Received: 2 November 2016 | Revised: 29 March 2017 | Accepted: 17 April 2017
DOI: 10.1002/aqc.2790

WILEY

RESEARCH ARTICLE

Harbour seals (*Phoca vitulina*) around an operational tidal turbine in Strangford Narrows: No barrier effect but small changes in transit behaviour

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Funding information
Natural Environment Research Council, Grant/Award Number: 406003863(MREKEP)

Abstract

1. Data were obtained from 32 electronic tags that were glued to the fur of harbour seals (*Phoca vitulina*) in and around Strangford Lough, Northern Ireland, during the environmental monitoring of the SeaGen tidal turbine.
2. This study provides the first detailed information on the behaviour of marine mammals close to a commercial-scale tidal energy device. The turbine did not prevent transit of the animals through the channel and therefore did not result in a 'barrier' effect.
3. However, the animals' behaviour did change when the turbine was operating, demonstrating the importance of allowing for behavioural responses when estimating collision risks associated with tidal turbines.
4. Tagged animals passed the location of the device more frequently during slack water than when the current was running. In 2010 the frequency of transits by tagged seals reduced by 20% (95% CI: 10–50%) when the turbine was on, relative to when it was off. This effect was stronger when considering daylight hours only with a reduction of transit rate of 57% (95% CI: 25–64%). Seals tagged during the operational period transited approximately 250 m either side of the turbine suggesting some degree of local avoidance compared with the pre-installation results.
5. The results presented here have implications for monitoring and managing the potential interactions between tidal turbines and marine wildlife. Principally that the design of telemetry studies for measuring change in response to developments should seek to understand and take into account variability in seal behaviour.
6. This study only looked at the effects of a single turbine rather than an array, and mitigation limited the ability to determine close range interactions. However, the study indicates that the effect of the turbine on Strangford Lough harbour seals was minor and that collision risk was reduced by the behaviour of the seals.

KEYWORDS

behaviour, coastal, environmental impact assessment, mammals, renewable energy, tracking

1 | INTRODUCTION

Power generation from tidal flows is a predictable, and potentially substantial, source of renewable energy. The UK, and Scotland in particular, have set ambitious targets for renewable energy; it has been estimated that the UK holds 50% of European tidal energy potential. However, many areas with fast flowing tidal currents, and therefore the potential for energy generation also contain diverse and abundant marine life. Concerns about environmental impacts have been raised during the consenting processes for proposed tidal developments, and many of these have focused on the effects on marine mammals (Boehlert & Gill, 2010; Copping et al., 2016). Very little empirical information has been available to date to assess these effects.

The principal concern has been the potential for physical injury to marine animals through direct contact with moving structures or parts of the devices (Wilson, Batty, Daunt, & Carter, 2007). An important secondary issue has been how the behavioural response of marine mammals to novel devices could affect their use of areas of high tidal flow and have fitness consequences for individuals and ultimately populations. Avoidance of turbines could lead to the displacement of individuals and to long-term exclusion from important habitats. The aim of this study was to investigate whether the establishment of an operational turbine in a restricted area of high flow, would act as a barrier to the passage of harbour seals. Concerns have been raised about the potential for such changes in individual behaviour to lead to population-level consequences. While the causal linkage between such changes (e.g. transit-rate) and the long-term sustainability of a local harbour seal population is complex and not well understood, the extent to which the turbine presence and operation restricted movement of harbour seals will provide valuable information for predictions of impacts for future projects. In addition, an estimate of close range transit rate is a necessary input to predict collision rates (Scottish Natural Heritage, 2016; Wilson et al., 2007). This study aimed to provide the first empirical information on the potential effects of an operating tidal turbine on harbour seals.

Marine Current Turbines' SeaGen (www.seageneration.co.uk) was the world's first operational commercial-scale tidal turbine. It was installed as a demonstrator project near Strangford in Northern Ireland, in 2008 (Figure 1). The Strangford Narrows are approximately 8 km long and connect Strangford Lough to the Irish Sea. The turbine is located near their narrowest part, where the tidal flow is constricted and accelerated. The turbine, a horizontal axis, twin rotor 1.2 MW tidal energy converter, operated between 2008 and 2013, generating approximately 10 Gigawatt hours. Decommissioning of the structure is planned for late 2017.

The turbine sits on a 3 m diameter tubular steel pile fixed to the bed of the Strangford Narrows in approximately 26 m of water. A crossbeam carries two 16 m diameter bi-directional rotors. There is a gap of 5 m between the lowest part of the discs swept by the rotors

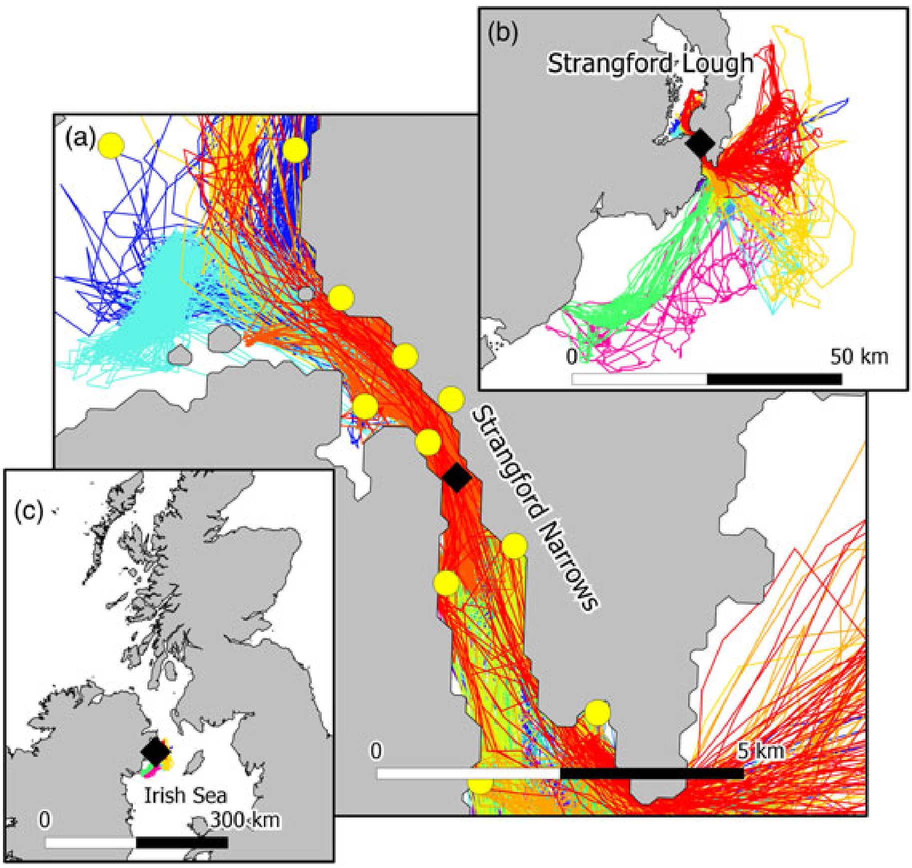

FIGURE 1 Map of the study area at three different scales. The tracks of the 11 harbour seals tagged in 2010 are colour-coded by individual. The position of the SeaGen turbine is shown by a black diamond. The locations of the major local haulout sites are shown by yellow circles. (a) Strangford Narrows in detail. (b) full extent of the tracks. (c) location of the study area

and the sea bed, and approximately 3–7 m between the top edge of the discs and the sea surface (depending on the state of the tide). The centres of each rotor are 27 m apart, meaning that from the outside edge of one rotor diameter to the outside edge of the other, measures 43 m. The rotors sweep approximately 4% of the local cross-section of the Narrows. Water flow past the device can reach up to 4 m s^{-1} and the turbine tip speed can reach 12 m s^{-1}. During operation of the turbine, a mitigation programme was in place to protect the local marine mammal populations from collision with the moving rotors. This involved shutting down the turbines if a marine mammal was detected within a mitigation zone. This zone was initially 200 m during the first few months of operation and was monitored visually by operators on the pile. Operations were restricted to daylight hours only. By the time the 2010 telemetry deployment reported here took place, this had reduced to 30 m from the turbine and was monitored remotely using a mechanical scanning sonar installed on the pile and operating at 300 kHz, allowing it to continue operating throughout the hours of darkness (Super SeaKing, Tritech, Aberdeen).

The installation of SeaGen provided an opportunity to investigate potential environmental impacts of tidal turbines and to refine methodologies for monitoring them. Owing to a high degree of uncertainty around potential impacts, an adaptive management and monitoring programme was set up to investigate and respond to the impact of the device on the marine mammal populations in the vicinity. One particular concern was for the harbour seal (*Phoca vitulina*) population associated with the Strangford Lough Special Area of Conservation (SAC). This species occurs along both coasts of the North Atlantic and North Pacific Oceans. The most recent harbour seal population estimate for Strangford Lough is currently 200 animals (Lonergan, 2013).

Baseline (pre-construction) telemetry data demonstrated that many of the seals that haul out and breed within the Strangford Lough SAC also spend time in the Irish Sea (McConnell, 2009). The Narrows is the only link between the lough and the sea, so animals have to pass within 500 m of the SeaGen turbine to make this journey. This restriction provides an ideal opportunity to examine the effects of an operational tidal turbine on harbour seal behaviour, and although the presence of the mitigation shutdown prevents any learning about near field behavioural responses this study provides insights into whether there is any support for the concern that tidal turbines may present a barrier to transiting animals.

This study uses movement data derived from three deployments of Sea Mammal Research Unit GPS Phone Tags (http://www.smru.st-andrews.ac.uk/Instrumentation/GPSPhoneTag/) on harbour seals in the vicinity of the Strangford Lough tidal turbine: before the installation of the turbine (2006), during the installation of the turbine (2008), and when the turbine was fully operational (2010). These data provide the first opportunity to investigate behavioural change in response to the construction and operation of an active underwater turbine. Importantly, during the 2010 deployment there were periods of continuous operation of the tidal device interspersed with periods when it was not operating. Such periods may have been due to feathering the blades in the water or raising the turbines out of the water. This allowed the effects of turbine operation on the behaviour of individual seals to be investigated.

2 | METHODS

2.1 | Turbine operation

Engineering tests during SeaGen's commissioning period, required that the turbine's rotors be stationary for prolonged periods. In normal operation, a tidal current of 1 m s^{-1} (the threshold for electricity generation) turned the rotor at 5 rpm, and beyond this point there was a steady increase in speed, to a maximum of 14.4 rpm. For this study, the turbine was considered to be on at times when either rotor was turning at or above 5 rpm. This threshold equates to a tip speed of 4 m s^{-1}, which is the lower end of the range of speeds considered to produce a significant risk of mortality to large cetaceans during collisions with ships (Vanderlaan & Taggart, 2007). A binary variable (turbine on or off) was defined from 5 minute averages of rotor speeds.

2.2 | Tidal flow

Tidal phase (0° high water, 90° mid ebb, 180° low water, 270° mid flood, and 360° high water) was computed from tidal heights at the secondary tidal port at Strangford (POLTIPS-3, National Oceanography Centre, UK). These data were not entirely consistent with the times at which the turbine operated (since it suggested that the rotors sometimes turned at high and low water) or the data on current speeds which were intermittently recorded using meters on the turbine. The discrepancy (up to 20 min) appears to be due to the complexity of water flow in the Narrows and, and was enough to complicate the separation of times when the turbine was halted from those when it had too little current to turn. Figure 2 plots the times of turbine operation against tidal phase at Strangford, and was used to define slack water at the turbine as times when tidal phase at Strangford itself was between 0° and 15° (high tides) or greater than 170° and less than 195° (low tides).

2.3 | Telemetry tag deployments

Thirty-six seals were fitted with electronic telemetry tags over the 3 years of deployments. One of these animals was tagged in both 2006 and 2008. The instruments were glued to the fur on the back of the animals' necks, and therefore detached during, or shortly before, the August moult. The tags collected GPS (Global Positioning System) location data and information on animals' diving and haulout behaviour, and relayed these through on-board mobile phone (GSM) modems. The three deployments collected data in 2006 (April–July, pre-installation), 2008 (March–July, during installation and commissioning) and in 2010 (April–July, operation). The seals were captured at sites in Strangford Narrows and the southern islands in Strangford Lough. Thirty-two tag deployments lasted longer than 10 days and only these were included in the analysis. All were adults, weighing between 66 and 104 kg, and a mix of males and females were caught each year (Table 1).

Tags were programmed to attempt to obtain a GPS location every 20 min (10 min in 2010) during surface intervals; 97.8% of the location estimates obtained were based on five or more satellites and had an estimated residual error less than 50 m. All other location estimates were discarded as unreliable.

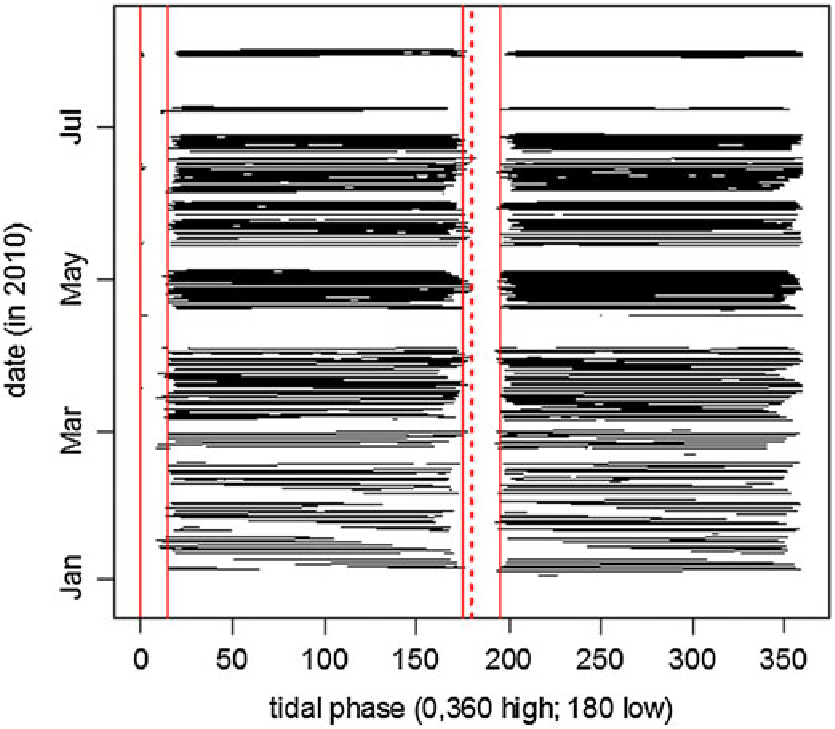

FIGURE 2 Comparison of times of operation of the turbine (defined as at least one rotor turning at 5 rpm or more) and tidal phase estimated from calculations of times of high and low tides at Strangford. Dotted lines are predicted high and low tides, solid lines define periods considered slack water in this study

The tags also recorded periods when they remained out of the water, almost all of which will have occurred when the animals were hauled out ashore. Each of these periods was stored as a 'haulout record', starting from when the conductivity sensor was continuously dry for 10 min and ending when it was continuously wet for 40 s.

2.4 | Animal tracks

The seals were assumed to travel in straight lines, and at constant speeds, between the GPS fixes. The tracks were filtered by deleting locations implying swim speeds considered implausible (more than 2.5 m s^{-1} greater than the speed of the current recorded at SeaGen at that time). This removed 1% of locations. Haulout records were then incorporated into the track data and the seals were treated as being stationary during haulouts.

2.5 | Transit definition

A line was drawn across the section of the Narrows containing SeaGen, perpendicular to the direction of the main tidal flow. Each time a seal crossed this line was considered a 'transit' past the device. The distance from the turbine and the time at which the transit took place was estimated for each transit.

2.6 | Uncertainty in transit locations and times

The track of each tagged seal's transit past the turbine was estimated by linear interpolation between the GPS fixes. This procedure introduces a degree of uncertainty in the positions and timing of each transit. In order to assess the degree of uncertainty in the interpolated track locations, the precision of the estimates of transit timings and locations was investigated. This was done by identifying sets of three consecutive locations that were all within the Narrows and did not include any haulout periods. There were 8627 such triplets. The uncertainties in the timing and location of transits were examined separately. Error in timing was investigated by comparing the time at which the animals would reach the second point, assuming constant speed between the first and third point, with the actual time of the second location. Error in horizontal transit location was examined by taking the perpendicular distance from a line drawn between the first and third points, and the second point. Given that the majority of the tracks run along the Narrows, this distance will be similar to the error in the transit location.

2.7 | Testing for differences between years

Differences in two features were investigated: the mean transit rate for each animal, and the distribution of these transits across the width of the Narrows. These were compared between years, between times when the turbine was operational or non-operational, between day and night, and in relation to tide and season.

It is difficult to use these data to test for statistically significant differences between years. Logistical constraints limited the number of animals that could be tagged, and the behaviour of these individuals varied. Very different amounts of data were also obtained from the individual animals. In addition, the tags used in 2010 were programmed to attempt to obtain locations every 10 min rather than every 20 min, as in previous years. Treating each of the transits made by an individual as an independent data point would result in pseudo-replication.

The uncertainty in the mean daily transit rate for the population was estimated by non-parametric bootstraps of the data. These used individual seal as the unit of resampling. The significance of differences

TABLE 1 Details of the seal tag deployments that were included in the analysis

Ref	Year	Mass (kg)	Sex	Tagging date	Track duration (days; 24 h periods)
gp4-GSM103–06	2006	100	M	03/04/2006	36
gp4-GSM106–06	2006	93	M	03/04/2006	91
gp4-GSM108–06	2006	71	M	03/04/2006	102
gp4-GSM152–06	2006	83	F	04/04/2006	83
gp4-GSM157–06	2006	87	M	04/04/2006	86
gp4-GSM330–06	2006	85	M	05/04/2006	90
gp4-GSM333–06	2006	83	M	05/04/2006	19
gp4-GSM446–06	2006	70	F	03/05/2006	75
gp4-GSM669–06	2006	100	M	03/05/2006	58
gp4-GSM948–06	2006	77	F	04/05/2006	58
gp4-GSM979–06	2006	78	F	04/05/2006	44
gp4-GSM981–06	2006	87	F	05/05/2006	57
gp9–712-08	2008	82	M	31/03/2008	98
gp9–770-08	2008	97	M	30/03/2008	102
gp9–771-08	2008	98	M	30/03/2008	103
gp9–886-08	2008	81	F	31/03/2008	124
gp9–887-08	2008	77	F	31/03/2008	85
gp9–841-08	2008	66	F	01/04/2008	28
gp9–843-08	2008	74	M	31/03/2008	124
gp9–895-08	2008	97	F	28/03/2008	71
pv33–01-10	2010	85	M	01/04/2010	83
pv33–02-10	2010	93	F	04/04/2010	109
pv33–03-10	2010	73	F	07/04/2010	89
pv33–04-10	2010	89	M	07/04/2010	87
pv33–05-10	2010	104	M	04/04/2010	86
pv33–06-10	2010	86	F	08/04/2010	81
pv33–07-10	2010	99	M	01/04/2010	97
pv33–08-10	2010	86	M	04/04/2010	85
pv33–09-10	2010	102	M	07/04/2010	95
pv33–10-10	2010	85	M	04/04/2010	103
pv33–11-10	2010	94	F	08/04/2010	93
pv33–12-10	2010	73	M	07/04/2010	96

was assessed by comparing the resulting confidence intervals. The significance of differences between the overall transit rates in 2010 when the turbine was operating and when it was not operating was investigated with the Wilcoxon signed-rank test and also by bootstrapping with individual as the unit of resampling. The same approach was used for looking at differences in relation to tidal, diurnal, and seasonal factors.

To compare the effect of year on the distributions of transit locations the Kolmogorov–Smirnov two sample test was used. This test was first applied to every combination of individual pairs. Years were compared by summing the natural logarithms of the *P*-values from the individual pair comparisons within each factor and subtracting from this the sum of the *P*-values of comparisons of individuals between factors. An empirical null distribution for the test statistic was generated by carrying out equivalent calculations for 1000 replicate datasets, in each of which the animals were randomly allocated to a year. This approach was used to compare 2006 with 2010. The distribution for animal gp9–887-08 was sufficiently different from a number of other individuals that the estimated *P*-values from these comparisons were zero (which cannot be logged). The significance of these comparisons would therefore entirely depend on what small numbers were chosen to approximate these values, so 2008 was not included in these comparisons. Comparisons were also carried out between the distributions of transit locations for individual seals when the turbine was on and off.

2.8 | The effect of the shutdown mitigation

Given that the turbine was shut down on a close approach of a potential marine mammal target, the potential for shutdown influencing tagged seal behaviour was examined by cross referencing the times and dates of each transit with the times and dates of the shutdowns recorded by the sonar operators. Because of the error associated with the track interpolation, a transit was considered a potential match with a shutdown if the estimated crossing time occurred within ten minutes of a shutdown time and if the start and end times of the track occurred either side of the shutdown time. The total number and frequency of shutdowns during the period of seal tag deployment was also calculated.

3 | RESULTS

3.1 | Telemetry performance and movement patterns

This study examined 2772 seal-days of track data. Mean track durations were similar for 2006 and 2008 but were slightly longer in 2010 (2006 71 days, 2008 68 days, 2010 92 days). Four tags in 2008 worked for less than 10 days, these were excluded from further consideration in this study. The remaining individual track durations are given in Table 1.

The major features of the 2010 tracks (when the turbine was operational) are broadly consistent with previous years (these tracks are shown in Figure 1). In all years there was a high degree of variability between seals, but a high degree of consistency within seals. Some seals spent their entire time within Strangford Lough, others never entered the Lough at all and some seals spent the entire time transiting up and down the Narrows when not hauled-out. One seal (pv33-11-10) remained in the Narrows and within 4 km of the turbine for the whole of the duration of the tag life.

3.2 | Transit rates

The transit rates were highly variable between individuals, but the overall mean daily transit rates were similar in the three years (Table 1).

TABLE 2 Mean daily transit rates by year. The main results exclude gp9–891-08 (few data) and pv33–11-10 (very different behaviour from other study animals). Figures in brackets include these two seals

	Transit rate (day^{-1})	
Year	Mean	95% C.I.
2006	0.27	0.07–0.57
2008	0.49 (0.45)	0.13–0.93 (0.08–0.90)
2006 & 2008	0.38 (0.36)	0.15–0.65 (0.13–0.61)
2010	0.35 (0.87)	0.03–0.70 (0.09–2.0)
All years	0.36 (0.53)	0.17–0.57 (0.22–1.0)

Animal pv33–11-10 behaved very differently from the rest, making 40% of all recorded transits, so the data were summarized both including and excluding this seal. The differences in the behaviour of the individual seals also led to broad confidence intervals around the estimated transit rates for when the turbine was on and off in 2010 (Table 2).

When the turbine was operating there was a within-seal reduction in transit rate of 20% (95% CI: 10–49%), from 1.09 per day to 0.87 per day (Table 3). Seal pv33–11-10, contributed a large proportion of the transits and showed less apparent effect of turbine operation on its behaviour. Excluding this seal resulted in a greater estimated reduction in transit rates of 35%, but also reduced the precision of the estimate (95% CI: 52–102%), so that the difference appeared less significant ($P < 0.04$, one-tailed test).

The effect of turbine operation was stronger (reduction in transit rate of 57%; 95% CI: 25–64%; $P < 0.01$, one-tailed test; all animals included) when the comparison was restricted to daylight hours (defined here as 0600 h to 1800 h local time). Few data for comparison over individual months precluded analysis of seasonal patterns in the data.

No significant difference was detected in the rate of transits between slack water and other times in 2010 alone. The direction of flow of the tidal current changes rapidly, with very little slack water (Figure 2) so very few data are available from those periods. However, combining data from all three years, but excluding times when the turbine was running, suggested that transit rates at slack water were 1.52 times (95% CI: 1.08–1.91) those detected at other times, a statistically significant increase.

3.3 | Distributions of locations of transits

Visual inspection of the distributions of transit locations suggested that they differed between years (Figure 3). In 2006, the majority of the transits occurred in the middle of the channel, in 2008, the peak in locations occurred on the east side of the channel. However,

TABLE 3 Details of all transits past the turbine in relation to the operation of the turbine and the state of the tide. Means both including and excluding seal pv33–11-10 are shown

	Numbers of transits			Days of data			Transit rate (day-^{1})		
Seal	Turbine on	Turbine off, Not slack water	Slack water	Turbine on	Turbine off, Not slack water	Slack water	Turbine on	Turbine off, Not slack water	Slack water
pv33–01-10	1	0	1	36.1	31.9	7.2	0.03	0	0.14
pv33–02-10	0	0	0	40.5	50.5	9.6	0	0	0
pv33–03-10	48	88	11	39.3	34.1	7.7	1.22	2.58	1.42
pv33–04-10	0	0	0	39.3	34.1	7.7	0	0	0
pv33–05-10	57	54	7	39.3	32.8	7.6	1.45	1.70	0.94
pv33–06-10	0	0	0	39.3	31.7	7.5	0	0	0
pv33–07-10	1	0	1	40.3	40.3	8.5	0.02	0	0.12
pv33–08-10	0	2	0	39.2	30.5	7.3	0	0.07	0
pv33–09-10	7	5	6	40.5	38.2	8.3	0.17	0.13	0.72
pv33–10-10	0	0	0	40.5	45.2	9.1	0	0	0
pv33–12-10	12	16	1	40.5	39.6	8.4	0.30	0.40	0.12
Mean (95% ci)	11.5 (1.4–24.5)	15.0 (1.3–32.5)	2.5 (0.5–4.8)	39.5	36.5	8.0	0.29 (0.03–0.63)	0.44 (0.04–0.99)	0.31 (0.07–0.61)
pv33–11-10	292	298	44	40.5	36.5	8.1	7.21	8.17	5.43
Overall mean (95% ci)	34.8 (3.3–86.3)	38.6 (3.5–91.3)	5.9 (1.0–13.9)	39.6	36.5	8.0	0.87 (0.09–2.10)	1.09 (0.09–2.55)	0.75 (0.13–1.72)

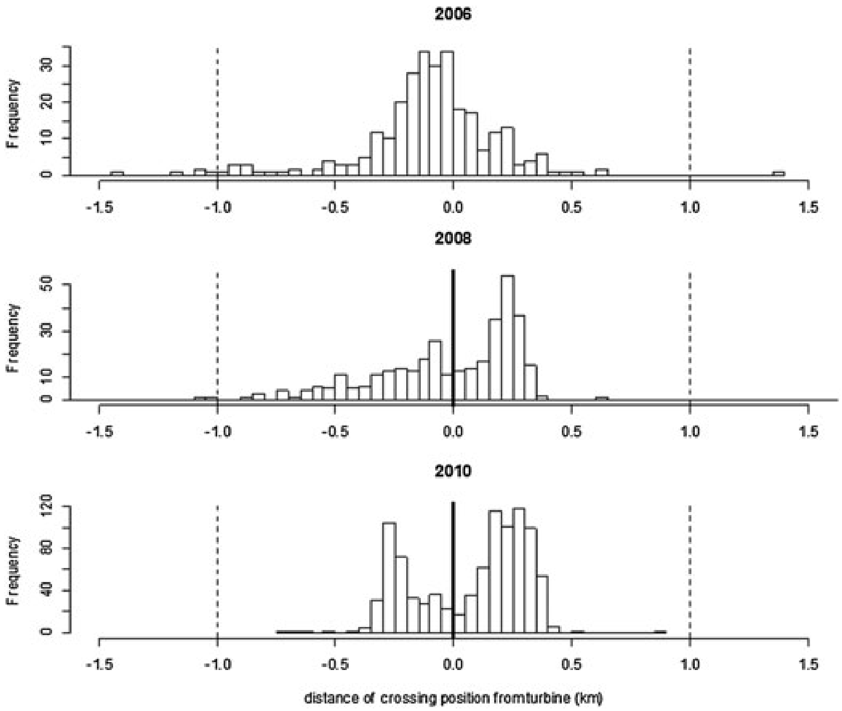

FIGURE 3 Frequency of transit crossing locations along a transect of the Narrows in relation to the position of the turbine (0 km, solid line in 2008 and 2010), grouped by deployment year. The x axis represents a line drawn across the Narrows perpendicular to the shore and through the turbine position (shown in Figure 1). The east and west boundaries of the Narrows are shown as thin dotted lines. The transits beyond these are apparent tracks over land – These are errors due to the straight line interpolations between some consecutive GPS location pairs with relatively longer time intervals gaps between them

in 2010 there was a distinct bimodal distribution with peaks in transits at approximately 250 m either side of the turbine location. However, there was a great deal of variation between the individuals within each year, and the Kolmogorov–Smirnov tests showed no significant difference between 2006 and 2010 ($P > 0.1$). This is effectively a result of the limited data available. While there were 1240 transit locations from these two years, there were only eight animals in each year that provided sufficient data to carry out the Kolmogorov–Smirnov tests on, and this effectively means the comparisons were between sets of only eight data points. Therefore the power of this test is low.

The effect of turbine operation on transit location was investigated (Figure 4). Only four animals (pv33–03-10, pv33–05-10, pv33–11-10 and pv33–12-10) provided sufficient data for such a comparison. However, none of these four comparisons indicated significant differences ($P > 0.10$ in each case).

3.4 | Uncertainties in transit location and timing

Figure 5 displays the transit segments from each year. The segments were of similar mean length in 2006 (2.0 km 95% CI 1.6–3.6) and 2008 (2.1 km 1.9–4.0), but were significantly shorter in 2010

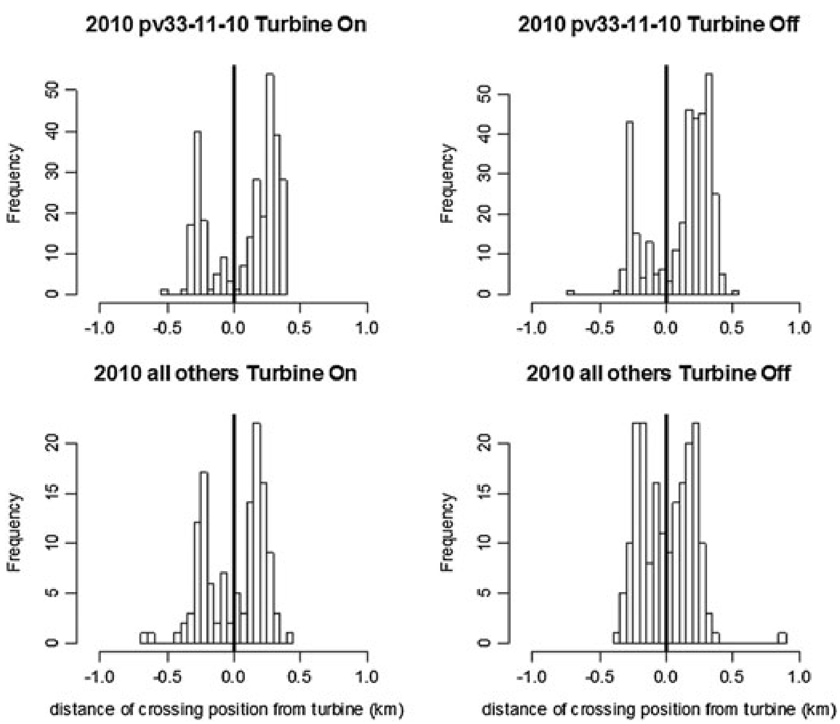

FIGURE 4 Frequency of transit locations along a transect of the Narrows in 2010, factored by turbine operation. The transect is shown in Figure 1 and is the same transect that is used in Figure 3. The position of the turbine is shown by a solid line at 0 km. The top panels display the data for seal pv33–11-10, which dominated the transits in 2010 (n ON = 292; n OFF = 342). The bottom panels show the transits from all other seals in 2010 (n ON = 126; n OFF = 192)

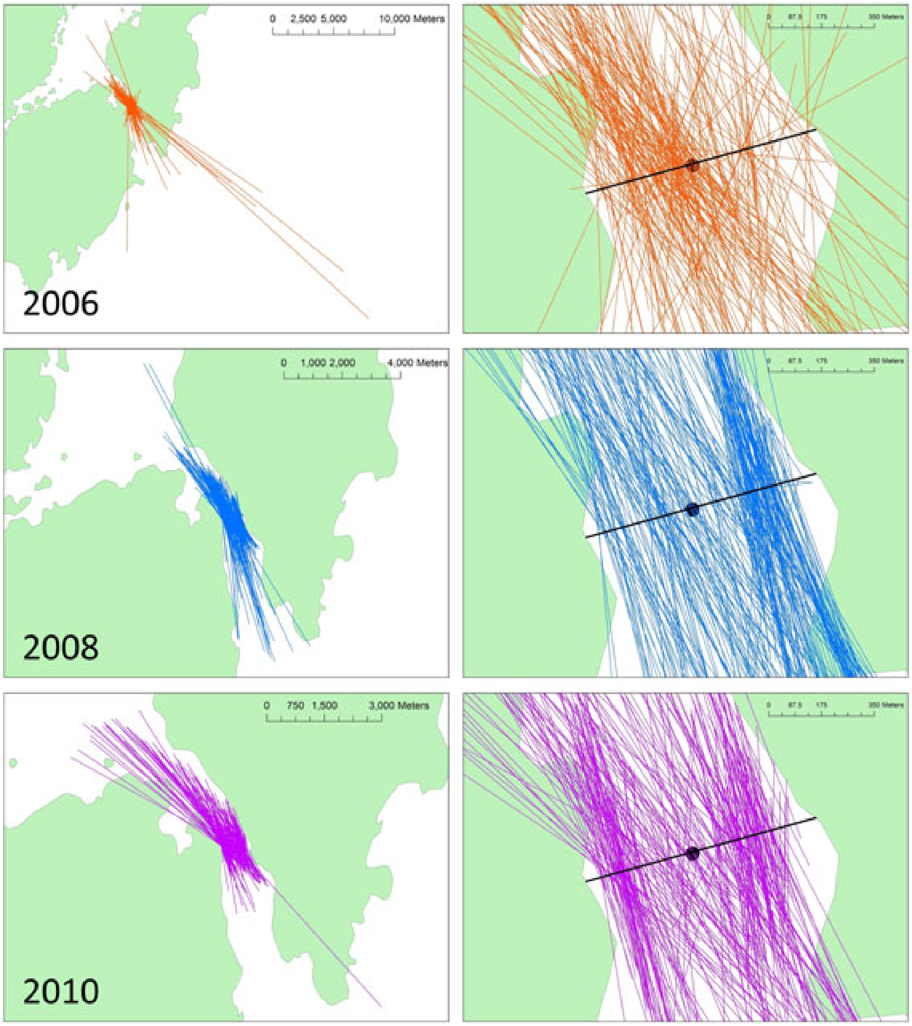

FIGURE 5 Map showing the seal transit segments in each year at two scales. The zoomed in scale on the right has the turbine position indicated by a black dot, and the solid black line used to determine transit position relative to the turbine

(1.5 km, 95% CI 1.3–2.8 km). This was as a result of the more frequent GPS fixes in 2010. In order to assess the degree of uncertainty in the estimated track locations as a result of straight line interpolation between GPS locations, the precision of the estimates of transit timings and locations was investigated using triplets of consecutive locations within the Narrows. There was considerable error in timing when comparing the time at which a seal travelling at constant speed would reach the second point in a triplet of locations, to the time associated with the central location; this means that the estimate of the time that a seal would reach the midway point between the first and last locations 20 min apart could be out by 10 min. With triplets 60 min apart this error could be as much as 40 min.

The error in location, estimated by calculating the perpendicular distance from the second point to the line linking the first and third point, increased with total distance between the end points of the triplet and turning angle when grouped by turning angle (Figure 6). For triplets less than 1 km in length, and that turned less than 90°, i.e. those that were most similar to the transits through the Narrows, 95% of the estimated locations were within 160 m of the actual GPS locations. This error is less than the width of the apparent dip in the histograms of the transit locations (Figure 3).

3.5 | The effect of shutdown mitigation

There were 121 precautionary shutdowns over the period of tag deployment in 2010 (April to July). This equated to an equivalent of 0.14 shutdowns per hour of operation, or 3 per day. From a total of 1506 transits that occurred while the turbine was operating, only four (0.3%) potentially matched with precautionary shutdowns.

4 | DISCUSSION

The environmental monitoring of the SeaGen turbine has produced a telemetry dataset with a very high precision and intensity of observation. It has answered a number of fundamental questions about the effects of SeaGen on the harbour seals in the vicinity. Harbour seals continued to travel through the Narrows, and transited past the turbine when it was operating, continuing to use haulout sites in the Narrows. Some of the transits were movement between the Inner

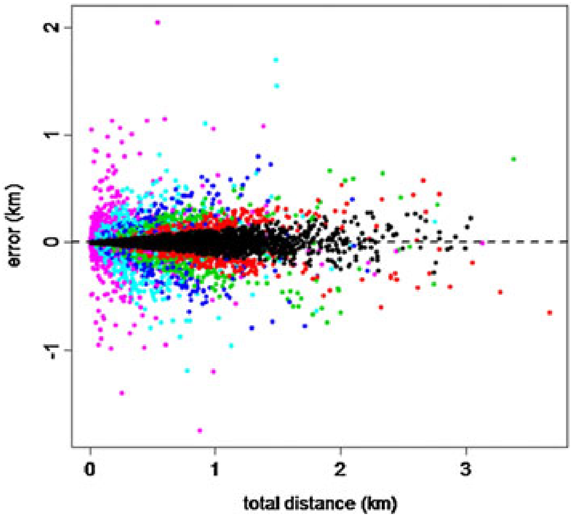

FIGURE 6 Estimating error in the location of transit points in relation to the total distance of the track segment. Each point represents the distance between the position of the second of a triplet of GPS locations and the location at that time estimated if the animals were assumed to travel at constant speeds between the first and third points). The points are colour coded according to the angle the track turned at the middle point (0 < = black, <300 = red, < 60 = green, < 90 = blue, < 120 = light blue, <150 = pink). The black points have been plotted over the others to show the range of uncertainty associated with them

Lough and the Irish Sea while others represented local movements within the Narrows.

The rate of transits varied greatly between animals. This reduced the statistical power to detect significant changes in the true transit rate of the local population. Nevertheless, there was clear evidence that the presence of an operating tidal turbine was not acting as a complete barrier to seals and they continued to transit the Narrows and move in and out of the Strangford Lough SAC. Indeed, some individual seals spent much of their time close to the turbine while it was operating.

It was not possible to measure the exact positions of seals underwater between surfacings, therefore the position of transits past the turbine were estimated based on straight line interpolation. The estimated transit locations varied in terms of their distance from the turbine position. Estimated transit locations spanned most of the width of the Narrows (including some immediately adjacent to the turbine site) but there was a large degree of variation in transit locations between animals. Despite this high degree of individual variability in seal behaviour, there appears to be some degree of local avoidance of the turbine – the spatial distribution of the transit locations changed visibly between 2006, 2008 and 2010 (Figure 3). A different sample of animals was tagged in each year, therefore individual responses to the installation of the turbine cannot be tracked and the assumption is that a representative sample of animals were tagged in each year. In 2010 when the turbine was fully operational, relatively few transits of the tagged seals occurred close to the turbine, and the distribution of transits suggest that a degree of avoidance was evident up to a distance of approximately 250 m either side of the turbine. This pattern of avoidance was similar regardless of whether the turbine was operating or not operating, suggesting that it was not a direct result of noise produced by the operating turbine, nor as a result of a behavioural response to the noise emitted from the sonar installed on the turbine for mitigation (shutdown) purposes which was only turned on when the turbine was operational (see below). It may be simply due to the presence of the structure, or a learned 'habit' of avoidance.

The uncertainty in the estimated timing of animals passing the device suggests that detailed dive depth information collected in this study cannot be used to determine the precise depth at which animals passed the turbine on each transit, although a measure of overall depth distribution in the vicinity of the turbine does provide some information to estimate collision risks.

There was also considerable uncertainty in transit locations, given the limitation of the straight line interpolation between surface locations. There was variability between years in the nature of the transit track segments; segments were shorter in 2010 than in previous deployments, although this was a result of the GPS tags obtaining locations every 10 min compared to every 20 min previously. Although the magnitude of error in the triplet analysis increased with increasing triplet length, there was no bias in the direction of the error. This suggests that there was no inter-annual sampling bias in the track data. There is always the possibility that seals went closer, or conversely further away from the turbine position while underwater, given our ability to determine the seals' true path between subsequent locations. However, the direction of this error should be similar between years. Furthermore, the magnitude of the location error estimated by the triplet analysis indicates that expected locational error from linear extrapolation would be <160 m, considerably less than the difference in peak transit location, providing confidence that this difference was representative of avoidance.

Telemetry is a particularly useful tool for collecting information about where a sample of seals go, where and when they haul out and how they behave while they are at sea. However, the high levels of individual variation in this study (and the limited sample size) reduced our ability to make population level inferences about responses to SeaGen. The intermittent operation of SeaGen in 2010 provided an opportunity to explore the effects of turbine operation on individual seal behaviour. The ability to measure the difference in behaviour of the same individuals between when the turbine was operating and when it was not operating allows for comparisons that were not possible when comparing between years. Simply comparing all the data across years showed no detectable change in the frequency of transit past the turbine site, nor could any statistical change in transit locations be detected. However, when the comparison was done within individuals (where there is more statistical power to detect differences), it became clear that the individual seals were reducing their frequency of transit when the turbine was operating by between 10 and 50%, with an overall average reduction of 20%. This effect was stronger in daylight, although the reasons for this are unclear. This could be because when surfacing, animals could see the surface-piercing pile during daylight, and were responding to the visual cue which would be less obvious at night.

There remains the possibility that the observed reduction in transit rates was in response to the noise emitted by the sonar device used for mitigation purposes, since the sonar was switched on whenever the turbine was operational. The sonar employed (Tritech SuperSeaKing) is a 300 kHz mechanical scanning sonar with a source level of 210 dB re 1 μPa at 1 m. The peak frequency of 300 kHz is above the top of the hearing range of harbour seals, however, it is possible that the sonar unit also produces lower frequency components, but captive trials at the Sea Mammal Research Unit indicated no overt behavioural responses to this system (T. Gotz, pers. comm.). This would also not explain the stronger response in daylight as the sonar operated continuously regardless of time of day.

The transits of the tagged seals were unaffected by any shutdown mitigation, only four of the tagged seal transits could have possibly resulted in a shutdown. However, shutdowns did occur with regularity – at a rate of approximately three per day over the period of the tag deployment in 2010. Therefore, seals were obviously still coming very close to the operating turbine demonstrating that there was no complete exclusion in closer range around the turbine. It is important to note, however, that as a result of the shutdown mitigation in place this study cannot provide any information regarding the behaviour of animals in very close range of an operating turbine and therefore cannot be used to inform on the degree of close-range evasive responses that seals may be capable of.

Assessing the biological significance of these observed responses is difficult. The observed reduction in transit rate will reduce the overall risk of collision with the turbine, particularly during daylight. The operational period reported on here did not represent operation at full capacity over the whole deployment period therefore it is difficult to predict the scale of the response and thus predict how transit rates may change under greater degrees of operation (or if there were multiple turbines present). The fact that tidal turbines do not operate at slack tide will always provide seals with some opportunities to move past them. There is also the question of whether measuring a statistically significant change in a metric such as transit rate has any real biological significance for individuals and consequently for populations. A significant change in transit rate for individuals or a group of individuals does not necessarily mean a significant ecological impact, whereas avoidance of an area previously important for foraging may have a more obvious consequence for individual fitness. Either way, the data collected here does not allow these potential consequences to be measured. There is a clear need for studies that can link changes in individual behaviour as a result of responses to renewable energy developments to the consequences for the health, survival and reproduction of individuals and ultimately the consequences for populations.

There are a number of implications of this work for future assessments of potential impact and future monitoring of marine renewable energy projects. This study confirmed that seals are not completely deterred from transiting past operational tidal turbines, although a degree of local avoidance was evident from changes in transit rates (particularly during the day) and changes in transit locations varying temporally (i.e. seals transit less often when turbine operating, particularly during the day) In addition, seals across all years transited relatively more at slack tide. These patterns will all serve to reduce the probability of collision between seals and operating tidal turbines. However, an additional aspect of seal behaviour that was not examined in this study was swim direction relative to current direction. Animals swimming with the current are likely to move faster past the turbine than animals swimming against the current and are thus less likely to be struck.

The degree of avoidance displayed by the tagged seals in 2010 suggests that collision risk may be much lower than would be predicted under current encounter models, which assume a uniform density of animals across a local area and do not incorporate any degree of avoidance response (Wilson et al., 2007).

Given that this was a study of only a single turbine, there may be a limit to the inference which can be drawn to other, more open tidal energy sites, or to larger arrays. Strangford is an unusual location in that seals have to pass within 500 m of the turbine to enter or leave the Lough so there is a natural limit to the degree that seals can avoid the turbine before a complete barrier effect would occur. Nonetheless, if the degree of avoidance observed here (~200–300 m) was observed around turbines arranged in larger arrays with this magnitude of spacing, this could result in avoidance of the whole array area and potentially barriers to movement. This behaviour would decrease the collision risk posed by the array, but may have implications for foraging success or result in increased energetic costs to divert around arrays.

This study has shown both the strength and the limitations of studying individuals with telemetry systems, especially since there is large variability in individual behaviour, exacerbated by the fact that different animals were tagged in the three deployments. In addition, without concurrent sampling of other extrinsic factors such as prey distribution, it may be difficult to attribute observed changes to specific developments as opposed to natural environmental variability. We recommend that the degree of inter-individual variability in behaviour in movement patterns should be assessed in a baseline deployment to consider the sample size that would be required to detect change in specific metrics. Repeat tagging studies will be most useful where inter-individual variation is low or responses particularly strong (i.e. complete avoidance of a development area) but the ability to detect more subtle changes in behaviour may be limited. An understanding of other factors that may be driving changes in behaviour over time will also be required. Other metrics must be monitored to reduce uncertainty about questions of direct collision risk and wider population consequences of behavioural changes. Thus individual behaviour studies such as these must complement other measurements made at other scales, for example monthly regular haulout counts, and/or annual pup production estimates will provide information about the status of the population that can be important for interpreting the consequences of small-scale behavioural responses. For example, ongoing long-term annual census and breeding surveys of the Strangford seal population and monthly haulout counts were important in establishing that these short range behavioural changes did not translate to changes in the local abundance and distribution of harbour seals (Savidge et al., 2014).

The key opportunity in this study was the intermittent operation of the turbine. It is therefore recommended that other individual-based monitoring studies of the effects of marine and renewable energy projects on behaviour consider wherever possible, some duty cycling or intermittency in effect, as before–after comparisons often suffer from low power. If turbine operation can be manipulated to provide an 'experimental design' allowing a contrast of operation vs non-operation, this can provide a good opportunity to understand seal responses. This is similar to the outcome of the telemetry study described in Russell et al. (2016) where comparisons in seal usage of an area between piling and non-piling periods provided a more powerful indication of the response of seals to offshore wind farm construction than a comparison of telemetry data collected pre-construction. However, given operational and commercial objectives it is unlikely that this would be a priority for any commercial developer but it is possible that the initial commissioning stages of projects may provide this contrast naturally.

ACKNOWLEDGEMENTS

We would like to thank the following individuals at Marine Current Turbines for their assistance during this study: David Ainsworth, Joseph Kidd, Cara Donovan and Felix Francis. Beth Mackey and Kate Grellier provided assistance in managing the seal telemetry deployments. Ian Boyd provided valuable comments on an earlier draft of this document. Simon Moss, with assistance from other colleagues at SMRU and SMRU Ltd, expertly handled the seals under Animals (Scientific Procedures) Act 1986 project licence PPL 60/3303. The work was funded by Marine Current Turbines and the UK Department of Energy and Climate Change's offshore energy Strategic Environmental Assessment programme. CES's contribution to this manuscript was partly funded by the Natural Environment Research Council Marine Renewable Energy Knowledge Exchange Programme (Contract 4060038637) and partly funded by SMRU Consulting. BM's contribution was partially funded by Natural Environment Research Council grant SMRU1001. The authors have no conflict of interest to declare.

REFERENCES

Boehlert, G. W., & Gill, A. B. (2010). Environmental and ecological effects of ocean renewable energy development a current synthesis. *Oceanography*, *23*, 68–81.

Copping, A., Sather, N., Hanna, L., Whiting, J., Zydlewsk, G., Staines, G., … Masden, E. (2016). Annex IV 2016 state of the Science Report: Environmental effects of marine renewable energy development around the world.

Lonergan, M. (2013). *Strangford seal counts: SMRU Ltd Report to Marine Current Turbines*. St Andrews: SMRU Ltd.

McConnell, B. J. (2009). Strangford lough, seal movements and behaviour. Report to Geotek and Hartley Anderson.

Russell, D. J. F., Hastie, G. D., Thompson, D., Janik, V. M., Hammond, P. S., Scott-Hayward, L. A. S., … McConnell, B. J. (2016). Avoidance of wind farms by harbour seals is limited to pile driving activities. *Journal of Applied Ecology*, *53*, 1642–1652.

Savidge, G., Ainsworth, D., Bearhop, S., Christen, N., Elsaesser, B., Fortune, F., … Whittaker, T. (2014). Strangford Lough and the SeaGen Tidal Turbine. In M. A. Shields, & I. L. Payne (Eds.), *Marine renewable energy technology and environmental interactions* (pp. 153–172). Berlin: Springer.

Scottish Natural Heritage. (2016). Assessing collision risk between underwater turbines and marine wildlife. SNH guidance note. Report by Scottish Natural Heritage.

Vanderlaan, A. S. M., & Taggart, C. T. (2007). Vessel collisions with whales: The probability of lethal injury based on vessel speed. *Marine Mammal Science*, *23*, 144–156.

Wilson, B., Batty, R. S., Daunt, F., & Carter, C. (2007). *Collision risks between marine renewable energy devices and mammals, fish and diving birds*. Oban, Scotland: Scottish Association for Marine Science.

How to cite this article: Sparling C, Lonergan M, McConnell B. Harbour seals (*Phoca vitulina*) around an operational tidal turbine in Strangford Narrows: no barrier effect but small changes in transit behaviour. *Aquatic Conserv: Mar Freshw Ecosyst*. 2017;1–11. https://doi.org/10.1002/aqc.2790