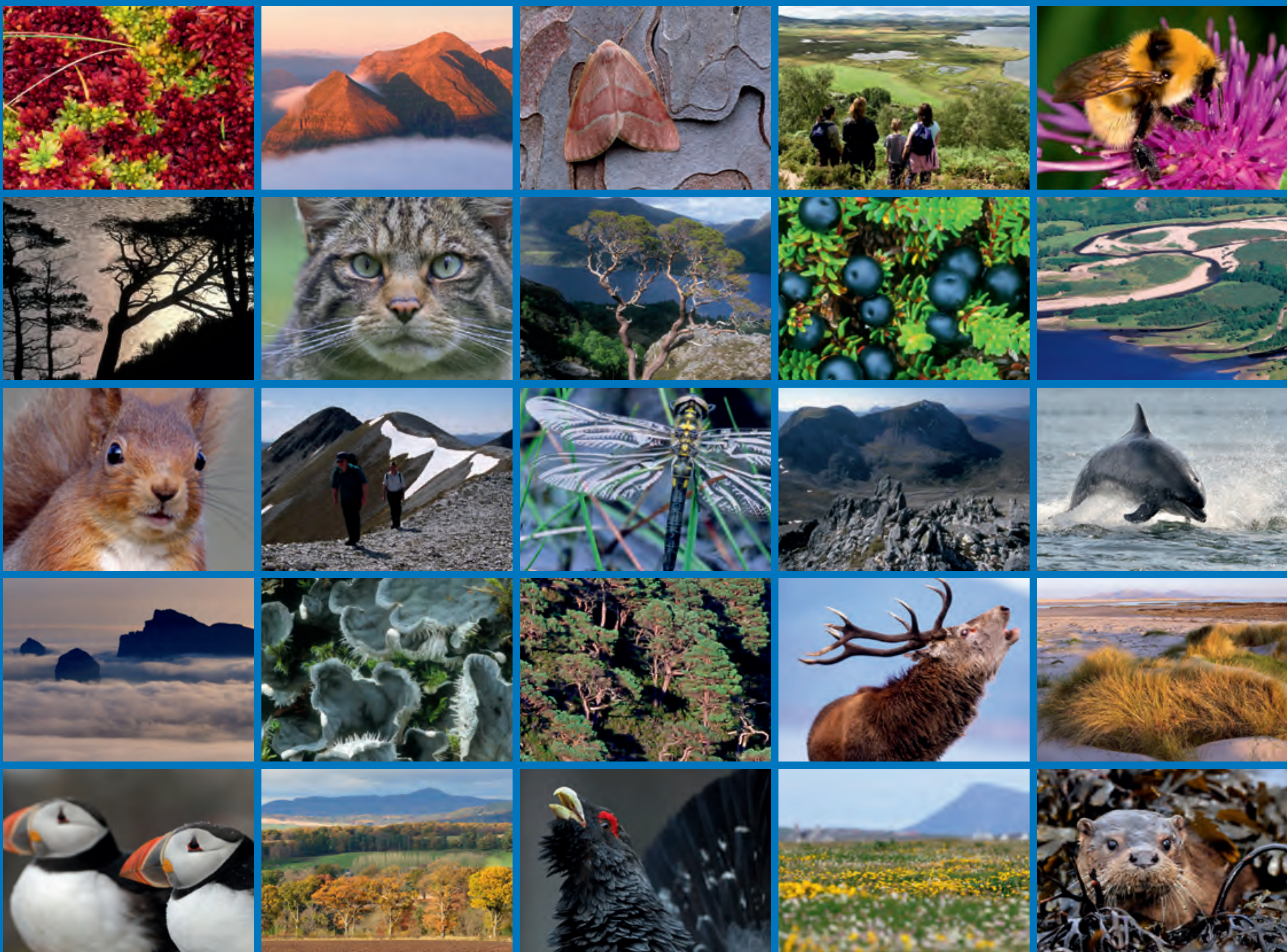
Scottish Natural Heritage
Commissioned Report No. 900

Data based estimates of collision risk: an example based on harbour seal tracking data around a proposed tidal turbine array in the Pentland Firth



COMMISSIONED REPORT

Commissioned Report No. 900

Data based estimates of collision risk: an example based on harbour seal tracking data around a proposed tidal turbine array in the Pentland Firth

For further information on this report please contact:

George Lees
Scottish Natural Heritage
Battleby
Redgorton
PERTH
PH1 3EW
Telephone: 01738 458621
E-mail: george.lees@snh.gov.uk

This report should be quoted as:

Thompson, D., Onoufriou, J., Brownlow A. & Morris, C. 2016. Data based estimates of collision risk: an example based on harbour seal tracking data around a proposed tidal turbine array in the Pentland Firth. *Scottish Natural Heritage Commissioned Report No. 900.*

COMMISSIONED REPORT

Summary

Data based estimates of collision risk: an example based on harbour seal tracking data around a proposed tidal turbine array in the Pentland Firth

Commissioned Report No. 900
Project No: 13112
Contractor: Sea Mammal Research Unit
Year of publication: 2016

Keywords

Harbour seal; collision risk; marine renewables; tidal energy; Pentland Firth; Inner Sound.

Background

This report presents an estimate of the risk of collision between harbour seals (*Phoca vitulina*) and tidal turbines on the basis of observed behaviour patterns derived from targeted telemetry tracking studies and recent population survey data. The collision risk associated with a proposed turbine array development in the Pentland Firth was used as a worked example of the method.

A brief summary of the movement data collected during transmitter deployments on harbour seals in the Pentland Firth study area in 2011 is presented, with an emphasis on information that is most likely to be of use in assessing the potential impacts of tidal turbine deployments.

Main findings

A process to estimate the number of times that telemetry tagged seals could pass through the area of a proposed turbine array is described. The method incorporates dive depth data to estimate the number of times tagged seals would have passed through the swept area of individual turbines in a hypothetical turbine array within the site.

Telemetry data from seals tagged at various sites in the Pentland Firth and Orkney were used to support an estimate of the number of seals likely to be at risk of interacting with such an array. The expected number of collisions between harbour seals and turbines in the array was based on details of their movements relative to the locations and movements of hypothetical tidal turbine blades, assuming that seals are oblivious to the presence of devices, i.e. show no avoidance and take no evasive action.

- It was estimated that 1.2 seals per year (approx. 95% confidence interval (C.I.) 0.8- 2.0) would collide with individual turbines.
- Scaling that estimate up to the full 86 turbine array suggested that 103 (approx. 95% C.I. 73 – 152) collisions would occur per year.

– This estimate was approximately 15% of the rate derived, previously, from collision risk models for the same site.

The preliminary information from collision experiments was then used to give estimated mortality rates from such collisions. The effects of interpolation error due to timing of GPS fixes and the small, but significant, GPS position error on the estimates of interaction rates are discussed and an attempt is made to incorporate estimates of variability from other sources such as population estimates. Areas where such error distributions are poorly understood and require additional research are highlighted.

For further information on this project contact:
George Lees, Scottish Natural Heritage, Battleby, Redgorton, Perth, PH1 3EW.
Tel: 01738 458621 or george.lees@snh.gov.uk
For further information on the SNH Research & Technical Support Programme contact:
Knowledge & Information Unit, Scottish Natural Heritage, Great Glen House, Inverness, IV3 8NW.
Tel: 01463 725000 or research@snh.gov.uk

Table of Contents **Page**

Acknowledgements

This study was funded by Scottish Natural Heritage and Marine Scotland, and delivered by the Sea Mammal Research Unit, through Scottish Government's Marine Mammal Scientific Support Research Programme.[1]

[1] http://www.gov.scot/Topics/marine/marine-environment/species/19887/20826/MMSS

1. INTRODUCTION

The UK is committed to a massive increase in renewable energy generation over the next 20 years and wind, wave and tidal power will all play a major role in meeting these targets. The tidal energy in the waters around the Inner and Outer Hebrides and Orkney Islands represents a considerable resource that will necessarily form part of Scotland's offshore renewable energy programme. There is, however, concern over the potential for interaction between marine mammals and tidal turbines. The most obvious, and probably the most important interaction at least in terms of public perception, is the potential for injuries or fatalities resulting from direct contact with moving parts of tidal power devices (Linley *et al*., 2009; Wilson & Gordon 2011).

Devices and marine mammals must coincide in both space and time in order for any such effects to occur. Currently there is a lack of any well-founded information on the behaviour of marine mammals during such proximate interactions so there can only be an estimate of the potential for collisions. How animals act in terms of avoidance or attraction towards devices and their ability to evade collisions will scale the potential collision risk assessment. Gaining a better understanding of behavioural responses to operating tidal turbines is therefore a priority. Methods for estimating such responses are being developed and tested and will be applied as soon as functioning turbines are available, with plans for such work in the Pentland Firth and Ramsey Sound in an advanced state. However, the absence of operating turbines and particularly the absence of turbine arrays means that such direct measures do not as yet exist.

In the absence of direct information on collision rates, risk assessments have relied on encounter risk models. Two models have been proposed for estimating the risk of collisions between marine mammals and tidal turbines in UK waters: a modified version of a model developed to estimate the number of birds that could be expected to collide with onshore wind farm turbines (Band *et al*., 2007) and a model based on movements and interactions developed to investigate predation by zooplankton (Gerritsen & Strickler, 1977; Wilson *et al*., 2007). A review of the existing models and an investigation into some of the basic assumptions of the effects of possible collisions are presented in separate reports http://www.smru.st-andrews.ac.uk/pageset.aspx?psr=152#mr.

In light of the lack of information on avoidance and/or evasion behaviour, encounter risk models all currently incorporate one important assumption: that the patterns of movement of marine mammals will be the same in a particular place irrespective of the presence or absence of an operating marine renewable energy device. That is, marine mammals show neither attraction nor avoidance behaviour, nor make any attempt to evade the moving parts. Under this assumption the number of marine mammals impacted can be derived from an estimate of how many will pass through the footprint of a device scaled by the likelihood of being hit by a blade based on the transit time of the animal and the rotation rate and number of blades.

Several factors are likely to influence both the likelihood and severity of such contacts (Wilson *et al.,* 2007). In a recent review for Marine Scotland (MR1 & MR2 of the MMSS/001/11 project available at http://www.scotland.gov.uk/Publications/2013/09/5811/3) a set of information requirements to refine such estimates were identified. To assess the probabilities of such occurrences information is needed on:

- Device characteristics, e.g. rotation rate, depth, spacing, blade length & number, etc.
- The short term and seasonal movement patterns of animals.
- The size of the population at risk.
- The dive patterns, depth usage and small scale movement patterns of individuals.
- Reactions to presence of devices.

- Avoidance/ Attraction of animals to the turbines.
- Evasive behaviour in close proximity to devices.

As part of a wider study of the behaviour of marine mammals in areas of high tidal energy jointly funded by Scottish Natural Heritage and Marine Scotland relevant information on the first four bullet points above have recently been collected. This report presents a brief summary of the movement data collected during transmitter deployments on harbour seals in the Pentland Firth study area, specifically concentrating on information that is most likely to be of use in assessing the potential for collisions between seals and tidal turbines.

A process of data reduction was carried out to estimate the number of times that telemetry tagged seals pass through the area of a proposed turbine array in the Inner Sound, Pentland Firth. Information on dive depth and on the likely turbine locations is then used to estimate the number of times tagged seals would have passed through the swept area of individual turbines in a hypothetical turbine array within the site. This estimate is then scaled by the likelihood of a seal being struck by a blade as it passes through the swept area, then scaled up to the relevant local population size and finally converted into an estimate of potential mortalities by taking account of information from collision experiments.

The effects of interpolation error due to timing of GPS fixes and the small but significant GPS position error on the estimates of interaction rates are discussed and an attempt is made to incorporate estimates of variability from other sources such as population estimates. Areas where such error distributions are poorly understood and require additional research are highlighted.

2. AIMS AND OBJECTIVES

- To describe the movements and diving behaviour of harbour seals in areas of high tidal flows, with particular emphasis on sites with proposed turbine deployments.
- To combine these movement data with population data and estimates of the likelihood of injury, so as to estimate the risk of collision between harbour seals and tidal turbines, the probability of death and the number of potential fatalities.
- To provide a test of the methods by estimating the potential mortality rate due to a proposed tidal array in the Pentland Firth.
- To compare the results of this data extraction method with those of alternative collision risk models for the same site.

3. METHODS

3.1 Telemetry studies

In order to study the movement and dive patterns of seals at an appropriately fine scale, SMRU GPS/GSM Phone Tags were used. These tags combine GPS quality locations (usually better than 10 m accuracy) with efficient data transfer using the international GSM mobile phone network and provide locations at a user controlled rate, together with complete and detailed individual dive and haul-out records. Tags incorporate a pressure sensor and relay dive depth data in the form of nine depth records evenly spread through each dive. They are small, weighing 370 g which is <1% of an average harbour seal's mass. Data are relayed via a quad-band GSM mobile phone module when the animal is within GSM coverage. This results in relatively low cost, high energy efficiency transmission with a high data bandwidth.

Due to limited battery capacity there is a direct trade-off between the temporal resolution of the location data and the life of the transmitter. In order to produce location data from the tagging date to the moult, when tags are expected to fall off, the tags were set to collect a GPS location fix at 8 minute intervals.

Eight harbour seals were caught between 29th and 31st March 2011 and six were caught between the 24th and 26th September 2011 using a combination of rush and grab techniques and tangle nets. Seals were caught at haulout sites in Gills Bay, the haulout sites closest to the proposed tidal turbine array site in the Inner Sound. Seals were anaesthetised with an intravenous dose of a Tiletamine-Zolazepam mixture (Zoletil™) and tags were glued to cleaned, dried fur on the back of the neck using a cyano-acrylate contact adhesive (Loctite 422™). Seals were released and left to recover on shore close to their capture site. Table 1 gives the tagging details of the study animals.

Table 1. Tagging data and morphometrics for harbour seals fitted with GPS/GSM tags in the Pentland Firth in March and September 2011.

Seal ID	Date	Tagging Location	Sex	Age class	Mass (kg)	Length(cm)	Girth (cm)
pv24-165-11	30/03/2011	Inner Sound, Pentland Firth	M	Adult	90.6	143	112
pv24-541-11	30/03/2011	Inner Sound, Pentland Firth	M	Adult	96.8	153	118
pv24-x625-11	31/03/2011	Inner Sound, Pentland Firth	M	Adult	98.6	151	114
pv24-622-11	31/03/2011	Inner Sound, Pentland Firth	M	Adult	91.4	150.5	111
pv24-394-11	30/03/2011	Inner Sound, Pentland Firth	M	Juv	49.6	128	89.5
pv24-590-11	30/03/2011	Inner Sound, Pentland Firth	M	Juv	49.8	133	92
pv24-598-11	29/03/2011	Inner Sound, Pentland Firth	F	Adult	84.6	136	113.5
pv24-580-11	29/03/2011	Inner Sound, Pentland Firth	F	Adult	89	146	114
pv24-148-11	24/09/2011	Inner Sound, Pentland Firth	M	Adult	76.2	143	126
pv24-153-11	26/09/2011	Inner Sound, Pentland Firth	F	Adult	72	144	100
pv24-150-11	26/09/2011	Inner Sound, Pentland Firth	F	Adult	86.6	136	119
pv24-112-11	24/09/2011	Inner Sound, Pentland Firth	M	Adult	92.8	156	122
pv24-155-11	24/09/2011	Inner Sound, Pentland Firth	M	Adult	95	154	109
pv24-151-11	25/09/2011	Inner Sound, Pentland Firth	M	Adult	84.8	140	117

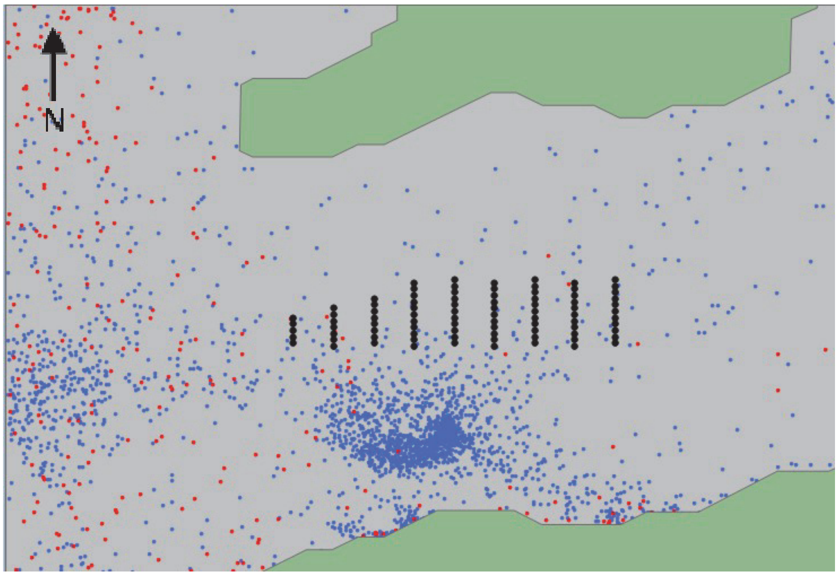


Figure 1. Positions of turbines within the hypothetical array in the Inner Sound, Pentland Firth (blue and red dots represent GPS location fixes for harbour seals).

3.2 Estimating numbers of seal passes through turbines

Estimating the number of times the tagged seals would have passed through the swept area of the turbines is an iterative process as outlined in the following sections.

3.2.1 Turbine array specification

A hypothetical array of 86 tidal turbines was placed into the proposed array site (Figure 1) using approximately the same layout as the hypothetical example presented in the MeyGen Environmental Statement (MeyGen Ltd). The example array comprised nine rows of turbines, aligned along north-south transects with between five and eleven turbines per row. Turbines were spaced 45m apart along the north-south rows and rows were spaced 160m apart along an east-west axis.

For the examples presented below, the turbines were assumed to be 20m diameter, 3 bladed devices, with the centre of rotation fixed 15m above the sea bed, giving 5m clearance between the blade tips and the sea bed. Sea bed depths were extracted from the TruDepth bathymetry database to provide a depth profile for each turbine row, extended to cover the entire channel from the mainland coast to Stroma.

3.2.2 Estimating number of potential turbine crossings

Data from the GPS location fixes were used to estimate the frequency of transits and the geographical positions at which seals pass through the channel and array site. The recorded time depth profiles were then used to assess the depth at which the seals crossed the individual turbine rows. The GPS position fixes obtained by the tag indicate the seals' XY positions to an accuracy of approximately +/- 10m. However, the tags were set to sample GPS only when at the surface, and in order to conserve battery power and provide a useful tag life they were further restricted to sampling at intervals of at least 8 minutes. Not all surfacing events produce successful GPS fixes, and the combination of these restrictions produced a sampling rate of approximately one successful GPS fix every 13 minutes (Figure 2) but with 57% of gaps being between 8 and 11 minutes.

The pressure sensors on the tags provided an 11 point depth profile for each dive with an accuracy of +/- 1m and the tags also transmitted the start and end times of each dive. The location and depth of each seal at any time could then be estimated by linearly interpolating the XY position assuming direct straight line movement between position fixes and linearly interpolating between successive time depth records. These data were used to identify the times, locations and swimming depths of all instances of seals crossing the turbine rows in the hypothetical array.

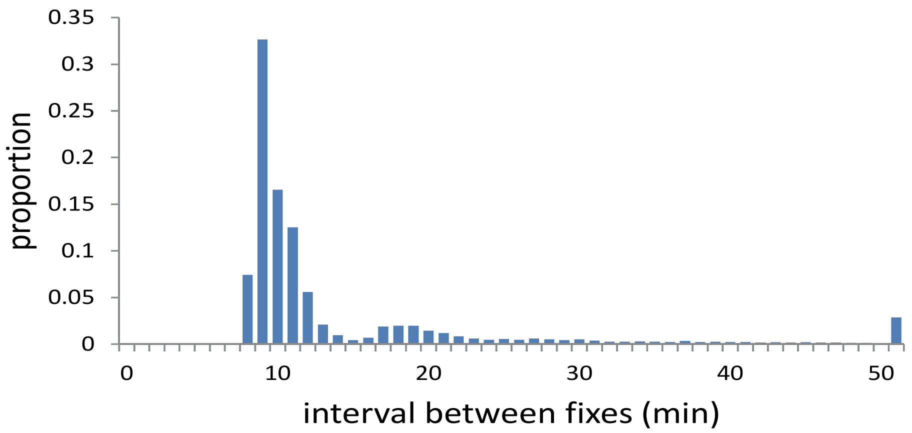


Figure 2. Frequency histogram of the intervals between successive GPS position fixes while seals were in the water.

The number of times the crossing locations coincided with the swept areas of individual turbines was then calculated (these will be referred to as turbine crossings). This was simply calculated as the number of row crossing events that occurred within a chosen radial distance of the centre point of each turbine. For the examples provided below this was set to 11m, equivalent to the length of a 10m turbine blade plus a correction to account for the length and circumference of a typical adult harbour seal (taken as 1.6m length, 0.3m diameter).

The total number of turbine crossings in the array was calculated in two ways to obtain an estimate of the variability. A single turbine was placed at 1m intervals along each of the nine turbine rows and the number of crossings was calculated for each location. Then for each row a random sample of *n* locations were selected and summed, where *n* equalled the number of turbines in that row. The row totals were then summed to produce an array total. The process was then repeated 600 times to provide an estimate of the variability of the estimate of array total.

All 86 hypothetical turbines were positioned in the array with turbines spaced at 45m intervals along the N-S rows starting at the southern boundary of the array and with rows spaced at 160m intervals west to east (Figure 1). The total number of turbine crossings was calculated for the entire array. The array was then moved 1m along the N-S axis and a new total was recorded. The process was repeated 600 times, moving 1m from the previous position each time, and each array total was taken as a sample. To maintain the same spacing as in the previous re-sampling exercise, the array was allowed to move up to 190m north and south of the array boundary. As a result of the distribution of seal tracks this will probably cause a slight increase in both the mean and the variability of the estimated crossing totals.

3.3 Converting turbine crossings into potential collision estimates

The next step was to calculate the probability of any crossing resulting in a collision. As in all the collision risk scenarios published to date, the assumption was made that seals' behaviour will not be influenced by the presence of turbines (see later for discussion of avoidance and evasion). Under that assumption, the likelihood of a collision is a simple function of the time during which any part of the seal is in the path of the turbine and the time interval between the arrivals of successive turbine blades. The time interval is simply the rotation period (i.e. 1/rate) divided by the number of blades. The time a seal is available to be hit is simply the length of time it takes to cross the swept face of the turbine. This will be a function of its travel speed (note this is speed over the ground, not speed through the water column) and the length of the seal. For the purposes of assessing collision risk a tapered spindle shape will have the same collision risk as a straight line except at very shallow crossing angles.

Harbour seal length varies between approximately 1m for a recently weaned pup up to approximately 1.6m for an adult male harbour seal (Table 1). As collision risk approximately scales to length it was possible to calculate different collision rates for different seal age/size classes.

In order to calculate speed over the ground, the calculations of the crossing points were all estimated assuming straight line movement at constant speed between successive locations.

3.4 Assessing the severity and consequences of impacts

At present a precautionary approach is taken that assumes any collision between a marine mammal and a tidal turbine blade will be lethal. This is unlikely to be true in practice. Although there is not any hard evidence for the likely injuries that will be suffered during impacts they will certainly be related in some way to impact speed, as well as point of contact on the seal. The impact speed will be a function of the rotation rate of the turbine and the distance of the impact point from the centre of rotation.

The rotation rate of the blade through the water will be a nonlinear function of the current speed; being stationary below some device specific stall speed and reaching a maximum at some intermediate current speed set by the specific design of the turbine and the local flow conditions. In addition, the speed of any particular point on a blade will be linearly related to the distance from the centre of rotation, being close to zero near the centre even at high rotation rates.

In the absence of other information, the available encounter risk models assume that marine mammals will not react to the presence of a turbine. Therefore it is assumed that the impact point will be at some random point on the blade. The probability that a collision occurs on any particular section of blade equals the proportion of the total swept area that is swept by that section and will be related to the distances from the centre (e.g. the outer 10% of the blade sweeps 19% of the total area while the inner 10% of the blade sweeps only 1%).

To illustrate the combined effects of the temporal patterns of flow and the position on the blade a frequency histogram of expected collision speeds was generated using the POLPRED (National Oceanography Centre) package to generate estimates of the current speeds at 10 minute intervals over the 28 day period from 4th March 2014 for a site in the Inner Sound. These current data were used to generate estimates of the blade speed assuming that the turbine stalls at a current speed of $0.8m.s^{-1}$ and reaches a maximum tip speed of $12m.s^{-1}$ for current speeds of $2.5m.s^{-1}$ and higher (Polagye, 2009). This is broadly similar to the pattern described for the SeaGen device in Strangford.

With the errors inherent in the telemetry location data it was not possible to be confident of precisely locating the points of impact along blades. Therefore, the assumption was made that seals will not react to the device and that they will pass through the swept area of any turbine at random points, with the frequency distribution of blade speeds representing the frequency distribution of blade impact speeds.

4. RESULTS

4.1 General movement patterns

A detailed description of the movements and behaviour patterns of seals within the Pentland Firth and Orkney waters is in preparation and a brief description is provided below of the results pertinent to the collision risk calculation. Figure 3 shows the swimming tracks of harbour seals tagged in the Inner Sound between Stroma and the mainland; eight in February 2011 and six in October 2011. All bar two of the seals continued to use haulout sites close to their capture sites on the mainland coast and concentrated their foraging effort within the high tidal energy area of the Pentland Firth. The two exceptions moved temporarily to haulout sites on the west coast of Orkney Mainland and spent their time foraging on the open shelf area to the west of Orkney. Figure 4 shows the swimming tracks of two harbour seals tagged at the same time (February 2011) at the same capture site in the Inner Sound, that show these two different foraging patterns.

Overall, the general patterns of movement of the tagged seals in the spring and autumn deployments were similar with the exception that seals in the autumn deployment only used the Pentland Firth haulout sites.

Preliminary examination of individual tracks and diving behaviour suggests that seals resident in the Pentland Firth dive mainly to the sea bed and spend a large proportion of their time transiting through the area very close to shore. Swimming tracks within the main channel of the Pentland Firth are clearly influenced by tidal flows. Some tracks of foraging seals are similar to predicted tracks of inanimate objects floating with the tide based on the POLPRED tidal flow model. Depending on tidal state at the start time of the prediction, inanimate objects entering the water near Stroma Island oscillate along an east west path stretching 10 to 15km west of Stroma or they oscillate along a track that stretches east of Stroma and turns south east into the North Sea, similar to the tracks shown in Figure 4.

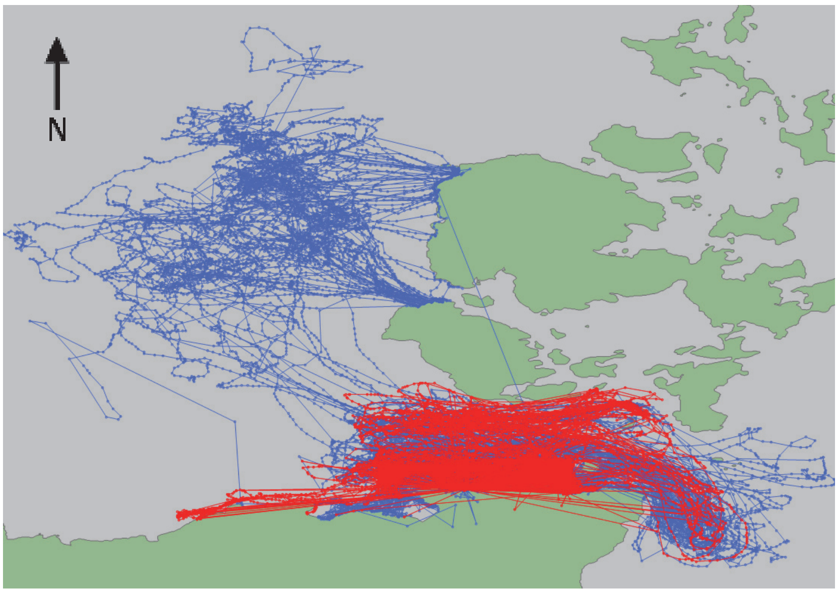


Figure 3. Tracks of harbour seals tagged in the Inner Sound between Stroma and the mainland in February 2011 (blue) and October 2011 (red).

4.2 Dive data for harbour seals in Inner Sound, Pentland Firth

A particular concern for developers and regulators is the likelihood of seals and turbine blades coinciding in time and space. In the current absence of information on the ability of seals to detect turbines and the likelihood of avoidance or attraction it is only possible to identify coincidence assuming zero response on the part of the seals. The number of times seals pass through an area with turbines will give part of the required information, but this will need to be scaled by how seals use the water column.

As an example of how the data may be used to inform these questions, the dive data from seals tracked in the Pentland Firth have been filtered to include only those dives estimated to have occurred within the planned footprint for the Inner Sound array (Figure 5).

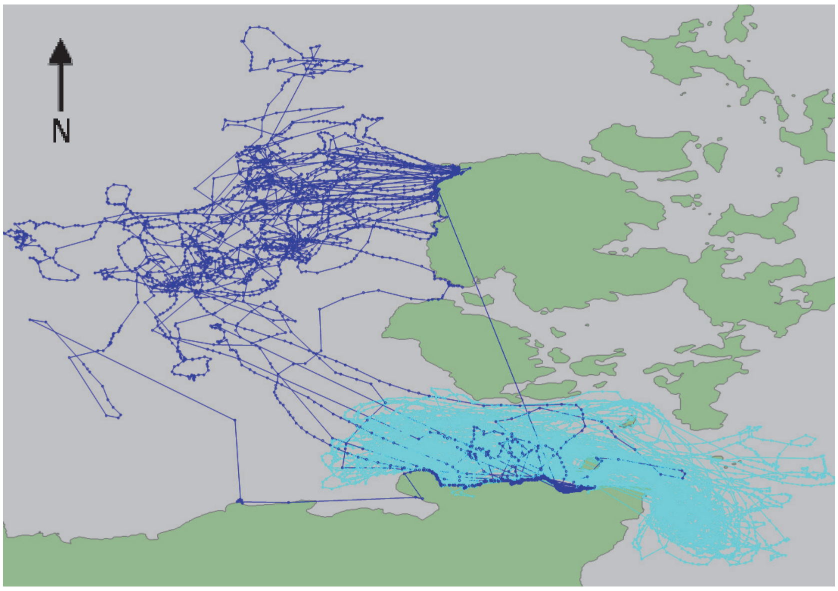


Figure 4. Tracks of two harbour seals tagged at the same time (February 2011) at the same capture site in Gills Bay in the Inner Sound between Stroma and the mainland.

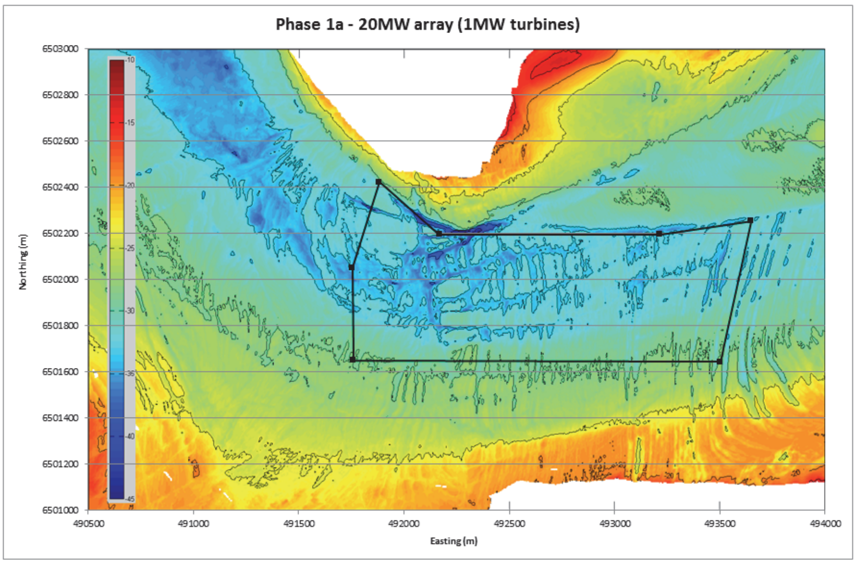


Figure 5. Approximate location and extent of the site for the proposed Inner Sound tidal turbine array (figure courtesy of MeyGen).

The dive locations are only as accurate as the tag location data will allow. Location quality from the GPS tags is very good, but still has some uncertainty, usually assumed to be +/-50 m. In addition, because of the constraints of battery power, there was a trade-off of temporal resolution for tag longevity, so a location fix is not received for every surfacing. The start and end points of individual dives are linearly interpolated between GPS location fixes assuming constant speed, straight line movement between points. To date there are no track data for harbour seals at finer temporal resolutions in this area so it is not possible to reliably predict the likely deviation from the assumed linear travel between locations. Because of this uncertainty it is not possible to accurately associate a water depth with each dive. However, the histogram of dive depths from the GPS/GSM tagged seals (Figure 6) suggests that most dives are likely to be benthic.

There are two alternative ways to use these data to describe the use of the water column. Figure 7 shows the distribution of all the spot depth values from the GPS/GSM tagged seals, these are taken at 10 percentile points within each dive (9 per dive) and a surface bar has been added to represent the 18% of time (mean over all dives in the box) spent at the surface by these seals. This gives an accurate representation of the use of different depths within the array site, averaged over the whole site.

Figure 8 and Table 2 present the same data but assuming that every dive goes to the sea bed and plotted to show where in the dive the seals spend their time in the water column.

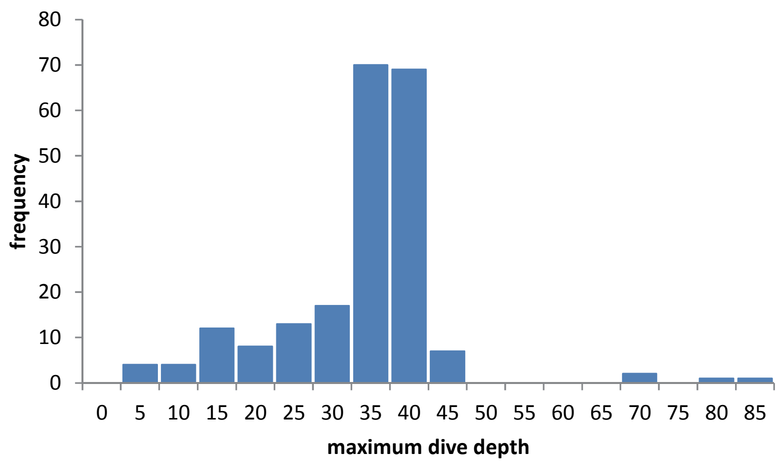


Figure 6. Frequency distribution of dive depths within the proposed array box in the Inner Sound.

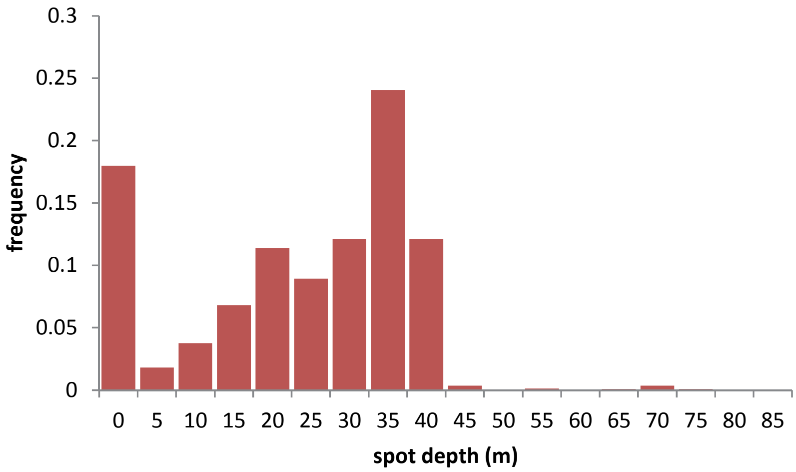


Figure 7. Frequency distribution of spot depth measurements, 11 equally spaced values throughout each dive in the array box.

Depth (prop. max depth)	**Proportion of time**
0	0.18
0.05	0.00
0.1	0.01
0.15	0.01
0.2	0.02
0.25	0.01
0.3	0.01
0.35	0.02
0.4	0.02
0.45	0.01
0.5	0.02
0.55	0.02
0.6	0.03
0.65	0.02
0.7	0.02
0.75	0.03
0.8	0.03
0.85	0.04
0.9	0.07
0.95	0.13
1	0.29

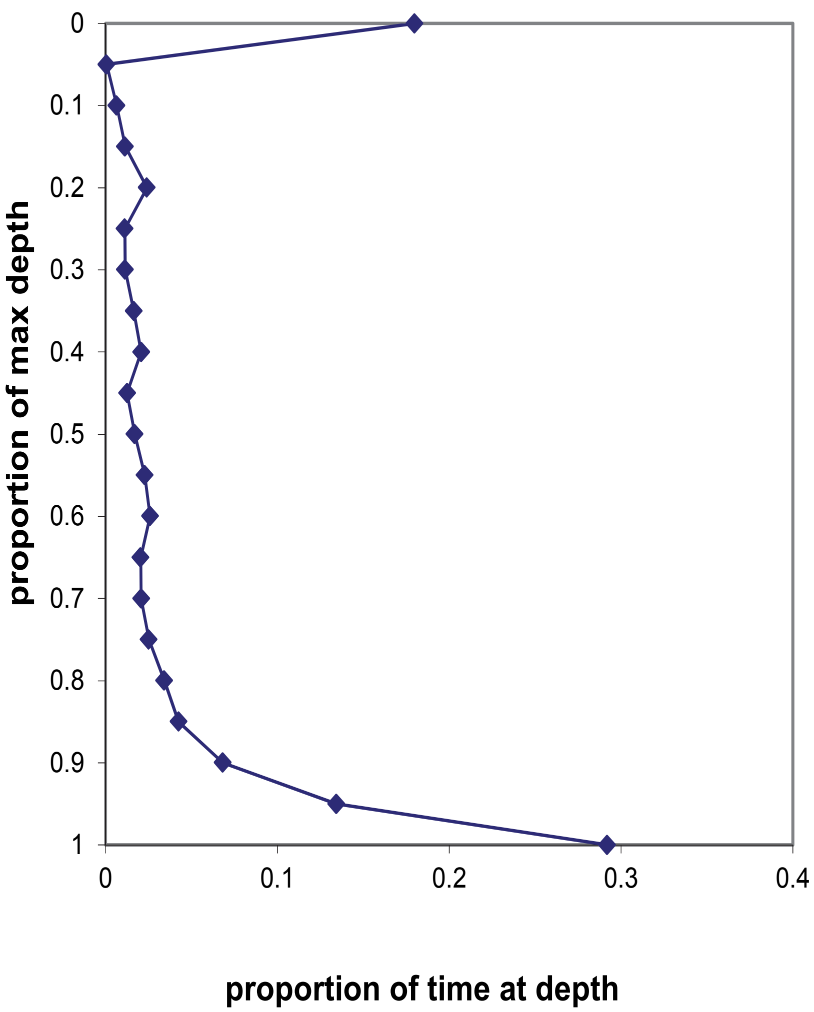


Figure 8 and Table 2. Proportion of time spent at depth expressed as a percentage of the maximum depth in each dive.

4.3 Seal movements relative to tidal flow in the Pentland Firth

Probability of collision will be related to the fine scale movement patterns of seals within tidal rapids. However, there is also a broader question of how seals distribute themselves throughout their range with respect to areas of high tidal energy. This will to some extent scale the collision probabilities by affecting the proportion of the local population that will be at risk.

Figures 9 and 10 show the swimming tracks of harbour seals tagged in the Inner Sound between Stroma and the mainland in February 2011 and October 2011 respectively. The background shading shows mean spring tide power as an indication of level of tidal energy, derived from POLPRED. The majority of seals in the autumn/winter sample and all seals in the spring sample spent most of their time in the Pentland Firth and appeared to spend a substantial proportion of their time either in or close to the high tidal energy areas of the main channel. The two seals that moved to haul-out sites on the west side of Orkney spent very little time in high tidal energy areas, apparently only foraging in offshore waters with slight tidal flows.

A closer inspection of the locations and tracks of seals within the Pentland Firth (Figure 11) indicates that a large proportion of the tracks followed the southern shore, with a high concentration of locations and apparent tracks within 200m of the coast.

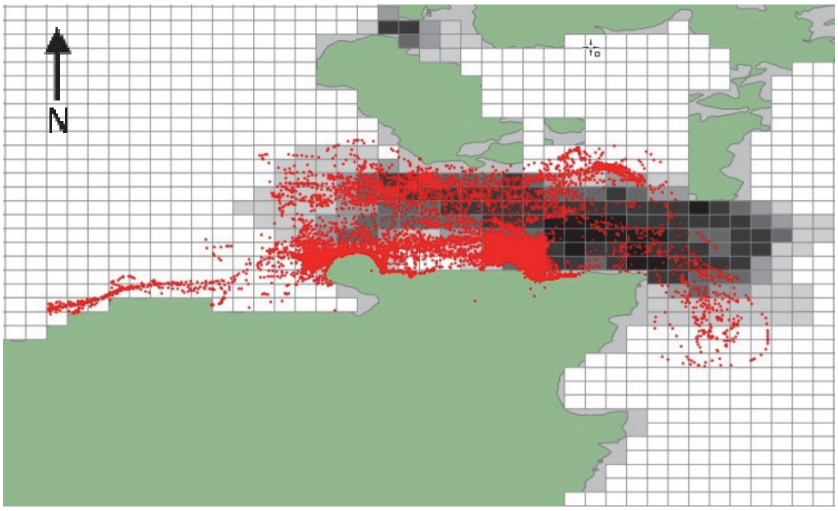


Figure 9. GPS locations of seals tagged in February 2011. Background grid shows the mean spring tidal power with darker shading representing regions with higher tidal energy.

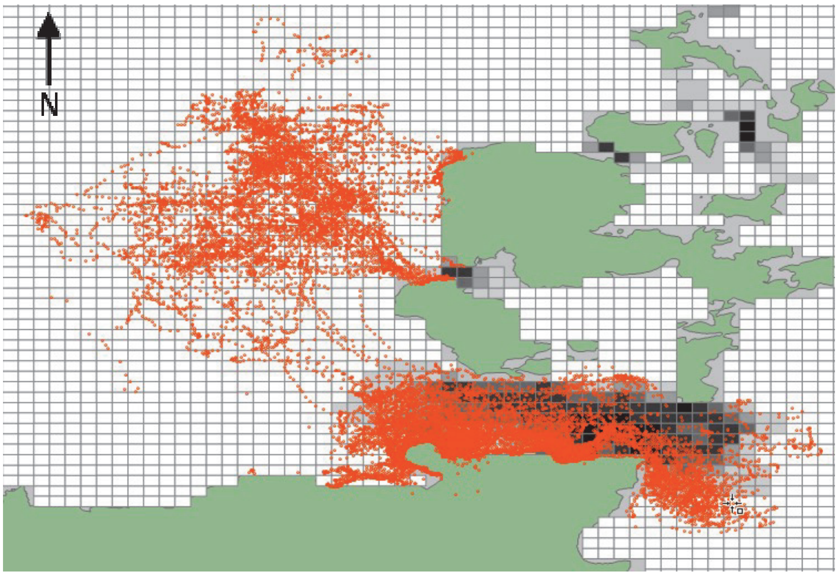


Figure 10. GPS locations of seals tagged in October 2011. Background grid shows the mean spring tidal power with darker shading representing higher tidal energy.

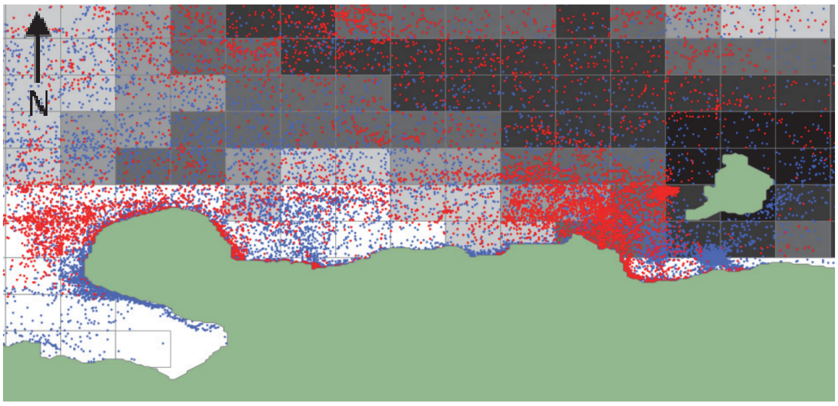


Figure 11. GPS locations of all seals tagged in the Pentland Firth showing high concentration of activity close to the coast in areas of relatively low tidal energy within the Pentland Firth to the west of the proposed array site. (Blue dots from seals tagged in February 2011 and red dots October 2011).

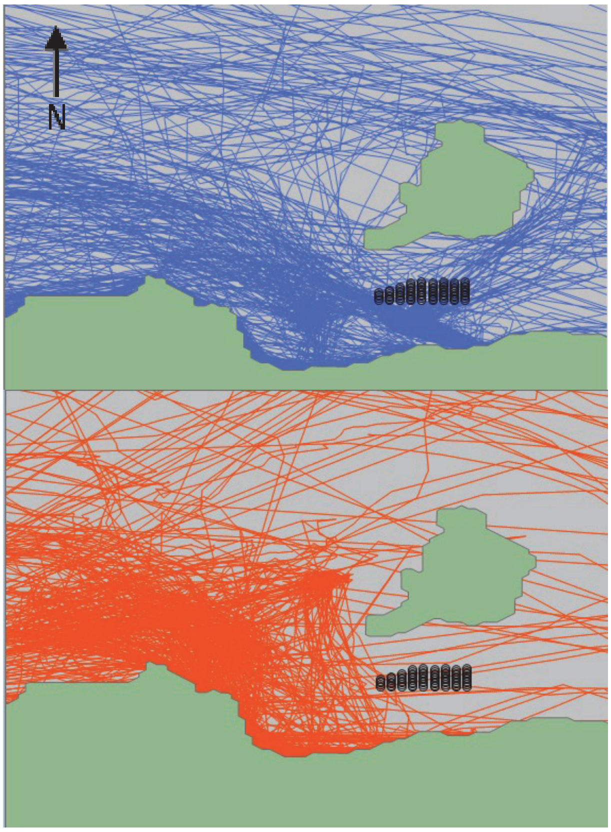


Figure 12. GPS locations of all seals tagged in the Pentland Firth showing high concentrations of activity close to the proposed array site in the Inner Sound. Blue lines represent the February 2011 deployments, red lines represent the September 2011 deployments and black circles represent the positions of turbines in the hypothetical array.

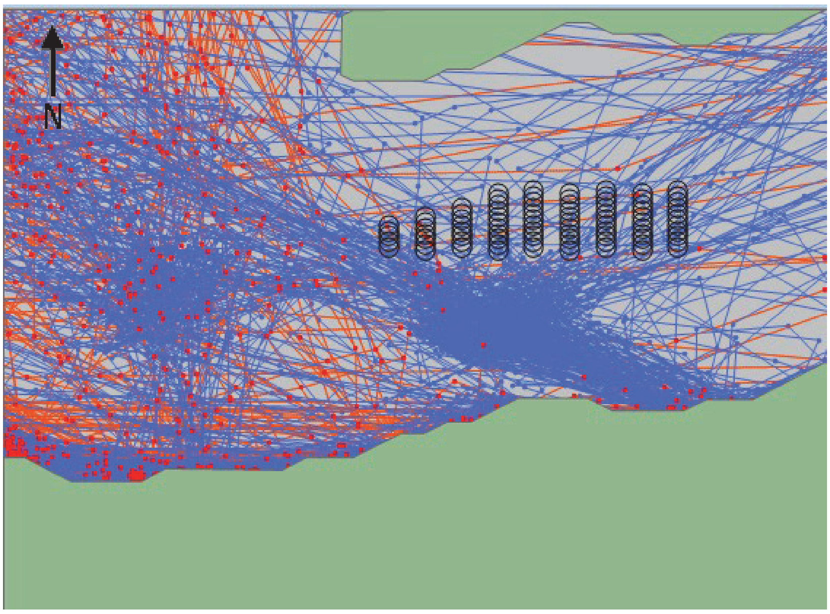


Figure 13. Closer view of the activity in the vicinity of the array site. Blue lines represent the February 2011 deployments, red lines represent the September 2011 deployments, dots represent actual position fixes and black circles represent the positions of turbines in the hypothetical array but are not shown to scale.

Figures 12 and 13 show that there was substantial seal activity in the vicinity of the proposed array site in the Inner Sound. However, the most intense activity appeared to be concentrated to the west and south of the array site, with relatively few tracks crossing through the site, especially in the September sample. These data represent the tracks of 14 harbour seals out of a local population of approximately 75 (see below). As such the observed distribution may not be fully representative of the population distribution; however, it is currently the best available representation of local distribution.

4.4 Estimating number of seal passes through turbines

4.4.1 Estimating seal passes through array site

Figure 13 clearly shows that seals transit through the proposed array site. Figure 14 shows the frequency distribution of crossing points for nine transects across the Inner Sound. Each transect is a turbine row extended to the mainland shore to the south and the Stroma shore to the north. Zero on the x-axis represents the southern edge of the proposed array. Each transit point represents the intersection of an interpolated straight line path between successive GPS location points. It is clear that the majority of transits through the Inner Sound are concentrated close to the southern shore, probably a consequence of the haulout sites being mainly along the mainland shore.

The estimated locations and the depths of all the crossings of the turbine rows by all 14 seals are shown in Figure 15. Only 6% of the total number of crossings recorded were within the boundaries of the hypothetical array site and only 11% were included if the boundaries were extended by 200m on either side of the turbine array. However, it is clear from the fact that several crossing points had estimated depths that exceeded the local water depth that there was interpolation error in the location of the dives and therefore also in the water depth estimates assigned to each dive. These potentially large interpolation errors between location fixes mean that the data must be interpreted with caution. However, 83% of crossings were more than 400m away from the array boundary.

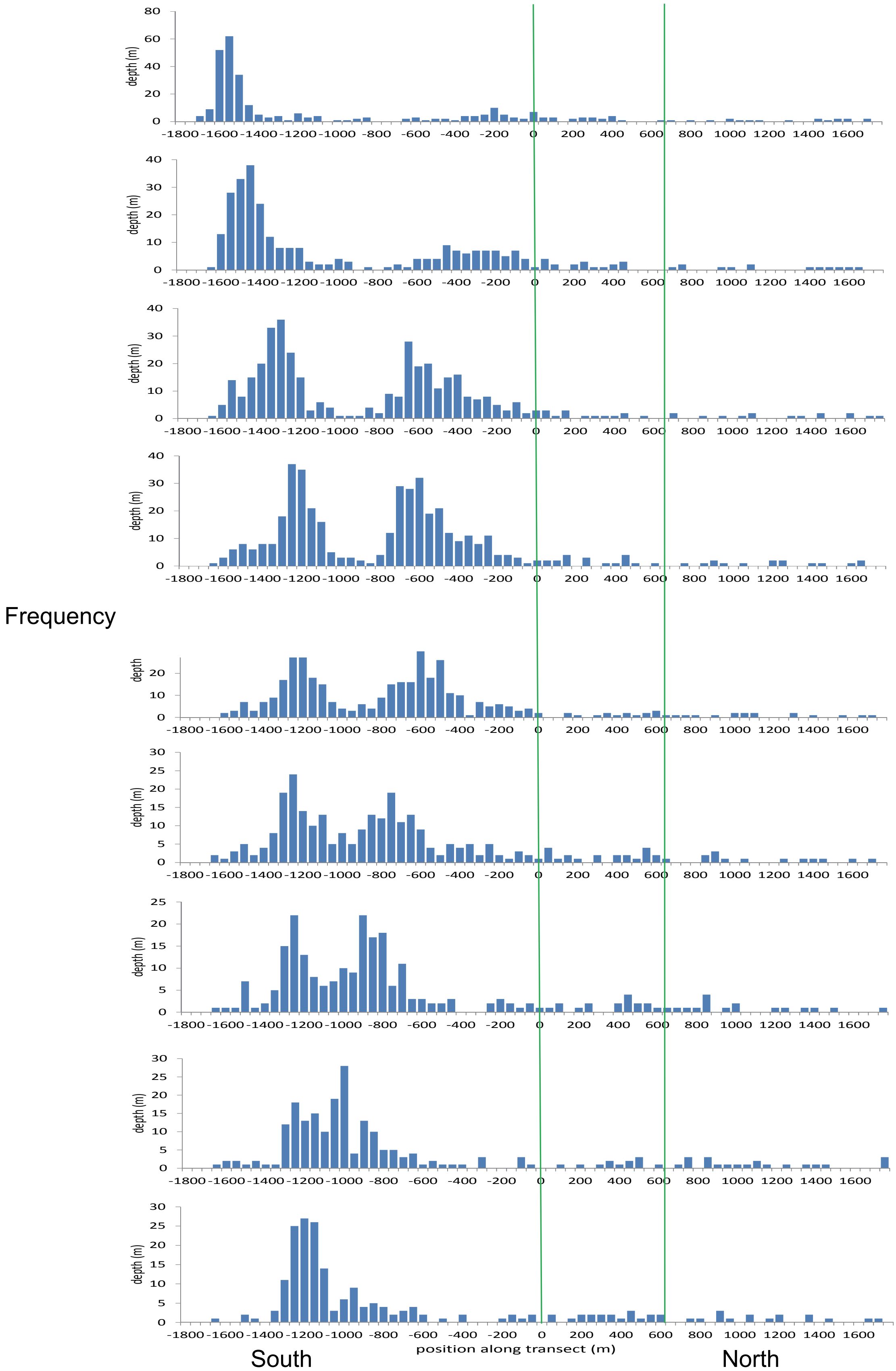


Figure 14. Frequency distribution of crossing points for nine transects across the Inner Sound. Each transect is a turbine row extended to the mainland shore to the south (-ve) and the Stroma shore to the north (+ve). Green bars represent the boundaries of the turbine array for each row. The top histogram is the westernmost turbine row.

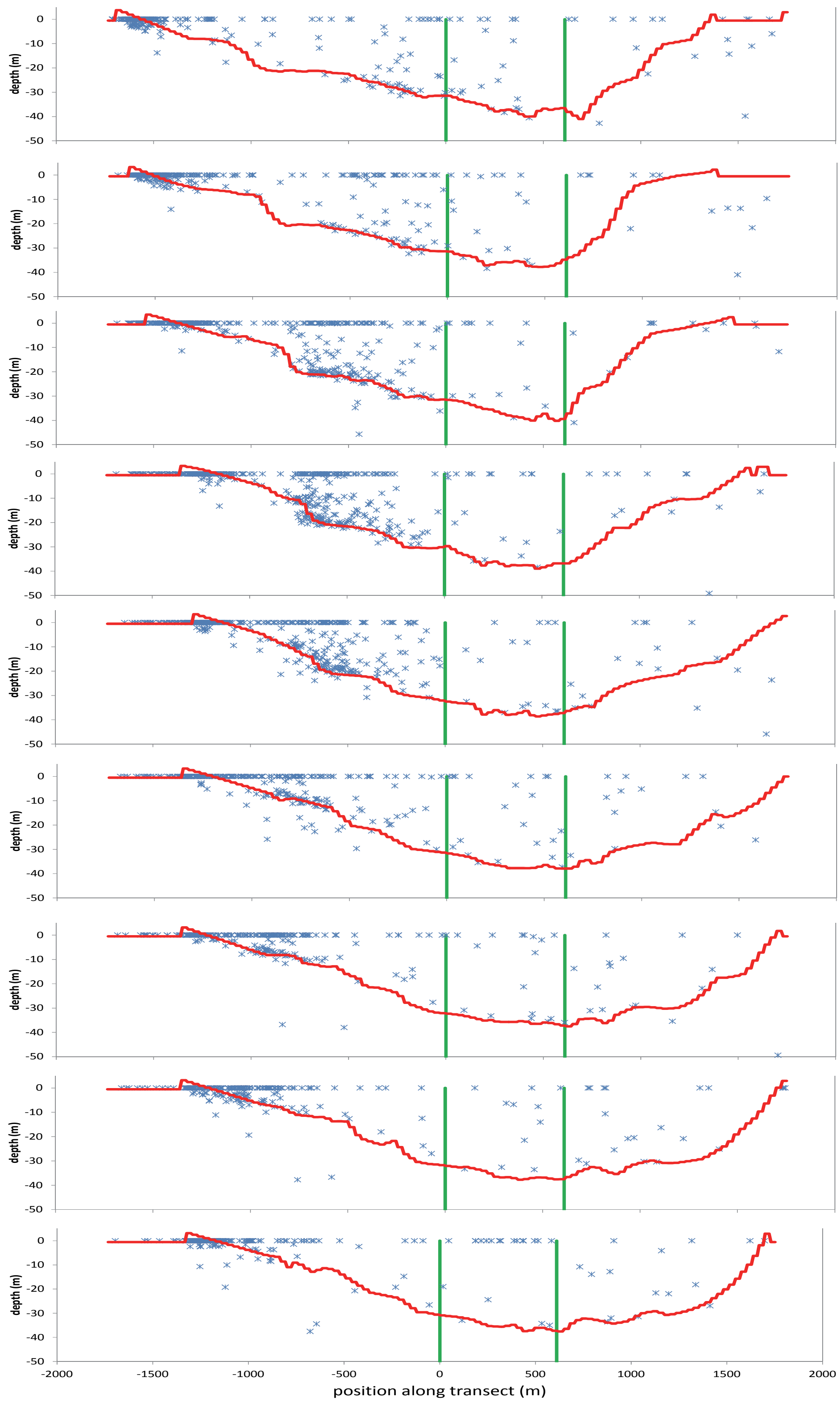


Figure 15. Estimated locations and depths of all crossing points for nine transects across the Inner Sound. Red line indicates sea bed depth. Each transect is a turbine row extended to the mainland shore to the south and the Stroma shore to the north. Green bars represent the boundaries of the turbine array for each row.

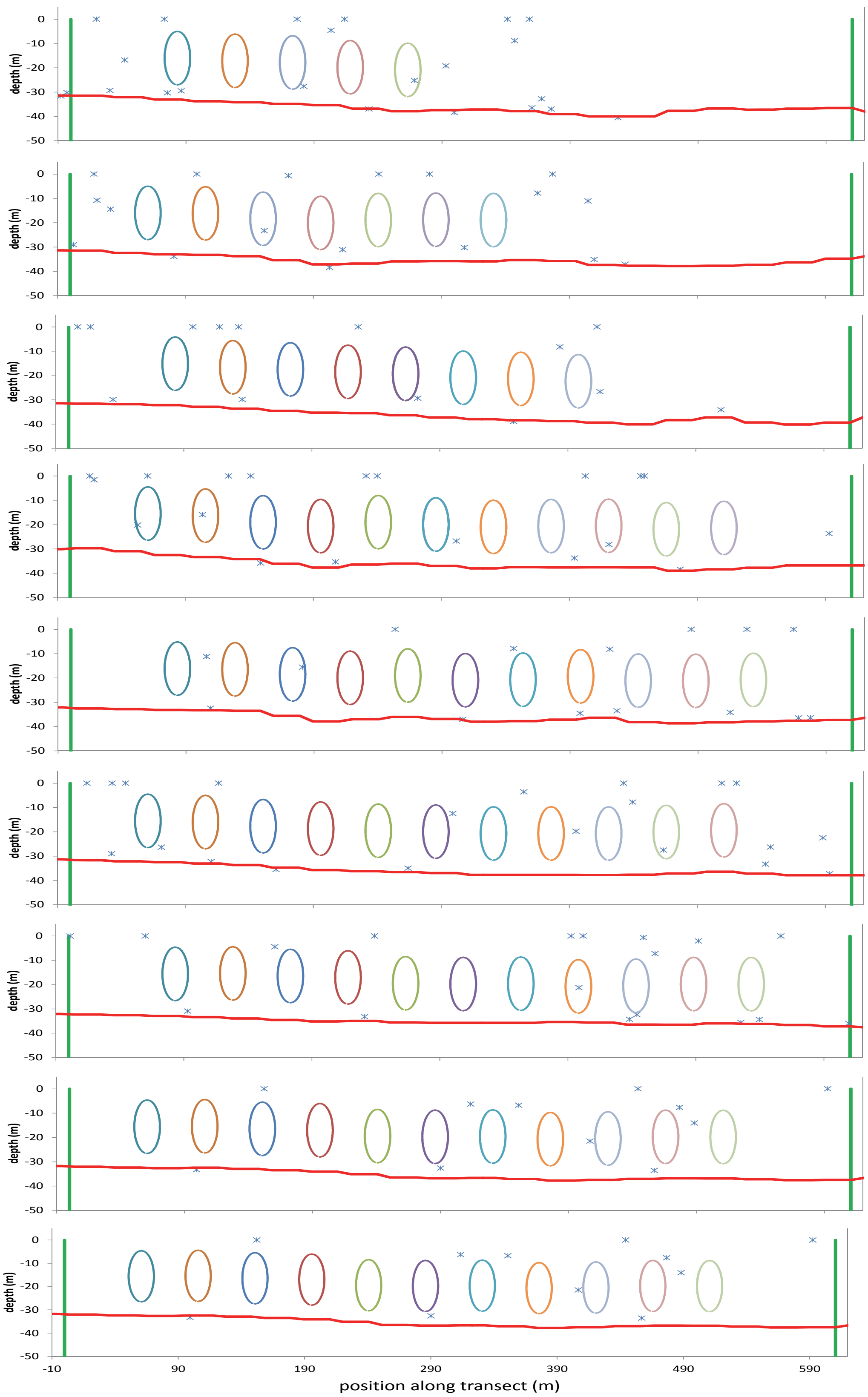


Figure 16. Estimated locations and depths of all crossing points for nine rows of turbines in the Inner Sound. Ellipses represent 20m diameter turbines centred 15m above the sea bed (red line) and at 45m intervals along the row. Each point represents one estimated crossing location. Green bars represent the boundaries of the turbine array for each row. Turbines appear as ellipses because of the different scales of the X and Y axes.

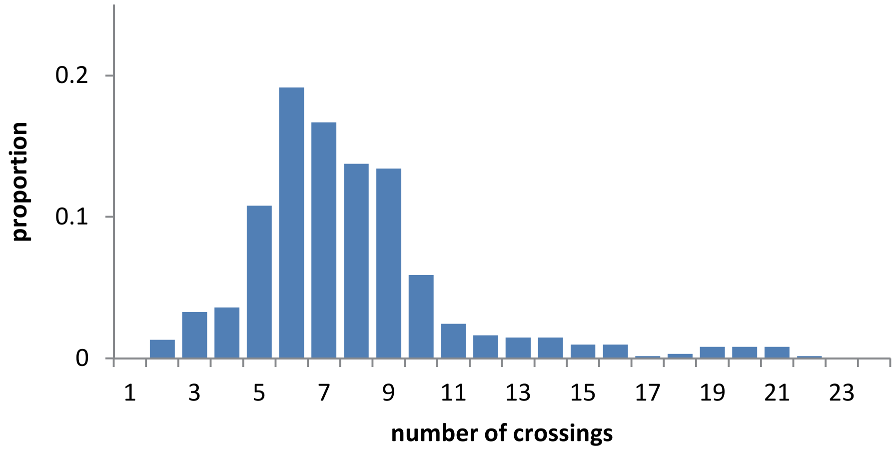


Figure 17. Frequency distribution of the number of times seals were estimated to have passed through the combined swept area of the 86 turbines in the hypothetical array in the 600 resamples.

Table 3. Summary statistics for the number of times the 14 tagged seals were estimated to pass through the swept disc of the 86 turbines in the proposed array.

Array crossings	
Mean	6.8
Standard Error	0.13
-95% C.I.	6.5
+95% C.I.	7.1
Minimum	1
Maximum	21
N of replicates	611

4.4.2 Estimating seal passes through swept areas of turbines

Figure 16 gives a more detailed view of the estimated locations and depths of all crossing points for nine rows of turbines within the turbine array site. Ellipses represent 20m diameter turbines centred 15m above the sea bed (giving a 5m clearance between the blade tips and the sea bed) and at 45m intervals along the row. Any crossing that coincided with the position of one of the turbine discs was classed as a turbine crossing and was therefore a potential collision. It is clear that few transits by seals occurred within the array boundaries and that even fewer of them passed through the swept area discs of the turbines.

However, there is error in the locations of the transits, so to obtain a more precautionary estimate of potential collisions the boundary was extended by +/- 200m. Resampling was then carried out from the distribution of crossing locations by repositioning the array (with turbine spacing fixed relative to each other) within that extended boundary. Six hundred resamples were obtained. The mean and variance of the replicates (Figure 17 and Table 3) were taken as representing the mean and variance of the number of potential collisions. The mean number of times that crossing points, from the telemetry data, coincided with the 86 turbines in the array, over the 600 resamples, was 6.8 (95% C.I. 6.5-7.1).

An alternative estimate of the number of potential collisions with turbines was obtained by placing a single turbine at 1m intervals along each row and recording the number of crossing locations that coincided with the position of the turbine disc in each of 600 replicates. The mean number of times the 14 tagged seals were estimated to have transited through a single turbine was 0.085 (95% C.I. 0.071 to 0.099).

Then for each turbine row the number of potential collisions that the tagged seals might have experienced, in the absence of any avoidance or evasive behaviour, was taken as being the mean number of turbine crossings per row times the number of turbines in that row. This was then summed over the nine rows to produce an estimate of 7.33 (95% C.I. 7.00-7.66) transits through all 86 turbines. This assumes that each turbine location was an independent sample which is not the case. However, both methods produce very similar means and confidence intervals.

The method for estimating the mean and variance based on resampling with the entire array was used to provide the best estimate of the number of times seals in the tagged sample would be expected to pass through the swept area of the turbines in the array (6.8 with 95% C.I. 6.5 - 7.1). The tags in the sample continued to transmit for an average of 93 days giving a total telemetry sample of 3.57 seal years' tracking data.

4.5 Estimating likelihood of collision

The estimate of number of transits through the swept area of the turbines must then be scaled to take account of the likelihood of a collision during those transits. As stated above, these calculations assume no reaction by a seal to the presence of a turbine. In that case, the probability of being hit is simply the probability that a blade will pass through the crossing point during the time a seal is passing through it. This will be a function of the number of blades and rotation rate of the turbine and the dimensions and swimming behaviour of the seal.

In the absence of high resolution track data at appropriate scales for assessing movements around device locations the models to date have assumed that movement patterns are random with respect to the orientation of the turbines. This is unlikely to be the case as the turbines will be oriented with their axis of rotation in line with the flow. Even if seals were swimming randomly with respect to the flow, their resulting tracks would tend to align with the current. Figure 18 shows the frequency distribution of the bearings of swimming tracks (i.e. tracks over the ground) that passed through the turbine array. It is clear that the distribution is not uniform.

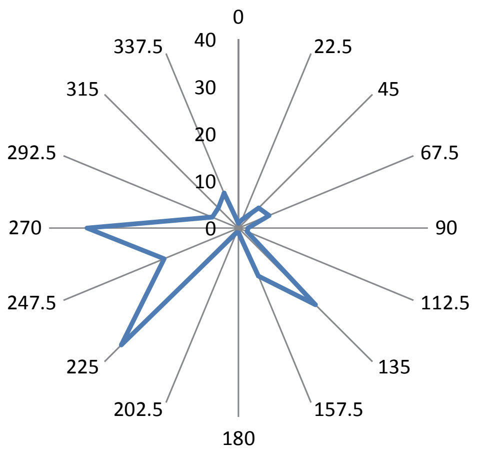


Figure 18. Frequency distribution of swimming track bearings for all tracks passing through the array site.

In order to assess the likely crossing angles, the bearing of the straight line between the previous and next location for each transit across the line of turbines within the turbine array footprint was calculated. Figure 19 shows the frequency distribution of these bearings. As the hypothetical turbines were oriented along a north south line the headings can easily be converted to crossing/transit angles.

A basic assumption of the encounter risk model is that transit angles will be random with respect to the orientation of the turbine. In that case the shape of the animal becomes critical in determining the period during which it is available to be hit by a blade. At a very shallow approach angle the body will be within the swept area of the blade for a long period. The tracking data allowed an examination of the undisturbed pattern of crossing angles. Figure 19 shows the frequency distribution of crossing angles calculated for the turbine array. Few crossing angles are less than 25°. For any angle greater than this the time that a spindle shaped object such as a marine mammal is available will be simply a function of its speed over the ground and its length. If the simplifying assumption is made that a seal is a straight line object of negligible width then the time it is available to be hit is the time taken to pass a particular point on the swept face of the turbine. This is simply the length of the seal divided by the speed, and the angle of approach is unimportant. This makes the simplifying assumption that only collisions with the leading edge of the blade are important. In the case of seals colliding with a turbine blade it is unlikely that collision with the flatter sides of a blade would cause any injury. This is equivalent to the one-dimensional rotor option of the CRM.

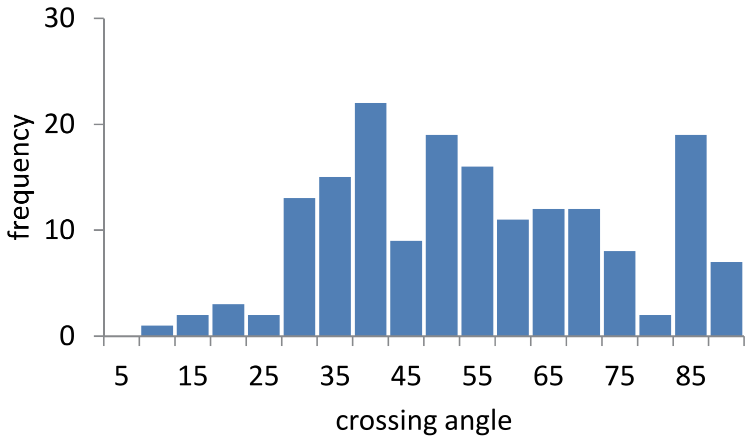


Figure 19. Frequency distribution of crossing angles calculated for the turbine array. Few crossing angles are less than 25°.

Harbour seal length varies between approximately 1m for a recently weaned pup up to 1.8m for a large adult male. The average length of an adult harbour seal is approximately 1.6m. This value is used here as it provides a conservative estimate for the population collision rate. Collision risk simply scales to length, so it is feasible to calculate different collision rates for different seal age/size classes.

Estimates of speed over the ground are made assuming straight line movement at constant speed between successive locations. As the distances between successive points were usually small (of the order of a kilometre or less) the curvature of the planet was ignored and speed simply calculated as the straight line distance between the preceding and succeeding location fixes divided by the time between these location fixes. There is the potential for large errors associated with these speeds as there is no evidence for straight line movement between location fixes, but assuming a straight line implies the slowest possible swim speed between successive points. If the seals swam along a more convoluted path their average swim speed would be faster and the time taken to transit the turbine disc would be shorter.

These errors will tend to overestimate the time of transit so in general they can be regarded as conservative. The speed across the ground between successive location fixes was therefore used as a conservative estimate of transit speed.

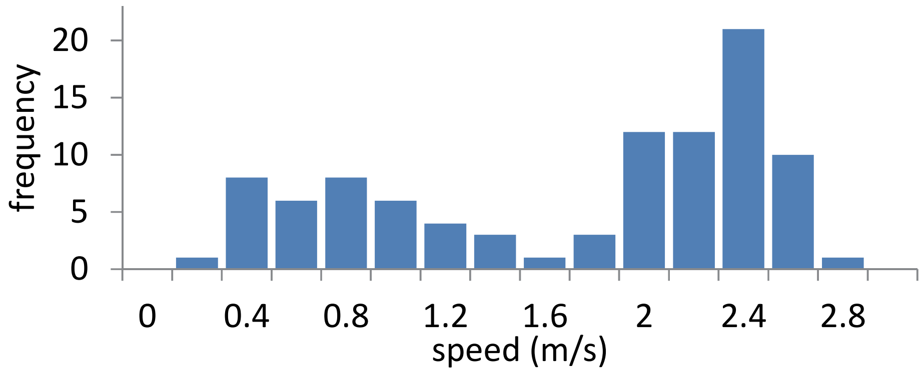


Figure 20. Estimated speed across the ground for all transits across the turbine rows, within the boundary of the turbine array site.

For each transit across a turbine row within the defined array the estimated time to cross the line was calculated, which was simply the length of the seal (assumed to be 1.6m in this case) divided by the speed of transit (Figure 20). Figure 21 shows the frequency of different transit times. Speeds were slightly higher for submerged transits resulting in shorter transit times than for surface transits. Transit speeds and times for submerged swimming were used in the following calculations.

These transit times can be combined with the rotation rate of the turbines to derive a probability of being hit. Table 3 lists those probabilities for turbines with 2 or 3 blades at a range of rotation rates with estimates of the standard error for each configuration. Clearly the fastest rotation rate with the 3 bladed turbine represents the worst case scenario with a probability of 0.85 of a transit resulting in a collision. For simplicity and as a conservative value the mean probability of collision for a 3 bladed turbine rotating at 12 RPM was used as representing the average value for all operating conditions. This gives a probability of collision of 0.67 (standard error = 0.02) for each transit.

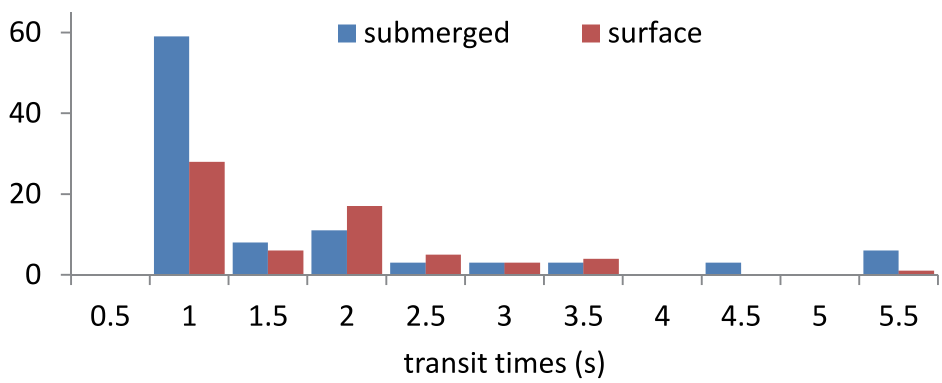


Figure 21. Frequency distribution of estimated transit times for all transits across the turbine rows, within the boundary of the turbine array site: blue bars represent submerged and red bars represent surface transits.

Table 4. Estimated collision probabilities for the estimated transits of turbines.

Rotation rate (RPM)		**12**	**12**	**20**	**20**	**16**
# blades		3	2	3	2	3
interval (s)		1.67	2.5	1	1.5	1.3
transit time (s)		*probability of collision*				
Mean	1.89	0.67	0.53	0.85	0.71	0.75
Standard Error	0.17	0.02	0.02	0.01	0.02	0.02
Median	1.01	0.61	0.40	1.00	0.67	0.76
Mode	0.66	1.00	1.00	1.00	1.00	1.00
Minimum	0.55	0.33	0.22	0.55	0.36	0.41
Maximum	15.02	1	1	1	1	1
N	173					

4.6 Estimating numbers of seals at risk

The estimated number of transits through turbines and the associated estimate of the number of collisions is based on the observed swimming tracks and diving behaviour of a sample of 14 seals fitted with telemetry devices. The seals were tracked for an average of 93 days each, giving a total of 3.57 seal-years of tracking data. To obtain an overall estimate of the number of collisions the number of potential collisions experienced by the sample of tagged seals must be scaled up to the local population size.

There is no clear or unequivocal method for determining the geographical scale over which to sum the population. Clearly the animals tagged at haulout sites in the vicinity of the proposed turbines are most likely to be impacted, but there is potential movement between seal haulouts in both the short and medium term. An analysis of the likelihood of movement between haulout sites as a function of the swimming distance between them is being carried out as part of a parallel project. In advance of that analysis there was an examination of the tracking data from capture sites in different parts of Orkney and the north of Scotland.

Figures 3, 4, 9 & 10 show the tracks of harbour seals tagged at the site in Gills Bay adjacent to the array site in the Inner Sound. Two individuals moved out of the Pentland Firth and used haulout sites on the west coasts of Hoy and Orkney Mainland. However, both returned on several occasions to haulout at sites in and around Gills Bay. It is clear that the majority of seals tagged close to the array site spent all or part of their time transiting through the Pentland Firth presumably as part of their normal foraging behaviour.

There is little tracking information to allow an assessment of the importance of nearby haulout groups. Figure 22a shows the tracks collected to date (November 2014) from four harbour seals tagged in September 2014 at sites on South Ronaldsay. So far none of these seals has moved into the southern half of the Pentland Firth. Figure 22b and 22c show the tracks of harbour seals tagged at sites in the Northern Orkney Isles, in Eynhallow Sound, around the southern coast of Eday in 2012. None of these seals came within 50km of the proposed array site.

The sample of seals tagged at each location is small, and the tracking periods last less than 6 months in most cases, so caution must be used in inferring the distribution of the whole population. However, if it is assumed that these patterns are representative of the behaviour of all seals using these sites on the Caithness coast and around the Orkney archipelago an informed estimate of the size of population likely to interact with the turbine array can be made.

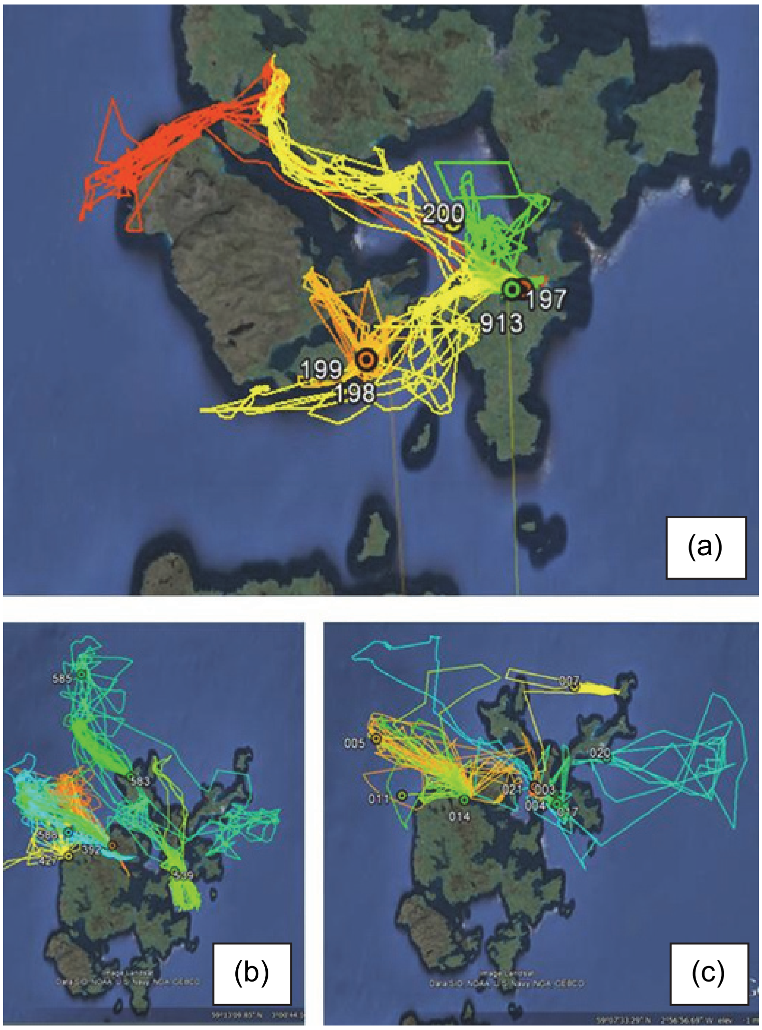


Figure 22. Tracks of harbour seals tagged with GPS/GSM transmitters at sites in the Orkney Islands. a) 4 seals tagged on South Ronaldsay, b) and c) seals tagged at Eynhallow and Eday in spring and autumn respectively. None of these animals moved down into the southern half of the Pentland Firth or the Inner Sound.

Figure 23 shows the distribution and size of all groups of harbour seals counted in SMRU's August air surveys of Orkney and the north Caithness coast. The figure also shows the radial distances from the tidal turbine array site in the Inner Sound.

To include all the seals at sites known to have been used by seals passing through the Inner Sound all haulout sites within a 10km radius of the proposed array site would have to be included. The number of harbour seals throughout the Orkney and North Coast management region has declined dramatically over the past 15 years (SCOS, 2014). The most recent counts for these sites were obtained in August 2013 and produced a total of only 54 harbour seals along the Caithness coast and on Stroma. If this area is expanded to radii of 15km, 20km and 25km the number of seals counted increases to 110, 183 and 361 respectively. Tables showing the counts by site and over the past 20 years are presented in Appendix 1. Counts during the August surveys are estimated to represent approximately 72% (95% C.I. 54-88%) of the total population associated with those sites (Lonergan *et al.,* 2012). For the tidal array in the Inner Sound the estimated number of harbour seals at risk would therefore be 75 (95% C.I. 61-100%).

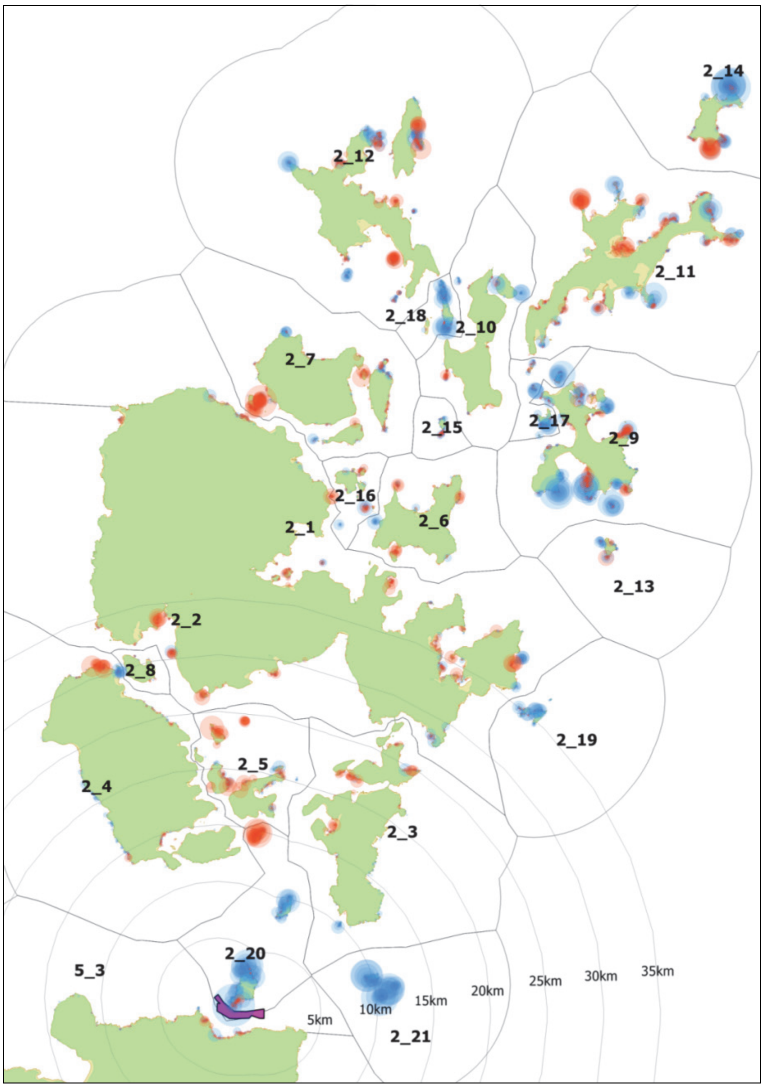


Figure 23. The distribution and size of all groups of harbour (red) and grey (blue) seals counted in SMRU's August air surveys of Orkney and the north Caithness coast. The figure also shows the radial distances from the tidal turbine array site in the Inner Sound. Black figures refer to SMRU survey blocks.

4.7 Estimating numbers of seals likely to be hit (collision risk)

The number of harbour seals that would be expected to collide with turbines in the hypothetical array in one year can be estimated as the product of the number of times tagged seals transited through the swept area of the turbines (Tr), the probability that they would have been hit during the transit (Pc) and the number of seals in the local population (N_{pop}) divided by the number of seal years represented by the tracking data (S_y):

$$N_{hit} = Tr * Pc * N_{pop}/S_y$$

For a single turbine placed at random in the array site the average number of times one of the fourteen tagged seals was estimated to have passed through a turbine was 0.085 (95% C.I. 0.071 to 0.099). Dividing by the sample size and duration of tag data produces an estimate of 0.024 (C.I. 0.020 to 0.028) for the probability that an individual seal would pass through a single turbine in one year. Multiplying that by the estimated number of seals at risk, of 75 (95% C.I. 61-100), produces an estimate of 1.8 (approx. 95% C.I. 1.2 – 2.8) seals passing through each turbine in a year.

For the hypothetical 86 turbine array the average number of tagged seals that were estimated to have passed through a turbine, over the survey period, was 7.33 (95% C.I. 7.00-7.66). Dividing by the sample size and duration of tag data and then scaling up to the local population size produces an estimate of 153 (approx. 95% C.I. 119 – 215) seals passing through a turbine each year in the entire 86 turbine array. Simply scaling the single turbine estimate by 86 produces a very similar estimate of 155 (approx. 95% C.I. 105 – 241) passes per year.

These turbine passage rate estimates must then be scaled by the probability of each pass resulting in a collision. For a 3 bladed turbine with 10m long blades rotating at 12rpm this was conservatively estimated to be 0.67 (95% C.I. 0.63 – 0.71). Applying this to the estimated number of passes suggests that a single turbine in the array would hit 1.2 (approx. 95% C.I. 0.8- 2.0) seals per year and that the array would be expected to produce, not taking into account avoidance or evasive behaviour, 104 (approx. 95% C.I. 66 – 171) collisions per year.

Similarly, scaling the estimate from the full 86 turbine array suggests that 103 (approx. 95% C.I. 73 – 152) collisions would occur per year. Again it is important to remember that this estimate assumes that harbour seals do not react to the presence of operating turbines, i.e. they do not show any avoidance or evasion behaviours and continue to move in the same way through the area when turbines are installed.

4.8 Estimating numbers of seals likely to be killed by strikes

At present a precautionary approach is taken that assumes any collision between a marine mammal and a tidal turbine blade will be lethal. This is unlikely to be true in practice. The severity of injuries that will be suffered during impacts will certainly be related in some way to impact speed and, potentially, point of impact.

Results from collision impact tests could potentially be used to estimate the proportion of collisions that are likely to result in death or serious injury to seals. Over the limited range of collision speeds (up to $5.3ms^{-1}$) tested in a parallel study of collision impact damage to grey seals (Thompson *et al.*, 2015) none were assessed as producing obvious skeletal trauma, muscle tears or organ damage. While the potential for concussion could not be assessed, that study suggested that most collisions at speeds below $5ms^{-1}$ were unlikely to cause fatal injuries, at least to grey seals (harbour seals, being smaller, may be less robust).

The impact speed will be a function of the rotation rate of the turbine and the distance of the impact point from the centre of rotation. The rotation rate of the blade through the water will be a nonlinear function of the current speed; being stationary below some device-specific stall speed and reaching a maximum at some intermediate current speed set by the specific design of the turbine and the local flow conditions. In addition, the speed of any particular point on a blade will be linearly related to the distance from the centre of rotation, being close to zero near the centre even at high rotation rates.

In the absence of other information, the available encounter risk models assume that marine mammals will not react to the presence of a turbine. Therefore it is assumed that the impact point will be at some random point on the blade. The probability that a collision occurs on any particular section of blade will be equal to the proportion of the total swept area that is swept by that section and will be a related to the distances from the centre (e.g. the outer 10% of the blade sweeps 19% of the total area while the inner 10% of the blade sweeps only 1%).

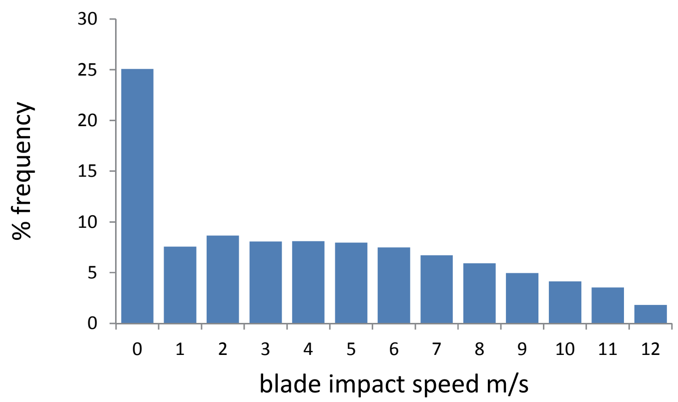


Figure 24. Frequency distribution of estimated blade speeds during collisions with randomly moving seals.

To illustrate the combined effects of the temporal patterns of flow and the position on the blade a frequency histogram of expected collision speeds was generated (Figure 24). The POLPRED package was used to generate estimates of the current speeds at 10 minute intervals over the period 4/3/2014 to 1/4/2014 for a site in the Sound of Islay. These current data were used to generate estimates of the blade speed assuming that the turbine stalls at a current speed of 0.8 $m.s^{-1}$ and reaches a maximum tip speed of 12 $m.s^{-1}$ for current speeds of 2.5 $m.s^{-1}$ and higher. This is broadly similar to the pattern for the SeaGen device in Strangford Lough. Figure 24 shows the frequency histogram of estimated blade speeds for collisions with seals swimming randomly with respect to the turbine position. It is apparent that most collisions would be with slowly moving blades. Under these assumptions, the blade speed in the majority (57%) of collisions would be less than 4 $m.s^{-1}$ (14$km.hr^{-1}$ or 7.8kt).

If these conditions represented the likely range of impacts assuming no avoidance or evasion, Figure 24 should represent the worst case scenario. Where speed of collision and injury can be assessed such as during collisions between pedestrians and motor vehicles, the relationship is sigmoidal, with no severe injuries at slow speeds and high rates of severe injury or death at high speeds (Rosen & Sander, 2009). The transition from low to high injury rates occurs over a narrow speed range. Although it is not known where this transition would occur in marine mammal tidal turbine collisions, the preliminary collision impact trials on grey seals suggest that slow speed impacts are unlikely to cause injuries. It is therefore possible that the majority of collisions would not result in serious injuries or death.

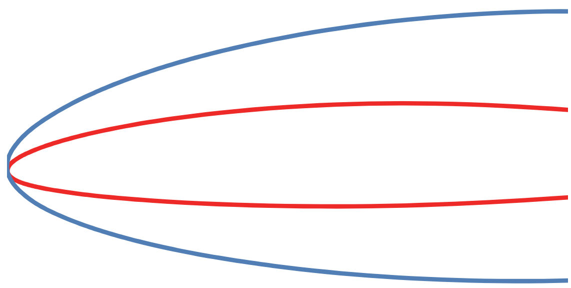


Figure 25. The profiles of the leading edge of a typical tidal turbine. Red profile is the tip and the blue is for a point at 71% of the blade length away from the centre.

The shape of the striking surface is also likely to influence the severity of injuries. The relatively sharp edged tip of a tidal turbine blade seems likely, intuitively, to be the most damaging section. However, the curvature of the leading edge decreases towards the centre of the turbine so that the leading edge becomes more rounded. Figure 25 shows the profiles of the tip of a typical turbine blade and the profile at 71% of the blade length. Over half of the impacts will occur closer to the centre than this so more than half of impacts will be with wider more rounded faces. Towards the inner end of a blade the profile approaches a circular shape with a large diameter. Such rounded shapes should, intuitively, be less damaging than the tip.

If the conclusions from the preliminary trials on grey seals hold, it is unlikely that impact speeds below 5.3 $m.s^{-1}$ would kill an adult of this species, directly. If collisions are at random points on the blade then less than 33 % of collisions would be at speeds above 5.3 $m.s^{-1}$. This suggests that around 2/3 of collisions would be unlikely to be fatal. However, caution is urged in the application of such a simple scaling factor at this stage because it is based upon a limited number of field trials, as well as upon the slightly larger grey seal species, and is unable to address the added risk of concussion or other less obvious injury which may affect an individual's health or vitality.

5. DISCUSSION

5.1 Analysis results

The analysis of telemetry data and population information presented here produced estimates of the potential collision rates for single and array scale deployments of tidal turbines at a specific site in the Inner Sound of the Pentland Firth. The resulting collision risk estimate is substantially lower than estimates derived for the same array site using a collision risk model. The results are specific to that one site, but can be replicated for any site with sufficiently detailed movement and diving data. As a result of targeted research funding from Marine Scotland and Scottish Natural Heritage such data are becoming available at many high tidal energy sites around Scotland. This type of analysis is now possible for several of these sites.

5.2 Accounting for variability

The data used in these calculations come from two main sources: The diving and movement data are from harbour seals fitted with SMRU GPS/GSM transmitters; the population data are from SMRU aerial survey data collected during the annual moult in August.

Count data represent the numbers of harbour seals hauled out and available to be counted at specific times and under tightly controlled environmental conditions. The variability of these counts results from the variability in seal haulout behaviour. This is taken into account when the survey counts are re-scaled to produce population estimates using telemetry derived haulout probability data (Lonergan *et al.,* 2012).

The telemetry devices used here produce accurate location fixes; tests on land demonstrate that after cleaning, 95% of locations have a distance error of less than 50 m. The frequency at which these locations are recorded is determined by a user-set sampling frequency and influenced by the surfacing behaviour of the seals. As a consequence location fixes are less frequent than dives so the locations of specific dives must be interpolated between the location fixes. This interpolation imposes an unknown level of error on the locations of dives. As a consequence, the time at which seals were estimated to pass a particular transect line was likely to be error prone. This in turn means that the positions and depths of the crossing points will also be prone to an unknown error. Attempts were made to incorporate some of that uncertainty into the estimates of collision risk by letting the locations of turbines vary throughout the array and re-sampling to obtain an estimate of the level of variability in the rate of seal transits through the swept areas of the turbines in the array. Estimates derived by summing 86 randomly located individual turbines or from randomly located groups of 86 devices in a fixed configuration were very similar suggesting that the variability in the data is unlikely to have a major effect on the mean collision estimate.

The estimate of number of collisions is the product of the population estimate, the estimated number of transits through the swept area of a turbine and the probability of being hit while transiting the turbine swept area. In a further attempt to avoid under-estimating error during the repeated re-scaling, the confidence limits were estimated by multiplying together the confidence limits for each scaling factor. This may have resulted in an over-estimate of the confidence intervals, but given the uncertainty in many of the assumptions this was taken as a reasonable approach.

The method used to scale the population was ad hoc and based on limited data for harbour seals tagged at haulout sites to the north of the turbine array. Further tagging work is planned for these sites in 2016. However, the main reason for the small sample size in the current telemetry deployment was that few harbour seals were found at the sites on the north side of the Pentland Firth. It is therefore unlikely that future telemetry results will significantly increase the estimated population at risk.

5.3 Comparison with SRSL model estimates

The SRSL model for Inner Sound (Wilson *et al.,* 2007; Batty *et al.,* 2012) calculates encounters per turbine per year for a 3 bladed 10m radius device using two harbour seal density estimates; 6.5seals/turbine/year using boat survey sightings data and 7.7 seals/turbine/year using a density estimate based on SMRU's summer survey counts. The estimate, in this study, for the same device was 1.2 collisions per year, approximately 16-18% of the SRSL estimates, depending on which density figure is used. When scaled up to the full 86 turbine array the SRSL model estimate based on haulout counts is 671 seal encounters per year compared with the mean estimate from this study of 104. Note that this estimate is calculated assuming no avoidance or evasion responses by seals to the presence of a moving turbine blade.

The SRSL model was based on a seal density of 0.202 km^{-2}. It is unclear precisely which sites were included in the total number of seals, but estimating the mean density of the most recent (2013) surveys using the same assumption of even distribution over a 30km radius around every haulout site would produce a seal density estimate of 0.173 km^{-2}. This is 85% of the value used in SRSL's model suggesting that seal density changes are not the main cause of the differences.

Dive profile data used in the SRSL model was provided by SMRU and was extracted from all the dives by harbour seals within the tidal array site. A more detailed inspection of those dives suggests that the proportion of time spent at the surface was underestimated. However, the potential upward bias this would have imposed on the SRSL model output is more than compensated for by the fact that assumed benthic dives did not all reach the sea bed. As a consequence the estimate of the proportion of time at mid-water depths was biased downwards. In combination the two biases will likely have cancelled out. Therefore it suggests that assumptions about dive behaviour were not the primary cause of the different collision risk estimates.

The main driver appears to be relatively fine scale patterns of movement. Collision risk or encounter rate models applied to date in the Inner Sound have been based on the most detailed available data on seal densities. However, the lack of fine scale movement data and fine scale habitat use information means that the models have been forced to assume even distributions of animals and random movement relative to the turbines.

The data presented above clearly show that these assumptions do not hold within the Inner Sound, where seal movements were apparently focused to the west of the array. Telemetry data from harbour seals at locations around the UK suggest that such assumptions could be unrealistic in any area and may be particularly unlikely to provide a useful description of seal behaviour in areas of high tidal energy. For example, harbour seal movement patterns in Kyle Rhea show a different pattern with intense concentration of foraging effort in a small area <1km^2, in the strongest part of the tide (Thompson, 2014) and little activity in the rest of the channel. In that case the fine scale difference in activity would lead to dramatically different collision risk estimates for nearby sites that could be either much smaller or much larger than a model estimate based on assumed uniform distribution.

5.4 Seal mortality

The main driver for developing methods to assess marine mammal collision risk is that regulators must assess the potential damage to protected populations. Legislation dictates that such assessments be based on the best available data and, where necessary, take a precautionary approach. This has led to the assumption that seals will be at risk of collision with tidal turbines and that any such collision should be assumed to be fatal.

As a consequence, even the reduced collision risk estimate produced here will be likely to restrict the permitting of tidal turbines in areas such as the Pentland Firth. However, these estimates do not incorporate any avoidance or evasion factor. They assume that seals will continue to behave in the same way in the presence or absence of turbines. This seems highly unlikely as seals should be able to detect turbines both visually and acoustically and are also likely to be able to modify their behaviour to avoid collisions. Any avoidance/evasion effect would act as a simple scaling factor, but there are currently no data available for any seal species on which to base a value for that factor.

The assumption that all collisions would result in death is clearly wrong. At low collision speeds there is little chance of any injury. Most collisions would be at less than a third of the maximum tip speed. In addition, many collisions will be with the much wider and rounder profiles towards the centre of the turbine. Such collisions are unlikely to be fatal. The results of the preliminary trials, albeit on grey seals, suggest that a significant proportion of collisions are unlikely to be fatal. Further collision trials with seal carcasses in 2016 will refine this estimate.

Even so, the main uncertainty in the assessment of collision and mortality risk is the lack of information on avoidance and/or evasion behaviour in the presence of moving turbine blades. Additional research to assess avoidance behaviour and determine the abilities of seals to evade moving blades will be needed to provide robust, defensible scaling factors.

6. REFERENCES

Band, W., Madders, M., & Whitfield, D.P. 2007. Developing field and analytical methods to assess avian collision risk at wind farms, (de Lucas, M., Janss, G. F. E. & Ferrer, M. eds.) *Birds and Wind Farms: Risk Assessment and Mitigation*, 259- 275pp, Quercus, Madrid.

Batty, R. S., Benjamins, S. & Wilson, B. 2012. MeyGen tidal-stream turbine array environmental impact assessment: modelling encounter rate between turbines and marine mammals. SAMS Research Services Ltd., unpublished report to MeyGen, commercial-in-confidence.

Gerritsen, J. & Strickler, J .R. 1977. Encounter probabilities and community structure in zooplankton. *Journal of the Fisheries Research Board of Canada*, **34**, 73 - 82.

Linley, A., Laffont, K., B. Wilson, B., Elliot, M., Perez-Dominguez, R. & Burdon, D. 2009. Offshore and coastal renewable energy: Potential ecological benefits and impacts of large scale offshore and coastal renewable energy projects. NERC Marine Renewables Scoping Study Final Report, Natural Environment Research Council, Swindon, 127pp.

Lonergan, M., Duck, C. D., Moss, S., Morris, C. & Thompson, D. 2012. Rescaling of aerial survey data with information from small numbers of telemetry tags to estimate the size of a declining harbour seal population. *Aquatic Conservation* **23**, 135-144.

MeyGen Tidal Energy Project Phase 1 Environmental Statement, http://www.meygen.com/the-company/reports-and-documents, accessed July 2015.

Polagye, B. L. 2009. Hydrodynamic effects of kinetic power extraction by in-stream tidal turbines, PhD Thesis, Department of Mechanical Engineering, University of Washington, Seattle, WA.

Rosén, E. & Sander, U. 2009. Pedestrian fatality risk as a function of car impact speed. *Accident Analysis and Prevention*, **41**, 536–542.

SCOS, 2014. Advice on matters related to the management of seal populations, Natural Environment Research Council, 161pp, http://www.smru.st-andrews.ac.uk/documents/2259.pdf.

Thompson, D. 2014. Studies of harbour seal behaviour in areas of high tidal energy: Part 1. Movements and diving behaviour of harbour seals in Kyle Rhea. Sea Mammal Research Unit. Unpublished report to Scottish Natural Heritage. 22pp.

Thompson, D., Brownlow, A., Onoufriou, J. & Moss, S. 2015. Collision Risk and Impact Study: Field tests of turbine blade-seal carcass collisions. Sea Mammal Research Unit, University of St Andrews, Report to Scottish Government, no. MR 5, St Andrews, 16pp.

Wilson, B. & Gordon, J. 2011. Assessment of risk to marine mammals from underwater marine renewable devices in Welsh waters Phase 1 - desktop review of marine mammals and risks from underwater marine renewable devices in Welsh waters On Behalf of The Welsh Assembly Government, JER3688R101122BW Version 4.

Wilson, B., Batty, R. S., Daunt, F. & Carter, C. 2007. Collision risks between marine renewable energy devices and mammals, fish and diving birds. Report to the Scottish Executive, Scottish Association for Marine Science, Oban, Scotland, PA37 1QA.

APPENDIX 1: Numbers of harbour seals (Pv) counted at haulout sites within 10, 15, 20 and 25 km range from the hypothetical array at the Meygen turbine site. Yellow highlights indicate values used in the text.

10 km radius	SPECIES	1989	1993	1997	2001	2005	2006	2007	2008	2009	2010	2012	2013
MAINLAND, SOUTH & WEST	Pv	0	0	0	0		0	0	0		0		0
SOUTH RONALDSAY & BURRAY	Pv	0	0	0	0		0	0	0		0		0
HOY	Pv	0	0	0	0		0	0	0		0		0
FLOTTA,CAVA,RYSA,FARA,	Pv	0	0	0	0		0	0	0		0		0
COPINSAY	Pv	0	0	0	0		0	0	0		0	0	0
SWITHA,SWONA,STROMA	Pv	89	121	57	91	*101*	27	24	14		25		5
PENTLAND SKERRIES	Pv	0	1	0	0		0	0	0		0		0
	Total	**89**	**122**	**57**	**91**		**27**	**24**	**14**		**25**		**5**
PENTLAND FIRTH	Pv			141	208	99	73	102	83		93	94	**49**

15km radius	SPECIES	1989	1993	1997	2001	2005	2006	2007	2008	2009	2010	2012	2013
MAINLAND, SOUTH & WEST	Pv	0	0	0	0		0	0	0		0		0
SOUTH RONALDSAY & BURRAY	Pv	0	0	0	0		18	0	0		0		1
HOY	Pv	0	53	111	32		28	49	22		21		14
FLOTTA,CAVA,RYSA,FARA,	Pv	0	0	0	0		0	0	0		0		0
COPINSAY	Pv	0	0	0	0		0	0	0		0	0	0
SWITHA,SWONA,STROMA	Pv	526	911	535	639	*101*	224	198	150		129		38
PENTLAND SKERRIES	Pv	0	1	0	0		0	0	0		0		0
	Total	**526**	**965**	**646**	**671**		**270**	**247**	**172**		**150**		**53**
PENTLAND FIRTH	Pv			141	208	101	73	102	83		93	95	**57**

20km radius	SPECIES	1989	1993	1997	2001	2005	2006	2007	2008	2009	2010	2012	2013
SOUTH RONALDSAY & BURRAY	Pv	106	40	64	81		92	22	32		35		33
HOY	Pv	7	53	111	58		28	49	22		21		14
FLOTTA,CAVA,RYSA,FARA, BO'BUTR	Pv	479	140	289	377		105	96	50		82		40
COPINSAY	Pv	0	0	0	0		0	0	0		0	0	0
SWITHA,SWONA,STROMA	Pv	526	914	535	683	*101*	240	206	184		129		39
PENTLAND SKERRIES	Pv	0	1	0	0		0	0	0		0		0
	Total	**1,118**	**1,148**	**999**	**1,199**		**465**	**373**	**288**		**267**		**126**
PENTLAND FIRTH	Pv			141	208	101	73	102	83		93	95	**57**

25km radius	SPECIES	1989	1993	1997	2001	2005	2006	2007	2008	2009	2010	2012	2013
SOUTH RONALDSAY & BURRAY	Pv	267	336	363	427		132	80	58		100		96
HOY	Pv	36	88	120	64		47	51	22		21		15
FLOTTA,CAVA,RYSA,FARA, BO'BUTR	Pv	690	801	575	596		359	258	164		180		154
COPINSAY	Pv	0	0	0	0		0	0	0		0	0	0
SWITHA,SWONA,STROMA	Pv	526	914	535	683	*101*	240	206	184		129		39
PENTLAND SKERRIES	Pv	0	1	0	0		0	0	0		0		0
	Total	**1,519**	**2,140**	**1,593**	**1,770**		**778**	**595**	**428**		**430**		**304**
PENTLAND FIRTH	Pv			141	208	101	73	102	83		93	95	**57**

www.snh.gov.uk

ISBN: 978-1-78391-360-2

Policy and Advice Directorate, Great Glen House,
Leachkin Road, Inverness IV3 8NW
T: 01463 725000

You can download a copy of this publication from the SNH website.

recycle

Scottish Natural Heritage
Dualchas Nàdair na h-Alba
All of nature for all of Scotland
Nàdar air fad airson Alba air fad