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Marine Scotland Science
Freshwater Laboratory,
Faskally,
Pitlochry,
PH16 5LB.

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Depth use and movements of homing Atlantic salmon (*Salmo salar*) in Scottish coastal waters in relation to marine renewable energy development

Jason D. Godfrey, David C. Stewart, Stuart J. Middlemas & John D. Armstrong

Marine Scotland Science, Freshwater Laboratory, Faskally, Pitlochry, PH16 5LB, UK

Executive Summary

The depth use of homing Atlantic salmon caught and released on the north coast of Scotland was recorded over 1-20 days using pop-up satellite telemetry during the summers of 2013 and 2014. Data were returned from 47 out of 50 salmon tagged in 2013 and 80 out of 85 salmon tagged in 2014. Overall the fish were predominantly surface-orientated, spending a median of 80.4% of their time in the upper 5m of the water column. There was, however, significant variation between individuals: the time spent in the upper 5 m ranged from 8-99%, while individual median swimming depths ranged from 0-28.5 m. All fish undertook dives to below 10m of depth and the mean maximum depth was 67 m (range 13-256 m), of similar magnitude to the likely available water depth. Pop-up locations were obtained for 122 tags and indicated that salmon swam in all possible directions from the release point.

Introduction

Scottish Government aims to generate the equivalent of 100% of its electricity requirements from renewable sources by 2020 (Anon 2011). Marine Renewable Energy (MRE) may be developed from wave, wind, and tidal currents, and concerns have been raised over the potential interaction between MRE installations and marine animals, including migratory fish such as Atlantic salmon (*Salmo salar*). The salmon is of great cultural and conservation importance across north and west Europe (Hindar *et al*., 2010) and forms an important component of the Scottish rural economy (Radford *et al*., 2004). Salmon stocks have been in decline over much of their range, partly due to reduced marine survival (ICES, 2014).

Malcolm *et al*. (2010) reviewed the potential for interaction between MRE development and Atlantic salmon in Scotland, and identified a number of potential interactions and knowledge gaps. Deleterious consequences could result directly from collisions with devices, at close range via the influence of electromagnetic fields (EMFs) associated with cabling for the devices, and over wide areas via noise generated during construction and operation (Dolman & Simmonds, 2010; Slabbekoorn *et al*., 2010; Gill *et al*., 2012). To assess the potential for these impacts it is, in the first instance, necessary to know the spatial overlap between salmon and the proposed devices. The lack of information on the swimming depths of homing salmon in Scottish coastal waters is therefore an important knowledge gap in assessing the potential impact of renewables (Malcolm *et al.,* 2010). Godfrey *et al.* (2014) presented information on the depth use of salmon tagged on the north coast of Scotland in 2013. This study was continued in 2014 and the results of both years are described in this report.

In Scotland, salmon spawn in rivers, where they generally grow for 1-3 years before smolting and migrating to the sea. They then typically spend a further 1-3 years feeding at sea before returning, most commonly to their natal river, to breed. Many salmon die after spawning, but some survive and return to sea as kelts, where they may regain condition and again return to rivers to spawn (Mills, 1989). Thus salmon are potentially vulnerable to MRE developments in coastal waters as post-smolts, post-kelts, and as maturing adults returning to home rivers to breed.

Studies of swimming behaviour have been conducted on post-smolts (Økland *et al.,* 2006; Davidsen *et al*., 2008; Hedger *et al*., 2008; Dempson *et al*., 2011; Thorstad *et al*., 2012), post-kelts (Hedger *et al*., 2009; Halttunen *et al*., 2009; Reddin *et al*., 2011; Lacroix, 2013) and to a lesser extent maiden salmon (those returning to rivers for the first time to spawn) (Sturlaugsson, 1995; Holm *et al.,* 2006; Davidsen *et al*., 2013). The depth use of maiden salmon is of particular interest as they comprise the majority of the breeding population (Shearer, 1992). However, studies examining the swimming depths of maiden salmon have sometimes been constrained by topography, and sample sizes have generally been small. Godfrey *et al*. (2014), using pop up satellite tags (PSATs), recorded the swimming depth, over 1-10 days, of 47 salmon returning to northern Scottish coastal waters, of which 45 were maiden fish. Results indicated that these individuals were highly surface-orientated although they also appeared to use all the available water column at times.

In addition to swimming depths, information is required on the migration routes of returning salmon in Scottish waters. Information was limited to the recovery and reporting of conventional tags at coastal netting stations (Shearer, 1992; Malcolm *et al*., 2010), until Godfrey *et al*. (2014) reported the locations of 34 salmon, via pop-up satellite telemetry, 1-10 days after initial capture on Scotland's north coast. The salmon tracked by Godfrey *et al*. (2014) were shown to travel up to 56 km per day, and their migrations were not strictly linked to the coast, with pop-up locations up to 100 km offshore.

The present study expands on the work of Godfrey *et al.* (2014), focussing on the area around the Pentland Firth, between Orkney and the Scottish mainland, which has been identified both as a region for the development of tidal energy (Shields *et al*., 2009) and as an area which a large proportion of homing Scottish salmon may traverse (Malcolm *et al*., 2010). Here we bring together both the initial results of Godfrey *et al.* (2014) from the summer of 2013 and the additional data obtained during the summer of 2014, providing detailed information on the swimming depths and pop-up locations of salmon in open coastal water predominantly on their first homing migration.

Methods

The methods used in the study are presented in Godfrey *et al*. (2014) and are summarised here, highlighting differences between the years. During the months of May and June, 2013 and May, June and July, 2014, salmon were caught in bag nets at Armadale (Lat. 58.556; Long. -4.093), near Bettyhill, on the north coast of Scotland. To minimise the impact of capture or tagging on subsequent behaviour, only fish in good condition and those >70 cm in length were retained: the mean length of fish used in the study was 78.2 cm in 2013 and 77.1 cm in 2014. Scale reading indicated that all the tagged fish were multi-sea-winter (predominantly two-sea winter (2SW)) maiden salmon, with the exception of four fish (three from 2013) that were identified as repeat spawners.

In 2013, a total of 50 PSATs, comprising 30 High Rate X-Tags (Microwave Telemetry, Inc.) and 20 MiniPATs (Wildlife Computers, Inc.) were fitted, and programmed to release from fish after 1 to 10 days of data collection. The MiniPAT release mechanism, though designed for use in sea water, was found to be functional in freshwater during the first year of the study. Thus longer deployments were possible in 2014, when a further 85 PSATS (all MiniPATs) were deployed (22 x 5 days, 21 x 10 days, 21 x 15 days and 21 x

20 days), without the risk of fish which entered rivers being lost from the sample. Fish handling and release protocols followed those described by Godfrey *et al.* (2014), except that the tag attachment system in 2014 was a modified version of that described by Lacroix (2013) because of the longer deployment periods used.

PSATs record and archive data during deployment, relaying the stored information, together with location, to the ARGOS satellite network (www.argos-system.org/) when the pop-up mechanism is activated. The tags were programmed to sample depth and temperature at intervals of 75 s (MiniPATs) and 10-95 s (X-Tags) depending on deployment duration. After release the tags had approximately 14 days of battery life to communicate the stored data. The extent of data recovered from tags via satellite is influenced by the sky view of the tag and the alignment of the aerial during the transmission phase, and may range from 0-100% depending on where the tag pops up. If tags can be physically recovered then it is possible for the complete dataset to be extracted from X-Tags, while recovered MiniPATs additionally allow the user to access archived data at very high resolution (1 or 3 s intervals). To date, 11 and 34 tags have been recovered from the 2013 and 2014 field seasons respectively.

Swimming depths are reported for salmon from the moment of release until the moment of tag pop-up, unless river entry (n=26) or predation events (n=4) were detected from the temperature data, or unless tags were released from fish early (Godfrey *et al.*, 2014). In these cases the tail of the depth records was trimmed so that the resulting data set represents the behaviour of free-swimming salmon at sea. Depth data were analysed as cumulative frequency, using the full resolution of the tags (0.5 m for MiniPATs, 1.35 m for X-Tags). In each year individuals with fewer than 200 depth records were excluded from the analysis (Godfrey *et al.*, 2014).

The error associated with pop-up position was estimated based on the measured drift of tags immediately following first location by the satellite network, for the time period equivalent to the elapsed time between tag detachment from the fish and first location by the satellite network (Godfrey *et al.*, 2014).

Results

Overall, 127 of the 135 tags deployed provided depth data (47 in 2013, 80 in 2014). However, tags with fewer than 200 depth records were excluded from subsequent analyses, leaving a total of 117 salmon with reliable depth records (43 in 2013, 74 in 2014).

All salmon performed some diving activity. The mean maximum dive depth was 66.7 m (range 13.4–256 m). The cumulative depth distributions in 2013 and 2014 are shown in Figure 1 and were similar between years. Salmon were predominantly surface orientated. The median proportion of time spent in the upper 5 m was 80.4%, although there was considerable variation among individuals (range 8-99%, inter-quartile range (IQR) 67.5-88.5%). In contrast, the median time spent at depths >20 m was only 6.7% (range 0-62 %, IQR 3.0-16.4%). Summary statistics of the proportion of time spent in 5m depth classes are provided in the appendix. Overall 122 of 135 tags provided a pop-up location (45 in 2013 and 77 in 2014), with 26 of these from rivers (6 in 2013, 20 in 2014). A total of 50 marine locations had an error <25km (28 in 2013 and 22 in 2014; Figure 2). The mean error associated with the marine locations was 7.6 km (7.2 km in 2013 and 8.1 km in 2014). The marine pop-up locations indicate movements in all possible directions from the release point, and up to 190 km off shore, though with a predominance of coastal locations.

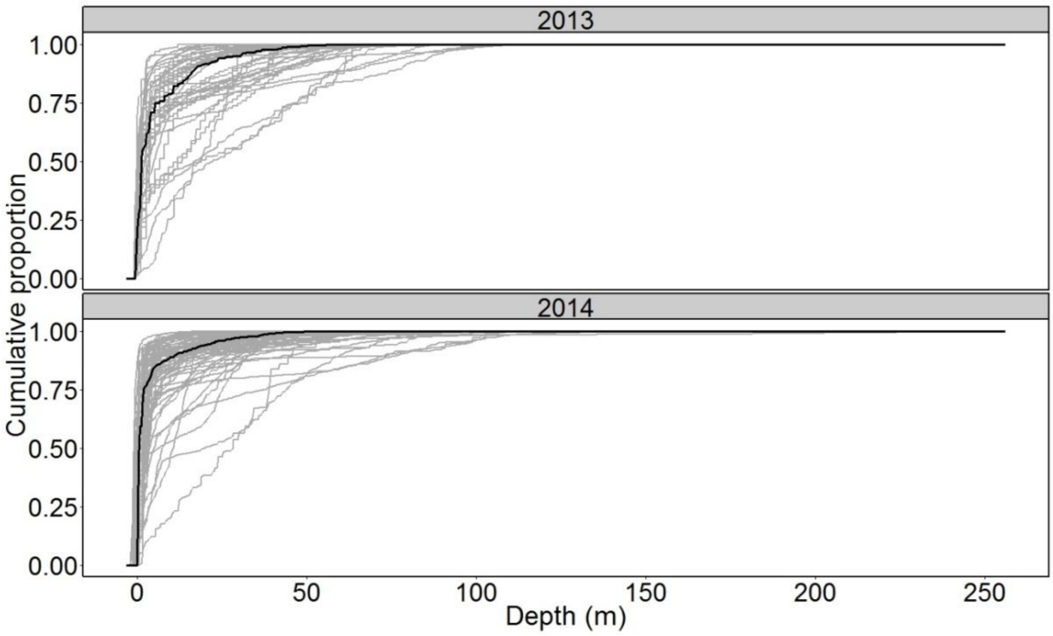

Figure 1 Cumulative frequency of swimming depths for Atlantic salmon in Scottish coastal waters in summer 2013 (upper panel, n=43) and 2014 (lower panel, n=74). Thick line indicates median, thin lines represent individuals.

Five salmon were located within 25 km of the release site after 5-10 at sea (Figure 2), while one individual (identified by an individually numbered Carlin tag that remained attached to the fish post pop-up) was re-caught at the Armadale netting site 26 days after being initially tagged there, having travelled 90km to the coast of Orkney in the meantime, implying that at least some of the fish sampled made somewhat peripatetic movements. Meanwhile some other salmon reached distant rivers in a relatively short period of time, implying more directed migration. Twenty six tags were released in rivers of the north and east coasts of Scotland: there were no pop-up locations in west coast rivers (Figure 2). A higher proportion of tags in 2014 entered rivers, reflecting the longer programmed deployment periods: 10% of fish with ≤ 5 day deployments and 33% of fish with 15-20 day deployments were known to enter rivers.

Discussion

The results presented here confirm and build on the findings of Godfrey *et al*. (2014), giving a more detailed picture of the swimming depths of Atlantic salmon principally on their first return migration to Scottish coastal waters. The sample is limited to larger (mainly 2SW) salmon, and the swimming behaviour of grilse (one-sea-winter salmon) remains as yet unexplored. Data from Scottish coastal waters can be compared with the reported depth use by adult salmon in other situations. The proportion of time spent in the upper 5 m of the water column by salmon tagged as kelts was 60-90% on the high seas (Reddin *et al*., 2011; Lacroix, 2013), and 94-99% when migrating away from rivers in fjords and estuaries (Halttunen *et al*., 2009; Hedger *et al*., 2009). Salmon migrating home through a fjord were also surface-orientated (mean swimming depths 0.5–2.5 m; Davidsen *et al*., 2013). Thus, the general pattern of depth use by salmon returning through Scotland’s northern coastal waters (median 80.4% of time at 0-5 m depths, mean 75.0%) is more akin to that of kelts that had returned to sea to feed, and less surface-orientated than that of homing salmon migrating through fjordic or estuarine environments towards rivers. The range of maximum diving depths (13–256 m) of adult salmon in the coastal waters around northern Scotland was similar to the depths available in the study area (the depth of water column at the pop-off locations ranged from 0.5–176 m), while dives of over 600 m by salmon have been recorded in the Labrador Sea (Lacroix, 2013). These data are therefore consistent with most salmon using the full extent of the available water column. Thus salmon on their homeward migration in the coastal zone were predominantly surfacedwelling, but most passed regularly through the water column, and some spent extensive time at depth.

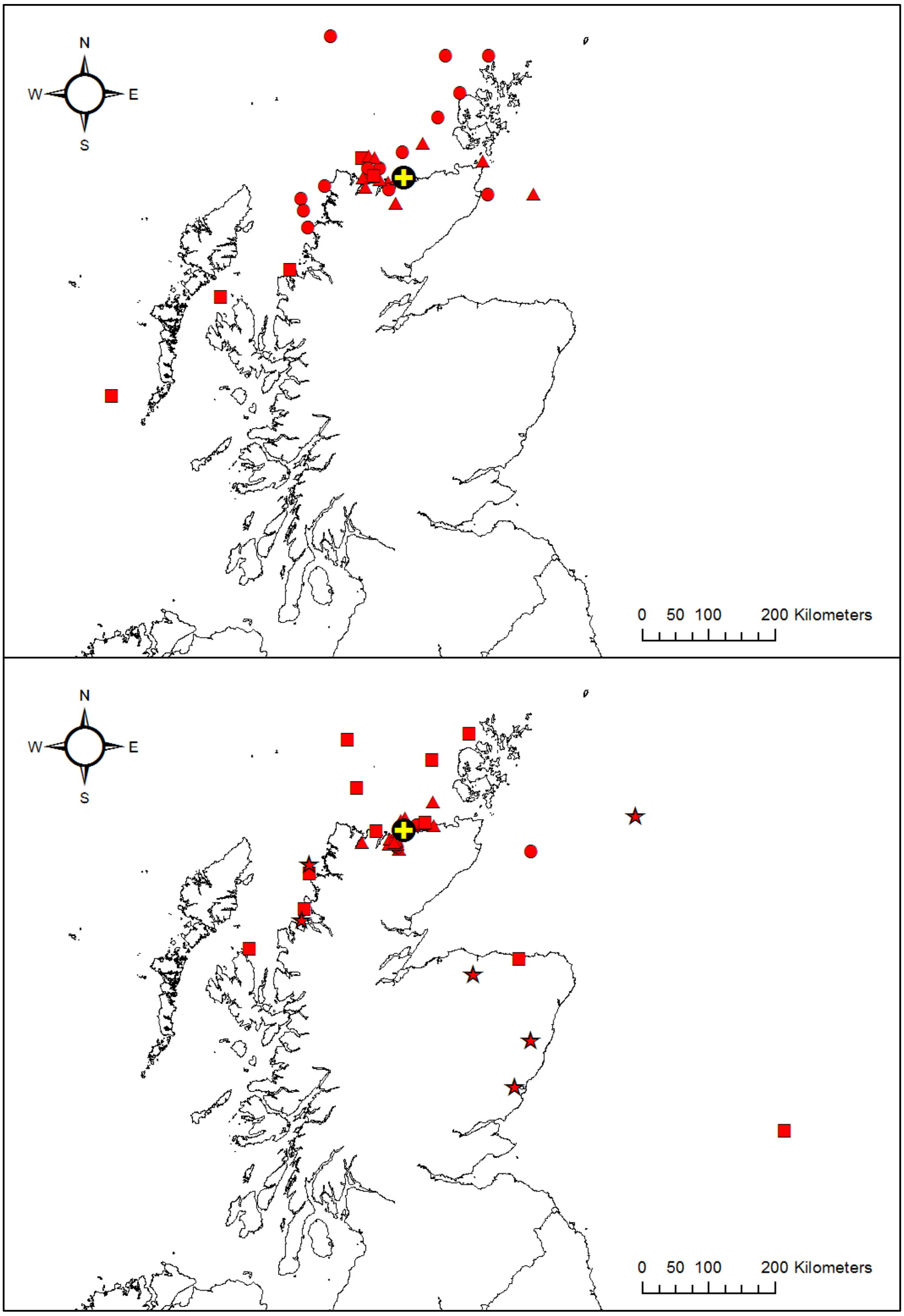

Figure 2 Map of Scotland showing satellite tag pop-up locations for salmon tagged and released at Armadale (shown by a cross) in 2013 (upper) and 2014 (lower). Time at sea varied: triangles (1-2 d); circles (2-5 d); squares (5-10 d); and stars (10-20 d). Locations were excluded if associated with an error of >25 km (n = 46) or if tags had been ingested by predators (n = 4).

There was considerable inter-individual variation in swimming depths in this study: for example, the individual proportion of time spent in the upper 5 m ranged from 8-99%. Sturlaugsson (1995) has previously noted different patterns of diving behaviour in Atlantic salmon, and Godfrey *et al*. (2014) identified two clusters of differing swimming depth behaviour in the 2013 data, but the reasons for differing uses of the water column are unclear. Diving behaviours may be associated with predator avoidance (Hastie *et al*., 2006, Lacroix, 2014), behavioural thermoregulation (Tanaka *et al*., 2000; Reddin *et al*., 2004), feeding (Reddin *et al*., 2011; Lacroix, 2013) and sampling the water column in search of olfactory cues from the home river (Westerberg, 1982; Døving *et al*., 1985). The behaviour of fish is likely to depend on the relative importance of different processes at any given time, which may vary with the geographic location (Lacroix, 2013) and the phase of migration (Middlemas *et al*., 2009) of the fish.

The swimming depths of salmon reported here have some general implications in relation to the development of MRE, while their similarity between years raises the confidence that these data can be used to extrapolate to future scenarios. Salmon used the entire water column and so could come into contact with any installed devices. The large majority of time was spent in the upper water column <20 m depth, but some individuals were more likely to use deep and mid-water zones. The preferential use of near-surface waters (median 80.4% of time at <5 m) implies that homing salmon are particularly likely to interact with surface-oriented installations such as those exploiting wave energy. With specific reference to the MRE development in the Pentland Firth region, the turbines currently licensed for this area have a minimum clearance of 8 m between the turbine blades and the water surface (Anon., 2012). All the tagged salmon in our study were recorded at depths below 8 m and therefore had the potential to interact with the proposed turbines, should they pass through the development area (detailed depth use data is shown in Appendix 1). Individuals spent a median of 15.2% of their time below 8 m depth (IQR 8.5-26.6%). However, the scatter in pop-up locations (Figure 2) suggests that salmon may not have well-defined routes in the region. Furthermore, while some salmon in the sample appeared to undertake direct migrations, the movements of others were more peripatetic, implying the potential for these latter individuals to traverse individual development sites on more than one occasion. However, it is not currently possible to predict what proportion of the salmon in areas such as the Pentland Firth pass across specific zones.

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Appendix 1

Summary statistics for percent of detections per fish within various depth classes by salmon (n=117) tagged on the north coast of Scotland, in the summers of 2013-14

	Time (%)						
Depth class (m)	Median	Lower quartile	Upper quartile	Min	Max	Mean	S.D.
0-5	80.447	67.521	88.455	7.943	98.242	75.012	18.979
5-10	4.824	3.118	9.273	0.518	25.362	6.889	5.517
10-15	2.556	1.511	5.218	0.193	30.331	3.895	3.915
15-20	1.837	1.118	3.286	0.000	18.112	2.711	2.865
20-25	1.458	0.746	2.881	0.000	13.426	2.146	2.322
25-30	1.125	0.446	2.268	0.000	19.145	2.021	2.932
30-35	0.813	0.335	2.064	0.000	10.803	1.692	2.116
35-40	0.554	0.111	1.457	0.000	16.898	1.333	2.265
40-45	0.313	0.035	1.071	0.000	7.294	0.958	1.529
45-50	0.162	0.000	0.856	0.000	5.629	0.636	1.064
50-55	0.062	0.000	0.637	0.000	8.286	0.608	1.267
55-60	0.032	0.000	0.488	0.000	6.070	0.510	1.019
60-65	0.000	0.000	0.324	0.000	12.443	0.420	1.311
65-70	0.000	0.000	0.109	0.000	2.533	0.230	0.552
70-75	0.000	0.000	0.078	0.000	2.788	0.192	0.486
75-80	0.000	0.000	0.031	0.000	3.180	0.173	0.530
80-85	0.000	0.000	0.004	0.000	2.245	0.130	0.404
85-90	0.000	0.000	0.000	0.000	2.813	0.111	0.391
90-95	0.000	0.000	0.000	0.000	2.240	0.085	0.312
95-100	0.000	0.000	0.000	0.000	2.292	0.088	0.347
100-105	0.000	0.000	0.000	0.000	1.852	0.059	0.267
105-110	0.000	0.000	0.000	0.000	1.224	0.040	0.168
110-115	0.000	0.000	0.000	0.000	0.394	0.011	0.056
115-120	0.000	0.000	0.000	0.000	0.843	0.017	0.102
120-125	0.000	0.000	0.000	0.000	0.436	0.007	0.048
125-130	0.000	0.000	0.000	0.000	0.496	0.010	0.056
130-135	0.000	0.000	0.000	0.000	0.165	0.001	0.015
135-140	0.000	0.000	0.000	0.000	0.111	0.001	0.011
140-145	0.000	0.000	0.000	0.000	0.120	0.001	0.011
145-150	0.000	0.000	0.000	0.000	0.081	0.001	0.008
150-155	0.000	0.000	0.000	0.000	0.033	0.000	0.003
155-160	0.000	0.000	0.000	0.000	0.035	0.000	0.003
160-165	0.000	0.000	0.000	0.000	0.000	0.000	0.000
165-170	0.000	0.000	0.000	0.000	0.000	0.000	0.000
170-175	0.000	0.000	0.000	0.000	0.000	0.000	0.000
175-180	0.000	0.000	0.000	0.000	0.000	0.000	0.000
180-185	0.000	0.000	0.000	0.000	0.000	0.000	0.000
185-190	0.000	0.000	0.000	0.000	0.000	0.000	0.000
190-195	0.000	0.000	0.000	0.000	0.000	0.000	0.000
195-200	0.000	0.000	0.000	0.000	0.000	0.000	0.000
200-205	0.000	0.000	0.000	0.000	0.000	0.000	0.000
205-210	0.000	0.000	0.000	0.000	0.000	0.000	0.000
210-215	0.000	0.000	0.000	0.000	0.000	0.000	0.000
215-220	0.000	0.000	0.000	0.000	0.000	0.000	0.000
220-225	0.000	0.000	0.000	0.000	1.040	0.009	0.096
225-230	0.000	0.000	0.000	0.000	0.000	0.000	0.000
230-235	0.000	0.000	0.000	0.000	0.000	0.000	0.000
235-240	0.000	0.000	0.000	0.000	0.000	0.000	0.000
240-245	0.000	0.000	0.000	0.000	0.000	0.000	0.000
245-250	0.000	0.000	0.000	0.000	0.000	0.000	0.000
250-255	0.000	0.000	0.000	0.000	0.000	0.000	0.000
255-260	0.000	0.000	0.000	0.000	0.312	0.003	0.029

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The Scottish Government
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