WICK SMOLT TRACKING PROJECT, 2016.

PREPARED BY: D. DEL VILLAR-GUERRA, N.R. GAULD, J.D. McILVENNY,

L.M. GODDIJN-MURPHY AND A.F. YOUNGSON

PREPARED FOR: BEATRICE OFFSHORE WIND FARM LTD

IN COLLABORATION WITH: THE FLOW COUNTRY RIVERS TRUST.

DATE: 01/03/2017

CONTENTS

Introduction ... 3

Background ... 3

Approach to smolt tracking. ... 6

Wick River and Bay ... 6

Main objectives of Wick Smolt Tracking Project in 2016. ... 8

Methods ... 8

The Wick arena: Hydrology and hydrography. ... 8

Tracking. ... 9

Fish. ... 10

Results ... 11

Data recording and filtering. ... 11

Tag detections. ... 13

Swimming Depth. ... 14

Time spent within range of the receiver array. ... 15

Individual fish's use of space. ... 15

Shoaling? ... 17

Northwards bias to swimming activity? ... 18

Conclusions. ... 19

Acknowledgements. ... 21

Appendix 1 A: Initial strings of detection events for individuals. ... 22

Appendix 1 B: Individuals' use of space. ... 27

Wick Smolt Tracking Project, 2016.

D. del Villar-Guerra[1], N.R. Gauld[2], J.D. McIlvenny[1], L.M. Goddijn-Murphy[1] and A.F. Youngson[1]

1 Environmental Research Institute, North Highland College, University of the Highlands and Islands, Thurso, Caithness KY14 7EE, UK

2. Marine Scotland Science, Freshwater Fisheries Laboratory. Pitlochry, Perthshire, PH16 5LB, UK.

INTRODUCTION

BACKGROUND

The recent advent of the marine renewables industry in the northern Moray Firth and the Pentland Firth has once again highlighted the almost total lack of information on the use of these waters by migrating salmon passing to and from the rivers of eastern and northern Scotland.

Malcolm et al (2010)[1] reviewed tagging studies of adult fish in the specific context of marine renewable development in Scottish waters. Guerin et al. (2014)[2] reviewed the migratory behaviour of Atlantic salmon (both adults and smolts) in the more general context of the other species of migratory salmonids. The particular focus of Guerin et al.'s review was particle-tracking modelling which appears to offer utility in an applied context but only if biological input data of sufficient quality is available. Recently, Youngson (2017)[3] re-examined the movements of adult salmon in the specific context of the Pentland Firth and the North Coast making use of unconventional sources of information. As a result of all these studies a better conceptual understanding of what might be going on in northern Scottish waters is now available. Signally, however definitive answers will not be possible until such time as new studies are carried out to generate empirical accounts of the movements of fish in, or near, the places that are now of particular interest.

The scope for interaction between salmon and renewables will depend on the locations of development, the migratory routes of juvenile salmon leaving their rivers, or of adult salmon returning to their home rivers, and the extent to which development locations and migratory routes overlap. Consideration must also be given to the duration of overlap and the possibility

[1] http://www.gov.scot/resource/doc/295194/0111162.pdf
[2] https://www.thecrownestate.co.uk/media/5534/published-eri-salmon-migration-report.pdf
[3] Fishermen's Knowledge: Salmon in the Pentland Firth. Flow Country Rivers Trust, 31pp.

of repeat overlap particularly in high-energy locations targeted for tidal turbines where tidal speeds often exceed the swimming capacity of fish and particularly smolts.

The nature of some of the possible interactions can be identified - collision, noise or electro-magnetic fields around cables conducting electricity (Malcolm et al., 2013)[4]. However, given the evident subtlety of the mechanisms that fish must use to guide their migrations it is possible that other modes of potential interference may remain to be discovered.

Multiple studies of migration routes will be required because many of the questions to be asked are context-specific. Regarding marine renewables, migrants to and from each river are likely to interact with each development in different ways - including zero interactions. It will not be possible to make the same observations in every location of interest. Instead, the strategy must be to make empirical observations of migrating fish where this is both relevant and technically possible, while also elucidating mechanisms in order to permit inference and generalisation on a wider scale. In this way it may be possible to satisfy data needs better that at present without specific knowledge for particular sites. Equally, mechanistic studies can be used to generate hypotheses to facilitate targeted studies where these are considered necessary.

Conventional tagging studies of adult fish, as also reviewed by Malcolm et al. (2010), can be treated as *de facto* tracking studies. Tracking fish in this way gives only two random points on the route of each individual – a capture point and a recapture point. However, given a sufficient number of studies and individuals, a composite picture of patterns of migration can be built up that resolves some of the gaps in the region of interest. This procedure results in the summary diagram of migratory routes for adult salmon in Scotland that Malcolm et al. present in Figure 23. However, tagging/ tracking Information is heavily biased towards the coastal zone where most of the fisheries that capture or recapture the fish take place. Moreover, the links between the various separate elements of the coastal pattern are uncertain and the links between the various coastal migrations and incoming routes from the sea or ocean are largely unknown.

There is no counterpart to Malcolm's Figure 23 for the outgoing migration of smolts. Conventional tagging studies of smolts have been carried out routinely over many years at some sites in eastern Scotland but these cannot also serve as tracking studies because the small fish are not susceptible to sampling by commercial nets or any other means. As a result, migrating smolts go undetected and their outward migration is probably the least known phase of the salmon's life-cycle. It is also one of the only two phases where interaction with renewables is possible.

If there are any negative effects on smolts during transit through renewables sites, it will not be possible to attribute these to their cause using a deploy-and-monitor arrangement due to

[4] http://www.gov.scot/Resource/0042/00426601.pdf

the almost certain lack of direct evidence of effect. Equally, with attenuation due to the time elapsed between smolting and at the adult return stage (the first option for monitoring) it is unlikely that any effect will be detectable due to the insensitivity of assessment methods. If it is detectable, experience of similar situations shows that any impact will not be readily attributed to its true source. These considerations make it particularly important to gain some direct understanding of the smolt migration with the aim of discounting the likelihood of interactions if possible and, where appropriate, removing the need for their consideration.

As per Malcolm et al.'s (2013) report, there are two possible approaches to gathering information – focussing primarily on the development sites or on the fish themselves. Both approaches are associated with major difficulties. Thus there are a range of possibilities for gathering data at particular locations by sampling fish by one means or another. However, the inherently low density of salmonids will impede attempts to interpret sampling data particularly when no or few fish are captured. Probability of detection and interpretation will be further impeded by shoaling or by high rates of travel.

The most relevant approach is to directly observe the routes that migrants take, identify any systematic behaviours that make travel non-random and use this knowledge to generalise to other situations of interest. The techniques now exist to track migrating fish, including smolts, using acoustic tags although the methods are largely untested in the extreme conditions associated with the high-energy environments targeted for marine renewables development. The particular attraction of the approach is that the point of origin of smolts (the river mouth) is known. However, the major technical challenge is to follow fish over extended distances away from this point towards, or away from, the locations of interest. This is the topic of the present report.

The Wick Smolt Tracking Project has its roots in the EU MERIKA and TURNKEY projects and in Guerin et al.'s (2014) report to The Crown Estate. As a consequence of the latter, ERI acquired the capacity to track smolts using acoustic tag technology. ERI has particular advantages in the deployment and servicing of tracking systems because of its close proximity to the Pentland Firth and the northern Moray Firth where several areas of particular interest are located. In addition, ERI has close contact with a support network centred on the local Salmon Fishery Boards (the Caithness and Northern Boards) and the Flow Country Rivers Trust (FCRT). The present project was a collaboration between ERI and FCRT. The involvement of the community through the Trust demonstrated high levels of local interest extending to an unusual level of practical advice and material support from both commercial and sports fishermen.

Approach to smolt tracking.

The Wick Smolt Tracking Project is the first study of its kind to be undertaken by ERI and one of the first to test the tracking technology in Scottish coastal waters. The technology consists of acoustic tags that emit individually coded signals that are detected by automatic listening stations (ALS) placed in fixed locations on the seabed in strategically designed spatial arrays. A conservative approach has been adopted to test the tracking equipment under local field conditions while also generating basic biological parameters for the timing and behaviour of smolts around the fresh water/ marine interface. Hydrological conditions around the interface are also considered because tidal currents are likely to constrain the direction and speed of the fish in the terrestrial frame-of reference represented by any ALS array. The aim is to be able remove the effects of tidal and other currents on observed behaviour in order to also consider vectors that more accurately describe the activity of fish in their aquatic frame-of-reference. Both empirical and mechanistic understandings will be required in the longer-term because both perspectives will be important in different contexts.

The overall strategy, therefore, is to advance the programme in steps based on accumulating evidence on both the behaviour of the fish and the characteristics of the tags and the ALSs. In particular, the tags have a modest range and the ALSs cannot be expected to perform with uniform spatial or temporal efficiency – especially in hydrographically active coastal locations. The operating characteristics of the ALSs must therefore be assessed *in situ*. In this context, therefore, the overall aims are twofold - to be able interpret data in an appropriate probabilistic framework and to be able to design effective arrays for extreme tidal environments. The latter must offset an acceptable probability of tag detection against a high level of spatial coverage with the aim of targeting efficient use of capital equipment and cost-effective ways of obtaining the required information.

Wick River and Bay

For several strategic reasons, Wick River/ Bay on the eastern Caithness coast was chosen as the location for smolt tracking. Wick is in close proximity to the BOWL development in the Moray Firth. Wick River is the closest salmon river on the south side of the Pentland Firth: the Firth is potentially a major thoroughfare for smolts heading north-west to their feeding grounds. The lower reaches of Wick River are relatively straight, low-gradient and, except at times of high discharge characterised by low current speeds and low turbulence. Consequently, the river/ estuary boundary is particularly suited to the efficient functioning of an ALS positioned to monitor the passage of tagged fish from the river towards the sea.

Crucially, Wick estuary and bay comprise a relatively uniform and symmetrical arena well-suited to testing a particular hypothesis on the intrinsic directionality of smolt movement. The hypothesis arises as follows. The ultimate destination of smolts leaving Wick river lies far to the west and north of the British mainland. It is likely therefore that successful completion of the smolt migration is dependent on an intrinsic northwards vector to swimming activity. The marine sector of the Wick Bay arena is orientated approximately - and the northern shore of the arena is aligned almost exactly - on an east to west axis (Figure 1). In Wick Bay, therefore, any northwards vector to the smolts' swimming activity cannot be fully realised because of the barrier posed by the bay's northern shore. Assuming that any confounding hydrographic vectors are likely to be weak – which is probably the case for Wick Bay and, in any case, open to modelling – a hypothesis on a northwards swimming vector should transform to a hypothesis on spatial distribution given the conformation of the bay.

Figure 1. The lower river, estuary and bay at Wick.

Thus, the alternative hypotheses are (1) that smolts make random use of estuary space measured relative to a transect across the bay (ie. no overall north/ south vector is detectable) or (2) that spatial distribution is biased towards the northern sector of the bay (consistent with a northwards bias in swimming activity). This is potentially important because if an intrinsic vector mechanism can be shown to be active it can be used to predict and test direction of travel beyond the confines of the Wick Bay arena. So, for example, demonstration of a consistent northwards swimming vector would lead to the conclusion that smolts leaving the Wick River (and other similar rivers) are not likely to fall within range of the BOWL development.

Main objectives of Wick Smolt Tracking Project in 2016.

1. Test ALS function under a range of challenging coastal conditions.
2. Model hydrographic characteristics of bay under various states of tide.
3. Determine timing (dates and time of day) of river exit/ sea entry.
4. Determine swimming depth of smolts in bay.
5. Test the hypothesis that smolts show an intrinsic northwards bias to their marine migration.

Methods

The Wick arena: Hydrology and hydrography.

Supporting environmental information was available for river temperature as monitored continuously (Tinytag Aquatic2, Gemini Data Loggers Ltd) at Bilbster and for river discharge as monitored continuously at Tarroul by the Scottish Environmental Protection Agency.

River discharge was at or near basal levels (ca. 0.3 $m^3. s^{-1}$) throughout the study period. This had the fortuitous effect of simplifying data interpretation because water speeds in the lower river and net speeds in the inner estuary can be assumed to be near-zero. Consequently, the aquatic and terrestrial frames of reference can be regarded as equivalent in the inner bay and the observed movement of the smolts is likely to be attributable to their own motor activity.

This consideration changes in the outer part of the bay. Wick Bay forms a local hydrographic cell in which current speed, direction and timings vary in a complex manner, driven by coastal tidal streams outside the bay. Beyond the entrance to Wick Bay, tidal speeds are rapid (> 1 $m.s^{-1}$) over most of both the flood and ebb tides. These values are much greater than the swimming capacity of smolts (ca. 0.15 $m.s^{-1}$). In the outer bay, therefore, the observed movement of smolts at any time is expected to reflect the product of two vectors – a swimming vector and a tidal vector which will greatly exceed the swimming vector over most states of tide. The tidal vector also changes direction every six hours as the flood and ebb tides flows south or north, respectively, along the coast.

University of the Highlands and Islands
Oilthigh na Gàidhealtachd agus nan Eilean

Tracking.

The tracking system comprised automatic listening stations (ALSs) (VEMCO, Canada) and a mixture of LP-7,3 acoustic id tags (Thelma Biotel, Norway) and id-depth transmitter tags (ADT-LP-7,3). The LP-7,3 tags transmitted unique codes at 69 KHz and were programmed to transmit at random intervals of between 20 and 40 s. The depth tags did so at fixed intervals of 29, 31 and 33 seconds. The battery life of the tags was estimated at ca. 90 days.

A single ALS was positioned in a linear section of Wick River of uniform channel dimensions just above head-of-tide at ND 345 517 (Figure 2 and 4). The ALS had unobstructed "sight" over a river reach of ca. 200m. The ALS was positioned in mid-water where the river was ca. 0.6m in depth (at basal rates of river discharge) and the channel ca. 15m wide.

Figure 2. Location of Wick River ALS.

Twenty-one ALSs were deployed at spacings of ca. 200 m in a double array design spanning the outer part of Wick Bay. The ALSs were buoyed at 2m above the seabed and micro-sited to avoid creel-lines or unfavourable substrate. The array was biased towards the south side of the bay with the intention of optimising fish detection based on a preliminary assessment of the tidal dynamics in the Wick bay hydrographic cell[5]. The resultant spatial design is shown in Figure 3.

All the ALSs were in place before fish tagging commenced.

[5] See http://www.researchgate.net/project/The-Pentland-Salmon-Initiative-A-research-partnership-exploring-the-potential-interactions-between-migratory-fish-and-marine-renewables-in-the-North-of-Scotland

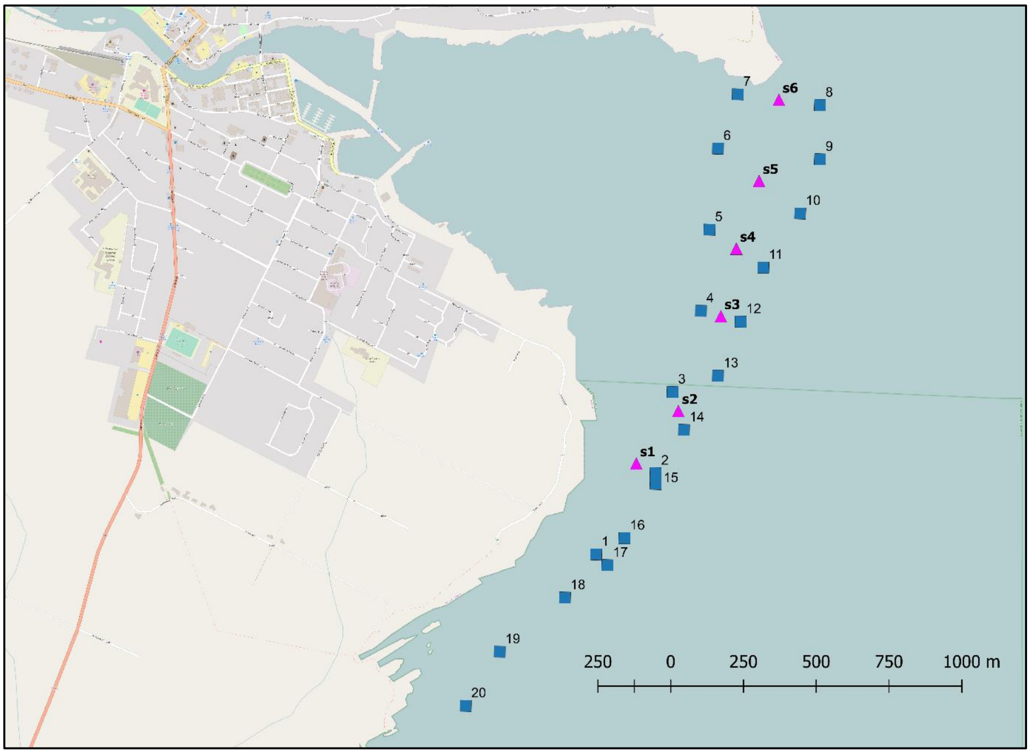


Figure 3. Spatial distribution of ALSs (blue) in Wick Bay and position of permanently positioned sentinel tags (black). The receiver identities are indicated.

Six LP-7,3 sentinel tags were permanently positioned within part of the marine ALS array in order to continuously monitor the operational characteristics of in-range ALS over the natural range of sea and tidal conditions. The sentinel tags were buoyed to 1m above the seabed.

The ALS signal detections were downloaded on logger recovery. VEMCO loggers process acoustic signals internally and VUE-software (VEMCO) was used to download and quality control them before permanently logging them into a database. Further quality control proved necessary post-processing and this was carried out as detailed below.

FISH.

On 23-24 April, 34 smolts of were captured by electric fishing over several locations (Figure 4) in the Wick River catchment. Acoustic tags were surgically implanted into large smolts (>135 mm fork length). The fish were tagged in accordance with the relevant animal welfare regulations, retained in a recovery tank for 1 hr and released back to the vicinity of their capture.

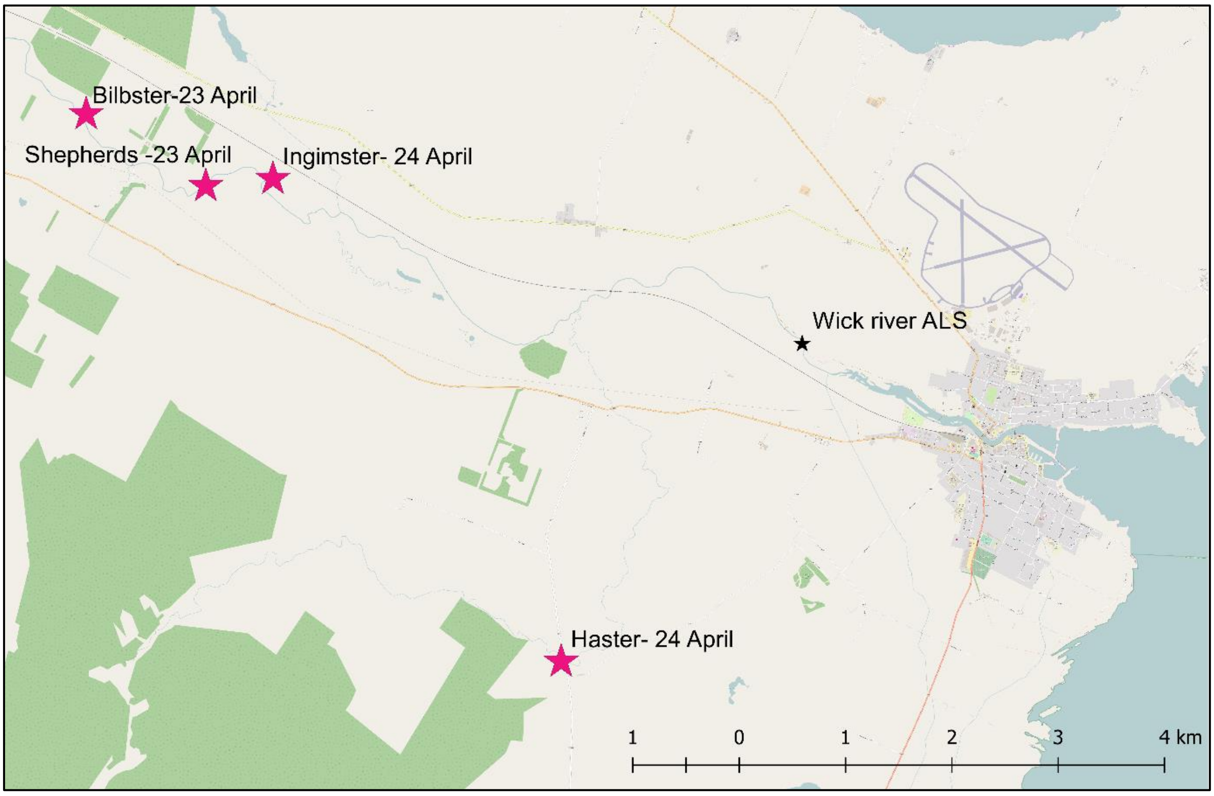


Figure 4. Locations of capture of smolts for tagging and acoustic listening station in Wick river.

RESULTS

DATA RECORDING AND FILTERING.

The ALSs were in position from 9th April to 27th June. Table 1 summarises logged data from individual ALSs accumulated over this time. Overall, most of the logged signals were from identifiable tags – ie. those known to be (1) borne by fish (2) permanently positioned sentinel tags or (3) test-tags used to check other aspects of receiver function.

In other cases, signals were logged with identity codes that did not correspond to tags known to be in the vicinity of the array. These are shown in red in Table 1. The data were probably artefacts of the logging system and are excluded from further consideration. The third column in Table 1 shows the number of legitimate tag codes (ie. known to be carried by fish in the Wick arena) that were logged by each receiver.

Table 1. Valid and spurious logged detections at individual ALS receivers and the number of valid fish tags logged by each receiver.

	Detections	Fish Transmitters logged
River		
Validated	61348	27
Rejected	zero	
1		
Validated		0
Rejected		
3		
Validated	16546	7
Rejected	22	
4		
Validated	33237	7
Rejected	53	
5		
Validated	42493	17
Rejected	136	
6		
Validated	36307	15
Rejected	68	
7		
Validated	4636	10
Rejected	75	
8		
Validated	142038	12
Rejected	222	
9		
Validated	111810	12
Rejected	72	
10		
Validated	162691	11
Rejected	179	

	Detections	Fish Transmitters logged
11		
Validated	148748	11
Rejected	125	
13		
Validated	41608	5
Rejected	219	
14		
Validated	106621	5
Rejected	410	
15		
Validated	94292	6
Rejected	330	
16		
Validated	12	3
Rejected	1	
18		
Validated		0
Rejected		
19		
Validated	11	1
Rejected	zero	
20		
Validated	950	1
Rejected	zero	
21		
Validated	20	1
Rejected	zero	

Preliminary inspection of the timings and the spatial distributions of legitimate transmitter codes demonstrated that further quality control was necessary. In general, logged records of individual tag codes known to be within the arena were present as strings of closely associated timings, occurring at the same or adjacent receivers, over relatively short periods of time (less than 1 hr). For some receivers, however, apparently authentic but probably spurious codes were recorded at single, isolated times at single receivers and, in some cases, these occurred many days after initial marine detection. An example is shown in Table 2.

Table 2. Example of spurious logging of a legitimate transmitter code.

Sequence	Date and time	Receiver ID	Sequence	Date and time	Receiver ID
1	28/04/2016 23:56	3	21	29/04/2016 00:05	15
2	28/04/2016 23:57	3	22	29/04/2016 00:05	15
3	28/04/2016 23:58	3	23	29/04/2016 00:08	15
4	28/04/2016 23:59	3	24	29/04/2016 00:08	16
5	28/04/2016 23:59	3	25	29/04/2016 00:09	16
6	29/04/2016 00:00	3	26	29/04/2016 23:01	11
7	29/04/2016 00:00	13	27	30/04/2016 23:02	11
8	29/04/2016 00:00	14	28	03/05/2016 04:19	11
9	29/04/2016 00:00	13	29	06/05/2016 16:27	10
10	29/04/2016 00:01	3	30	10/05/2016 07:46	5
11	29/04/2016 00:01	14	31	15/05/2016 16:16	11
12	29/04/2016 00:01	3	32	15/05/2016 21:56	10
13	29/04/2016 00:01	14	33	24/05/2016 01:45	10
14	29/04/2016 00:02	14	34	30/05/2016 01:42	6
15	29/04/2016 00:02	3	35	07/06/2016 05:28	10
16	29/04/2016 00:02	13	36	10/06/2016 09:39	11
17	29/04/2016 00:02	3	37	14/06/2016 02:08	11
18	29/04/2016 00:02	15	38	22/06/2016 04:57	11
19	29/04/2016 00:03	14	39	22/06/2016 12:53	10
20	29/04/2016 00:03	15	40	27/06/2016 03:22	11

Table 2 shows that from the first marine detection at 23.56 on 28th April, until 00.09 on 29th April, logging within the array was essentially continuous. Thereafter, intermittent and almost certainly spurious single detections (shown in red) were logged at apparently random intervals. Fortuitously, false detections were infrequent and therefore unlikely to impact otherwise valid strings of data. In the example shown, only 15 false detections were logged over the 60 days between 29 April and 27th June.

Final filtering of the data was therefore carried out by inspection. Only plausibly continuous strings of logged timings and receiver positions were retained.

TAG DETECTIONS.

Twenty-seven of the 34 fish tagged on 23rd-24th April were subsequently detected at the ALS positioned at head of tide. The total period over which individuals were first detected was from 28th April to 21st May. Individuals were continuously present near the ALS over periods ranging from 2 - 18 minutes. Two fish (IDs 1121 and 1122) were repeatedly detected over a period of four days although they reached and left the ALS area at different dates. The timing of first detections was mostly by night. The range of timings of first detections was from 20:31 hr to 02:14 hr (UTC) indicating that the fish were not migrating during the main hours of daylight.

Twenty-six of the 27 fish detected at head of tide were subsequently detected in the marine array. One track was discarded (ID 1130) at this stage as a result of quality control issues associated with an unexplained fault in the logged time-stamp. For the others, the delay between last detection at head-of-tide and first detection in the marine array (~8 km distance) varied from five hours to 35 days with a median value of 1 day. First detection in the marine array was again mostly at night and the range of timings was 20:20hr to 04:16hr UTC.

The timings of all the logged events within the initial string of detections are shown for each receiver and each tagged fish in Appendix 1A. A single example is shown in Figure 5, below, for illustrative purposes.

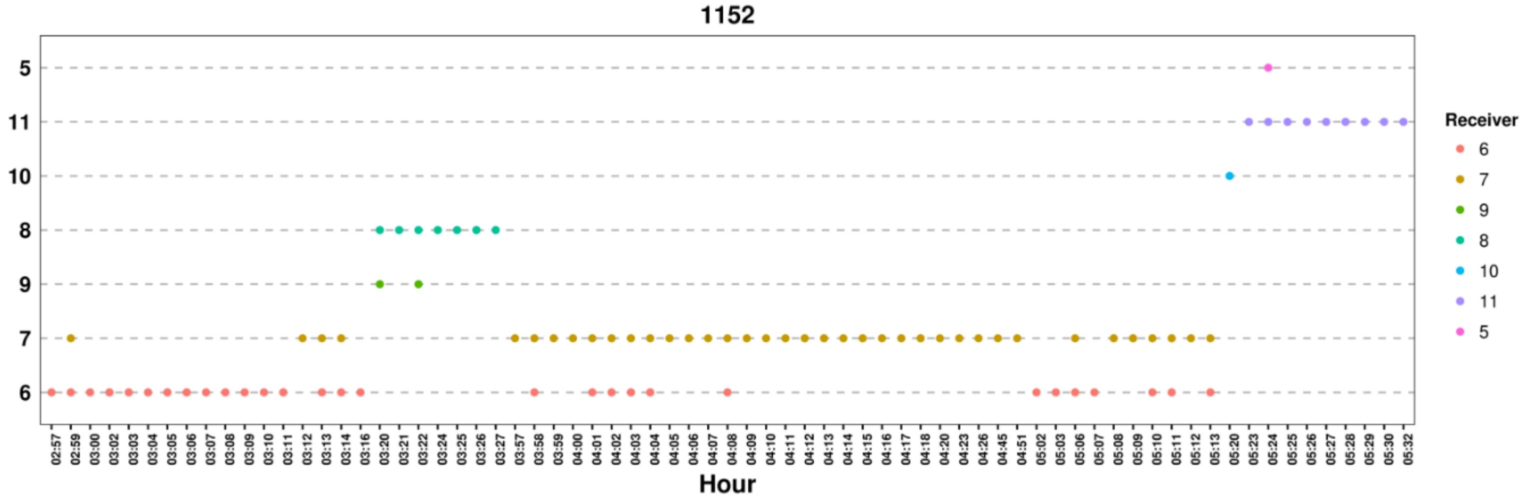


Figure 5. Times and locations (ALS ID) for initial string of detection events for transmitter ID 1152. See Figure 3 for location of ALSs.

Transmitter 1152 was first detected in the marine array at Receiver 6 on 4th May at 02:57 hr. The fish remained in this vicinity until 03:16 and, towards the end of this period, occasionally also fell within the range of Receiver 7. Thereafter, the fish moved out to within range of Receiver 8, occasionally also falling within range of Receiver 9, and it remained in this vicinity until 03:27. The fish was then undetected for 30 mins before returning to a position within range of Receivers 6 and 7 at 03:57, remaining with range of Receiver 7 until 04:51. The fish then moved out of range again before returning to the vicinity of Receivers 6 and 7 for a further period lasting until 05:13. By 05:20 the fish had moved south to within range of Receiver 11 (via single detections on Receivers 10 and 5) where it remained until 05:33 when it was last detected. Receivers 7 and 11 are about 500m apart.

SWIMMING DEPTH.

Swimming depth was repeatedly logged within in the marine array for three Individuals, as per Table 3. Swimming depth varied between 1 and 4m. Water depth within the array varied between 15 and 30m at lowest astronomical tide. Therefore, these smolts utilised the surface layers of the water column during their time in the marine array.

Table 3. Logged swimming depth for individual tags codes.

		Swimming depth (m)		
Tag ID	**n**	**median**	**min**	**max**
101	18	2	2	2
102	23	3	3	4
103	39	1	1	4

Time spent within range of the receiver array.

The duration of the initial string of marine detections varied between 10 and 408 minutes (Figure 6). The modal value was 30-40 minutes.

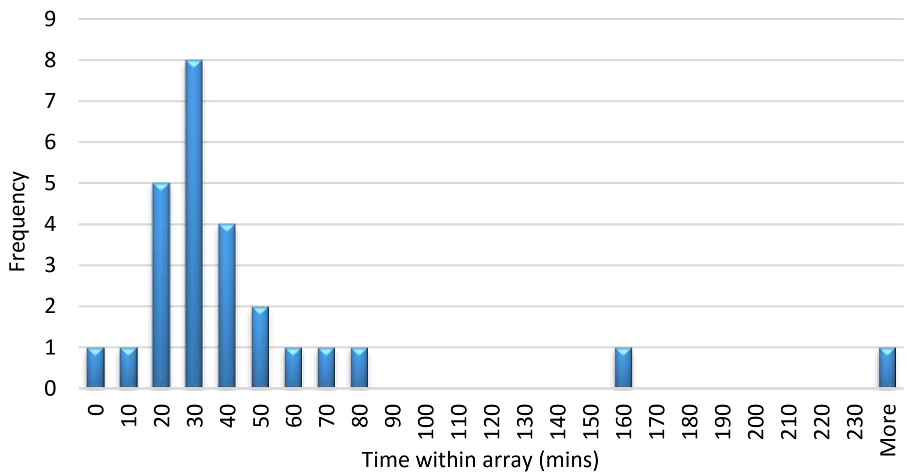


Figure 6. Duration of initial string of marine detections.

Individual fish's use of space.

Individual fish's logged use of space in the vicinity of the marine array is shown in Appendix 1B.

In Figure 7, a single example (Tag 1109) is shown for illustrative purposes.

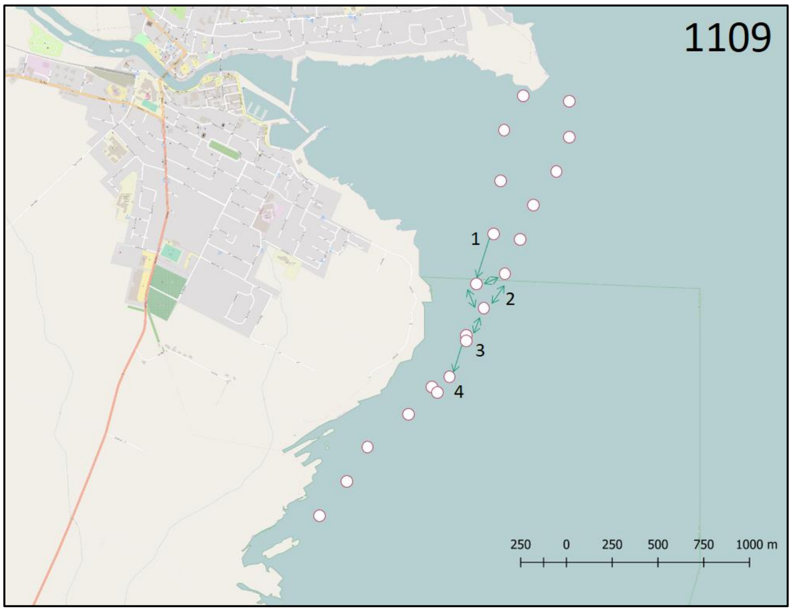


Figure 7. Spatial distribution of detections for Transmitter ID 1109.

Tag 1109 was first logged (1) at Receiver 4 and subsequently moved south in four discernible phases to final detection at Receiver 16 (4). At the intervening stages, simultaneous detections were made at multiple receivers (as indicated by double-ended arrows) in patterns due either to minor changes in the fish's location or due to temporal variation in the effective range of receivers. The timings of the various detections and the occurrence of simultaneous detections are shown in the matching figure below (Figure 8). Fish 1109 passed across the range of the array in 16mins.

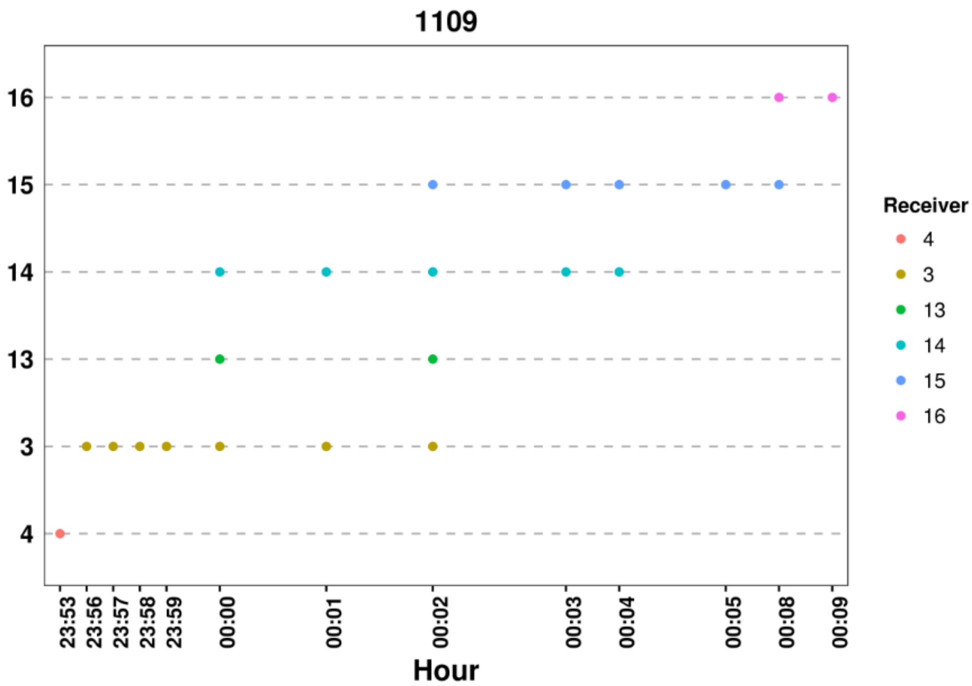


Figure 8. Times and locations (ALS ID) for initial string of detection events for transmitter ID 1109.

FCRT

University of the Highlands and Islands
Oilthigh na Gàidhealtachd agus nan Eilean

SHOALING?

Figure 9 shows the dates on which individuals passed through the marine array. The first detection was on 28th April and most fish passed before 11th May. The last individual to pass did so on 10th June.

Overall, fish were present in the array on 14 dates and on 6 of these dates only single tagged fish were present, indicating substantial levels of independence. Even when several fish were present in the array on the same date, further levels of likely independence were apparent.

On the night of 28th-28th April, for example, four individuals passed the array – Tag IDs 1108, 1109, 1110, and 1126. The panels in Appendix 1 show that 1110, 1109, 1126 were present in the array at around the same time but that 1108 was detected only several hours later. For the three fish associated in time, the panels in Appendix 2 show that only 1109 and 1126 were also spatially associated in space. Indeed, 1109 and 1126 were detected by Receiver 3 within a period of several minutes.

In a further example, six fish passed the array during the night of 6th – 7th May (Transmitter IDs 1107, 1123, 1127, 1148, 1119 and 1124). Only two – 1127 and 1123 – were closely associated in time. The same fish were also spatially associated, both being detected repeatedly at Receiver 6 over a period of around 20mins.

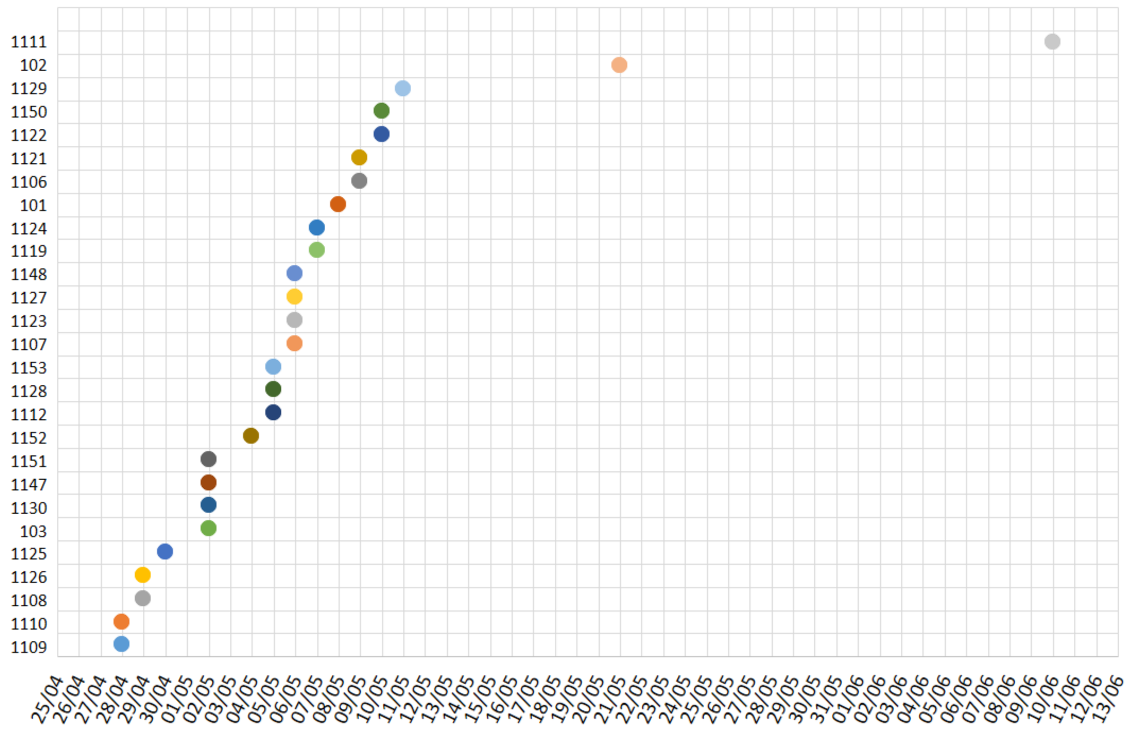


Figure 9. Date of the initial string of marine detections for individual fish

NORTHWARDS BIAS TO SWIMMING ACTIVITY?

Table 4 shows the number of occasions on which single transmitters were first logged at each receiver position. As expected, all first detections occurred in the northern sector of the array between the South and North Heads - and between Receivers 3 and 7. As also expected, most (24 of 26) first detections occurred in the inner component of the array and only two were logged in the outer component.

Table 4. Number of transmitters first logged at each receiver position.

	Receiver ID	First detections of tag (n)
	7	4
	6	8
Inner array	5	7
	4	3
	3	2
	8	1
	9	0
Outer array	10	1
	11	0
	12	0

Figure 10 shows the spatial distribution of first detections. The approximate mid-line of the bay is indicated by the broken line. The line's western end is fixed by narrow gap between the inner breakwaters in Wick Harbour. That part of the array spanning the mid-line of the bay has been divided into three areas - a central sector (receivers 5, 10 and 11) flanked by a northern (receivers 7, 6, 8 and 9) and a southern sector (receivers 4, 12, 3 and 13), as indicated.

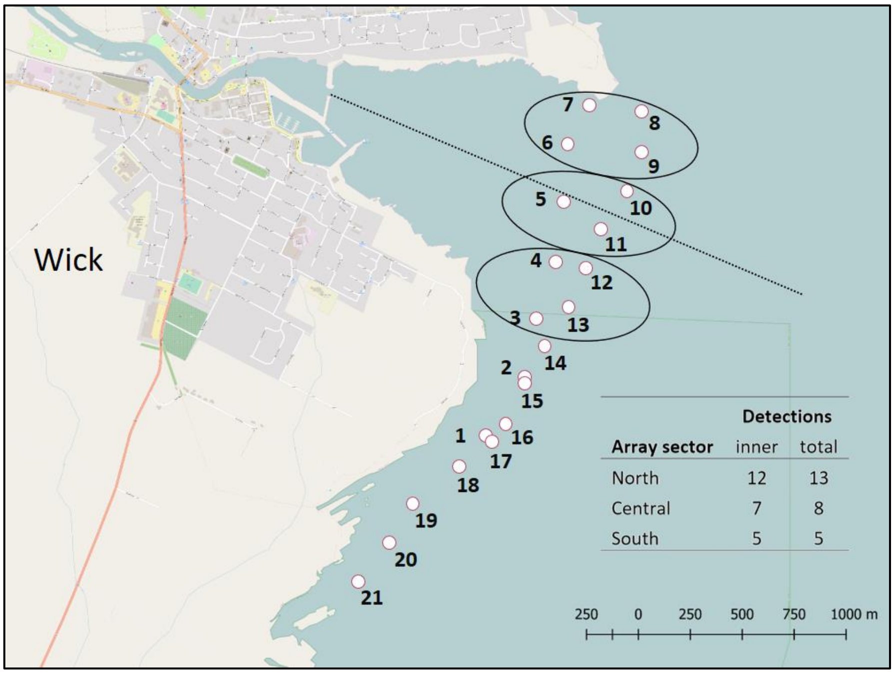


Figure 10. Spatial distribution of first detections of individual tags within the receiver array.

In the inner array, a total of 24 first detections were made over all three sectors. Twelve, 7 and 5 first detections occurred in the northern, central and southern sectors, respectively (see inset Table). Considering both the inner and outer arrays, the corresponding values were 13, 8 and 5, respectively.

Comparing the northern and southern sectors suggests that individuals were ca. 2.5 times more likely to approach and enter the array to the north than to the south, suggesting, in turn, that the fish did not disperse symmetrically to left or right in the inner bay. Overall, fish tended to bear northwards as their arena expanded from the entry point-source (at the inner breakwaters) to the ca. 1200m transect of the outer bay represented by the receiver array.

CONCLUSIONS.

This project proved informative and, as per the overall research strategy, it presents a sound first step to achieving ERI's ambition to move receivers into effective arrays on a broader spatial scale. This will target detection of smolts in the wider coastal zone, particularly to the north of the present study location, in order to further test the hypothesis that smolts show an intrinsic tendency to a northwards swimming vector.

Thus, the 2016 marine array detected the passage of 24 of 26 fish that were plausibly likely to pass through it following their earlier detection in the receiver located at head-of-tide. One individual was not detected in the marine array and another may have been but was considered undetected because of doubt related to quality-control issues on the string of logged detections. In addition, another individual (ID 1111) is provisionally considered to have been present in the array although it was detected only on a single occasion (at Receiver 8). It is concluded, therefore, that the marine array detected most, but possibly not all, of the fish passing through it.

Further, 24 of 26 fish that were detected were logged on a sub-set of 5 of the 21 receivers deployed in the marine array. All the detected fish were logged on a sub-set of 11 receivers. This indicates that if, for future studies, the objective of the Wick array is detection only, then many of the receivers in the 2016 Wick array design can be withdrawn. For example, high rates of detection (>90%) would still be expected from only 5 receivers. Released receivers would become available to extend the array design to cover more distant locations of potential interest, off-setting extended coverage against a (small) reduction in the rate of detection by the modified array.

ALSs were positioned on the sea-bed in depths of 15-30m to remove them from any interference with, or from, shipping and to lower their exposure to wave motion and turbulence. The swimming depths of smolts in the array were logged in the 1- 4 m range. This suggests that the acoustic signals were presented to the receivers obliquely from above. Consequently, the signals were probably not susceptible to screening by marine growth or by the local contours of the sea-bed, expanding the operational range of the receivers towards their full technical specification.

All the fish detected in the marine array had previously been detected at head of tide. This indicates that the in-river receiver was fully effective, at least in the operating environment that pertained as smolts exited the river in 2016. However, no high-flow/ high turbulence episodes occurred over the duration of the study. The likely efficiency of tag detection by a single in-river receiver should be tested over a wider range of conditions to inform the design of similar future studies.

On the whole, fish were shown to traverse the marine array relatively rapidly. Inspection suggests that on the outer edge of the receiver array, fish movements were substantially affected by the tidal flows predicted from the computer simulation of local tidal dynamics. The simulation also indicates that inanimate particles without an intrinsic capacity for directed movement should re-present to the array on successive phases of the tide as they are swept north or south. Given the relatively low swimming capability of smolts (ca. 0.15 $m.s^{-1}$) their overall movement will necessarily be dominated by local tidal speeds which in mid-tide outside Wick Bay are around 0.5 to 0.8 $m.s^{-1}$. However, smolts did not re-present to the receiver array. This indicates that their swimming capacity was sufficient to remove them from the influence of the dominant effects of local tidal flows within one tidal cycle (ca. 12 hr). More detailed analysis of tidal effects on fish tracks, particularly for the outer part of the array in the interface between Wick Bay and the open coast, will necessitate considering tracks in the context of detailed hydrographic data and/ or simulations.

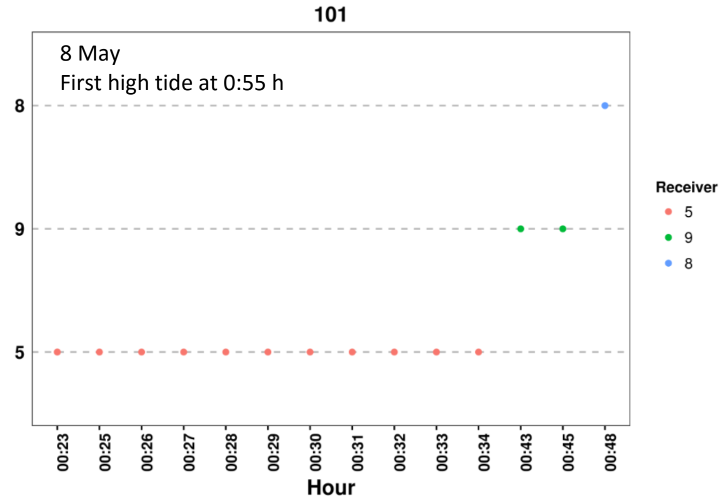
Finally, as discussed in the introduction to this report, the practical utility of tracking studies in an applied context will be found to rely on a consideration of mechanisms rather than empirical data. As also discussed above, the conformation and alignment of the Wick arena is conducive to testing the hypothesis that smolts should show a tendency to direct their swimming activity to the north. In support of this, the distribution of the Wick smolts passing through the array appeared to be biased northwards suggesting that, overall, their prior swimming activity, between the point of entry to the bay and their arrival at the array, had not been random but directed towards north. This finding is encouraging and should be examined further.

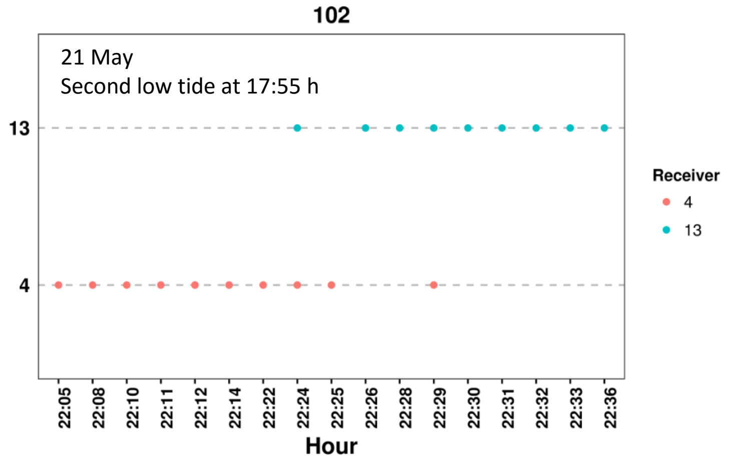
However, it should also be treated with caution until more detailed investigation and/ or confirmatory studies are carried out. Behavioural studies of this kind are notoriously prone to interference from unrecognised, confounding effects. In the present case, the possible effects of channel conformation or micro-hydrographic effects in the inner part of Wick Bay, for example, are obvious candidates to discount. In addition, smolts are considered to be shoaling fish. Shoaling is likely to synchronise the behaviour of the individuals, confounding any hypothesis test that relies on individuals acting independently. Inspection showed that although some of the tagged fish in the present study were closely associated in time/ space as they passed through the array, most were not.

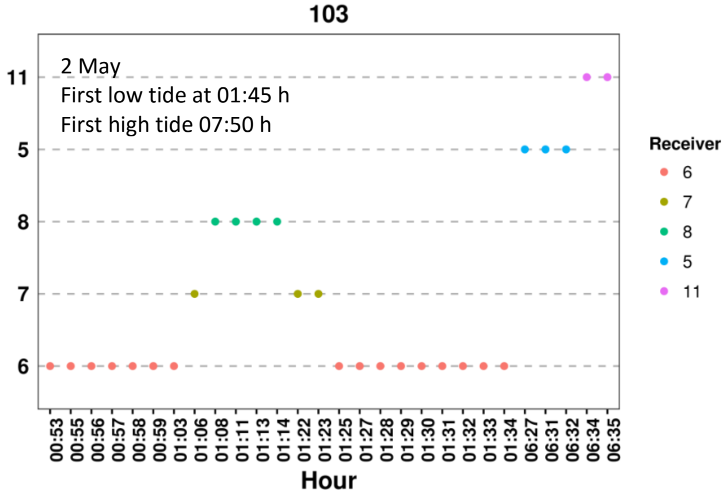
ACKNOWLEDGEMENTS.

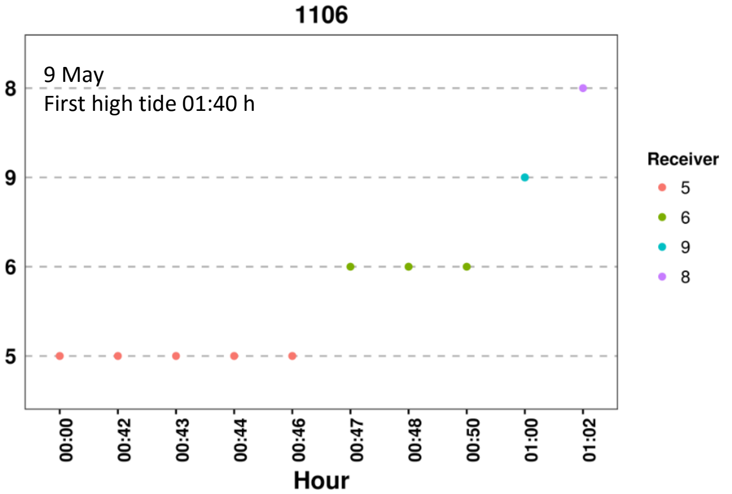
We wish to acknowledge the support of the Flow Country Rivers Trust. We acknowledge help from John Mackay (FCRT), Colin Richards, Corrie Cormack of Wick Angling Association and Ronnie Plowman, also of WAA, and skipper of *Ma-Rona* which laid the receivers. Malcolm Bremner (Harbour Master in Wick), Jim Cassidy (ERI) and Hugh Mackay of Mackay Underwater Technology (MUT) all provided advice and technical support.

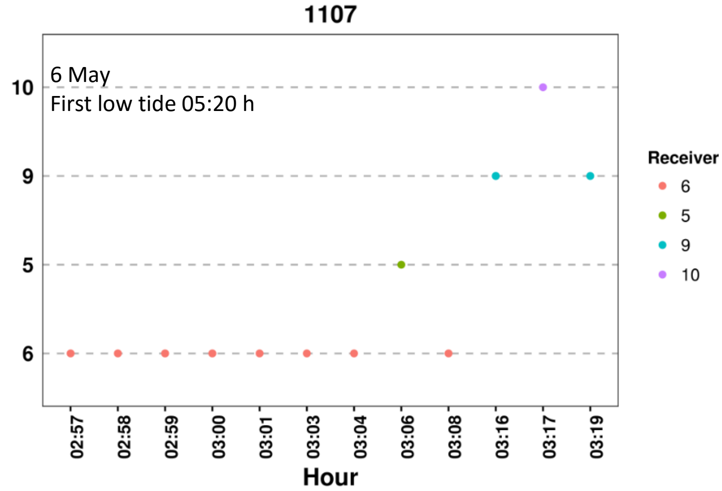
APPENDIX 1 A: INITIAL STRINGS OF DETECTION EVENTS FOR INDIVIDUALS.

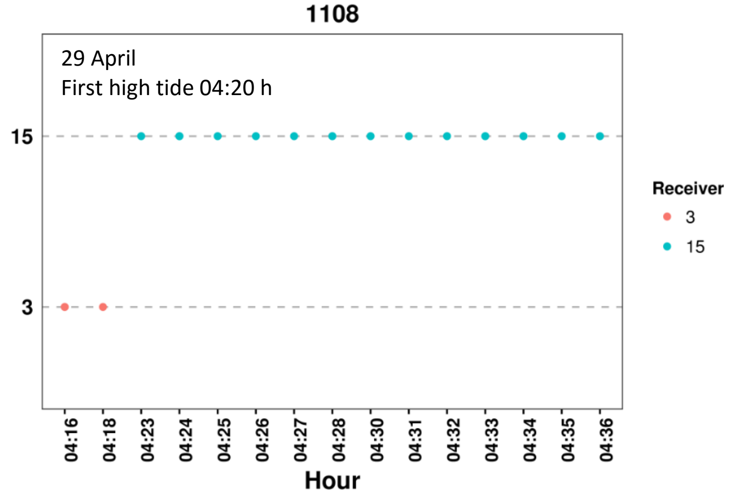






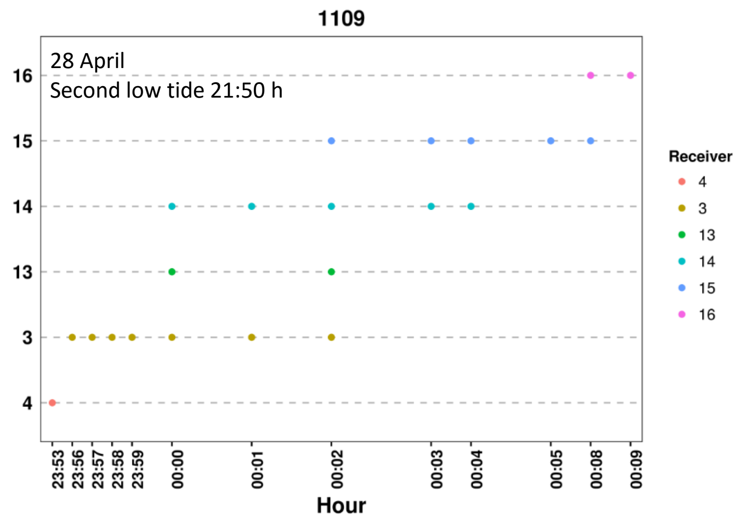


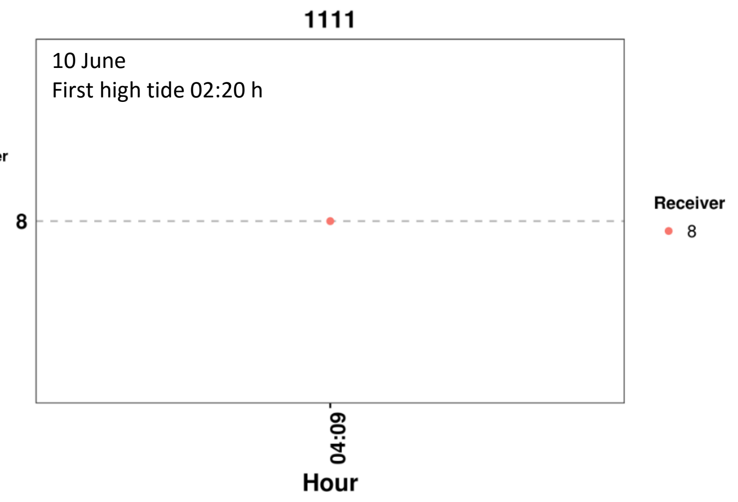


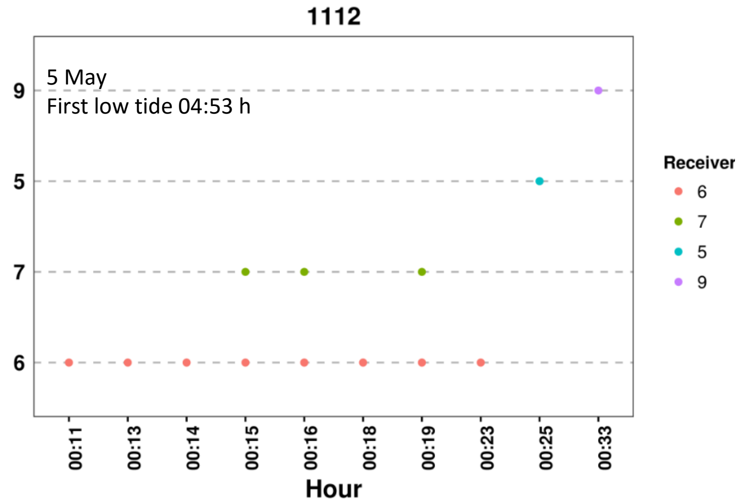


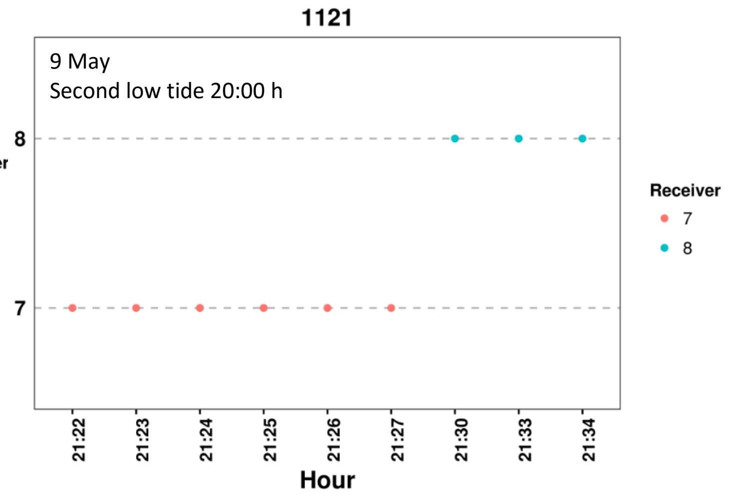
FCRT

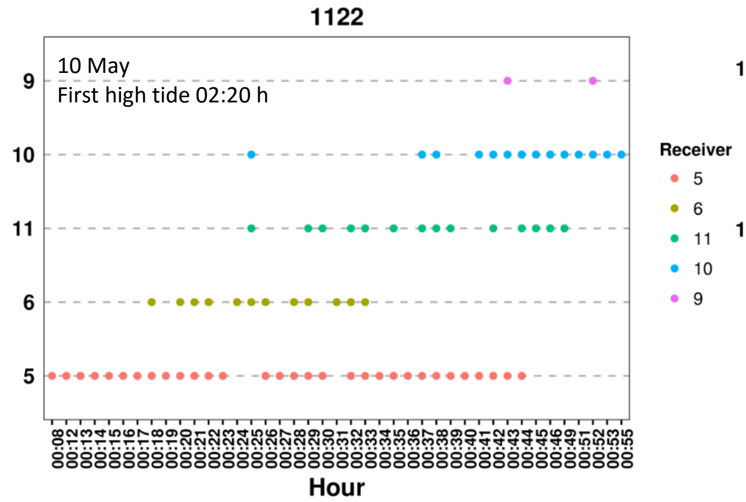
University of the Highlands and Islands
Oilthigh na Gàidhealtachd agus nan Eilean

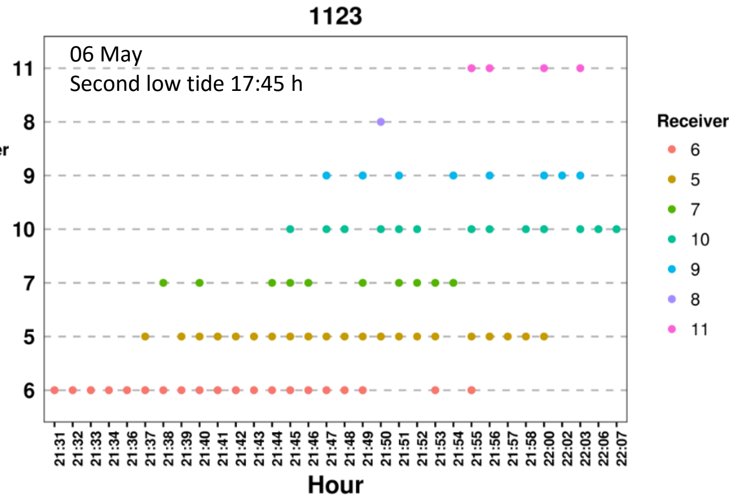

1109
28 April
Second low tide 21:50 h
16
15
14
13
3
4
23:53
23:56
23:57
23:58
23:59
00:00
00:01
00:02
00:03
00:04
00:05
00:08
00:09
Hour
Receiver
4
3
13
14
15
16

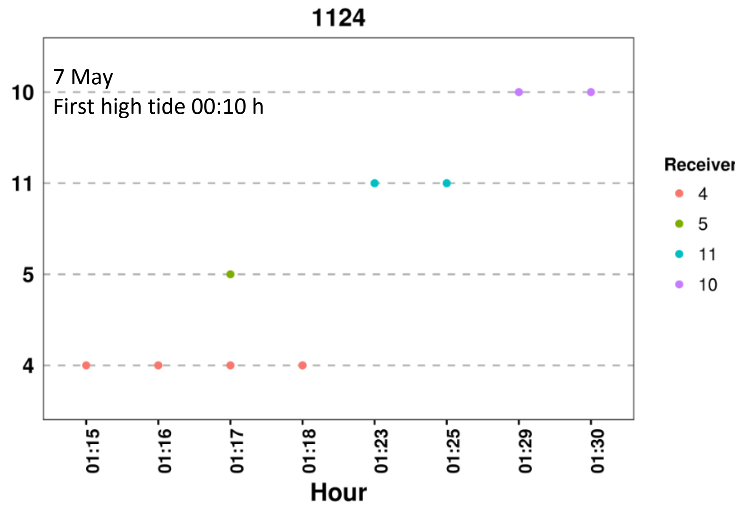

1111
10 June
First high tide 02:20 h
8
04:09
Hour
Receiver
8

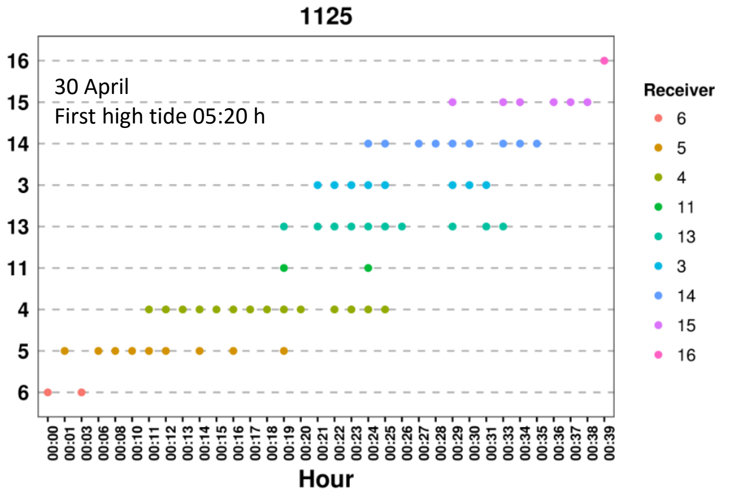

1112
5 May
First low tide 04:53 h
9
5
7
6
00:11
00:13
00:14
00:15
00:16
00:18
00:19
00:23
00:25
00:33
Hour
Receiver
6
7
5
9

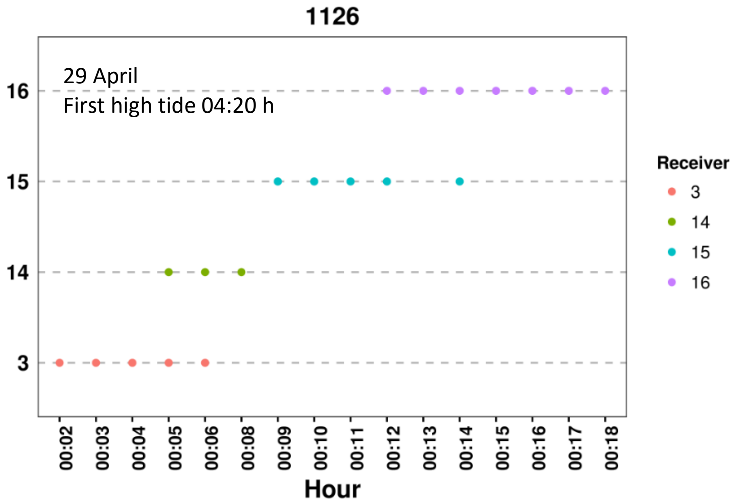

1121
9 May
Second low tide 20:00 h
8
7
21:22
21:23
21:24
21:25
21:26
21:27
21:30
21:33
21:34
Hour
Receiver
7
8

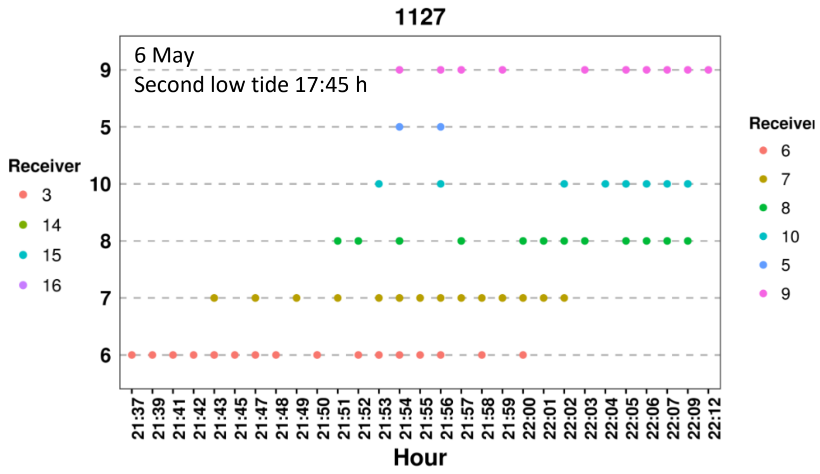

1122
10 May
First high tide 02:20 h
9
10
11
6
5
Hour
Receiver
5
6
11
10
9

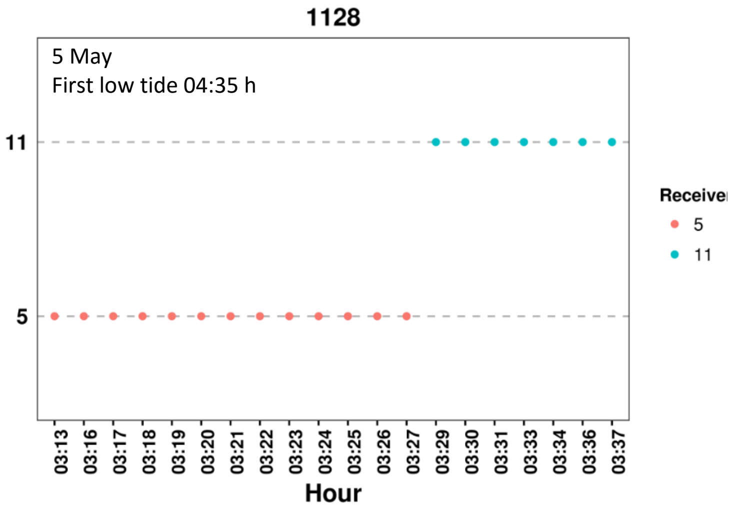

1123
06 May
Second low tide 17:45 h
11
8
9
10
7
5
6
Hour
Receiver
6
5
7
10
9
8
11

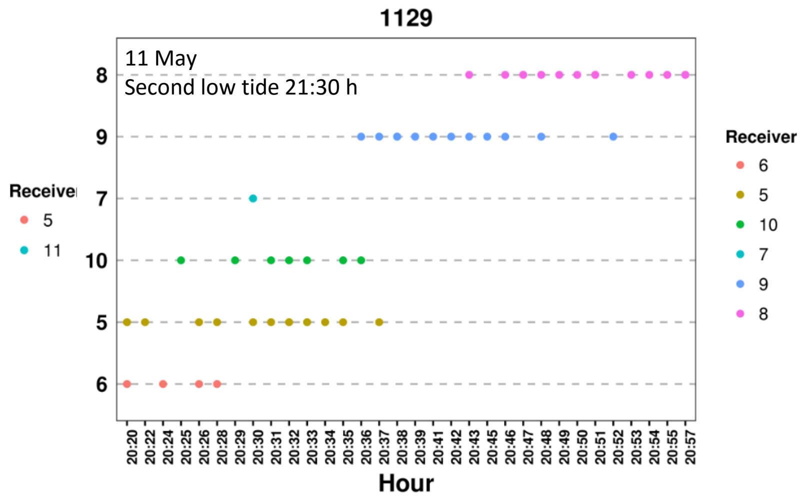

1124
7 May
First high tide 00:10 h
10
11
5
4
01:15 01:16 01:17 01:18 01:23 01:25 01:29 01:30
Hour
Receiver
4
5
11
10

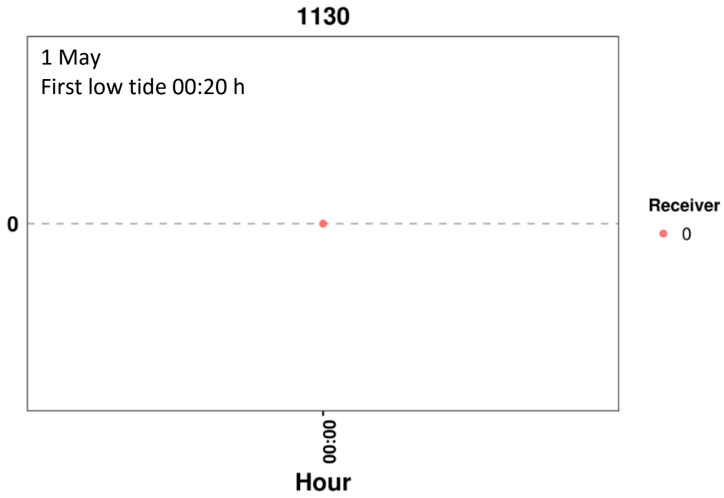

1125
30 April
First high tide 05:20 h
16
15
14
3
13
11
4
5
6
00:00 00:01 00:03 00:06 00:08 00:10 00:11 00:12 00:13 00:14 00:15 00:16 00:17 00:18 00:19 00:20 00:21 00:22 00:23 00:24 00:25 00:26 00:27 00:28 00:29 00:30 00:31 00:33 00:34 00:35 00:36 00:37 00:38 00:39
Hour
Receiver
6
5
4
11
13
3
14
15
16

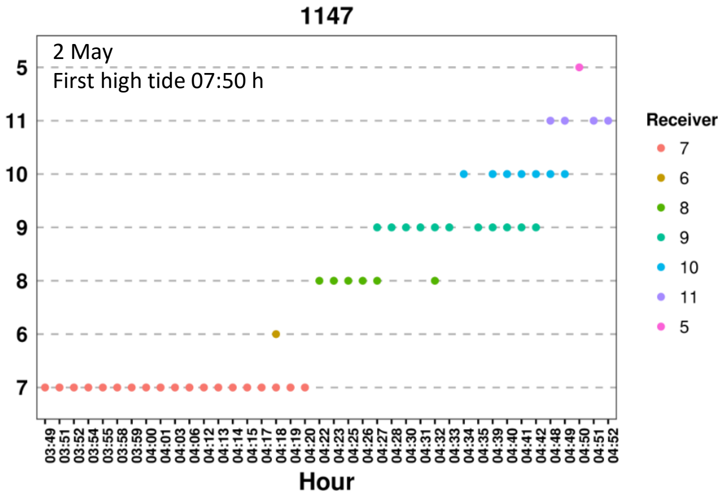

1126
29 April
First high tide 04:20 h
16
15
14
3
00:02 00:03 00:04 00:05 00:06 00:08 00:09 00:10 00:11 00:12 00:13 00:14 00:15 00:16 00:17 00:18
Hour
Receiver
3
14
15
16

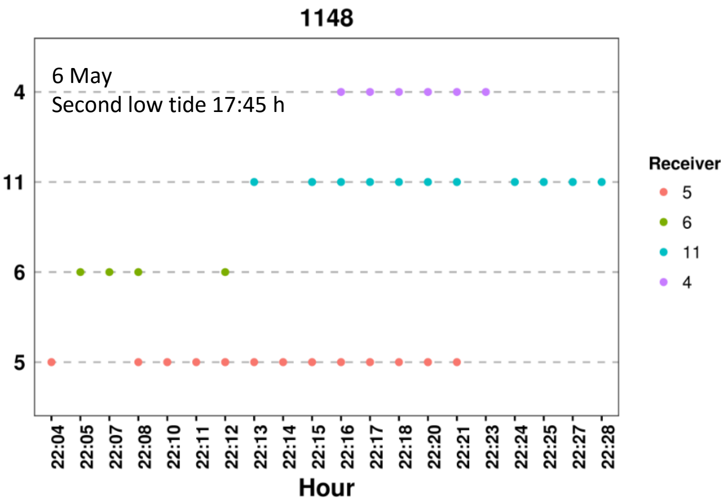

1127
6 May
Second low tide 17:45 h
9
5
10
8
7
6
21:37 21:39 21:41 21:42 21:43 21:45 21:47 21:48 21:49 21:50 21:51 21:52 21:53 21:54 21:55 21:56 21:57 21:58 21:59 22:00 22:01 22:02 22:03 22:04 22:05 22:06 22:07 22:09 22:12
Hour
Receiver
6
7
8
10
5
9

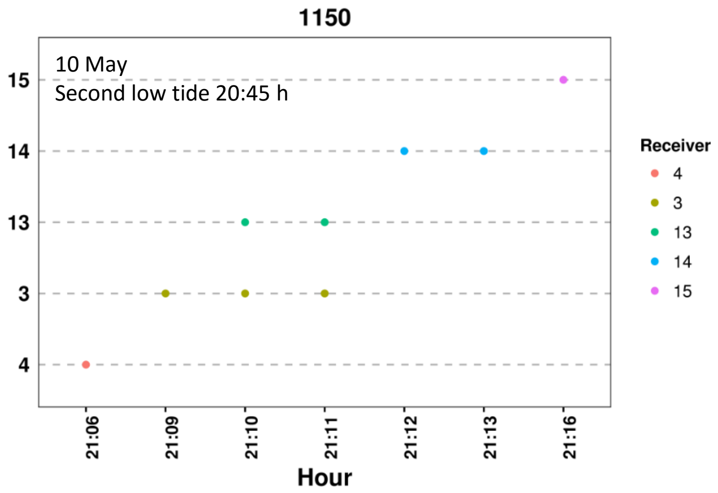

1128
5 May
First low tide 04:35 h
11
5
03:13 03:16 03:17 03:18 03:19 03:20 03:21 03:22 03:23 03:24 03:25 03:26 03:27 03:29 03:30 03:31 03:33 03:34 03:36 03:37
Hour
Receiver
5
11

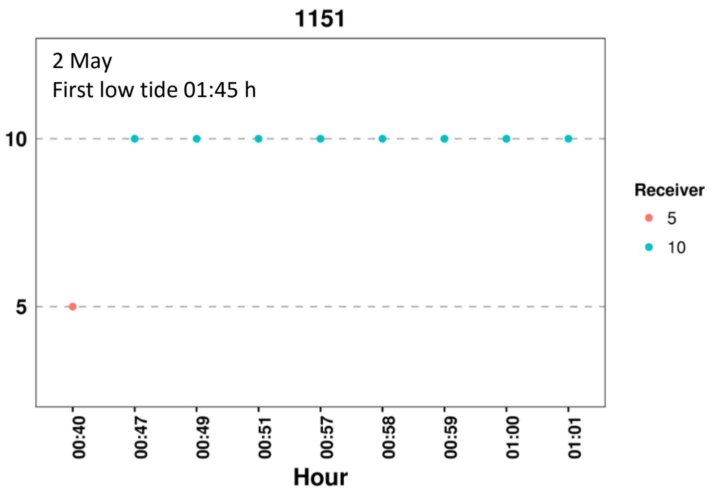

1129
11 May
Second low tide 21:30 h
8
9
7
10
5
6
20:20 20:22 20:24 20:25 20:26 20:28 20:29 20:30 20:31 20:32 20:33 20:34 20:35 20:36 20:37 20:38 20:39 20:41 20:42 20:43 20:45 20:46 20:47 20:48 20:49 20:50 20:51 20:52 20:53 20:54 20:55 20:57
Hour
Receiver
6
5
10
7
9
8

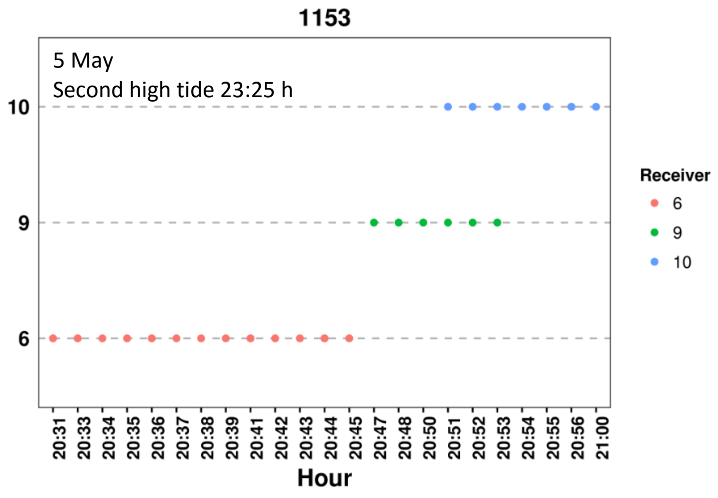

1130
1 May
First low tide 00:20 h
0
00:00
Hour
Receiver
0

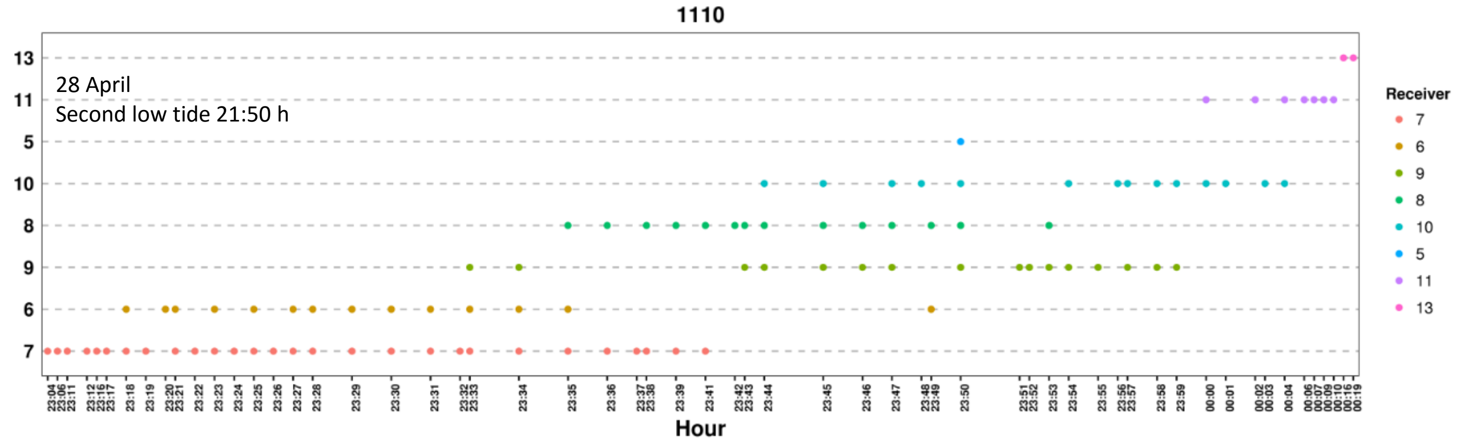

1147
2 May
First high tide 07:50 h
5
11
10
9
8
6
7
03:49 03:51 03:52 03:54 03:55 03:58 03:59 04:00 04:01 04:03 04:06 04:12 04:13 04:14 04:15 04:17 04:18 04:19 04:20 04:22 04:23 04:25 04:26 04:27 04:28 04:30 04:31 04:32 04:33 04:34 04:35 04:39 04:40 04:41 04:42 04:48 04:49 04:50 04:51 04:52
Hour
Receiver
7
6
8
9
10
11
5

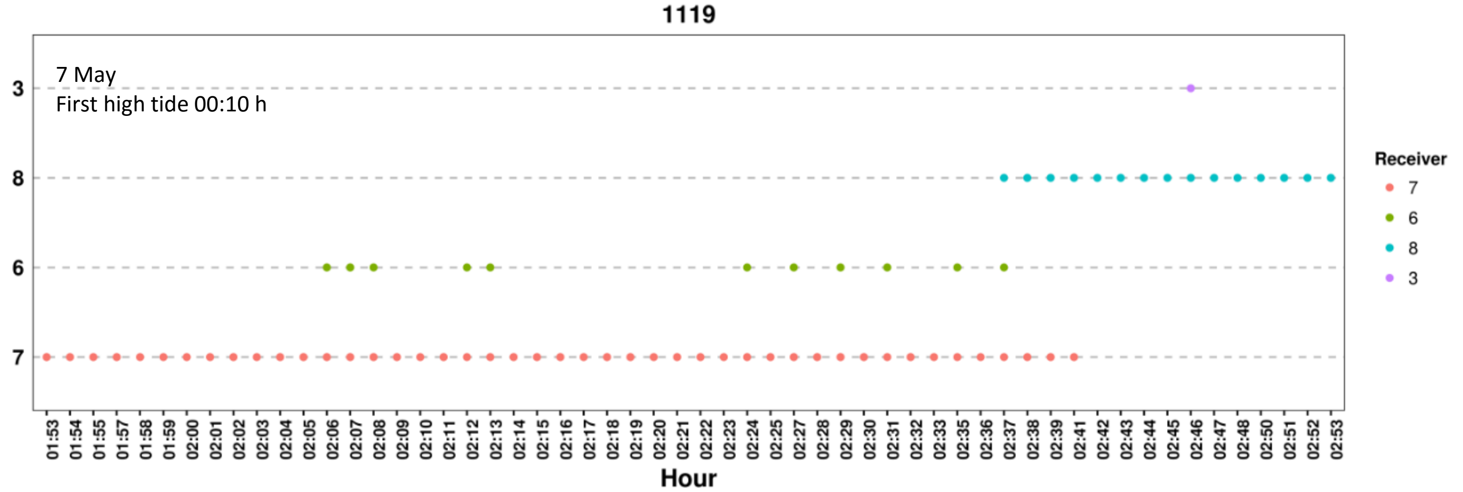

1148
6 May
Second low tide 17:45 h
4
11
6
5
22:04 22:05 22:07 22:08 22:10 22:11 22:12 22:13 22:14 22:15 22:16 22:17 22:18 22:20 22:21 22:23 22:24 22:25 22:27 22:28
Hour
Receiver
5
6
11
4

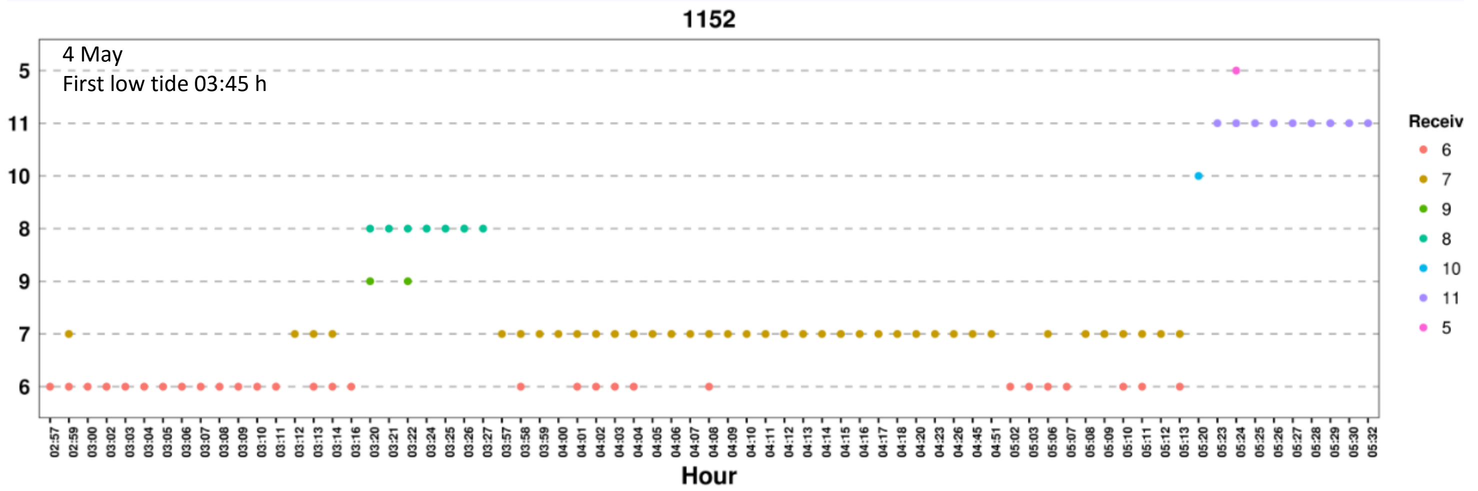

1150
10 May
Second low tide 20:45 h
15
14
13
3
4
21:06 21:09 21:10 21:11 21:12 21:13 21:16
Hour
Receiver
4
3
13
14
15


1151
2 May
First low tide 01:45 h
10
5
00:40 00:47 00:49 00:51 00:57 00:58 00:59 01:00 01:01
Hour
Receiver
5
10

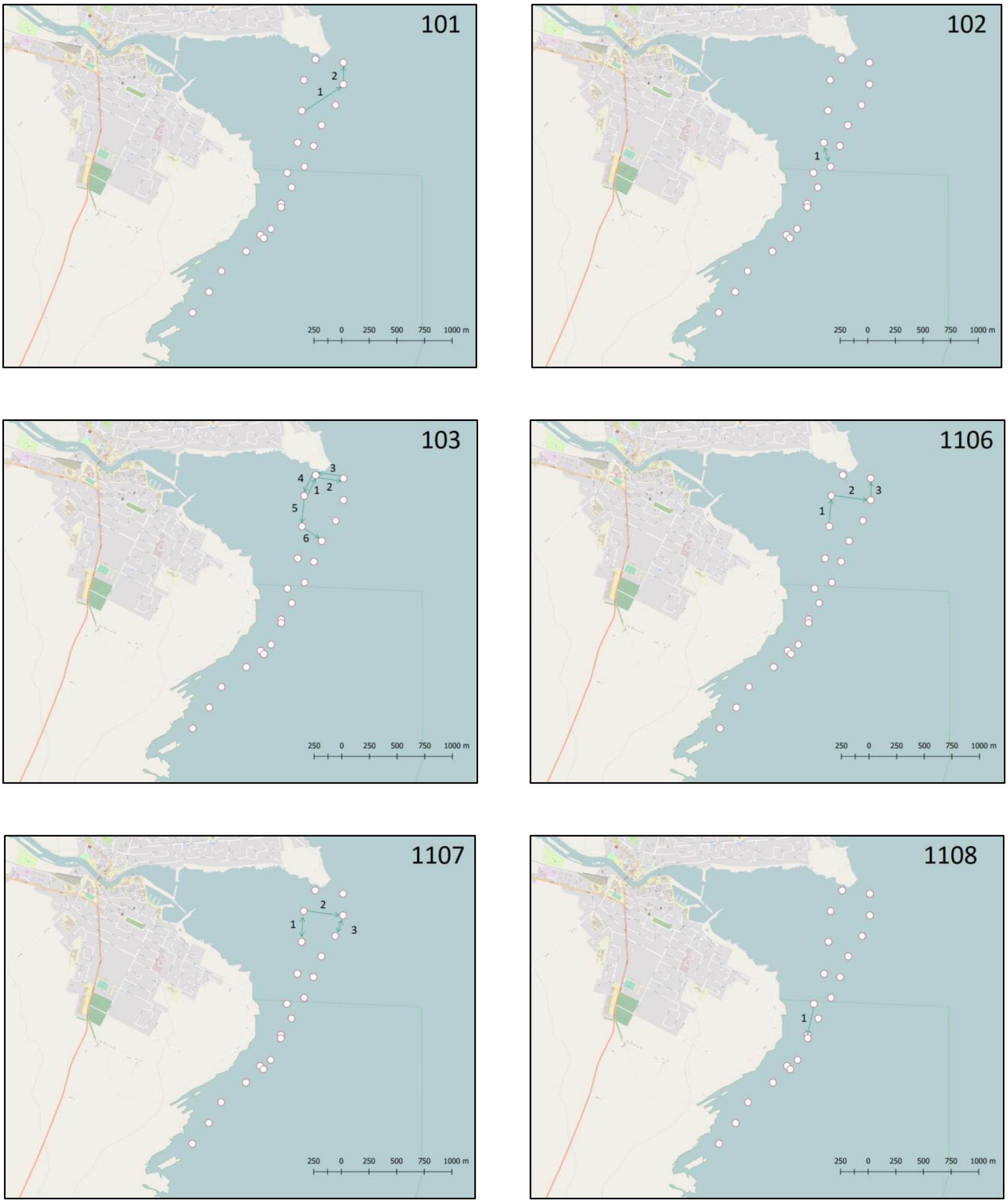

1153
5 May
Second high tide 23:25 h
10
9
6
20:31 20:33 20:34 20:35 20:36 20:37 20:38 20:39 20:41 20:42 20:43 20:44 20:45 20:47 20:48 20:50 20:51 20:52 20:53 20:54 20:55 20:56 21:00
Hour
Receiver
6
9
10

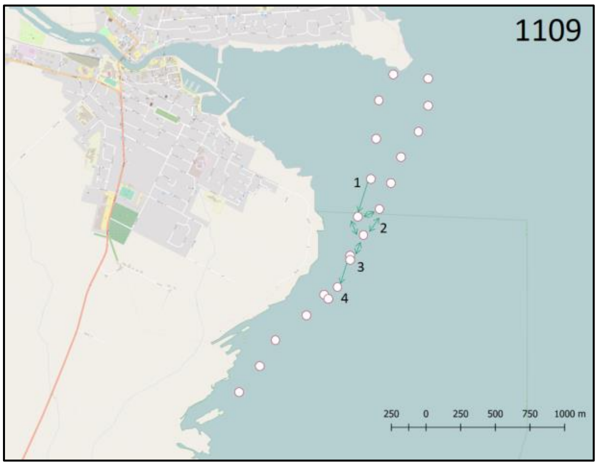

1110
28 April
Second low tide 21:50 h
13
11
5
10
8
9
6
7
Hour
Receiver
7
6
9
8
10
5
11
13

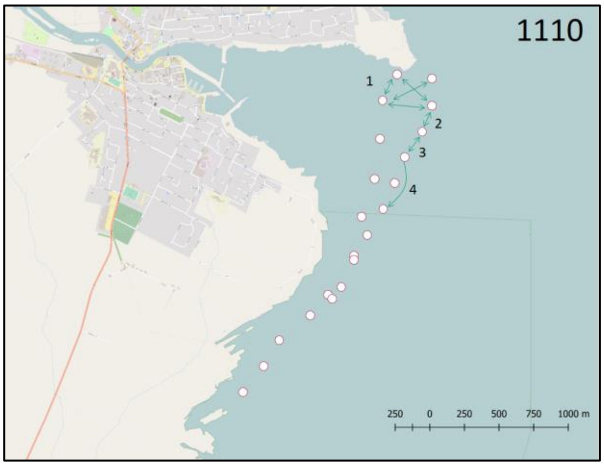

1119
7 May
First high tide 00:10 h
3
8
6
7
Hour
Receiver
7
6
8
3


1152
4 May
First low tide 03:45 h
5
11
10
8
9
7
6
Hour
Receiv
6
7
9
8
10
11
5

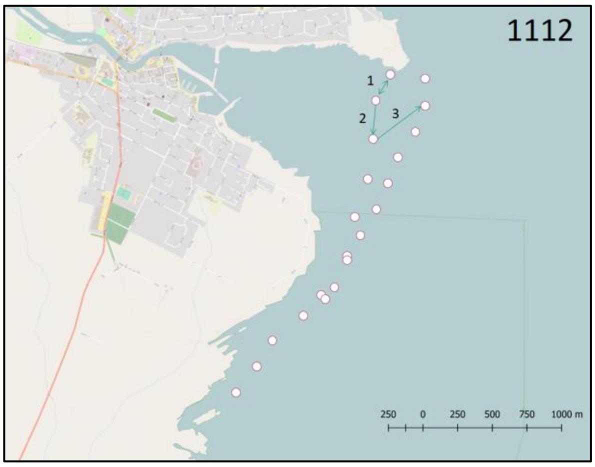
APPENDIX 1 B: INDIVIDUALS' USE OF SPACE.

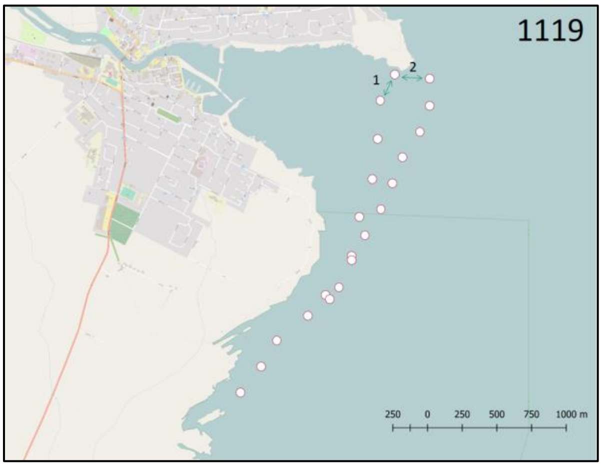


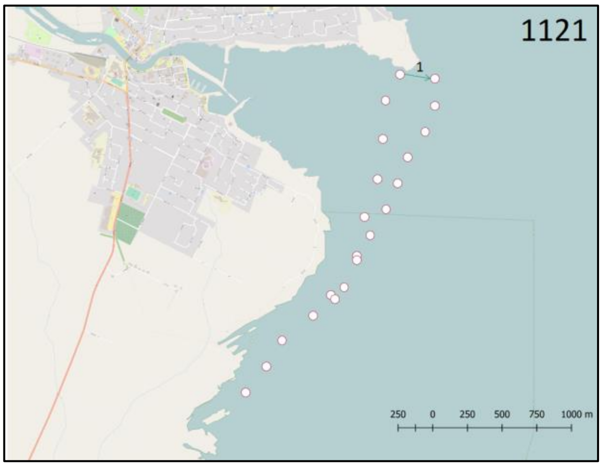

1109
1
2
3
4
250 0 250 500 750 1000 m

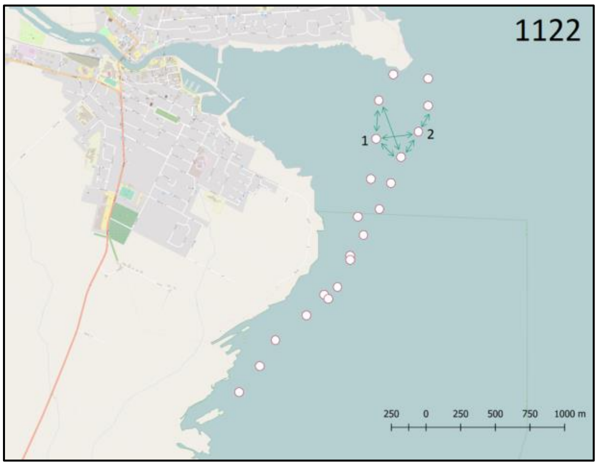

1110
1
2
3
4
250 0 250 500 750 1000 m

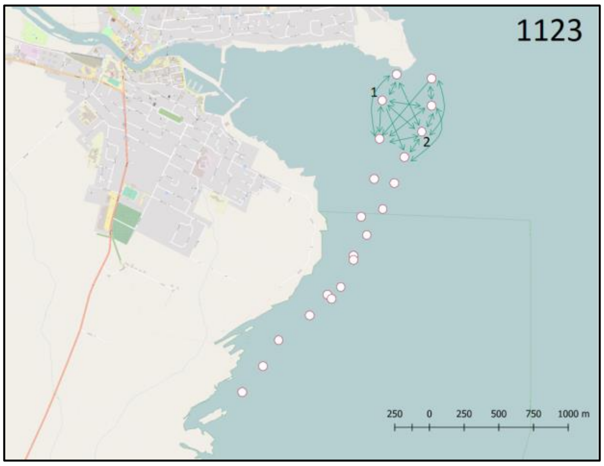

1111
1
250 0 250 500 750 1000 m

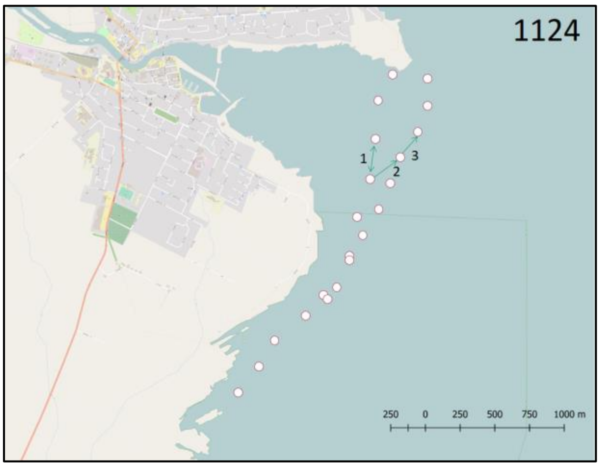

1112
1
2
3
250 0 250 500 750 1000 m

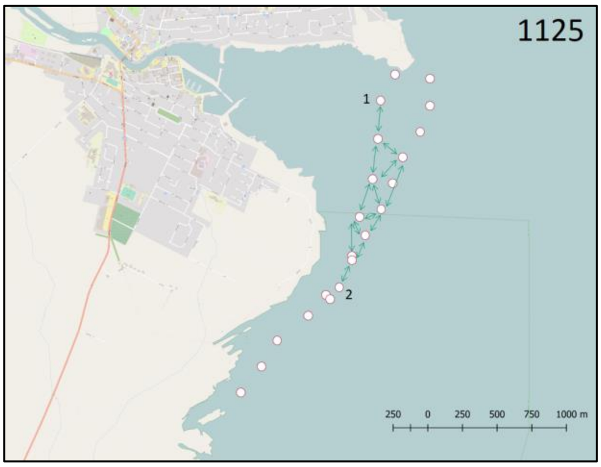

1119
1
2
250 0 250 500 750 1000 m

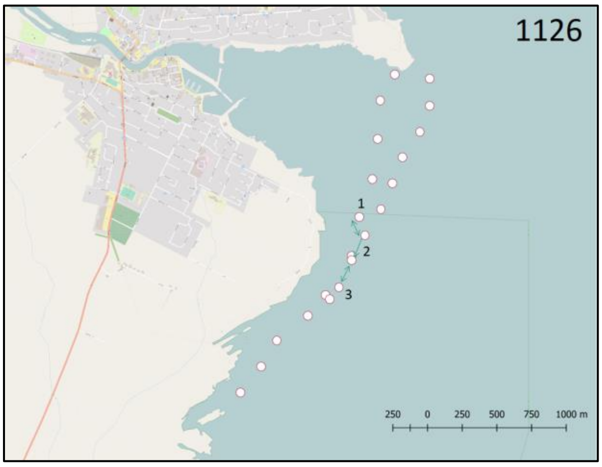

1121
1
250 0 250 500 750 1000 m

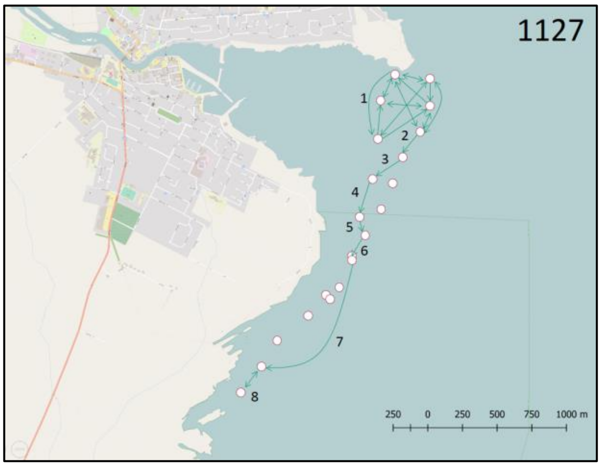






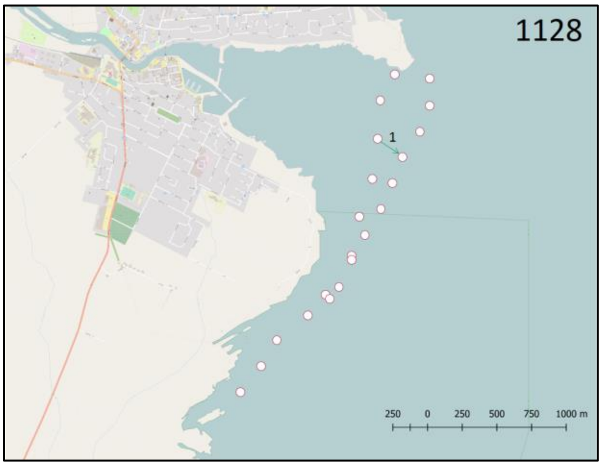


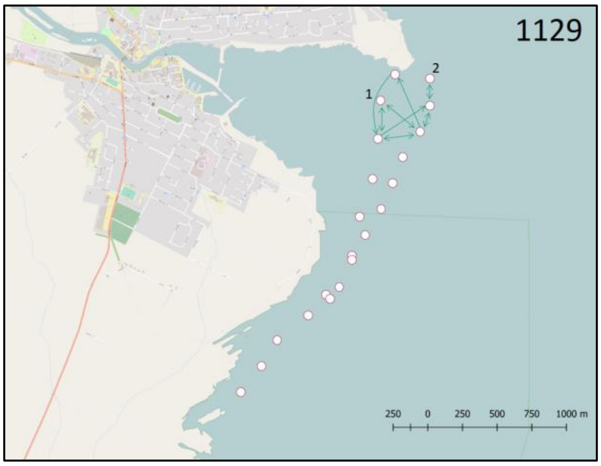


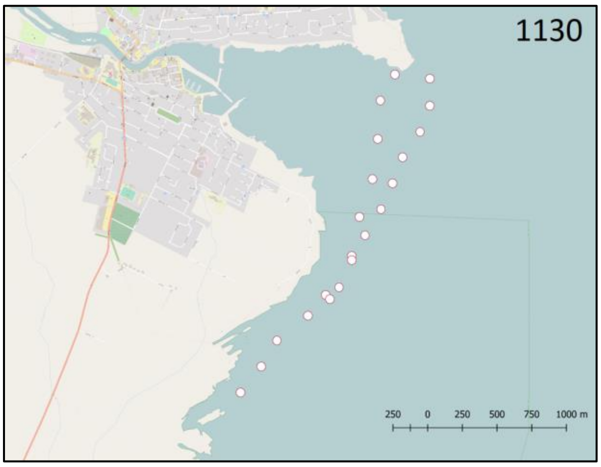


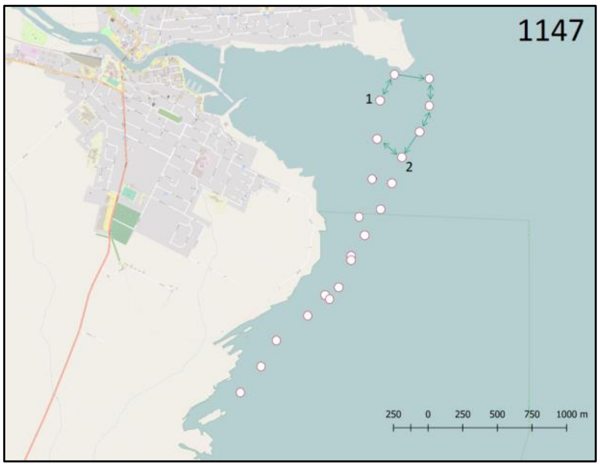
FCRT

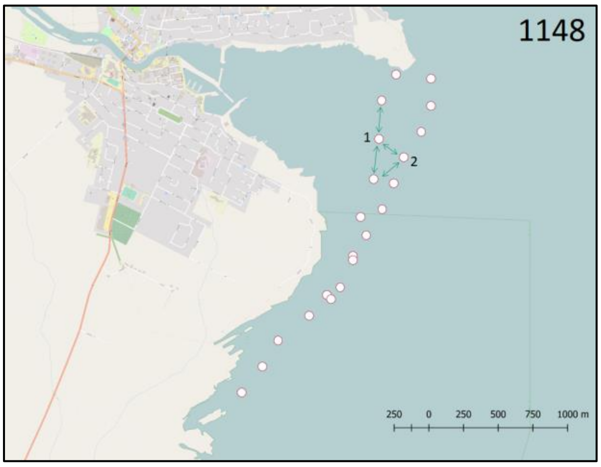
University of the Highlands and Islands
Oilthigh na Gàidhealtachd agus nan Eilean

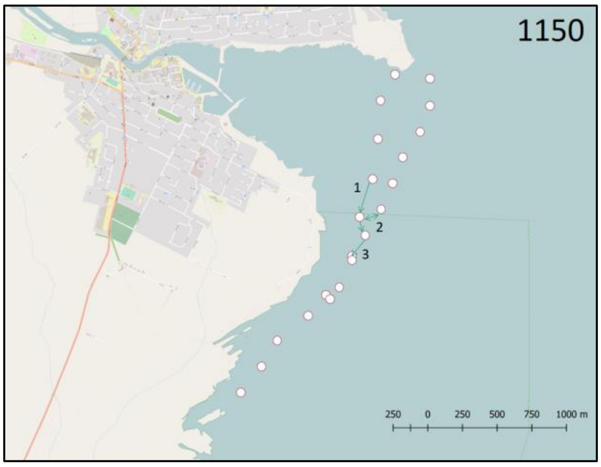

1128
1
250 0 250 500 750 1000 m

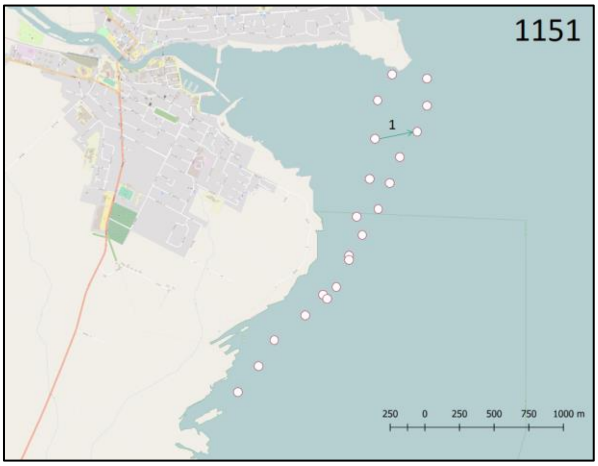

1129
1
2
250 0 250 500 750 1000 m

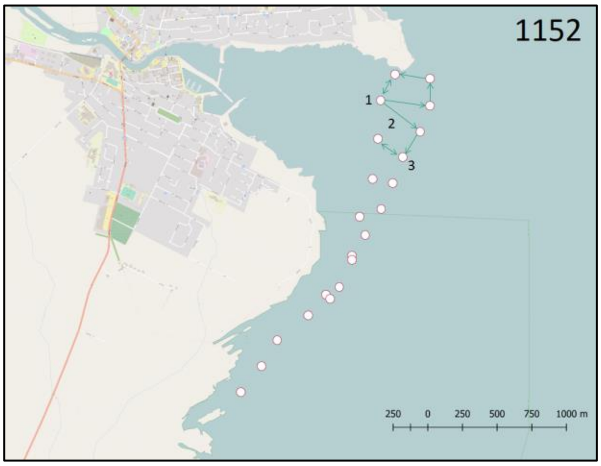

1130
250 0 250 500 750 1000 m

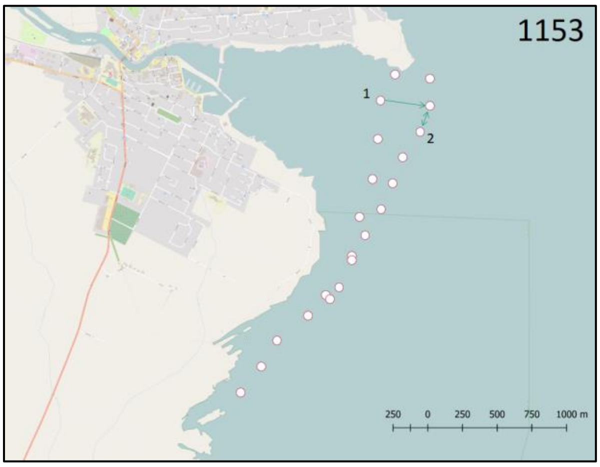

1147
1
2
250 0 250 500 750 1000 m


1148
1
2
250 0 250 500 750 1000 m


1150
1
2
3
250 0 250 500 750 1000 m


1151
1
250 0 250 500 750 1000 m


1152
1
2
3
250 0 250 500 750 1000 m


1153
1
2
250 0 250 500 750 1000 m