Harbor Seal – Tidal Turbine Collision Risk Models. An Assessment of Sensitivities.

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Executive Summary

There has been growing interest in generating electricity from tidal currents, but there are still concerns about the potential environmental effects of tidal turbines. One of these concerns is the risk of collision by marine mammals with spinning tidal turbines. Most estimates of marine mammal collision risk with tidal turbines have used either an Encounter Risk Model (ERM) which is based on a predator-prey model, or a Collision Risk Model (CRM) which was first developed for predicting bird collisions with wind turbines. CRM estimates are based on transit rates of the animals and the probability of collision for each transit.

In order to explore the sensitivities of the collision risk models to various inputs, we analyzed data that were available to us from the Strangford Lough MCT SeaGen project. We had access to tagged seal data from 2006, 2008 and 2010 as well as turbine and current data starting after the installation of the turbine in 2008 through 2010. Seal tags provided information on the timing and location of seals as well as their dive depth. We also had measures of current speed, direction and turbine RPM. Based on tidal data for Strangford Lough, we estimated current speed and direction at other times during which we had seal tag data. Based on analyses of the seal tag and current data, the following patterns emerged:

- Seal vectors (i.e. seal swim speed and direction from GPS tag locations):
  - Given the dominant aspect of current in a tidal environment, the direct use of seal vectors over ground (as measured from one GPS location to the next) is cautioned.
  - Calculating seal vectors through the water, but accounting for the current vector and the seal vector over ground is more appropriate.
  - In this dataset, seals swam in all directions over ground and in relation to the current, however, seals almost exclusively swam into the current.
  - Seal swim speed through the water tended to increase with increasing current velocity.
- Seal dives:
  - Seal dives in Strangford Lough tended to follow a 'U' shape and were similar to dives reported at other sites.
- Seal habitat use:
  - Seal habitat use across Strangford Lough was not uniform.
  - Seals in Strangford Lough tended to do most of their diving in areas outside of the highest current flow areas.
- Seal Avoidance:
  - Using Brownian Bridge methods to interpolate seal movement between GPS locations suggests that within 200 m of the turbine, ~66% of seals in 2008 and 2010 avoided the area, when compared to 2006.
  - Caution should be used in interpreting this estimate of avoidance as there is a great deal of inter-individual difference between seals in each year of data, this trend is inferred from few tagged seals.

The exploration of collision risk model sensitivities showed the following trends:

- Use of the tip speed ratio of the SeaGen turbine decreased collision risk by 12%
- Use of the turbine RPM across a tidal cycle instead of average RPM increased collision risk by 5%.
- Use of seal swim speeds through the water measured in Strangford Lough increased collision risk by 3%.
- Seal swim direction (upstream vs downstream) increased CRM estimates by 10%
- The assumption of a 'U' shaped as opposed to a 'V' shaped dive, decreased collision risk estimates by 63%, but it was clear that the dive data from Strangford Lough, and other tidal sites, that seals consistently use 'U' shaped dives in these areas.
- Seal 'density' had the biggest effect on collision risk estimates. Use of measured transit rates in Strangford Lough, reduced collision risk estimates by 27% from estimates based on average seal density.
- Avoidance has a direct multiplicative effect and therefore reduced collision risk by 66%.

It is clear from the Strangford Lough data, that seal tag data can greatly inform and improve collision risk estimates, however, it would be preferable for the growth of the tidal turbine industry if such in depth research were not needed at every tidal turbine site. There are four other potential tidal turbine sites, in addition the Strangford Lough, where seals (harbor or grey seals) have been tagged. These data could provide needed information to verify if seals use these different habitats in similar or different ways. To date, the analyses of these data have shown the following trends:

- There is a high degree of inter-individual variation in the use of tidal areas.
- Local abundance varies by tidal cycle and thus collision risk is not equal over the tidal cycle.
- Depth distributions of diving seals are similar across sites with most time spent at the surface or seabed.

Seal morphometric data from the San Juan County Marine Mammal Stranding Network may help inform models that predict the consequences of collision. The harbor seals in this dataset are on average small compared to other populations. The majority of adults were classed as in good nutritional health while the majority of subadults and pups were in poor nutritional state.

Based on the above findings we suggest the following priorities for future work:

- Avoidance needs to be further investigated to understand how it varies with distance from turbine, across individual, tidal state and locations.
- Fine scale habitat use needs further refinement as this also has large implications in collision risk. This includes inter-individual variability, as well as variation across tidal state, current speeds, current directions and across sites.

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1. Introduction

1.1 Background

A number of governments around the world have implemented targets for the generation of alternative (i.e. non-fossil fuel) energy. This has led to the expansion of alternative energy generation using relatively mature technologies (e.g. wind and solar) and the development of new technologies, including Tidal Instream Energy Converters (TISEC) which convert the energy of tidal currents into electricity. Along with the development of these new technologies, there has been a concerted effort to understand their potential environmental effects, especially the risk of collision of marine mammals with tidal turbines (Polagye et al. 2011). To date, there is still a large degree of uncertainty about marine mammal collision risk because a) pilot projects have not happened in areas with sufficient numbers of marine mammals, b) tidal operators have not monitored for collisions of marine mammals, or c) tidal operators were required to shut the turbine down when marine mammals were located near the turbine so as to avoid potential collisions.

This has meant that predictions of the environmental effects of marine mammals colliding with tidal turbines has been reliant on collision risk models. While these models do provide quantitative estimates of collision risk, estimates can vary a great deal depending on the modeling approach as well as the uncertainties in input parameters for those models. Consequently there is still too much uncertainty in collision risk estimates to 'retire' this stressor and remove this risk as a potential regulatory hurdle. In order to decrease the uncertainty in collision risk estimates, this project focused on harbor seals and MCT-SeaGen style horizontal axis rotor turbines and had the following goals.

- Implement and test current collision risk models to assess their sensitivity to input parameters using empirical data from the Strangford Lough MCT SeaGen tidal turbine project.
- Review other currently available seal datasets that might allow further refinement of collision risk models.
- Provide harbor seal morphometric data to inform future models that predict the consequences of a collision to individual harbor seals.
- Provide priorities for future research that could reduce uncertainty in collision risk models.

1.2 Project Description

The probability of a collision between a marine mammal and a tidal turbine depends on the following (Thompson et al. 2014):

1) The characteristics of the turbine (location, size, rotation speed, spacing, etc.).
2) The short term (> 1 day) and seasonal movement patterns of animals (or density estimates).
3) The dive patterns, depth usage and small scale movement patterns of individual animals.
4) The reactions of animals to the presence of devices (avoidance, attraction, evasion).

In Section 2 of this report, we implement two standard collision risk models and parameterize them with inputs and assumptions similar to those used by Band (2014) and use this as our 'standard' model with which to evaluate model input sensitivities. We then alter these standard inputs and assumptions with empirical data collected at Strangford Lough to assess the sensitivity of the collision risk models. While we do explore the sensitivity of the collision risk models to inputs related to all four of the points listed above, we focus most of our attention on **Points 3 and 4**. We do this for the following reasons.

Turbine characteristics (**Point 1**) are set for a given project. Their main design criteria are determined long before a project or deployment site is considered. That is not to say that they do not affect collision risk, but they are, in practice, parameterized by the developer and turbine manufacturer and thus do not lead to collision risk uncertainty for any given tidal turbine project. For a more thorough evaluation of the effects of turbine characteristics on collision risk, the reader is referred to Band (2014).

Short term and seasonal movements of animals (**Point 2**) have obvious implications to collision risk as they affect density, which in turn has a direct multiplicative effect on collision risk. This can therefore have a large effect on collision risk estimates (e.g. Band 2014), but decreasing the uncertainty due to this input parameter can only be achieved by improved estimates of animal movements or density at the project site. While we do explore these inputs as part of this project, seal tag related data from Strangford is restricted between March-and July making seasonal comparisons of movements and resulting changes in density impossible.

We do, however, extensively review the available Strangford Lough seal tag data to assess collision risk sensitivity in regards to **Points 3 and 4** which were an agreed upon focus in the scope of work discussed prior to starting this project. In relation to **Point 4**, different authors working on different systems have used avoidance, attraction, and evasion in different ways. To avoid confusion, we define these terms for this project in the following way. **Avoidance** is the deliberate movement of an animal away from an object (in this case a tidal turbine) at ranges at which the turbine is detectable to the animal, but at which there is no immediate danger of collision. **Attraction** is the opposite of avoidance in that the animal moves towards the object in question. **Evasion** is the attempted movement away from an object at close range to the object. The implication here is that it is possible that an attempt to evade a turbine may be unsuccessful due to proximity to the turbine (i.e. there is an immediate risk of collision if evasion fails), whereas a 'failure' to avoid an object would not result in an immediate collision.

Section 3 provides a high level synopsis of seal datasets collected around tidal turbines or in areas where tidal turbine projects have been proposed. A more detailed review of these datasets is provided in **Appendix 3**. This is provided to highlight datasets that might help inform further refinement of collision risk model inputs related to seals.

Section 4 provides a description and synopsis of harbor seal morphometric (seal size, weight, etc.) data collected by the San Juan County Marine Mammal Stranding Network. The dataset itself is provided as a companion Excel spreadsheet to this report. These data are provided to inform models that predict the level of injury likely to be sustained by a seal if a collision were to occur (e.g. for killer whales, Carlson et al. 2014). And finally, **Section 5** discusses priorities for future work given the findings of the previous sections.

2. Risk Models

This section of the report deals with the first goal of this project. Namely:

- **Implement and test current collision risk models to assess their sensitivity to input parameters using empirical data from the Strangford Lough MCT SeaGen tidal turbine project.**

We do this in several stages. Section 2.1 introduces the risk models and their input parameters. Sections 2.2 and 2.3 present data collected as part of the Strangford Lough MCT SeaGen tidal turbine project. This includes both data on the turbines themselves (Section 2.2) and seal tag related data (Section 2.3). The purpose of these sections is to explore these datasets and the sensitivity of the collision risk models to these inputs, where appropriate. Figures in these sections that depict seal collision risk on the y-axis, are not meant to give absolute collision risk estimates, but rather to give the reader an estimate of the change in whichever parameter is depicted on the x-axis. All other input parameters are kept constant within these plots. It is also important to point out that the confidence intervals in these plots are solely a result of the confidence intervals of the seal density data used as an input and are not related to the parameters being depicted in those figures.

In Section 2.4 we work sequentially through the strike risk models starting from a model that uses the least amount of site specific information, to a final model that is informed as best as possible by the Strangford Lough data. The rationale for this was that site specific studies add costs to tidal turbine projects. By comparing collision risk model outputs using assumptions versus site specific data we can help prioritize the collection of site specific data. This section, in other words, assesses the sensitivity of the collision risk models to various inputs. We also compare the collision risk models and discuss their relative merits.

2.1 The Models and their inputs

There are two main risk models that have been used in the marine renewable energy sector. These are the Encounter Risk Model (ERM, Wilson et al. 2007) and the Collision Risk Model (CRM, Band 2012). Both these original models have been modified in the sections below to reflect the reality that the turbine rotors have a maximum speed of rotation. At current speeds in both ebb and flood directions, flows at greater than 2.3 m/s results in no further increases in the rotational speed of the turbine blades. The input parameters in the two models have been labeled so that the same inputs are labeled the same way between the two models to aid in comparisons between the models.

2.1.1 The Encounter Risk Model (ERM)

The ERM model is based on a predator-prey model that estimates the number of encounters between a predator (turbine blade) and its prey (diving animal), and is expressed in the following equation

$$\begin{aligned}\text{No of collisions} &= \text{Density per } m^3 \times \text{No. of blades } \times \text{blade area } \times \text{relative speed of animal to blade}\\ &= D \times b \times \left((c\ sin\gamma + 2\frac{L}{f})(R + \frac{L}{f}) \right) \times (\Omega\, \pi R + \frac{u_a^2}{3\, \Omega\, \pi R})\\ &\text{and } \Omega = \frac{\lambda\ min(v,\ 2.3)}{2\ \pi\ R}\ \text{, the rotational speed of the blade.}\end{aligned}$$

Equation 1

where D = Density of seals per m^3

b = Number of spinning blades on the turbine

c = Chord width of the blade

γ = Pitch angle of the blade relative to the horizontal plane

L = Length of the seal

f = 4; a constant that defines the seal's effective cross section as that of a `long stick shaped' prey

R = Blade length, or radius of the turbine

λ = Tip speed ratio, a constant that determines the relationship between current speed and the rotational speed of the turbine blade

v = Velocity of the water current at the turbine

Ω = Rotational speed of blade in revolutions/s. At Strangford Lough, the maximum rotational speed
is reached at current speed, v=2.3 m/s.

u_a = Seal swimming speed relative to the water

The ERM defines density of seals per m^3, D, as the density of seals 'at risk' of collision with the turbine blades. However, not all seals are at risk of collision with a turbine blade, as only a proportion, Q, of seals will be located at the depth at which the turbine is located. When only surface density of seals, D_A, is known or estimated, such as numbers derived from MMO survey observations, the translation to density of seals per m^3, D, is done by dividing surface areal density D_A by the turbine diameter, and multiplying by the proportion of time that seals are found in the range of turbine depth, i.e.,

$$\text{Density per } m^3 = \frac{D_A \times Q}{2\ R}$$

Equation 2

The terms in the ERM that describe `blade area' describe the length and width of the blade with allowance in both for the effective radius of the seal (i.e. a seal encounters a blade whenever the area of the prey overlaps with the area of the blade). The swimming seal is assumed to have a non-spherical shape such that their profile at-risk-of-collision is long and thin, and aligned to have a minimum cross-section relative to the turbine blade. Band (2012) sets the limit for the effective radius of a long thin prey with random alignment relative to the blade at L/4. Therefore, $c\ sin\gamma$ describes the width of the turbine blade, as viewed along the direction of relative approach. To allow for the overlap between blade and seal we add 2L/4, or two times the effective radius of the seal following Band (2014). The two is included because it is assumed the blade could collide with either the upper or lower blade edge. Likewise, we add L/4 to the blade length.

The relative speed of the approaching seal to the turbine blade is calculated under the assumption of a (random) uniform distribution around a sphere; the sphere permits the assumption of random orientation and direction with respect to the current flow into the spinning blades. Following Wilson et al. (2007) and Band (2014), we initially assumed (and later show in **Section 2.3.1**) that blade speed at currents > 1 m/s exceed seal swim speed. Therefore, the mean speed of the approaching seal is a function of both current velocity that informs rotational speed of the turbine blade, and seal speed. At water currents <2.3 m/s, the rotational speed increases and the relative strike risk increases as the ERM assumes a constant average swim speed through the water. At currents >2.3 m/s, however, the rotational speed stays constant, as does the relative strike risk under the assumption of constant swim speed through the water. It is important in understanding the ERM that it considers the swimming speed of the animal in the strike risk calculation, as this is an important differentiation from it and the CRM.

By multiplying the cross-sectional blade area measured in m^2 by the relative approach speed of the seal to the blade in (m/s), we have described the volume of water swept per unit time. The ERM estimate of the number of collisions is therefore given as number of collisions/s. The ERM is modified to account for non-operational current speeds (i.e. cut-out speeds at <1 m/s), and can be (and is here) modified further if there is a speed threshold above which the turbine's rotational speed is already at maximum.

2.1.2 The Collision Risk Model (CRM)

In contrast, the CRM model was originally developed to estimate the collision risk of birds to terrestrial wind turbines. It estimates collision risk by first estimating the number of transits by animals past a turbine and then multiplies this transit rate by the risk of collision during a single transit (Band 2012) as follows:

$$\text{No of collisions} \quad = \quad \text{No of transits} \times \text{Risk of collision during a single transit}$$

Equation 3

It is possible that the number of transits can be directly estimated if some kind of in-situ underwater monitoring of the turbine blades records numbers of transiting animals (e.g. the SeaKing sonar used in Sparling and Lonergan (2013) to estimate seal transit rate). In this case, number of transits enters directly into the CRM. If a surface estimate of seal density is available, it must be translated, as in Equation (2) of the ERM, to density (*D*) per m^3 and then to number of transits per unit time as follows:

$$\text{No of transits} = D \times \pi R^2 \ \times \ v$$

Equation 4

Number of transits is a function of current speed, such that the formula describes how many seals pass through the turbine blades per second in a cylinder with area $\pi R2$ and length v, where v, or current speed, is measured in m/s.

The CRM also calculates the risk of collision during a single transit. The probability of a collision at distance *r* along the blade for a single transit through the spinning blades of a turbine, *p(r)*, is calculated as follows:

$$p(r) \;=\; \frac{b\Omega}{2\pi v}\left[\;|\;c\;\alpha\;cos\;\gamma\;\pm\;c\;sin\;\gamma| + max(L,\;L\frac{\alpha}{f}\;)\;\right]$$

$$\text{where } \alpha = \frac{v}{r\;\Omega}$$

$$\text{and } \Omega = \frac{\lambda\;min(v,\,2.3)}{2\;\pi\;R}\;,\text{ the rotational speed of the blade.}$$

Equation 5

where *b* = Number of spinning blades on the turbine

v = Velocity of the water current at the turbine

c = Chord width of the blade

γ = Pitch angle of the blade relative to the horizontal plane

L = Length of the seal

f = 4; a constant that defines the seal's shape as that of a `long stick shaped prey'

λ = Tip speed ratio, a constant that determines the relationship between current speed and the rotational speed of the turbine blade

Ω = Rotational speed of blade in revolutions/s. At Strangford Lough, the maximum rotational speed is reached at current speed *v* = 2.3 m/s.

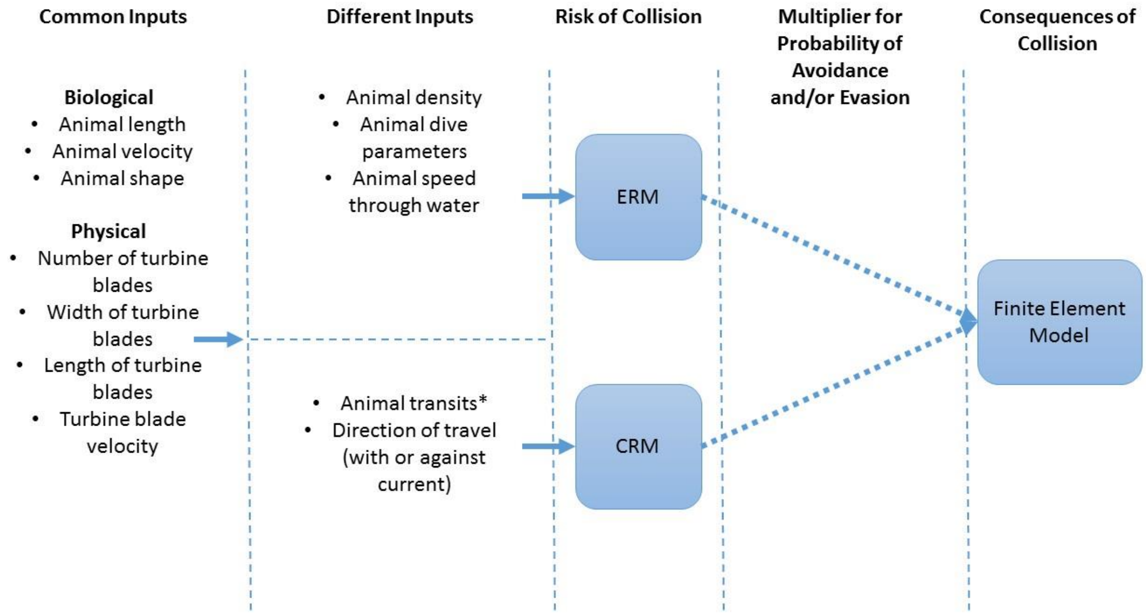
R = Blade length, or radius of the turbine

p(r) is then summed, or integrated, for chord widths along the length of the blade to give the collision risk for one seal transit through the rotors.

Geometrically, the *c α cos γ* term describes the proportion of a circle of radius *r* that is occupied by rotor blades. The terms ±*c sin γ + max (L, L/f α)* describe the time taken for the seal to clear both the width of the blade from back to front, and for it to fully clear its own length. But, as *Ω* is exactly linked to *v* by the tip speed ratio λ, the single transit collision risk, perhaps surprisingly, does not depend on the speed of the water current when it is <2.3 m/s. In the CRM, it doesn't matter how fast an animal approaches, the proportion of the rotor area 'blocked' to passage is the same, and the chance of passage without contact with blades is determined by the relative position of animal and blades, and not on the current speed. Instead, the collision risk depends on 1) the geometry of the turbine through the number of blades, 2) the pitch angle, 3) the chord width of the blade (and how this varies over the length of the blade), 4) the radius of the blade, and 5) the length and effective radius of the seal, at current speeds <2.3 m/s.

However, when rotational speed of the blades have reached their maximum at current speeds >2.3 m/s, there is a decoupling between strike risk and current speeds. At this speed threshold, the water current that is assumed to carry the seal gets faster, but the rotational speed of the blades stays constant; this translates to a decline in the per transit collision rates as the time spent in the strike risk zone between the blades is shorter.

In conclusion, the two collision risk models have very different origins but both estimate collision risk per unit time. Figure 1 is provided to illustrate the common and different data inputs to the ERM and CRM and how their results might be used in models of the consequences of collision.



*Animals transits through the turbine swept area incorporates animal dive parameters.

Figure 1 Depiction of the common and different inputs into the ERM and CRM models, how avoidance and evasion are incorporated into their outputs and how these in turn might be fed into a consequences of collision model.

2.2 Strangford Turbine Data

In this section we present likely assumptions that would be made for turbine related collision risk model inputs if one did not have specific data to inform these inputs. We then present SeaGen data collected in Strangford Lough and discuss how the assumption based versus empirical based model inputs will likely affect collision risk estimates. The only turbine related parameter we examined was the turbine speed, as this was the only variable we had access to.

The Strangford Lough SeaGen turbine was installed in 2008 in 25 m deep water (with fluctuations of 2 m due to tidal variation), and is moored to the sea floor 400 meters from the closest shore. The turbine is optimally designed to operate for more than 20 out of 24 hours, and with top rotational rates greater than 10 revolutions per minute (RPM). The two turbine rotors are propelled by tidal flows that stream in and out of Strangford Lough at speeds of up to 4 m/s. The turbines do not rotate if the tidal speed drops below 1 m/s. Turbine related data were collected from sensors on the turbine. The data included current velocity and direction, as well as turbine RPM. These sensors did not work continuously, but we had access to data from August 2008 through December 2010.

2.2.1 Velocity of the turbine blade

This section explores the relationship between turbine blade velocity and collision risk estimates. The CRM model calculates a changing blade velocity based on the number of blades on the turbine, the 'tip speed ratio' or λ (velocity of the blade tip / current velocity), the turbine blade size and the current velocity. Because much of this information is not commonly available from turbine developers, Band (2014), based on tidal energy literature, assumed a tip speed ratio of 6 for two bladed turbines and 5 for three bladed turbines. Both the RPM and current velocity were recorded during turbine deployment. These are plotted in Figure 2 as well as the assumed Band (2014) RPM predictions for 2 bladed turbines. If one optimizes the tip speed ratio to the measured SeaGen data, one finds the best fit at a tip speed ratio of 5.1. To explore the effect of tip speed ratio on collision risk, we ran the ERM and CRM models with different tip speed ratios (Figure 3). As tip speed ratio increases, so does risk, therefore using the empirical SeaGen tip speed ratio of 5.1 decreases collision risk relative to that calculated using an assumed value of 6.

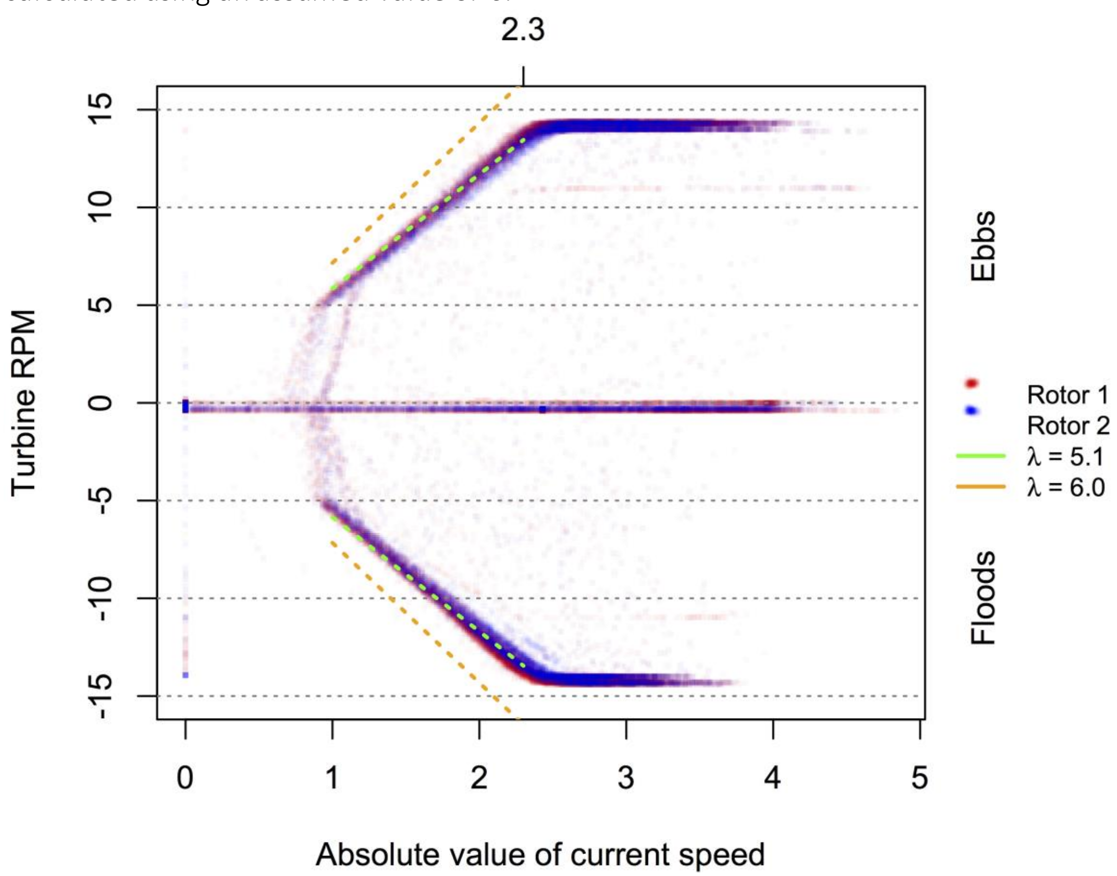


Figure 2 Plot of recorded SeaGen turbine speed (RPM) versus current speed (m/s) in Strangford Lough. Both rotors are depicted, one in blue and the other in red. Cut in speed for the rotors is 1 m/s and RPM increases until a current speed of 2.3 m/s is reached; at which time the rotors feather and RPM does not exceed 14.4. The tip speed ratio, λ, determines the relationship between current speed and the turbine blade's rotational speed. For comparison to Band (2014), his 2 bladed estimate is shown for λ=6, we also show λ=5.1 which was optimized for the SeaGen in Strangford Lough.

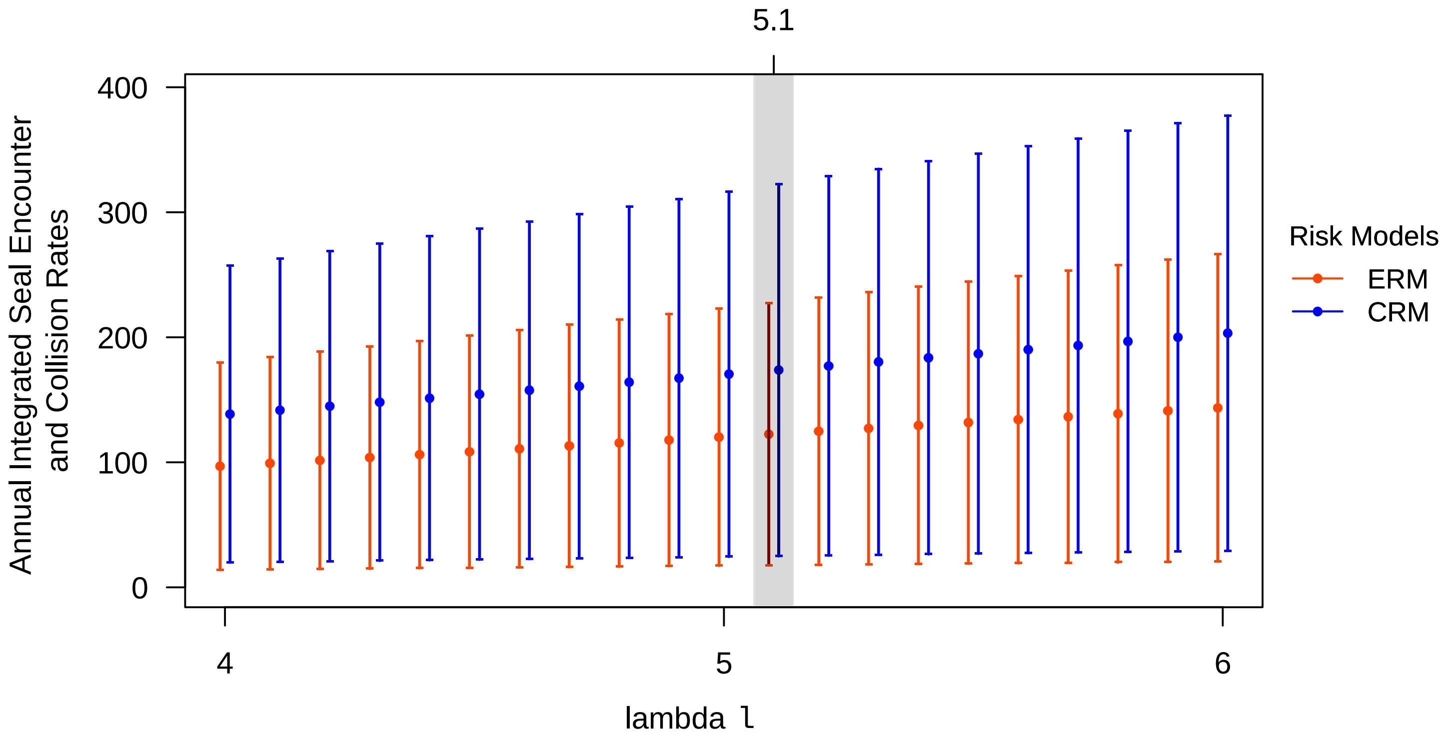


Figure 3 Relationship between tip speed ratio (λ) and collision risk model estimates.

2.3 Strangford Seal Data

In this section we present likely assumptions that would be made for seal related collision risk model inputs if one did not have specific data to inform these inputs. We then present seal data collected in Strangford Lough and then discuss how the assumption based versus empirical based model inputs will likely affect collision risk estimates. We split this section by the four areas where Strangford Lough seal tag data could inform collision risk model inputs. These are seal swim speed and direction, seal dives, seal 'density' and seal avoidance. The reader is reminded that the section on seal swim speed and direction (**2.3.1**) use analyses in 2-D while the section on seal dives (**2.3.2**) deals with the third vertical dimension. As such, for the purpose of simplifying analyses, they ignore other dimensions. For example, the swim speed through the water is a minimum estimate as it is calculated between two points on the surface, while the seal may have taken a circuitous route underwater to get from one point to the next.

As part of the environmental monitoring program at the SeaGen project, harbor seals were tagged in 2006 (12 animals), 2008 (9 animals), and 2010 (12 animals) with SMRU GPS/GSM tags which record the animal's location and depth over time. The Strangford Lough deployments were the first ever deployments of GPS/GSM tags (Hastie et al. 2014). The tags were designed to collect GPS location data and information on diving and haul-out behavior and relay the data through mobile telephones incorporated into each instrument. The three time periods of tag deployment were as follows: in 2006 (April– July, pre-installation, 'pre'), in 2008 (March–July, during installation and commissioning, 'construction') and in 2010 (April–July, turbine operation, 'operational'). The seals were captured in the

Strangford Narrows and the southern islands in Strangford Lough. Animals tagged contained similar mixes of age and sex across the 2006, 2008 and 2010 deployments (Savidge et al. 2014). Further details on the MCT SeaGen project and seal tag data can be found in (Keenan et al. 2011, Savidge et al. 2014).

The seal tag data were provided by the Sea Mammal Research Unit (SMRU), University of St. Andrews, to us in Access databases with tables for 'GPS' data and 'dive' data. To save power and memory space, the seal tags were programed to record a GPS location at regular intervals. In 2006 and 2008, the GPS tags were programmed to transmit a location signal every 20 minutes, whereas in 2010, tags transmitted every 10 minutes. However, because the seals dive, the Fastloc GPS is not able to measure a position at regular intervals and not every surfacing results in a location being recorded. These data are recorded in the 'GPS' tables. The tags also record the depth of the seal during each dive. Therefore, there are dives that do not have a location recorded by the GPS unit. These were instead linearly interpolated by SMRU from the GPS data and stored in the 'dive' tables. This distinction is made as we used the 'GPS' and the 'dive' locations for slightly different analyses. The sample size from the tag data are presented in Table 1. As we were interested in seal data specific to the tidal areas around the SeaGen turbine, we subset the seal tag data by only using tag data with locations within Strangford Narrows (Figure 4).

Table 1 Sample size of seal 'GPS' and 'dive' tag data.

Year	'GPS' sample size	'GPS' Strangford Narrows sample size	'Dive' sample size	'Dive' Strangford Narrows sample size
2006	12,744	3,340	187,533	33,590
2008	9,441	3,605	186,986	37,331
2010	49,897	25,765	211,262	69,559

In 2006, there were 9 out of 12 tagged animals that swam through the narrows past a line drawn from the north to south shores at the turbine. In 2008, there were 7 out of 9 tagged seals, and in 2010 there were 9 out of 12 tagged seals that swam through the narrows.

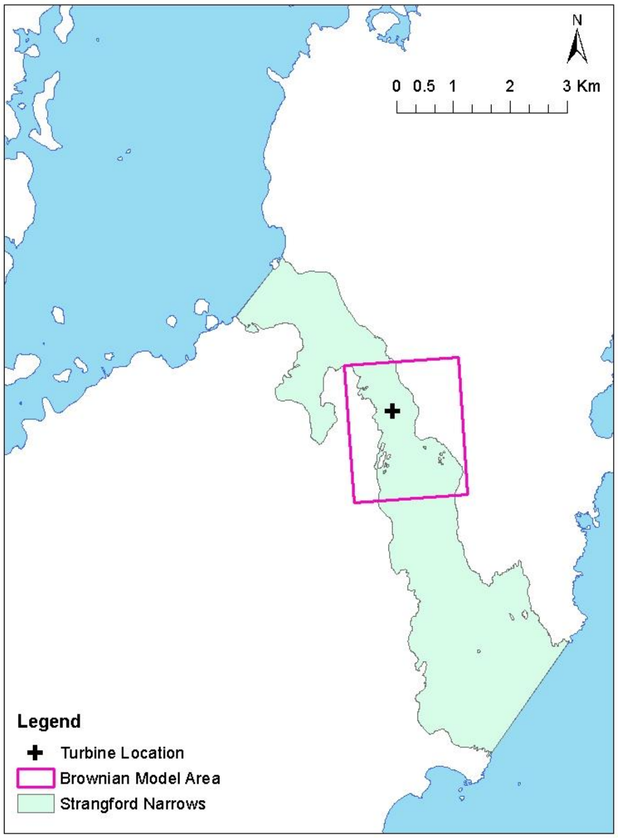


Figure 4 Map of study area showing the SeaGen turbine location, the Brownian model area used in Section 2.3.4, and the Strangford Narrows.

2.3.1 Seal swim speed through the water

This section explores the relationship between seal swim speed and direction through the water and collision risk estimates. If one did not have specific swim speed and direction information from seals in a tidal inlet, an average swim speed of 1.2 m/s could be used(Lesage et al. 1999, Band 2014), with random assumptions about direction of approach (i.e. 50% upstream, and 50% downstream). The problem with this approach in tidal areas is that, just as pilots on long flights must account for the combined vectors of their speed and direction through the air and the speed and direction of the air itself to calculate their actual speed and direction over ground, seal movements within tidal inlets also need to account for the movement and direction of the water through which the seals are moving. This is especially true for seals given that typical seal swim speeds are not that different than the current speeds in tidal inlets.

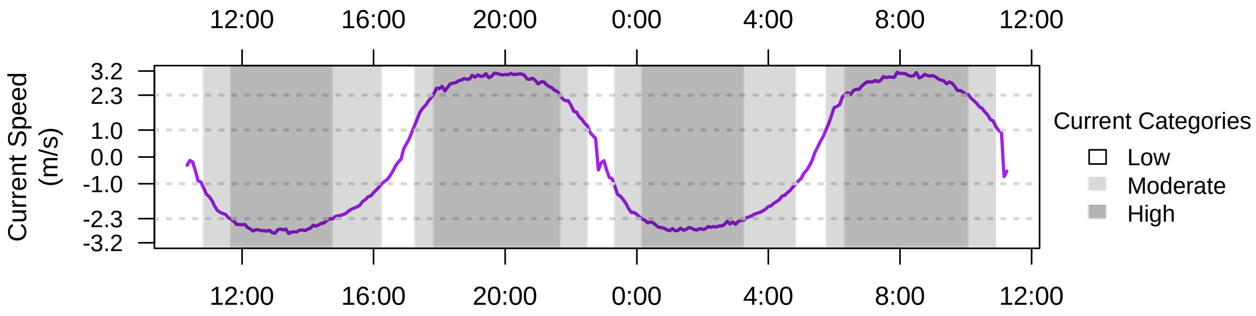


Figure 5 Current velocity as measured at the SeaGen turbine (purple line) between 10:15 June 23 2010 and 11:15 June 24 2010. Shades of grey show the current velocity classes low (<1 m/s; turbine blades not rotating), moderate (between 1 m/s and 2.3 m/s; blades moving at less than maximum rotational speed), and high (>2.3 m/s; blades have reached maximum rotational speed).

The seal tag data can be mined for information about swim speed through the water. Tag data can be used to inform us directly about seal swim behavior in the vicinity of the turbine, particularly about how changes in turbine rotational speed can affect seal strike risk as swimming patterns adapt to changes in current velocities (Figure 5). For example, we can partition the tag data into current velocity classes that match when the turbine is not spinning (low: <1 m/s), increasing rotational speed (moderate: between 1 m/s and 2.3 m/s), and when the turbine has reached maximum rotational speed (high: >2.3 m/s). These swim speed patterns can be included in models where appropriate. For example, the ERM directly incorporates animal swim speed (through the water) into the risk scaling. The model assumes an average swim speed through the water regardless of the current speeds. The risk scales up through the increases in rotational speed of the turbine blades. When the maximum rotational speed of the blades has been reached at 2.3 m/s, the relative risk stays constant if swim speed is an average that is also assumed constant.

There is no direct assumption for seal speed in the CRM; it assumes that the animal swim speed is the same as the current with random alignment relative to the blades, but allows for animals approaching from both upstream and downstream directions. Seals are swimming in a complex vector field of currents, and the tag data can inform us about the likely alignment and direction of approach for seals located in the turbine region.

To explore the Strangford Lough tag data, the speed and direction of seal movements over ground was calculated using the 'dive' location tag data, which, as mentioned above, was linearly interpolated by SMRU from the 'GPS' location data. We also had current speed and direction data at the SeaGen turbine when it was operational. In order to extrapolate this data on current speeds to time periods when the turbine was not operational (i.e. previous years) we used the following approach. Poltips software (http://noc.ac.uk/using-science/products-services/software/poltips3-tidal-prediction-software) tidal highs and lows in Strangford Lough for the three years of data were obtained. We interpolated between these highs and lows using a cosine function as appropriate for areas with tidal rise and fall times of between 5 and 7 hours. We could therefore estimate the tidal height and the change in tidal height (in m / min) during the times when we had current measurements at the SeaGen turbine and compare that to the recorded current speed (Figure 6). The current meter on the turbine occasionally got 'stuck' and reported the same current for successive time periods which was an obvious data error, and thus these data were removed. We were unable to automatically remove the few other times when the current meter slowly changed in an erroneous way (i.e. was 'sticky' as opposed to completely stuck), such as the trace of readings starting from the center of Figure 6 and looping to the right of the figure. These were relatively few in comparison to the remaining data so did not appreciably interfere with our ability to estimate a trend in the data. The mean trend was estimated using the kernel smoothing function in R selecting a bandwidth of 0.0005 m/min and a Gaussian weight function (ksmooth; Wand and Jones 1995). This trend was then used to estimate tidal speed during the time of every seal speed estimate which was estimated by dividing the distance between two successive locations by the time difference of those two locations.

It should be noted that tidal speed estimates were made at the turbine location. The further a seal is from the turbine, the less accurate this estimate will be, but was for this project, the best estimate we could generate. Using a spatially explicit model of tidal speeds could help improve these estimates, such as used by Kregting and Elsäer (2014) and discussed in **Section 2.3.3**. For this project, we therefore restricted our analyses of seal swim speed and direction to within 200 m of the turbine location. This resulted in 746 dives in 2006; 269 dives in 2008; and 815 dives in 2010 being considered in these analyses.

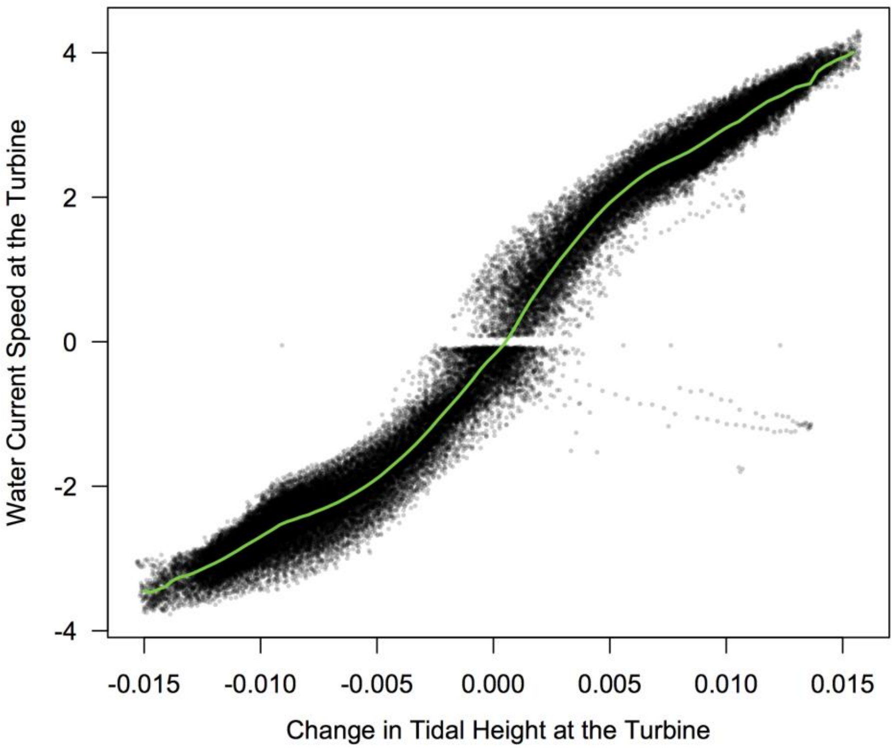


Figure 6 Relationship between measured water current speed at the turbine and estimated change in tidal height (m / min). Green line is the kernel-smoothed estimate of this relationship.

In addition to estimates of current speed, we also needed estimates of current direction. These were obtained from data from the SeaGen turbine. Again, there was some 'stickiness' in the sensors such that zero degrees were recorded consistently during certain time periods when they could not have been. Ignoring those data, it is clear that a very peaked and bimodal direction of current flow exists at the turbine location (Figure 7). The mean direction during flood tides was 341° while it was 157° during ebb tides. These values were used for current direction during flood and ebb tides.

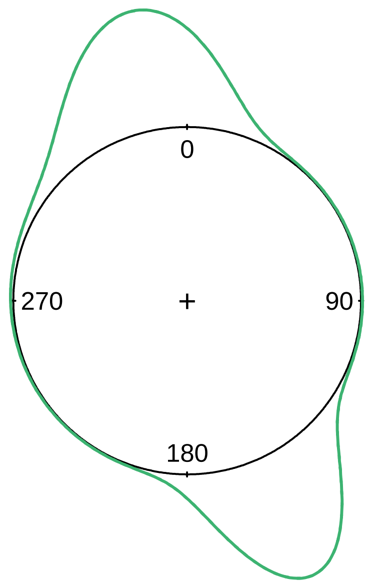


Figure 7 Circular density of 2010 current direction data from sensors on the SeaGen turbine. The relative distance of green line from black line of the circle indicates more measurements in that direction.

Using the above information on the seal movement over ground from individual dives and the current movement, we combined these vectors to estimate the seal's vector (speed and direction) through the water for individual dives. Figure 8 and Figure 9 depict the results for 2006 and 2010 (2008 data showed similar trends). Directions are depicted in clockwise angles from the direction of the current. In other words, a direction of 0° or North indicates that the seal is moving in the same direction as the current. A direction of 180° indicates that the seal is moving in the opposite direction as the water. In both years, the movement of seals over ground near the turbine is spread out in many directions relative to the current direction (top row of circles in Figure 8 and Figure 9), however, the seal direction through the water is almost exclusively against the current (bottom row of circles in Figure 8 and Figure 9). This means that as the seal is moving upstream, downstream, or to the side, they are usually doing so while facing into the current. This also means that seals moving over ground towards a turbine but from the upstream side are likely to be facing away from the turbine. If turbines are detected by seals using sight, this would decrease their chance of detecting the turbine. If turbines are detected by sound, their orientation should make little difference. However, the orientation away from the turbine would likely make it easier for the seal to evade the turbine once it was detected by the animal. The data suggest that a seal's approach of a turbine is likely to be from a number of different directions, thus the CRM assumption that seal movement is always downstream towards a turbine (e.g., Band 2014) will cause an under estimate of collision risk. The ERM assumes random approach angles and so fits better with the data.

Seal speed over ground was similar across years and current velocity categories and was much lower than average swim speeds for harbor seals (1.2 m/s). Seal speed through the water was however much higher and increased with current velocity. In both years, the distribution of seal speeds through the water was flat and variable for low current velocities but showed more peaked distribution at moderate and high current velocities. The median values for 2010 data were 1 m/s for low current velocities, 1.4 m/s for moderate current velocities and 2.5 m/s for high current velocities.

Figure 10 depicts the changes in seal swim speed used in the ERM and direction (upstream/downstream) used in the CRM. Since the CRM does not depend on swim speed, there is no effect of using tag derived values in this model. For the ERM, as swim speed increases, the collision risk increases. Thus, using an average swim speed of 1.2 m/s would produce an under estimate of collision risk during moderate (median swim speed 1.4 m/s) and high current states (median swim speed 2.5 m/s) for the ERM. Seal swim speed In the CRM, there is no explicit input for seal speed as the seal is assumed to be passively transported with the current to the turbine. However, after current velocities exceed 2.3 m/s the turbine blades have reached maximum rotational speed and no longer increase speed with current velocity. This decoupling of speed terms at high current speeds, means that seals are assumed to be transported to and through the turbine strike zone faster, as the blades rotate at a constant speed, and the strike risk per transit decreases in the CRM. However, because the CRM risk also increases the number of transits at current velocity increases, the effect is that the two competing risks cancel one another out, such that the overall risk stays flat at current velocities >2.3 m/s.

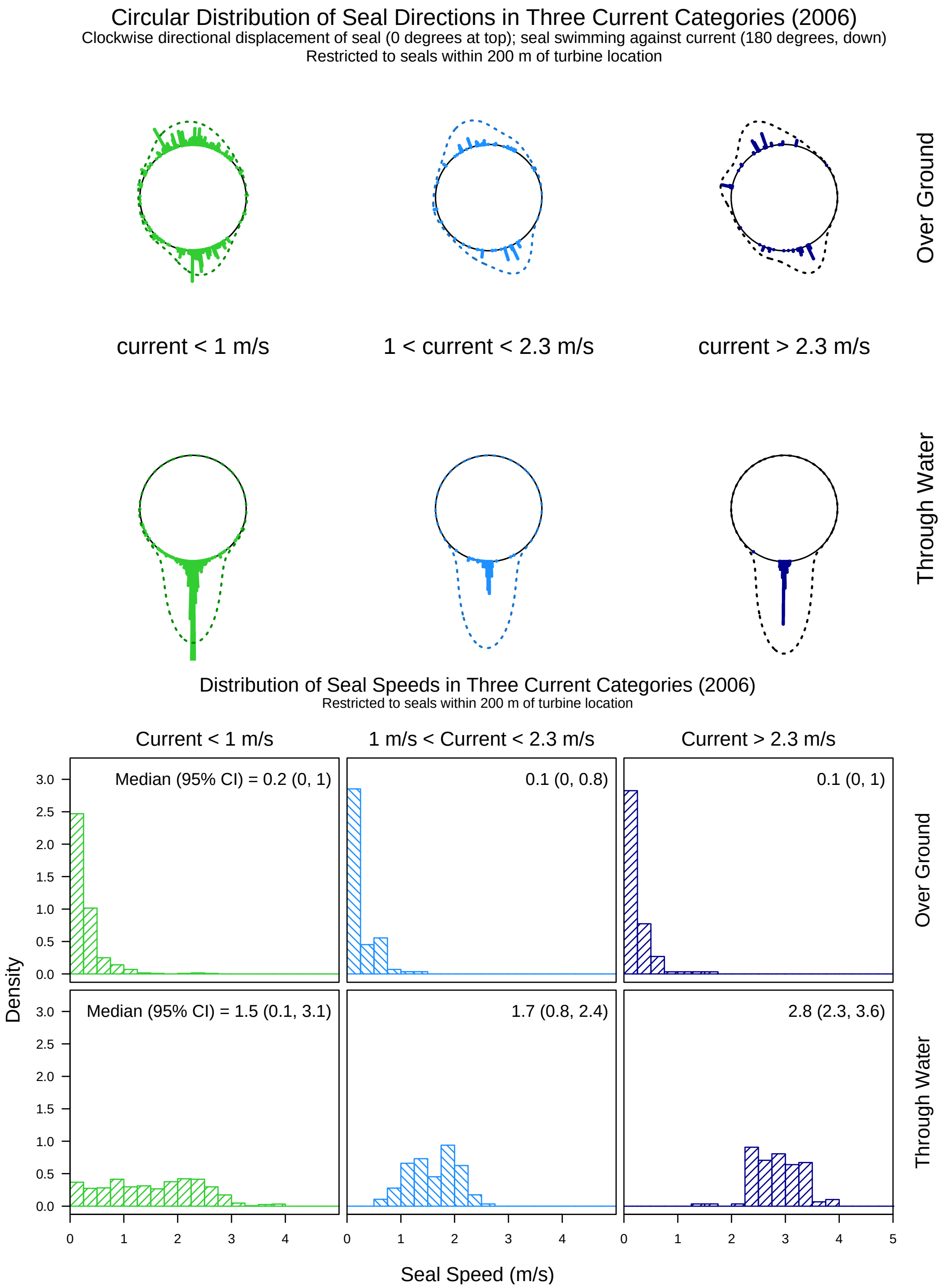


Figure 8 Plots of seal swim direction and speed from single dives in 2006 within 200 m of the turbine location and by current velocity class. **Top**: Circular clockwise distribution of seal direction in relation to the water flow direction (i.e. North = with current; South = against current). Top row shows direction over ground and the bottom row shows direction through the water. **Bottom**: Top row shows distribution of seal speed over ground while the bottom row shows seal speed through the water.

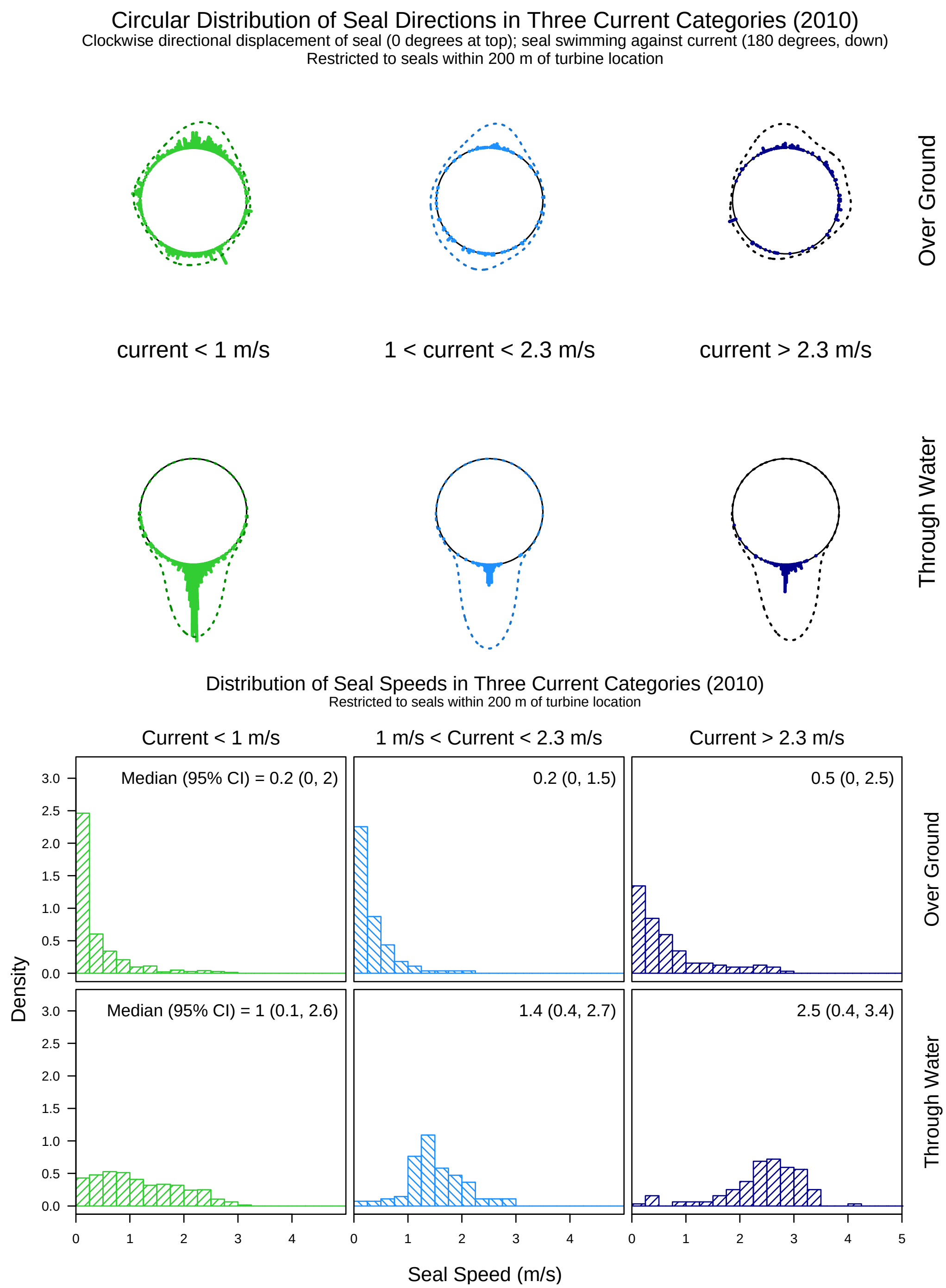


Figure 9 Plots of seal swim direction and speed from single dives in 2010 within 200 m of the turbine location and by current velocity class. **Top**: Circular clockwise distribution of seal direction in relation to the water flow direction (i.e. North = with current; South = against current). Top row shows direction over ground and the bottom row shows direction through the water. **Bottom**: Top row shows distribution of seal speed over ground while the bottom row shows seal speed through the water.

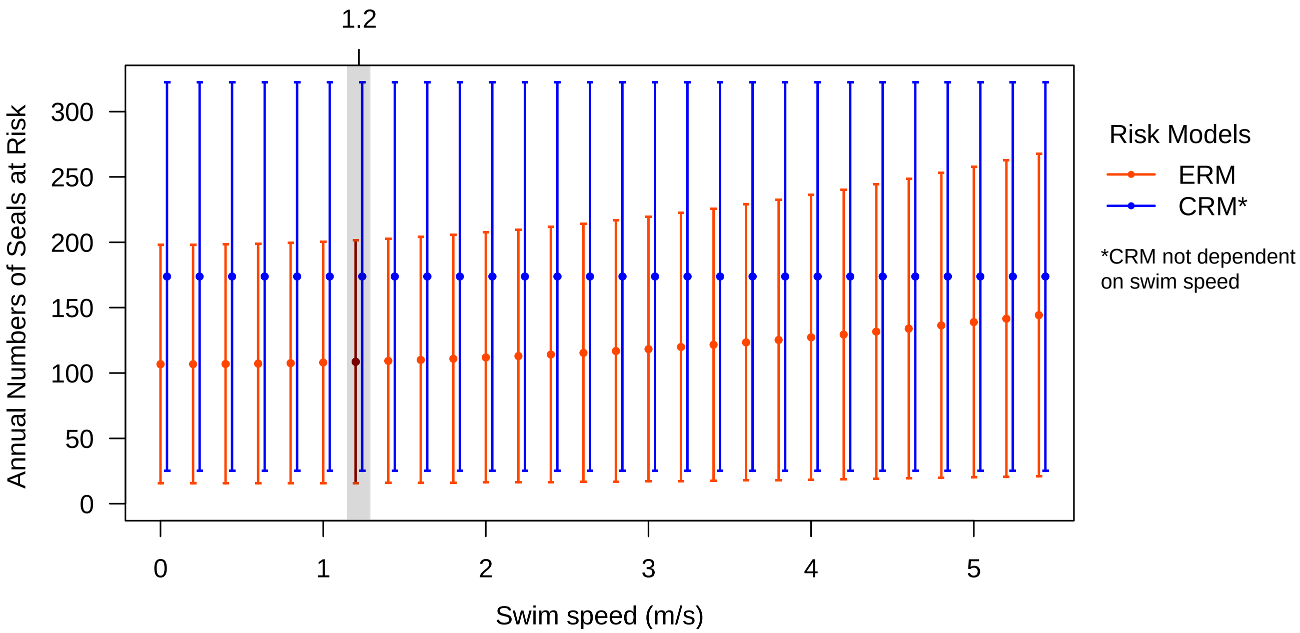


Figure 10 Relationship between seal swim speed and model outputs. Note that the CRM numbers of seals at risk stay constant while the ERM numbers increase with seal speed.

2.3.2 Seal dives

This section explores the relationship between seal dive patterns and collision risk estimates. Estimating the number of seals at risk of collision with a turbine requires an estimate of the density of seals per meter^3 in the depths containing the blades of the turbine (ERM); or an estimate of the number of seals transiting this collision region, per unit time (CRM). It is straightforward to mathematically translate between the two as shown in Equation 4. However, for the usual applications of collision models, the number of transits per unit time at turbine depth is not known. Instead, an estimate of animals per m^2 over all depths, D_A, is known. In order to translate between D and D_A, we need to know something about where the animal is likely to be in the water column, and what proportion, Q, of time they spend at depths that overlap the depth of the spinning blades (i.e., Equation 2).

Data from high-density animal tags can inform such quantities as surface duration and dive duration, as well as the proportion of time spent at various dive depths. To explore these parameters, we extracted dive data from an area within 200 m of the turbine during the 'pre', 'construction' and 'operational' periods (i.e. 2006, 2008, and 2010 data). For each individual dive, the tag stored a depth at nine points equally spaced throughout the duration of the dive, independent of the duration of the dive. Figure 11 plots the quantiles of the dive depth data to show the variability across seals within year. These results suggest that dives were on average shallower during construction and operational phases, and that there were fewer dives around the turbine in 2008 compared to 2006 and 2010.

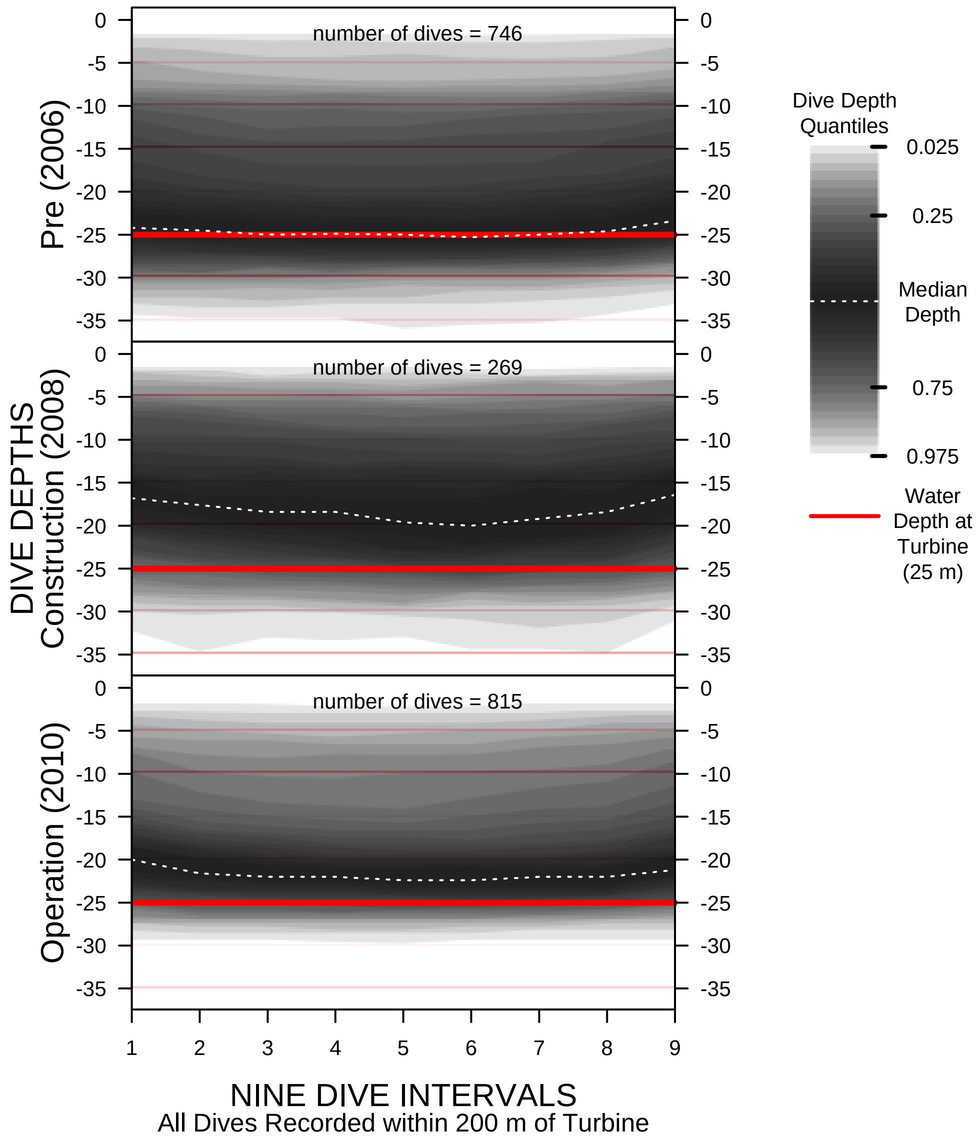


Figure 11 Seal dive profiles in the vicinity of the turbine across years. Depths are collected at 9 evenly spaced intervals across the duration of each dive (x-axis).

Figure 12 depicts dive depth variability across current velocity categories. We observed that at intermediate current velocity (1-2.3 m/s) the seals made their deepest dives on average, when compared to higher and lower current velocities.

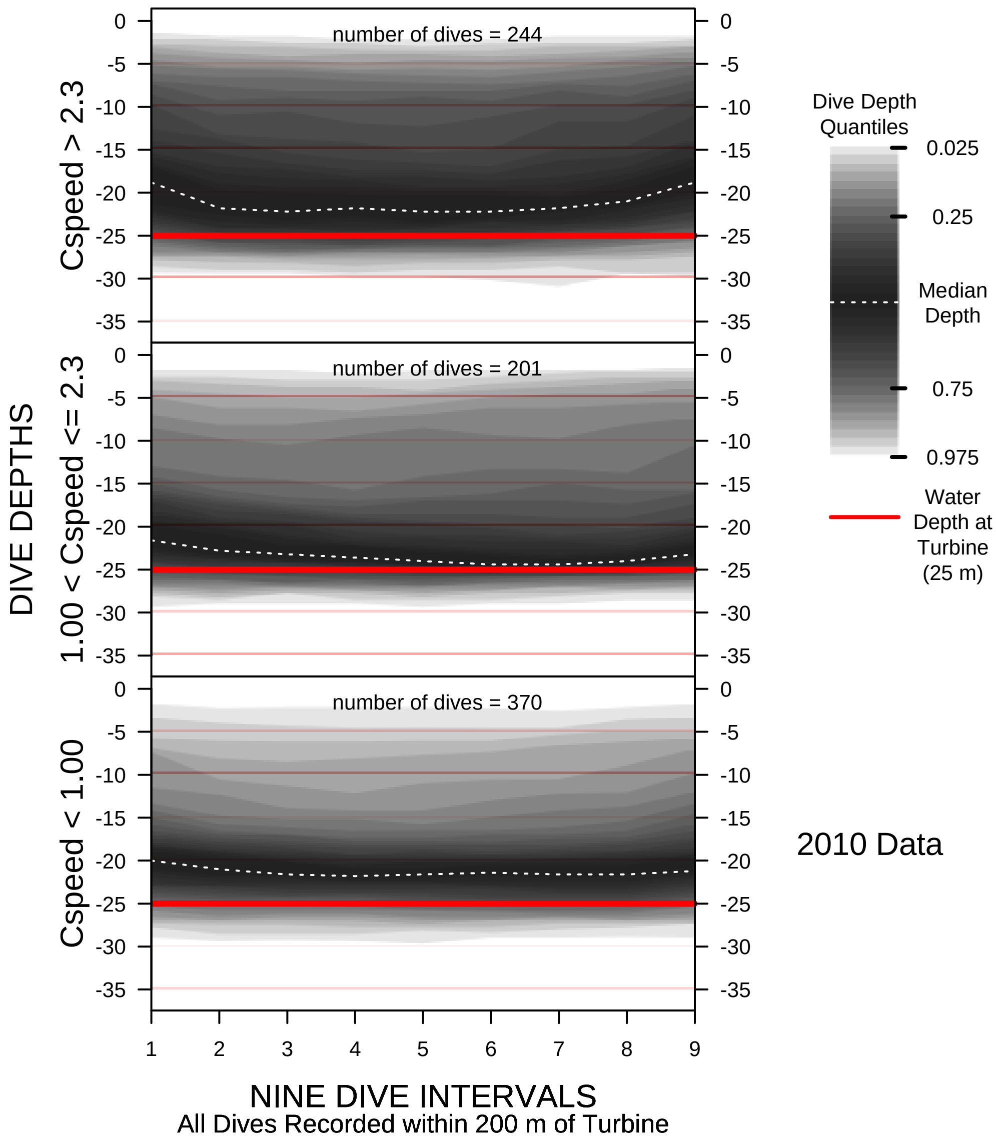
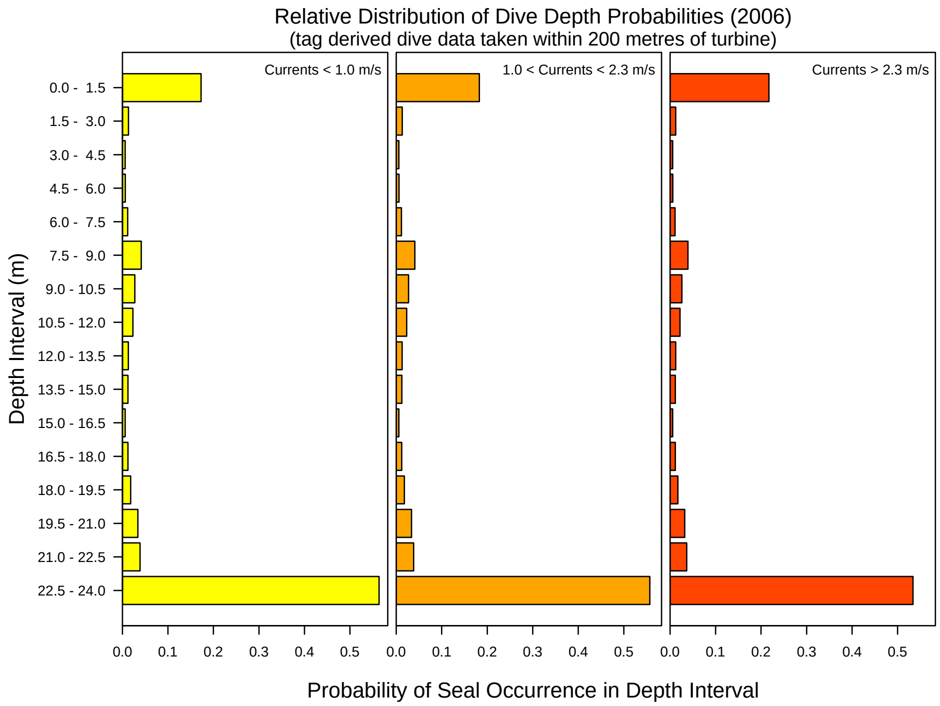


Figure 12 Seal dive profiles in 2010 across three different current speed categories estimated at the turbine. Depths are collected at 9 evenly spaced intervals across the duration of each dive (x-axis).

Seal dives are often classified as ‘U’ shaped or ‘V’ shaped, where the letter’s `shape’ is a way to visualize where the seal is located in the water column. The tag data from Strangford Lough suggests that these animals are performing ‘U’-shaped dives. (Figure 12).

We used consecutive depth intervals of 1.5 meters to estimate the time spent in each interval. This is key in the translation from D_A to D, by informing the likelihood of a seal being in the depth intervals of the turbine. Using 1.5 m depth bins, these data were extracted for each year and tidal velocity class (Figure 13). Band (2014) assumed for U-shaped dives that probabilities of seals being in bins were as follows: top bin = 0.18, intermediate bins = 0.017, deepest bin = 0.49. Because there was a difference in dive profiles between years, the 2010 dive probability was input. We compared 2006 and 2010 dive depth profiles in Figure 13, in which the top depth interval includes the time spent at the surface, not diving. When analyzing just this depth interval within 200 m of the turbine, we found that median surface durations were similar across years (2006: 48 s; 2008: 48 s; 2010: 56 s).

We used the 2010 data to calculate the proportions, Q_{mod} and Q_{high}, of time seals spent at depths overlapping those of the turbine during moderate (1-2.3 m/s) and high (>2.3 m/s) current velocity categories. The depth profile of Q_{mod} and Q_{high} are plotted in Figure 13 and entered the model summed over the depth categories (or portions thereof) that overlapped the turbine, i.e., Q_{mod} =0.204 and Q_{high},=0.197). For example, when current velocity category was high, Q_{high} was used to calculate proportion at risk, and when current velocity category was moderate, we used Q_{mod}. There is no risk when the turbine is not turning when the current velocity was <1 m/s. This modification was implemented when testing risk model sensitivity to assumptions of dive profiles. The effect of dive profiles on collision risk estimate are reported in **Section 2.4**.



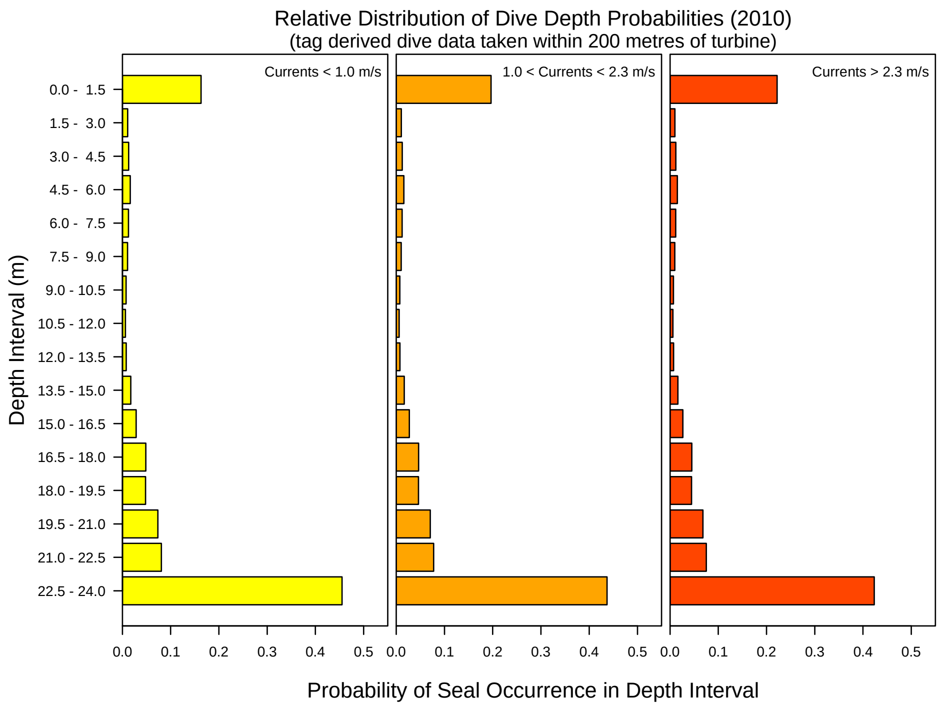


Figure 13 Probabilities of seals being in each depth interval within 200 m of the turbine during 2010. This was used as part of the input into collision risk models.

We have now built a model in which both the turbine characteristics and the seal characteristics are evolving over the tidal cycle. We worked with 5-minute time intervals as this was the time resolution of the in situ current speed, direction and turbine rotational speed data. For each 5 minute step through the tidal cycle, we fit both the ERM and the CRM updating if the turbine was spinning, and if so at what rotational speed, as well as the proportion of seals at risk at depth (Q), and for the ERM, swimming speed (by current velocity category). Figure 14 shows how the encounter risk (ERM; in red) and collision risk (CRM; in blue) scale with changes in current velocity. There is no risk at current velocities <1 m/s, there is increasing risk for current velocities from 1 to 2.3 m/s, and a constant risk at current velocities >2.3 m/s.

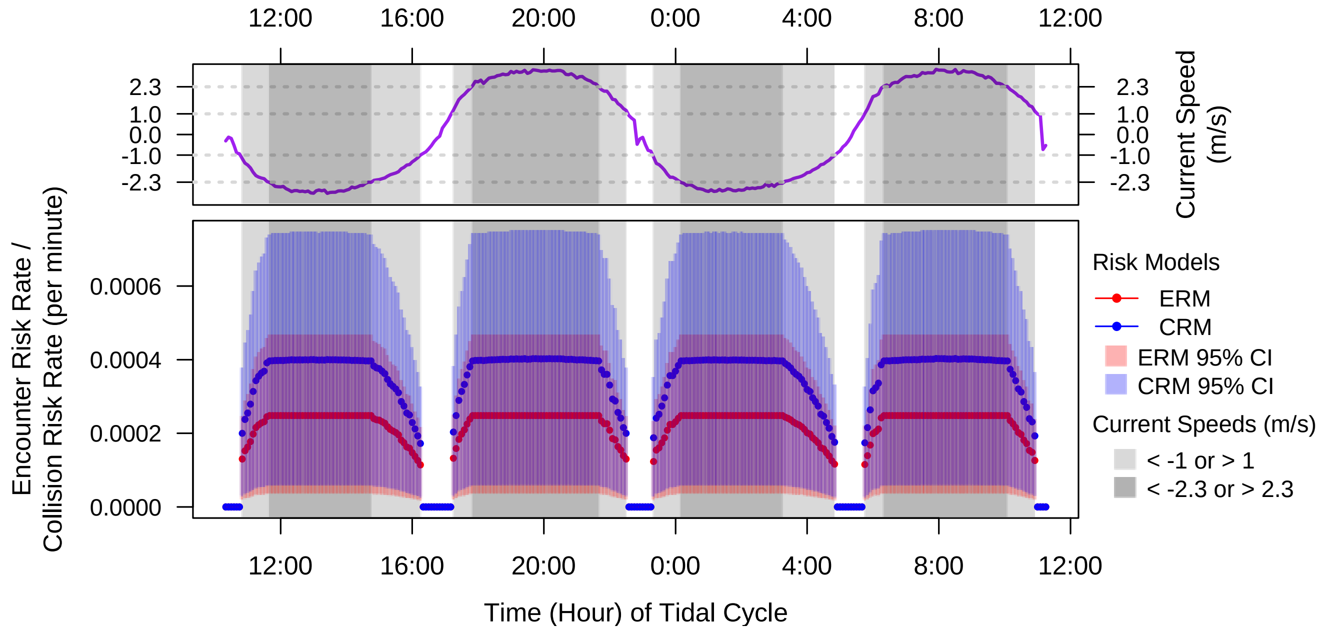


Figure 14 The top panel depicts the current speed over a single tidal cycle (2 highs and 2 lows) between 10:20 June 23, 2010 and 11:15 June 24, 2010. Current speed was measured by in-situ sensors at the SeaGen site, shading in figures shows periods turbine was operational (blades rotate only at speeds >1 m/s). Median risk, and 95% confidence limits are shown as points and translucent vertical lines to allow the evolution of the estimates of risk to evolve over the tidal tide for the ERM (red) and CRM (blue) models.

2.3.3 Limitations of using mean seal density estimates

Because of the different origins of the CRM and ERM, one model uses animal transits (CRM) as the main animal input while the other (ERM) utilizes animal densities. As presented in Equation 4, there is a simple mathematical approach to convert from one to the other, however this makes the assumption that the density of animals is evenly distributed throughout the study area, or in other words, that habitat use by seals is uniform. This section explores the Strangford Lough seal data to determine if this assumption is correct, but first we discuss the pros and cons of using density or transit data as inputs into collision risk models.

Density has the advantage that it is a common metric that is often available for different areas with both point estimates and confidence intervals. However, it is usually calculated over large spatial and temporal scales whereas the risk of collision occurs over very small spatial scales and specific temporal scales. This mismatch brings into question the appropriateness of using average densities over large spatial and temporal scales to estimate risk at specific locations and time periods.

On the other hand, tag derived data can provide very localized data at finer spatial and temporal scales that match better with the scales relevant to turbine collision risk. However, tag data is not commonly available for specific areas (i.e. a dedicated study would be needed) and long time series of an individual's dive and surface patterns may be very specific to the individual tagged and unrepresentative of the wider population given the small sample size that can be typically achieved. In addition, one has to assume that the animals that were tagged are representative of the larger population as the estimated transit rate from the tagged animals needs to be scaled up to the size of the local population that might interact with the turbine. It is not entirely clear how best to deal with potential individual variation in habitat use as one scales these numbers of transits up to the population level, but the degree of inter-individual variation should be considered. For example, sub-sampling and bootstrapping approaches can be used to explore the influence of particular individuals on overall trends.

In order to test the assumption of uniform spatial habitat use across tidal cycle, we analyzed seal dive locations in Strangford Narrows in relation to where they were occurring and what the tidal current was likely to be at that location. Kregting and Elsäer (2014) developed a hydrodynamic model for Strangford which shows this to be a dynamic site with current velocity changing over time and space. Although it would be ideal to use this hydrodynamic model to estimate the current velocity and direction for each seal dive (e.g. to calculate seal swim speed and direction as in Section 2.3.1), this was infeasible for this current project scope. Instead we selected a representative ebb and flood period over which to calculate current velocities. Between April 1 and July 22, 2010 when the 2010 seal tag data were collected, the mean tidal exchange (difference between high and low) was 2.71 m. The Kregting and Elsäer (2014) hydrodynamic model did not have predictions during the 2010 tag data period, but did have predictions for a comparable period in October 2010. Dr. Kregting provided us with an Arc GIS shapefile with current predictions during the max exchange of a representative (i.e. an exchange ~2.71 m) flood and ebb tide during October 2010 (Figure 15).

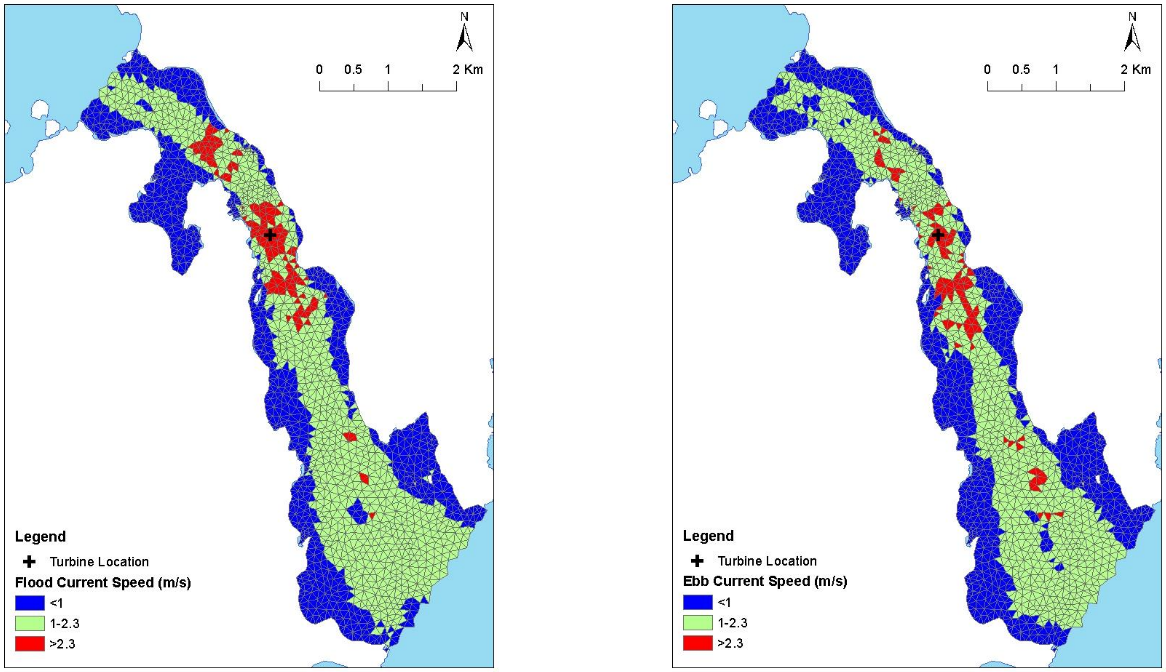


Figure 15 Current velocities (m/s) in Strangford Narrows during representative flood (left) and ebb (right) tides provided by Dr. Kregting.

Current velocities >2.3 m/s are clustered in several areas in the Strangford Narrows (Figure 15). To better understand the spatial distribution of dives during different tidal states, we focused on 2010 data and calculated the number of dives in each of the Kregting and Elsäer (2014) polygons and divided by the area of each polygon to estimate 'dive density' (dives / m^2). Figure 16 shows the results for flood and ebb during high and low current velocities. The density classes were grouped so that they were consistent across the sub-panels, but approximate five quantile breaks for the high flow ebb data. Dive density is higher during the high current periods, but remain on the periphery of the highest flow areas. The most persistent high dive density area across tidal velocities is located along the eastern shore of the Narrows starting approximately at the turbine latitude and heading north to the inner lough. It is important to note that these analyses included all dive data, so the dives counted near haul outs may not be foraging dives. In spite of this, there is little evidence to suggest that seals are using the Strangford Narrows in a uniform way.

There is also further evidence that seals in Strangford Narrows use the area differently across different tidal states. Lonergan et al. (in review) found that seals were more likely to transit the narrows during slack tide than during flood or ebb tidal states. In exploring the GPS dataset, we found 70.8% of the GPS locations within 200 meters of the turbine were transmitted during slack tides (although this may be confounded by the tags not transmitting during active under water diving activity). These data illustrate the risk of using average animal density (over space and time) to assess collision risk as habitat use is not consistent across the study area and across tidal cycles. This could result in very different estimates of collision risk, depending on whether density estimates or in situ estimates of transit rates are used. We do not quantify this potential difference in this section, but do so as part of our scenario testing in **Section 2.4**.

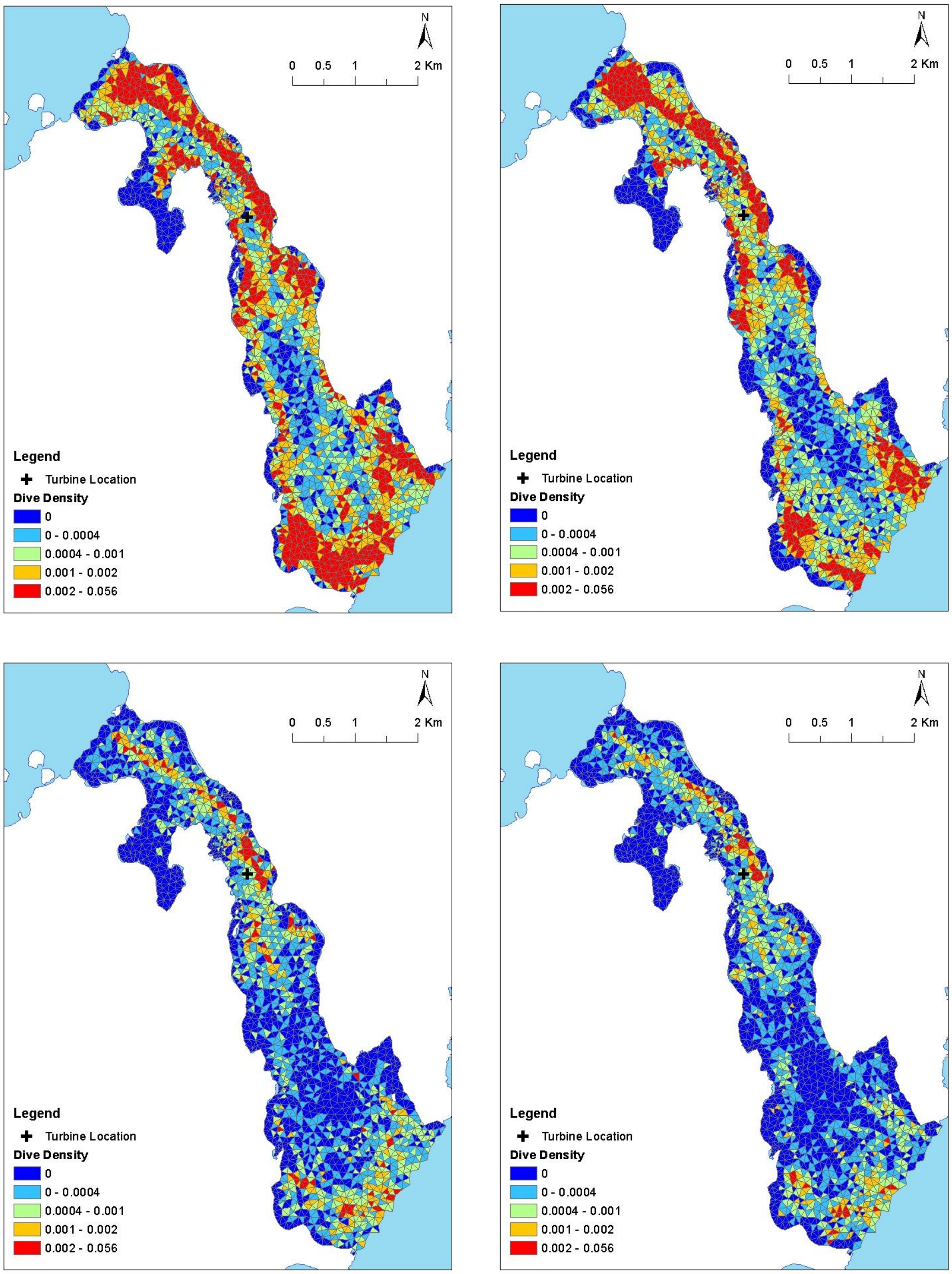


Figure 16 Plots of seal dive density (number of dives / m^2) in 2010. Top Left: during flood tides > 2.3 m/s at turbine. Top Right: during ebb tides > 2.3 m/s at turbine. Bottom Left: during flood tides < 1 m/s at turbine. Bottom Right: during ebb tides < 1 m/s at turbine.

2.3.4 Seal avoidance of the turbine

As mentioned earlier in this report and illustrated in Figure 1, avoidance is not calculated directly in the ERM or CRM, but is used as a multiplier outside of the estimated number of collisions from those two models. There is a great deal of uncertainty regarding the level of avoidance that might be demonstrated by animals, and the level of avoidance may vary by species, location or device. For example, Band (2014) estimated collision risk under avoidance scenarios from 0 to 99%. The Scottish Natural Heritage guidance on assessing collision risk currently (September 2015) open to public comments, recommends calculating collision risk estimates with 50, 90, 95, 98 and 99% avoidance rates (Band 2015). Thus it is clear that we still cannot say much about how seals are behaving in close proximity to turbines. The uncertainty regarding levels of avoidance clearly has large implications for collision risk estimates. In this section, we further explore the Strangford Lough seal tag data to better inform avoidance rates of harbor seals at this location.

For this set of analyses we used the 'GPS' tag data. As mentioned above, GPS locations vary in how often they are collected as they do not transmit under water and seals spent a significant amount of time diving. This requires interpolation between GPS locations. Rather than use a linear interpolation as was done for the 'dive' tag data we used a Brownian Bridge model that assumes seals move following a random walk process model between GPS locations (Nielson et al. 2013). This provides a probability density surface in the study area based on the GPS locations. In brief, the Brownian Bridge probability density is an estimate of the relative time spent in an area. The Brownian Bridge probability density function must be integrated to find the fraction of time spent in a given region. This integration is approximated by discretizing time into arbitrarily small intervals according to the time between consecutive GPS fixes for each seal. The model then provides an empirical estimate of a movement path using discrete GPS location data.

For this implementation of Brownian Bridge methods, we assumed that the GPS locations had 2-D normally distributed location errors, with mean uncertainty of 50 meters (based on the estimated location error of the GPS tags). All land was masked from the prediction surface. The resolution of the grid for which we estimated the Brownian Bridge probability density was a 20 m by 20 m grid surface restricted to a region within a few kilometers of the turbine (purple rectangle in Figure 17). A single Brownian Bridge probability surface was generated for each tag in each year (those results presented in Appendix 2) and then combined, such that the final surface for each year weighted each tag equally, regardless of how many transits that seal made. Raw 'GPS' tag data, and the Brownian surface densities are shown in the top two panels of Figure 17. Each year is presented as a separate panel in each row. The histograms in the bottom panel depict the relative probabilities of observing a seal in the region within 200 meters of the turbine. The key result is that the probabilities are higher for the 'pre' turbine scenario compared to both 'construction' and 'operational' stages. This means that there were more seals dives in the region where the turbine is located prior to the turbine being installed. We interpret this as being avoidance of the turbine. The number of dives within a 200 meter radius of the turbine location was 746, 269, and 815 dives from 9, 7, and 9 tagged seals in 2006, 2008 and 2010 respectively. It is important to note that there was a great deal of inter-individual variability and how they used the habitat around the turbine in the Strangford Narrows, and this is clearly seen in the seal's individual Brownian Bridge spatial estimates (see Appendix 2).

In order to quantify the difference in probability surfaces as a potential indicator of the degree of seal avoidance within 200 m of the turbine we summed the 20 m x 20 m gridded probabilities of seals being in the 200 m zone during 2008 and 2010 (as shown in the bottom panel of Figure 17) and divided these by the sum of seal probabilities in the same area during 2006. This resulted in values of 0.33 and 0.32 for 2008 and 2010 respectively. This suggests that about 66% of seal transits during construction and operation of the turbine may have avoided the area within 200 m of the turbine and that this potential avoidance was similar for construction and operational periods. This is higher than the ~20% reduction in transit rates within each year while the turbine was operational vs not operating reported by Lonergan et al. (in review), but lower than 4 out of 5 of the avoidance rates suggested by Scottish Natural Heritage (Band 2015). The avoidance rate used has a direct and clear effect on collision risk estimates. Use of 66% avoidance rate will decrease collision risk estimates by 66%.

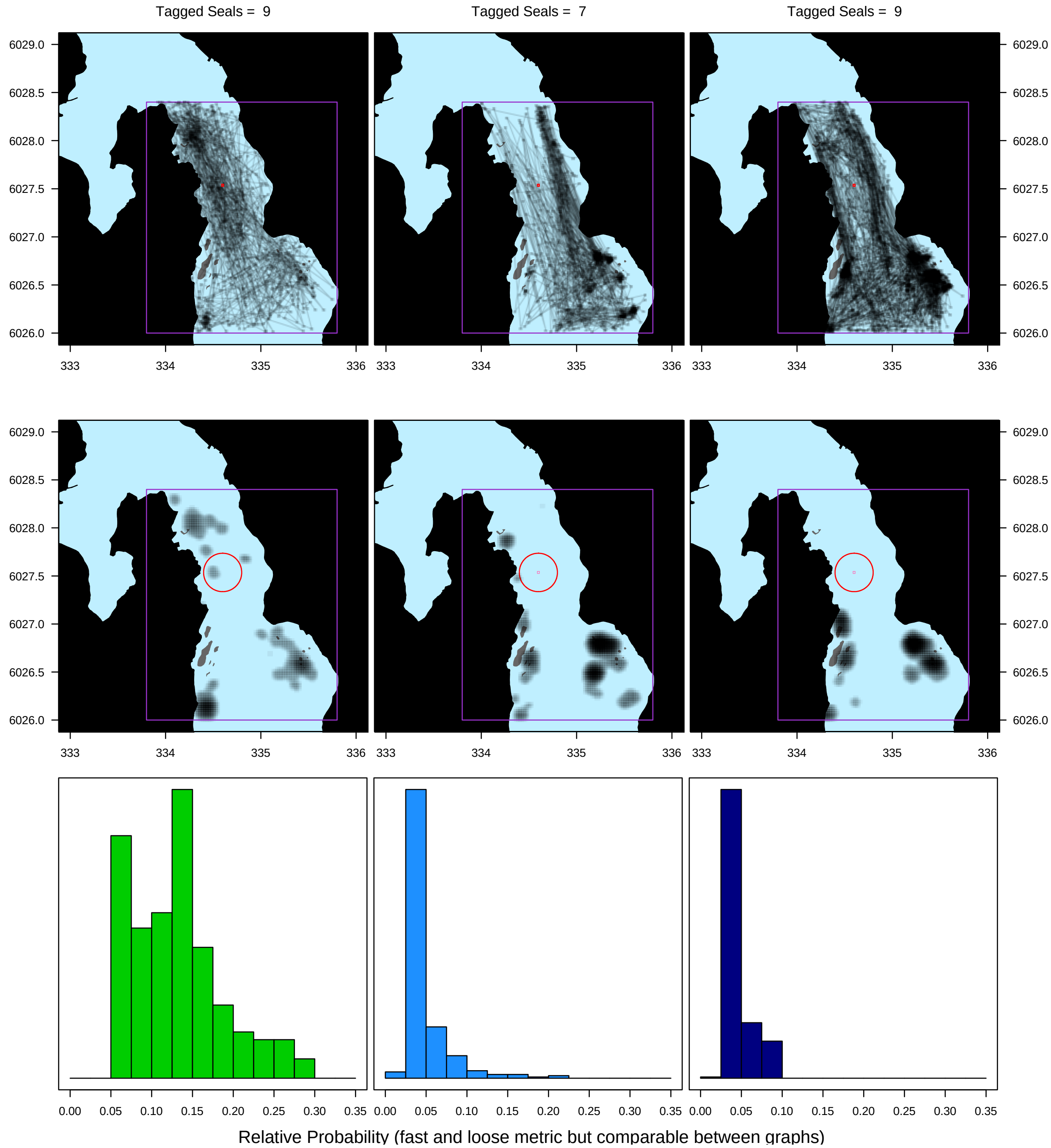


Figure 17 Top panel: movement of tagged seals within several km of the turbine (purple box) based on lines drawn from one GPS location to the next. Middle panel: density of seals based on the Brownian Bridge model. The red circle indicates a 200 m radius around the turbine location. Bottom panel: histograms of the occupancy probability of seals within the 200 m radius around the turbine. Columns from left to right are 2006 (pre), 2008 (construction), 2010 (operation).

2.4 Sensitivity testing of model inputs

In this section we systematically test the sensitivity of collision risk models to inputs explored in Sections 2.2 and 2.3. The data collected in Strangford Lough as part of the SeaGen project provided a number of variables with which to parameterize and explore sensitivities of risk models. In total, we ran eight different scenarios (Table 2). Specific details of the inputs used for our scenarios are provided in Appendix 1, but in brief, each scenario added another input parameter for which we had empirical data from Strangford Lough to the previous scenario. The first scenario uses 'standard' ERM/CRM inputs based on assumptions Band (2014) used, updated with site specific information that is generally available. Harbor seal densities were taken from Jones et al. (2013) who provide estimates of seal density (and their 95% CI) in 5x5 km grid cells. We used the value of 43.49 (6.275; 80.705) per 25 km^2 reported for the grid cell which contained the SeaGen turbine. These were converted to transit rates for the CRM using Equation 4.

Scenario 2 changed the tip speed ratio from 6 as assumed by Band (2014) to our measure of 5.1 based on SeaGen data (see Section 2.2.1). Scenario 3 utilized actual RPM of the SeaGen turbine across a representative tidal cycle (i.e. ~25 hour period) based on current speed (see Section 2.2.1). This moves the models from being a yearlong increment that uses average current speed, proportion of time the turbine is not spinning, etc. to a more dynamic model with 5 minute increments that calculates turbine RPM based on current velocity. The ERM and CRM models were run at 5 minute increments during this representative tidal cycle and these results multiplied by the 352.75 tidal cycles in Strangford in 2010 to estimate collision risk for a year.

The remaining scenarios were based on the seal tag analyses discussed in earlier sections. Swim speed and direction through the water (see Section 2.3.1) were incorporated in scenarios 4 and 5 while dive profiles (see Section 2.3.2) were added in scenario 6. Seal 'density' (see Section 2.3.3) was explored in scenario 7 by utilizing the transit rates calculated by Sparling and Lonergan (2013) from the SeaKing sonar mounted on the turbine. Since these estimates of transits were from an operational turbine, we assumed that these estimates of transits included avoidance. Therefore we multiplied these collision risk numbers by 3 to remove the expected avoidance of 66%. The final scenario (8), utilized our estimate of avoidance (see Section 2.3.4).

Table 2 Description of the scenarios run to explore risk model sensitivities.

Scenario #	Scenario / Variable	Description
1	Standard ERM/CRM	The 'standard' ERM/CRM models using 2 bladed turbine, average current measured over 2010 at the turbine location and downstream swim direction (for CRM). Other assumptions are comparable to those in Band (2014); seal densities as reported for the Strangford Narrows (Jones et al. 2013). A 'V' shaped and 'U' shaped dive based on Band (2014) assumptions is used.
2	Turbine Tip Speed Ratio	Tip speed ratio as determined from best fit to SeaGen data (λ = 5.1).
3	Turbine RPM	Usage of RPM across the tidal cycle as measured on the SeaGen. Also includes 'shut-down' periods as typical operations during a full tidal cycle.
4	Seal swim speed	Use of empirical measures from seal tags: for currents from 1 to 2.3 m/s, swim speed = 1.4 m/s; for currents > 2.3 m/s, swim speed = 2.5 m/s
5	Seal swim direction	Use of empirical measures from seal tags: used upstream seal movement in the CRM (ERM already assumes random direction of seal approach)
6	Seal dive profiles	Use of empirical measures from seal tags: probabilities in dive depth bins as determined from 2010 Strangford Lough tags
7	Seal 'density'	Use of transit rates of seals as estimated from sonar at the SeaGen turbine by Sparling and Lonergan (2013).
8	Avoidance	Use of empirical measures from seal tags: 66% avoidance

2.4.1 Results

In **Section 2.3.2** Strangford tag data clearly showed 'U' shaped dives, and the review of other available seal datasets in **Section 3** also shows a consistency of 'U' shaped dives across tidal sites. As such, we only report in our first scenario (1A) the collision estimates based on 'V' shaped dives. The assumption of 'U' shaped dives results in a large decrease (63% reduction) in collision estimates (Table 3) for both ERM and CRM. Use of the actual tip speed ratio of 5.1 as opposed to an assumed tip speed ratio of 6 caused a 12% reduction in both ERM and CRM. Use of RPM across a tidal cycle causes a small reduction in collision numbers of 5% in the ERM. The only reason there is a 3% reduction in collision numbers in the CRM when we implement RPM across a tidal cycle is because we have decoupled seal swim speed and current velocity when the currents are > 2.3 m/s (see **Section 2.3.1**).

Seal swim speed only enters into the ERM model and increases ERM collision estimates by 3%. Seal direction through the turbine is already assumed to be random in the ERM (which is what we report it to be in **Section 2.3.1**) and thus seal direction does not change collision risk estimates for the ERM. The

CRM can only take direction of seals as upstream or downstream. The use of upstream transits in the CRM increases collision risk estimates by 10%. There is little difference (2%) in collision risk estimates based on actual dive profiles in Strangford Lough tagged seals versus the 'U' shaped dives that Band (2014) assumed. The change of 'density' from the average reported density for Strangford Narrows to the measured transit rates of seals by a sonar mounted on the turbine (taking account of avoidance) causes a reduction of 27% in collision risk estimates for both models. Since avoidance is a multiplier, our estimates of avoidance reduce collision risk by 66%.

Table 3 Results of scenario testing. Estimates (and 95% CI) are number of seals per year at risk of collision with the turbine. Numbers 1 through 6 have been multiplied by 2, to account for the 2 operating rotors at SeaGen. The seal density for 7, 8 come directly from the underwater SeaKing sonar measuring transit rates at the turbine where its field of view included both rotors. The % change for comparisons are also provided.

Scenario	ERM	ERM % Change	CRM	CRM % Change	% Change Comparison
1A: V shaped dives (standard)	339.1 (48.9, 629.2)		541.2 (78.1, 1004.3)		
1B: U shaped dives (standard)	124.6 (18.0, 231.3)	37%	198.9 (28.7, 369.2)	37%	1B vs 1A
2: Tip speed ratio	110.1 (15.9, 204.4)	88%	174.4 (25.2, 323.6)	88%	2 vs 1A
3: RPM	104.4 (15.1, 193.0)	95%	167.1 (24.1, 310.0)	96%	3 vs 2
4: Seal swim speed	108.0 (15.6, 200.4)	103%	167.1 (24.1, 310.0)	100%	4 vs 3
5: Seal swim direction (upstream)	108.0 (15.6, 200.4)	100%	183.9 (26.5, 341.2)	110%	5 vs 4
6: Seal dive profile	109.8 (15.8, 203.8)	102%	186.9 (27.0, 346.9)	102%	6 vs 5
7: Seal density	80	73%	136.1	73%	7 vs 6
8: Avoidance	26.4	33%	44.9	33%	8 vs 7

2.4.2 Discussion

The CRM produced collision estimates that were consistently between 1.5 and 1.7 times the estimates of the ERM, which is consistent with other comparisons (Band, 2014). The single biggest effect on collision risk in our scenarios was due to avoidance, which is not surprising given that it is a direct multiplier on model outputs. This was in spite of the fact that our estimates of avoidance (66%) were lower than what other sometimes assume avoidance to be (> 90%). One needs to bear in mind that our estimate of avoidance is in the area out to 200 m from the turbine. Presumably, avoidance increases with decreasing range to the turbine.

The next biggest change in collision risk in our scenarios was shifting from an assumption of 'V' shaped dives to 'U' shaped dives. Given that seal tag data to date from harbor and grey seals suggest that these animals predominantly utilize 'U' shaped dives in tidal inlets, and that our tag informed dive profiles resulted in similar numbers as if one assumed a standard 'U' shaped dive (as Band, 2014 used), it seems appropriate to suggest that future collision risk estimates use a standardized 'U' shaped dive in parameterizing models. There seems little need to use site specific dive profiles.

The difference in collision estimates between the use of published seal density for Strangford Lough and the use of in situ estimated transits was considerable (27% decrease). This is perhaps not surprising given the evidence presented in Section 2.3.3 that shows that seal use of Strangford Narrows varies by location and time. The spatial-temporal scale miss-match between density and collision risk is large, which suggests that direct measures of transits past a turbine would give better estimates of collision risk. It is considered a benefit to the CRM that transits are a direct input into that model.

The fact that the CRM assumes that animals are moving at the same speed as the current, and typically downstream does not seem biologically correct. In Strangford Narrows, seals swim into the current and could pass through the turbine from any direction. It is considered a benefit that the ERM assumes seal direction to be random and allows for seal speed to be independent of current speed. Given the relative strengths of these two models, one work around might be to use seal transit estimates, but convert these to densities (using Equation 4) and run an ERM.

3. Review of Seal Datasets

This section of the report deals with the third goal of this project. Namely:

- **Review other currently available seal datasets that might allow further refinement of collision risk models.**

Due to the expansion of the tidal energy industry and the concern surrounding the risks posed to marine megafauna, there is a requirement for knowledge on how marine animals use tidal environments. Potential interactions are poorly understood, largely due to the complexity of tidal stream environments that make traditional survey and monitoring methods challenging. Although tide patterns have long been known to influence seal haul out behavior, the behavior of seals within fast flowing, turbulent environments is less well known. In the UK in recent years much interest has focused on understanding how seals use tidal environments and a number of datasets are starting to emerge. The purpose of this section of this report is to review these studies with a view to synthesizing the current state of knowledge, to identify similarities and differences across datasets and to determine whether there are common factors across studies which shape seal behavior and explore the extent to which we can generalize across sites and between species.

The detailed review of currently available seal datasets is provided in Appendix3 of this report. In brief though, a total of 92 harbor seals and 17 grey seals have been tagged for studies in five different tidal locations that have been considered for tidal energy projects. All of these tags collected data on seal location, dive depth, and haul out timing/location. These seals showed a great deal of inter-individual variation in the use of tidal areas and there is evidence that some individuals are tidal habitat 'specialists'. The proportion of tidal habitat 'specialist' varied by site. The local abundance of seals varied across the tidal cycle but depth distributions were quite similar across sites, with most of their time spent on the surface or at the seabed. This is consistent enough that the use of a 'standard' depth distribution in collision risk models across sites is appropriate.

There were differences across sites that would have implications for collision risk models. Use of tidal current varied by site, as did the use across the tidal cycle. There are also seasonal differences in habitat use across sites, with some sites only having a seasonal presence of seals.

While some analyses have been conducted on the datasets reviewed here, given the findings of Section 2 of this report, further analyses of these seal datasets are warranted in relation to tidal covariates to determine the level of variability in habitat use across tidal sites and to better inform collision risk models. Some further analyses are ongoing by SMRU and SMRU Consulting with support from Marine Scotland, so coordination, to avoid replication of effort, is warranted.

4. Seal Morphometrics

This section of the report deals with the second goal of this project. Namely:

- **Provide harbor seal morphometric data to inform future models that predict the consequences of a collision to individual harbor seals.**

4.1 Introduction and methods

The Whale Museum (TWM) has fulfilled the role of the San Juan County Marine Mammal Stranding Network since 1982. Within this county in Washington State (Figure 18), TWM responds to marine mammal strandings which are reported by the public to the Stranding Network via a free telephone hotline. Trained stranding volunteers respond to the stranded animal and collect a standard set of data including location, stranding date, species, age class, sex, and basic morphometric measurements including length and girth. Data are logged through a standardized US Federal reporting form called a 'Level A' form and are entered into a National database managed by NOAA Fisheries. Data are also logged in TWM's Access database for long-term storage and analysis. Dead animals in good postmortem condition are collected for a complete necropsy and the appropriate tissues are submitted for diagnostic testing.

For this report, all 'Level A' data for harbor seal strandings were exported into an Excel spreadsheet. Information on blubber thickness and nutritional condition was collected from past necropsy reports and collated with the spreadsheet. All quantitative measurements were converted into metric units[1] and any measurements listed as "estimates" were filtered out. Analysis for adults and subadults was restricted to dead animals, as measurements for live adults were assumed to be estimates; however, both live and dead pups were analyzed. Descriptive statistics were determined separately for each age group. Because the consistency of age class has changed over the years, yearling and subadults were combined into one category ("subadults"). Pups were analyzed as one large group as well as separately in the subcategories of "weaned pups," "nursing pups," and "premature pups."

The percentage of animals in each nutritional state was determined for all animals, where the information was available. Nutritional state was broken down into four categories: excellent, good, fair, and poor. Some terms were reassigned to the closest matched category for consistency purposes. For example, "adequate" was changed to "fair" and "emaciated" was changed to poor.

The opportunistic collection of marine mammal carcasses may result in a considerable bias. Given that stranding events can be skewed towards less healthy individuals, our analyses likely represent minimum estimates for nutritional condition and blubber thickness.

[1] All data entered prior to 2005 were assumed to be US Standard measurements unless otherwise indicated.

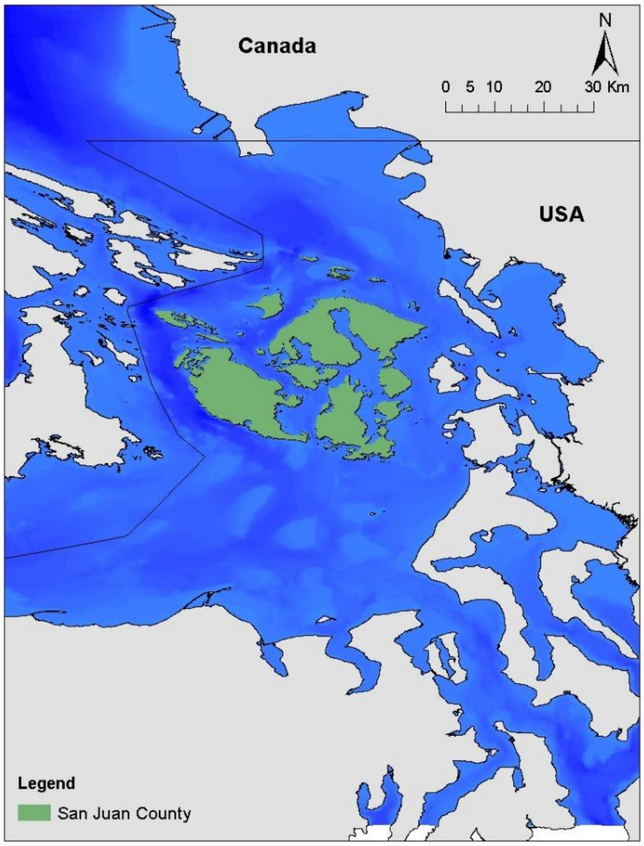


Figure 18 Map of San Juan County in North West Washington State, USA.

4.2 Results

The full dataset of harbor seal morphometrics is provided in the separate file called 'TWM Harbor Seal Morphometrics.xlsx'. There were a total of 1,822 records in this dataset spanning from 1982 to 2015, of which 13% were adults, 3.3% subadults, 74% pups and 9.7% unknown. Where data were available in the spreadsheet, these were combined to generate the descriptive statistics in Table 4. Harbor seals from the northern Gulf of Alaska are the smallest population of harbor seals in terms of size. Adult males are on average 160 cm long and weigh 87 kg while females are on average 148 cm long and 65 kg (Perrin et al. 2009). The adult seals in this morphometric dataset are just below the average length of the Gulf of Alaska population and females are just below the average weight, but males are 27 kg lighter, on average. The sample sizes for each metric vary as these were not consistently available in the dataset. The majority of adult seals were in good nutritional condition, while the majority of subadults and pups were in poor nutritional condition (Table 5).

A much smaller number of animals had a potential cause of death (N=201). All age classes had a large proportion of non-human trauma and infectious/inflammatory potential causes of death, while only younger age classes had substantial proportions of toxic/nutritional cause of death (Table 6). Details of these potential cause of death are included in the 'TWM Harbor Seal Necropsy Data.xsls' file.

Table 4 Harbor seal morphometrics by age class and gender.

ADULTS	***Length (cm)***	***Girth (cm)***	***Weight (kg)***	***Blubber depth (cm)***
Females	145.23	96.98	61.20	2.61
N	*45*	*31*	*17*	*11*
SD	*16.46*	*16.37*	*18.01*	*2.07*
Males	156.30	102.09	60.40	2.26
N	*42*	*17*	*9*	*10*
SD	*18.96*	*13.18*	*29.68*	*1.28*
SUBADULTS	**Length (cm)**	**Girth (cm)**	**Weight (kg)**	**Blubber depth (cm)**
Females	117.61	76.15	34.56	1.10
N	*16*	*11*	*9*	*4*
SD	*18.74*	*15.38*	*20.06*	*1.19*
Males	111.32	68.53	16.39	N/A
N	6	*3*	*3*	*0*
SD	*16.53*	*21.50*	*11.34*	*N/A*
PUPS	**Length (cm)**	**Girth (cm)**	**Weight (kg)**	**Blubber depth (cm)**
Females	76.76	48.36	8.45	2.12
N	*382*	*223*	*320*	*35*
SD	*8.54*	*8.17*	*2.92*	*1.49*
Males	78.47	48.70	9.44	1.84
N	*358*	*229*	*310*	*29*
SD	*9.25*	*6.20*	*10.70*	*1.25*
All Pups	77.77	48.72	9.03	2.00
N	*815*	*473*	*651*	*69*
SD	*9.23*	*7.58*	*7.79*	*1.36*

Table 5 Harbor seal nutritional condition.

	Nutritional Condition (%)			
	Excellent	**Good**	**Fair**	**Poor**
Adults	13.8	51.7	3.4	31.0
Subadults	0.0	16.7	16.7	66.7
Pups	8.3	22.0	16.7	53.0

Table 6 Necropsy potential cause of death. Sample sizes as follows: Adults = 41; Weaners = 47; Pups = 113.

	Adults	*Weaners*	*Pups*
Trauma (not including human interaction cases)	36.6	23.4	15.0
Congenital/genetic	7.3	0.0	2.7
Human Interaction (boat strike, fisher, gunshot, etc.)	7.3	8.5	0.0
Toxic/Nutritional	2.4	38.3	46.0
Infectious/Inflammatory	43.9	21.3	24.8
Other	0.0	4.3	3.5
Undetermined	2.4	4.3	8.0

5. Priorities for Future Work

This section of the report deals with the final goal of this project. Namely:

- **Provide priorities for future research that could reduce uncertainty in collision risk models.**

This report has parameterized two standard collision risk models and explored their sensitivities to various input parameters. The overarching drive for this work has been to better understand collision risk, the models that have been used to estimate risk, and to progress towards reducing the uncertainty surrounding that risk. A number of inputs to the models have little effect on collision risk estimates and thus it is hard to justify conducting more research to get better estimates for those inputs. However, there were clearly a number of inputs that make significant differences in collision risk estimates and further research to better estimate and understand trends in these inputs across sites is warranted. Based on our results we would prioritize future collision risk research in the following order, with highest priority first.

1. Avoidance

We have provided an estimate of avoidance at 200 m from the SeaGen turbine. Lonergan et al. (in review) have also reported ~20% reduction in transits past the turbine while it was operational. This was an estimate across the breadth of Strangford Narrows at the location of the turbine and thus incorporates seal transits at various distances from the turbine. A better understanding of how avoidance changes with distance from the turbine is needed, both to better inform collision risk models, but also to inform estimates of barrier effects in commercial scale arrays. A better understanding of how avoidance changes by individual, location and turbine is also needed. Avoidance, like other seal behavior in tidal inlets, is likely to vary by tidal state as well. We have only estimated avoidance across all tidal states at this point.

2. Fine scale habitat use

Seal use of Strangford Narrows is complex and variable through space and time. This is common across animal species that use tidal inlets and is likely to be driven by complex relationship between physical processes and the foraging behavior of these animals (Benjamins et al. 2015). These have obvious implications for collision risk. If density estimates are to be used for collision estimates, then they must be corrected to reflect habitat selection over fine scale tidally influenced flow dynamics, and how those scale with the dynamics of turbine operation. Better measurement of collision risk inputs that scale appropriately with the temporal and spatial dynamics of the system is a priority, in conjunction with a better understanding of fine scale habitat use.

If on the other hand, seal tag data are used to inform transit rates or density, an understanding of the inter-individual and inter-site variability in habitat use will be needed to extrapolate, either to the population at that site, or at other sites. This includes both where and when the animals are using the habitat, but also how this use relates to tidal state, current speed and current direction.

3. Models themselves

   - Restrict the use of averages as inputs to models that are applied to temporally, spatially dynamic systems

- Make models more realistic of three-dimensional seal movements (rather than linear interpolation) by using tags with accelerometers, and/or tags with flow meters.
- More research into seasonal habitat use as well as other tidal covariates.
- Explore the effect of using different set foraging strategies, and how different tactics will be differentially affected by the presence of a turbine, or turbine array (e.g., active pursuit vs ambush foraging).

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Appendix 1. Risk Model Inputs

Symbols used in Appendix Table below.

D = Density of seals per m^3
b = Number of spinning blades on the turbine
c = Chord width of the blade
γ = Pitch angle of the blade relative to the horizontal plane
L = Length of the seal
f = 4; a constant that defines the seal's effective cross section as that of a `long stick shaped' prey
R = Blade length, or radius of the turbine
λ = Tip speed ratio, a constant that determines the relationship between current speed and the rotational speed of the turbine blade
v = Velocity of the water current at the turbine
Ω = Rotational speed of blade in revolutions/s. At Strangford Lough, the maximum rotational speed
is reached at current speed, *v*=2.3 m/s.
u_a = Seal swimming speed relative to the water

Table 7 Inputs to CRM and ERM and literature/data sources.

	Scenario 1b Standard U-dive	Scenario 1a Standard V-dive	Scenario 2 Tip Speed	Scenario 3 RPM	Scenario 4 Swim Speed	Scenario 5 Swim Direct.	Scenario 6 Dive Profile	Scenario 7 Seal Density	Scenario 8 Avoidance
D_A	Jones et al. 2013	Jones et al. 2013	Jones et al. 2013	Jones et al. 2013	Jones et al. 2013	Jones et al. 2013	Jones et al. 2013	Sparling and Lonergan 2013	Sparling and Lonergan 2013
b	2	2	2	2	2	2	2	2	2
c	0.5 m[B]	0.5 m[B]	0.5 m[B]	0.5 m[B]	0.5 m[B]	0.5 m[B]	0.5 m[B]	0.5 m[B]	0.5 m[B]
γ	20 degrees[B]	20 degrees[B]	20 degrees[B]	20 degrees[B]	20 degrees[B]	20 degrees[B]	20 degrees[B]	20 degrees[B]	20 degrees[B]
L	1.6 m[B]	1.6 m[B]	1.6 m[B]	1.6 m[B]	1.6 m[B]	1.6 m[B]	1.6 m[B]	1.6 m[B]	1.6 m[B]
f	4[C]	4[C]	4[C]	4[C]	4[C]	4[C]	4[C]	4[C]	4[C]
R	8 m	8 m	8 m	8 m	8 m	8 m	8 m	8 m	8 m
λ	6[C]	6[C]	5.1	5.1	5.1	5.1	5.1	5.1	5.1
v		v^1	v^1	v^2	v^2	v^2	v^2	v^2	v^2
u_a	1.2[C]	1.2[C]	1.2[C]	1.2[C]	1.2[C]	1.2[C]	1.2[C]	1.2[C]	1.2[C]
nop^1	0.124[C]	0.124[C]	0.124[C]	0.133	0.133	0.133	0.133	0.133	0.133
Q	0.196[C]	0.196[C]	0.196[C]	0.196[C]	0.196[C]	0.196[C]	0.197/ 0.204	0.197/ 0.204	0.197/ 0.204
Direct-ion	Downstream	Downstream	Downstream	Downstream	Downstream	Upstream	Upstream	Upstream	Upstream
Time	Year	Year	Year	Year	Year	Year	Year	Year	Year

A Jones et al. 2013

B Sparling and Lonergan 2013

C Band 2014

v^1 Average current velocity measured by turbine sensors (2.1375 m/s)

v^2 5-minute averages of velocity measured by turbine sensors over entire tidal cycle

nop^1 Proportion of time the turbine blades are not spinning comes from the current velocity measured by sensors at the turbine

Appendix 2. Individual Brownian Bridge Estimates between GPS locations.

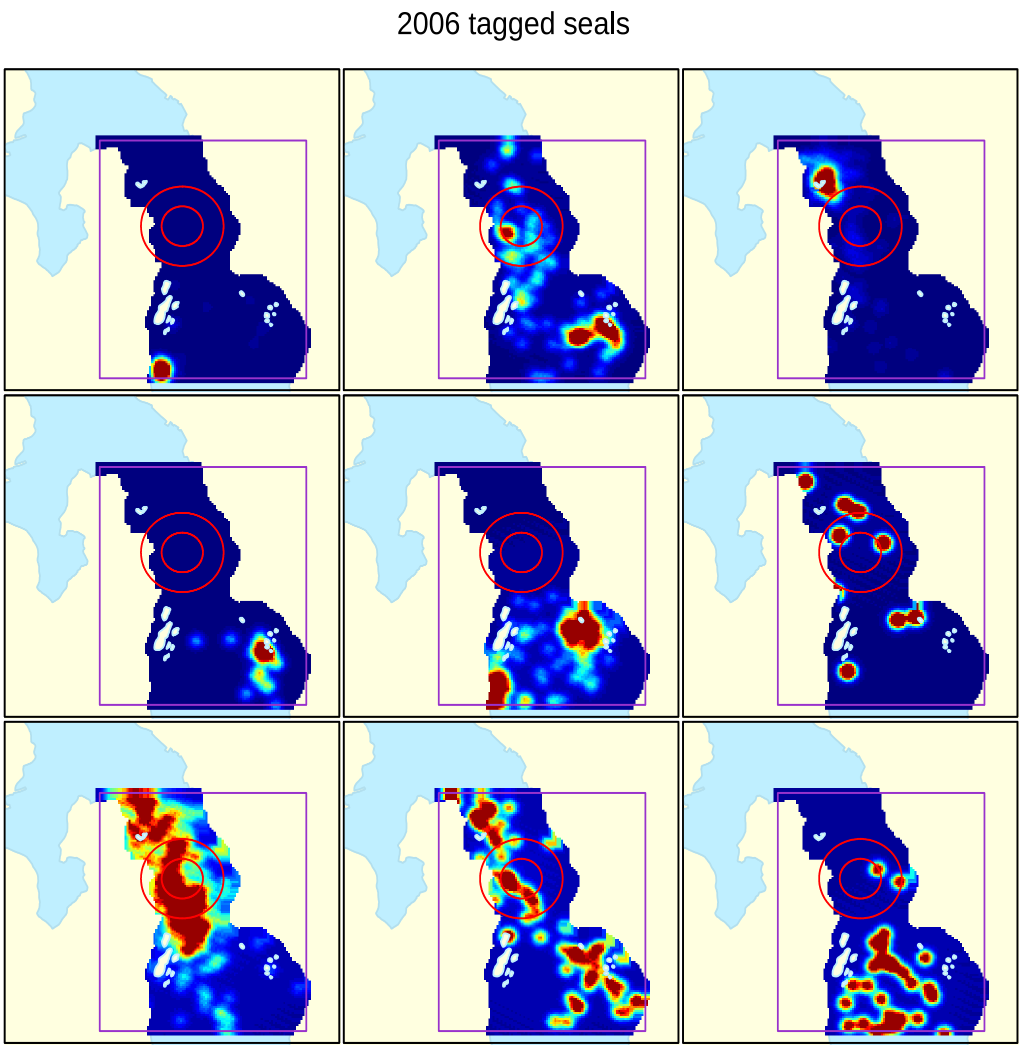

Figure 19 Brownian Surface for 9 seals tagged in 2006 in Strangford Narrows. Each seal's surface is plotted as its own panel. Red circles denote 200 and 400 m radius circle around the turbine.

2008 tagged seals

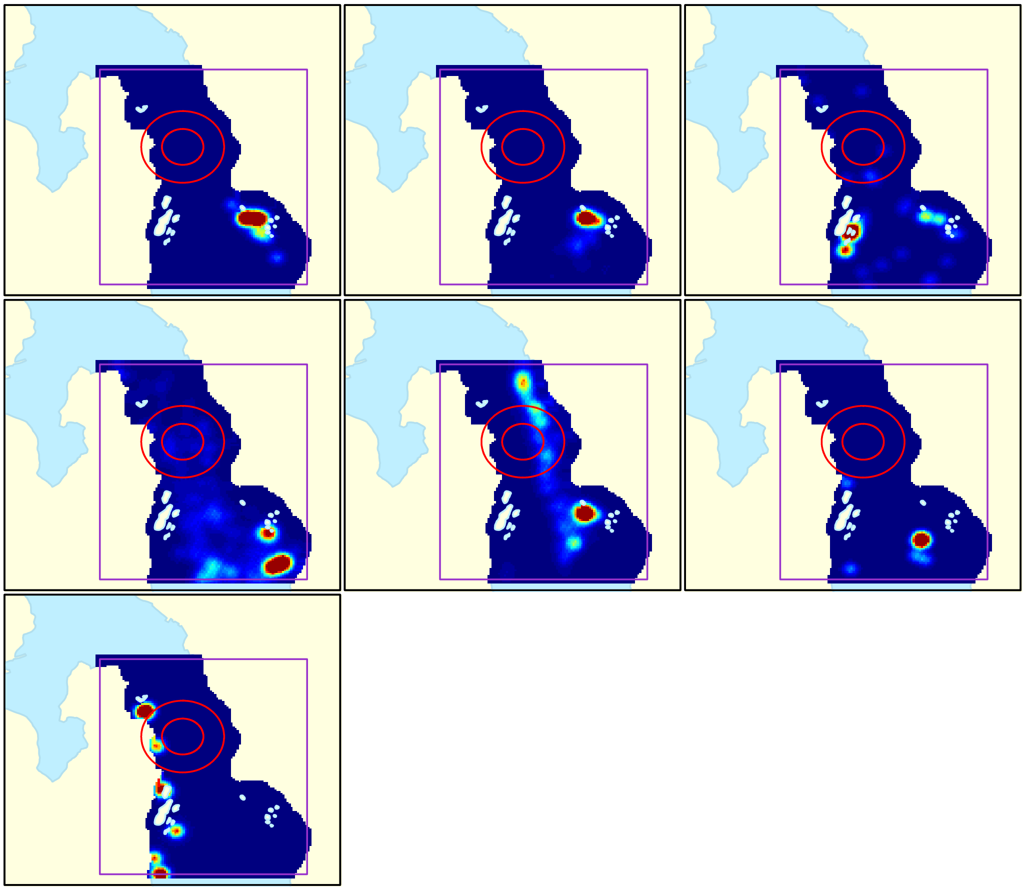

Figure 20 Brownian Surface for 7 seals tagged in 2008 in Strangford Narrows. Each seal's surface is plotted as its own panel. Red circles denote 200 and 400 m radius circle around the turbine.

2010 tagged seals

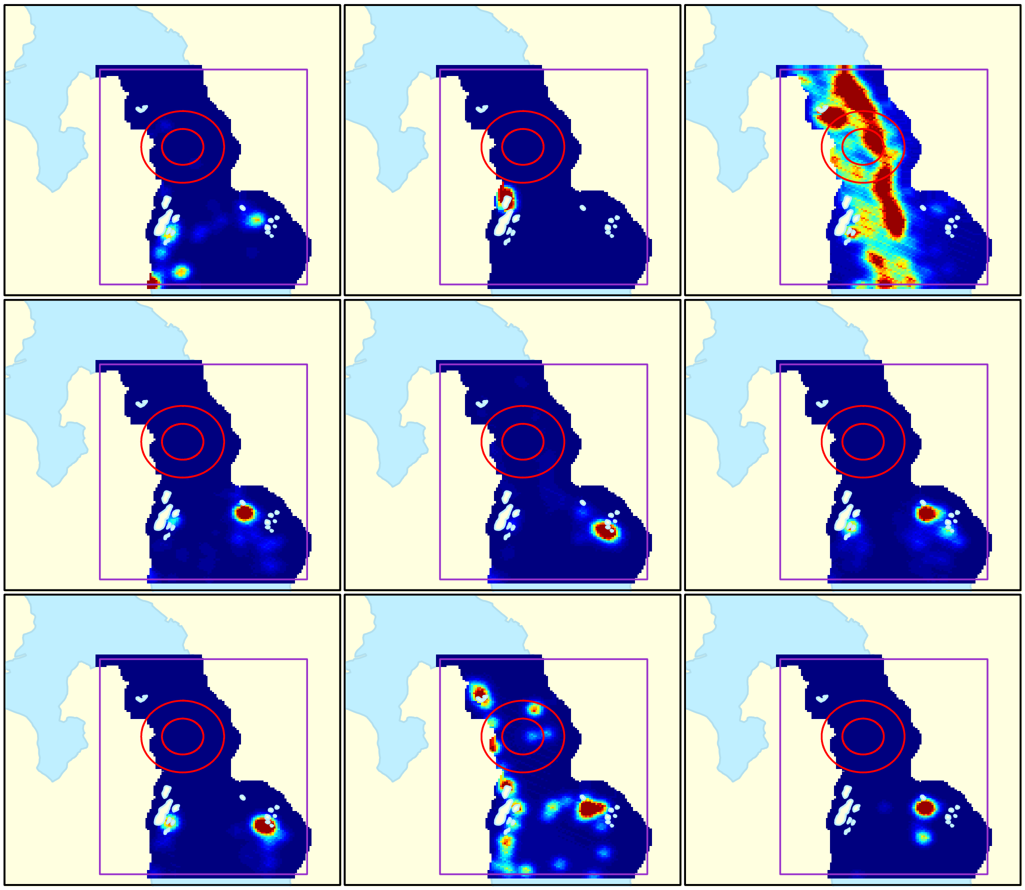

Figure 21 Brownian Surface for 9 seals tagged in 2010 in Strangford Narrows. Each seal's surface is plotted as its own panel. Red circles denote 200 and 400 m radius circle around the turbine.

Appendix 3. Detailed Review of Seal Datasets

Please see attached document.