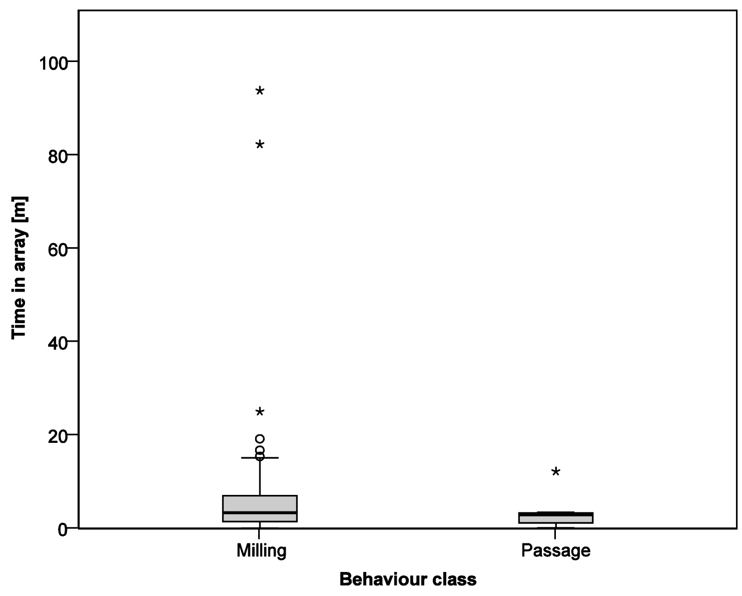


Figure 20. Duration of individual array visits in passage (n = 7) and non passage (n = 43) runs for salmon in 2011 and 2012 (data combined).

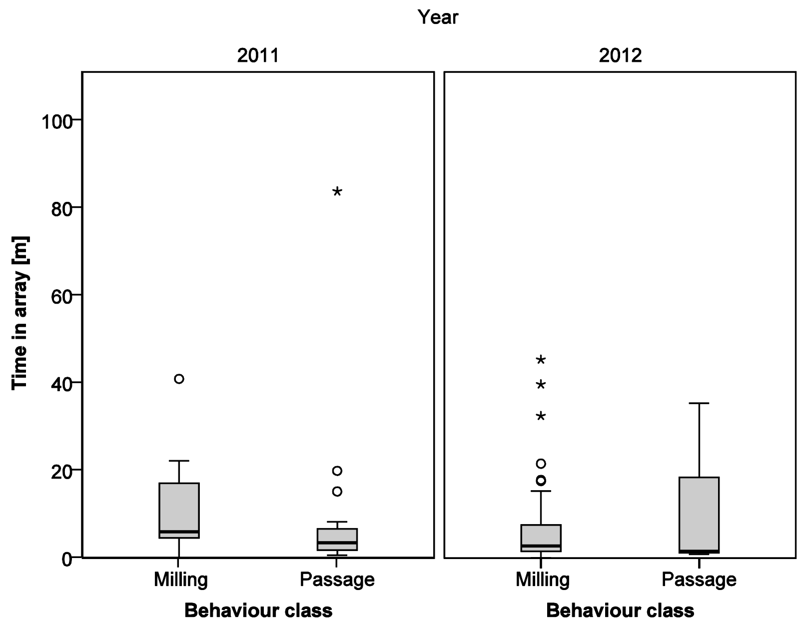


Figure 21. Duration of individual array visits in passage (n = 15 [2011] and 3 [2012]) and non passage (n = 23 [2011] and 45 [2012]) runs for sea trout in 2011 and 2012.

3.3 Diel variations in fish movements

Salmon entered the array 32 times during the day and 18 times at night. Although bordering on significance (P = 0.06) there was no significant difference (Mann Whitney U-test: Z = 1.872, n = 43, P >0.05) between the time spent in the array in non passage tracks during the day (mean 4.38 ± 4.74 minutes) and night (mean 17.22 ± 28.65 minutes) (Figure 22). Two salmon ascended the weir for the first time during the day and three ascended during the night (both second ascents occurred during the day). Although the difference was not significant (Mann Whitney U-test: Z = 0.577, n = 5, P >0.05) the average ascent time during the day (1.54 ± 1.51 minutes) was less than that at night (6.16 ± 5.28 minutes) (Figure 24).

Sea trout entered the array 59 times during the day and 26 times at night. There was no significant difference (Mann Whitney U-test: Z = 1.677, n = 67, P >0.05) between the time spent in the array in non passage tracks during the day (mean 7.60 ± 10.56 minutes) and night (mean 9.62 ± 7.64 minutes) (Figure 23). Six sea trout ascended the weir for the first time during the day and 11 ascended during the night (the one second ascent occurred during the day). Although the difference was not significant (Mann Whitney U-test: Z = -1.608, n = 5, P >0.05) the average ascent time during the day (21.52 ± 30.21 minutes) was greater than that at night (4.03 ± 4.31 minutes) (Figure 25). The greater average time during the day reflects a few sea trout spending a far greater time in the array than the majority of the others.

3.4 The influence of fish size on movement

Although the data for sea trout collected in 2011 identified that 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, these patterns were not significant within the extended baseline. For salmon the only significant relationships with fish length observed were a positive correlation between salmon length and average speed in the array (Pearson correlation: n = 50, r = 0.471, P = <0.01) and a negative correlation with the time between first detection in the array and ascent (Pearson correlation: n = 7, r = -0.782, P = <0.05).

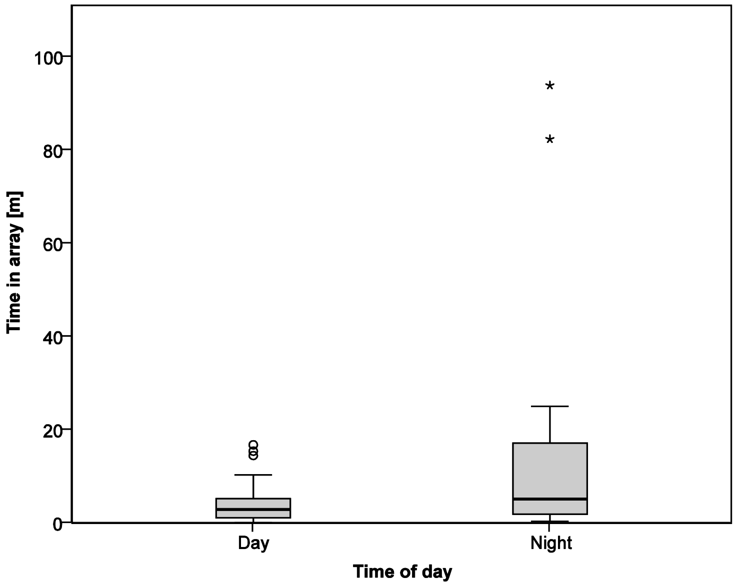


Figure 22. Box plot showing the relative time spent in the array during non-passage visits of salmon to the array in the day (n = 28) and at night (n = 15) in 2011 and 2012 (data combined).

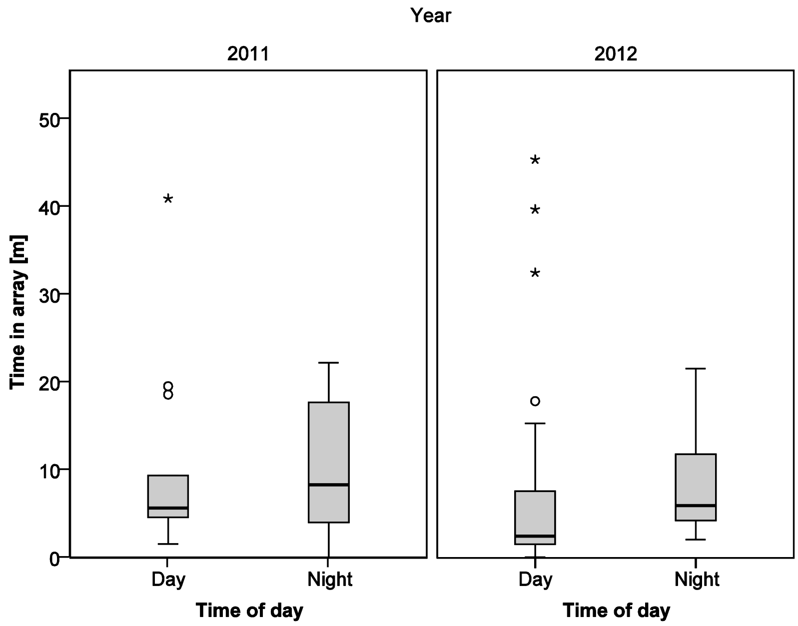


Figure 23. Box plot showing the relative time spent in the array during non-passage visits of sea trout to the array in the day (n = 14 [2011] and 38 [2012]) and at night (n = 8 [2011] and 7 [2012]) in 2011 and 2012.

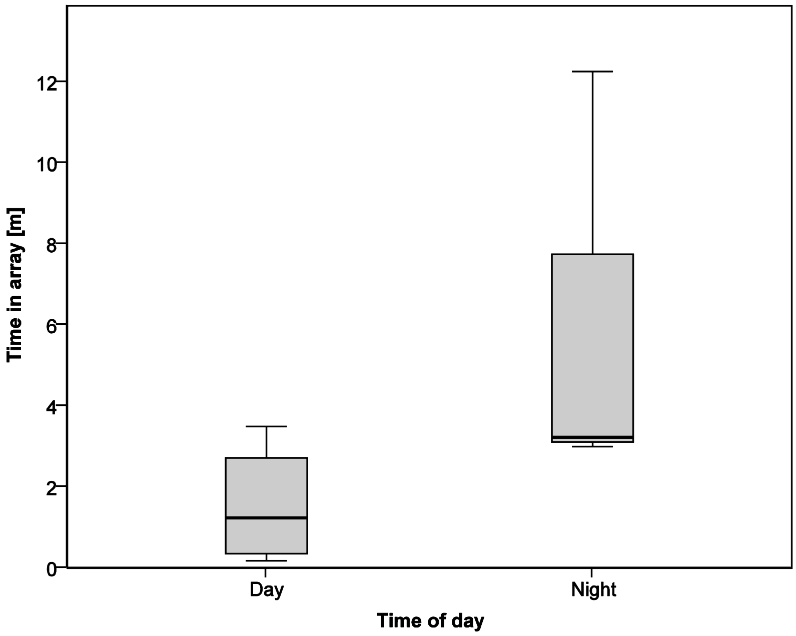


Figure 24. Box plot showing the relative time spent in the array during passage runs for salmon in the day (n = 4) and at night (n = 3) in 2011 and 2012 (data combined).

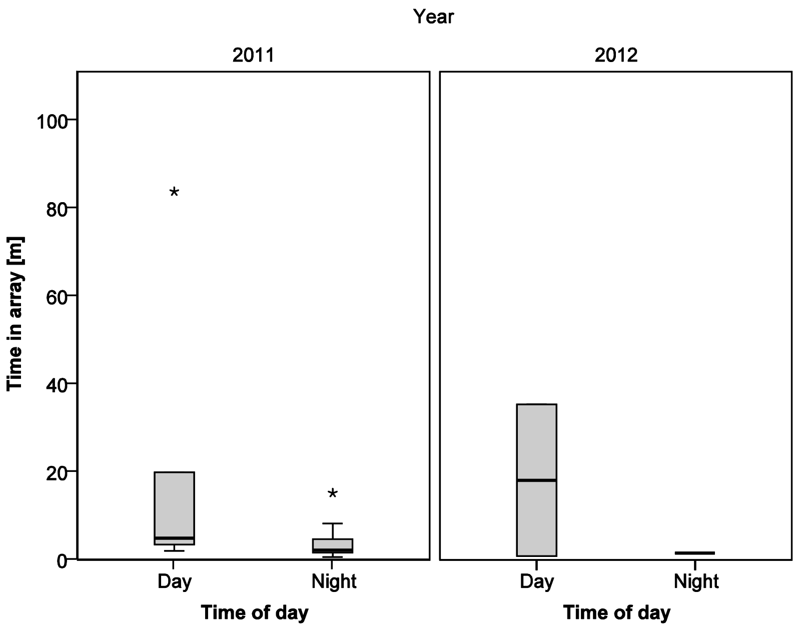


Figure 25. Box plot showing the relative time spent in the array during passage runs for sea trout in the day (n = 5 [2011] and 2 [2012]) and at night (n = 10 [2011] and 1 [2012]) in 2011 and 2012.

3.5 Environmental influences on timing of movement

3.5.1 Movements in 2011

In 2011 fish were generally observed to move at periods of elevated flow (Figure 26 and Figure 27), but these periods of high flow followed shortly after releases of the tagged fish 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 28). Indeed, fish were generally observed to move at the peak of spring tides (Figure 28), 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.

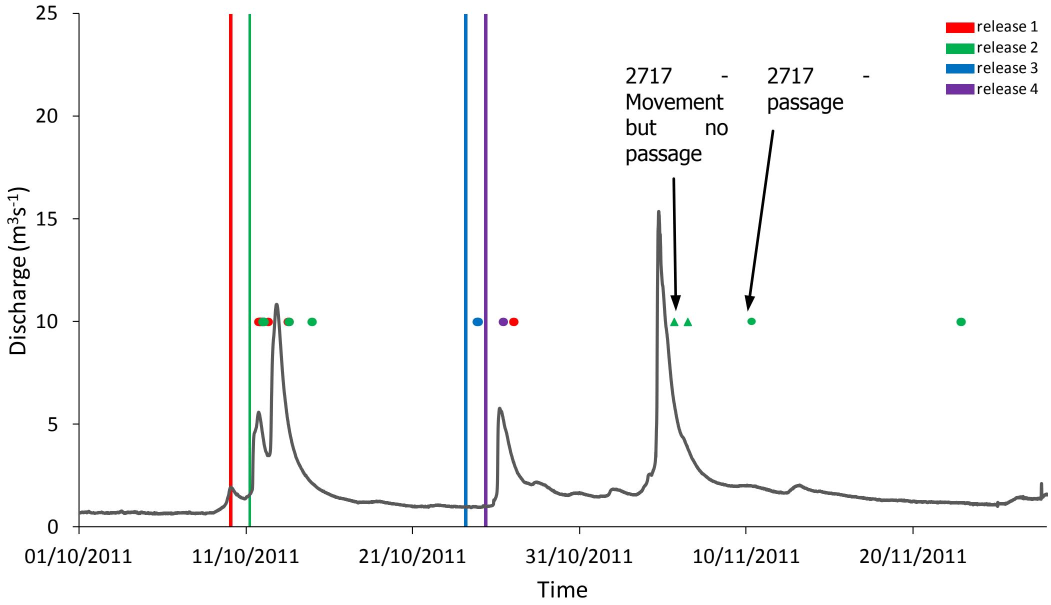
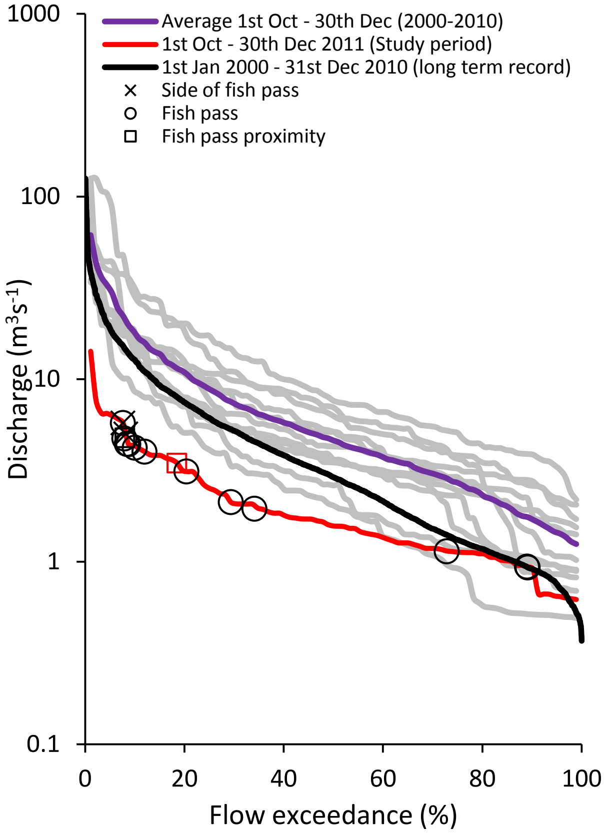


Figure 26. Time series of discharge over the 2011 study period with fish movements represented as points in time. Each point is colour coded according to its release batch. Note: all dots are representative of passage with the exception of the triangular points representing tag no. 2717 labelled in the diagram. This movement was independent of the fish's subsequent passage (also labelled).

A)



B)

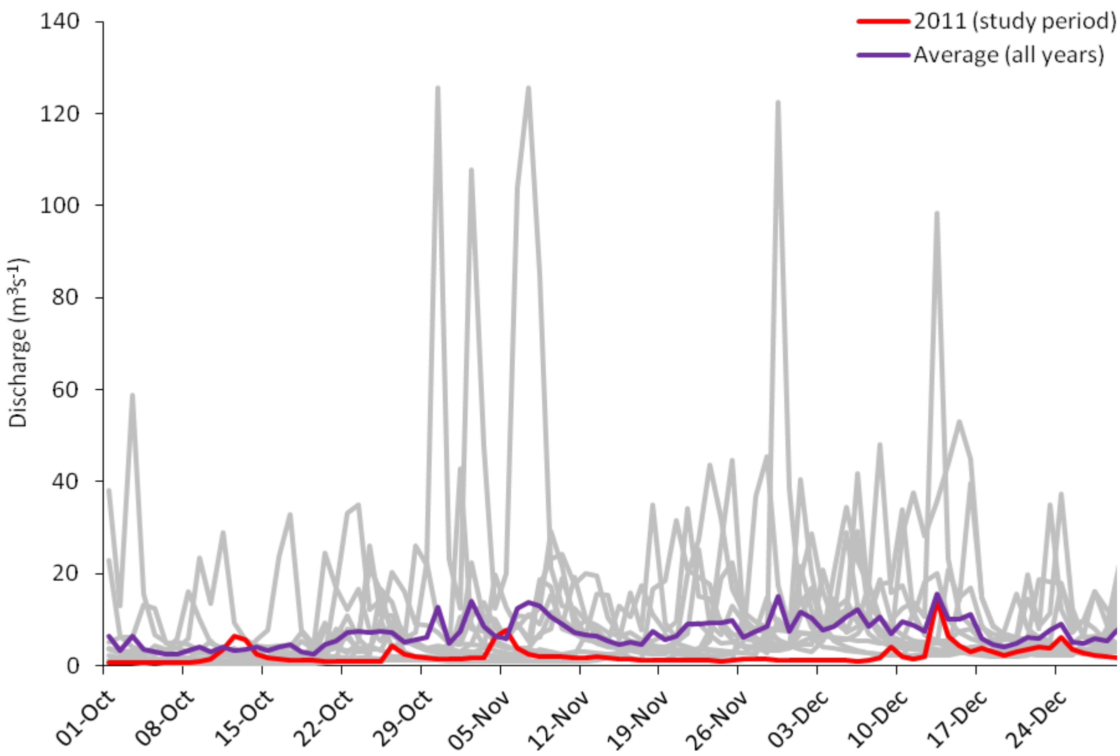


Figure 27. A) Flow exceedance curves for the 2011 study period (red), the same period in other years (grey) and the period average over all years (purple). The timing of passages in relation to exceedance probability and their ascent route is indicated. B) Comparison of the hydrograph over the study period (red) with the same period in other years (grey) and the period average over all years (purple).

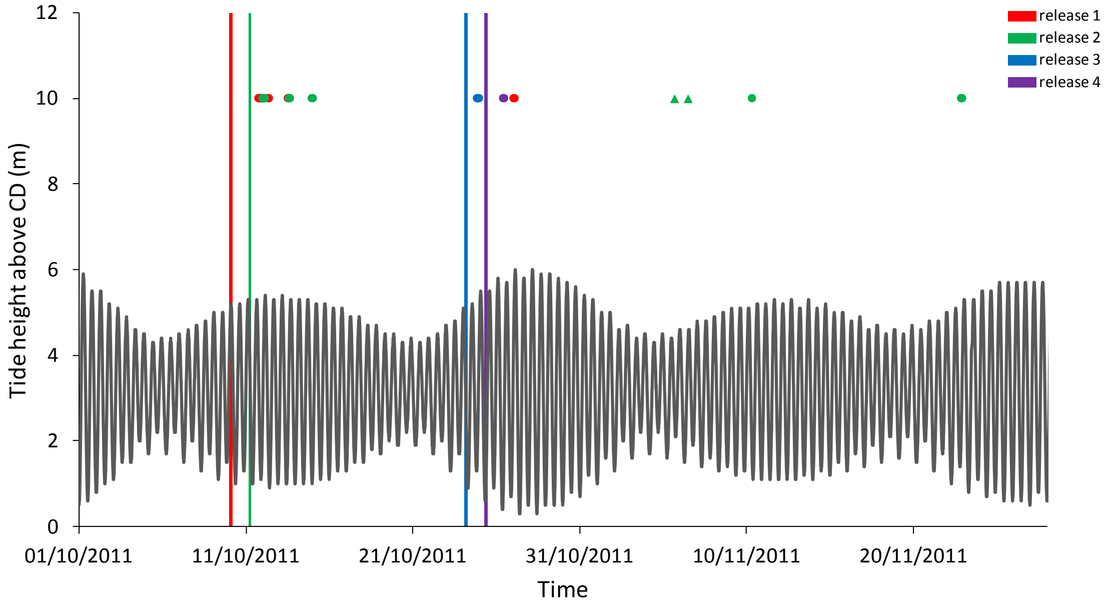


Figure 28. Time series of tides over the 2011 study period with fish movements represented as points in time. Each point is colour coded according to its release batch.

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 29).

No obvious trends were observed in the movement of fish in relation to temperature over the study period (Figure 30).

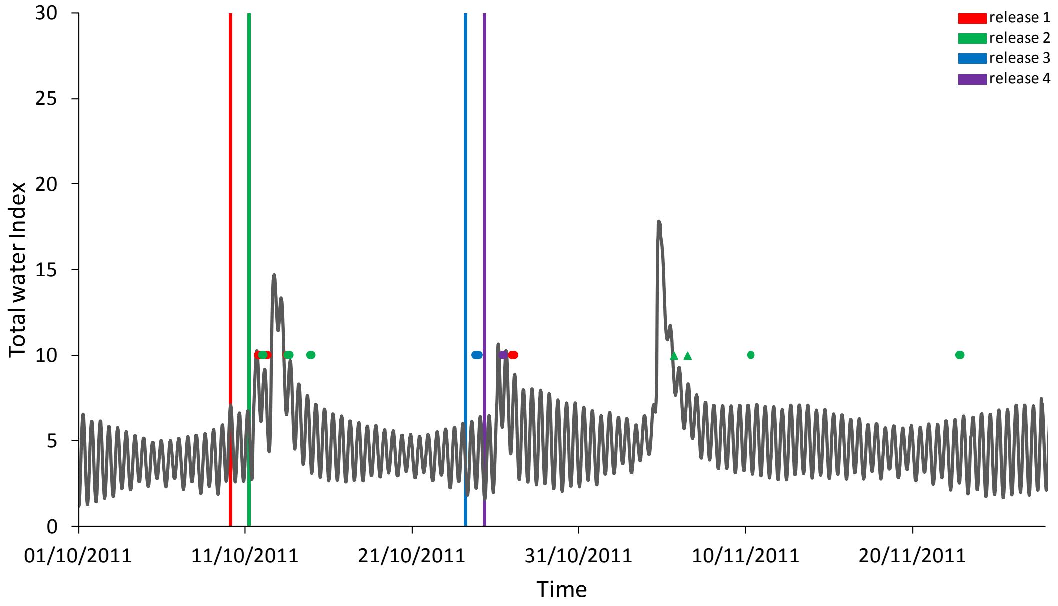


Figure 29. Time series of total water index (tide + discharge) over the 2011 study period with fish movements represented as points in time. Each point is colour coded according to its release batch.

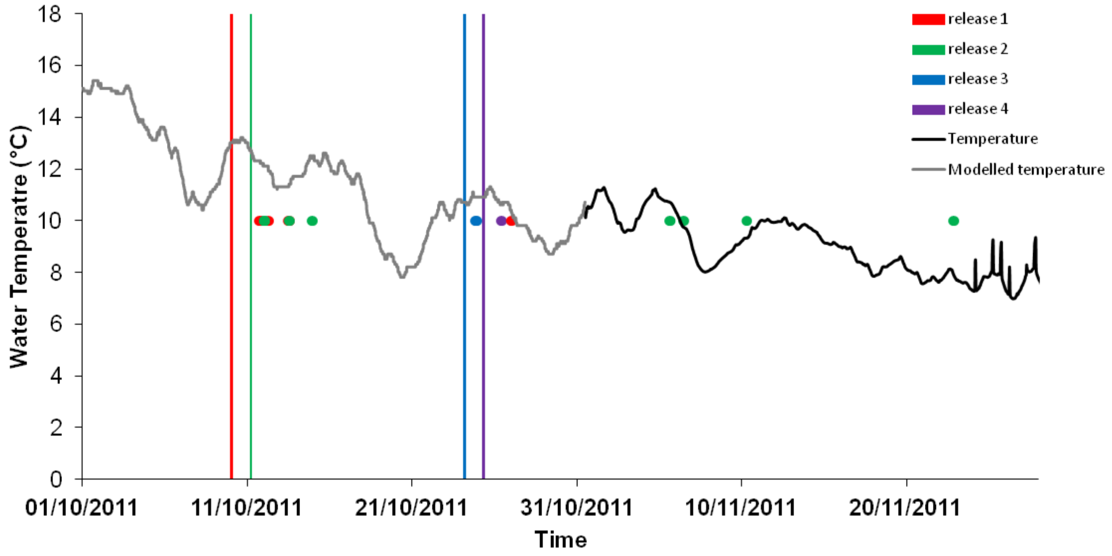


Figure 30. Times series of temperature over the 2011 study period with the movements of fish represented as points in time. Each dot is colour coded according to its release batch.

3.5.2 Movements in 2012

The hydrological conditions of 2012 were markedly different to those experienced in 2011 with a number of large flood pulses occurring between September and December, including two exceptionally large floods (Figure 31). The movements and ascents of all but two fish (2500 and 2556) were almost immediately after release so were seemingly independent of the hydrological conditions at the time. Three fish (2647, 2626 and 2584) were observed to reappear below the weir a few weeks following their first ascent, potentially as a response to the spate flows of mid October. Of these 2584 was detected to move down through the fish pass whereas the other must have come directly over the weir.

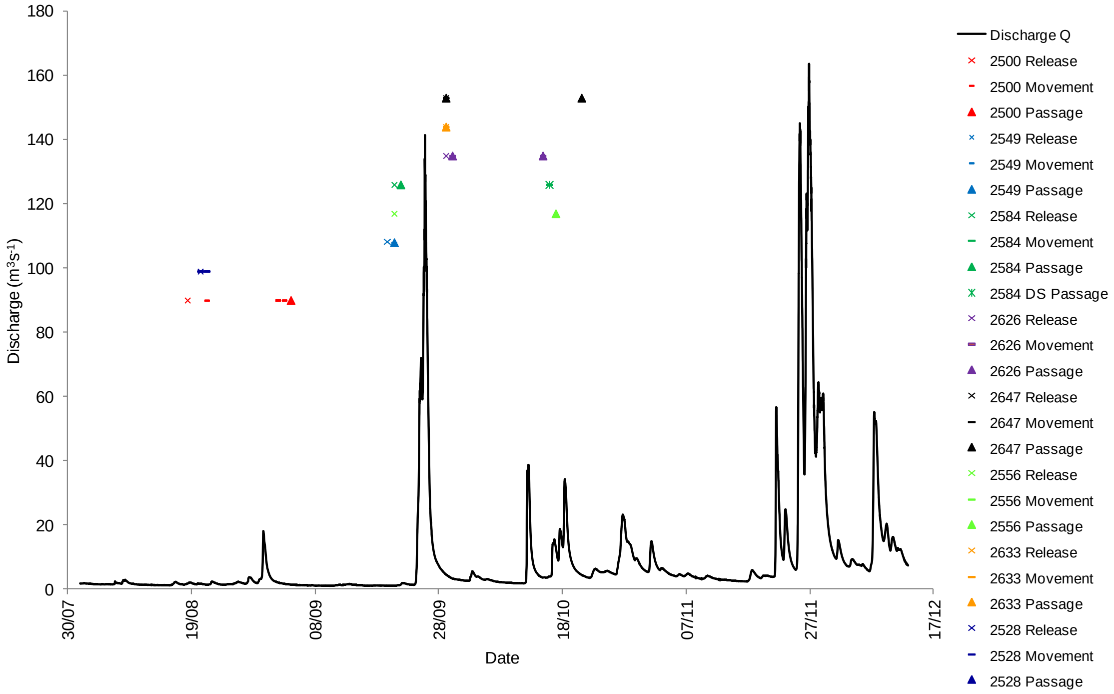


Figure 31. Time series of discharge over the 2012 study period with fish movements represented as points in time.

Freshwater discharge was generally much higher in 2012 that in 2011 with eight spates of greater magnitudes than the highest spate observed during the 2011 study period (Figure 32). In 2012 there were two extreme floods with discharges >80 m^3s^{-1} and for short periods of time the discharges exceeded 100 m^3s^{-1}. So whilst 2011 could be considered a period of unusually low flows 2012 was conversely a period of some exceptional floods.

There was no clear observable trend between fish movements and passages with either tidal regimes (spring or neap) (Figure 33). Of the fish whose movements were independent of release (2500 and 2556, plus the two second ascents) there was an indication these were associated with periods of spring tides. Although they were also all associated with freshets or spates. There was no trend observed between passage and water temperature (Figure 34) which declined from around 16 °C in late August to around 6 °C in mid November.

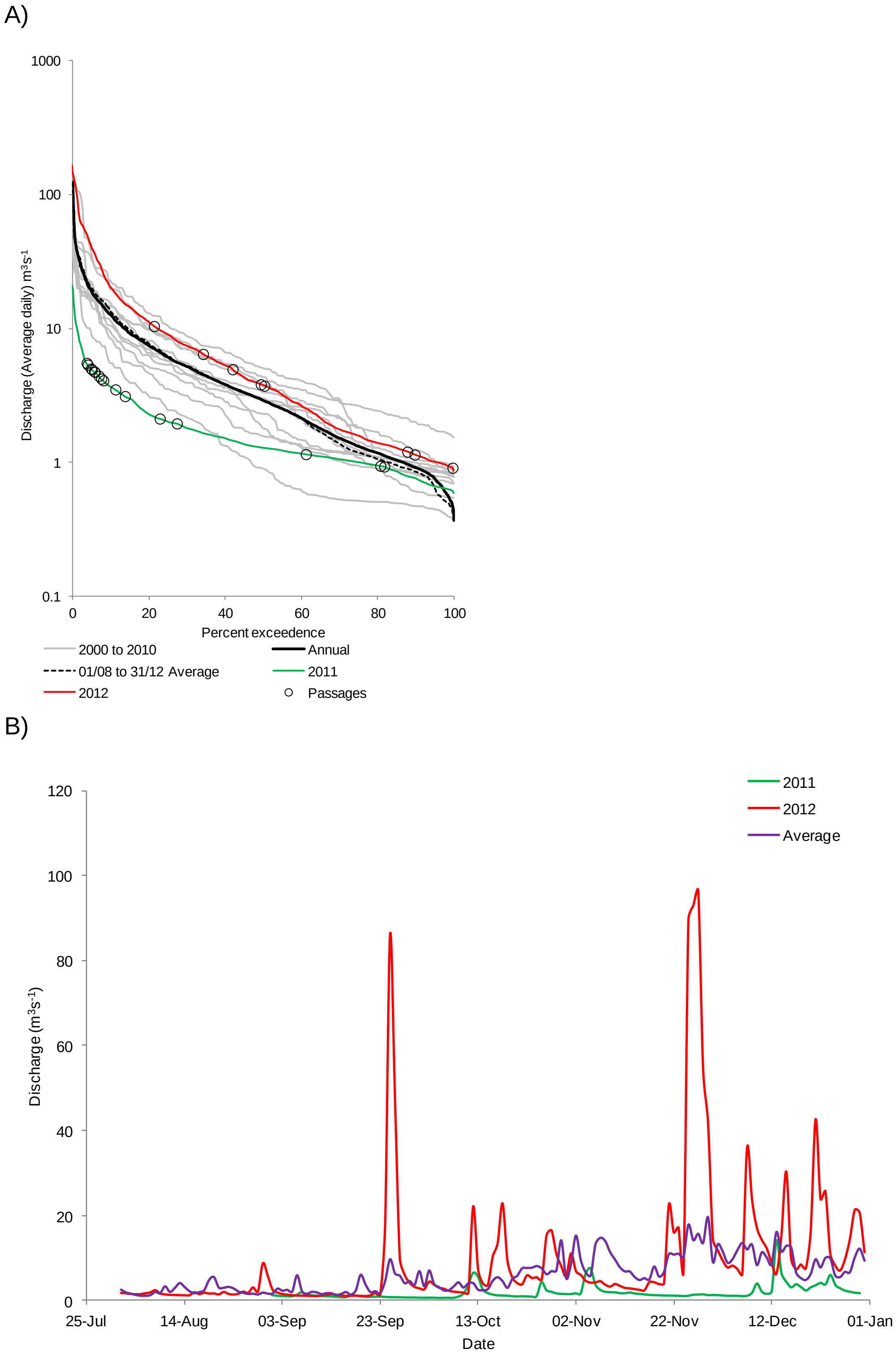


Figure 32. A) Flow exceedance curves for the study period in 2012 (red) and 2011 (green), the same period in other years (2000-2010, grey), the period average over all years (black dashed) and the annual averages (black). The timing of passages in relation to exceedance probability and their ascent route is indicated. B) Comparison of the hydrograph over the study period in 2011 (red) with the same period in 2011 (green) and the period average over all years (purple).

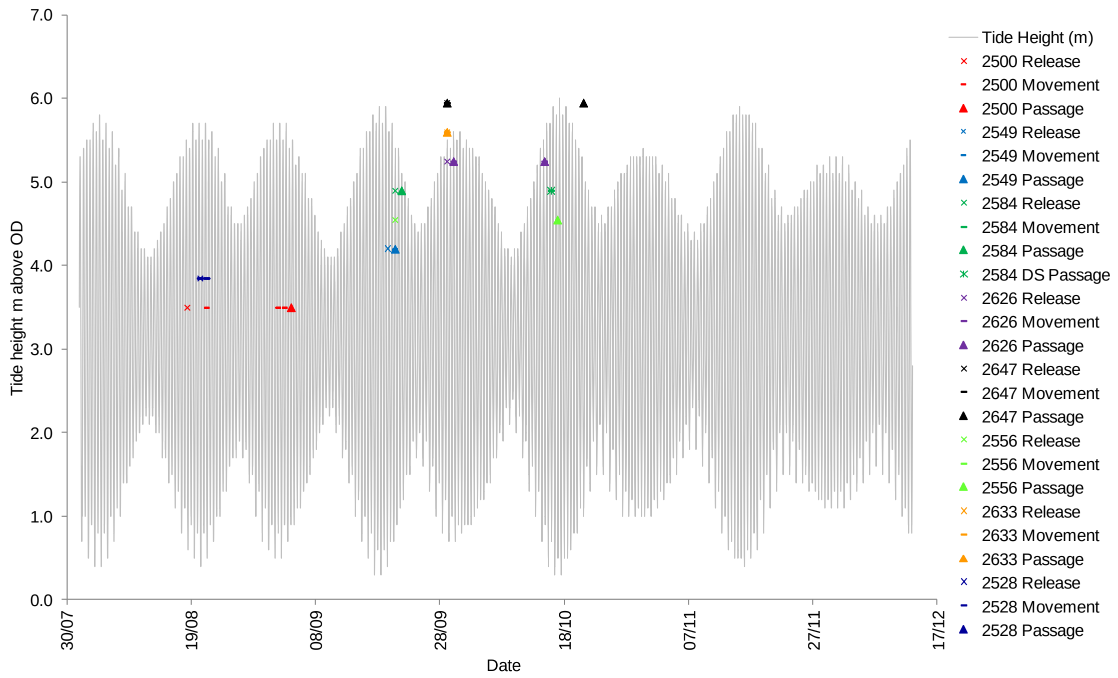


Figure 33. Time series of tides over the 2012 study period with fish movements represented as points in time.

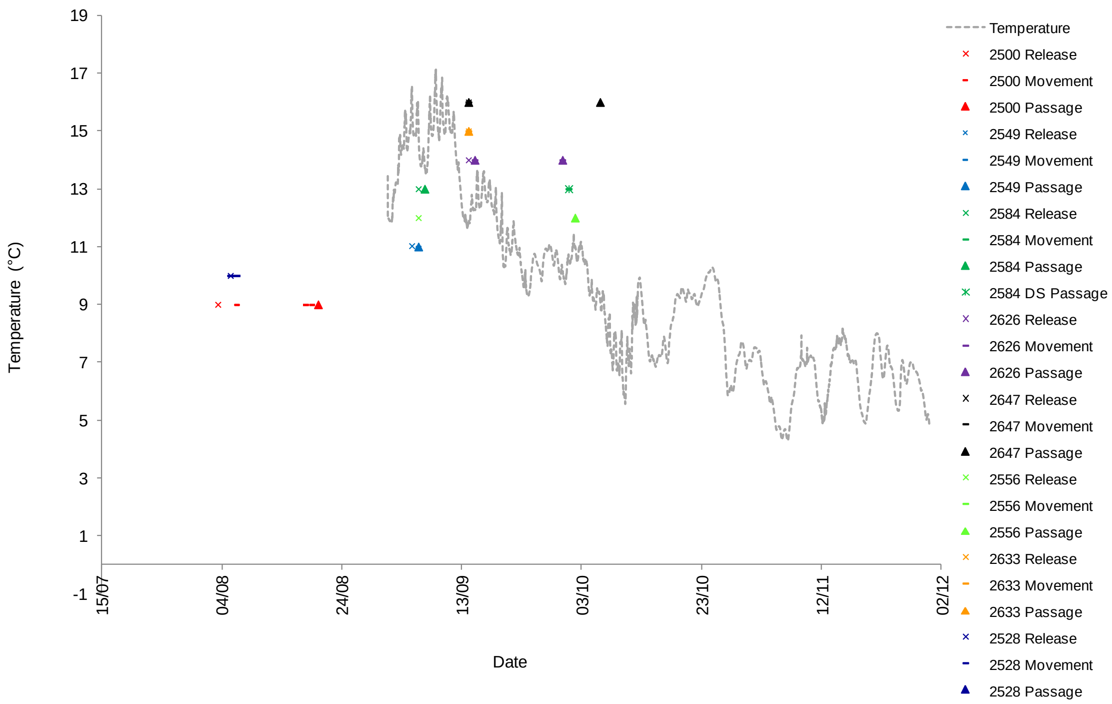


Figure 34. Time series of water temperature over the 2012 study period (excluding the period prior to 31st August) with fish movements represented as points in time.

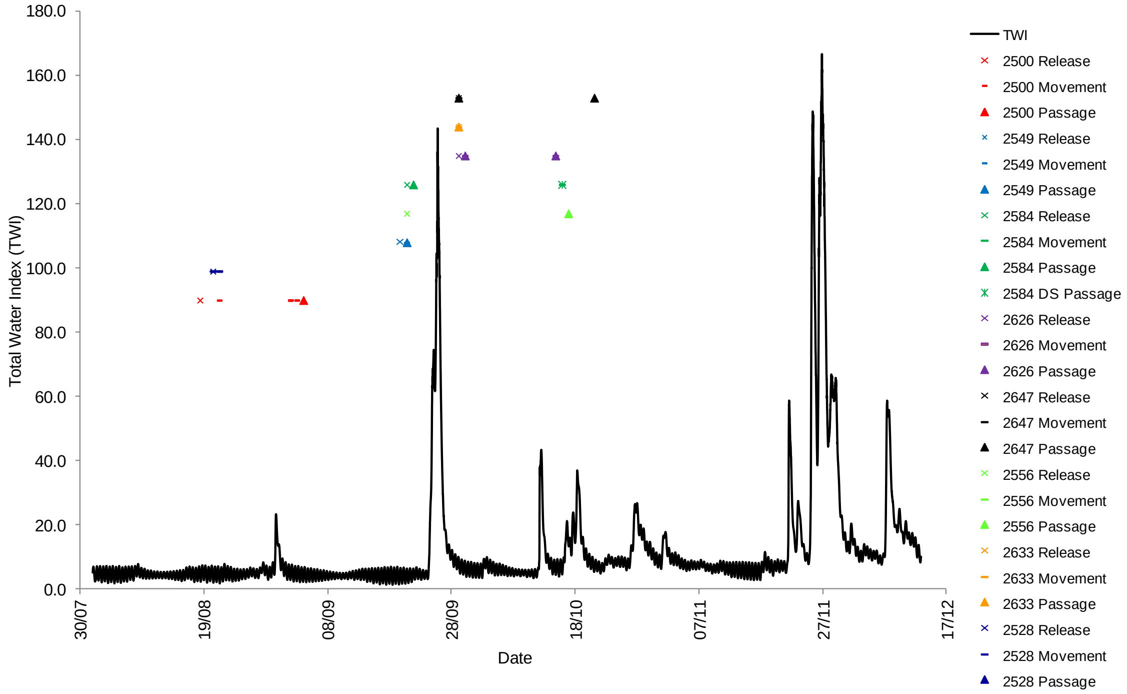


Figure 35. Time series of total water index (tide + discharge) over the 2012 study period with fish movements represented as points in time. Each point is colour coded according to its release batch.

3.5.3 Relationship with discharge and tide height

Over all there was no clear pattern between the timing of first entry into the array (Figure 36) or passage (Figure 37) of sea trout and salmon with the TWI. Salmon tended to enter at higher values of TWI >6.0 and no sea trout entered at values lower than 2.0. The majority of passages occurred at TWI values <10.0 although one salmon passage (second ascent) occurred at a TWI of 16.4 (Figure 37).

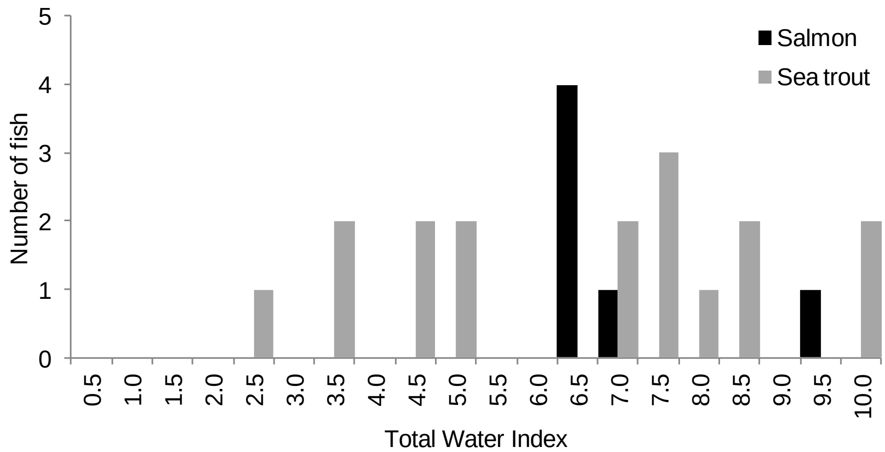


Figure 36. Relationship between the timing of the first entry into the array of salmon and sea trout in 2011 and 2012 and the total water index (discharge + tide).

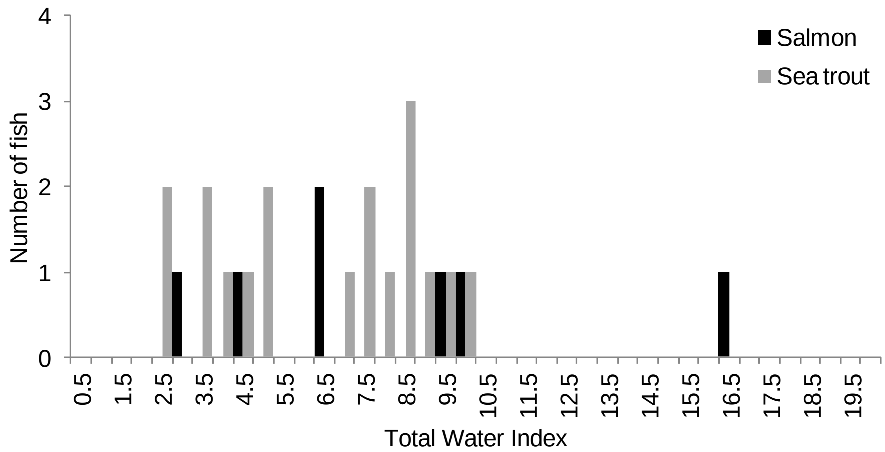


Figure 37. Relationship between the timing of passage over the weir of salmon and sea trout in 2011 and 2012 and the total water index (discharge + tide).

There was no clear pattern in first entry to the array or passage (Figure 38) when discharge and tide were considered together. For salmon there was potential indication that at times of low flow first entry only occurred during high tides (>5m) whilst under higher flows (around 5 m^3s^{-1}) salmon could enter the array at low tide. However, this may be an artefact of the low sample size. Four fish of the 23 tracked exhibited more than 4 tracks in the array prior to first passage. This included:

Sea Trout 2500 – 39 non-passage tracks in August 2012, all tracks at flow <2 m^3s^{-1}
Salmon 2528 – August 2012, all tracks at flows <2 m^3s^{-1} (no recorded passage)
Salmon 2549 – September 2012, most activity at flows <2 m^3s^{-1} (eventual passage at a discharge <1 m^3s^{-1})
Sea Trout 2717 – 14 tracks in 2011 at wide range of flows (only 380mm in size)

The majority of all other tracks for fish that ascended the pass within 4 visits were recorded at discharges between 3 and 6 m^3s^{-1}.

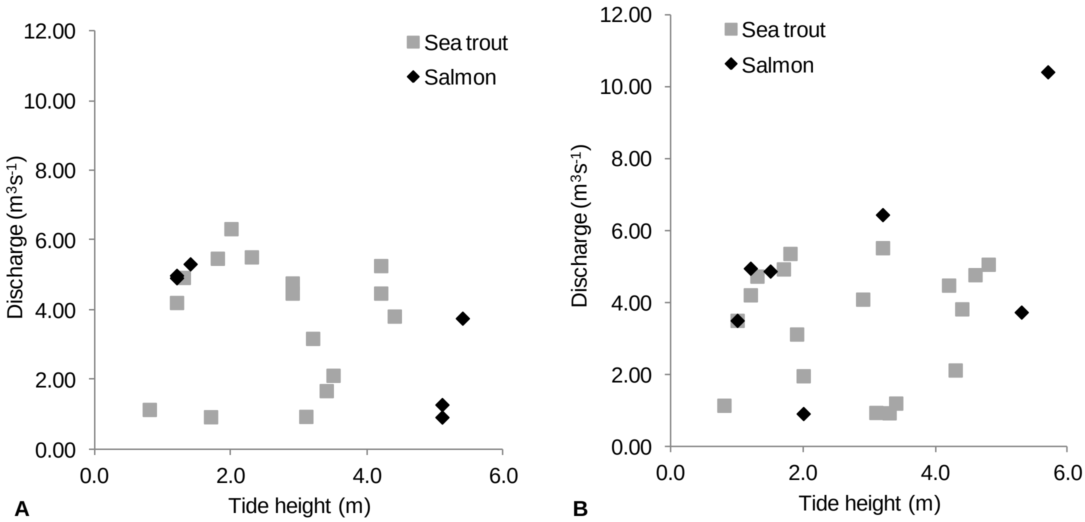


Figure 38. Discharge and tide conditions during (A) first entry into the array and (B) passage tracks for salmon and sea trout in 2011 and 2012.

3.5.4 Relationship with state of tide

Salmon appeared to enter the array at all states of tide and through the full range of tide heights (Figure 39) although distribution of movements across the tidal regime was not equal. The majority of salmon tracks started around the time of high tide Whitby (90-100% of the daily maximum height) and on tides over 5m above CD. However, there was also a peak in movements on tide heights between 1.0 and 1.5m around 20-30% of the daily high tide value. Given the low number of salmon observed it is likely that this reflects the movements of an individual fish. The timing of passage tracks for salmon in relation to absolute and relative tide height followed a similar pattern to the non-passage tracks (Figure 40). Although there are only a few passage tracks, four of the seven all occurred around low tides (<40% of the daily maximum tide) with two of the remainder occurring at high tide (>90% of the maximum tide height for that day).

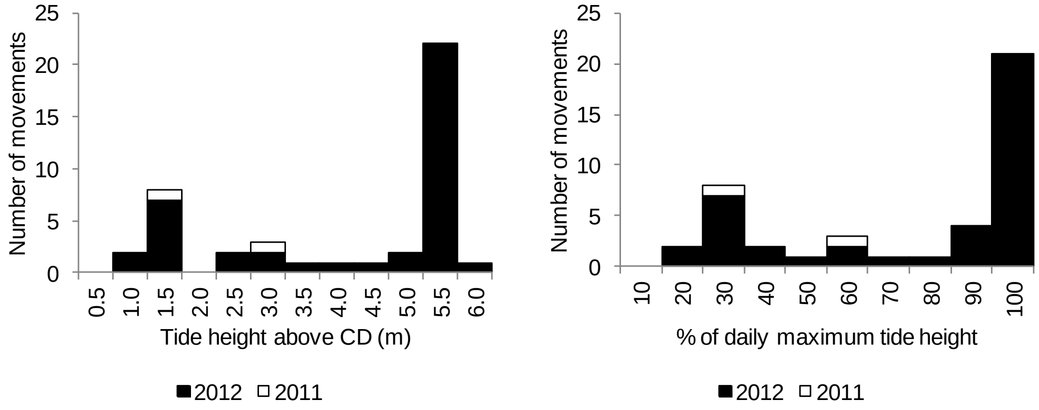


Figure 39.a) Number of salmon that entered the array during non-passage movements in relation to tide height and b) to the proportion of maximum tide height on the day of fish movement.

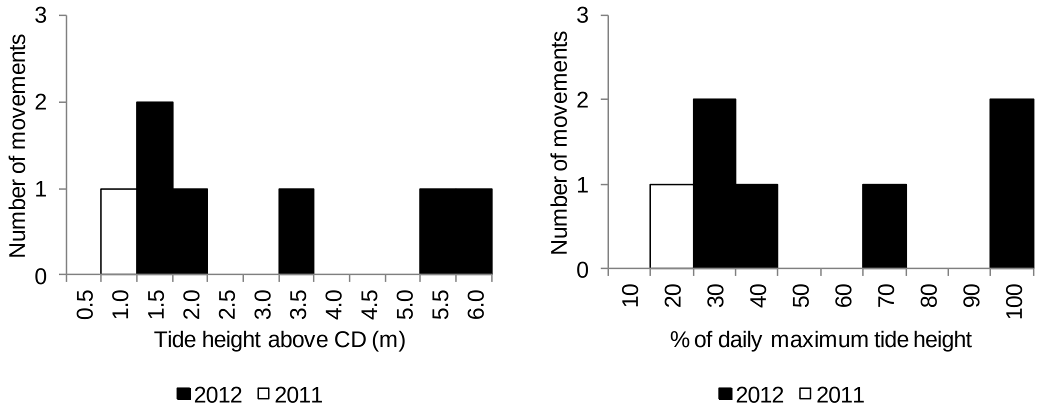


Figure 40.a) Number of salmon that ascended the weir in relation to tide height and b) to the proportion of maximum tide height on the day of fish movement.

The pattern of non passage movements of sea trout in relation to absolute and relative tide height appeared to be different in 2011 and 2012. In 2011 the majority of movements occurred around the mid tide (1.5 to 3.0m, 40-70% of tide height). However, in 2012 a high proportion of non passage tracks started around high tide (tide height >5.0m and 90-100% of the daily maximum height) (Figure 41). No tracks were observed at these absolute heights during 2011 although some fish did enter the array on the top of the tide. Only three new passage runs were observed and this fitted the pattern observed in 2011 (Figure 42).

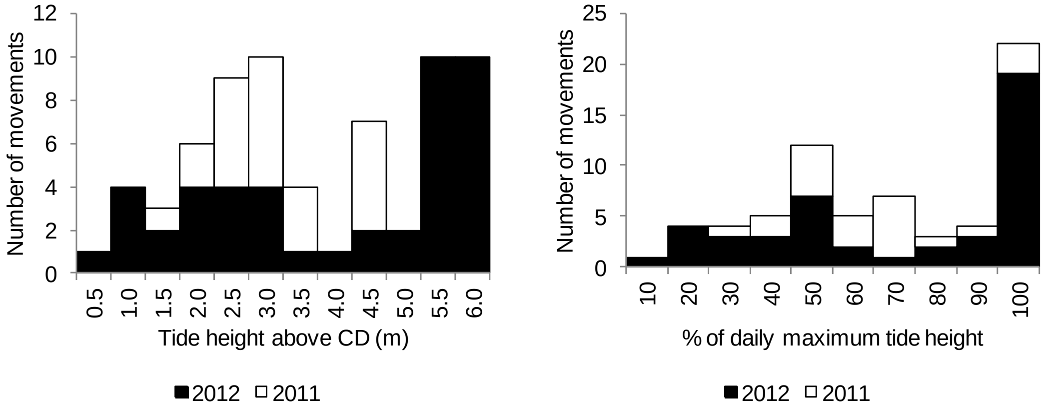


Figure 41. a) Number of sea trout that entered the array during non-passage movements in relation to tide height and b) to the proportion of maximum tide height on the day of fish movement.

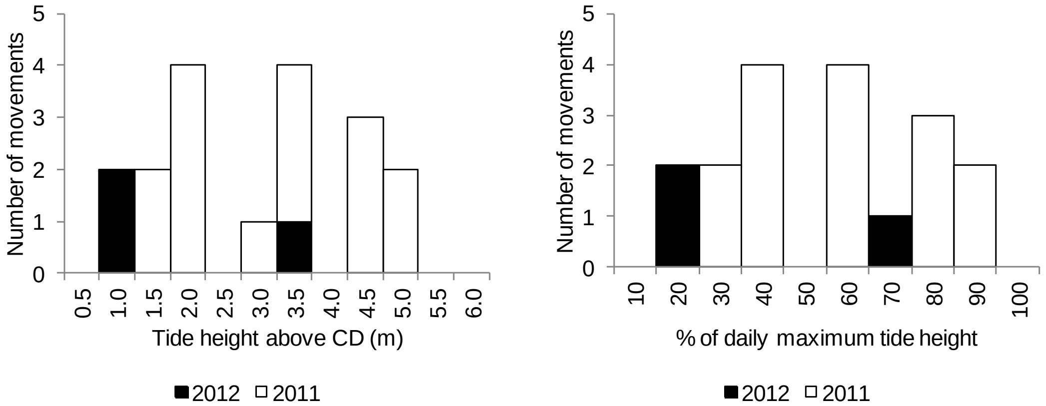


Figure 42. a) Number of sea trout that ascended the weir in relation to tide height and b) to the proportion of maximum tide height on the day of fish movement.

Salmon entered the array on all states of the tide during non passage runs, with a tendency to favour a rising tide (n = 22) rather than an ebbing tide (n = 14). Four and three tracks started during low water slack and high water slack respectively (Figure 43). Non-passage tracks that started on an ebbing tide (mean time in array 10.35 ± 21.52 minutes) were on average slightly longer than those on a flood tide (6.02 ± 6.12 minutes) and the few starting at low water slack appeared to last the longest (26.68 ± 44.94 minutes). However, there was no significant difference between the track duration (Kruskall-Wallis test χ^2 1.091, n = 43, df = 3, *P* >0.05). Passage tracks occurred on all states of the tide and there was no discernible difference in their duration (too few samples to test statistically) (Figure 44).

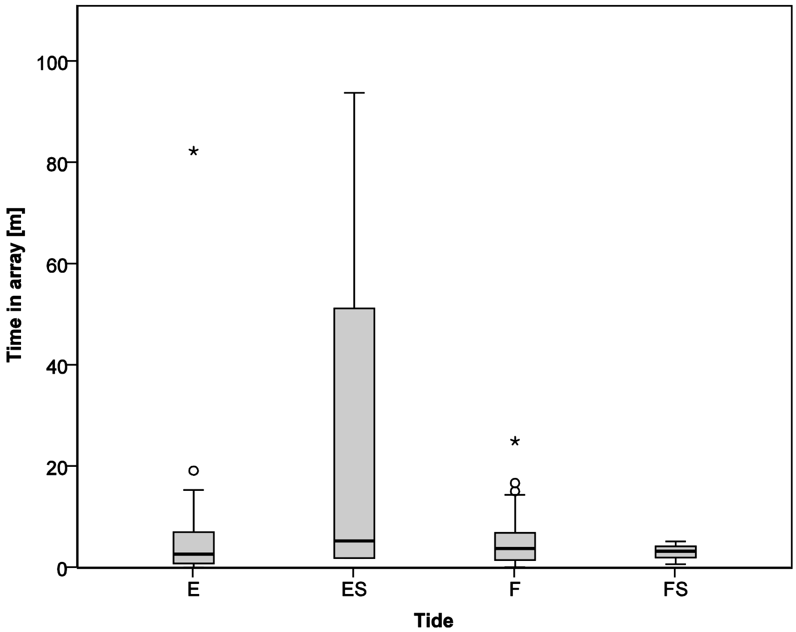


Figure 43. Amount of time spent in the array on non-passage runs of salmon during ebbing (E, n = 14), low water slack (ES, n = 4), flooding (F, n = 22) and high water slack (FS, n = 3) stages of the tide in 2011 and 2012.

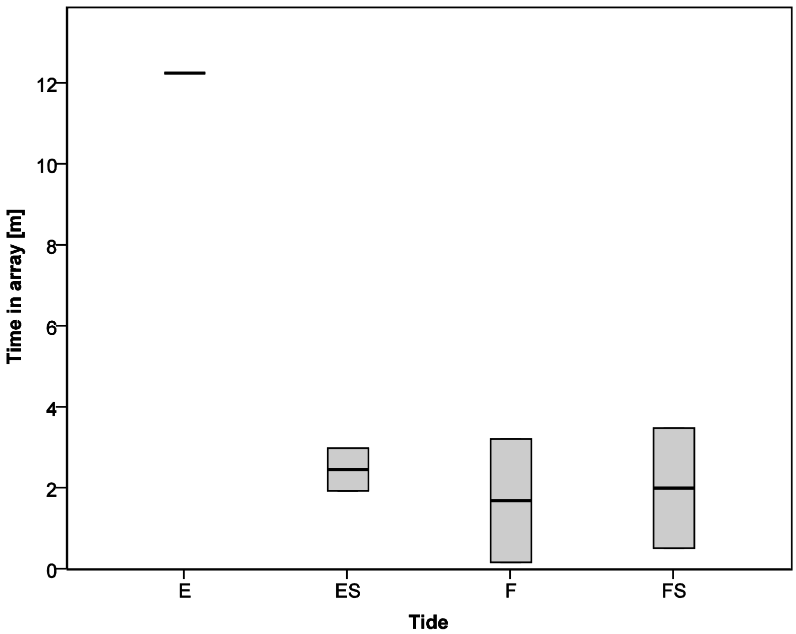


Figure 44. Amount of time spent in the array on passage runs of salmon during ebbing (E, n = 1), low water slack (ES, n = 2), flooding (F, n = 2) and high water slack (FS, n = 2) stages of the tide in 2011 and 2012.

Sea trout were observed to enter the array during non passage track on all states of the tide with a tendency to favour ebbing tides (n = 34) over flooding tides (n = 24). In 2012 tracks were also observed to start around low water and high water slacks (Figure 45). Non-passage tracks that started on an ebbing tide (mean time in array 10.35 ± 21.52 minutes) were on average slightly shorter than those on a flood tide (9.85 ± 11.90 minutes) and the seven starting at high water slack had an average duration of 7.66 ± 14.34 minutes. However, there was no significant difference between the track duration (Kruskall-Wallis test χ^2 3.518, n = 67, df = 3, P >0.05).

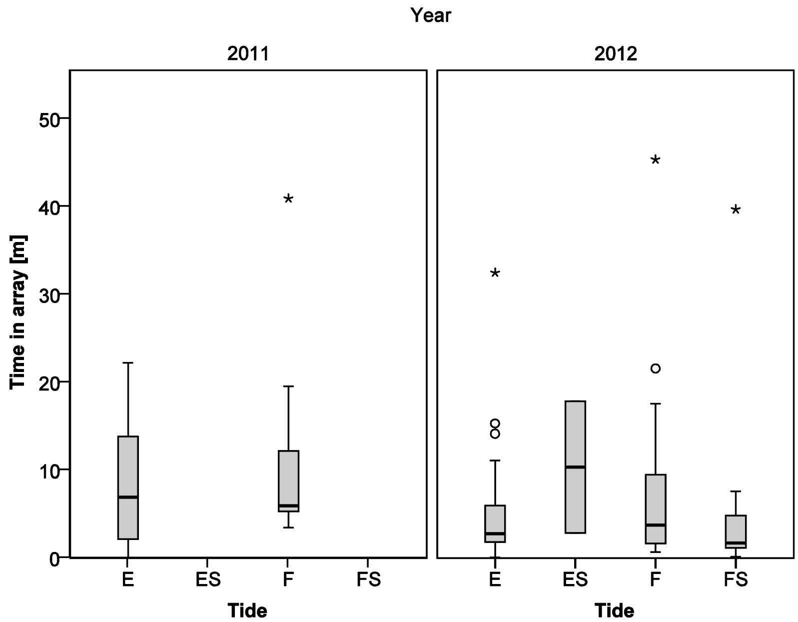


Figure 45. Amount of time spent in the array on non-passage runs of sea trout during ebbing (E, n = 34), low water slack (ES, n = 2), flooding (F, n = 24) and high water slack (FS, n = 7) stages of the tide in 2011 and 2012.

The majority of passage tracks for sea trout were observed to start on ebbing (n = 5) and flooding tides (n = 12), with only one passage occurring around low water slack (Figure 46). Passage tracks that started on an ebbing tide (mean time in array 26.82 ± 34.57 minutes) were on average longer than those on a flood tide (4.92 ± 6.12 minutes) although the duration of tracks on ebbing tides was much more variable. There was no significant difference between the track duration (Kruskall-Wallis test χ^2 3.489, n = 18, df = 2, P >0.05).

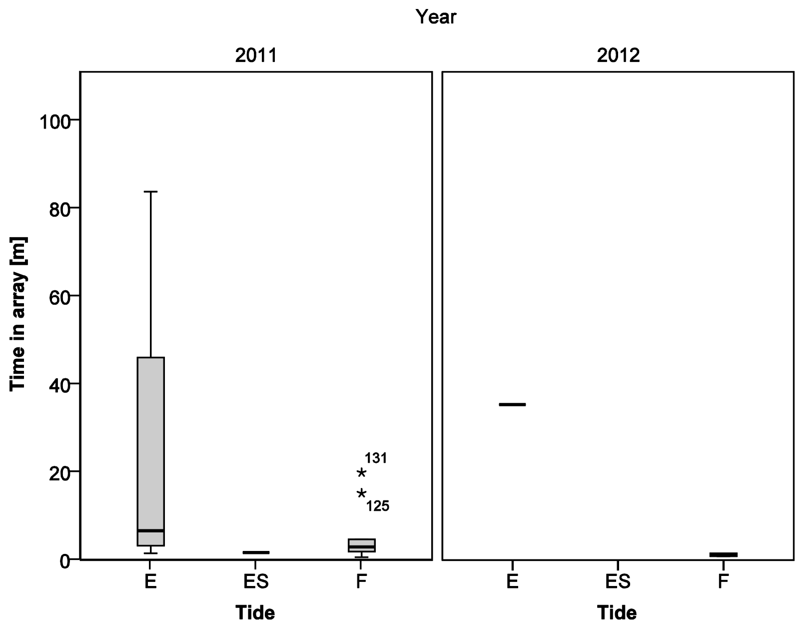


Figure 46. Amount of time spent in the array on passage runs of sea trout during ebbing (E, n = 5), low water slack (ES, n = 1), flooding (F, n = 12) and high water slack (FS, n = 0) stages of the tide in 2011 and 2012.

3.6 Hydraulic conditions within the array in 2011

Hydraulic surveys using an ADCP along four transects in the hydrophone array (Figure 47) were interpolated to produce a “flow map” of the pool (Figure 48). 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 3.8).

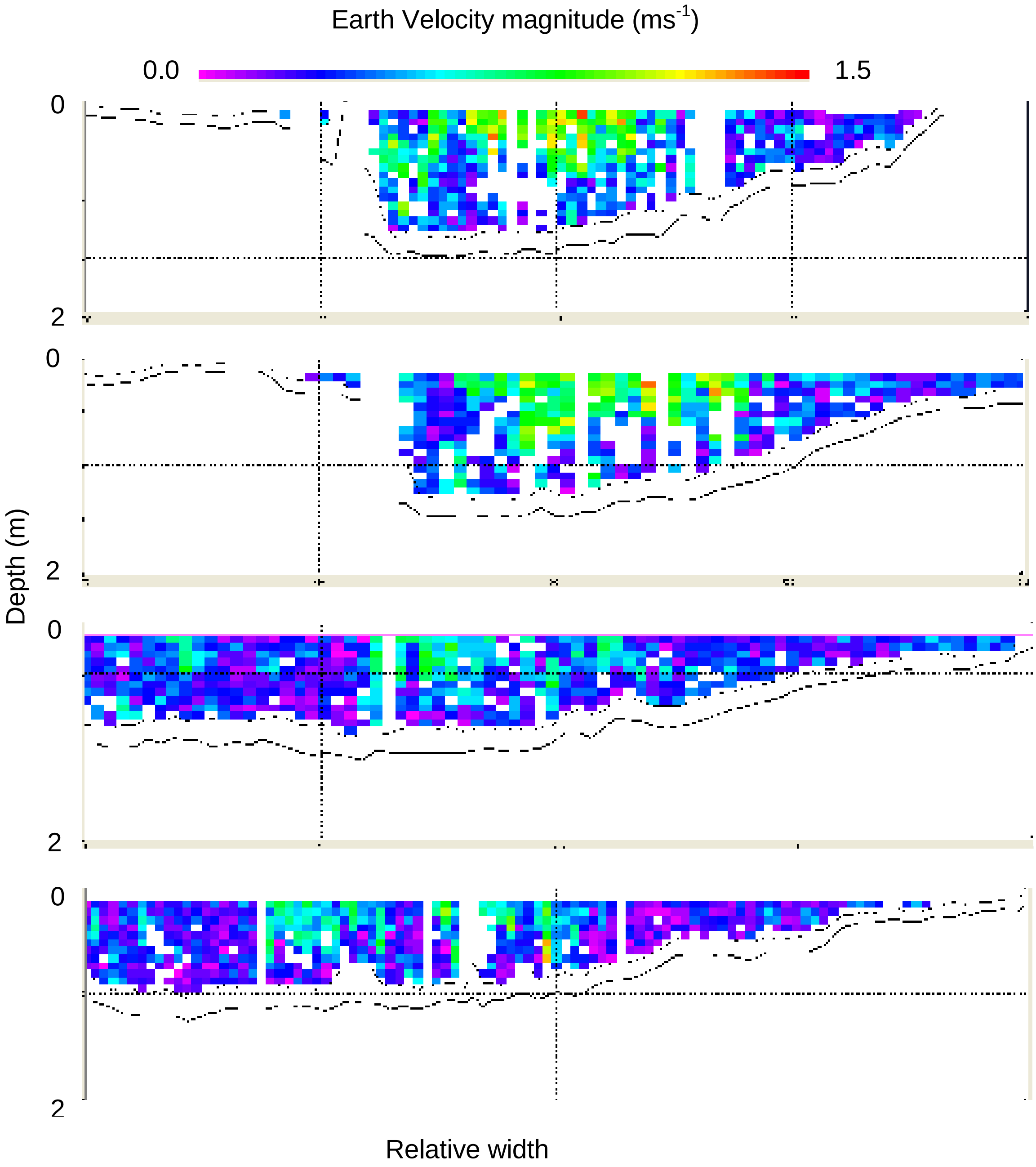


Figure 47. Cross sectional flow profiles of ADCP transects 1-4.

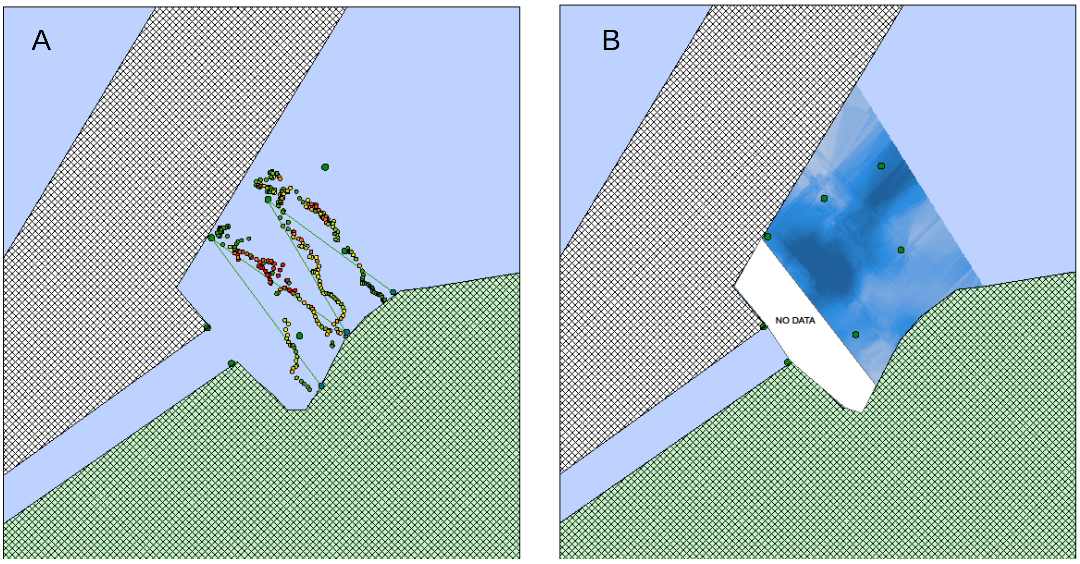


Figure 48. a) Example of depth averaged transects taken using the ADCP and b) the interpolated output of all data (darker blue corresponds to higher flow). Note: no adequate data was obtained near the fish pass due to turbulent flows.

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

3.7.1 All tracks (2011 and 2012 combined).

Although track counts were evenly distributed throughout the array (Figure 49), residence time was not evenly distributed (Figure 50a). When tracks for 2011 and 2012 were combined, fish 2500 in 2012 was observed to exhibit a very high number of tracks within the array and also spent an unusually large amount of time at the rear of the array (Figure 50b). Given this unusual behaviour and disproportionally large number of tracks non-passage data for fish 2500 were treated separately from the rest in all further analyses of micro-scale behaviours (see Appendix 4). 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 centre and the back of the pool (Figure 50c). The highest frequency of tag echoes were detected within 1.5-2.5 m of the fish pass (Figure 51). The average (± 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.

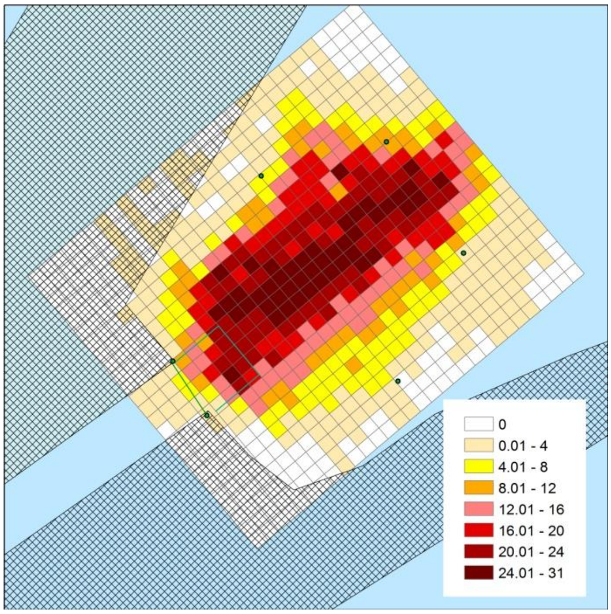


Figure 49. All sea trout tracks combined: count of tracks to pass through each grid cell.

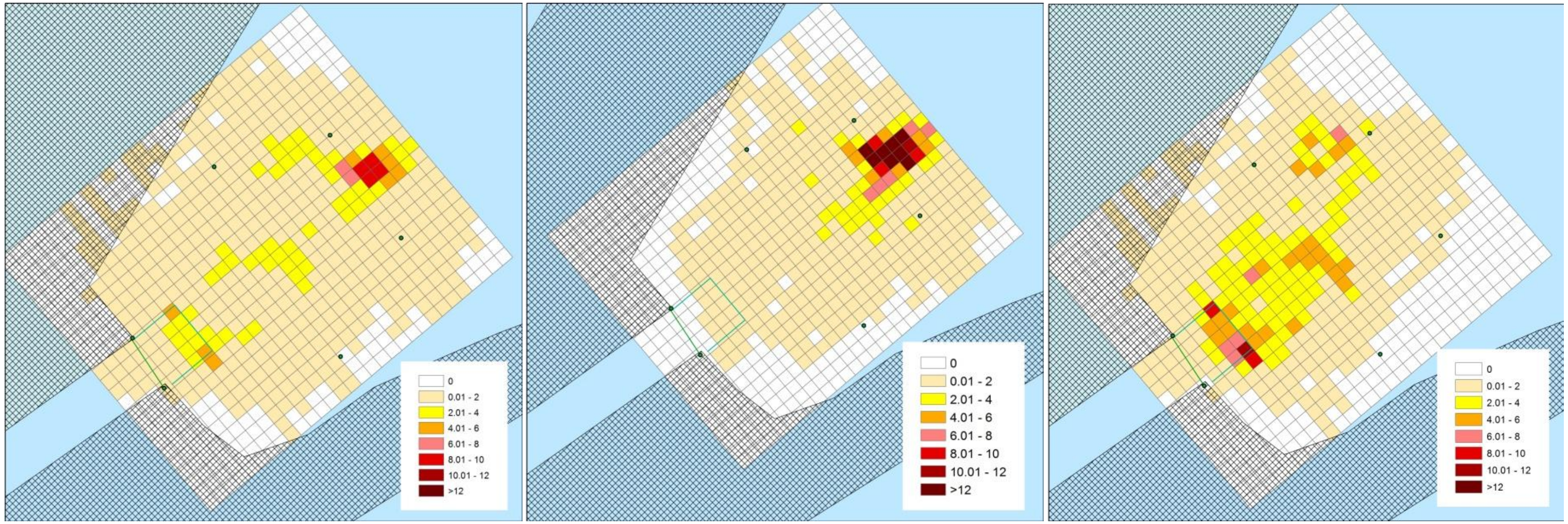


Figure 50.Average time (sec) spent in each grid cell during all sea trout tracks (left), fish 2500 (middle) and all tracks excluding fish 2500 (right) that entered the array (passage and non passage tracks combined).

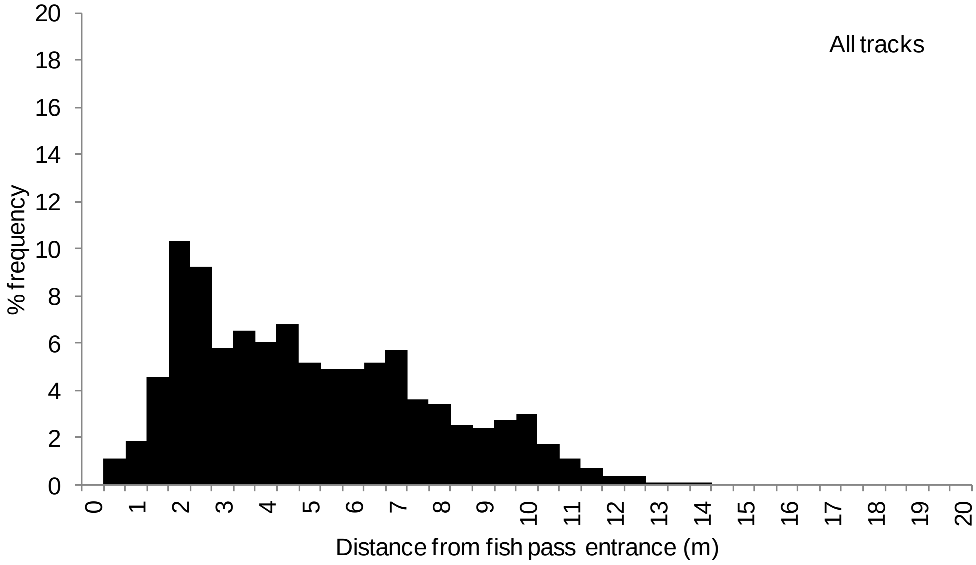


Figure 51. Numbers of tag echoes detected in the array against distance from the entrance to the fish pass (m) as a percentage of the total number of tag echoes recorded

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 52), but there were fewer obvious differences in residence time within the array with hot spots occurring around the fish pass entrance, the middle and rear of the array (Figure 53). However, on passage tracks sea trout appeared to spend longer in the vicinity of the fish pass entrance (<2m) than they did during non passage tracks. The general patterns of tag echo proximity in relation to the fish pass entrance were similar between passage and non-passage tracks (Figure 54).

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).

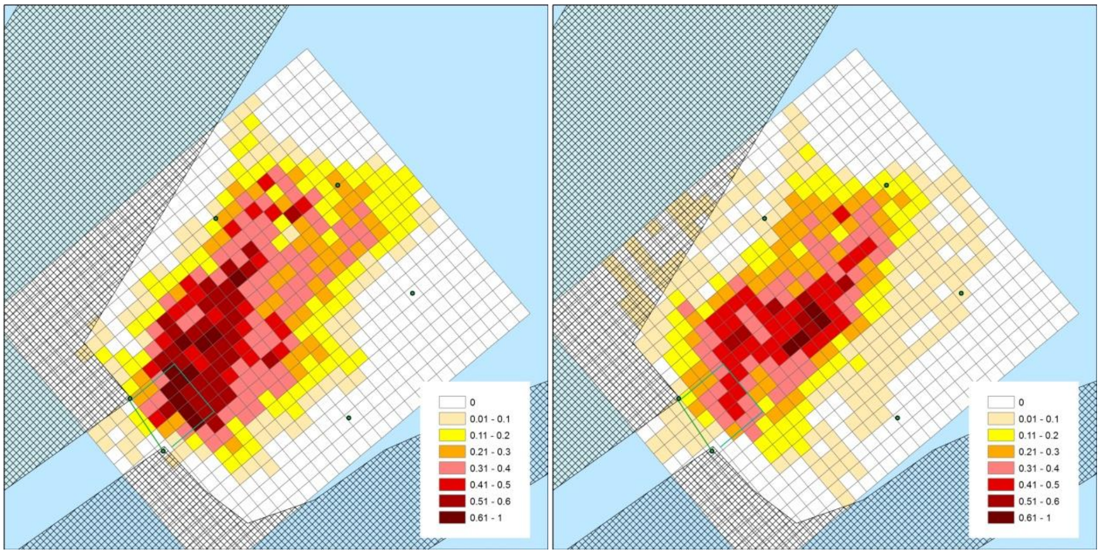


Figure 52. Proportion of sea trout tracks to pass through each grid cell during passage (left) and non-passage (right, excluding fish 2500) visits to the array.

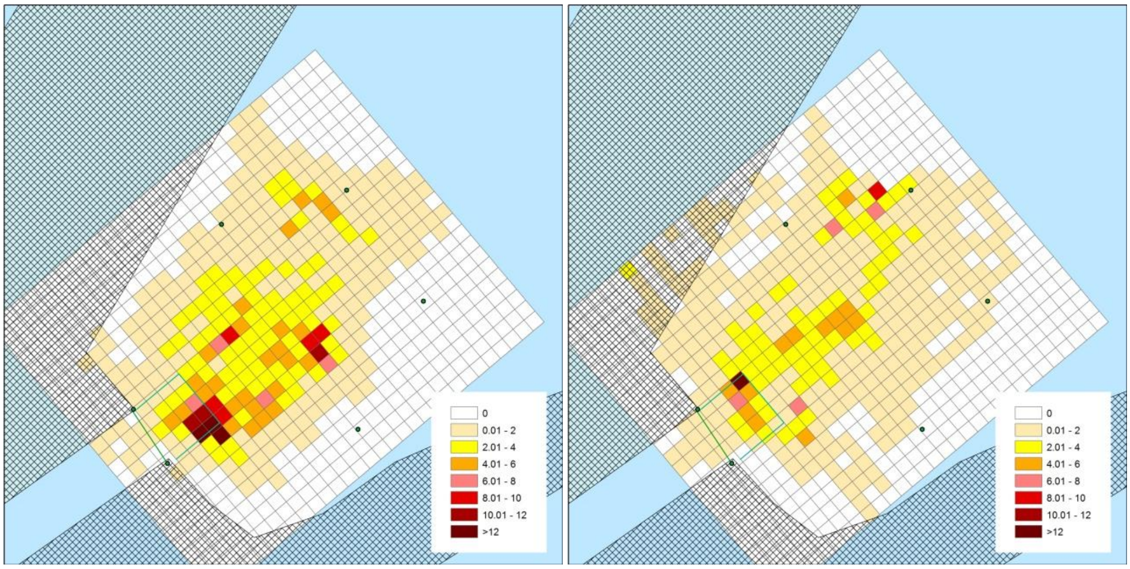
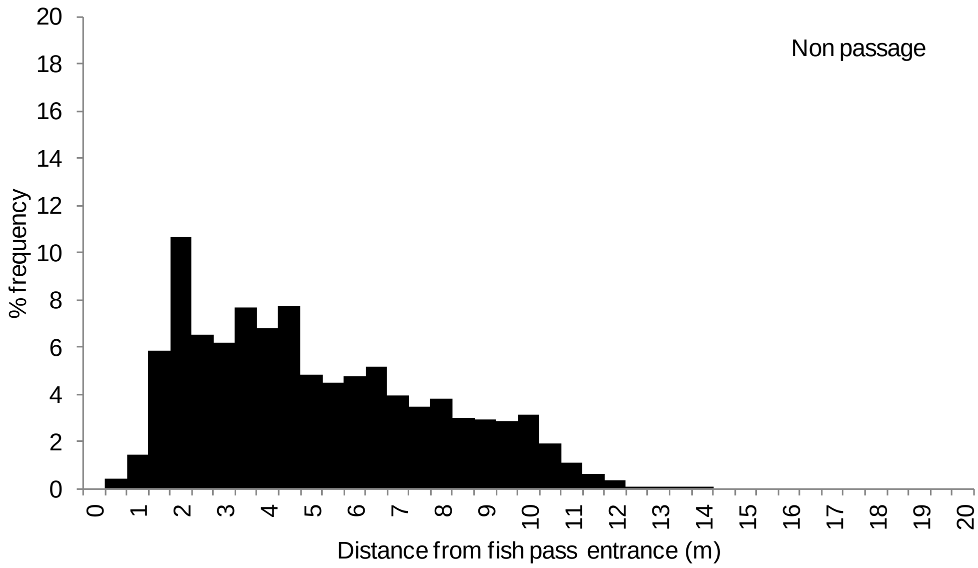


Figure 53. Average time (seconds) spent in each grid cell by sea trout during passage (left) and non-passage (right, excluding fish 2500) visits to the array.



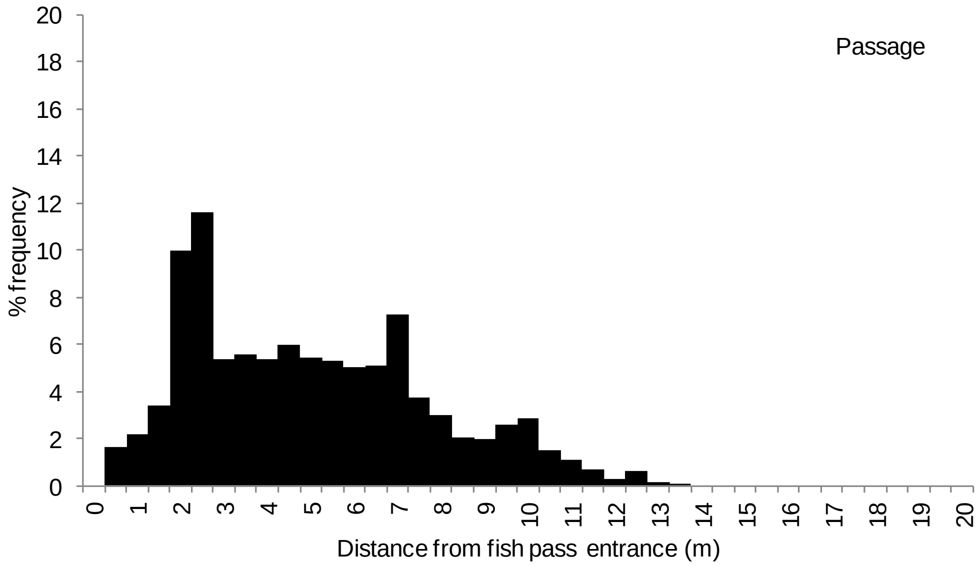


Figure 54. Numbers of tag echoes detected in the array as a percentage of the total number of tag echoes recorded in sea trout passage and non-passage runs, against distance from the entrance to the fish pass.

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 55). 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 56). The frequency of tag echoes decreased with distance above a 2.5 m proximity from the fish pass entrance during the day. This trend is also seen in tracks made during the night although the number of echoes detected around 10m from the fish pass was greater at night than during the day. However this pattern appears to be influenced by the behaviour of a low number of fish. In both day and night tracks the highest tag echo frequencies were within a 1.5-2.5 m proximity of the fish pass (Figure 57). 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)($t(38) = 0.19$, $P = 0.985$).

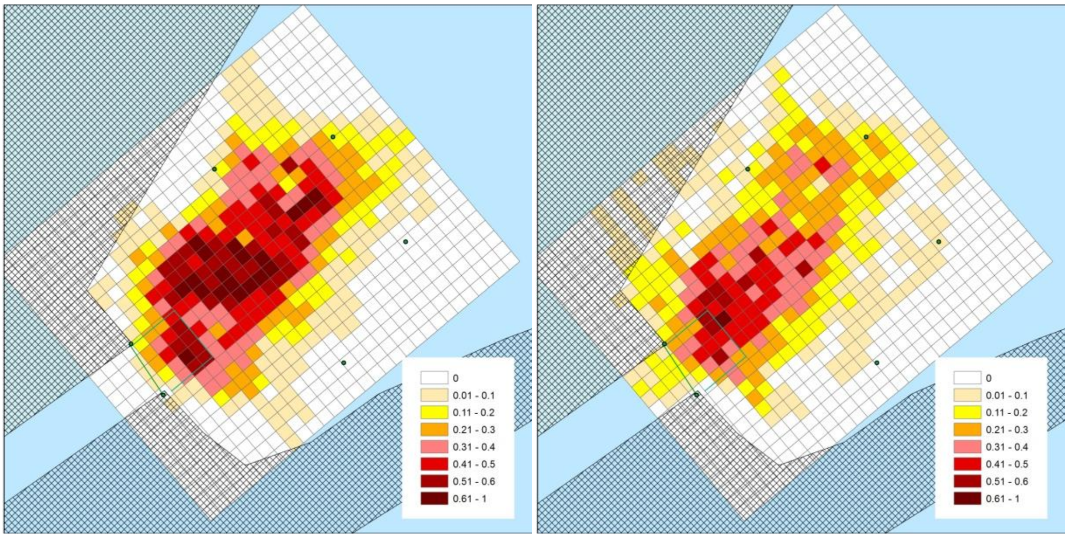


Figure 55. Count of sea trout tracks to pass through each grid cell (standardised by number of tracks in each group) during the day (left) and at night (right).

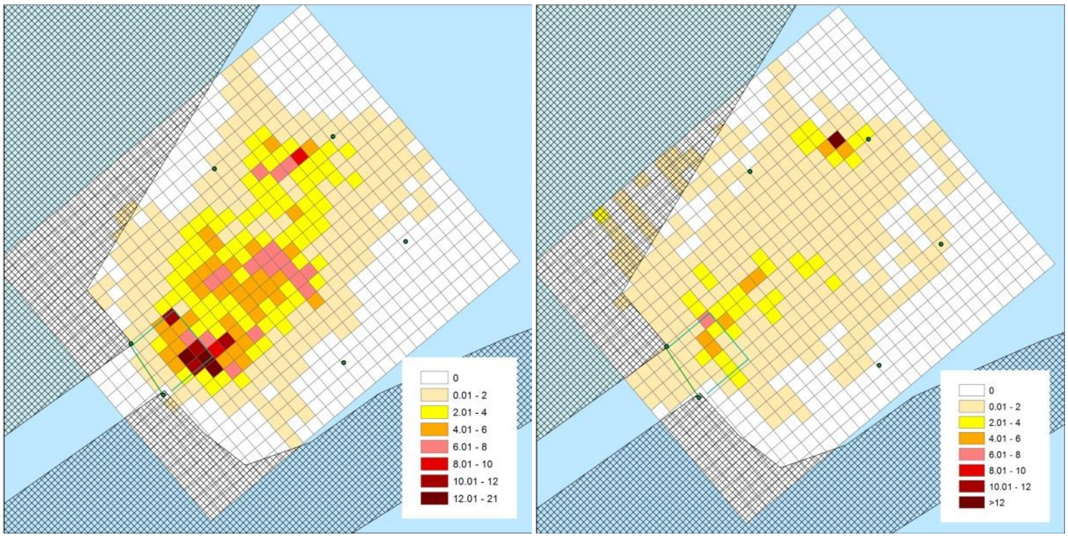


Figure 56. Average time (seconds) spent in each grid cell by sea trout during the day (left) and at night (right).

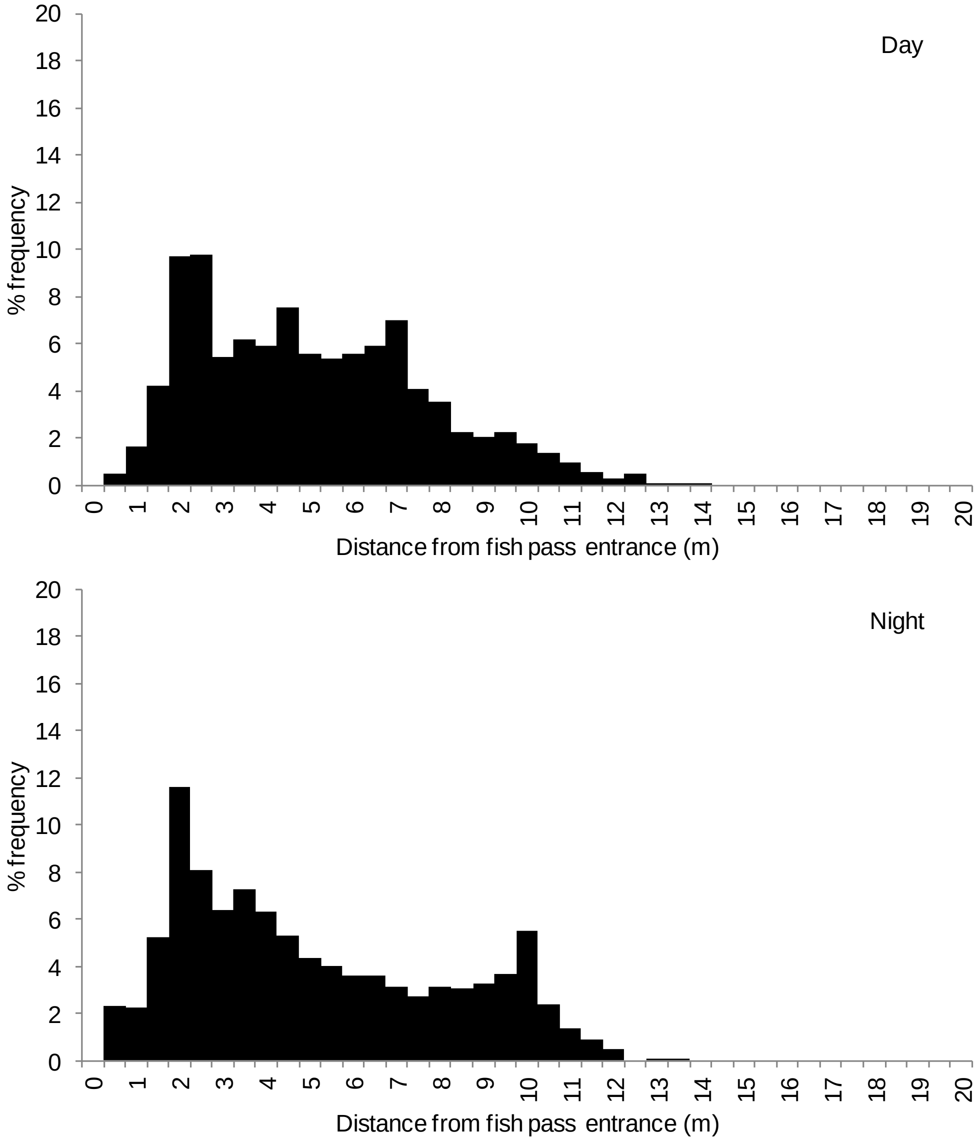


Figure 57. Numbers of tag echoes detected in the array as a percentage of the total number of tag echoes recorded during the day and at night, against distance from the entrance to the fish pass.

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 58: left) but residence time was highest near the fish pass (Figure 59: left). In contrast hotspots of track counts during flooding tides were located at the front of the array, near the fish pass entrance along with residence time hotspots (Figure 58 and Figure 59: right).

Trends in the frequency of tag echoes with distance from the fish pass entrance were similar between ebbing and flooding tides, with frequencies generally decreasing with distance from the fish pass (above a distance of 2.5 m). The highest frequencies of tag echoes were recorded at 1.5 – 2.5 m proximity in ebbing and flooding groups with tracks on ebbing tides occupying locations around 2m from the fish pass a slightly higher proportion of the time (Figure 60).

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 (Kruskall-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 (Kruskall-Wallis test: $\chi^2 = 1.53$, d.f. = 2, P = 0.47).

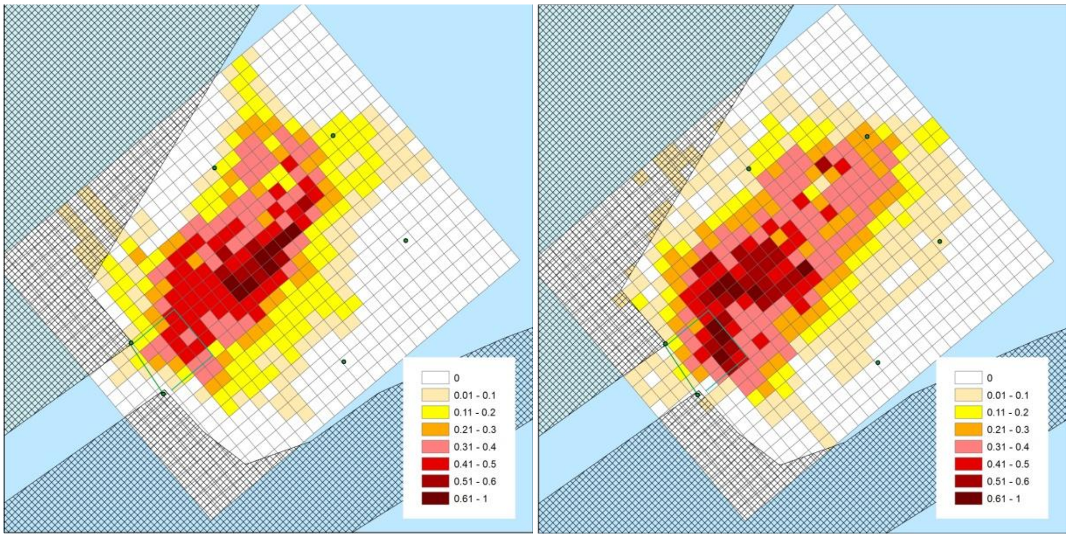


Figure 58. Counts of sea trout tracks to pass through each grid cell (standardised by the number of tracks in each group) recorded during an ebbing (left) and a flooding (right) tide.

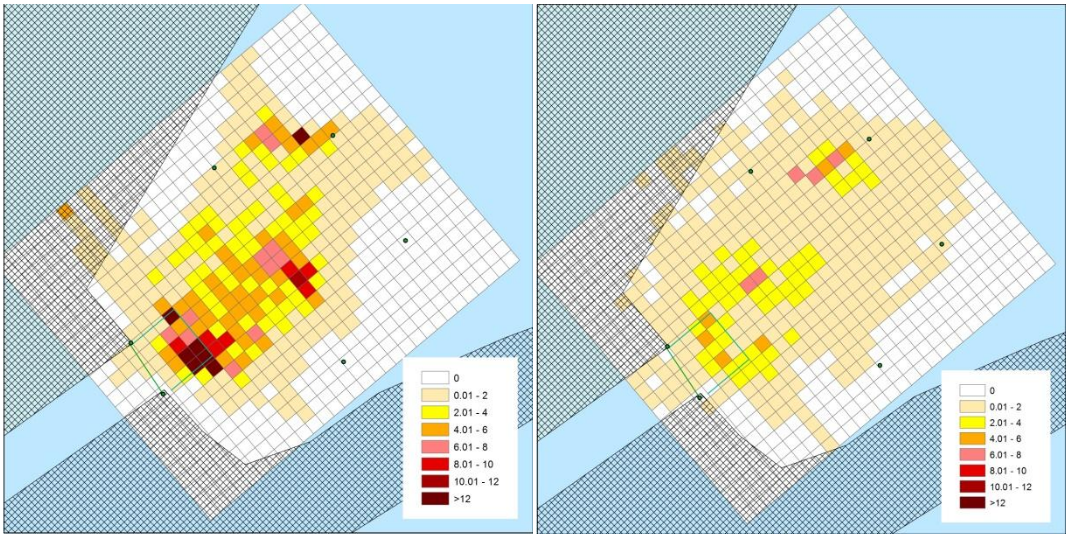


Figure 59. Average time (seconds) spent in each grid cell in sea trout tracks recorded during an ebbing (left) and a flooding (right) tide.

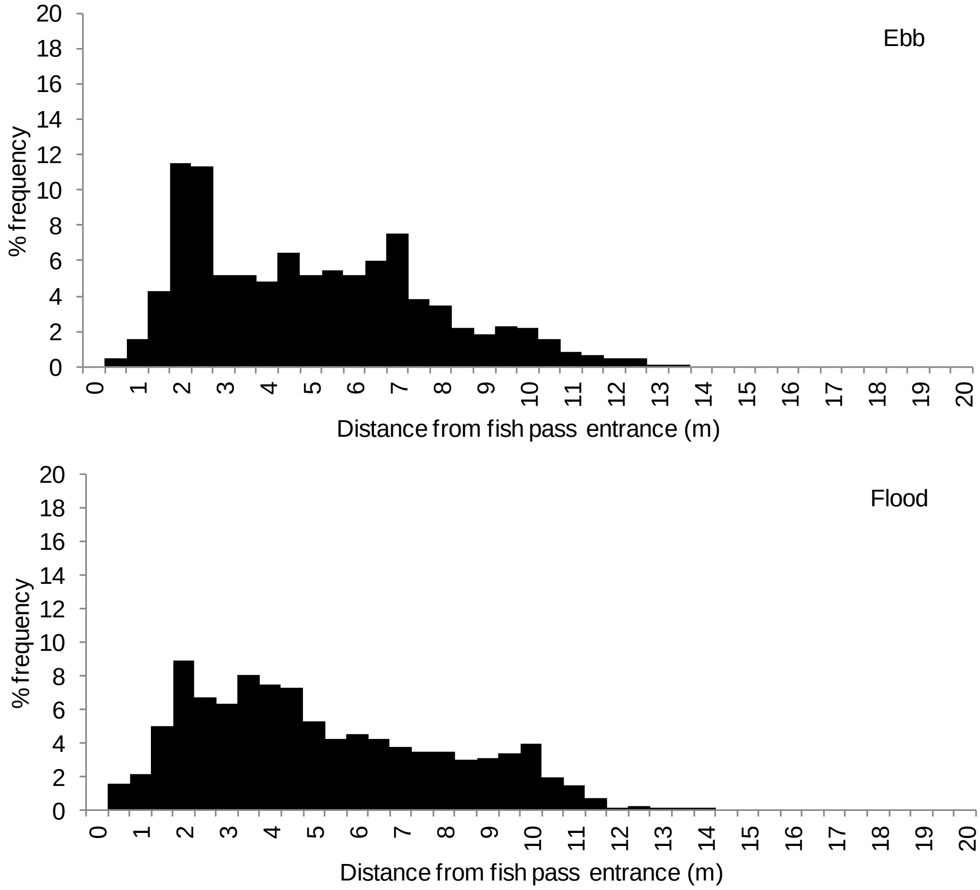


Figure 60. Numbers of tag echoes detected in the array as a percentage of the total number of tag echoes recorded at different tide states, against distance from the entrance to the fish pass.

3.8 Quantitative analysis of micro scale behaviour of salmon within the array

3.8.1 All tracks combined (2011 and 2012)

Salmon tracks from 2011 and 2012 (n = 50) were observed to pass through all grid squares within the footprint of the hydrophone array with the highest number of tracks crossing grid squares towards the left hand side of the array (facing downstream) (Figure 61a). Whilst there appeared to be close overlap in distribution in terms of the number of tracks in each grid square there was no pattern in terms of the average time spent each grid square (on average <5s per square), with just one square exceeding this value towards the mouth of the fish pass (Figure 61b).

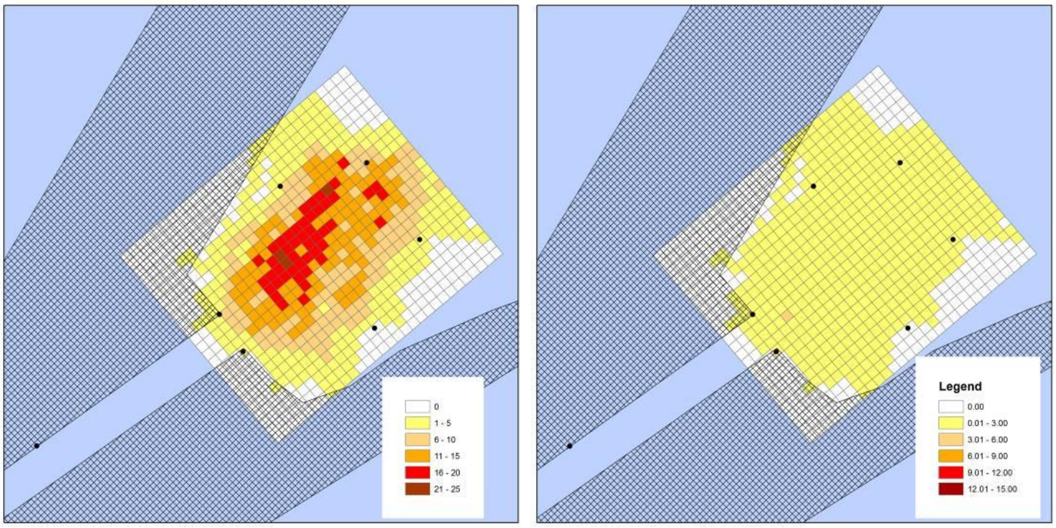


Figure 61. All salmon tracks combined: (a) count of tracks to pass through each grid cell and (b) average time (sec) spent in each grid cell by salmon that entered the array (all tracks combined).

The distribution of all tag echoes within the array exhibited a bimodal distribution with a peak of activity around 2-3m from the mouth of the fish pass and another around 8-9m from the fish pass (Figure 62). One salmon made 102 approaches within 2m of the fish pass entrance during one track; however the average number of approaches during the remaining 49 tracks was 1.4 ± 2.5 with a range of 0 to 11.

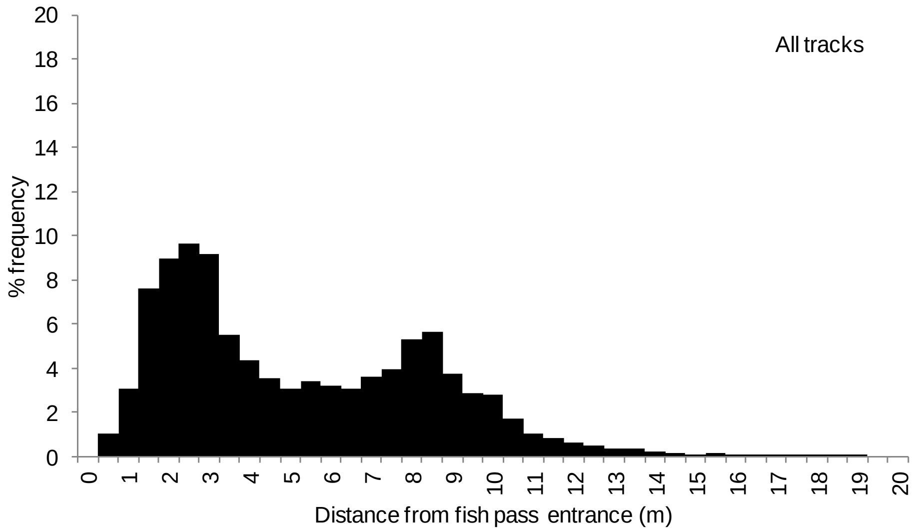


Figure 62. Numbers of tag echoes detected in the array against distance from the entrance to the fish pass (m) as a percentage of the total number of tag echoes recorded.

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

The distribution of salmon activity in the grid indicated that tracks were widely dispersed during non passage milling behaviour with few hot spots in terms of the number of tracks passing through each grid cell (Figure 63b). However, the distribution of passage tracks were more focussed towards the central axis of the grid and the fish pass with nearly all tracks passing through one grid cell in the centre of the grid in line with the flow and the entrance to the fish pass (Figure 63a). As for all tracks the average time spent in each grid square was very low, generally reflecting the low proportion of tracks passing through the same grid cell (Figure 61).

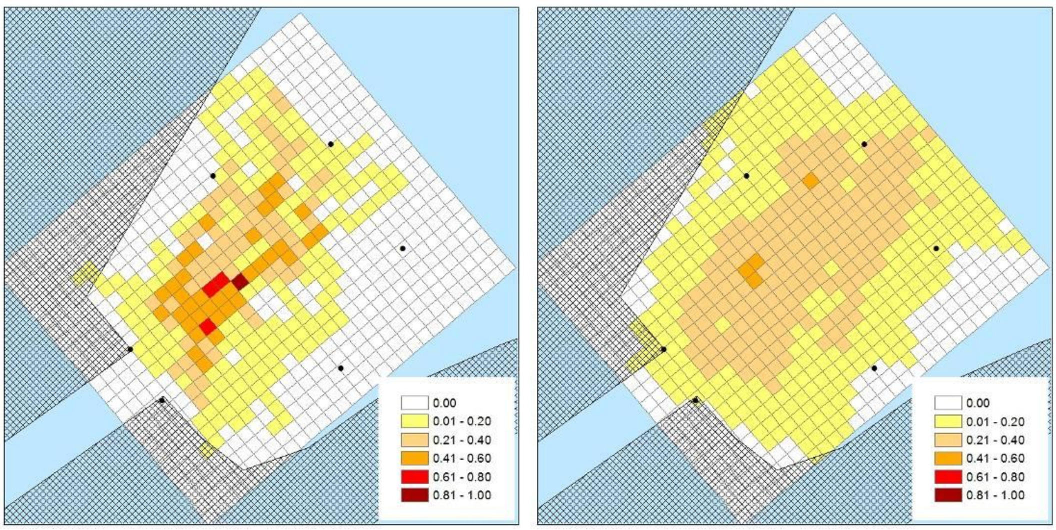


Figure 63. Count of salmon tracks to pass through each grid cell (standardised by number of tracks in each group) during passage (left) and non-passage (right) visits to the array.

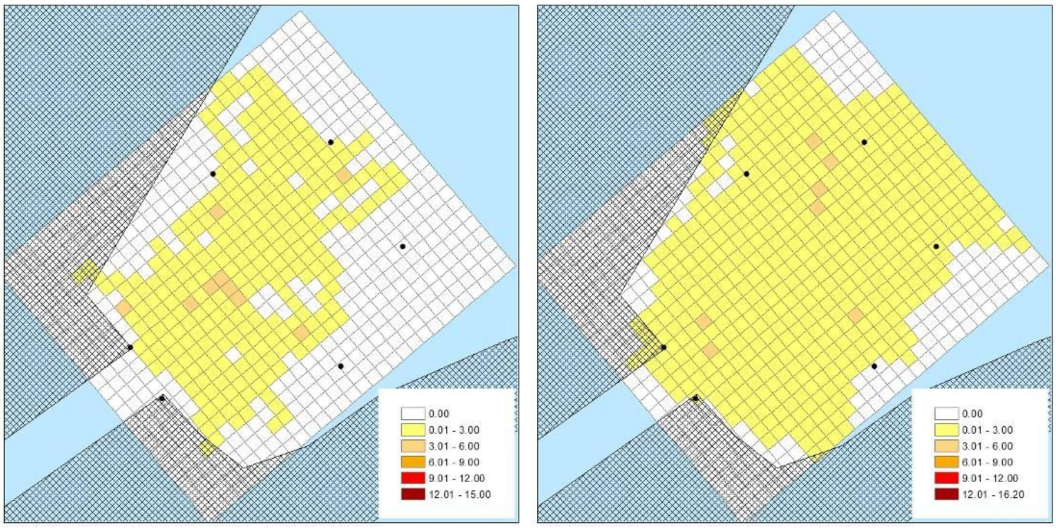


Figure 64. Average time (sec) spent in each grid cell by salmon during passage (left) and non-passage (right) visits to the array.

The distribution of tag echoes in non-passage tracks (n = 43) within the array exhibited the same bimodal distribution seen for all tracks combined (since they were the dominant type of track) with a peak of activity around 2-3m from the mouth of the fish pass and another around 8-9m from the fish pass (Figure 65). Passage runs (n = 7) indicated a peak of activity around 3-4m from the mouth of the fish pass (Figure 65). Excluding the one salmon that made 102 approaches within 2m of the fish pass entrance during one track, the average number of approaches during non-passage tracks was 1.2 ± 2.3 whilst in passage track only two salmon made more than one approach to the fish pass (2 and 11 approaches). There was no significant difference in the number of approaches between non-passage and passage tracks (Mann Whitney U test U = 1.973, n = 50, *P* >0.05).

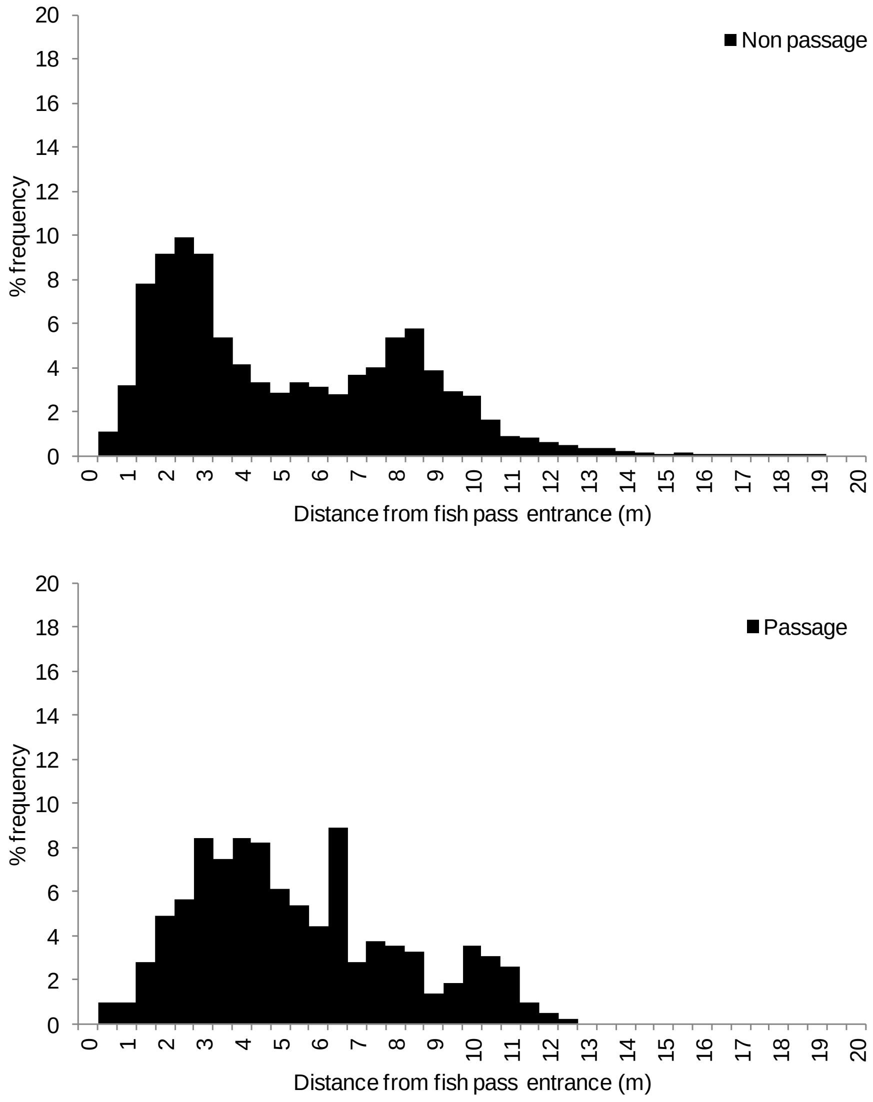


Figure 65. Numbers of tag echoes detected in the array as a percentage of the total number of tag echoes recorded in passage and non-passage runs, against distance from the entrance to the fish pass.

3.8.3 Diel variations in spatio-temporal distribution within the array

The distribution of salmon tracks in the array was similar between day (n = 31) and night (n = 19) although there appeared to be a hot spot for night tracks towards the centre of the array (Figure 66). The average time spent in each grid cell was low and tracks were widely dispersed although again there appeared to be a few areas (one towards the front of the array and one towards the rear) that had a relatively high average occupancy time (Figure 67). Proximity of tag echoes to the mouth of the fish pass showed bimodal distribution in both day and night, although fish appeared to be more active closer to the fish pass at night (2-3m) than during the day (3-4m) (Figure 68). There was no significant difference in the number of approaches between day and night tracks (Mann Whitney U test U = 1.033, n = 50, P >0.05).

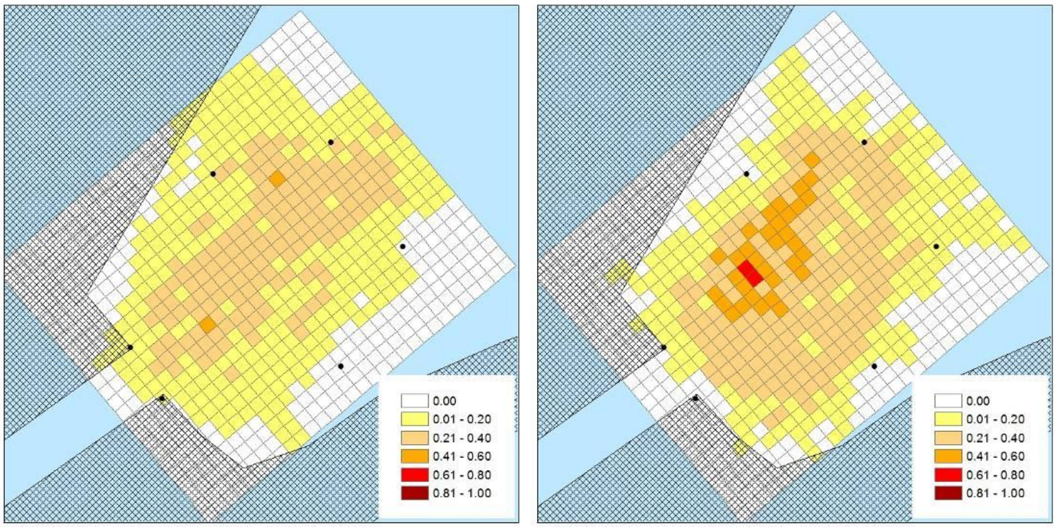


Figure 66. Count of salmon tracks to pass through each grid cell (standardised by number of tracks in each group) during the day (left) and at night (right).

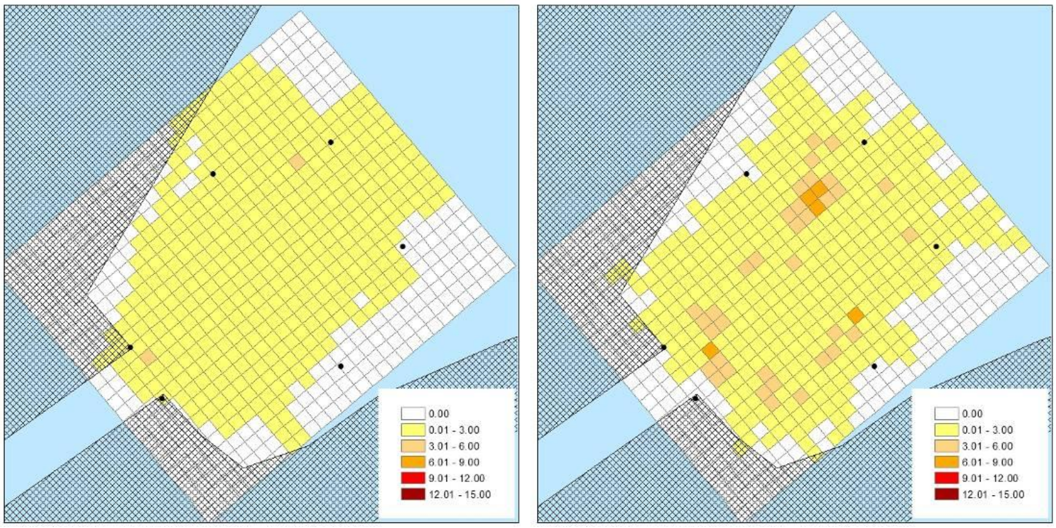


Figure 67. Average time (seconds) spent in each grid cell by salmon during the day (left) and at night (right).

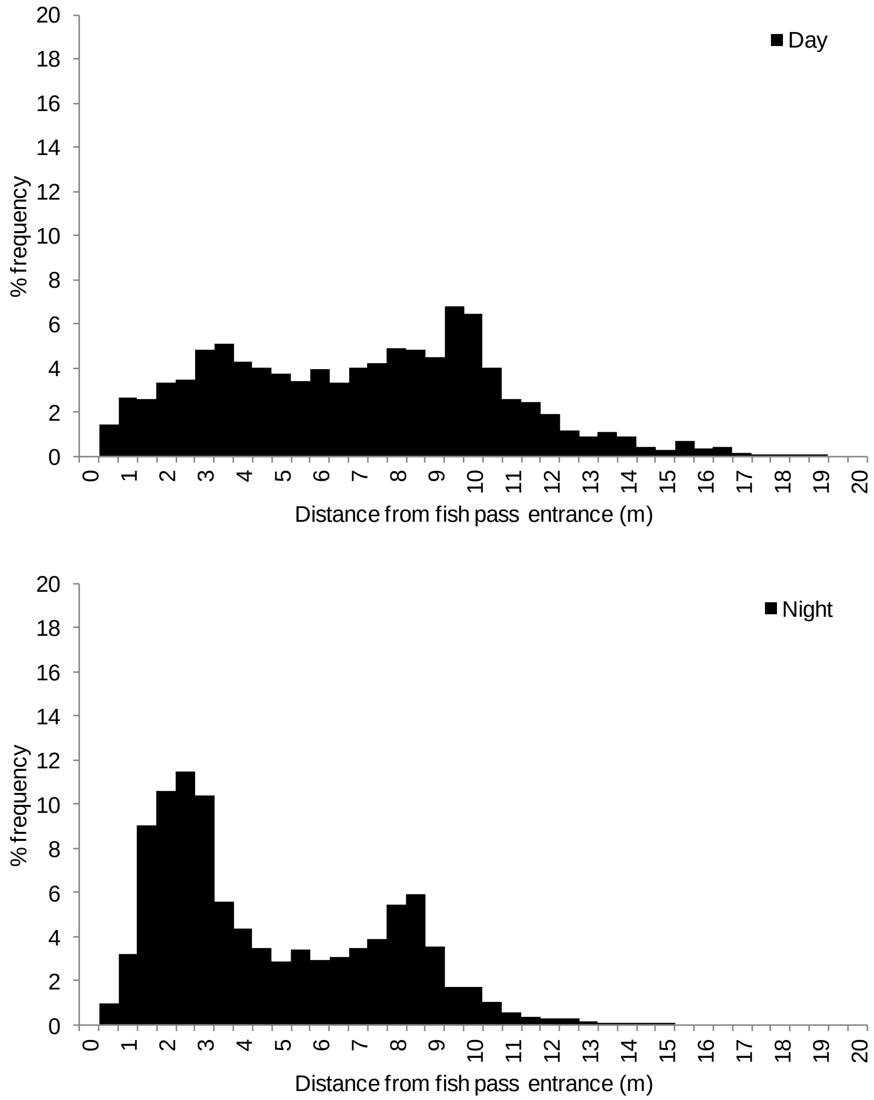


Figure 68. Numbers of tag echoes detected in the array as a percentage of the total number of tag echoes recorded during the day and at night, against distance from the entrance to the fish pass.

3.8.4 Tide state and spatio-temporal distribution within the array

The distribution of tracks in the array appears to be different for the different states of the tide (Figures 69 and 70). Distribution of tracks appeared to be more widespread on a flooding tide than on an ebbing tide, and tracks during a low water slack (although there were only 6 of them) were probably restricted in the approach within the array (hence the apparent hot spots) (Figure 70). The distribution of time spent in the array was similar between ebbing and flooding tide and hot spots were observed for tracks at low water slack (high average times near the mouth of the fish pass) and at high water slack (hot spots at the rear of the array). This pattern was highlighted by the distribution in proximity of tag echoes to the mouth of the fish pass (Figure 71). However, given the relatively low number of tracks for low water and high water slack this pattern should be treated with caution (n = 6 and n = 5 respectively).

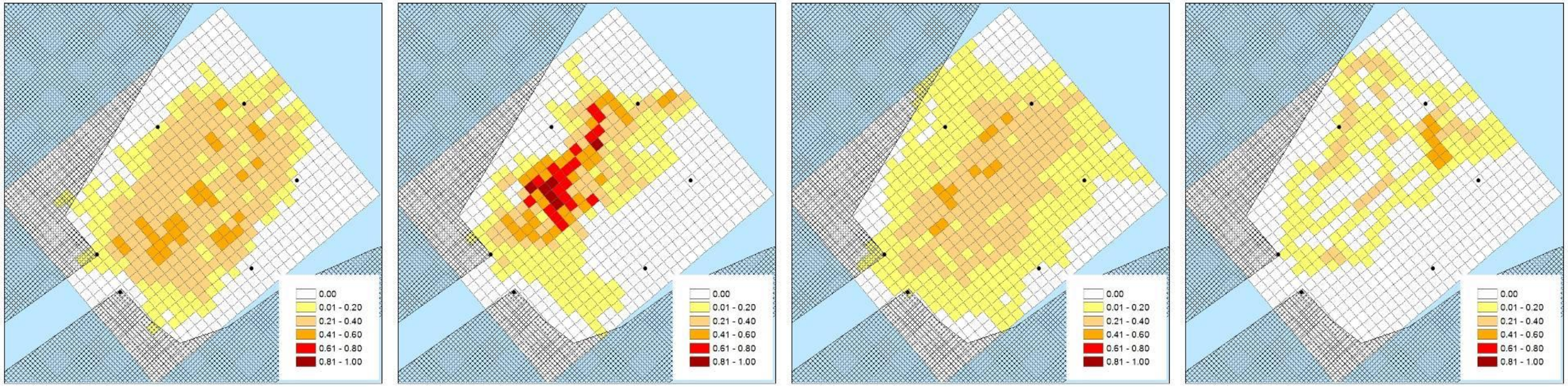


Figure 69. Counts of salmon tracks to pass through each grid cell (standardised by the number of tracks in each group) recorded during an (a) ebbing, (b) low-water slack, (c) flooding and (d) high-water slack tide.

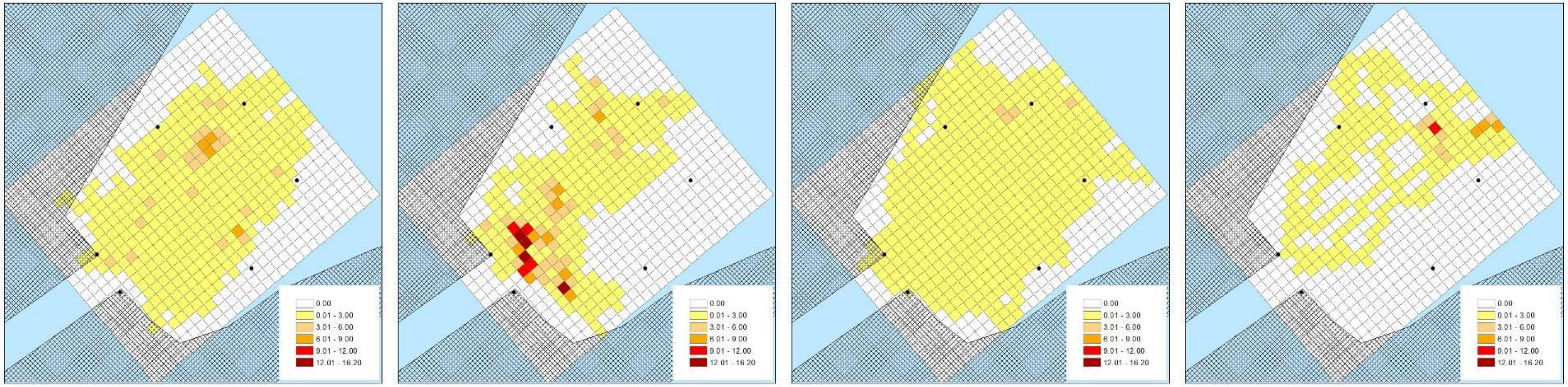


Figure 70. Average time (seconds) spent in each grid cell in salmon tracks recorded during an (a) ebbing, (b) low-water slack, (c) flooding and (d) high-water slack tide.

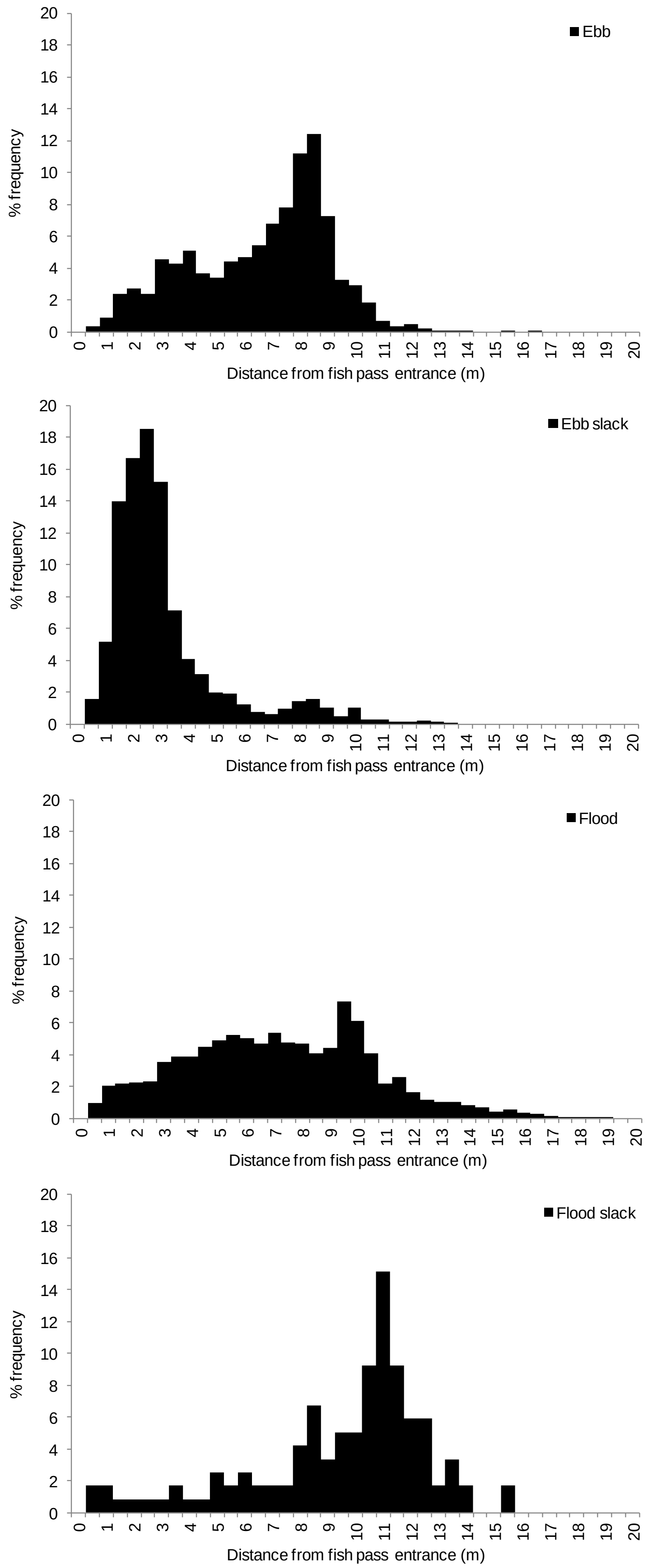


Figure 71. Numbers of tag echoes detected in the array as a percentage of the total number of tag echoes recorded at different tide states, against distance from the entrance to the fish pass.

3.9 Array entry

The predominant route for entry into the array was from immediately downstream (B), with 49 first tag echoes in sea trout tracks (57%) and 25 first tag echoes on salmon tracks (50%) recorded between these points (Table 5). Route A (entry from towards the left hand bank) with 25 sea trout tracks and 16 salmon tracks appearing in this location, was the second most used route. Only one entry was observed by route C (a sea trout in 2011) and the entry of 19 tracks were indeterminate.

Table 5. Analysis of all fish tracks that enter the array by routes A, B and C for salmon and sea trout in 2011 and 2012.

Year	Entry in to array	Species Salmon	Sea Trout
2011	Indeterminate		7
	A	2	13
	B	1	16
	C		1
2012	Indeterminate	8	4
	A	14	12
	B	25	33
	C	0	0

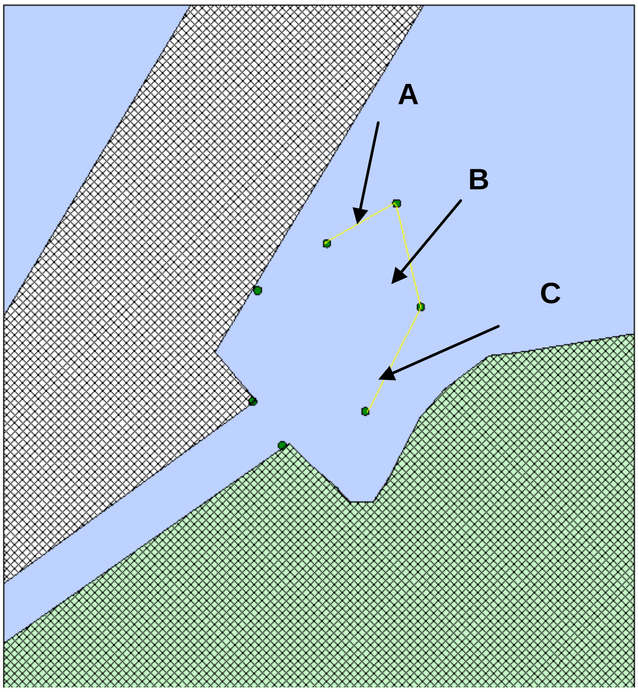


Figure 72. Analysis of all fish tracks that enter the array by routes A, B and C.

4 Discussion

4.1 Overview study findings

This report summarises the extended baseline for 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 in 2011 and 2012. The report includes an analysis of the extended dataset for sea trout and an analysis of the limited data for salmon micro-behaviour around the existing fish passage facilities. The extended sea trout dataset can be used to determine any effects of the hydropower scheme and where possible to evaluate mitigation measures proposed to ensure that upstream fish passage is not compromised. The micro-behaviour of sea trout established in 2011 and reported by Walton et al. (2012) is replicated here. This report should be viewed as an extension of that report to include an insight into salmon micro-behaviour.

Over both years comprising the pre-implementation study 48 sea trout and 14 salmon were tagged for tracking. Of these 13 of the salmon were tagged in 2012 following a disproportionally high sampling effort to obtain them (during the same surveys around 100 sea trout were captured). Of the tagged fish 6 salmon (43%) and 17 sea trout (35%) were detected within the hydrophone array, 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). Unfortunately, the two mobile loggers used to detect movements of tagged fish downstream of the weir were not operational due to developmental issues the manufacturer could not address. It must be noted that the study period was short in 2011 (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). The study period was longer in 2012 (starting in mid August) although few fish were running around this time and the majority of fish studied migrated during September and October. Unfortunately, flow conditions in the River Esk vary dramatically both intra- and inter-annually (Figure 25), 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.). This contrasted with 2012 which was characterised by higher than average flows and a number of exceptionally large flood events during the study period. This discharge regime also influenced the timing of sampling and tagging activities in 2012 as a number of surveys had to be cancelled due to unfavourable and dangerous flow conditions.

Five of the salmon and all of the sea trout that were detected in the array were also observed to pass the weir. Of these two sea trout were also observed to descend via the fish pass some time after their initial upstream migration. Additionally in 2012 two salmon were observed to pass the weir for a second time a considerable period after their initial passage (around 3 weeks).Of the fish detected in the array, most (66% of salmon and 70% of sea trout) ascended within 48 hours of release and five fish did so within 6 hours (one within 20 minutes), highlighting that upstream migration was not compromised by the tagging procedure. All but one fish detected in the array successfully ascended the weir over the two years. In 2011 15 fish were known to ascend the weir and of those 11 were confirmed to ascend through the pool-traverse pass, 2 were confirmed to ascend via a route to the side of the weir and 2 fish ascent routes could not be confirmed giving a passage efficiency for the old pool-traverse weir of between 73-87%. In 2012 all but one of the fish detected in the array was observed to pass the weir and all of those were confirmed to ascend the new Larinier pass giving a passage efficiency of 88%. In 2011 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). In 2012 all fish ascended via the fish pass (this was confirmed by the use of H1 within the fish pass itself). When the new Larinier fish pass was constructed in summer 2012 a new elver pass was installed in the location that fish had previously traversed via the side of the fish pass. It is not clear whether the presence of this elver pass may have affected the ability of fish to traverse the weir via this route at elevated flows. The elver pass was in place throughout the 2012 study period although it was removed in late 2012. 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 3). Eight fish entered the array only once before ascending. There were no clear patterns in relation to the timing of movements and these seemed mostly to be related to the time that the fish were initially captured and release, with most fish passing within 1-2 days following release.

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 flooding tides (Stasko, 1975; Brawn, 1982; Potter et al., 1992; Priede et al., 1988), but there appear to be differences between rivers 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 sea trout 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. 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 sea trout tracks from 2011 were overlaid, 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 spent 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.

Sea trout 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).

This report also presents insights on behaviour from micro-scale analysis for salmon, although this is severely limited by the sample size (6 fish, 50 tracks [43 non-passage, 5 ascents and 2 second ascents]). When all salmon tracks were overlaid, most cells within the grid are intersected by at least one track and the area within the array is well covered by multiple tracks. The analysis of the number of tracks indicated that most tracks passed through the centre of the grid and the area in front of the fish pass. The sum of all time intervals in each grid cell revealed few hot spots and time was spent throughout the pool.

Location data for salmon tracks exhibited different patterns in proximity to the fish pass for the different groups of tracks (i.e. passage, non-passage, day, night, ebbing tide and ebbing/flooding tide). This was particularly apparent for tracks during different stages of the tide when fish were more active closer to the mouth of the fish pass on low water slack but were more active towards the rear of the grid during high water slack. Also, non passage tracks appeared to exhibit a bimodal distribution in activity in respect to proximity to the fish pass. The reason for this is unclear and the result should also be treated with caution given the low sample sizes both in total number of salmon and the number of tracks associated with high and low water conditions.

Analysis of non passage behaviour of sea trout and salmon indicated that some fish exhibited unusually protracted behaviour in the array. During the study a four of fish exhibited protracted activity in the array prior to first passage (more than 4 tracks prior to first passage). For example in 2011 one sea trout made 14 approaches to the array and fish pass during the period of study before finally ascending the pass, again in 2012 one sea trout made 40 visits to the array over a prolonged period before it ascended the weir and also spent an unusually large amount of time occupying a location at the downstream end of the array. In 2011 the fish was the smallest sea trout tagged (380mm) whereas in 2012 this fish was a relatively large sea trout (527mm) but was active during relatively low flows at the start of the study (only ascending after a small freshet). Other than the very small sea trout, the other three fish that exhibited protracted activity were all active early in the season (August/September) and all at flows below $2m^3s^{-1}$. Most other fish were observed to be active at flows between 3 and 6 m^3s^{-1}. It is therefore possible that, although passage is still possible below 2 m^3s^{-1}(one of the fish with protracted behaviour passed at a flow <1 m^3s^{-1}), passage of the weir may be restricted at low flows. It is also possible smaller individuals are less committed and physiologically able to negotiate the flows in the weir and that at this early time of year some other cues for migration were not present, although this could not be confirmed from the present study. Therefore, it is possible that whilst data for fish from most tracks can be pooled within each species for future analysis, there may be different migratory behaviours observed relating to different individuals, sizes of fish and/or different seasonal behaviours that may need to be considered in future analyses.

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 lowest flow of water in the 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). 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 either the old or new 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).
- 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 changed with the installation of the new Larinier pass and installation of the elver pass (although later removed). Whilst no fish were observed to pass via the side of the fish pass (or indeed via the baulk pass) in 2012, its altered conditions may influence the performance of the fish pass itself.

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 in 2011 and abnormally high spate conditions in 2012 and it is unclear whether the distribution of movements across the grid presented truly represent the situation under more normal autumn flow conditions. However, given both extremes are included in the baseline more confidence can be gained than from the use of a single year's data as a baseline.

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. Two downstream movements through the fish pass were observed (sea trout) over the period and a further two salmon were observed to ascend the fish pass twice (around 3 weeks after their initial upstream passage), it is possible that more fish may have moved downstream passage outside of the fish pass although this could not be determined. Given the timing of these movements it appears these are fish that should still be undertaking upstream migrations prior to spawning. In 2012 these downstream movements could be associated with potential displacement during spates and/or fish being unable to pass Sleights Weir further upstream.

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 the baseline, a hydrophone was placed in the fish pass (giving a definitive identification of ascent route). Unfortunately in 2012 the hydrophones that were 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) encountered technical problems for which the manufacturers were responsible. This is a significant flaw in the study design and every effort should be made to address this in future studies. 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

The Archimedes screw turbine was installed in 2012 and once the turbine becomes active (2013), 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.

Contractor's were employed by the EA to co-ordinate and manage the pre-installation phase (2011 and 2012), 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 (as in 2012) - provided the staff are trained to electric fish and posses 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).

The low numbers of salmon tagged and the very high effort taken to catch them, relative to the numbers of sea trout caught over the same period, highlight the significant risk of putting too much focus on salmon as the indicator species for the post-implementation assessment of the hydropower scheme. The dataset for salmon (6 fish tracked out of 14 fish tagged) provides a very limited dataset in terms of general inference and statistical robustness. Whilst salmon are obviously an important species, both as a fishery and in terms of the conservation status of the Esk SAC, it is recommended that most effort is put into providing a robust assessment of the hydropower scheme using sea trout as the baseline model species whilst using any salmon available to provide an additional insight into their micro-behaviour around turbines and fish passes.

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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 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: An 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.

Appendix 1

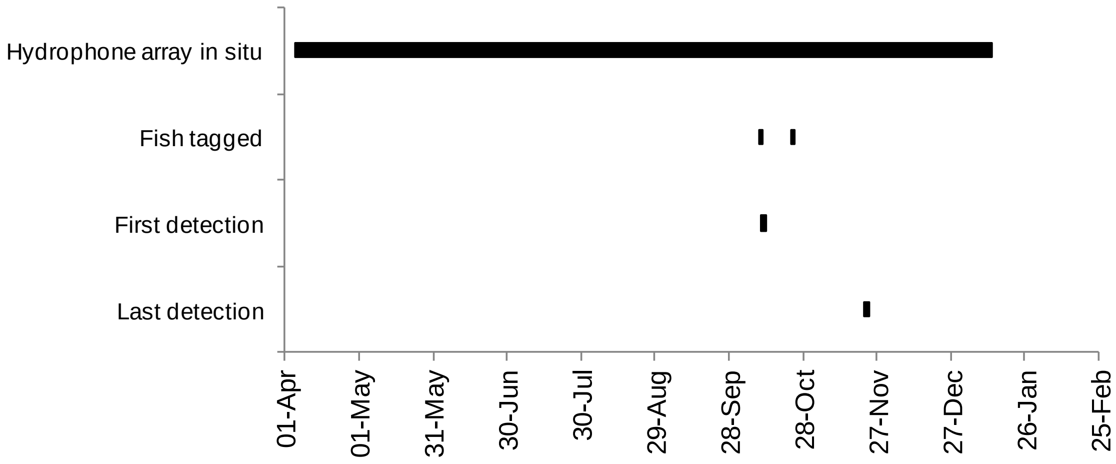
Summary of fish tagged in 2012

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

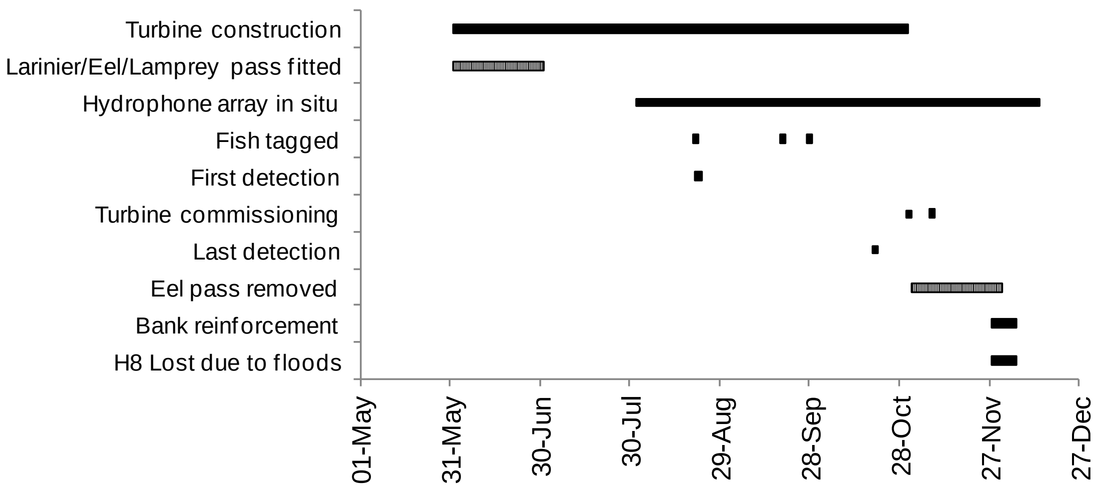
Summary of fish tagged in 2011

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



Time Line 1 – Events during monitoring for 2011



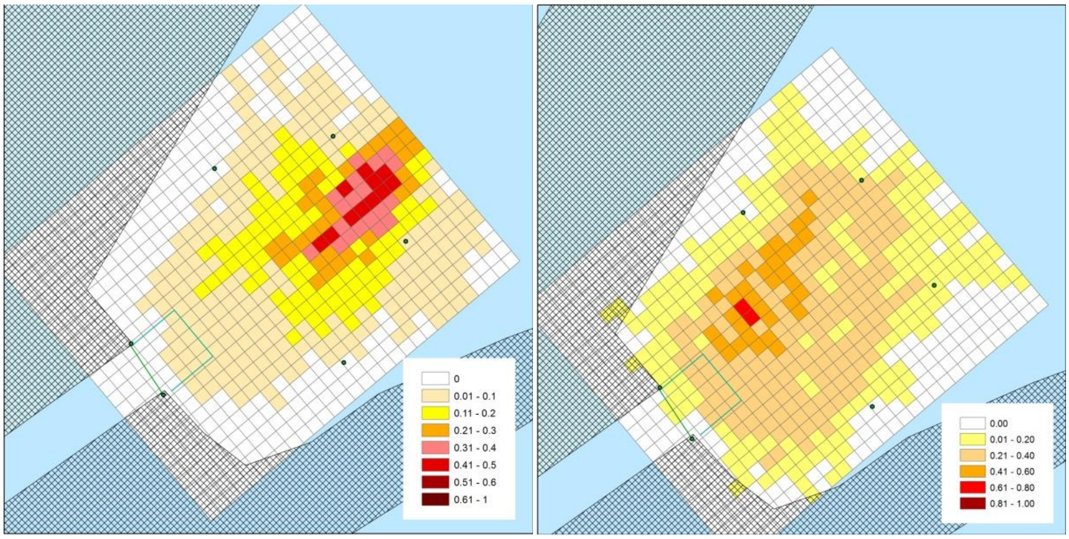
Time Line 2 – Events during monitoring for 2012

Appendix 3

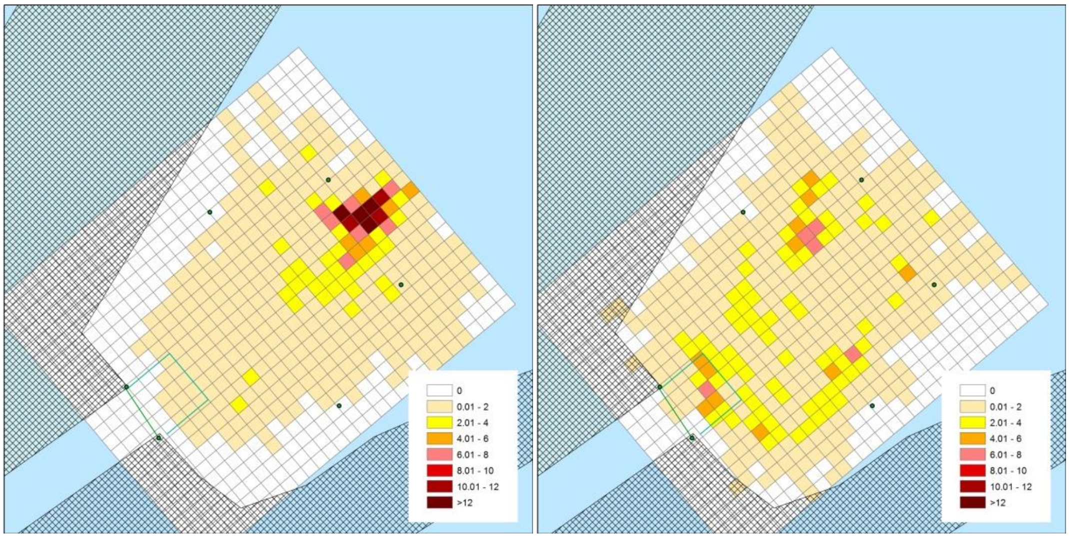
Data from a previous tracking study (July-September 2010) carried out by the Environment Agency.

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 4



Proportion of tracks of sea trout 2500 (2012) to pass through each grid cell during the day (left) and night (right).



Average time spent by sea trout 2500 (2012) in each grid cell during the day (left) and night (right).

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