# MIGRATION OF ATLANTIC SALMON (*SALMO SALAR*) SMOLTS AND POST-SMOLTS FROM A SCOTTISH EAST COAST RIVER.

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# 1. Abstract

The near-shore migratory behaviour of Atlantic salmon (*Salmo salar,* Linnaeus 1758) migrating to sea for the first time is poorly understood. This study aims to assess whether salmon smolt survival is consistent along the River Dee in Aberdeenshire, through Aberdeen harbour and early in their marine migration out to ten kilometres from shore. This study also looks at the patterns of directional movement in the sea during the first 10 km of post-smolt migration to distant feeding grounds and provides estimates of missed detections based on range testing and simulation results.

One hundred and sixty wild salmon smolts were implanted with acoustic transmitters (tags) in three tributaries of the Aberdeenshire Dee in 2017 (n=60) and 2018 (n=100). Several tags each year were capable of transmitting temperature and depth (2017 n=15, 2018 n =40) readings. These temperature depth tags were used as a proxy for predation. Smolt progress down river and out to sea was monitored remotely by a large array of Acoustic Listening Stations (ALSs), moored in the river (individual receivers), harbour and marine environment (gates of ALSs). One marine gate (IN), consisting of 35 receivers was deployed in 2017, four kilometres from the mouth of Aberdeen Harbour. In 2018, a second marine gate (OUT) was added, consisting of 98 additional receivers 10 km from the mouth of Aberdeen Harbour. In addition, an Acoustic Doppler Current Profiler (ADCP) was deployed in 2018, to measure marine currents allowing for determination of the actual swimming vectors taken and speeds of post-smolts at sea.

Using detections as a proxy for survival and lack of detection as a proxy for mortality (this must be treated with some caution as some tags may not be in the original study animal and might still be counted as surviving or fish passing a receiver without being detected, tag failure or tag ejection might account for some of the presumed mortality); mortality was different in Aberdeen Harbour and in early marine migration between years. The upper river in 2017 shows that of the 46 fish tagged at Dinnet Burn only 25 (54%) were later detected in the river. In 2018 five (83%) of the six fish tagged at Dinnet were later detected in the river. In 2017, all 33 tags that left the lower river passing the last river ALS (R12) and entered Aberdeen Harbour (H1) successfully migrated through the harbour (leaving the last gate of ALS (H2)). However, in 2018, of the 83 tags that left R12, three tags (3.6%) were not

detected entering at the H1 gate and a further three tags failed to successfully migrate through Aberdeen Harbour. The highest mortality rate (5.3 % $km^{-1}$) was recorded was between H2-IN gates in 2017, where seven smolts (21.2% of the remaining smolts) were not detected again. In 2018 the highest mortality rate (5.1 % $km^{-1}$) was between R12-H1 gates where three smolts (3.6% of remaining smolts) were not detected again. Mortality and mortality rates were similar to that found in other studies. One tag (2.2% of the remaining temperature and depth tags) in this study showed a temperature spike indicating a predation event by a warm-blooded predator (either bird or mammal). Two further tags (4.4% of the remaining temperature and depth tags) showed unlikely depth profiles suggesting evidence of predation by a marine fish.

The most parsimonious model predicting smolt river migration success (binomial) showed year of tagging as by far the largest effect. Variables that had a marginal effect (explaining some variation) include: Tag burden (by length), tag burden (by weight), group size and river flow at time of release.

The bearings taken by individual fish between H2-IN were not significantly different between years (in 2017 106$^{o}$ from north and 2018 96$^{o}$ from north). However, in 2018, bearings were significantly different between the H2-IN gate (96$^{o}$ from north) and between IN-OUT gate (128$^{o}$ from north).

The ADCP data were used to account for the effects of current. After correction, the mean actual headings taken by individual fish between H2-IN gates were not significantly different between years but the mean heading between H2-IN and between IN-OUT gates in 2018 remained significantly different. Between IN-OUT gates fish were swimming actively on a mean heading of 158$^{o}$ from north (circular sd ± 37$^{o}$) and at a median speed of 0.57 $ms^{-1}$ equivalent to 3.98 body-lengths $s^{-1}$.

This study highlights how smolt migration patterns vary greatly between years in a river with very few manmade structures, a busy harbour and during the construction of a wind farm. However the study also indicates that the majority of smolt losses occurred during the river migration in 2017 and 2018, however when considered as a percentage loss per kilometre the greatest loss occurs in the early marine environment in 2017 (5.30 (%) $km^{-1}$).

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# Acknowledgements

It takes a major effort to successfully capture and tag smolts in a river, and then deploy moorings in the river and sea to monitor their progress. I could never have managed any of this without many other people, all of whom were critical to the work. Dr Francis Neat jumped at the chance to support this project and me providing most of my training in tagging and fish handling, and along with Dr James Thorburn, deserves major thanks.

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# Author’s Declaration

I hereby declare that the material presented in this thesis is the result of original research, conducted between September 2016 and January 2019, under the supervision of Professor Colin Adams and Dr. Ian Davies. This work has not been submitted towards the fulfilment of any other degree and is based, for the most part, on individual research carried out by myself. The current predictions and modelling used to estimate smolt vectors in 2017 was completed by Dr. Barbara Berx at Marine Scotland Science but the analysis is fully my own work.

Printed Name: Robert A.K. Main

Signature: ___________________________

# 2. Introduction

## 2.1. Background

The Atlantic salmon (*Salmo salar,* Linnaeus, 1758), is an anadromous fish species which spawns in freshwater and does much of its growing to sexual maturity in the marine environment. Atlantic salmon is an iconic species in Scotland and has significant conservation and economic value worth ca. £80 million to the Scottish economy (Malcolm et al., 2019; PACEC, 2017). The natal rivers of Atlantic salmon are distributed throughout the North Atlantic, from Spain to Norway including the United Kingdom and Ireland, the Russian Kola Peninsula, Iceland and Greenland and down the Eastern Canadian and American coast to Maine (Youngson and Hay, 1996). Atlantic salmon hatch from eggs laid in the gravel of a freshwater river. After a period of time in freshwater, most depart the river and head to feeding grounds in the high seas. Some however, reach sexual maturity without leaving freshwater though this is more common for males and unusual for females (Shearer, 1992). The simplified anadromous life cycle is shown below in Figure 2.1.

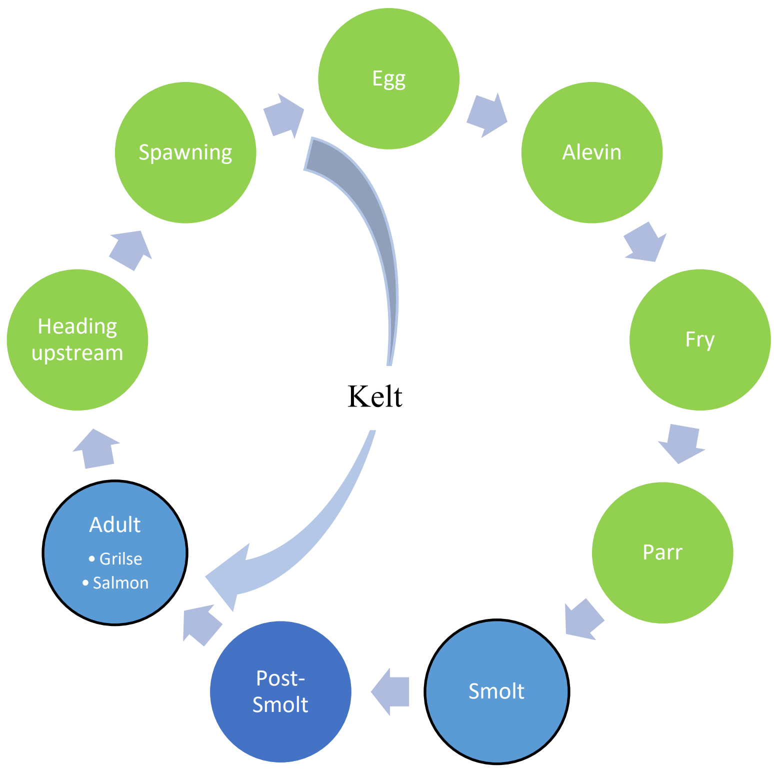



Figure 2.1: the Atlantic salmon lifecycle adapted from Shearer (1992) This is split into river (green), high seas feeding (dark blue) and life stages which straddle both the river and high seas (light blue with dark border). Kelt migration is shown re-joining the adult population at sea.

Allan & Ritter (1977) defined seven life stages for Atlantic salmon: alevin, fry, parr, smolt, post-smolt, salmon and kelt. Three phases of the salmon lifecycle occur solely in freshwater. These are the alevin, fry and parr stages.

The alevin stage is relatively brief, lasting days to a few weeks during which the freshly hatched salmon is still attached to its yolk sack and still residing in the redd. Fry and parr usually spend between one and seven years in the river (up to seven years in the most northerly parts of the salmon's range and more commonly between 1-3 years in Scotland) (Gurney et al., 2008; Malcolm et al., 2019). Parr then undergo morphological, physiological and behavioural changes becoming smolts. McCormick et al. (1998) and Thorpe & Morgan (1978) summarized the process by which this smolting occurs. The changes prepare the fish for, and allow them to make, a migration down river and eventually enter the sea. Wild smolts usually weigh 10-80g (Thorstad et al., 2012b). Morphological changes include increasing in length, silvering of the body and darkening of the fins margins. Physiological changes help the smolt adapt to the demands of the marine environment. These include changing visual pigments, an increasing salt tolerance through the development of chloride cells in the gills (McCormick et al., 1998). Behavioural changes include increased shoaling and negative rheotaxis (downstream orientation). A reduction in territorial behaviour and aggression are thought to aid shoaling(McCormick et al., 1998).

Smolts rapidly migrate down river when conditions are optimal, usually in spring to early summer (Thorstad et al., 2012b). Baggerman (1960) described the morphological, physiological and behavioural changes as 'primers' with the optimal conditions being the 'releasing' factors allowing migration to proceed. From studies mostly in Norway, America and Canada, we have learnt a great deal through recent acoustic and data storage tagging (DST) work on the behaviour of smolts as they migrate down river (Thorstad et al., 2012b).

When a salmon enters the marine environment, until the end of their first winter at sea, they are termed post-smolts (Allan and Ritter, 1977). Very little is known about the movement and behaviour of post-smolts from Scotland (Malcolm *et al.*, 2010). Post-smolts have been shown to migrate long distances in the sea (Finstad et al., 2005; Lacroix and McCurdy, 1996; Thorstad et al., 2012b). Malcolm et al. (2010) presented the findings of smolt tagging studies in Scotland including from the Girnock Burn (a tributary of the Aberdeenshire Dee). At about the peak of activity of a marine fishery for salmon off the coast of west Greenland (ca.

1973), 57 post-smolts from the Girnock were captured feeding West of Greenland. Similar findings were reported for smolts tagged in other Scottish rivers (Dee, Tay and North Esk) (Malcolm *et al.*, 2010). Studies conducted using trawling to specifically target post-smolts off the Scottish and Norwegian coasts also caught Scottish origin post-smolts (Holm et al., 2000; Shelton et al., 1997). In addition, a great deal of sampling effort has been expended around Norway after post-smolts were reported as by-catch in the herring fishery there. This work culminated in the SALSEA-Merge Project (Holm et al., 2000). The work was continued by Fisheries Research Services (FRS, now Marine Scotland Science) and the RV Scotia undertook dedicated and opportunistic sampling cruises with some success (Shelton et al., 1997; Turrel et al., 1997). The evidence suggests that Scottish Atlantic salmon post-smolts may migrate into the Norwegian Sea and can also make much further migrations to feed off West Greenland.

After a lengthy migration, salmon return after one (1SW) or multiple winters at sea (MSW), to spawn in their natal rivers into which they navigate with great precision (Menzies, 1949). There is some straying where occasionally adults will return to the "wrong" river but this affects <3-6% of returnees (Jonsson et al., 2003; Stabell, 1984). Adult salmon can return in all months of the year, with peaks in spring, summer and in some rivers, autumn. Salmon returning to rivers in the spring and autumn are usually MSW fish with the summer months dominated by 1SW fish (colloquially known as grilse). The proportions of 1SW to MSW fish can vary from year to year and river to river (Shearer, 1992). Atlantic salmon can reach over 30kg in weight but are more commonly are between 3 and 6kg.

Once adult salmon have spawned, survivors migrate downriver and return to sea. They are termed kelts until they return to salt water.

The abundance of adult salmon returning to home waters has declined by as much as 70% for some components of the stock across much of the species range over the last 30 years (Chaput, 2012), pointing towards the species being under considerable pressure. The decline in returning adult numbers has been associated with higher mortality during marine migration (ICES, 2014). The total nominal catch for the North-East Atlantic Commission area (NEAC) has decreased from a high of over 4500 tonnes in 1973 to around 960 tonnes in 2018 (ICES, 2019). The reductions in numbers returning in early years were offset in part by this decrease in exploitation by coastal, estuarine and in-river fisheries (Gurney et al., 2015). However adult numbers have continued to decline in recent years, raising concerns that any further impact on the spawning biomass may lead to a further reduction in recruitment to the adult population in vulnerable rivers, several of which are designated as Special Areas of Conservation (SACs) under the Conservation (Natural Habitats, & c.) Regulations 1994 (as amended). This downward trend may result in rivers not being at carrying capacity for juvenile salmon. Indeed, evidence from the recent National Electrofishing Programme for Scotland (NEPS) indicates several catchments in Scotland that are below the benchmark (reference conditions) that might be expected (Malcolm et al., 2019).

Change is also evident at the site for the study presented here. Salmon trapping facilities operated by Marine Scotland on the Baddoch and Girnock Burns in the upper catchment of the Aberdeenshire River Dee show that adult numbers have declined since the 1960's ( Scottish Government Web page 1). By the mid-1990s, adult numbers were generally insufficient to fully stock the tributaries, with juvenile salmon (Glover et al., 2019, 2018) and smolt production (Bacon et al., 2015) being below the bench mark figure as a result. At the catchment scale, juvenile salmon densities in the River Dee were recently classified as grade 2 for fry and grade 3 (the scale used in the NEPS survey is from category 1-3, 1 being above the set benchmark, 3 being the upper 95% confidence interval of the observed mean is below the benchmark see Malcolm et al., 2019)

## 2.2. Marine migration in Atlantic salmon post-smolts.

A more detailed picture of the early marine phase of the post-smolt migration has been pieced together over the last two decades and reviewed by Thorstad et al. (2012b). Relatively few data are available on post-smolt swimming behaviour during early marine migration once smolts enter the coastal zone and beyond (Dempson et al., 2011; Finstad et al., 2005; Holm et al., 2000; Kocik et al., 2009; Lacroix and McCurdy, 1996; Shelton et al., 1997; Thorstad et al., 2012b). These data suggest that post-smolts rapidly move away from the coast and generally migrate within 7 m of the surface, and usually within the top 3 m (Davidsen et al., 2008; Holm et al., 2000; LaBar et al., 1978; Shelton et al., 1997). They generally swim closer to the surface at night then during the day (Davidsen *et al*., 2008). It is proposed that this near surface swimming behaviour helps to avoid predation, allows them to utilise faster surface currents or access lower salinity water (Thorstad et al., 2012b). It also makes them accessible to modified pelagic trawls (Holm et al., 2000; Shelton et al., 1997). During this phase, post-smolts seem to migrate actively and rapidly with an overall seaward vector (Thorstad et al., 2012b) although some spend prolonged periods in the fjord and estuarine areas (Dempson et al., 2011). Most of these data have been derived from telemetry studies using passive acoustic telemetry receiver arrays and fish implanted with acoustic transmitters, using individuals of both farmed and wild origins. Such studies require very considerable capital and consumables investment and are logistically demanding, and so until recently, many studies have been based on relatively few fish tagged, in some studies as low as a few individuals.

Studying the migration of Atlantic salmon as they transition from the freshwater to the marine phase of their life cycle requires tracking equipment which can function in both fresh and salt water. Acoustic telemetry offers a viable method of tracking fish in both environments, unlike radio telemetry, where the signal strength markedly decreases in deeper and more saline water.

## 2.3. Acoustic Telemetry

Telemetry is defined (Thorstad et al., 2013) as technology which allows measurements to be made at a distance. Acoustic telemetry uses transmitters that emit a series of acoustic signals over a short period of time called “pings”. These “pings” are detected by a hydrophone, logged on a receiver and decoded into unique individual identification numbers (IDs) (Kessel et al., 2014). Transmitters can be implanted into smolts, and emit pings as the smolt migrates down river, allowing a sequence of detections to be recorded on receivers.

Active and passive tracking are the two methodologies predominantly utilised for tracking salmon smolts. Active tracking involves an operator with a receiver in the field following tag transmissions in real time as the tag moves (Thums et al., 2013). Passive acoustic telemetry makes use of fixed receivers which also contain data logging facilities, deployed at strategic locations often in a particular pattern (an array) which record tagged individuals as they pass within range of each receiver (Flaten et al., 2016). Passive acoustic telemetry can provide information about the movements of Atlantic salmon in their natural freshwater and marine environments without the need to be present to observe the movement first-hand. The tracking of individual animals via acoustic telemetry has been increasingly used as a viable research tool, with tag sizes decreasing and battery life being extended (Klimley et al., 2013). Small tags are now available that can be implanted into young life stages of fish, such as smolts, at an acceptable burden to the individual animal carrying the tag (Brown et al., 2010; Cooke et al., 2013; Thorstad et al., 2013; Walker et al., 2016).

While acoustic telemetry was first used to track fish in the 1970s, the recent miniaturization of acoustic tags, along with integration of depth and temperature sensors, has meant that it has been possible to address more complex questions about migration behaviour, such as swimming depth and body temperature, of migrating smolts (Kessel et al., 2014; Klimley et al., 2013; Thorstad et al., 2013). Measurements of body temperature can also be used to detect predation events by mammals and birds, as the temperature readings will increase if the tagged fish is consumed and digested, until it reaches the body temperature of the predator. Provided the predator comes within the detection range of a receiver, the tag may be detected and the temperature change recorded by the receiver will thus indicate a predation event. Alternatively, following a predation event, the tag could also pass through a predator and be detected on one or more receivers for a prolonged period (as the tag would not be moving) at ambient temperature, potentially indicating mortality. To successfully track the migration of salmon smolts down river and into the marine environment with passive tracking techniques, receivers need to be deployed in a pattern designed to provide data of a quality to address the aims of the study.

Salmon smolts can be captured in the river by various methods such as fyke netting, electro fishing or in a rotary screw trap (RST) as they begin their migration. The activated tag is then surgically implanted into the peritoneal cavity under general anaesthetic, via an abdominal incision (Brown et al., 1999; Deters et al., 2012; Newton et al., 2016). After a brief recovery period, tagged fish are then released back into the wild to continue their journey down the river and out to sea.

After tagging and release, it is not safe to assume that the tag always reflects the movements of the smolt tagged. The progression of the tagged smolt to sea may be slowed or halted for a number of reasons. The stress of surgery or the lingering effects of anaesthesia may cause the loss of tagged individuals from the study prior to detection on any receiver, as fish may suffer undetected tagging related mortality. Alternatively, they may be more prone to predation (Gibson et al., 2015). Tags may also never be detected as they may become faulty or ejected from the smolt entirely through the body wall or via the surgical wound if stiches become broken (Brunsdon et al., 2019). For the purposes of this thesis, I will assume that tags detected moving down the river and out to sea are in fact still inside the original smolt unless evidence presents itself in the data to refute this. However, it is important to be aware of this assumption.

Passive acoustic monitoring has several specific advantages and several challenging points for the tracking of salmon smolts and post-smolts, as summarised below.

### 2.3.1. Advantages

- Acoustic tags are relatively small, depending on transmission frequency, down to 4mm in diameter and 11 mm in length (Vemco V4 180kHz tag).
- Code maps can provide thousands of unique ID numbers.
- IDs detected from other studies can be passed to the project managers of those studies through the tag manufacturers.
- Tags can transmit information from other sensors included in the tag (e.g. depth, temperature, salinity, acceleration or tilt)
- The improved battery life of small acoustic tags which has been extended over recent years now means that, depending on transmission duration and repeat rate, tag life may be extended to up to 225 days for V7 tags (the common size used for salmon smolts) transmitting randomly between 45s and 135s (avrage = 90s).

### *2.3.2.* Challenges

Like all methods of observing animal behaviour, acoustic telemetry has several potential drawbacks that need to be acknowledged. The main drawbacks are:

- Tagging effects on smolts,
- Reliance on the transmission being detected to gather data,
- Detection range,
- Uncertainty in the precise position of the individual,
- Costs (tags, receivers and boat time) and
- The effects of environmental and anthropogenic noise on the detection of tag transmissions.

Atlantic salmon smolts are relatively small and at a particularly stressful time in their development. Implanting a tag inside a fish will almost certainly alter its behaviour to some extent (Wilson et al., 2016). The tag size to fish size ratio is an important consideration. The small size of wild smolts in Scotland means the debated 2% tag:body mass ratio (Deters et al., 2012; Jepsen et al., 2015; Winter, 1996) is an important factor to consider. However this tag burden guide has been shown to be conservative, with Lacroix and colleagues suggesting a maximum tag length of less than 16% of fish length and a tag weight of less than 8% of fish weight (Lacroix *et al.*, 2004). The tagging process is invasive and any extra weight gained by the fish from the tag must be manageable for that individual fish. Tag weight has the potential to affect buoyancy, feeding behaviour, swimming speed and ultimately survival (Brown et al., 1999; Jepsen et al., 2002). This usually means only the largest smolts in a natural population are of a suitable size for tagging with current acoustic technology that is capable of delivering any significant detection range at sea. To achieve an adequate detection range in the sea (e.g. >200m) and allow for the size of the wild smolts, tag choice is effectively limited to the smallest tags between 7-9mm diameter in the 69kHz range (as the 180kHz attenuates to rapidly in the marine environment).This limits the choice to Vemco V7-V9 and Thelma Biotel tags 7.3-9mm (Cooke et al., 2013; Lothian et al., 2018; Newton et al., 2016; Thorstad et al., 2013). Based on Lacroix *et al* (2004), a smolt of 135mm (FL) and 27g in weight could be implanted with a tag of less than 21.6mm length and 2.16g weight; for a smolt of 140mm (FL) and 35g in weight a tag less than 22.4mm long and 2.8g weight would be acceptable. It is important to acknowledge at the planning stage that selecting smolts from the large size categories may add bias to a study. For example, larger individuals are often reported to show faster swimming speeds and higher survival rates and therefore size selection might produce results that are not fully representative of the population as a whole (Thorstad et al., 2012b). To design and undertake a successful telemetry study on salmon smolts, all the potential effects that may compromise data quality need to be considered and mitigated as much as is possible prior to commencing the study.

All acoustic tags transmit a signal and these need to be detected and decoded successfully by a receiver and logged in the receiver's memory. Thus a major consideration in any acoustic telemetry study is the range at which a tag can be detected reliably and how environmental conditions influence tag detection range. The detection range is critical to the planning the layout of receivers. The detection range of a receiver is dependent upon its location and this may vary over time with changes in ambient conditions (e.g. background noise levels) (Kessel et al 2013, Cooke et al 2012). Receivers need to be securely mounted to some fixed structure. This usually consists of a floated line attached to a weight to which the receiver is securely attached. This complete set up, receiver plus mooring and mounting is called an Acoustic Listening Station (ALS). Gathering data on receiver efficiency, "Range Testing" should inform the specific locations for ALSs. These data should be used to create an appropriate pattern of ALSs to maximise the probable detections of tags. The pattern of ALSs laid out in the field is termed an array.

As salmon smolts generally migrate in one direction, seawards, array layout often focuses on passage down a river and out to sea through either a harbour or an opening into an estuary, fjord or open sea. Smolts in wider river courses, or post-smolt movements in estuaries and the open sea, often require several ALSs arranged in a specific pattern to reliably detect tag transmissions at strategic milestones on the migration route. These are termed "gates", and comprise of ALSs in lines with overlapping receiver detection ranges which provide 100% coverage, for example across an estuary (Kessel et al., 2014). While the detection coverage might be theoretically 100%, allowance must be made for variations in the prevailing environmental conditions and their impact on the actual detection range of receivers at any time (Abecasis et al., 2018; Gjelland and Hedger, 2013; Jepsen et al., 2002; Kessel et al., 2014; Selby et al., 2016). When tag transmissions are not detected by a gate with overlapping detection ranges, (possibly resulting from temporal variation in detection efficiency) this can have a profound effect on the interpretation of the data, particularly when survival is being inferred. To gain an understanding of the likely number of missed detections in a gate (or array), it may be necessary to deploy tags at fixed positions (sentinel tags) within each gate. These sentinel tags have a known transmission sequence, giving a predictable number of transmissions over time (Abecasis et al., 2018). By using the actual detections of sentinel tags by the receivers and comparing this to the expected theoretical numbers of sentinel tag transmissions, the "detection efficiency" of the array can be monitored throughout the experiment (Gjelland and Hedger, 2013; Selby et al., 2016). Kessel *et al* (2014) reported detection range varied in a Norwegian fjord between 45m and 620m depending on depth, salinity, stratification and wave action during range testing for one study. With this degree of variability it is easy to see why, even in the best arrays, some expected tag detections may be missed (Kessel et al., 2014).

Amongst the many factors that may affect detections, environmental noise has a large effect on the detection range of acoustic tags (reviewed by Kessel *et al.*, 2014). Other factors include (<100m deployed depth) sea state/surface conditions, background/ambient noise, bathymetry, substrate and obstructions amongst others (Gjelland and Hedger, 2013). Anything that adds noise to the water can mask the transmission of the tag, and obstructions can cause the tag transmissions to be reflected, leading to missed detections or errors in the received tag detections or decoding (Jepsen et al., 2002; Kessel et al., 2014).

Water depth is also an important consideration when using acoustic receivers as they often have a maximum recommended deployment depth (e.g. for a Vemco VR2AR and Thelma Biotel TBR receivers this is 500 m). Acoustic receivers need to be deployed correctly to monitor the subject animal. For Atlantic salmon smolts and post-smolts, the receivers need to be relatively close to the surface, certainly close enough to maximise the chance of receiving detections, and if deployed in a gate, spacing should be derived from the results of range testing carried out prior to the main experiment, as described above. ALS mooring design will also play a crucial part in getting the best data. Moorings need to be acoustically quiet and stay where they are deployed - not always a simple task. Many of the detection issues listed above such as wave action and noise are more significant near the surface. This is also the most common zone of the water column used by smolts during migration, compounding the difficulties of detecting them reliably. Small 69kHz acoustic tags with the ability to store data in the same way as larger Data Storage Tags (DST) may aid in addressing this deficiency and have recently become available. If the acoustic tags also off loaded all data upon passing a receiver, and not just on recovery, much more information might be successfully gathered.

Acoustic tags are expensive compared to more conventional tags. Conventional tags include plain marker tags such as carling tags, which consist of a simple piece of plastic anchored to the fish (Drenner et al., 2012). Other tags like Passive Integrated Transponder (PIT) tags are also much cheaper to manufacture, allowing deployment in much greater numbers (Klimley et al., 2013). The cost of a single acoustic ID tag can be up to £250 (GBP), currently with sensor tags (depth & temperature) up to £330. While PIT and other tags are cheaper to buy, (typically £1-2 per tag) the necessary equipment and cabling to detect a PIT tag is relatively costly or impossible to install in many large or fast flowing rivers unless there is a pre-existing natural or manmade structure making the necessary detection range, of between 20-100 centimetres, acceptable to the objectives of the work (Klimley et al., 2013).

## 2.4. Marine Renewable energy generation and Government Drivers for monitoring salmon at sea

The Scottish Government has ambitious targets for renewable energy generation. These plans include 100% of Scotland's demand for electricity from renewable sources by 2020 and by 2030 to deliver 50% of the energy for Scotland's heat, transport and electricity consumption via renewable sources. Estimates show Scotland has a massive potential for offshore renewable power generation. This is estimated at 25% of Europe's offshore wind resource, 25% of the tidal resource and 10% of the wave resource. However exploiting this resource may have consequences for salmon during both the initial post-smolt and returning adult migrations. The Marine Scotland Freshwater Fisheries Laboratory developed the National Research and Monitoring Strategy for Diadromous Fish (NRMSD) (Malcolm *et al.*, (2010). The NRMSD set out the main knowledge gaps surrounding the migration of salmon and other freshwater fish that migrate to sea with the aim of prioritising research and allow assessment of the risk of constructing renewable energy generating stations.
These were split into two themes:

1. What routes and depths do salmon smolts use as they leave Scotland?
2. What routes and depths do adult salmon use in Scottish coastal waters on their return to spawning rivers?
3. Potential impacts of noise from installation and operation of OMRE generators on salmon
4. What are the likely effects of electromagnetic fields from generators and associated cabling on salmon?
5. How many fish might be struck or otherwise disabled by blades of sub-sea generators?

Theme 2: Current and near-term research actions to implement a better understanding of Atlantic salmon populations to support the knowledge base underlying risk assessments for Offshore and Marine Renewable Energy (OMRE) developments

1. Understanding and detecting changes to salmon at a population level
2. Can potential changes in population levels be determined as significant with respect to conservation status and fisheries?

This strategy also suggested how the knowledge gaps might be filled with further study and research. This MSc tracking project directly fits into Theme 1 part 1: What routes and depths do salmon use when they leave Scotland.

The NRMSD was integrated and consolidated into the Scottish Marine Energy Research (ScotMER) programme (Scottish Government Webpage 2)and an evidence map produced which prioritised knowledge gaps and suggested study types that may fill some of the gaps.

Acoustic telemetry offers an opportunity to add some valuable data to fill in some of the knowledge gaps presented in the ScotMER diadromous fish evidence map. The evidence map and the NRMSD suggested that there was little or nothing known about near coast or wider scale migration routes of salmon smolts on the East Coast of Scotland. This led to the instigation of several tracking programmes including a large-scale project in the Moray Firth in 2016 initiated by Beatrice Offshore Wind farm Ltd (BOWL) carried out by the University of Glasgow and MSS. MSS followed this work up with a 4 year programme tracking smolt migration in the Aberdeenshire River Dee and early marine migration., of which this study forms part.

The impact of Offshore and Marine Renewable Energy (OMRE) on migrating salmon may come from several different impact pathways. These include noise impacts, predator aggregations (new and/or increased), collision with tidal turbines underwater and potential navigation issues resulting from new cable electromagnetic fields (EMF).

Noise impacts may be from construction or operation at OMRE and can come from increased vessel activity or physical construction such as pile driving. This may affect post-smolt migration and the migration of returning adult salmon (Gill et al., 2012).

Predator aggregation may be seen at new OMRE sites as birds, mammals and fish may be attracted to novel locations and the structures themselves offer shelter, a place to rest and a build-up of biological material that may be an aggregation of food for larger animal like large fish and seals. These fish, seals and birds may opportunistically feed on passing salmon.

Subsea tidal turbines have the potential for fish to collide with rotating blades in much the same way bird collide with wind turbines. This is a very difficult area to monitor as tidal turbines are often in physically demanding location requiring strong currents to function.

Early investigations of EMF has suggested that power transmission cables may be a particular concern are in shallow, near-shore water, often the same water that salmon use in their final approach to natal rivers (Gill and Bartlett, 2010).

These impact mechanisms taken alone may have negligible population level effects on salmon but when considered in the context of the declining trend in adult salmon returns these impacts may cumulatively affect the population negatively as a whole.

## 2.5. Other factors affecting the survival of salmon smolts

Young salmon are a food source for many animals including birds, mammals and other fish. In the river, fish such as brown trout (*Salmo trutta*) and pike (*Esox lucius*) frequently consume young salmon. Birds, like goosander (*Mergus merganser*), cormorant (*Phalacrocorax carbo*) are also implicated in the consumption of migrating smolts in the river. Some aquatic mammals such as seals, (*Phoca vitulina* and *Halichoerus grypus*), otter (*Lutra lutra*) and American mink (*Neovison vison*) have been recorded as predators of smolts (Feltham, 1995, 1990; Heggenes and Borgstrøm, 2006; MacLean and Feltham, 1996) with seals witnessed on the River Dee as far up as Banchory (50km from the sea). Thorstad et al (2012b) provided an overview of the threats smolts face on their migration to the sea.

Pollution, pesticides, man-made obstruction and other anthropogenic activities also affect the survival of young salmon and smolts in the river and pesticides in particular may possibly be detrimental to post-smolt survival in the sea (McCormick et al., 1998; Moore et al., 2007).

## 2.6. Tracking Atlantic salmon in the Aberdeenshire Dee

As previously stated, the River Dee in Aberdeenshire has shown a marked decline in Atlantic salmon numbers over recent years. As a result, the River Dee Trust (RDT) and River Dee District Salmon Fishery Board instigated an acoustic tracking programme utilising Vemco V5 tags on the 180kHz frequency system to monitor where the loss of smolts may be occurring in the river. Marine Scotland Science (MSS) have partnered with this tracking programme in two main ways. Firstly, through the Freshwater Fisheries Laboratory in Pitlochry, MSS have been assisting with stock assessments and led the upper catchment in-river acoustic tagging programme, using Vemco V5 tags, to enhance the already active RDT tracking programme. Secondly using a separate 69kHz system, in tandem with the RDT in-river programme, MSS and the RDT have also begun to monitor smolts in the River Dee and post-smolt movements in Aberdeen Bay and beyond to 10km from the mouth of Aberdeen Harbour. The in-river 69kHz receivers are co-located with the Dee Trust 180kHz receivers. It is this study that is, in part, presented in this thesis and is partially funded by Aberdeen Offshore Wind Farm Ltd.

As previously indicated, very little is known about early marine mortality of post-smolts on the east coast of Scotland (Malcolm et al, 2010). Chaput (2012) and ICES (2019) showed increased mortality over the years and a reduction in returning adults indicating a higher marine mortality. If marine survival is low and subsequent numbers of returning adults are potentially below the level required to maintain the population of salmon at carrying capacity in some rivers (Chaput, 2012; Malcolm et al., 2019), then there is a chance that even small changes in successful migration and survival of post-smolts in the marine environment might have a larger impact on the numbers of returning adults thus reducing smolt production even further. Marine renewable energy generating station located inappropriately may unwittingly put additional strain on already struggling salmon populations. This is one of the main drivers for this research.

This thesis aims to fill in some of the information surrounding the early marine migration routes and mortality of smolts from the River Dee, to predict the most likely routes Dee post-smolts take in the marine environment and explore whether they are likely to interact with local marine renewable energy installations.

## 2.7. The aims of this study are to:

Biological-

- Determine the spatial pattern of migration success along the River Dee in Aberdeenshire.
- Assess the estimated near-shore migration success of Atlantic salmon post-smolts exiting the River Dee.
- Examine whether salmon post-smolts show any patterns of directional movement in the sea during the first 10 km of their migration from the River Dee to distant feeding

grounds.

Technical

- Provide estimates of missed detections based on range testing and simulations and use these results to assess if the layout of ALSs (the array) is fit for purpose

# 3. Materials and Methods

## 3.1. Study Location

The River Dee in Aberdeenshire, Scotland, rises in the Cairngorms and flows generally eastwards through Aberdeenshire before discharging into the North Sea via Aberdeen Harbour some 140 km from its source (Figure 3.1). The North Sea east of Aberdeen Harbour steadily increases in depth to about 60 m four kilometres from shore. Immediately east of the harbour breakwaters, it offers migrating smolts 180 degrees of open sea from North to South with an Easterly aspect (Figure 3.1).

## 3.2. River conditions

The two years of this study showed different patterns in river discharge (Figure 3.1), as measured at the Scottish Environment Protection Agency (SEPA) gauge at the Park station (NGR: NO 79739 98317). The river discharge in 2017, during the main smolt migration period (April-June), was generally lower than that in 2018 and lower than the river average at Park of 47 $m^3s^{-1}$. In April, the 2017 discharge was low until the 28$^{th}$ when there was a rapid rise from 13 $m^3s^{-1}$ to 125 $m^3s^{-1}$. In 2018, the river discharge was higher through April remaining above the average discharge level for most of the month including two separate periods of higher flow. The general trend for higher discharge in 2018 continued until mid-May where it returned to a level of 13 $m^3s^{-1}$. In 2017, fish tagging started on the 5$^{th}$ of April but only small numbers of fish were tagged before the 16$^{th}$ of April when the numbers of smolts of the size required to tag started to increase. The last fish was tagged on the 25$^{th}$ of April. In 2018, the first fish was tagged on the 19$^{th}$ of April with several fish tagged each day from then on. The 3$^{rd}$ of May saw the largest number of fish tagged (n=57). The last fish was tagged on the 23$^{rd}$ May after a replacement for a faulty tag was received.

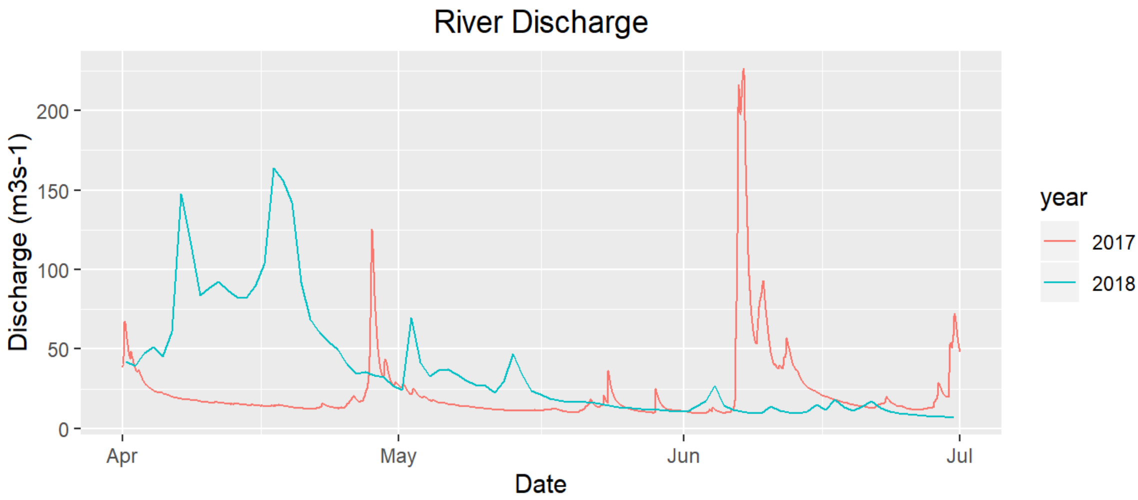



Figure 3.1: Discharge levels in the River Dee in Aberdeenshire between April and July during 2017 (red line) and 2018 (blue line) measured at the SEPA gauge at the Park station (NGR: NO 79739 98317).

## 3.3. Fish Tagging

### 3.3.1. Fish Capture location

Atlantic salmon smolts (n=160, (2017 n=60, 2018 n = 100)) were captured in rotary screw traps (RST, n=2) and fyke nets (FN, n=2) over two years. RSTs were deployed on the Beltie (57°03.46’, -2°32.85’) and the Sheeoch (57°33.19’, -2°22.60’) Burns and FNs were deployed in the Dinnet (57°04.75', -2°52.64’) and Sheeoch Burns (57°35.60’, -2°22.80’) below the RST location in the River Dee catchment during low flow periods (Figure 3.1). See Annex 1 for details of tagged fish.

### 3.3.2. Fish Tagging Procedure

Both RSTs and FNs were checked daily (between 9am - 2pm) and captured smolts were processed and released on the same day. Smolts greater than 135 mm fork length ($L_f$, mm) were anaesthetised by immersion in five litres of solution containing tricaine methanesulfonate (MS-222, 0.08 mg $l^{-1}$). Anaesthetised smolts were measured for length ($L_f$, mm) and mass (M, g) prior to tagging.

Once measured and weighed, the fish were placed on a surgical platform consisting of a foam board with a v-shaped groove which had been pre-soaked in river water. All equipment was sterilised between each fish and care was taken, as far as possible in a field location, to ensure aseptic techniques. An incision between 10-12 mm was made using a single use scalpel in the ventral surface of the smolt, anterior to the pelvic girdle. Tags (69 kHz Thelma Biotel 7.3 mm (2017) or 69 kHz Vemco V7 (2018), (see Tag Specifications section below) were activated, following the manufacturer's instructions, and tested prior to sterilisation in a bath of 70% ethanol. The activated tag was then rinsed in sterile saline solution and inserted into the peritoneal cavity and the incision closed with two interrupted sutures (Vicryl 4-0 violet, Ethicon, Johnson & Johnson Medical N.V., Belgium) secured with surgeon knots. Fish were aspirated with a 0.04 mg $l^{-1}$ MS-222 solution throughout the procedure. This was carried out under Home Office Licence (numbers 60/4411 (2017) and 70/8928 (2018)).

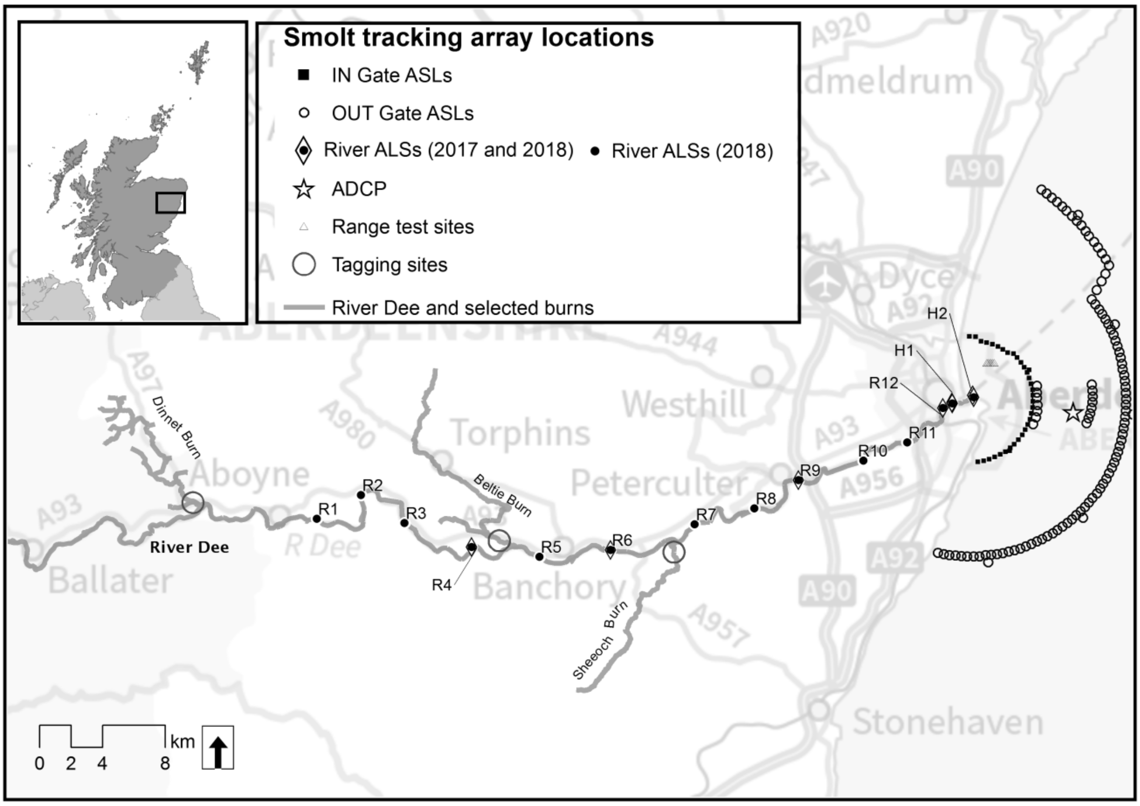



Figure 3.2 The study site including the main stem of the River Dee and the three tributaries Dinnet, Beltie and Sheeoch Burns where smolts were captured and tagged. In-river ALS locations are marked and labelled (diamonds with black dot = 2017 and 2018, black dots only 2018) as are tagging locations (rings). The two marine gates are also shown. The IN gate ALS locations (small squares) deployed in 2017 and 2018 and the OUT .gate and extra ALS locations (small rings) deployed in 2018 only. ALSs of interest are labelled (e.g. R6). Inset map shows geographical extent within Scotland. Contains OS data © Crown copyright and database right (2020), © British Crown and OceanWise, 2020. All rights reserved. License No. EK001-20140401. Not to be used for Navigation.

### 3.3.3. Fish Release

After surgery, smolts were transferred into a bucket of fresh aerated river water to recover. As soon as they recovered equilibrium (independently swimming upright), they were transferred into a secure holding pen in the river, where they were allowed to further recover for a minimum of two hours. Tagged smolts were then released, along with some untagged smolts, into the river at least 100 m downstream of the capture location. Smolts captured at the Dinnet Burn were released in the main stem of the River Dee below the Dinnet Islands (57.079507°N, -2.867418°W).

### 3.3.4. Tag Specifications

Sixty Thelma Biotel tags were used in 2017. Fifteen of these tags (tag type: ADTT-LP-7) transmitted temperature and depth along with associated unique IDs. The remaining 45 transmitted only ID (tag type: ATID-LP-7,3). All tags had a fixed delay of 30 seconds between code transmissions (all tags are detailed in Table 3.1).

In 2018, 100 Vemco V7 tags were used. Thirty of these tags were capable of transmitting depth and temperature (V7TP-2L-069k-1), and the remaining 70 were ID only tags (V7-2L-069k-1). Vemco tags were set to transmit with a random delay between 50 and 100 seconds to reduce the risk of multiple tags persistently transmitting at the same time.

Table 3.1: Specification details for tags used during 2017 and 2018 for tracking smolts and for range testing.

| Tag name | Manufacturer | Dimensions (L x D, mm) | Mass in air (g) | Number | Power (dB re 1µPa at 1m) | Year | Purpose |
|---|---|---|---|---|---|---|---|
| ADTT-LP-7,3 | Thelma Biotel | 22 x 7.3 | 2 | 15 | 139 | 2017 | Fish tag |
| ATID-LP-7,3 | Thelma Biotel | 18 x 7.3 | 1.9 | 45 | 139 | 2017 | Fish tag |
| ART-LP-7,3 | Thelma Biotel | 19 x 7.3 | 1.9 | 2 | 139 | 2017, 2018 | Range test tag |
| V7TP-2L-069k-1 | Vemco | 22 x 7 | 1.7 | 30 | 137 | 2018 | Fish Tag |
| V7-2L-069k-1 | Vemco | 18 x 7 | 1.6 | 70 | 136 | 2018 | Fish Tag |
| V7-2L-069k-1 | Vemco | 19 x 7 | 1.6 | 4 | 137 | 2018 | Range test tag |

## 3.4. Range testing

### 3.4.1. Prior to the study

A five day tag detection range test was carried out in Aberdeen Bay in November 2016 to estimate the spacing required between ALSs for the following years' of study. In total, six ALSs were deployed (comprising a VR2AR, rope canister and weights) and recorded transmissions of two range test tags deployed on ropes approximately 12 m below the sea surface attached to the first and last ALSs of the range test array (Figure 3.3). Thelma Biotel tags were used (ART-LP-7,3), which mirrored the power and size of the ID tags used in 2017. Tags were not in the 0-6 m usual swimming depth range of smolts due to navigational concerns (ropes just under the surface of the sea risk interfering with vessel activities), however they were as close as possible at about 12 m depth. The weather over this period ranged from flat calm, Beaufort Force 1 to Force 7-8. This gave an excellent range of conditions over which detection probability was assessed. These tags and receivers were then turned off and stored ready for deployment in 2017.

### 3.4.2. Range Testing during the Study at Sea

Range test tags were deployed in the marine gates (discussed below) during the main study periods in 2017 and 2018. In 2017, two range test tags were located on receivers in the IN gate and in 2018 a total of six tags were deployed (two in the same locations in the IN gate and four in the OUT gate) (Figure 3.2). The Thelma Biotel range test tags (ART-LP-7,3) above were used in both 2017 and 2018. In 2018, Vemco V7 (V7-2L-069k-1) tags were also deployed. These tags were floated above ALSs as close to the swimming depth of smolts as possible (approximately 12 m depth for navigational reasons). The range test tags were also the same power and type as the tags implanted in the smolts in each year.

### 3.4.3. Fish Passage Simulations.

Using the Great Lakes Acoustic Telemetry Observation System (GLATOS) R repository of code the range test data were converted to a probability of detection at any given distance. This probability curve was used to generate the probability of detecting an individual tag transmission from a tagged fish passing the array and transmitting, copying the transmission rate of the tags used (either a fixed delay of 30 s during 2017 or a random delay between 50-100 s in 2018). The simulated tagged fish were given a random speed within the inter quartile range of recorded fish speeds and passed at varying distance from receivers. The R code was used to simulate fish crossing the marine gates using the actual number of expected fish (fish detected at the previous gate) and the actual distance between ALSs. The simulation was repeated 10,000 times to estimate the mean probability of detecting a fish crossing the array. The results of the range testing were also used to simulate the probability of detecting tagged fish at different swimming speeds and receiver spacing.

## 3.5. Receiver Locations

Fish passage down river and out to sea was monitored remotely using moored Acoustic Listening Stations (ALSs). Three types of Vemco receivers were used in this project (VR2W, VR2AR and VR2Tx). One VR2W was used in 2017 in the River Dee, this only records tag detections (including any additional sensor data encoded into the tag transmission). The more advanced VR2Tx and VR2AR models record additional environmental data at their locations, such as temperature and background noise, as well as tag detections. The VR2AR models come equipped with an acoustic release and are used in conjunction with a rope canister and flotation section to completely submerge the receiver, avoiding the need to mark locations at the water surface. The acoustic release can be later triggered (by an acoustic signal) that releases the buoyage bringing it to the surface. All ALSs were deployed a minimum of two weeks prior to the commencement of tagging. The numbers of ALSs varied between years but in each year the same core of ALSs locations were used with four common river receiver locations, four common harbour locations and 35 common sea locations, with additional ALSs added in year two. The spacing required between ALSs was calculated based on results of a range test study carried out over a five-day period in 2016, described above.

The overall array arrangement of ALSs in this project consisted of single ALSs in strategic positions in the river, pairs of ALSs in the harbour forming gates and arcs of ALSs in the sea forming larger gates (Figure 3.2 & Figure 3.3) as described below. During the 2018 deployment this was the largest acoustic telemetry array in the UK and possibly Europe tracking young salmon, down the river and out to 10 km for shore, nearly 90 km in total.

### 3.5.1. River

In 2017, four ALSs were located in the river, in 2018 eight further locations were added (Figure 3.2). The ALSs consisted of a single 30 kg clump weight with a welded metal rod to support the receiver above the riverbed in an upright position. The receivers were mounted to the vertical rod using cable ties and jubilee clips and the weight was secured to the riverbank using 14 mm polypropylene lead line rope.

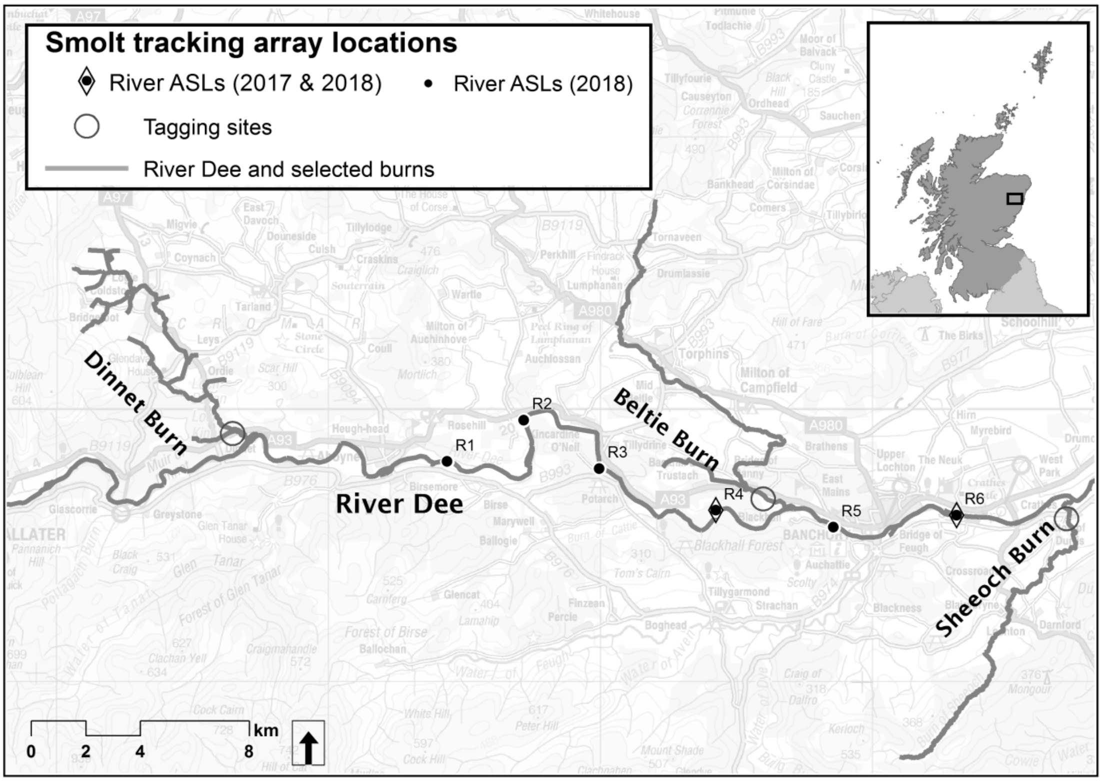



Figure 3.3: The River Dee showing locations of the tributaries Dinnet, Beltie and Sheeoch Burns where tagging took place (rings) and locations of the in-river ALS locations (diamonds with black dot = 2017 and 2018, black dots only 2018). Contains OS data © Crown copyright and database right (2020)

### 3.5.2. Harbour

In both 2017 and 2018, four ALSs were placed in the harbour in two "gates" consisting of a pair of ALSs each. These gates provided a theoretical 100% coverage of the harbour channel (Figure 3.4). However, Aberdeen Harbour is extremely busy and shipping traffic noise likely adversely affected the detection probability of tags (efficiencies are presented Table 4.1 and Table 4.2). One pair of ALSs consisted of a simple weighted rope with 2 floats at the surface and one tensioning buoy approximately 4 m off the seabed. Receivers were secured to ropes using cable ties and located 2.5 m above the bed of the harbour and secured to shore via a separate 14 mm rope. The remaining two ALSs were lowered off the harbour wall and secured to access ladders under tension to hold the receivers off the bed in the correct orientation.

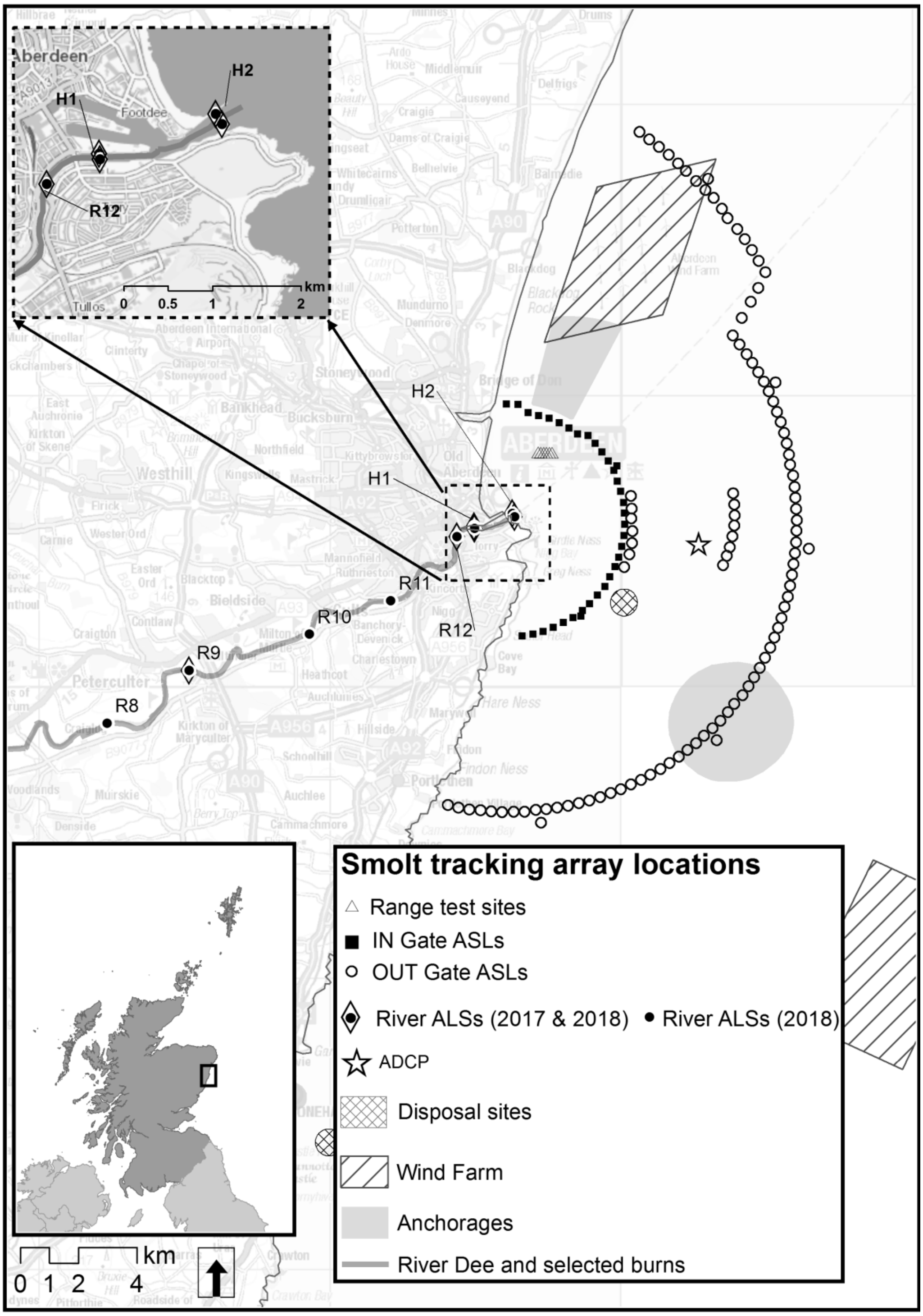



Figure 3.4: The lower River Dee and Aberdeen Bay showing the ALS location in the river diamonds with black dot = 2017 and 2018 black dots = 2018 only), Harbour (zoomed inset (diamonds with black dot = 2017 and 2018) and locations of marine gates of ALSs (IN gate of ALSs (IN gate 2017 and 2018 = small squares, OUT gate and extra receivers 2018 only = small rings), range test (sentinel tags = triangles). ALSs of interest are labelled (e.g. R6). The position of the ADCP is also marked (star) Contains OS data © Crown copyright and database right (2020), © British Crown and Ocean Wise, 2020. All rights reserved. License No. EK001-20140401. Not to be used for Navigation. Contains public sector information licensed under the Open Government Licence v3.0.

### 3.5.3. Sea

Arcs of ALSs were placed in the sea east of the harbour mouth at varying distances forming the marine gates. These ALSs were positioned so as to create overlapping detection ranges. One arc was deployed in 2017, located four kilometres from the mouth of Aberdeen Harbour. This consisted of 33 ALSs, each spaced 380 m apart an additional two ALSs were deployed to act as range test stations (Figure 3.4). The range test stations had subsurface buoys with active tags deployed below them at about 12m depth. These tags transmitted in accordance with Table 3.1. In 2018, the same 35 ALS locations were used again and an additional 96 ALSs were deployed in an arc forming the second marine gate, 10 km from the mouth of Aberdeen Harbour, again with a 380 m spacing, along with a further 5 range test ALS stations (Figure 3.4). The second arc dog-legged to avoid construction activities at an offshore wind farm in Aberdeen Bay.

VR2AR receivers were mounted in rope canisters designed at MSS in Aberdeen and were floated two meters above a 70 kg chain link anchor on the seabed. VR2Tx receivers were designed to be recovered by Remotely Operated Vehicle (ROV). The ROV mooring consisted of a simple three metre rope with an 11” float at the top and a 35 kg anchor weight at the bottom. A VR2Tx was secured to the rope, using cable ties, two meters above the weight.

## 3.6. ADCP Placement

An Acoustic Doppler Current Profiler (ADCP) was deployed in 2018 in between the two marine gates, at 61 m depth (Figure 3.4). This was programmed to record current speed and direction in various depth bins over the smolt migration period. The water column was divided into five separate bins 0-6 m, 6-12 m, 12-20 m, 20-40 m and 40-60 m deep. The upper bin (0-6 m) also provides a rough metric of sea surface state as the data becomes noisier and incomplete as the sea surface become disturbed by worsening weather and increasing wave heights.

## 3.7. Data

Data were downloaded from ALSs using VUE software (Vemco, Nova Scotia, Canada) when receivers were recovered, exported and subsequently analysed in R (R Core Team (2016)).

Environmental data on river flow were provided by the Scottish Environment Protection Agency (SEPA) The Park station was chosen to use as a representation for this project (57° 04.525', -2° 20.1459').

Sunrise and sunset times were calculated in “suncalc” package in R (Thieurmel and Elmarhraoui, 2019). This used the latitude and longitude to determine dusk, dawn, sunrise and sunset times. Bearings were calculated using “fossil” which used the latitude and longitude of ALSs to calculate the bearing and direction from one to the next (Vavrek, 2011).

Circular direction was calculated using "circular" which allowed the directions to be used as a 360° range of bearings and the use of circular statistics for the direction of fish migration (Agostinelli and Lund, 2017).

Range testing was carried out using the Vemco range test software and simulated smolt tracks were carried out using R code published by the Great Lakes Acoustic Telemetry Observation System (GLATOS).

In the most part, medians and interquartile ranges are reported as the behaviour of individual fish is very variable.

## 3.8. Fish migration behaviour

Migration in salmon smolts is primarily a downstream movement and therefore can be measured by the progression of detections on ALSs towards the sea. Fish were classed as starting a migration upon first detection on a river ALS (back calculated if any particular smolt was missed on an ALS). No ALSs were located in the tagging burns, as suitable locations could not be identified. Successful migrations were defined as tags passing out of the river and over the IN gate, to allow a comparison between years. It is also worth noting that any fish passing over the second marine gate will also have successfully migrated; however, this was not comparable over both years. Tags that were detected on an ALS and subsequently failed to appear at any other ALSs were assumed lost to the study and therefore unsuccessful in their migration. There are many factors which could contribute to this loss including tag failure, tag ejection, noise, predation or other causes of mortality. Some detection of tags may not present the typical behaviour of a smolt and these were individually investigated to assess whether the tag remained the original study animal. This involved looking at the specific behaviour of a tag to see if it progressed back up the river or temperature depth tag to look for increases in temperature or unusual tag depths (continued depths below 10m for example) out with the usual patterns seen in the study. Tag detections that appeared to skip an ALS or gate of ALSs were used to assess receiver efficiency.

The movement of tags between ALSs can be broken down into two parts: residency events and movement events. Residency events, in this study, are defined as two consecutive detections on the same ALS or gate, within one hour of each other. Movement events are defined as periods between residency events when fish are detected on different ALSs or gates. These two event types were calculated using the Vtrack package in R (Vtrack, Queensland University, Australia).

### 3.8.1. River and Harbour Migration

Rates of River Movement (RORM) were calculated in Vtrack (Campbell et al., 2012) by dividing the distance between ALSs or gates by the time between detections (duration). River distances between ALSs or gates were measured using ArcGIS® (software by Esri, www.Esri.com) and followed the natural course of the river measured in kilometres. Time elapsed was calculated as the difference in time between the last detection at one ALS or gate and the first detection at the next ALS or gate. In the harbour and in the sea, the straight-line distance between the ALSs were used, and calculated in R. A subset of these data was also used to compare Total River Time (TRT, hours) from tagging location to the exit of Aberdeen Harbour (H2), total rate of River Movement (TotRORM, $ms^{-1}$) from tagging to leaving the harbour and Total Travel time through the Harbour (TTH, hours) from the last detection on river receiver 12 (R12) to the final detection on the last harbour receiver (H2).

### 3.8.2. Early Marine Migration

Rates of Marine Movement (ROMM) were also calculated in the same way as in the river but using a straight line distance. This gives the minimum ROMM, as fish may not have taken a direct route from one point of detection to the next point of detection. Where depth and temperature tags have been used, data were screened for any unusual events such as tags moving to the seabed and remaining there or again getting warmer rapidly.

Direction of tag travel was recorded in a straight line from the midpoint of the last gate of ALSs in the harbour (H2) to the first detection on an individual ALS in the IN gate and also between the IN-OUT gates in a straight line between individual ALSs, giving ground speed and bearing. This was then compared to the current speed and direction. This allows a determination of the influence of the current on individual tagged smolts and post-smolts and to ascertain the Actual Fish Swimming Speed (AFSS) and Actual Fish Heading (AFH). Only IDs detected at H2 were used in this calculation, giving an accurate time of departure and thus tidal state. The same subset was used to calculate tidal state on departure broken down into ebb and flood.

## 3.9. Current speed and direction

The ADCP deployed in 2018 directly measured tidal elevation and current speed ($u$ and $v$ components of velocity). The measured currents were subtracted from the apparent $u$ and $v$ components of the fish detection data (fish and tide combined) to give the actual swimming direction and speed of individual fish. The ADCP data included the main component of tidal currents, and also other water movements such as wind driven surface movements throughout its deployment.

To predict tidal currents and elevations during 2017, the data collected using the ADCP in 2018 were analysed using the T_Tide toolbox in Matlab (Pawlowicz et al., 2002). The same toolbox was used to predict eastward and northward velocities (u and v components of velocity) and water elevation, using only constituents with a signal-to-noise ratio greater than one, to ensure good quality of predictions. The analysis and modelling of hydrographic data were carried out by the Oceanography section in Marine Scotland Science in Aberdeen. This prediction is also based on the bottom bins (40-60 m) of ADCP data, which removes the elements of interference from surface wind and other non-tidal factors. This allowed a comparison of current influence on individual fish in both 2017 and 2018. Although they are the most accurate information available, these data lack the individual weather and other factors that may play a part in the surface water movements.

## 3.10. Data analyses

Movement data were tested for normality using a Shapiro-Wilk test. Depending on whether the data were normally distributed or not, the difference between years and between marine gates in 2018 was tested with a t-test or a Wilcoxon Test (Dytham 2011). A Watson's two-sample Test of Homogeneity was used for bearings in circular data (Dytham 2011).

## 3.11. Modelling

A generalized linear model (GLM) was fitted to the tag detection data in R. As a proxy for survival, tags detected at the IN gate were awarded a value of one, and tags that were not detected were awarded zero, and thus a binomial distribution model was appropriate here. This was corrected in 2018 for tags detected at the OUT gate that were not detected in the IN gate (n=6, 8.2%). Factors that may have influenced the progression of tagged fish down river and out to sea were tested in the model to ascertain if they had the potential to cause a significant difference in the probability of a tagged individual being detected at IN gate. This detection at the IN gate was used as a proxy for survival. Variables used included tag burden by weight (tag weight/fish weight as a percentage), Tag burden by length (length of tag/fish length as a percentage), day of year (centred to tagging period for each year), tagger, group size (number of tagged fish released at each location each day), river flow ($m^3 s^{-1}$) at time of release and tagging site were investigated. These variables were tried in different combinations to find which best explained the variation in the tag detection data. After fitting several models to the data, the MuMIn package was used to select the model that best explained variation in survival to the IN gate by ranking the models by AICs and selecting the models within 6 delta values of the lowest AIC scoring model. The most parsimonious model was chosen.

The probability ($P$) of survival can be calculated as follows:-

$$P = \frac{1}{1 + e^{-(a+bx)}}$$

Where $e$ is the natural log, $a$ is the intercept of the model, $b$ is the coefficient of the factor predicting the effect (variable) and $x$ is the numerical value of the factor for which you wish to predict.

# 4. Results

## 4.1. Smolts tagged and receiver efficiencies

### 4.1.1. Smolts

In 2017, 60 salmon smolts were caught at three different sites (Dinnet Burn n= 46, Beltie Burn n= 10 and the Sheeoch Burn n= 4) and tags implanted. Of these 60 fish tagged, 22 tags, (representing 36% of tags), were subsequently not detected on any ALS. Thirty three tags (55%) were detected at the lower river (R12; Figure 3.4) prior to entering the harbour and all 33 were detected leaving the last set of harbour ALSs (H2). Twenty six tags (43%) were detected at the IN gate (4 km from the harbour mouth) (Figure 4.1).

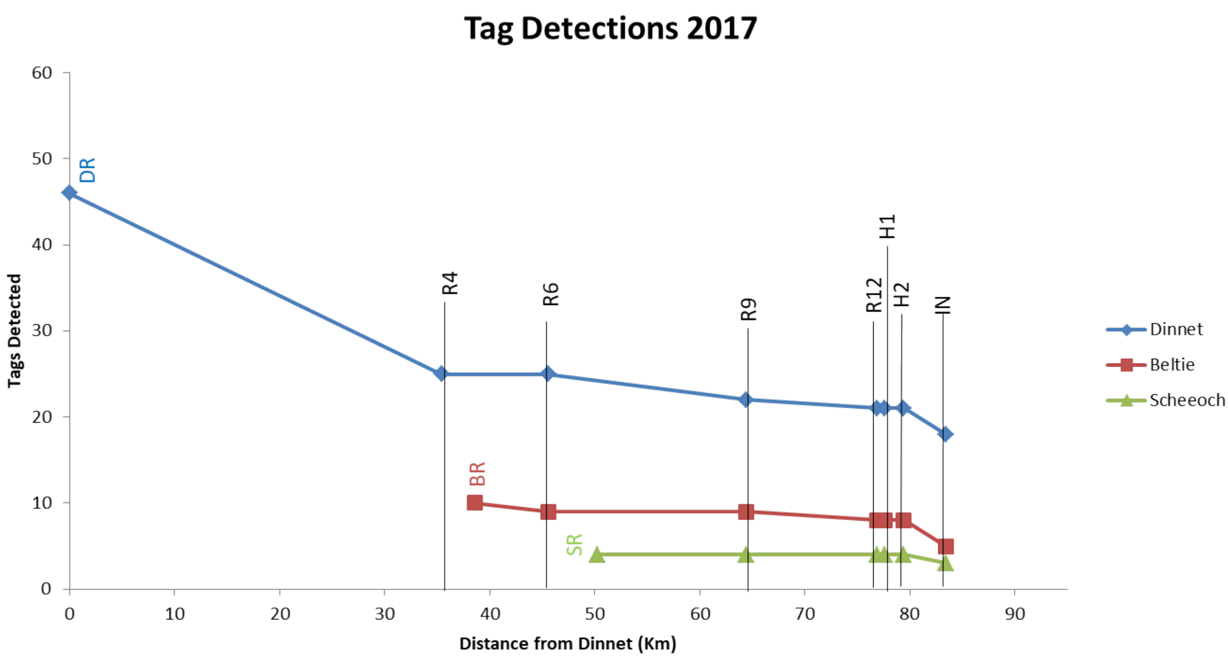



Figure 4.1: 2017 tag detections at various stations from the three release sites Dinnet (blue line), Beltie (red line) and Sheeoch (green line) Burns. Also shown are the release sites at Dinnet (DR), Beltie (BR) and Sheeoch (SR). Receiver locations are marked by vertical black bars and labels (R4).

In 2018, 100 salmon smolts were caught at the same 3 sites (Dinnet Burn n= 6, Beltie Burn n= 32 and the Sheeoch Burn n= 62) and tags implanted. Of these, 11 tags (11%) were not subsequently detected on any ALS. Eighty three tags were detected at the end of the river (R12) prior to entering the harbour and 77 were detected leaving the last set of harbour ALSs (H2). Seventy three tags (73%) were detected at the IN gate (4 kilometres form the harbour mouth) and 68 tags (66%) were detected at the OUT gate (10 km from the harbour mouth) (Figure 4.2). These data have been corrected for tags missed at IN and subsequently detected at OUT (n=6).

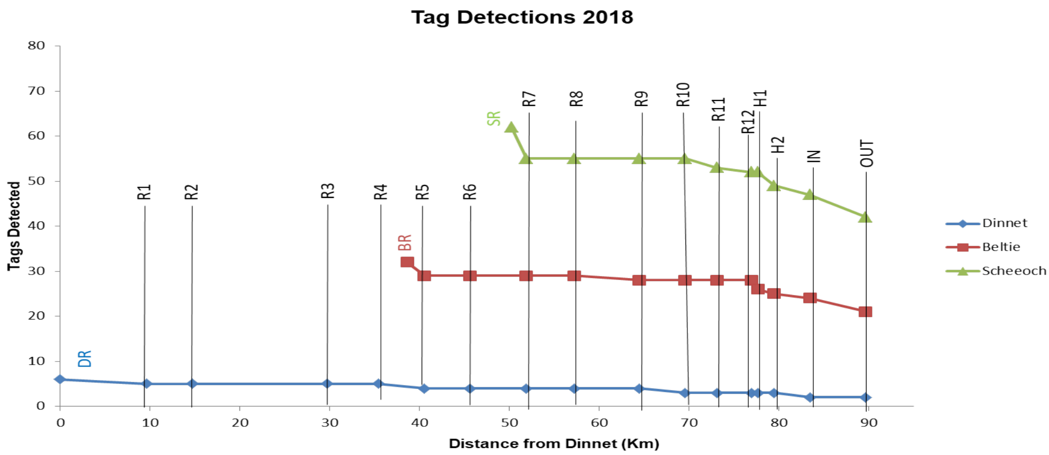



Figure 4.2: 2018 tag detections at various stations from the three release sites Dinnet (blue line), Beltie (red line) and Sheeoch (green line) Burns Also shown are the release sites at Dinnet (DR), Beltie (BR) and Sheeoch (SR). Receiver locations are marked by vertical black bars e.g R1.

### 4.1.2. Smolt tagging and river flow.

Smolts of the correct size (> 135mm for ID tags and > 140 for sensor tags) were tagged as they were caught and often a small rise in water or a more localised rise in the water level of the burn resulted in increased numbers of smolts becoming available. Localised changes if water level in the burn, where fish were caught, may not be reflected in the river discharge data as these relate to the main stem of the River Dee and not the individual burn level (Figure 4.3).

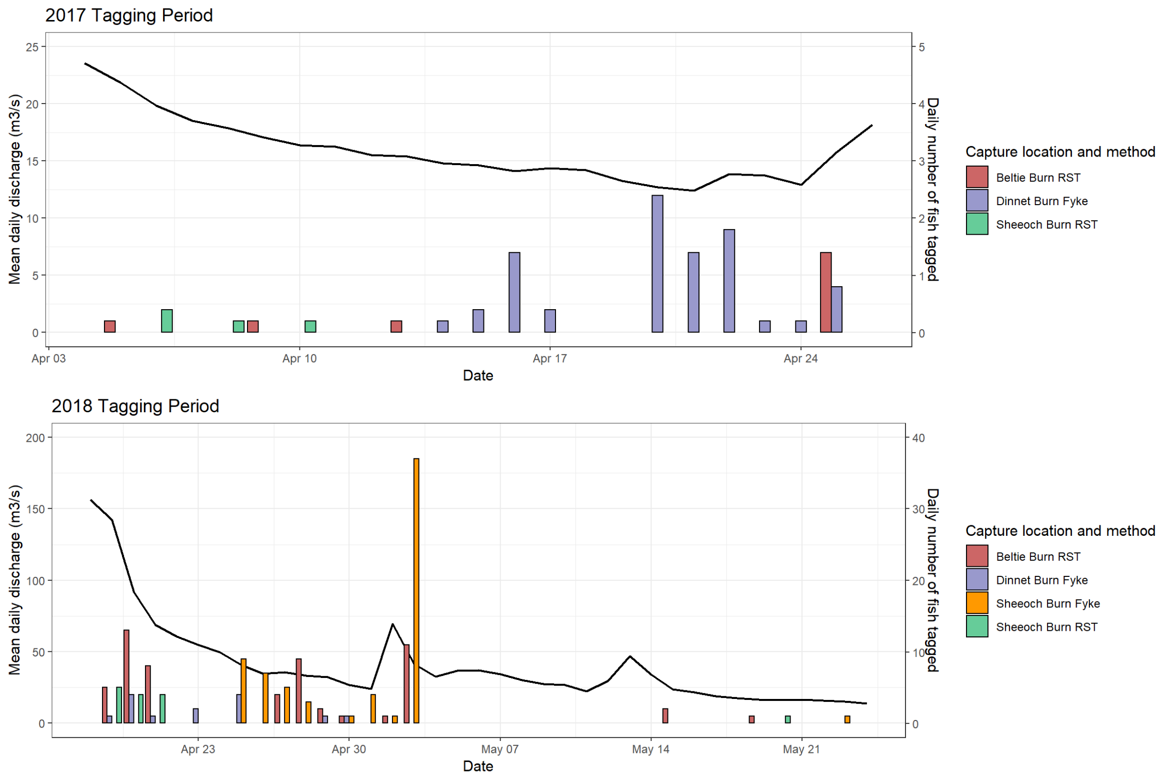



Figure 4.3: Mean daily river discharge at the Park measuring gauge (black line $m^3s^{-1}$) and daily catches of fish in each of the 3 Burns, Beltie (red), Dinnet (blue), Sheeoch Fyke (yellow) and Sheeoch RST (green) for the 2017 and 2018 tagging periods.

### 4.1.3. ALS efficiencies, transmitters detected and lost

While the modelling and simulations in section 4.5 provide a useful comparison, the detections on individual ALS locations can also be used to give an indication of receiver efficiency and calculate the number of transmitters (tags) missed (Table 4.1 and Table 4.2). These results show the particular areas where transmitters are missed and where individual ALS locations or gate detection efficiencies are relatively poor. The detections on an ALS (receiver or ALS gate) can be corrected for missed transmitters by identifying records of transmitters on subsequent ALSs. These data can be used to calculate the percentage of transmitters missed and the receiver efficiency percentages at ALS locations. The detection efficiency at R12 (2017 = 90.9% and 2018 = 100%) and H2 (2017 = 97% and 2018 = 93.5%) were good in both years; however, H1 had a detection efficiency of only 55% in 2018 compared to 90.9% in 2017. It is not possible to calculate efficiencies for the last gate in the system and as such the IN gate in 2017 and the OUT gate in 2018 have no data and the reported tag loss will be the worst case. If the detection efficiency of 91.8% recorded at the IN gate in 2018 is representative of the conditions experienced in 2017 then there may have been 2 transmitters missed (7.7% of transmitters) missed in 2017. Corrected, this would have given an estimated total of 28 passing the IN gate.

Table 4.1: Results of receiver efficiency calculations in 2017 showing the corrected Figures for total transmitters, transmitters missed, transmitters detected, ALS detection efficiencies (%)

| Station | R4 | R6 | R9 | R12 | H1 | H2 | IN |
|---|---|---|---|---|---|---|---|
| Detections | 11 | 33 | 25 | 30 | 30 | 32 | 26 |
| Transmittes Missed | 14 | 1 | 10 | 3 | 3 | 1 | NA |
| Total Transmitters (corrected) | 25 | 34 | 35 | 33 | 33 | 33 | 26 |
| Transmittes Missed (%) | 56.0 | 2.9 | 28.6 | 9.1 | 9.1 | 3.0 | NA |
| Detection Effency (%) | 44.0 | 97.1 | 71.4 | 90.9 | 90.9 | 97.0 | NA |

Transmitter loss was also calculated and can be considered a proxy for mortality. As presented below in section 4.2, initial transmitter losses before first detection were 22 (36%) in 2017 and 11 (11%) in 2018. Calculating mortality % $km^{-1}$ allows comparisons to be draw between other studies. In both 2017 and 2018, transmitter losses (estimated mortality) in the lower river were between 0-2.1 % $km^{-1}$. In 2017 no losses were recorded through Aberdeen Harbour, but in 2018 estimated mortality through the harbour was between 2.1-5.1 % $km^{-1}$.

Estimated early marine mortality was between 1.3-5.3 % $km^{-1}$ (Table 4.3 and Table 4.4).

Table 4.2: Results of receiver efficiency calculations in 2018 showing the corrected Figures for total transmitters, Transmitters missed, transmitters detected, ALS detection efficiencies (%).

| Station | R1 | R2 | R3 | R4 | R5 | R6 | R7 | R8 | R9 | R10 | R11 | R12 | H1 | H2 | IN | OU |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Detections | 2 | 1 | 5 | 3 | 1 | 7 | 85 | 84 | 65 | 76 | 68 | 83 | 44 | 72 | 67 | 68 |
| Transmittes Missed | 3 | 4 | 0 | 2 | 32 | 26 | 3 | 4 | 22 | 10 | 16 | 0 | 36 | 5 | 6 | Na |
| Total Transmitters (corrected) | 5 | 5 | 5 | 5 | 33 | 33 | 88 | 88 | 87 | 86 | 84 | 83 | 80 | 77 | 73 | 68 |
| Transmittes Missed (%) | 60.0 | 80.0 | 0.0 | 40.0 | 97.0 | 78.8 | 3.4 | 4.5 | 25.3 | 11.6 | 19.0 | 0.0 | 45.0 | 6.5 | 8.2 | Na |
| Detection Effency (%) | 40.0 | 20.0 | 100.0 | 60.0 | 3.0 | 21.2 | 96.6 | 95.5 | 74.7 | 88.4 | 81.0 | 100.0 | 55.0 | 93.5 | 91.8 | Na |

Table 4.3: showing the transmitter loss in 2017 measured between ALSs or gates for each giving the calculated mortality as a percent and the percent mortality per kilometre.

| ASL Movement | D-R4 | R4-R6 | R6-R9 | R9-R12 | R12-H1 | H1-H2 | H2-IN |
|---|---|---|---|---|---|---|---|
| Transmitter Loss | 21 | 1 | 3 | 2 | 0 | 0 | 7 |
| mortality (%) | 45.7 | 2.9 | 7.9 | 5.7 | 0.0 | 0.0 | 21.2 |
| mortality (%) $km^{-1}$ | 1.3 | 0.3 | 0.4 | 0.5 | 0.0 | 0.0 | 5.3 |

Table 4.4: Showing the transmitter loss in 2018 measured between ALSs or gates for each giving

the calculated mortality as a percent and the percent mortality per kilometre.

| ASL Movement | D-R1 | R1-R2 | R2-R3 | R3-R4 | R4-R5 | R5-R6 | R6-R7 | R7-R8 | R8-R9 | R9-R10 | R10-R11 | R11-R12 | R12-H1 | H1-H2 | H2-IN | IN-OUT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Transmitter Loss | 1 | 0 | 0 | 0 | 4 | 0 | 7 | 0 | 1 | 1 | 2 | 1 | 3 | 3 | 4 | 5 |
| Mortality (%) | 16.7 | 0.0 | 0.0 | 0.0 | 10.8 | 0.0 | 7.4 | 0.0 | 1.1 | 1.1 | 2.3 | 1.2 | 3.6 | 3.8 | 5.2 | 6.8 |
| Mortality (%) $km^{-1}$ | 1.7 | 0.0 | 0.0 | 0.0 | 2.1 | 0.0 | 1.2 | 0.0 | 0.2 | 0.2 | 0.7 | 0.3 | 5.1 | 2.1 | 1.3 | 1.1 |

These Table 4.3 and Table 4.4 can be summarised in to river, estuary (harbour) and early marine mortality (Table 4.5).

Table 4.5: Summary of the percent rate of loss per kilometre (% $km^{-1}$) (estimated mortality) per habitat type (Rover, Estuary and Early Marine)

| Year | River | Estuary | Early Marine |
|---|---|---|---|
| 2017 | 0.59 | 0.00 | 5.30 |
| 2018 | 0.22 | 2.87 | 1.15 |

## 4.2. River Migration

### 4.2.1. The Rate of River Movement (RORM)

The median RORM (ground speed) between ALSs in the river was 0.40$ms^{-1}$ (Inter Quartile Range (IQR = 0.12-1.07) for 2017 and 0.11$ms^{-1}$ (IQR = 0.06-0.15) for 2018. The in-river RORMs were not normally distributed in either 2017 or 2018. A Wilcoxon Rank Test was used to test the similarity of the RORMs between 2017 and 2018. This showed that the RORMs between years were significantly different (W = 7624, p-value = 0.0002) with 2017 having a higher RORM between ALS stations. This RORM gives a sense of migration speed between ALSs but to consider the Total Rate of River Movement (TotRORM) from the point of release (after tagging) to entering the sea at H2 is a useful metric to compare across studies. The median TotRORM between years was also compared and calculated as 0.08 $ms^{-1}$ (IQR = 0.04-0.12) in 2017 and 0.06 $ms^{-1}$ (IQR = 0.04-0.09) which were not normally distributed and not significantly different (W = 1294, p-value = 0.1666) using a Wilcoxon Rank Test.

### 4.2.2. Total River Time (TRT)

The total time spent in the river by tagged fish was also calculated. The median TRT in 2017 was 200 hours (IQR = 168 – 393) and in 2018 was 155 hours (IQR = 119 – 245). In both

2017 and 2018, the TRT were not normally distributed, thus a Wilcoxon Rank Test was used to test the similarity of the TRT between 2017 and 2018. This showed the total river migration times were significantly different (W = 1467, p-value = 0.008) with fish in 2018 migrating through the river in a shorter TRT.

### 4.2.3. Time through the Harbour (TTH)

Time taken to migrate through the harbour was compared between 2017 and 2018. The median migration time from last detection on R12 to last detection at H2 was 2.51 hours (IQR = 1.22 - 27.02) in 2017 and 1.52 hours (IQR = 1.11 – 7.29) in 2018. Both the 2017 and 2018 TTH times were not normally distributed, as such a Wilcoxon Rank Test showed that the time taken to migrate through the harbour was not significantly different between the two years (W = 1566, p-value = 0.1525).

### 4.2.4. Depth and temperature tags in the river and harbour

The transmissions from tags capable of sensing depth and temperature were recorded through both years (2017 n=15 and 2018 n=30). The range of depths (Figure 4.4) and temperatures (Figure 4.5) recorded by these tags are shown below.

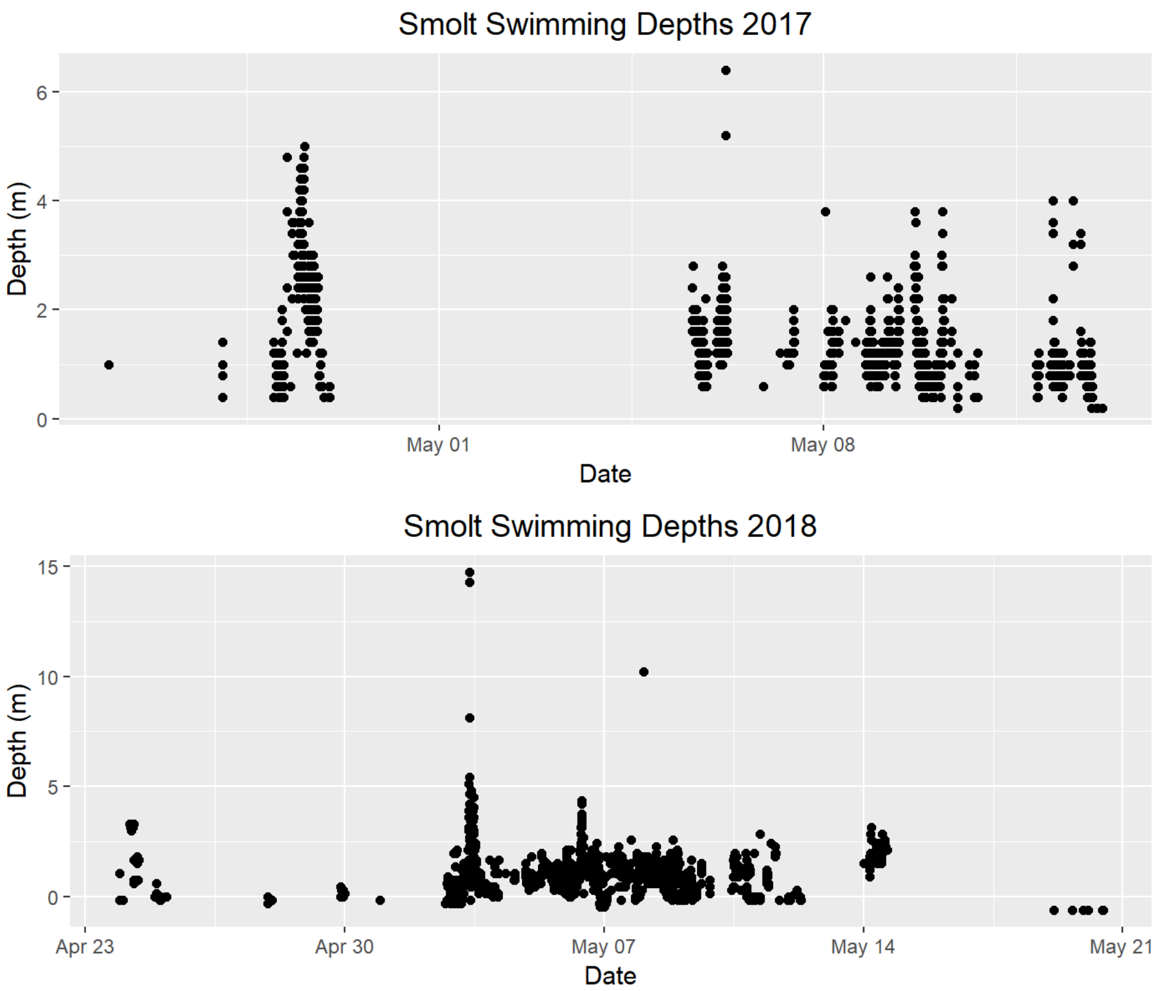



Figure 4.4: Smolt swimming depths in 2017 and 2018. Individual tag transmissions of depth are recorded (black dots) for 2017 and 2018.

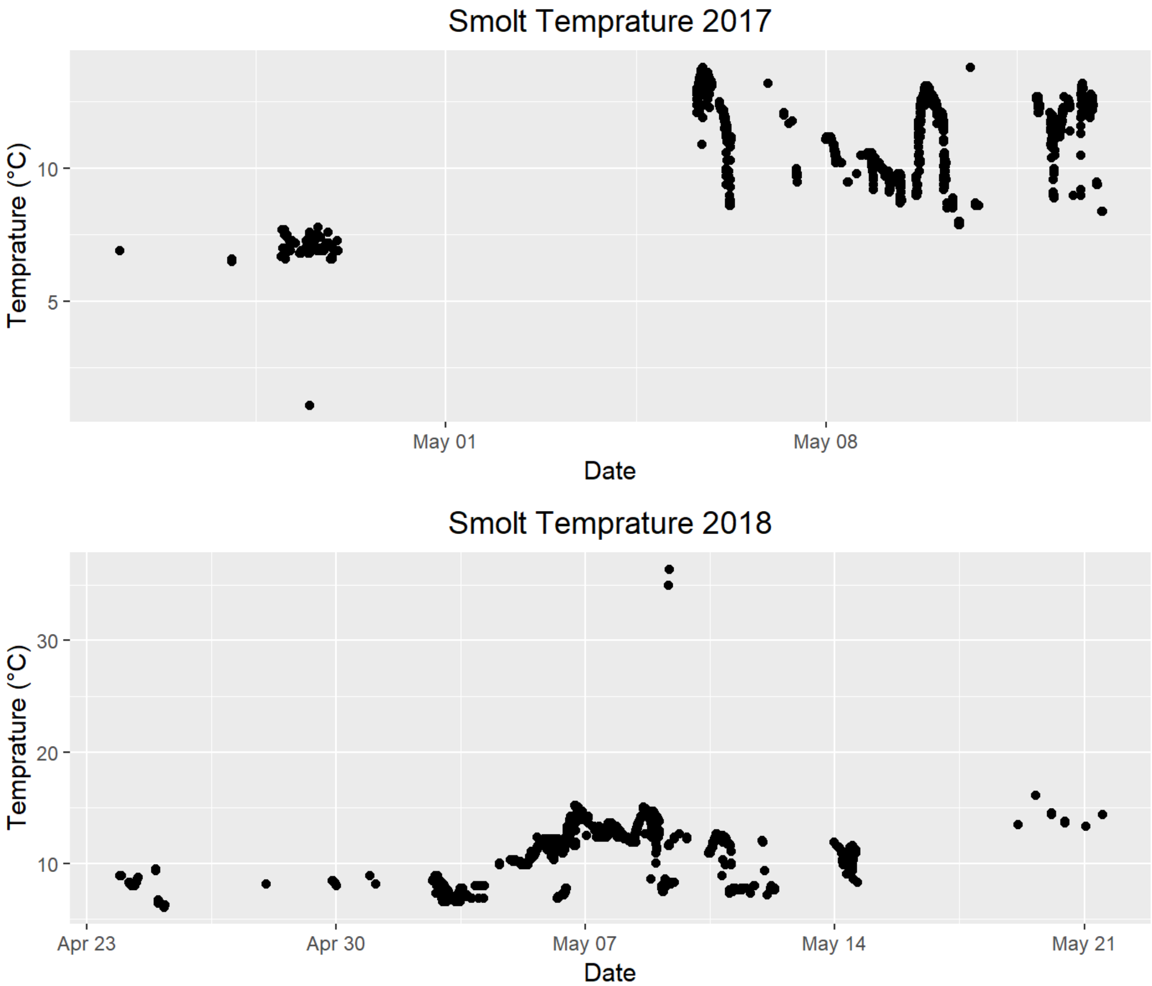



Figure 4.5: Smolt swimming temperatures in 2017 and 2018. Individual tag transmissions of temperature are recorded (black dots) for 2017 and 2018.

Off these 45 tags implanted into salmon smolts only one tag transmitted a temperature reading above 30°C. This spike in temperature occurred at gate H2 and was preceded by a rapid drop in temperature. This is consistent with a predation event by a mammal or bird as the mouthful (or stomach full) of cold water rapid rise in temperature as the stomach contents return to the animals normal body temperature (Figure 4.6).

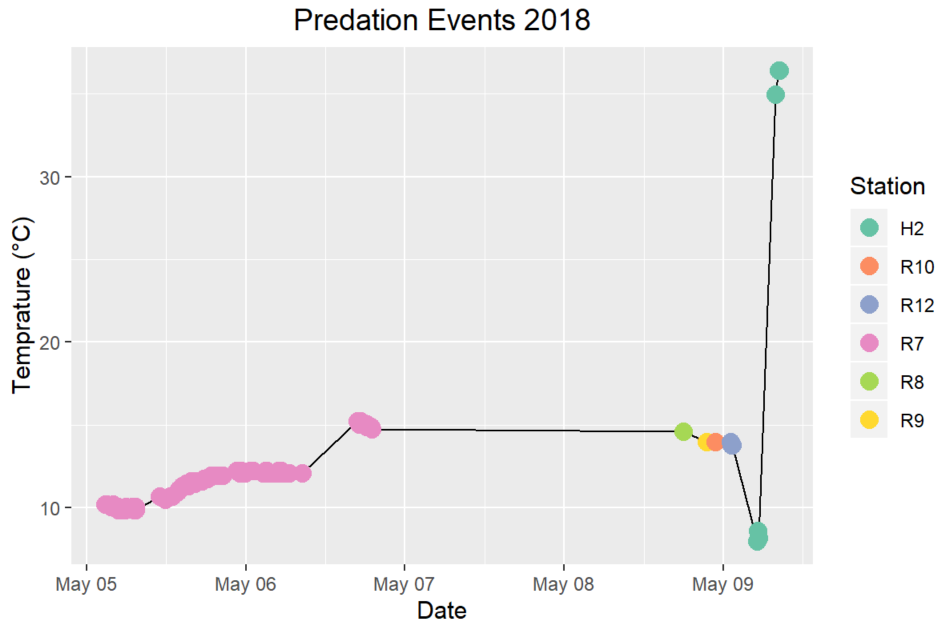



Figure 4.6: Temperature plot from transmitter (tag) serial number 20 in 2018 showing a drop in temperature followed by a rapid increase to 36.4°C. Coloured dots represent the ALS the tag was detected at.

Several of the depth records in 2018 also showed some unusual activity with one showing a depth of 10.2 m through the H2 gate and one at 14.7 m, while at the OUT gate (Figure 4.7). While this seems unusual, it is not possible to explicitly say if this was predation or not, as some smolt have been shown to make deeper dives in other studies. That said, of the 45 tags capable of transmitting depth in 2017 and 2018 only two (6.6%) go below 7 m, in 2018. In 2017, these patterns were absent with a max depth of 6.8 m and a maximum temperature of 13.8 °C.

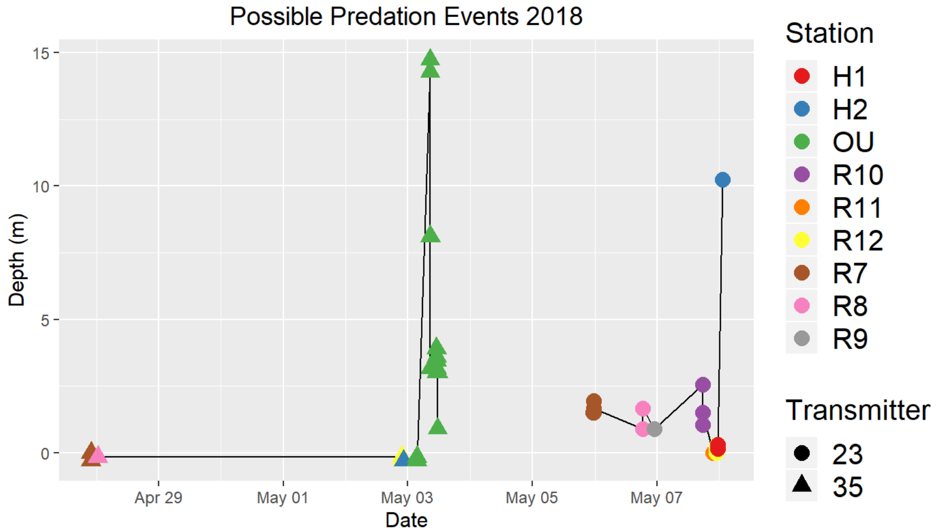



Figure 4.7: Depth plot from transmitter (tag) serial numbers 23 and 35 in 2018 showing an increase in swimming depth. Coloured shapes represent tag serial number 23 (round) and tag 35 (triangular) with the colour representing the ALS station number.

## 4.3. Marine Migration

### 4.3.1. Rate of Marine Migration

ROMs (ground speed) in the marine environment were measured from the outer ALS gate in the harbour (H2) to the first marine gate (IN), and from IN to second marine gate (OUT). Receivers were located at H2 and IN in both 2017 and 2018 and on the OUT gate only in 2018. The ROMs were compared where possible between 2017 and 2018 (H2-IN gates) and between H2-IN and IN-OUT gates in 2018. The median ROM between the H2-IN gates was 0.44 $ms^{-1}$ (IQR = 0.38 - 0.54) in 2017 and 0.45 $ms^{-1}$ (IQR = 0.37-0.53) in 2018. Both 2017 and 2018 ROMs between the H2-IN gates were normally distributed, the ROM between H2 - IN were compared for 2017 and 2018 using a t-test. This showed the ROMs were not statistically different ($t = -0.44$, $df = 47.43$, p-value = 0.66). The median ROM between the IN-OUT gates in 2018 was 0.37 $ms^{-1}$ (IQR = 0.21 - 0.58) this, however, was found to not be normally distributed. A Wilcoxon Rank Sum Test was used to compare the ROMs between the H2-IN and IN-OUT gates in 2018. This showed the ROM between H2-IN and IN-OUT were not significantly different ($W = 1142$, p-value = 0.13).

### 4.3.2. Actual Fish Swimming Speed (AFSS)

The data gathered from the ADCP was used to adjust the detected ROMs (speed over the ground) recorded on ALS to account for the effects of tide on the tagged fish. This showed the median AFSSs between the H2-IN gates was 0.46 $ms^{-1}$ (IQR = 0.35 - 0.55) in 2017 and 0.45 $ms^{-1}$ (IQR = 0.38 - 0.52) in 2018. The AFSSs were not significantly different (t = 0.464, df = 46.549, p-value = 0.963). The median AFSS for 2018 between the IN-OUT gates was 0.57 $ms^{-1}$ (IQR = 0.50 - 0.65). Comparing this to the AFSS between the H2-IN gates in 2018 showed a highly significant difference (t = -3.48, df = 68.5, p-value <0.001).

When these ROMs were converted to fork lengths per second ($L_f s^{-1}$) the same trend was observed with both 2017 and 2018 not being significantly different between H2-IN gates (t = 0.018, df = 47.67, p-value = 0.98) and between IN-OUT being significantly faster (t = -3.5994, df = 69.391, p-value < 0.001). In 2017, the median fish fork length swimming speed was 3.26 $L_f s^{-1}$ (IQR 2.48 – 3.9) and in 2018 it was 3.12 (IQR 2.62-3.78) between the H2-IN gates. In 2018, the median fish actual swimming speed between the IN-OUT gates was 3.98 $L_f s^{-1}$ (IQR 3.54-4.54)

### 4.3.3. Direction of Marine Travel

Directions in the marine environment were also measured between the H2-IN gates and between the IN-OUT gates. Receivers were located in the IN gate in both 2017 and 2018, but the OUT gate only in 2018. An ADCP was deployed in 2018, making detailed recordings of the current speed and direction during the period of post-smolt migration.

In 2017, the mean bearing (circular mean) of travel between H2-IN gates was 106° from North (circular sd ± 39°) and in 2018 the mean bearing was 96° from North (circular sd ± 34°), both in an East South East direction. Watson's Two-Sample Test of Homogeneity shows the two samples are from populations with a similar mean (Test Statistic: 0.066, Level 0.05 Critical Value: 0.187). In 2018, where both the IN and OUT gates were present, the mean bearing of travel between H2-IN and from the IN-OUT (128 ° from North, circular sd ± 46°) were also tested using Watson's Two Sample Test of Homogeneity and were found to be from populations with significantly differing means (Test Statistic: 0.3632, Level 0.05, Critical Value: 0.187). To summarise, between years the bearings taken by tagged smolts between H2-IN gates are similar but in 2018 the bearings between H2-IN and IN-OUT are significantly different. The mean current direction during the Flood tide is 183° from North and during the Ebb tide is 28° from North (i.e. aligned North and South along the coastline). Of the fish detected at H2, significantly more left the harbour on an Ebb tide (20 out of 24 recorded in 2017 and 23 out of 35 in 2018, chi squared test $\chi^2$=15.6, p<0.001). These findings are plotted in Figure 4.8.

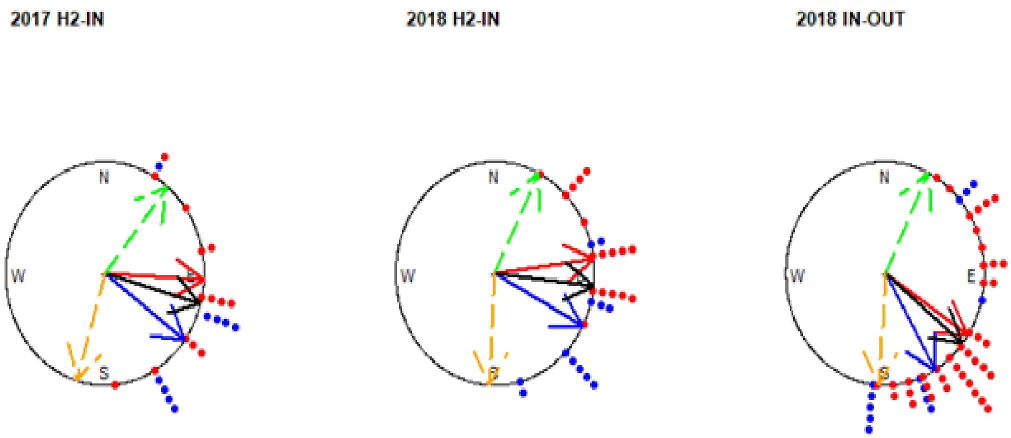
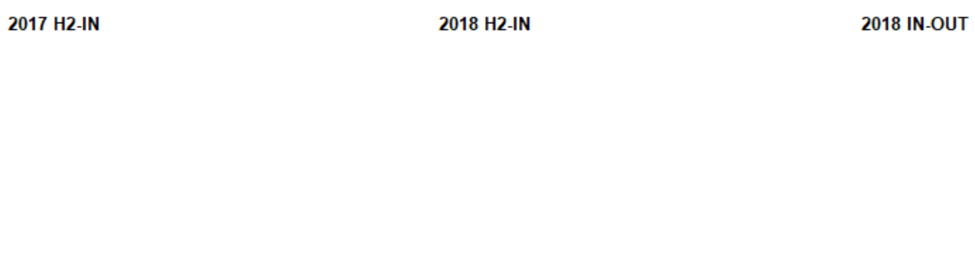



Figure 4.8: Plots showing recorded fish bearings with Ebb tide (red points) and flood tide (blue points), with arrows showing mean movement directions (black), mean movement direction during an Ebb tide (Red) and Flood tide (Blue). Mean current directions during fish movements are also plotted for 2017 and 2018 from ADCP data, ebbing (dashed green) and Flooding (dashed orange) with modelled data used in 2017.

### 4.3.4. Actual fish headings

The data gathered from the ADCP were used to adjust the detected movements recorded on ALS to account for the effects of tidal currents on the tagged fish. This gave the actual (Lagrangian) heading and speed of the individual fish. The mean actual fish heading between the H2 - IN gate in 2017 was 94$^o$ (circular sd ± 23$^o$) from north and was 107$^o$ in 2018 (circular sd ± 49$^o$) using a Watson's Two-Sample Test of Homogeneity with 0.05 as the critical value shows the two sample are not significantly different (Test Statistic: 0.086, Level 0.05 Critical Value: 0.187). The actual fish heading in 2018 from the IN-OUT was 158 $^o$ from north (circular sd ± 37$^o$). Comparing the actual fish movements in 2018 between H2-IN gates and between IN-OUT gates showed that swimming headings were significantly different (Test Statistic: 0.362, Level 0.05 Critical Value: 0.187), this is shown in Figure 4.9.



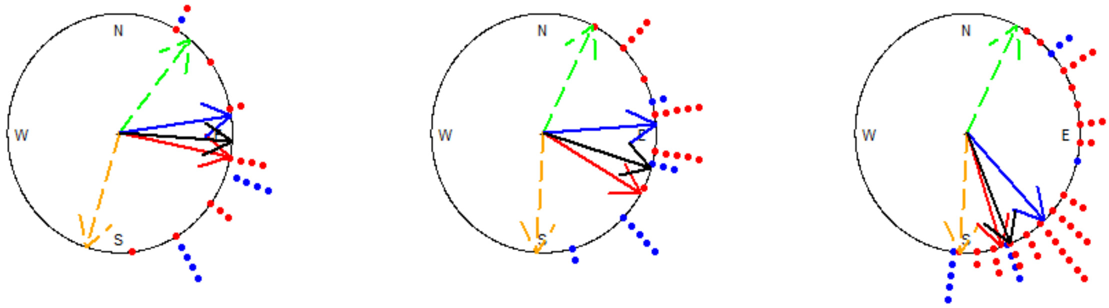



Figure 4.9: Plots showing fish bearings recorded on ALSs with Ebb tide (red points) and flood tide (blue points), with arrows showing the mean actual fish swimming heading (black) after the adjustment for current speed and direction, mean movement direction during an ebb tide (Red) and flood tide (Blue). Mean current directions during fish movements are also plotted for 2017 and 2018 from ADCP data, ebbing (dashed green) and Flooding (dashed orange) with modelled data used in 2017.

## 4.4. Fish Passage Simulation and Modelling

### 4.4.1. Fish Passage Simulation

Using data gathered from the range testing, fish passage simulations were run using the IN and OUT gate spacing, the IQR fish swimming speeds and the tag transmission rates. This derived the probability of detecting a tag passing an ALS in the IN or OUT gates. A simplified example of this is shown in Figure 4.10 and is based on the findings of this study, fish taking 826s to cover the 380m detection range at the 2017 actual fish swimming speed of 0.46 $ms^{-1}$. From the simulations at the worst preforming gate (OR12, 2018), the data show the probability of detecting a single fish passing the ALS gate is 0.95. However, in 2018, six fish were detected on the OUT gate but not on the IN gate suggesting there may be localised reductions in the detection probabilities at some points in the ALS gate under certain conditions. Table 4.6 shows the results of the simulations. Using the two worst range test stations, the probability of detecting fish at varying speeds and with varying ALS separations was simulated. This showed that at both range test stations the probability of detecting fish decreased with increasing swimming speed.

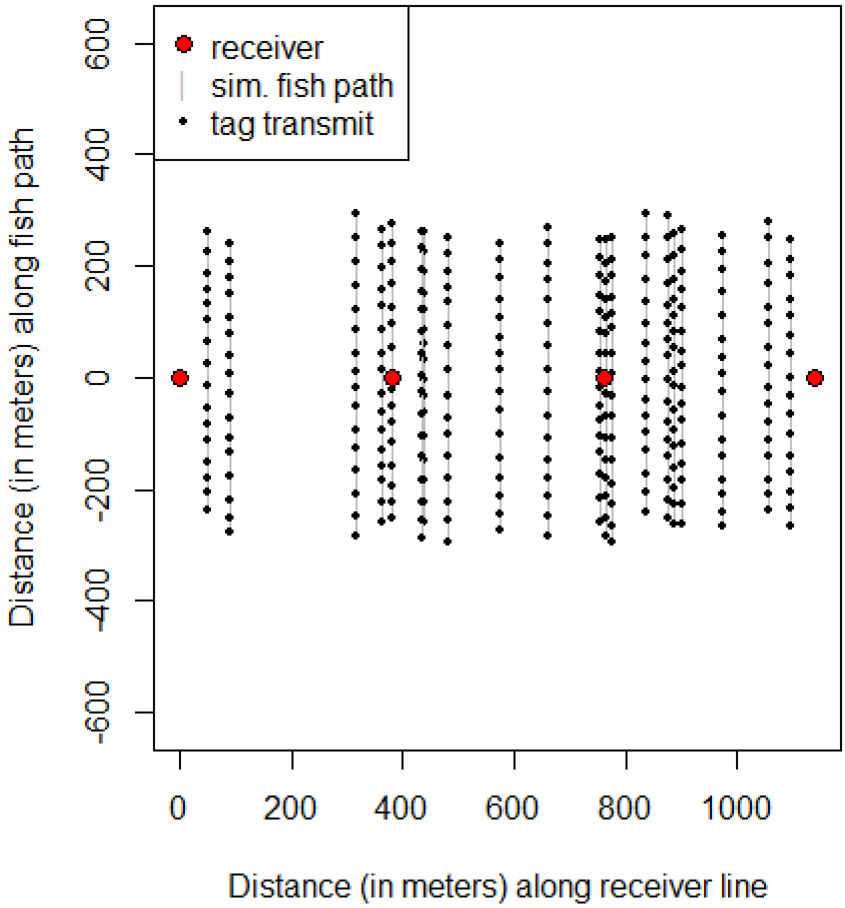



Figure 4.10: Example of simulated fish paths (grey line) with tag transmissions (black dots) based on the tags used and fish swimming speeds recorded as fish pass an ALS line (red dots represent receivers).

The reduction in the probability of detection started at a lower swimming speed at OR12 than at IR13. The receiver spacing simulations were similar with the probability of detecting tag transmissions falling with increased distance between the ALSs, again OR12 dropped at a lower separation distance than IR13.

Table 4.6 Fish passage simulation results showing year of sentinel tag deployment, type of tag, deployment location and the probability of detecting a single fish passing the array at the given sentinel tag location, the mean probability over ten thousand runs of the simulation and the standard deviation around the mean.

| Year | Tag Type | Location | Probability of detecting fish | Mean probability for 10000 simulations | SD |
|---|---|---|---|---|---|
| 2017 | ART-LP-7,3 | IR13 | 1 | 1 | 0 |
| 2017 | ART-LP-7,3 | IR36 | 1 | 1 | 0 |
| 2018 | V7-2x-069k-1 | IR13 | 1 | 1 | 0 |
| 2018 | V7-2x-069k-1 | IR36 | 1 | 1 | 0 |
| 2018 | ART-LP-7,3 | OR12 | 0.986 | 0.947 | 0.053 |
| 2018 | V7-2x-069k-1 | OR24 | 1 | 1 | 0 |
| 2018 | V7-2x-069k-1 | OR44 | 1 | 1 | 0 |
| 2018 | ART-LP-7,3 | OR82 | 1 | 0.999 | 0.003 |

Simulations were also run to explore how swimming speed and receiver spacing affected the probability of detection. These were simulated using the worst preforming range test stations to give a worst case scenario. These were IR13 in 2017 and OR12 in 2018 and are shown in Figure 4.11.

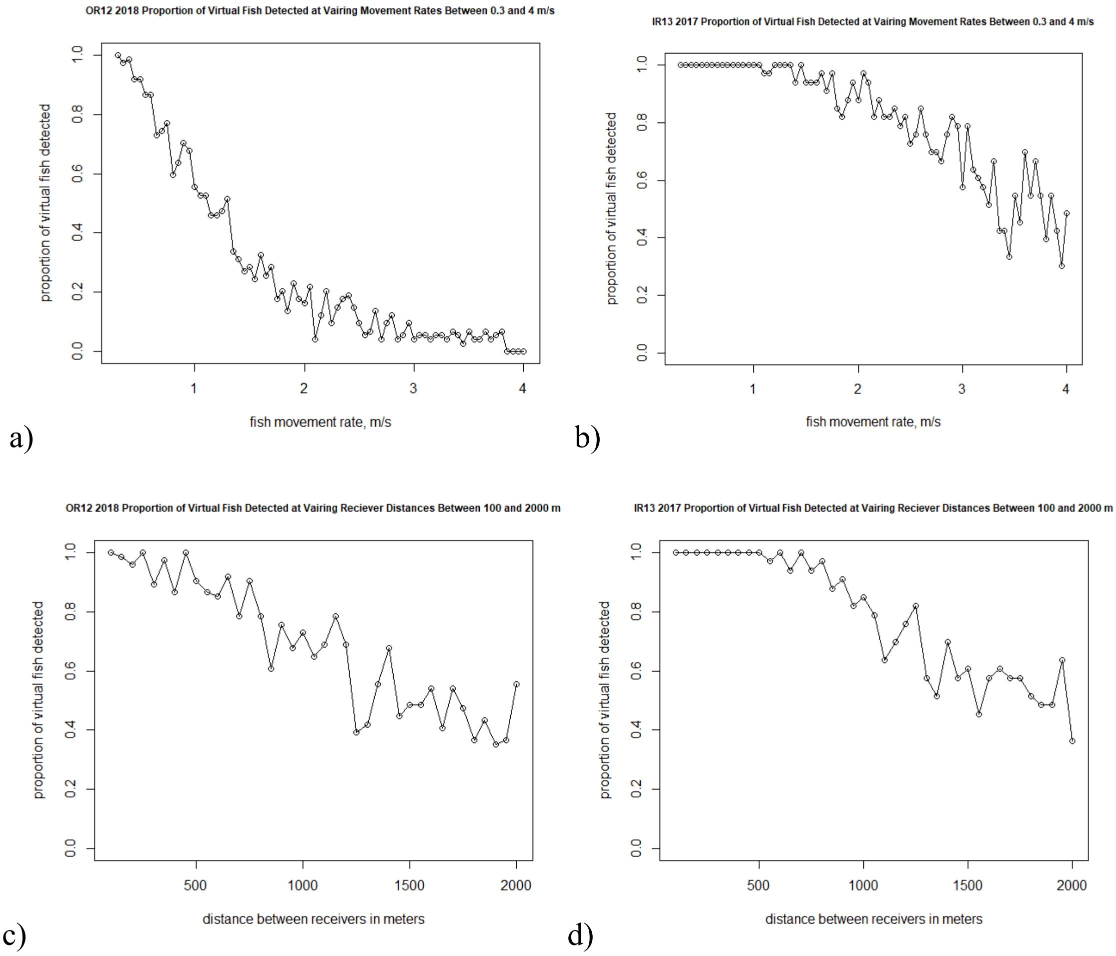



Figure 4.11: simulations of the probability of detecting a tagged fish based on the range test results showing fish detections probabilities at varying fish swimming speeds (a, b) and at differing receiver spacing (c and d).

### 4.4.2. Modelling

Modelling was undertaken to investigate factors that may affect the survival of smolts to the IN gate. Using the tag detection at the IN gate as a proxy for survival, individual fish were awarded one if they were detected or a zero if not detected, Figures were also corrected in 2018 for tagged fish detected on the OUT gate but not the first (n=6).

#### 4.4.2.1. Model factor correlation

Correlations between variables were investigated (Figure 4.12). A correlation was found between tag length and tag burden by length (length of tag / length of fish expressed as a percentage). As such, tag length was removed from models and tag burden by length was used.

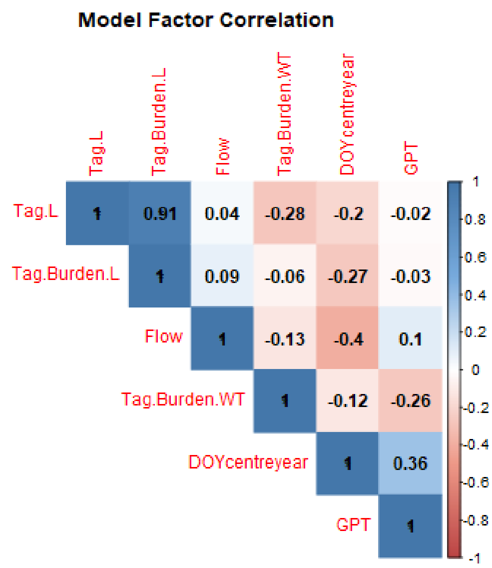



Figure 4.12: Plot to investigate any correlation between variables used in the model showing the correlation coefficients.

#### 4.4.2.2. Model Selection

Models were run in R and the model selection function in MuMIn (Barton, 2019) used to rank these models by Akaike's Information Criteria (AIC). Models with a delta value of less than six were taken forward and re-compared (Table 4.7). The most parsimonious model predicting successful migration to the IN gate (binomial) showed year of tagging as by far the largest effect. There was no evidence of an effect from day of year centred around the dates of tagging in each year, release location or the interaction between group size and day of year. Variables that had a marginal effect explaining some variation in migration success include Tag burden (by length), tag burden (by weight), group size and flow. Model selection results are presented in Table 4.7

Table 4.7: Results of the model selection process showing the final models. Tag.Burden.WT (tag burden by weight (g) as a percentage of smolt mass (g)), Tag.Burden.L (tag length as a percentage of the fish length (mm)), as.factor(Year) (2017 or 2018), DOYcentreyear (julien day centred to the period of tagging in each year), Flow (the average daily river flow at the time of release ($m^3s^{-1}$)) and GPT (number of tagged fish released at each site each day).

| Model | df | logLik | AICc | delta | weight |
|---|---|---|---|---|---|
| Tag.Burden.L + as.factor(Year) | 3 | -96.94 | 200.03 | 0 | 0.302 |
| as.factor(Year) | 2 | -98.36 | 200.8 | 0.763 | 0.206 |
| Tag.Burden.WT + as.factor(Year) + GPT | 4 | -96.56 | 201.37 | 1.337 | 0.155 |
| Tag.Burden.L + as.factor(Year) + GPT | 4 | -96.92 | 202.09 | 2.058 | 0.108 |
| Tag.Burden.L + as.factor(Year) + Flow + GPT | 5 | -96.14 | 202.66 | 2.628 | 0.081 |
| Tag.Burden.WT + as.factor(Year) + Flow + GPT | 5 | -96.17 | 202.74 | 2.704 | 0.078 |
| Tag.Burden.WT + Tag.Burden.L + as.factor(Year) + DOYcentreyear + Flow + GPT | 7 | -94.11 | 202.96 | 2.932 | 0.07 |

### 4.4.3. Model Output

The model selected showed that Year (as a factor) was significant in predicting the probability of survival to the IN gate ($z=-3.77$, $df=159$, $p<0.001$). While tagging locations were constant both years the proportion of fish tagged at each site varied across years. This spatial variation in the number of fish tagged at each location may be causing the model to show a strong indication of Year. Exposure to predation will be higher in fish that travel further down the river course.

```
Call:
glm(formula = Surv.to.IN ~ as.factor(Year), family = binomial(link = "logit"),
    data = surviveToIN)

Deviance Residuals:
   Min      1Q  Median      3Q     Max
-1.641  -1.066   0.776   0.776   1.293

Coefficients:
                    Estimate Std. Error z value Pr(>|z|)
(Intercept)          -0.2683     0.2605  -1.030 0.303148
as.factor(Year)2018   1.3142     0.3462   3.796 0.000147 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 211.70  on 159  degrees of freedom
Residual deviance: 196.72  on 158  degrees of freedom
AIC: 200.72

Number of Fisher Scoring iterations: 4
```

## 4.5. Range testing

### 4.5.1. 2016 Range test

Figure 4.13 shows the results of the range test performed in Aberdeen Bay in 2016. From these results, the spacing between the receivers of 380 m was deemed to be appropriate. This is based on the tag passing a maximum distance of 190 m or dead centre of two deployed ALSs. There was a 77% probability of detecting a single transmission from the Thelma Biotel range test tag at 190 m. The examples below go into more detail around passage time over ALSs and the number of transmissions made by tags during the time they are within detection range in each year. Probabilities of detecting single transmissions from tags are not the same as actual fish detection and should not be confused.

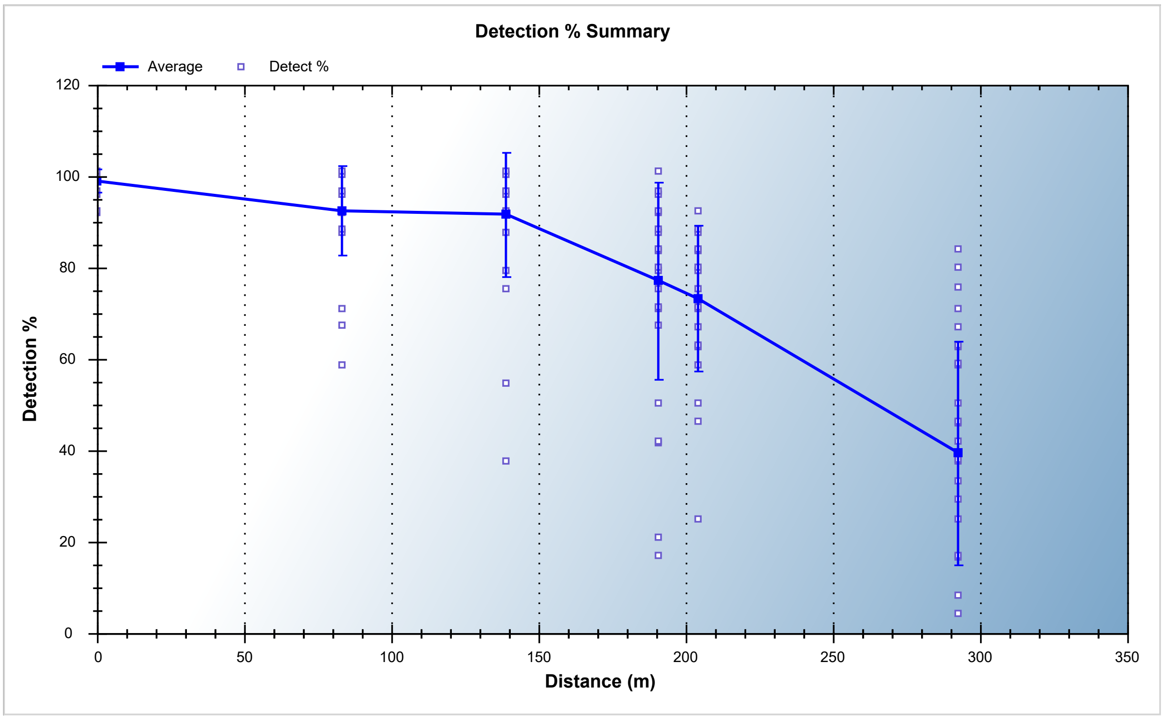
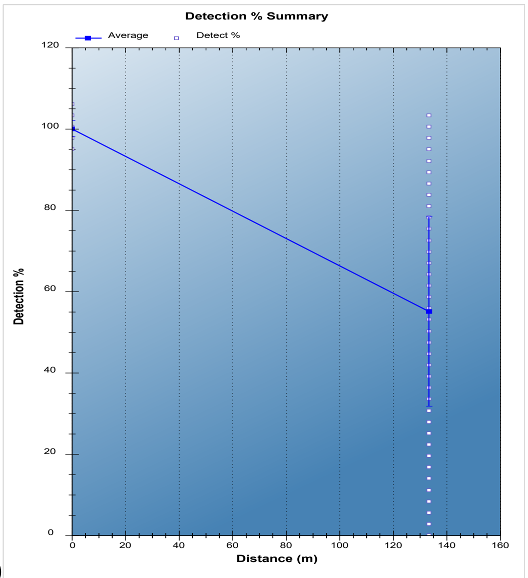


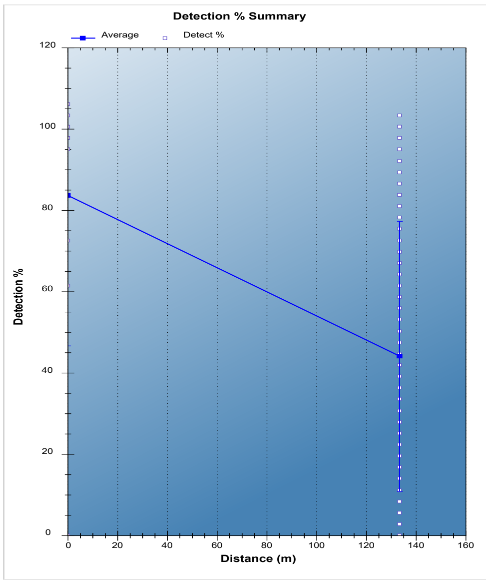

Figure 4.13: Results from a 5 day range test in in Aberdeen Bay during 2016 showing the percent of tag detections at certain distances where ALSs were deployed. The solid blue squares are the average detection percentage at each ALS location; white squares show 3 hourly detection percentages. The error bars are ± 1 standard deviation from the average detection percentage.

### 4.5.2. Range testing in the Harbour

The percentage of tag detections at the H2 gate varied between 2017 and 2018 with the average probability of detection of an individual transmission in 2017 being 78% at 67 m (1/2 way between the 2 ALSs in the gate) whereas in 2018 the average probability of detection of an individual transmission was 63% (Figure 4.14).




a)

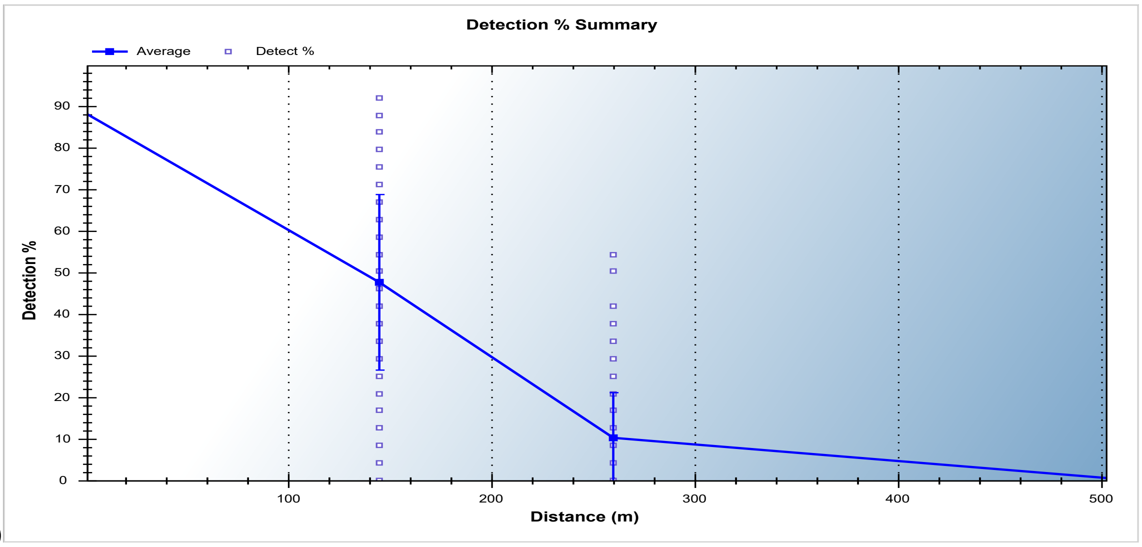



b)

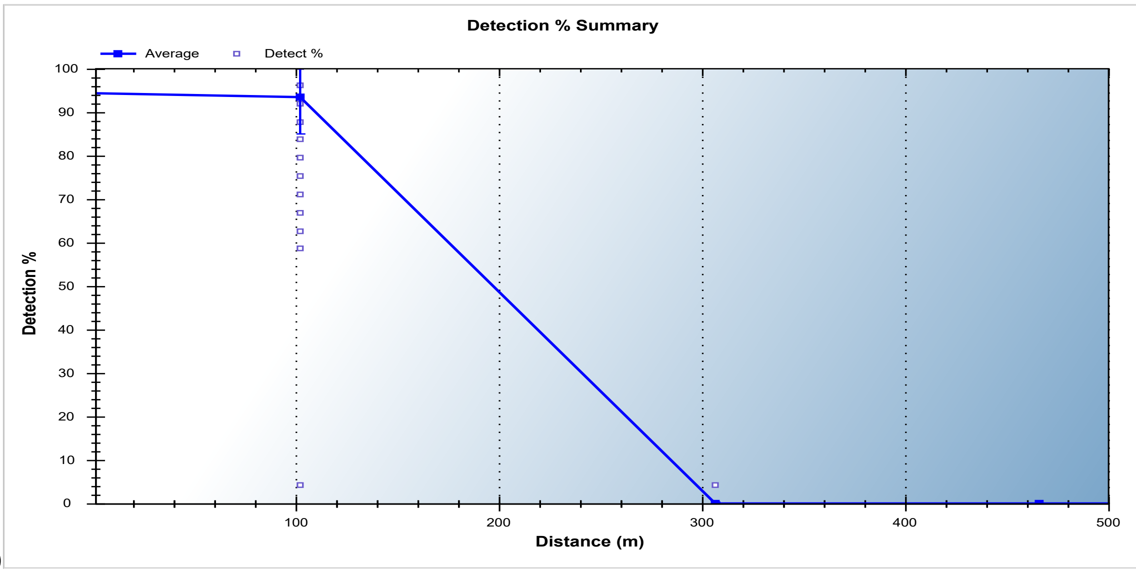
Figure 4.14: Results from the sentinel tag transmissions at the H2 gate deployed in a) 2017 an b) 2018 showing the percent of tag detections at the 2 ALSs forming the gate combined. The solid blue squares are the average detection percentage at each ALS location (north breakwater or old south breakwater); white squares show actual 3 hourly detection percentages. The error bars are ± 1 standard deviation from the average detection percentage.

### 4.5.3. Range testing at marine gates

Range testing at IN and OUT gates showed variable results across the each gate and between years at the same ALS range testing location. The 2017 marine gate range testing suggested the probability of detecting a single tag transmission at 190 m was 36% (north, ALS-IR13) and 60% (South, ALS-IR28) (Figure 4.15). In 2018, the range testing showed a detection probability of 68% (north, ALS IR13).




a)




b)

Figure 4.15: Results from the sentinel tags deployed in a) the north (ALS = IR13) or b) the south (ALS = IR28) of the IN gate and during 2017 showing the percent of tag detections at distances where ALSs were deployed. The solid blue squares are the average detection percentage at each ALS location; white squares show actual 3 hourly detection percentages. The error bars are ± 1 standard deviation from the average detection percentage.

In 2018, the same sentinel tag locations were used in the IN gate, along with four more locations in the OUT gate. Results from several of these stations are presented (Figure 4.16). IR13 in the IN gate gave a 66% probability of detecting a single transmission at 190 m, OR12 gave an 18% chance and OR28 gave a 68% chance.

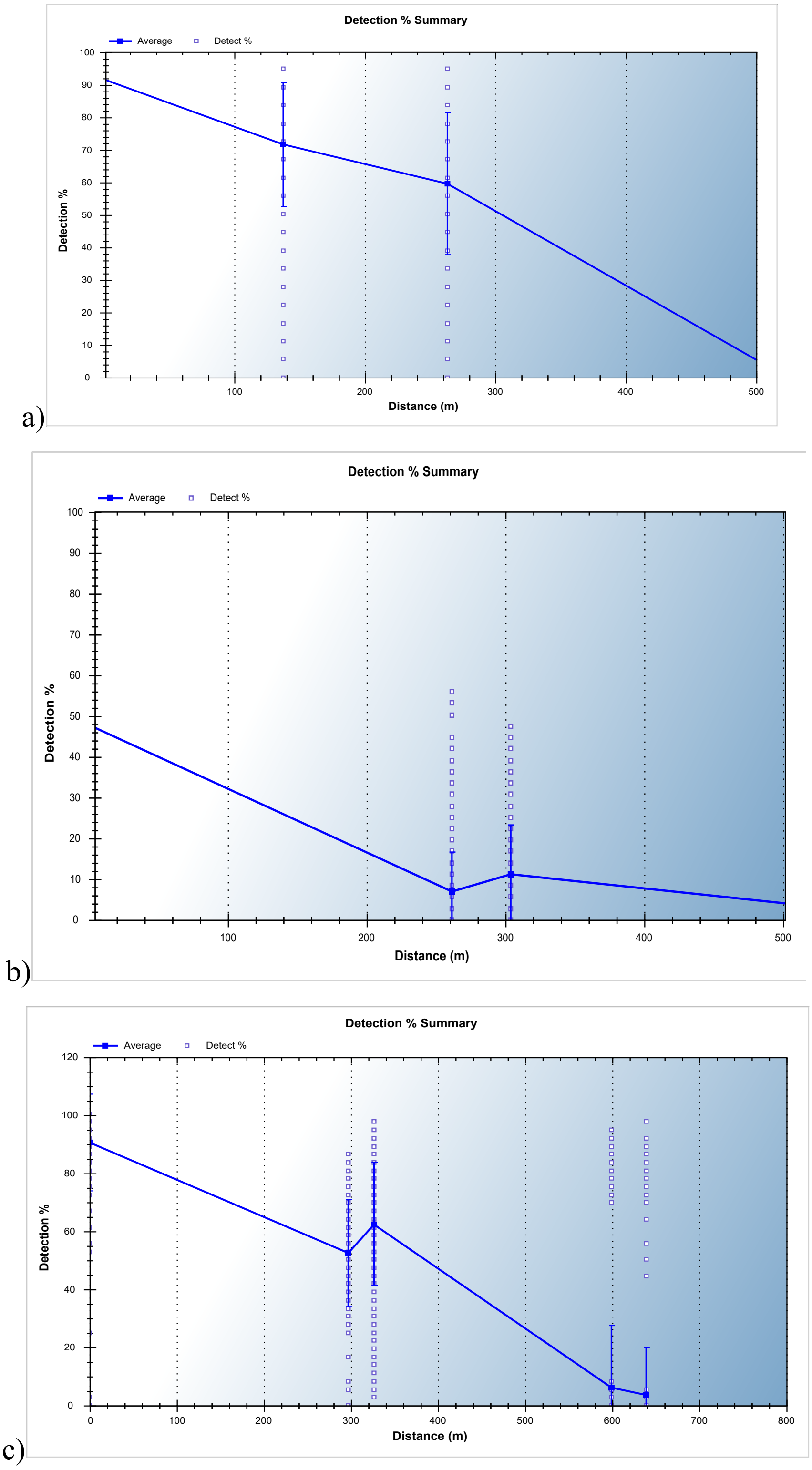



Figure 4.16: Results from the sentinel tags deployed in a) the north of the IN gate (ALS = IR13) b) north of the OUT gate (ALS = OR12) and c) the middle of the OUT gate (ALS = OR28) during 2018 showing the percent of tag detections at distances where ALSs were deployed. The solid blue squares are the average detection percentage at each ALS location; white squares show actual 3 hourly detection percentages. The error bars are ± 1 standard deviation from the average detection percentage.

# 5. Discussion

## 5.1. Study aims

The first biological aim of this thesis was to investigate migration success of smolts as they migrate down the River Dee in Aberdeenshire, as they pass through the harbour and post-smolts as they make their initial entry into the marine environment to 10 km distant from the mouth of Aberdeen Harbour.

The second biological aim was to investigate whether post-smolts showed any pattern of directional movement in the sea during the first 10 km of their migration to distant feeding grounds.

The technical aim was to provide estimates of missed detections based on range testing and simulation results to assess if the layout of ALSs (the array) is fit for purpose.

## 5.2. Study findings

### 5.2.1. Estimated Survival

This study shows that that smolts and post-smolts showed spatial variation in estimated survival in the River Dee, Aberdeen Harbour and early in their marine migration. Survival varied not only between years but also between the river, harbour and in early marine migration.

This study uses lack of detections as a proxy for mortality and detections as a proxy for survival and as such this must be treated with some caution. Transmitter (tag) failure or ejection might account for some of the mortality presented or a fish might simply slip past a receiver without detection, and tags that are detected may not be still in the original study animal. Despite this, the mortality rates per kilometre suggested by this study in the river and harbour are consistent with, or lower than, those reported in the review by Thorstad *et al.*, (2012b) which showed median mortality of 2.3 % $km^{-1}$ (range of 0.3-7.0 % $km^{-1}$) for river, 6.6 % $km^{-1}$ (range 0.6-36 % $km^{-1}$) for estuary (Harbour). However, the early marine migration in 2017 showed a higher rate of mortality (5.3 % $km^{-1}$) compared to an average of 1.4 % $km^{-1}$ (range of 0.3-3.4 % $km^{-1}$) for early marine migration in the same Thorstad *et al.*, (2012b) paper. There were several differences in mortality in the three habitat types over the two years of this study and this may represent inter-annual variation. The data presented in Table 4.3 and Table 4.4 have been corrected for fish missed at ALS gates and therefore represent as true an estimate of mortality as is possible. No evidence was seen of a relationship between length and survival to the IN gate (see modelling below). Loss is relatively high in the river, with 27 tagged smolts (45%) not detected in the harbour in 2017. Most of the loss was suffered in the long stretch of river (35.5km) between Dinnet and the R4 receiver, even though the rate of loss per kilometre 1.3 % km-1 is relatively low. Aberdeen Harbour is a very busy commercial port which has operated for over nine centuries in the mouth of the River Dee. The harbour has more than 9000 vessel arrivals a year and turns over more than £38 million. It operates ferry service links to the Scottish island groups of Orkney and Shetland and supplies many oil and gas instillations in the North Sea with vital supplies of equipment and food. Despite all this activity, there was no loss of smolts from the study in 2017 as they passed through the harbour. In 2018, out of the 83 fish that passed the last river receiver (R12) three were lost before entering the harbour (H1) and a further three failed to leave the harbour (H2). Harbour dredging was ongoing during the time smolts were present in the harbour in 2018. However, no direct evidence was seen that this contributed to the loss of smolts. Of the 6 smolts lost around the harbour area, at least one was recorded as being predated, as the detected temperature increased to 36.4 °C, indicating a predation event by either a mammal or bird which have higher body temperatures than that of ectothermic fish in temperate waters (excluding some sharks) (Ancel et al., 1997; Austin et al., 2006; Kuhn and Costa, 2006). Birds (goosander, cormorant) along with others and aquatic mammals (seals), otter and mink) are suspected predators on smolts (Feltham, 1995, 1990; Heggenes and Borgstrøm, 2006; MacLean and Feltham, 1996). One other smolt is thought to have been predated in the harbour, most probably by a marine fish as the depth of the tag rapidly increased to nearly 15m but did not increase in temperature. One further tag showed a similar pattern at the OUT gate. It is not possible to be certain as smolts may occasionally make dives in the marine environment while feeding or swimming. This use of relatively deep water was not normal behaviour for the other tags (n=45 total temperature depth tags deployed) none of which went below 7 m and thus may represent predation by a marine fish as the temperature shows no increase, these tags were not detected again after these observations. These findings are also consistent with other studies in Canada and Norway where species such as striped bass (*Morone saxatilis*), cod (*Gadus morhua*) and saithe (*Pollachius virens*) are found to aggregate near the mouths of river in anticipation of the smolt run (Daniels et al., 2018; Gibson et al., 2015; Thorstad et al., 2012a). This suspected fish predation rate of 2.4% is below the 25% recorded in a study in Norway (Thorstad et al., 2012a), although this study used hatchery raised post-smolts which may not have the natural predator avoidance skills of the wild post-smolts used in this study. This provides a minimum estimate of predation, as only events logged on a receiver located at an ALS are recorded. Any predation event out with the range of a receiver will not be recorded.

### 5.2.2. Swimming Speed in the river and harbour

Rate of River Movement (RORM) between ALS was significantly different across study years and highly variable between individual fish in each year. This is consistent across studies and well documented (Stich et al., 2015; Thorstad et al., 2012a, 2012b). The Total River Time (TRT) was significantly longer in 2017 than in 2018. In 2017, the majority of fish were tagged at the Dinnet Burn (n=46 of 60) some 78 km upriver of the IN gate while in 2018 the majority of the fish were tagged at the Sheeoch Burn (n=62 of 100) only 30km from the IN gate. This difference in distance may have accounted for the significant difference in total time spent in the river between years. Total Rate of River Movement (TotRORM) from the point of release (after tagging) to entering the marine environment at H2 showed a swimming speed between ALSs that was similar in both 2017 and 2018 further supporting the suggestion that the difference in fish numbers tagged at sites further up the catchment in 2017 was the primary cause of the longer migration times recorded. The TotRORM are within the, rather large, range 0.2 to 60 km day$^{-1}$ reported by Thorstad and colleagues (Thorstad et al., 2012b). However, modelling did not suggest that tagging location had a significant effect on survival to the inner array (IN). This is discussed further in the modelling section below.

The time taken to migrate through the harbour (TTH) was not statistically different between 2017 and 2018. More fish left the harbour on an ebb tide which is consistent with other studies (e.g. Tytler et al., 1978; Moore et al., 1995)

### 5.2.3. Swimming direction and speed in the marine environment

As the now post-smolts leave Aberdeen harbour to begin their migration to distant feeding grounds, they are offered an un-interrupted 180-degree expanse to access the North Sea. The results of this study show that post-smolts progress from the harbour to the IN gate on a similar bearing in both 2017 (106º) and 2018 (96º). This may be caused by the freshwater discharge from the river influencing the path that the post-smolts take. The ADCP data does not appear to support this as the current is aligned with the coast. It is possible that direction of travel is influenced by a salinity gradient or by the freshwater current travelling at a speed that post-smolts cannot escape from, but this is unknown. However, from the observed swimming speeds (discussed below) post smolts seem perfectly capable of escaping most currents.

Between the IN-OUT marine gates, the post-smolts in 2018 swam on a significantly different bearing (158º) going further towards the south than the 108º between the harbour and the first marine gate (IN). They had a median AFSS of 3.98 $L_f\,s^{-1}$, which is higher than reported in the Thorstad et al review (2012b). The 158º from north heading taken in this study would seem counterintuitive as it does not directly lead towards the known Norwegian Sea feeding ground for these post-smolts.

Much work has focused on post-smolt distributions at feeding grounds (Holm *et al.*, 2000; Haugland *et al.*, 2006; Malcolm *et al.*, 2010) and their stock of origin (Holm et al 2000, Holst et al 2000). However, exactly what routes post smolts from the East Coast of Scotland use to reach the feeding grounds has so far not been identified. Trawling undertaken in the late 1990s on the West Coast of Scotland identified the shelf edge current as being an important vehicle in the transport of post smolt to feeding grounds (Shelton et al., 1997) and some work was done in the North Sea as far east as the Norwegian Coastal Current (Turrel et al., 1997) which identified potential post-smolt migration routes. What is clear from the study presented here is that for post-smolts from the River Dee to get to the Norwegian Sea they will need to make a change to head in a more northerly direction at some point on their migration.

Several theories exist as to the migratory cues used by post-smolts to navigate and the most likely seems to be that the post-smolts make use of currents to boost their travel speed (Mork et al., 2012; Ounsley et al., 2019; Shelton et al., 1997; Turrel et al., 1997). In the North Sea, the currents show a predominantly anticlockwise gyre with southward residual currents on the east coast of Scotland off Aberdeen. Off mainland Europe, the residual current moves in a northward direction towards Norway and up the Norwegian Coastal Current (Ozer et al., 2015; Winther and Johannessen, 2006). Four scenarios can be envisioned (Figure 5.1). Scenario 1 is a direct path from the Dee to the Norwegian Sea; a trip of approximately 1200 km due north. The second scenario is a path that crosses the North Sea on the Dooley current and then the Norwegian Coastal Current (NCC) to get to the feeding grounds a trip of around 1500 km. The third crosses further south on the Central North Sea Water (CNSW) and up the NCC a trip of about 1800 km. The first 3 scenarios were postulated by Turrell et al in their 1997 paper . The fourth scenario is to use the anticlockwise gyre of currents in the North Sea to migrate all the way down the east coast of Britain and then ride the current all the way back up the West Coast of Europe into the Norwegian Coastal Current and into the feeding grounds; an approximate 2350 km trip, almost twice the distance of the direct route. From the ground speed (post-smolt speed and current speed) data gathered in this study, it seems that post-smolts migrate quickly with an median actual fish swimming speed (AFSP, adjusted for the effect of current) of 0.57 $ms^{-1}$ (interquartile range of 0.50 and 0.65) from the IN gate to OUT gate (approximately 43 to 56 km $day^{-1}$). At this speed, it would take post-smolts 18-21 days on a direct path (scenario 1) to reach the feeding rounds in the Norwegian Sea. Post-smolts following scenario 2 on the Dooley Current would take approximately 26-34 days, scenario 3 on the CNSW would take between 32 -41 days. Post-smolts making the scenario 4 trip would take 42-55 days perhaps twice as long as scenario 1. These speeds are adjusted to take account the influence of the current. The post-smolt migration speeds seen in this study are in excess of the values used in the models by Mork et al. (2012) and Ounsley et al (2019) of 20 $cms^{-1}$ (17.3 km $day^{-1}$). Recapture data from several studies indicate travel rates of between six and 26 km $day^{-1}$ after entry into the sea (Shelton et al., 1997, Holm et al., 2003). It is therefore not likely the smolts from this study remain in the main southward current all the way down the east coast to then migrate up the whole west European cost to Norway. Nor from the swimming direction observed, does it seem likely they are making the direct route (scenario 1). They may make use of the Dooley Current (scenario 2) or the CNSW. With the 20 cm $s^{-1}$ (17.3 km $day^{-1}$) used by Mork et al (2012), the scenario 3 journey might take 106 days. Mork et al (2012) investigated the overlap of the modelled particles with actual captures of tagged fish from the SALSEA-Merge surveys. While the model gave a good overlap with the Southern stock, the Northern stock was not predicted as well but improved as post-smolt swimming speed increased. This may be very relevant if the fish in this study are traveling faster than previously reported.

The use of the ADCP to record current speed and direction during post-smolt migration and having this data concurrent with the migration of smolts allowed the actual fish swimming speed and direction to be calculated. This shows that fish are swimming faster than their ground speed during their initial marine migration. They are actively trying to swim further to the south on a heading of 158° from north (SE) at a median swimming speed of 3.9 $L_f s^{-1}$. A median speed of 3.9 $L_f s^{-1}$ (median 0.57 $ms^{-1}$, 49 km $day^{-1}$) may prove unsustainable for a post-smolt over longer distances, although Peak & McKinley (2011) found that wild smolts between 12.4 and 21.1 cm can hold position indefinitely in currents speeds up to 1.26$ms^{-1}$, although Tang & Wardle (1992) reported the maximum sustained swimming speed of a 15 cm smolt to be 0.54 $ms^{-1}$ in the laboratory.

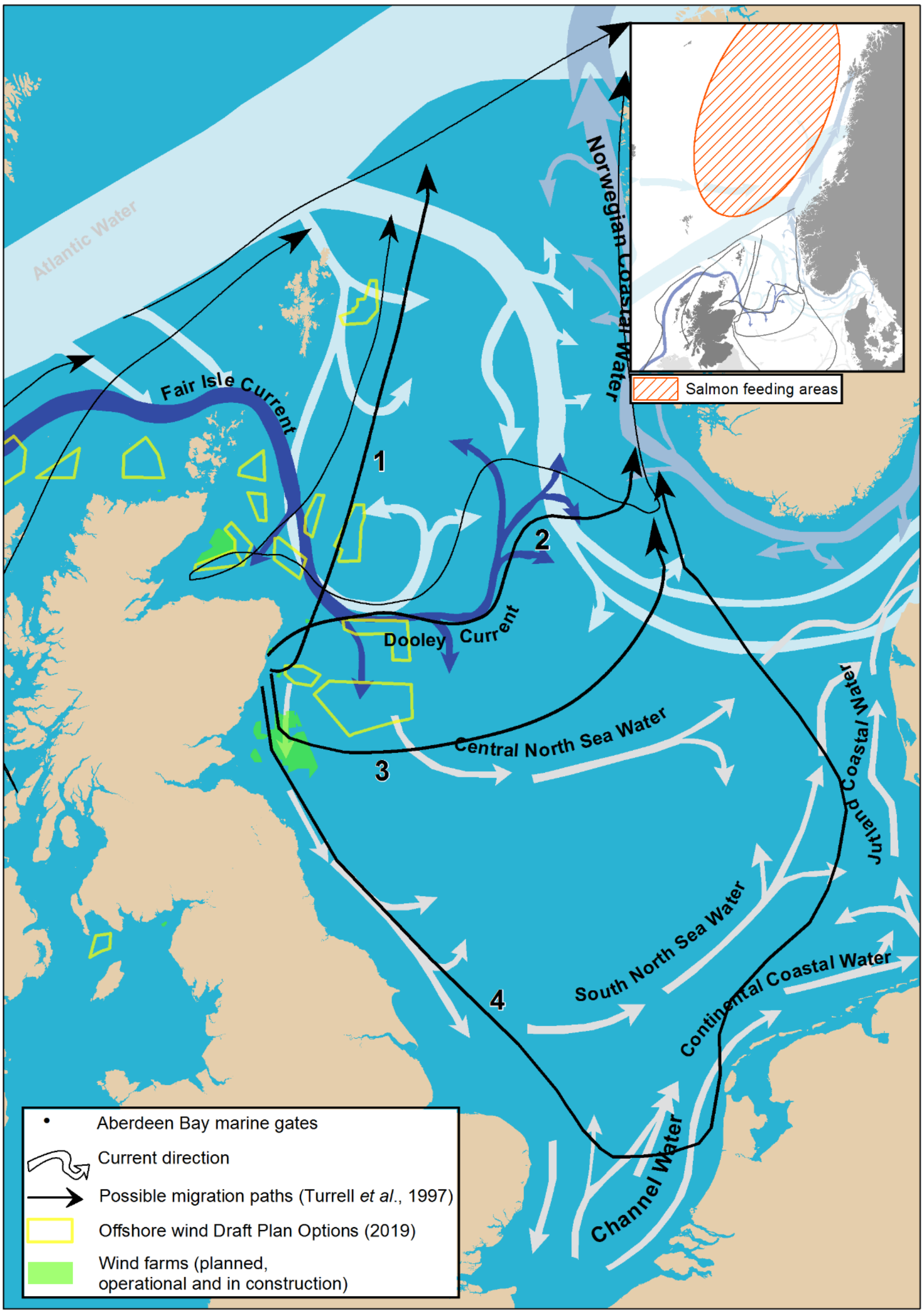



Figure 5.1: main currents in the North Sea and potential post-smolt migration routes (thin black arrows), with the main feeding grounds in the Norwegian see shown in the zoom box. Smolt migration scenarios are numbered 1-4. The main map has been reproduced from Turrell et al., 1997 with extra smolt migration routes, existing wind farm leases sites (green highlighted fill) and 2019 draft plan options for new renewable wind developments added (yellow outline). Contains OS data © Crown copyright and database right (2020), © British Crown and Ocean Wise, 2020. All rights reserved. License No. EK001-20140401. Not to be used for Navigation. Contains OS data © Crown copyright and database right (2020).

This study shows that post-smolts in the natural environment are sustaining median speeds of 3.9 $L_f\ s^{-1}$ over a period of several hours (median 5.9h IQR 3.3-8.7h) up to 10 km from shore. This is more in line with the findings of Booth (Booth, 1998) where smolts were shown to swim at 4.39 body lengths $s^{-1}$ and burst speeds up to 10 body lengths $s^{-1}$. This might be a near shore adaptation as post-smolts attempt to escape the coastal waters where there is thought to be a larger concentration of predators.

### 5.2.4. Survival Modelling

The modelling done in this study compared the detection of tags at the IN gate (as a proxy for survival) against other explanatory variables gathered during the study. The locations of capture were fairly spread out on the river (27 km, 39 and 78 km from the IN gate). The most parsimonious model showed that year (as a factor) explained the majority of the variation in the data. There may be several reasons for this. The most obvious are the difference in proportions of fish tagged at each tagging site each year and as such the location fish were tagged warrants further investigation in detail with a dedicated study. As mentioned above, in 2017 the majority of fish were tagged at the Dinnet Burn (n=46 of 60) some 78 km upriver of the IN gate while in 2018 the majority of the fish were tagged at the Sheeoch Burn (n=62 of 100) only 30 km from the IN gate. 2017 had a lower flow rate compared to 2018 this could have affected the survival of all smolts in 2017 if they miss the best window to migrate (Hansen and Jonsson, 1989), but this shows no significance in the model. Tagging started earlier and was finished sooner in 2017, and so missing the migration window seems unlikely. Correcting the data at the IN gate, using the percentage of tags missed in 2018 (8.2%), only added two additional fish that may have survived to the IN gate in 2017.

### 5.2.5. Range Testing

Detection efficiency varied spatially across the array and also varied between years at some ALSs and ALS gates. The detection efficiency in the river varied greatly from between where 1 of 33 tags passing (3%) were detected up to 100%. There were enough receivers to correct for missed detections in both 2017 and 2018 giving a good approximation of where tag losses occurred. Detection efficiency of the ALSs in the H1 gate during 2017 were good (90.9%) but in 2018 H1 performed poorly missing 36 tags (55%). However, ALSs in the H2 gate had very good detection efficiencies (97% in 2017 and 93.5% in 2018). In 2017, for the last gate, IN efficiency can only be estimated using the sentinel tag data. This was positive in that it shows an excellent probability of detecting all tags passing (Table 4.6). In 2018, the OUT gate detected six fish missed on the IN gate, a proportion of 8.2%, this showed in fact the IN gate in 2017 may have, under natural environmental conditions, allow fish to pass undetected (two fish in 2017 may have passed if the 2018 figure of 8.2% is representative).

The extensive review of range testing in acoustic telemetry by Kessel et al., (2014) recommends using several methods to establish detection range including a dedicated pre-study range test, during study fixed sentinel tags and a post study modelling exercise. All three of these recommendations were carried out in this study with differing results. The data from range testing and simulations showed that this array, of river, harbour and marine ALSs, was capable of a good level of accuracy in detecting smolts during their early marine migration (see Table 4.6). However, the simulations gave an unrealistically optimistic probability of detecting tag transmissions. Analysis of the actual recorded acoustic detections showed that river detection efficiency is between 3% and 100%. Also, in the IN gate, with a simulated theoretical 100% coverage and a very high ($p>0.99$) modelled probability of detection (Table 4.4), six acoustically tagged fish still passed without detection. Localised noise or interference is most likely the source of this difference. This may also be the case in Aberdeen Harbour where frequent boat traffic and harbour maintenance activities may mask or interfere with the acoustic transmissions being properly received and decoded. Noise has been proposed as a factor in the reduction of detection probability in several studies and reviews (Kessel et al., 2014) and this is supported by the poor range testing results from ALS OR12 in 2018 of 48% at the ALS location and a drop to 14% at 300 m distance ALS OR12 was located inside the northern limit of the wind farm construction site and vessel traffic was concentrated around a turbine located approximately 1.4 km to the South West. However, the turbine installation used a new suction bucket design which had a much lower estimated noise output during installation than if pile driving had been used. When all of the data were analysed, this array including the river, harbour and marine components provided robust data to assess the main hypotheses posed in this thesis.

### 5.2.6. Interaction with Marine Renewable Energy Generation

The migration data in this study may have been affected by construction of The European Offshore Wind Deployment Centre (EOWDC). As the data above suggests, there may be a lack of detections of tagged post-smolts near the construction activities this may be giving a false impression that smolts move in a more southerly direction. This needs further investigation, and if further work is done with this data, should be made a priority.

As can be seen in Figure 5.1 there is potential overlap in the placement of planned offshore wind farms and the possible migration routes of post-smolts from the east coast of Scotland. Information from the current study suggests that post-smolts from the River Dee would not interact with the wind farm in Aberdeen Bay. However, the migratory routes of River Dee post-smolts further away from the estuary, and from post-smolts from other estuaries and rivers on the east of Scotland, have not been identified and more work is required to ascertain the extent of overlap and potential impact this overlap may have on post-smolts migration. Offshore wind farm sites have a number of potential unintentional interactions that may affect salmon including post-smolt and adult migration. These include direct construction effects of noise, increase boating traffic, EMF and aggregations of predators (fish, mammal and diving birds) (Gill et al., 2012; Russell et al., 2014).

## 5.3. Conclusions

### 5.3.1. Mortality

Estimated mortality of migrating smolts in the River Dee from the capture site used in this study to sea entry is between 17 and 45%. The percentage loss per $km^{-1}$ of river is not unusual in comparison to published studies. Similarly, the loss rates seen in the estuary (Aberdeen Harbour) not unusual in comparison to published studies. The early marine mortality in 2017 was higher than expected.

### 5.3.2. Directional Swimming in Post-Smolts

The directional vectors of smolts leaving the harbour were not random. Furthermore, they were significantly different between the H2-IN gate and IN-OUT gates with a change from an early swimming heading of 94° (2017) or 107° (2018) to a swimming heading of 158° between 4 and 10 km distant from the harbour.

# 6. Recommendations

- ## River Management

The River Dee Trust and River Dee District Salmon Fisheries Board do an enormous amount of conservation and habitat restoration work. Much of the mortality in this study appears to be in the River and Harbour (2018) areas. This is particularly true when fish migrate over a longer distance. For example, further investigation of the area between Dinnet and R4 (but particularly to R1) should be undertaken.

- ## Fish Release

Wild fish in the tributaries show a tendency to migrate at night. Some way of releasing fish, such as a cage timed to open after dark, may allow smolts a more natural migration after release.

- ## Array design

Simulations are not a robust substitute for physical range testing. Caution should be used when designing an array if purely simulated data is all that is available to assess detection probability, and suitable precautionary factors should be built into the design.

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# 8. Annex 1

Table 8.1: Table of fish tagged in 2017, including the fish number, serial number and other measurements taken at the time of tagging. Depth temperature tags have two separate consecutive Tag Numbers (Tag No) and the serial number corresponds to the individual fish with the data repeated in two rows.

| Fish | Date | Capture Time | Tagging Time | Release Time | FL (mm) | Weight (g) | Tag No | serial number | Capture Location | Release Location | Tagger | Data entered | Photo | Tags Type | Diameter (mm) | Length (mm) | Weight air (g) | Weight water (g) | Power output (Db) | Tag Burdon (% by Weight) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 06/04/2017 | 10:45 | 11:30 | 13:45 | 144 | 25 | 25 | 1 | Sheeoch RST | Below Bridge | E Edwards | 27/04/2017 | | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 4.4 |
| 2 | 06/04/2017 | 10:45 | 11:30 | 13:45 | 144 | 25 | 26 | 1 | Sheeoch RST | Below Bridge | E Edwards | 27/04/2017 | | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 4.4 |
| 5 | 09/04/2017 | 10:15 | 10:30 | 12:40 | 141 | 25 | 27 | 2 | Beltie | Below Bridge | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 4.4 |
| 5 | 09/04/2017 | 10:15 | 10:30 | 12:40 | 141 | 25 | 28 | 2 | Beltie | Below Bridge | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 4.4 |
| 13 | 16/04/2017 | 08:30 | 12:20 | 14:30 | 149 | 35 | 29 | 3 | Dinnet Burn | Main Stem Dee | M Paterson | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 3.1 |
| 13 | 16/04/2017 | 08:30 | 12:20 | 14:30 | 149 | 35 | 30 | 3 | Dinnet Burn | Main Stem Dee | M Paterson | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 3.1 |
| 23 | 20/04/2017 | 09:00 | 12:18 | 16:30 | 149 | 33 | 31 | 4 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 3.3 |
| 23 | 20/04/2017 | 09:00 | 12:18 | 16:30 | 149 | 33 | 32 | 4 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 3.3 |
| 24 | 20/04/2017 | 09:00 | 12:25 | 16:30 | 140 | 27 | 33 | 5 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 4.1 |
| 24 | 20/04/2017 | 09:00 | 12:25 | 16:30 | 140 | 27 | 34 | 5 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 4.1 |
| 31 | 20/04/2017 | 09:00 | 13:46 | 16:30 | 153 | 38 | 35 | 6 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 2.9 |
| 31 | 20/04/2017 | 09:00 | 13:46 | 16:30 | 153 | 38 | 36 | 6 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 2.9 |
| 33 | 21/04/2017 | 09:00 | 10:59 | 14:30 | 154 | 36 | 37 | 7 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 3.1 |
| 33 | 21/04/2017 | 09:00 | 10:59 | 14:30 | 154 | 36 | 38 | 7 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 3.1 |
| 28 | 20/04/2017 | 09:00 | 13:23 | 16:30 | 147 | 33 | 39 | 8 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 3.3 |
| 28 | 20/04/2017 | 09:00 | 13:23 | 16:30 | 147 | 33 | 40 | 8 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 3.3 |
| 20 | 20/04/2017 | 09:00 | 11:55 | 16:30 | 147 | 33 | 41 | 9 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 3.3 |
| 20 | 20/04/2017 | 09:00 | 11:55 | 16:30 | 147 | 33 | 42 | 9 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 3.3 |
| 12 | 16/04/2017 | 08:30 | 12:15 | 14:30 | 142 | 33 | 43 | 10 | Dinnet Burn | Main Stem Dee | M Paterson | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 3.3 |
| 12 | 16/04/2017 | 08:30 | 12:15 | 14:30 | 142 | 33 | 44 | 10 | Dinnet Burn | Main Stem Dee | M Paterson | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 3.3 |
| 15 | 16/04/2017 | 08:30 | 12:30 | 14:30 | 140 | 33 | 45 | 11 | Dinnet Burn | Main Stem Dee | M Paterson | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 3.3 |
| 15 | 16/04/2017 | 08:30 | 12:30 | 14:30 | 140 | 33 | 46 | 11 | Dinnet Burn | Main Stem Dee | M Paterson | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 3.3 |
| 27 | 20/04/2017 | 09:00 | 13:05 | 16:30 | 157 | 40 | 47 | 12 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 2.8 |
| 27 | 20/04/2017 | 09:00 | 13:05 | 16:30 | 157 | 40 | 48 | 12 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 2.8 |
| 32 | 21/04/2017 | 09:00 | 10:55 | 14:30 | 164 | 50 | 49 | 13 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 2.2 |
| 32 | 21/04/2017 | 09:00 | 10:55 | 14:30 | 164 | 50 | 50 | 13 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 2.2 |
| 30 | 20/04/2017 | 09:00 | 13:40 | 16:30 | 143 | 32 | 51 | 14 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 3.4 |
| 30 | 20/04/2017 | 09:00 | 13:40 | 16:30 | 143 | 32 | 52 | 14 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 3.4 |
| 25 | 20/04/2017 | 09:00 | 12:33 | 16:30 | 153 | 40 | 53 | 15 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 2.8 |
| 25 | 20/04/2017 | 09:00 | 12:33 | 16:30 | 153 | 40 | 54 | 15 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ADTT-LP-7.3 | 7.3 | 22 | 2 | 1.1 | 139 | 2.8 |
| 58 | 25/04/2017 | 09:00 | 15:22 | 17:40 | 138 | 28 | 2095 | 16 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4.3 |
| 57 | 25/04/2017 | 09:00 | 15:11 | 17:40 | 138 | 30 | 2096 | 17 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4 |
| 51 | 25/04/2017 | 10:00 | 11:49 | 14:30 | 137 | 23 | 2097 | 18 | Beltie | Below Bridge | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 5.2 |
| 54 | 25/04/2017 | 10:00 | 12:10 | 14:30 | 135 | 26 | 2098 | 19 | Beltie | Below Bridge | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4.6 |
| 53 | 25/04/2017 | 10:00 | 12:02 | 14:30 | 142 | 29 | 2099 | 20 | Beltie | Below Bridge | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4.1 |
| 45 | 22/04/2017 | 10:00 | 13:40 | 16:00 | 149 | 34 | 2100 | 21 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 3.5 |
| 4 | 08/04/2017 | 10:00 | 11:26 | 13:26 | 136 | 28 | 2101 | 22 | Sheeoch RST | Below Bridge | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4.3 |
| 6 | 10/04/2017 | 13:50 | 14:15 | 16:20 | 137 | 23 | 2102 | 23 | Sheeoch RST | Below Bridge | R Main | 27/04/2017 | | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 5.2 |
| 60 | 25/04/2017 | 09:00 | 15:36 | 17:40 | 141 | 27 | 2103 | 24 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4.4 |
| 56 | 25/04/2017 | 10:00 | 12:28 | 14:30 | 137 | 25 | 2104 | 25 | Beltie | Below Bridge | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4.8 |
| 3 | 06/04/2017 | 11:45 | 11:46 | 13:45 | 138 | 24 | 2105 | 26 | Sheeoch RST | Below Bridge | E Edwards | 27/04/2017 | | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 5 |
| 47 | 22/04/2017 | 10:00 | 14:00 | 16:00 | 143 | 31 | 2106 | 27 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 3.9 |
| 1 | 05/04/2017 | 09:30 | 09:55 | 12:07 | 138 | 25 | 2107 | 28 | Beltie | Below Bridge | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4.8 |
| 34 | 21/04/2017 | 09:00 | 11:02 | 14:30 | 155 | 36 | 2108 | 29 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 3.3 |
| 42 | 22/04/2017 | 10:00 | 12:40 | 16:00 | 143 | 30 | 2109 | 30 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4 |
| 35 | 21/04/2017 | 09:00 | 11:08 | 14:30 | 139 | 35 | 2110 | 31 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 3.4 |
| 7 | 13/04/2017 | 09:10 | 09:45 | 12:00 | 139 | 28 | 2111 | 32 | Beltie | Below Bridge | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4.3 |
| 21 | 20/04/2017 | 09:00 | 12:02 | 16:30 | 138 | 28 | 2112 | 33 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4.3 |
| 37 | 21/04/2017 | 09:00 | 11:22 | 14:30 | 145 | 35 | 2113 | 34 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 3.4 |
| 41 | 22/04/2017 | 10:00 | 12:35 | 16:00 | 140 | 32 | 2114 | 35 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 3.8 |
| 48 | 23/04/2017 | 08:45 | 11:07 | 14:00 | 143 | 32 | 2115 | 36 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 3.8 |
| 46 | 22/04/2017 | 10:00 | 13:50 | 16:00 | 148 | 35 | 2116 | 37 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 3.4 |
| 44 | 22/04/2017 | 10:00 | 13:00 | 16:00 | 144 | 32 | 2117 | 38 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 3.8 |
| 36 | 21/04/2017 | 09:00 | 11:12 | 14:30 | 139 | 30 | 2118 | 39 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4 |
| 38 | 21/04/2017 | 09:00 | 11:25 | 14:30 | 141 | 37 | 2119 | 40 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 3.2 |
| 40 | 22/04/2017 | 10:00 | 12:30 | 16:00 | 148 | 32 | 2120 | 41 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 3.8 |
| 39 | 22/04/2017 | 10:00 | 12:20 | 16:00 | 149 | 35 | 2121 | 42 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 3.4 |
| 49 | 24/04/2017 | 09:00 | 11:30 | 13:30 | 147 | 30 | 2122 | 43 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4 |
| 14 | 16/04/2017 | 08:30 | 12:24 | 14:30 | 138 | 33 | 2123 | 44 | Dinnet Burn | Main Stem Dee | M Paterson | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 3.6 |
| 11 | 16/04/2017 | 08:30 | 12:10 | 14:30 | 139 | 32 | 2124 | 45 | Dinnet Burn | Main Stem Dee | M Paterson | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 3.8 |
| 16 | 16/04/2017 | 08:30 | 12:35 | 14:30 | 138 | 30 | 2125 | 46 | Dinnet Burn | Main Stem Dee | M Paterson | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4 |
| 17 | 16/04/2017 | 10:15 | 10:40 | 13:00 | 137 | 25 | 2126 | 47 | Dinnet Burn | Main Stem Dee | M Paterson | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4.8 |
| 19 | 17/04/2017 | 09:00 | 14:15 | 16:30 | 139 | 29 | 2127 | 48 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4.1 |
| 9 | 15/04/2017 | 08:40 | 14:12 | 16:30 | 139 | 26 | 2128 | 49 | Dinnet Burn | Main Stem Dee | M Paterson | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4.6 |
| 22 | 20/04/2017 | 09:00 | 12:10 | 16:30 | 139 | 26 | 2129 | 50 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4.6 |
| 10 | 15/04/2017 | 08:40 | 14:24 | 16:30 | 139 | 30 | 2130 | 51 | Dinnet Burn | Main Stem Dee | M Paterson | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4 |
| 18 | 17/04/2017 | 09:00 | 14:10 | 16:30 | 137 | 27 | 2131 | 52 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4.4 |
| 55 | 25/04/2017 | 10:00 | 12:19 | 14:30 | 137 | 22 | 2132 | 53 | Beltie | Below Bridge | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 5.5 |
| 8 | 14/04/2017 | 08:50 | 11:10 | 13:20 | 138 | 30 | 2133 | 54 | Dinnet Burn | Main Stem Dee | M Paterson | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4 |
| 29 | 20/04/2017 | 09:00 | 13:13 | 16:30 | 138 | 29 | 2134 | 55 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4.1 |
| 43 | 22/04/2017 | 10:00 | 12:45 | 16:00 | 142 | 30 | 2135 | 56 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4 |
| 26 | 20/04/2017 | 09:00 | 12:53 | 16:30 | 139 | 28 | 2136 | 57 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4.3 |
| 59 | 25/04/2017 | 09:00 | 15:28 | 17:40 | 140 | 30 | 2137 | 58 | Dinnet Burn | Main Stem Dee | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 4 |
| 50 | 25/04/2017 | 10:00 | 11:44 | 14:30 | 141 | 31 | 2138 | 59 | Beltie | Below Bridge | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 3.9 |
| 52 | 25/04/2017 | 10:00 | 11:57 | 14:30 | 137 | 24 | 2139 | 60 | Beltie | Below Bridge | R Main | 27/04/2017 | y | ATID-LP-7.3 | 7.3 | 18 | 1.9 | 1.2 | 139 | 5 |

Table 8.2: Table of fish tagged in 2018, including the fish number, serial number and other measurments taken at the time of tagging. Depth temperature tags have two separate consecutive Tag Numbers (Tag No) and the serial number corresponds to the individual fish with the data repeated in two rows.

| Fish | Date | Capture time | Tagging Time | Release tiem | Fork Length (mm) | Weight (g) | Tag No | Serial No | Spp | Stage | Capture location | Release Location | Tagger | Data entered | Photo | Tags Type | Diameter | Length (mm) | Weight air (g) | Power output (Db) | Tag Burdon (% by Weight) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 117 | 19/04/2018 | 09:00 | 14:30 | 16:30 | 146 | 29 | 2389 | 43 | Atlantic salmon | Smolt | Dinnet | Dinnet Islands | R Main | | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.9 |
| 117 | 19/04/2018 | 09:00 | 14:30 | 16:30 | 146 | 29 | 2390 | 43 | Atlantic salmon | Smolt | Dinnet | Dinnet Islands | R Main | | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.9 |
| 123 | 19/04/2018 | 12:42 | 13:38 | 15:50 | 149 | 28 | 2391 | 44 | Atlantic salmon | Smolt | Beltie RST | 3 | R Main | 25/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 6.1 |
| 123 | 19/04/2018 | 12:42 | 13:38 | 15:50 | 149 | 28 | 2392 | 44 | Atlantic salmon | Smolt | Beltie RST | 3 | R Main | 25/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 6.1 |
| 129 | 20/04/2018 | 12:30 | 13:22 | 16:30 | 138 | 22 | 4311 | 142 | Atlantic salmon | Smolt | Beltie RST | 4 | R Main | 25/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 7.3 |
| 127 | 20/04/2018 | 12:30 | 12:54 | 16:30 | 138 | 24 | 4313 | 143 | Atlantic salmon | Smolt | Beltie RST | 4 | R Main | 24/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 6.7 |
| 126 | 20/04/2018 | 10:05 | 11:19 | 13:25 | 135 | 22 | 4314 | 144 | Atlantic salmon | Smolt | Sheeoch RST | 2 | R Main | 25/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 7.3 |
| 125 | 20/04/2018 | 10:05 | 11:11 | 13:25 | 141 | 26 | 4315 | 145 | Atlantic salmon | Smolt | Sheeoch RST | 2 | R Main | 25/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 6.2 |
| 124 | 20/04/2018 | 10:05 | 11:05 | 13:25 | 139 | 25 | 4316 | 146 | Atlantic salmon | Smolt | Sheeoch RST | 2 | R Main | 25/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 6.4 |
| 133 | 21/04/2018 | 09:40 | 10:55 | 13:00 | 142 | 29 | 2395 | 46 | Atlantic salmon | Smolt | Sheeoch RST | 3 | R Main | 25/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.9 |
| 133 | 21/04/2018 | 09:40 | 10:55 | 13:00 | 142 | 29 | 2396 | 46 | Atlantic salmon | Smolt | Sheeoch RST | 3 | R Main | 25/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.9 |
| 130 | 21/04/2018 | 11:40 | 12:55 | 14:57 | 146 | 29 | 2397 | 47 | Atlantic salmon | Smolt | Beltie RST | 3 | R Main | 25/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.9 |
| 130 | 21/04/2018 | 12:40 | 12:55 | 14:57 | 146 | 29 | 2398 | 47 | Atlantic salmon | Smolt | Beltie RST | 3 | R Main | 25/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.9 |
| 131 | 21/04/2018 | 09:40 | 10:44 | 13:00 | 146 | 29 | 2399 | 48 | Atlantic salmon | Smolt | Sheeoch RST | 2 | R Main | 25/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.9 |
| 131 | 21/04/2018 | 09:40 | 10:44 | 13:00 | 146 | 29 | 2400 | 48 | Atlantic salmon | Smolt | Sheeoch RST | 2 | R Main | 25/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.9 |
| 132 | 21/04/2018 | 09:40 | 10:50 | 13:00 | 137 | 26 | 4319 | 149 | Atlantic salmon | Smolt | Sheeoch RST | 2 | R Main | 25/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 6.2 |
| 118 | 21/04/2018 | 09:00 | 13:53 | 16:20 | 135 | 27 | 4320 | 150 | Atlantic salmon | Smolt | Dinnet | Dinnet Islands | R Main | | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.9 |
| 119 | 23/04/2018 | 09:00 | 12:05 | 14:05 | 142 | 34 | 2393 | 45 | Atlantic salmon | Smolt | Dinnet | Dinnet Islands | R Main | | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.0 |
| 119 | 23/04/2018 | 09:00 | 12:05 | 14:05 | 142 | 34 | 2394 | 45 | Atlantic salmon | Smolt | Dinnet | Dinnet Islands | R Main | | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.0 |
| 136 | 25/04/2018 | 10:20 | 11:35 | 14:00 | 150 | 35 | 2373 | 35 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 28/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 4.9 |
| 136 | 25/04/2018 | 10:20 | 11:35 | 14:00 | 150 | 35 | 2374 | 35 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 28/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 4.9 |
| 134 | 25/04/2018 | 10:20 | 11:05 | 14:00 | 148 | 33 | 2375 | 36 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 28/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.2 |
| 134 | 25/04/2018 | 10:20 | 11:05 | 14:00 | 148 | 33 | 2376 | 36 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 28/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.2 |
| 120 | 25/04/2018 | 09:00 | 13:50 | 16:00 | 142 | 33 | 2385 | 41 | Atlantic salmon | Smolt | Dinnet | Dinnet Islands | R Main | | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.2 |
| 120 | 25/04/2018 | 09:00 | 13:50 | 16:00 | 142 | 33 | 2386 | 41 | Atlantic salmon | Smolt | Dinnet | Dinnet Islands | R Main | | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.2 |
| 135 | 25/04/2018 | 10:20 | 11:17 | 14:00 | 140 | 29 | 4158 | 138 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 28/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.5 |
| 137 | 26/04/2018 | 10:30 | 10:52 | 14:00 | 144 | 34 | 2357 | 27 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 28/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.0 |
| 137 | 26/04/2018 | 10:30 | 10:52 | 14:00 | 144 | 34 | 2358 | 27 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 28/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.0 |
| 139 | 26/04/2018 | 10:30 | 11:22 | 13:30 | 146 | 44 | 2365 | 31 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 28/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 3.9 |
| 139 | 26/04/2018 | 10:30 | 11:22 | 13:30 | 146 | 44 | 2366 | 31 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 28/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 3.9 |
| 138 | 26/04/2018 | 10:30 | 10:57 | 13:30 | 136 | 27 | 4152 | 132 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 28/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.9 |
| 54 | 27/04/2018 | 10:00 | 10:41 | 13:05 | 154 | 34 | 2341 | 20 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 28/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.0 |
| 54 | 27/04/2018 | 10:00 | 10:41 | 13:05 | 154 | 34 | 2342 | 20 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 28/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.0 |
| 142 | 27/04/2018 | 10:00 | 10:55 | 13:05 | 153 | 36 | 2361 | 29 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 28/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 4.7 |
| 142 | 27/04/2018 | 10:00 | 10:55 | 13:05 | 153 | 36 | 2362 | 29 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 28/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 4.7 |
| 141 | 27/04/2018 | 10:10 | 10:48 | 13:05 | 141 | 27 | 2387 | 42 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 28/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 6.3 |
| 141 | 27/04/2018 | 10:10 | 10:48 | 13:05 | 141 | 27 | 2388 | 42 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 28/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 6.3 |
| 143 | 27/04/2018 | 12:00 | 12:45 | 14:55 | 135 | 29 | 4139 | 119 | Atlantic salmon | Smolt | Beltie RST | 3 | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.5 |
| 144 | 27/04/2018 | 12:00 | 12:53 | 14:55 | 137 | 29 | 4155 | 135 | Atlantic salmon | Smolt | Beltie RST | 3 | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.5 |
| 156 | 27/04/2018 | 10:43 | 12:44 | 15:49 | 147.1 | 33.71 | 4309 | 140 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | | | V7-2L-069 | 7 | 18 | 1.6 | 136 | 4.7 |
| 148 | 28/04/2018 | 12:00 | 12:43 | 16:30 | 144 | 27 | 2343 | 21 | Atlantic salmon | Smolt | Beltie RST | 2 | E Edwards | 28/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 6.3 |
| 148 | 28/04/2018 | 12:00 | 12:43 | 16:30 | 144 | 27 | 2344 | 21 | Atlantic salmon | Smolt | Beltie RST | 2 | E Edwards | 28/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 6.3 |
| 151 | 28/04/2018 | 12:00 | 14:03 | 16:30 | 148 | 33 | 2359 | 28 | Atlantic salmon | Smolt | Beltie RST | 4 | R Main | 28/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.2 |
| 151 | 28/04/2018 | 12:00 | 14:03 | 16:30 | 148 | 33 | 2360 | 28 | Atlantic salmon | Smolt | Beltie RST | 4 | R Main | 28/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.2 |
| 147 | 28/04/2018 | 12:00 | 12:37 | 16:30 | 138 | 27 | 4121 | 101 | Atlantic salmon | Smolt | Beltie RST | 4 | E Edwards | 28/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.9 |
| 149 | 28/04/2018 | 12:00 | 12:53 | 16:30 | 144 | 30 | 4122 | 102 | Atlantic salmon | Smolt | Beltie RST | 4 | E Edwards | 28/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.3 |
| 152 | 28/04/2018 | 12:00 | 14:10 | 16:30 | 141 | 28 | 4124 | 104 | Atlantic salmon | Smolt | Beltie RST | 4 | R Main | 28/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.7 |
| 150 | 28/04/2018 | 12:00 | 13:55 | 16:30 | 142 | 27 | 4129 | 109 | Atlantic salmon | Smolt | Beltie RST | 4 | R Main | 28/04/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.9 |
| 155 | 28/04/2018 | 12:00 | 14:29 | 16:30 | 140 | 28 | 4131 | 111 | Atlantic salmon | Smolt | Beltie RST | 4 | R Main | 28/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.7 |
| 153 | 28/04/2018 | 12:00 | 14:16 | 16:30 | 136 | 26 | 4135 | 115 | Atlantic salmon | Smolt | Beltie RST | 4 | R Main | 28/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 6.2 |
| 154 | 28/04/2018 | 12:00 | 14:23 | 16:30 | 138 | 29 | 4136 | 116 | Atlantic salmon | Smolt | Beltie RST | 4 | R Main | 28/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.5 |
| 145 | 28/04/2018 | 09:45 | 11:05 | 16:00 | 143 | 30 | 4318 | 148 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | E Edwards | 28/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.3 |
| 146 | 28/04/2018 | 09:45 | 11:16 | 16:00 | 140 | 32 | 4322 | 152 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | E Edwards | 28/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.0 |
| 121 | 29/04/2018 | 09:00 | 12:30 | 16:00 | 141 | 29 | 2381 | 39 | Atlantic salmon | Smolt | Dinnet | Dinnet Islands | R Main | | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.9 |
| 121 | 29/04/2018 | 09:00 | 12:30 | 16:00 | 141 | 29 | 2382 | 39 | Atlantic salmon | Smolt | Dinnet | Dinnet Islands | R Main | | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.9 |
| 55 | 29/04/2018 | 11:10 | 11:35 | 13:45 | 138 | 22 | 4130 | 110 | Atlantic salmon | Smolt | Beltie RST | 3 | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 7.3 |
| 56 | 29/04/2018 | 11:10 | 11:45 | 13:45 | 135 | 29 | 4137 | 117 | Atlantic salmon | Smolt | Beltie RST | 3 | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.5 |
| 122 | 30/04/2018 | 08:45 | 10:00 | 13:00 | 153 | 40 | 2363 | 30 | Atlantic salmon | Smolt | Dinnet | Dinnet Islands | R Main | | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 4.3 |
| 122 | 30/04/2018 | 08:45 | 10:00 | 13:00 | 153 | 40 | 2364 | 30 | Atlantic salmon | Smolt | Dinnet | Dinnet Islands | R Main | | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 4.3 |
| 58 | 30/04/2018 | 10:30 | 11:07 | 14:45 | 140 | 26 | 4138 | 118 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 28/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 6.2 |
| 57 | 30/04/2018 | 12:00 | 12:25 | 14:25 | 137 | 29 | 4310 | 141 | Atlantic salmon | Smolt | Beltie RST | 4 | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.5 |
| 62 | 01/05/2018 | 10:15 | 11:25 | 13:25 | 147 | 31 | 2379 | 38 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.5 |
| 62 | 01/05/2018 | 10:15 | 11:25 | 13:25 | 147 | 31 | 2380 | 38 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.5 |
| 60 | 01/05/2018 | 10:15 | 11:03 | 13:25 | 145 | 31 | 2383 | 40 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.5 |
| 60 | 01/05/2018 | 10:15 | 11:03 | 13:25 | 145 | 31 | 2384 | 40 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.5 |
| 61 | 01/05/2018 | 10:15 | 11:10 | 13:25 | 138 | 26 | 4111 | 91 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 6.2 |
| 59 | 01/05/2018 | 10:15 | 10:50 | 13:25 | 135 | 24 | 4112 | 92 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 6.7 |
| 63 | 02/05/2018 | 10:53 | 11:15 | 13:20 | 140 | 27 | 4110 | 90 | Atlantic salmon | Smolt | Beltie RST | 4 | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.9 |
| 64 | 02/05/2018 | 09:47 | 10:13 | 12:15 | 139 | 27 | 4113 | 93 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.9 |
| 85 | 03/05/2018 | 10:00 | 14:45 | 18:00 | 146 | 29 | 2347 | 22 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.9 |
| 85 | 03/05/2018 | 10:00 | 14:45 | 18:00 | 146 | 29 | 2348 | 22 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.9 |
| 83 | 03/05/2018 | 10:00 | 13:35 | 18:00 | 141 | 29 | 2349 | 23 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.9 |
| 83 | 03/05/2018 | 10:00 | 13:35 | 18:00 | 141 | 29 | 2350 | 23 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.9 |
| 82 | 03/05/2018 | 10:00 | 13:30 | 18:00 | 153 | 37 | 2351 | 24 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 4.6 |
| 82 | 03/05/2018 | 10:00 | 13:30 | 18:00 | 153 | 37 | 2352 | 24 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 4.6 |
| 79 | 03/05/2018 | 10:00 | 13:05 | 18:00 | 149 | 38 | 2353 | 25 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 4.5 |
| 79 | 03/05/2018 | 10:00 | 13:05 | 18:00 | 149 | 38 | 2354 | 25 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 4.5 |
| 75 | 03/05/2018 | 10:00 | 12:25 | 18:00 | 148 | 31 | 2355 | 26 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | C Pert | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.5 |
| 75 | 03/05/2018 | 10:00 | 12:25 | 18:00 | 148 | 31 | 2356 | 26 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | C Pert | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.5 |
| 71 | 03/05/2018 | 10:00 | 10:38 | 18:00 | 149 | 37 | 2367 | 32 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | E Edwards | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 4.6 |
| 71 | 03/05/2018 | 10:00 | 10:38 | 18:00 | 149 | 37 | 2368 | 32 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | E Edwards | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 4.6 |
| 70 | 03/05/2018 | 10:00 | 10:40 | 18:00 | 146 | 37 | 2369 | 33 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | E Edwards | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 4.6 |
| 70 | 03/05/2018 | 10:00 | 10:40 | 18:00 | 146 | 37 | 2370 | 33 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | E Edwards | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 4.6 |
| 69 | 03/05/2018 | 10:00 | 11:20 | 18:00 | 143 | 37 | 2371 | 34 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | E Edwards | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 4.6 |
| 69 | 03/05/2018 | 10:00 | 11:20 | 18:00 | 143 | 37 | 2372 | 34 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | E Edwards | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 4.6 |
| 68 | 03/05/2018 | 10:00 | 11:08 | 18:00 | 143 | 33 | 2377 | 37 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | E Edwards | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.2 |
| 68 | 03/05/2018 | 10:00 | 11:08 | 18:00 | 143 | 33 | 2378 | 37 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | E Edwards | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 5.2 |
| 67 | 03/05/2018 | 10:00 | 11:03 | 18:00 | 135 | 24 | 4105 | 85 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | E Edwards | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 6.7 |
| 66 | 03/05/2018 | 10:00 | 10:55 | 18:00 | 137 | 25 | 4106 | 86 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | E Edwards | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 6.4 |
| 73 | 03/05/2018 | 10:00 | 11:57 | 18:00 | 138 | 28 | 4107 | 87 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | E Edwards | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.7 |
| 72 | 03/05/2018 | 10:00 | 11:55 | 18:00 | 138 | 24 | 4108 | 88 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | E Edwards | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 6.7 |
| 65 | 03/05/2018 | 10:00 | 10:38 | 18:00 | 135 | 24 | 4109 | 89 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 6.7 |
| 74 | 03/05/2018 | 10:00 | 12:01 | 18:00 | 138 | 27 | 4114 | 94 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | E Edwards | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.9 |
| 77 | 03/05/2018 | 10:00 | 12:45 | 18:00 | 138 | 29 | 4115 | 95 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.5 |
| 81 | 03/05/2018 | 10:00 | 13:10 | 18:00 | 137 | 27 | 4116 | 96 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.9 |
| 80 | 03/05/2018 | 10:00 | 13:16 | 18:00 | 137 | 28 | 4117 | 97 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.7 |
| 84 | 03/05/2018 | 10:00 | 13:45 | 18:00 | 138 | 24 | 4118 | 98 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 6.7 |
| 78 | 03/05/2018 | 10:00 | 12:55 | 18:00 | 138 | 30 | 4119 | 99 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.3 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 76 | 03/05/2018 | 10:00 | 12:37 | 18:00 | 143 | 27 | 4120 | 100 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | C Pert | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.9 |
| 93 | 03/05/2018 | 10:00 | 15:08 | 18:00 | 142 | 29 | 4123 | 103 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.5 |
| 112 | 03/05/2018 | 14:20 | 17:01 | 19:05 | 141 | 28 | 4125 | 105 | Atlantic salmon | Smolt | Beltie RST | 3 | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.7 |
| 108 | 03/05/2018 | 14:20 | 16:46 | 19:05 | 142 | 31 | 4126 | 106 | Atlantic salmon | Smolt | Beltie RST | 3 | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.2 |
| 99 | 03/05/2018 | 10:00 | 15:27 | 18:00 | 146 | 31 | 4127 | 107 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.2 |
| 92 | 03/05/2018 | 10:00 | 15:06 | 18:00 | 136 | 28 | 4128 | 108 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.7 |
| 89 | 03/05/2018 | 10:00 | 15:00 | 18:00 | 141 | 26 | 4132 | 112 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 6.2 |
| 107 | 03/05/2018 | 14:20 | 16:41 | 19:05 | 139 | 29 | 4133 | 113 | Atlantic salmon | Smolt | Beltie RST | 3 | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.5 |
| 109 | 03/05/2018 | 14:20 | 16:50 | 19:05 | 136 | 26 | 4134 | 114 | Atlantic salmon | Smolt | Beltie RST | 3 | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 6.2 |
| 111 | 03/05/2018 | 14:20 | 16:58 | 19:05 | 137 | 27 | 4140 | 120 | Atlantic salmon | Smolt | Beltie RST | 3 | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.9 |
| 113 | 03/05/2018 | 14:20 | 17:05 | 19:05 | 138 | 31 | 4141 | 121 | Atlantic salmon | Smolt | Beltie RST | 3 | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.2 |
| 103 | 03/05/2018 | 14:20 | 16:26 | 19:05 | 135 | 24 | 4142 | 122 | Atlantic salmon | Smolt | Beltie RST | 3 | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 6.7 |
| 106 | 03/05/2018 | 14:20 | 16:37 | 19:05 | 143 | 30 | 4143 | 123 | Atlantic salmon | Smolt | Beltie RST | 3 | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.3 |
| 110 | 03/05/2018 | 14:20 | 16:54 | 19:05 | 140 | 31 | 4144 | 124 | Atlantic salmon | Smolt | Beltie RST | 3 | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.2 |
| 104 | 03/05/2018 | 14:20 | 16:31 | 19:05 | 135 | 27 | 4145 | 125 | Atlantic salmon | Smolt | Beltie RST | 3 | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.9 |
| 105 | 03/05/2018 | 14:20 | 16:34 | 19:05 | 139 | 26 | 4146 | 126 | Atlantic salmon | Smolt | Beltie RST | 3 | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 6.2 |
| 101 | 03/05/2018 | 10:00 | 15:32 | 18:00 | 145 | 39 | 4147 | 127 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 4.1 |
| 102 | 03/05/2018 | 10:00 | 15:36 | 18:00 | 139 | 33 | 4148 | 128 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 4.8 |
| 100 | 03/05/2018 | 10:00 | 15:29 | 18:00 | 137 | 27 | 4149 | 129 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.9 |
| 90 | 03/05/2018 | 10:00 | 15:01 | 18:00 | 144 | 29 | 4150 | 130 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.5 |
| 88 | 03/05/2018 | 10:00 | 14:55 | 18:00 | 141 | 27 | 4151 | 131 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.9 |
| 94 | 03/05/2018 | 10:00 | 15:09 | 18:00 | 148 | 31 | 4153 | 133 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.2 |
| 97 | 03/05/2018 | 10:00 | 15:20 | 18:00 | 140 | 27 | 4154 | 134 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.9 |
| 91 | 03/05/2018 | 10:00 | 15:03 | 18:00 | 141 | 35 | 4156 | 136 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 4.6 |
| 96 | 03/05/2018 | 10:00 | 15:18 | 18:00 | 136 | 26 | 4157 | 137 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 6.2 |
| 98 | 03/05/2018 | 10:00 | 15:25 | 18:00 | 139 | 33 | 4317 | 147 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 4.8 |
| 95 | 03/05/2018 | 10:00 | 15:12 | 18:00 | 150 | 33 | 4321 | 151 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 4.8 |
| 86 | 03/05/2018 | 10:00 | 14:50 | 18:00 | 137 | 26 | 4323 | 153 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 6.2 |
| 114 | 15/05/2018 | 11:15 | 11:45 | 13:55 | 135 | 17 | 4056 | 84 | Atlantic salmon | Smolt | Beltie RST | 4 | E Edwards | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 9.4 |
| 115 | 15/05/2018 | 10:00 | 10:35 | 13:00 | 148 | 29 | 4308 | 139 | Atlantic salmon | Smolt | Beltie RST | 3 | E Edwards | 29/05/2018 | Y | V7-2L-069 | 7 | 18 | 1.6 | 136 | 5.5 |
| 116 | 23/05/2018 | 09:20 | 11:23 | 13:25 | 150 | 37 | 4128 | 49 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 4.6 |
| 116 | 23/05/2018 | 09:20 | 11:23 | 13:25 | 150 | 37 | 4129 | 49 | Atlantic salmon | Smolt | Sheeoch Fyke | Sheeoch Fyke | R Main | 29/05/2018 | Y | V7TP-2L-0 | 7 | 21.5 | 1.7 | 137 | 4.6 |