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Collision risk and impact study: Examination of models for estimating the risk of collisions between seals and tidal turbines

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1 Executive Summary

The rate at which collisions can be expected to occur between marine mammals and tidal energy generation devices is potentially important to both the conservation of these species and the industry. Developers need to identify potential adverse effects of their proposed developments. For seals, this means demonstrating, among other things, that development and operation will not have an adverse effect upon the integrity of any SACs for which seals are a qualifying interest. Seals are seen as a particular problem in this respect because they frequent coastal locations where most tidal turbine developments have been proposed.

The major difficulty in estimating likely rates of collision is the lack of information on how animals will respond to active turbines. It is possible that they will be attracted, increasing their overall risk, though it seems more likely that they will avoid some potential collisions. Without such information, which is likely to be difficult to collect even once there are operational turbines, estimation is limited to encounter rates. Encounter rates are defined as the number of seals per unit time which turbines would strike if seals did not respond to the presence of the device. Those can be rescaled by assuming rates of avoidance, but that process will necessarily be approximate.

This report examines two models that have been proposed for estimating the rate at which seals can be expected to encounter tidal turbine blades. It also summarises a method that has been applied to calculate the risks to riverine fish from passing through hydroelectric power stations. The assumptions and implications of using the methods are discussed.

One approach was developed at SAMS Research Services Ltd (SRSL; Batty *et al*., 2012). It simplifies calculations by simplifying the shape of animals into spheres that would be of equivalent risk and assuming that animals' speeds are independent of their direction relative to the turbine blade. The two versions of that model seem to have errors in the equations they present, but their overall intent is clear.

An alternative approach was a development of the Band model for the risk of birds being struck by wind turbines. That 2012 model assumed the animal's motion was parallel to the axis of rotation of the turbine. Counterintuitively, the model's representation of a "flapping bird" is a more appropriate approximation of a seal than is its "gliding bird" one. The model was broadly similar to the one presented by von Raben for fish passing through a hydroelectric power plant.

The two approaches produce broadly similar results from their different simplifications. Given the greater uncertainty in the animals' responses, either could be used to give an estimate that will be less of an overestimate than simply estimating the number of animals likely to pass through the disc swept by a turbine rotor. If more detailed comparisons, such as between devices, are required, then a better estimate could be made by averaging the risks over an estimate of the likely joint distribution of animal speeds, directions and orientations throughout the tidal cycle.

In practice, the results of any assessments of overall risk are likely to be determined by the assumptions made about animals' ability to avoid collisions. Until data on avoidance rates become available, further refinements of the models of encounter rates may be of limited value.

2 Introduction

Collision with moving rotor blades has been identified as one of the potential risks to seals that may result from the operation of tidal turbines. Estimation of the numbers of animals that can be expected to be affected is difficult. This document looks into the details of two methods that have been proposed for calculating this risk and also summarises a model that has been used for the related problem of estimating the effect on fish of passing through the turbines in hydroelectric power stations.

The SRSL model (Wilson *et al*., 2007; Batty *et al*., 2012) assumes that the direction of motion of the animal and rotor are independent, which seems unlikely in fast flowing water.

A modified version of the Band (2000) model of risks to birds from terrestrial windfarms was used by Marine Scotland in the Appropriate Assessment of the Islay demonstrator project. The way in which that implementation calculated the expected number of transits through the area swept by the rotor, and some details of how it approximated the shape and orientation of the animals, are questionable.

The von Raben (1957) representation of fish passing through power station turbines has many similarities to the Band model, though in that design of turbine the water flows in through the sides of a chamber housing the rotor rather than parallel with the axis of rotation.

This document concentrates on the risks that would be experienced by individuals that were unaware of the existence of the rotor. All three of the methods discussed here treat animals' responses to devices as a multiplier on the risk, reducing the number of collisions by a fixed proportion. The size of that proportion, which has been tentatively estimated at values ranging from below 50% (for fish) to 99.8% (for some birds), seems likely to be more important than the details of the model to the final estimates of overall collision risks.

3 Models

3.1 SRSL model

The SRSL model was initially described in Wilson *et al*., (2007). A slightly revised presentation of it is contained in Batty *et al*., (2012), which estimates collision risks for the Meygen development in the Pentland Firth. Band, (2012, 2013) also applied the method to the Meygen development and the EMEC tidal turbine test site, and commented on its assumptions and simplifications.

This model represents the overall rate of collisions between animals and turbines as the product of three terms. The first of these is an encounter rate, based on the local population density. This is then modified by the probabilities that an animal avoids (diverts its path to go round) a device and that an animal, which has not avoided a turbine, evades (dodges) its blades. Wilson *et al*., (2007) and Batty *et al*., (2012) describe the first part of this, the rate at which encounters between animals and devices occur. Those authors highlight the lack of information available of behavioural responses to turbines, and concentrate on modelling encounter rates, the number of collisions per unit time that could be expected to occur between turbines and animals that were unaware of the devices. For similar reasons they do not consider the effects of collisions, this document therefore describes and discusses their estimation of encounter rates.

They followed Gerritsen & Strikler, (1977), who modelled underwater predator-prey encounters and derived an equation (Eq 4, Wilson *et al*., 2007) relating the encounter rate, Z, to prey density, D:

$$Z = D\,A\,(u_a^2 + 3u_b^2) / 3u_b \qquad (1)$$

Here u_a is the velocity of the prey and u_b that of the predator, which is assumed to move faster than the prey. The encounter area, A, for a conventional turbine is the area projected by the blades onto the surface perpendicular to their axis of rotation modified to allow for the size of the animal. The risk to animals from multiple blades during passage through the area swept by a single turbine is not independent, Band (2012) and Batty *et al*., (2012) therefore combine blades into a single area, which Batty *et al*. further reshape into a circle of equivalent area.

Equation 1 assumes that the blade is moving faster than the animal. Both of the later documents also give the form, transposing u_a and u_b, that applies when the seals move faster than the device. Gerritsen & Strickler (1977) go on to discuss optimal strategies for predators of different speeds, but these are of limited relevance to tidal turbines because they assume that the effective distance at which "predators" (in this case turbine blades) can affect "prey" (in this case seals) declines as their speed increases.

The formulation depends on the assumption that the directions of movement of the "predator" and "prey" are independent of each other, their relative speed and their orientation. That assumption seems unlikely to be correct for animals swimming within water that is moving, at a similar speed to the animal's maximum swimming speed, towards a turbine blade rotating in a plane perpendicular to the general direction of the water's flow. Wilson *et al*., (2007), Batty *et al*., (2012) and Band (2012, 2013) all make the further simplification of treating seals as being effectively spherical, though Band disagrees with the other authors on the size of sphere that would have an equivalent risk to a seal of a particular length. The validity of these simplifications can only be assessed by constructing more detailed models, though the comparison (in Band 2013) of the SRSL model with the results of the modified Band model, which treats seals as consisting of two cones, suggests that the two methods produce broadly similar results.

Wilson *et al*., (2007) go on to estimate the density, per cubic metre, of animals at the turbine as the product of the probability of being within the depth range of the turbine rotor [P] and twice the blade length [R_b] divided by mean water depth at the site [H] (Wilson *et al*., 2007, Eq 5):

$$D = P\ 2R_b / H \qquad (2)$$

This equation seems to be missing a term for the abundance of animals per square metre of water surface, N, among other issues. It could be modified to give:

$$D = N\ P/(2\ R_b) \qquad (3)$$

In this formulation, the density of animals is their abundance per square metre of surface multiplied by the probability they are in the depth range of the rotor and divided by the height of the area swept by that rotor. This does assume that P means the proportion of animals between the highest and lowest depths reached by the rotor tips and that the distribution of animals between these depths is uniform.

Batty *et al*., (2012) recast the calculation of the number of animals per unit volume to a calculation of the proportion of time they spent between particular depths (Batty *et al*., 2012, Eqn 9):

$$\mathrm{Ti} = \delta(B_i P_i \ + \sum_{j=i}^{j=n} \left(\frac{D_j}{d} + \frac{D_j}{a}\right) P_j) / (\textstyle\sum_{i=1}^{i=n} B_i P_i \quad + \displaystyle\sum_{j=i}^{j=n} \left(\frac{D_j}{d} + \frac{D_j}{a}\right) P_j) \qquad (4)$$

They went on to explain the terms in the equation thus: Ti is the time allocation to any depth interval, Di is the depth interval (distance between upper and lower bounds), d is the descent rate, a is the ascent rate, Bi is the bottom time, P the proportion of time spent in each depth range bin and δ is the total proportion of time spent diving. This is then repeated for all depth range bins from the surface to the sea bed.

This formulation is also problematic as it stands, largely because the subscripts seem to confound dives to particular depths with the parts of dives that are at particular depths. It was probably intended to read:

$$\mathrm{Ti} = \delta(B_i P_i + \sum_{j=i}^{j=n} \left(\frac{D_i}{d} + \frac{D_i}{a}\right) P_j) / (\sum_{i=1}^{i=n} B_i P_{i_i} + \sum_{j=i}^{j=n} \left(\frac{D_i}{d} + \frac{D_i}{a}\right) P_j) \qquad (5)$$

Moving from time allocations at depth to numbers of transits past a point would most easily be done by calculating the expected number of animals per unit volume at the appropriate depth and scaling this with the speed of the water current and the frontal area of the turbine. However, if the distribution of dive depths and shapes is known, it might be more straightforward to work from numbers of dives, as Wilson *et al*., (2007) did. The text in Batty *et al*., (2012) is not explicit about which approach was used in their assessment.

3.2 Modified Band model

The Scottish Natural Heritage Collision Risk Model, also known as the Band model, was developed to estimate the number of birds that could be expected to collide with onshore windfarms (Band, 2000). A modified version of it has been used by Marine Scotland to predict the rate of collisions between seals and the demonstrator tidal array that is planned for the Sound of Islay. Davies & Thompson (2011) give an overview of the modified method that builds on the more detailed information about the original Band model given by Band (2000). Band (2013) applied both this model and the SRSL one to data from the EMEC site, and expressed a preference for the SRSL model for seals.

The form of the modified model, as implemented in the Sound of Islay, is summarised below and its assumptions and implications are briefly commented on. This examination uses information in the two papers plus spreadsheets associated with the impact assessment for the development (copies of the spreadsheets were provided by SNH for this review). The data used in the Sound of Islay assessment are then considered in detail. Differences in how the method was applied to the EMEC data, in Band (2013), are also mentioned.

3.2.1 Details of model

The model considers seals to be at risk during each of a set of discrete transits they make through the device. It has four parts:

- The number of transits per year given the animals are unaware of the device based on the behaviour and local abundance of animals.
- The proportion of time the device operates.
- The average probability of collision during a transit, given the animal is unaware of the device.
- A correction factor to represent the animals' ability to avoid colliding with blades.

All four parts of the model are calculated and multiplied together for average conditions. Band (2000) comments that more precise estimates could be constructed by integrating over the tidal cycle. However, the uncertainties in the various parameters used within the estimation process may limit the amount of practical benefit that could be gained from this refinement.

3.2.1.1 Number of transits

This part is based on the first of the two methods presented in Band (2000). Those methods treat birds that fly directly through rotors (such as ones with turbines on their path between roosting and foraging sites) and those that forage around the devices (such as raptors and other territorial birds) differently. The modified method preserves the idea of discrete transits through the device, from the first method, but tweaks the simplification that birds' motion is orientated along the turbine's axis of rotation. Seals and birds need to regularly return to the surface of the water to breathe, so their trajectories are considered as series of dives for estimating the number of transits. However, the risk of collision during a transit still treats all motion as being parallel to the axis of the turbine.

Rather than being based directly on local density, the Islay calculation of the number of transits through the underwater volume that would be swept by the turbine blades started from an estimate of the expected number of animals in an area around the device location. This was then multiplied by twice the estimated number of dives per hour made by an average seal, with the doubling allowing for the fact that each dive has to return to the surface. The proportion of these transits that pass through a turbine of radius r is then estimated as the proportion, out of the volume of water under the survey area that is less than r above or below the centre of the turbine that is within one animal's length of the volume swept by the blades.

The major difficulty with this part of this implementation of the model is that the risk of collision it estimates is effectively only applied to animals that are on the surface directly above the rotor[1]. The formulation means that the estimated number of transits at risk of collision would be doubled by doubling either diameter of the rotor blades or the distance between their leading and trailing edges. Intuitively, doubling the diameter might be expected to quadruple the number of transits at risk. The effect on the number of transits at risk should be fairly insensitive to changes in the distance between the leading and trailing edges of a blade (though it might affect the risk of collision for each of the transits). That may indicate an error in the spreadsheet used in the Islay assessment.

A very simple way to recalculate the estimate is to assume that seals travel in straight lines during the descent and ascent phases of their dives, as is done in the SRSL calculations for the Meygen proposal (Batty *et al.*, 2012). Figure 2 in Davies and Thompson (2011) shows the necessary correction, and the text of that document appears to describe that modification. However, it does not seem to have been used in the assessment spreadsheets.

3.2.1.2 Proportion of time the device operates

Turbines are assumed to either be stationary or operating at full speed (Davies and Thompson, 2011). In the Islay assessment, data from Strangford Lough were used to estimate the proportion of time they operated, though that could be modified by using technical data for particular devices combined with local information on current speeds through the tidal cycle.

3.2.1.3 Probability of collision during a transit (without avoidance)

The collision risk estimate for an unaware individual transiting through the turbine described in Davies and Thompson (2011) and within the Sound of Islay assessment spreadsheet appears to be exactly the same as those given in Band (2000). This model assumes that each individual moves along a path that is parallel with the axis of rotation of the turbine. It therefore assumes that the direction of flow of water in front of the turbine blade's leading edge is unaffected by the rotor's movement. In reality, viscous effects will transmit some motion to this water. However, this effect has been considered small enough to be neglected in both theoretical designs of turbine arrays, where effects are only propagated downstream, and models of collision risks for riverine fish passing through turbines in hydropower plants (Von Raben, 1957; Deng *et al.*, 2007).

Estimates of risk are calculated separately for each of a set of concentric rings about the turbine centre. The risk is estimated by effectively unrolling each ring so that the turbine blades sweep a set of diagonal stripes across the path of the animal (Band, 2000: Figure 3). Another, possibly more intuitively obvious representation, might use a frame of reference where the blade is stationary and the bird travels diagonally to reach the same conclusion. As the original Band model represents birds, its calculations are complicated by a need to allow for flapping wings. It considers a bird to effectively consist of a cross, with the body aligned with the turbine's axis of rotation and the wings crossing the mid-point of that. The probability of collision then takes slightly different forms depending on the shape of the bird and its speed relative to that of the turbine blade (Band, 2000, Eq 2).

For a slow moving long narrow bird ($\alpha < \beta$):

$$p(r) = (b\Omega/2\pi v) (K \,|\pm c \sin\gamma + \alpha c \cos\gamma| + 1) \qquad (6)$$

For a shorter, wider, faster bird ($\alpha > \beta$)

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[1] This was probably not intentional, but is visible in the spreadsheet. Cell F45 calculates the "Number of transits of swept volume per year" from "Number of dives within risk area in horizontal projection", which is given as F44*F21/F25.

F44 is the "Number of transits of rotor depth zone", twice the number of dives

F25 is the "Area of survey block"

F21 is the "Total swept area in horizontal projection", calculated "2*F12*F20*F14", these are defined as: "Risk radius"; "Total depth of risk area (blade plus 2*animal)" and "Number of turbines".

$$p(r) = (b\Omega/2\pi v) (K \mid \pm c \sin\gamma + \alpha c \cos\gamma \mid + w\alpha F) \qquad (7)$$

where: b = number of blades in rotor
Ω = angular velocity of rotor (radians/sec)
c = chord width of blade
γ = pitch angle of blade
R = outer rotor radius
l = length of bird
w = wingspan of bird
β = aspect ratio of bird ie l / w
v = velocity of bird through rotor
r = radius of point of passage of bird
α = v/rΩ
F = 1 for a bird with flapping wings (no dependence on ϕ)
= (2/π) for a gliding bird
K = 0 for one-dimensional model (rotor with no zero chord width)
= 1 for three-dimensional model (rotor with real chord width)

(Band, 2000)

(In these equations |x| means the absolute value of x, so |-2| = |2| = 2)

The Sound of Islay Assessment adopts this formulation treating harbour seals as gliding "birds" with length 1.8m and "wingspan" 0.4m. While it would seem strange to consider seals to "flap", the model considers the wings of flapping birds to fill a disc centred on the middle of their bodies, while during gliding the wings remain horizontal. This difference has no effect on the estimate of collision risk for individuals directly above or below the turbine's centre, but substantially reduces the estimated collision risk for those at the level of the centre. This results in the calculated collision risk for gliding birds being only two-thirds of that for flapping birds. Band (2012) comments that the flapping bird shape is a more appropriate representation of marine mammals. The short "wingspan" of the seals in the Islay assessment, as compared to their length and the ratio of the blade and animal speeds, meant that the only difference "flapping" makes to their risk of collision is in the central 5% of the turbine, which accounts for around 0.25% of the total swept area.

So, for seals, the Band model effectively becomes:

$$p(r) = (b\Omega/2\pi v) [K \mid \pm c \sin\gamma + \alpha c \cos\gamma \mid + l] \qquad (8)$$

The first term (bΩ/2πv) is one over the distance the animal moves in the time between passages of the leading edge of consecutive blades crossing its path. In the simple version of the model (K=0), where only collisions with the leading edge of blades are considered, the calculation simplifies to be the animal length divided by the distance the animal moves between potential collisions.

The Islay assessment sets K=1 in order to allow for collisions where the animals are struck by parts of the front face of the blade away from its leading edge. The term "c sinγ" is the effective thickness of the blade measured perpendicular to the axis of rotation of the turbine (the assumed direction of movement of the animal). The term "α c cosγ" is a correction to account for the effect of the pitch of the blade on the time for which it intersects the path of the animal. The overall formulation therefore calculates the probability of an animal being struck by comparing the length of the animal and thickness of the blade to the speed of the animal.

The approximation that animals move along lines parallel with the axis of rotation of the turbine is not consistent with the assumption, used in the first part of the Islay assessment, about the number of transits past turbines. More importantly, the discrepancy between the speeds of swimming and current also make the inclusion of a risk of collision to animals travelling "upwind" seem less plausible. The differences in the calculated "upwind" and "downwind" collision risks in the Band model only comes from the pitch of the blades, though Band (2000) commented that using different velocities for the two directions might be beneficial. Averaging over "upwind" and "downwind" movement using the same speed over the ground has the effect of increasing the collision risk estimated in the Islay assessment by around 10%. While "upwind" movement will only be possible against relatively slowly moving water, the slower animal velocity it implies will increase the risk of an encounter with a turbine blade on each transit that does occur.

The thickness of the turbine blade has some effect on the estimated collision risk, doubling or halving the values used in the Islay assessment changes the results by around 10%. The assessment used the default blade profile provided by Band (2000): that of a modern Aerpac turbine blade, but with an altered maximum thickness. As Davies & Thompson (2011) suggest, changing the shape to more accurately reflect blade designs suitable for tidal turbines may have a small effect on the results.

3.2.1.4 Avoidance

Very little is known about animals' ability to avoid/evade being struck as they pass through turbines. Such data are very limited even for birds passing through terrestrial windfarms. The Band models therefore use a simple multiplier to account for avoidance.

3.2.2 Data used in the Sound of Islay assessment

This section goes through each of the four parts of the modified Band model in turn describing and evaluating the data used in the Sound of Islay assessment for harbour seals.

3.2.2.1 Number of transits

The Sound of Islay Assessment said:

"… the SMRU Marine mammal survey data from shore based observations over a 12 month period from July 2009 to August 2010, as described in the SMRU Report Number MMM 0309 SPR – Sound of Islay. Using the observation data, the average number of harbour seals recorded within the survey area was 1.9 seals per hour."

Because the calculations calculate a proportion of dives within the area that are at risk of collision by dividing the area of the turbine by the area over which observations were made, the size of the study area cancels out. The size of the area is then a matter of convenience: large areas may contain sufficient variation to make their results unrepresentative of the actual risk, while small ones might need to be observed for a very long time in order to obtain estimates with sufficient precision. Davies and Thompson (2011) state "grey seals make approximately six dives per hour, while harbour seals make around 12" (SMRU, pers. comm. 2010). They then double this to allow for the fact that each dive has to return to the surface. The Islay Assessment multiplies 1.9 by 12 to estimate that a total of around 23 harbour seal dives occur in the survey area each hour.

However, the description of the observation data is slightly ambiguous. The Assessment interprets it as meaning the average, over all times, of the number of seals present in the area was 1.9. However, the wording "recorded […] 1.9 seals per hour" could also be interpreted as indicating that there were slightly less than two distinct sightings of animals each hour. That alternative reading fits with the way such data are often collected, and the wording used within the report. Each of the observations could simply involve one surfacing event, and therefore correspond to the time between a pair of consecutive dives. So, if all surfacings were seen, the number of transits through the water layer at the depth of the planned turbine would have been somewhere between 2 and 23. A further complication is that some surfacings, or even animals, within the survey area may not have been seen. Twenty-three could therefore be an underestimate. Detailed re-examination of the observation data, consideration of data from tagged animals, and an estimate of the detectability of seals in the water, might allow the refinement of this estimate.

The survey area in the Sound of Islay covered 3,530,973m^2. Harbour seals were taken to average 1.8m in length. The planned development consisted of ten turbines each having 10.5m radii blades with a depth of 0.52m along its axis of rotation.

The volume within one animal-length of the rotating blades of one turbine was:

$$V_1 = \pi\,(10.5+1.8)^2\,(0.52+1.8+1.8) = 1958.2\ \text{m}^3$$

The volume of water under the survey area at the relevant depth:

$$V_2 = 2(10.5+1.8)\ 3530973 = 86861936\ \text{m}^3$$

So $10(V_1/V_2) = 2.25 \times 10^{-5}$ of dives made by animals within the survey area are calculated to pass through the turbines. Given 1.9 animals diving 12 times each per hour, this produces the total of 90 transits per year reported by the environmental assessment for that development. This calculation involves various assumptions about the stability of the rate of transit between night and day and different seasons.

This estimate can easily be recalculated to include the correction suggested by Davies and Thompson (2011), if it is assumed that seals travel in straight lines during the descent and ascent phases of their dives. If the vertical speed of diving seals is taken as 1.5m/s and mean current speed as 2.7m/s, then seals, assuming they make no effort to move horizontally, that dive from points within an area of the sea surface equal to almost twice the area swept by the turbine blades will pass through the turbine. The numbers of transits passing through the device will be unchanged by seals deliberately angling their dives, provided any such efforts are independent of the animals' positions relative to the device. In reality, when the current is faster than the animals swim, there will be two areas of this size containing animals that will pass the turbines during the descent or ascent phases of their dives, rather than a single group passing through once. However, that makes no difference to the calculations. The approximation neglects the thickness of the blades because it is much less than their diameter.

$$P(\text{transit passes through one turbine}) = \frac{\text{areaswept} * \text{currentspeed/verticalspeed}}{\text{surveyarea}}$$

$$= \frac{\pi\,(10.5+1.8)^2\ (2.7/1.5)}{3530973}$$

$$= 0.00024$$

The result is that, if there are an average of 1.9 seals in the area, a total of 968 transits pass through the set of ten turbines each year, rather than the 90 calculated in the Appropriate Assessment document. This difference is due to the area swept by the turbine rotor being much larger than the area of sea bed covered by the moving blades.

3.2.2.2 Proportion of time the device operates

In the Islay Assessment the turbines were assumed to operate for 71.5% of the time, on the basis of operational data from the SeaGen device in Strangford Lough (Davies and Thompson, 2011). Basic data on local conditions and the patterns of operation of particular devices will be a necessary part of Developers' assessment of the financial viability of proposed projects and therefore should be available for any future assessments.

3.2.2.3 Probability of collision during a transit (without avoidance)

The collision risk calculation for an unaware individual transiting through the turbine described in the Sound of Islay assessment spreadsheet closely follows Band (2000), though the maximal thickness of the blade is set to 1.5m. Davies & Thompson (2011) do suggest that it might be better to use a different blade shape than the default provided.

3.2.2.4 Avoidance

The Islay Assessment used Band's (2000) default value of 98% of potential collisions being avoided/evaded, dividing the estimated impact of the devices by a factor of 50. Davies & Thompson (2011) discuss the uncertainty around this correction, and tabulate results for values between 95% and 99.8%, but do not present any data to inform the choice.

3.3 Von Raben model

Many fish either need to pass or are accidentally carried through electricity generating turbines installed within dams. The risks they face have been studied both empirically and through numerical analyses. Von Raben (1957) estimated this risk, and his formulation is still the basis of work in this field. His basic equation for the risk of collision for a fish of length l passing through a Kaplan turbine with b blades rotating at N rpm can be expressed as (Deng *et al*., 2007):

$$P(\text{collide} \mid l, b, N, \theta) = l\, b\, (N/60) \cos(\theta) / V_{axial}$$

Here V_{axial} is the speed of water flow in the direction parallel with the axis of rotation of the turbine and θ is the angle between that direction and the direction the water flows in. The term θ is required because water enters Kaplan turbines through gates in the outer wall of a chamber behind the rotor and the fish are assumed to be aligned with the resulting direction of flow of the water.

In experimental studies, von Raben (1957) found that lower proportions of fish were damaged than his equation predicted and therefore introduced the concept of a "mutilation ratio" to correct for this. He interpreted this in terms of glancing blows to extremities causing less harm, rather than the fish managing to evade collisions. He provisionally estimated that 43% of the number of eels predicted by the model were struck in one particular device, though he cautioned that this ratio was likely to be variable and that the flexibility of eels may make them unrepresentative of other species (von Raben, 1957). Empirical studies of salmon and trout passing through turbines on two Swedish rivers (Ferguson *et al*., 2008) produced results that were more similar to the results of the model.

3.4 Avoidance and evasion

Wilson *et al*., (2007) make a useful distinction between avoidance, large scale movement by which animals divert round the outside of a device, and evasion, smaller scale movement that prevents a collision with a particular turbine blade. They suggest that the probability of an animal not avoiding a turbine in its path and that of not evading an approaching blade can be applied as multipliers to an estimate of encounter rate to convert it to an estimate of collision rate. However, they go on to state that there was insufficient information available for them to estimate these probabilities, and restrict their analysis to the calculation of encounter rates. Davies and Thompson (2011) acknowledge the lack of data but consider the combined effect of avoidance and evasion to reduce collisions by at least 95%, by extrapolating from data on birds' behaviour around terrestrial windfarms. The Sound of Islay Appropriate Assessment assumes that 98% of potential collisions are avoided/evaded.

There are several reasons to doubt whether flying birds and swimming creatures have similar abilities to escape potential collisions:

- Birds are smaller than seals.
- Turbines turn more slowly in water than air.
- Approach speeds in the water will generally be slower than in the air.
- Birds generally fly much faster relative to both wind and turbine speeds than most creatures swim relative to tidal flows and marine turbine speeds.
- Air provides less resistance, easing turning and dodging.
- The detectability of turbine blades may be different in air and water. Sound and other vibration carry further in water, but light levels are much lower, especially in turbid inshore areas.
- Differences in intelligence and behaviour may affect abilities to evade collisions.

- A flying bird can use gravity to accelerate downwards; marine mammals are close to neutrally buoyant so can only accelerate upwards or downwards by increasing swimming effort.

Some of these differences point towards higher proportions of flying birds than swimming seals escaping potential collisions, while others suggest lower values. However, it is likely to be difficult to estimate the magnitude of any difference.

Avoidance is largely a matter of animals perceiving the device to be a threat at a sufficient distance. For example, an animal that responds to the threat by swimming across the current, away from the rotor's hub, at half the water's speed will avoid the danger provided it notices it before it approaches within a distance equal to one rotor diameter upstream of the device. The exact shape of such a danger area will depend on the animals' swimming speeds and direction of escape relative to the current.

4 Conclusion

There are difficulties with both the approaches that have been applied to estimating rates of collision between seals and tidal turbines, but the issues with the SRSL method appear much more fundamental than those for the modified Band model. The latter is broadly consistent, in how it calculates the probability of collision given an animal passes through the area swept by the rotor at a particular speed, with von Raben's calculations for fish. The main difficulties with how it was used in the Sound of Islay Assessment concern the number of transits considered to be at risk and the assumed speeds and direction of movement of the animals.

Band (2012, 2013) got broadly similar values from fitting both models to data. While that doesn't prove that either one is correct, it does suggest that the very different simplifying assumptions they use have similar effects. The Band model formulation would be easier to extend to incorporate more realistic interdependence of the speed, direction and orientation of the animal relative to the turbine, and also the turbine's speed. In principle it would be possible, for each distance from the turbine's centre and each minute over the monthly neap-spring tidal cycle, to integrate over a distribution of animal orientations and animal speeds through the water, given current speed and orientation. If those distributions could be specified appropriately, calculating overall risk would just require averaging that, weighted by the expected numbers of animals in the water to give an overall level of risk. The calculations would be slightly convoluted, and perhaps too complicated to carry out on a spreadsheet. However, whether that was worth doing would depend on the level of precision required and the data available to support it.

At the other extreme, a very simple index of risk could be generated by estimating the rate at which animals are likely to pass through the disc swept by the turbine. That would overestimate the risk and neglect issues around turbine design. But again, given the lack of knowledge of behavioural responses to turbines this might be as useful a measure as any of the more complex approaches.

The uncertainty in the behaviour of animals around tidal turbines is sufficiently large to limit the benefits of detailed modelling of the chance of an unaware individual being struck while passing through the area swept by a turbine rotor. In principle the size and shape of both the animal and the rotor blades will affect the risk of collision, but if the number that would be struck if unaware needs to be divided by somewhere between 2 and 500 to give the actual expected number of collisions, then accounting for the details of the physical system may be relatively unimportant. The sorts of data likely to be available for calculating the correction factor are also important: at best these are likely to be an estimate of the proportion of transits that result in collisions. Unless reasonable amounts of data are obtained for several specific combinations of parameter values and are used to extrapolate to other situations, a formal model may not offer much practical advantage over a simple scaling on the local density of animals

Overall, it seems that either of the methods could be used to give a rough estimate of the rate of encounters that could be expected between unaware seals and operational tidal turbines. Without detailed information on the behaviour of animals around active devices, it probably doesn't much matter which approach is taken. If further detail is required, then the Band model would appear easier to extend. A risk of using a detailed calculation is that the results may appear spuriously precise. Realistically, there is currently no information on which to base any estimates of the uncertainty around any estimate of expected rates of collisions.

If the, apparently fairly weak, assumption that there will be more avoidance of collisions than attraction of animals, calculated encounter rates could be directly used as an upper bound on the risk from the devices. In that case, refining the models to incorporate distributions of speeds, orientations and directions of movement would be beneficial. However, if the avoidance of collisions by seals is similar to that observed for birds in windfarms, the result may be a fifty-fold overestimate of the potential risks of developments.

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