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Review

A Probabilistic Methodology for Determining Collision Risk of Marine Animals with Tidal Energy Turbines

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Abstract: Commercial development of tidal stream energy is hampered by technical and financial challenges, and impeded by uncertainty about potential environmental effects that drive environmental risk assessments and permitting (consenting) processes. The effect of greatest concern for operational tidal stream energy devices is the potential for marine animals to collide with turbine blades, resulting in injury or death. Due to the turbulent and often turbid waters that frequently characterize tidal turbine sites, there is an absence of empirical evidence about collisions with marine animals. This paucity of observations often leads to risk-averse permitting decisions that further restrict the deployment of tidal energy devices that are needed to collect this evidence. This paper relies on the framework of stressors and receptors that is widely used in marine energy studies and outlines a stepwise probabilistic methodology that applies existing knowledge to further elucidate the risk to marine animals from operational tidal turbines. A case study using striped bass from the Bay of Fundy, Canada, accompanies the methodology, to partially demonstrate its application.

Keywords: risk assessment; tidal stream energy; environmental effects; collision risk; marine renewable energy

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1. Introduction

The global expansion of marine renewable energy (MRE) devices (e.g., tidal stream and riverine turbines, wave energy converters, and others.) is an integral part of an overall strategy to address the impacts of climate change [1–3], ensure a sustainable transition towards renewable energy sources [4,5], and meet national energy security needs using locally generated electricity [6]. As an emerging industrial sector, MRE development to date has been limited to the deployment of single devices, pilot projects, and small demonstration-scale arrays [7]. The establishment of large-scale commercial arrays is essential for meeting climate change and energy security goals, but is hindered by a variety of factors, including difficulties in obtaining regulatory approvals due to uncertainty about the environmental effects on marine ecosystems and their constituents [8–11]. This uncertainty stems from a paucity of post-installation environmental monitoring data for single MRE devices and demonstration-scale arrays that confounds our ability to differentiate between unknown (but perceived) and realized risks for marine ecosystems stemming from MRE development [12].

A framework for assessing the environmental effects of MRE technologies focuses on understanding the interactions between 'stressors' (i.e., those parts of an MRE device or system that may cause harm) and 'receptors' (i.e., those components of the ecosystem that may elicit some response to the stressor) [12–14]. For tidal stream energy technologies, the risk of collisions between marine animals (particularly marine mammals, diving sea birds, fish, and sea turtles) and the moving parts of devices (e.g., turbine blades and rotors, or dynamic technologies like tidal kites or oscillating blades; [15,16]) are generally unknown, but are considered to be the greatest potential risk of turbine operations [12]. As such, collision risk (i.e., the likelihood that animals might be harmed by coming into contact with the moving parts of MRE devices [17]) has been the subject of much research (reviewed in [16]), including modelling exercises (e.g., [18–20]), experiments conducted under controlled laboratory conditions (e.g., [21–23]), and in situ studies around various operational turbine technologies (e.g., [24–26]). Collectively, this body of knowledge provides substantive evidence to suggest that when marine animals can detect operational tidal turbines, they can exhibit avoidance or evasion behaviors [17,27] and take measures to prevent being struck by turbine blades [28–33]. Indeed, collisions between marine animals and tidal turbines are expected to occur infrequently [12]. However, the paucity of empirical collision data from post-installation monitoring programs, or analogues from other marine industries, has hampered the coalescing of evidence needed by various regulatory agencies to permit the expansion of some tidal energy projects beyond single devices and small demonstration-scale arrays.

Despite the availability of adaptive, risk-based approaches to MRE project permitting (e.g., 'Survey-Deploy-Monitor' [34,35]), the absence of conclusive empirical evidence about the probability of collisions and their consequences has led to risk-averse permitting decisions for tidal energy projects in some jurisdictions [36,37]. These decisions inadvertently restrict the deployment of tidal energy devices in locations and at scales that are required to collect the very evidence about collision risk that is being sought. This paradox may in turn limit expansion of the MRE sector and hamper global efforts to address the impacts of climate change, ensure a sustainable transition of our energy systems, and provide national energy security.

In the absence of conclusive empirical collision risk data, expansion of the MRE sector still requires a means by which to assess the risk of collisions a priori to facilitate project permitting and support sector growth. Assessing the risk to a marine animal of approaching an operational turbine, being struck by a turbine blade and suffering a critical injury or mortality is determined by the probability of the event occurring and the consequences of the event (e.g., [38]). This risk can be envisaged as a sequence of dependent events, each with an associated probability of occurring, that must coincide for collision risk to be realized [39]. The purpose of this study is to describe the process of collision risk for tidal turbines from a risk management perspective, and expand on the work of Copping et al. [39] to advance a conceptual, probability-based framework for quantifying the associated likelihoods for the sequence of events inherent to collision risk. To that end, we first outline the sequence of events that comprise this framework, and then demonstrate its application (to the extent currently possible) using striped bass (*Morone saxatilis*) in the Minas Passage, Bay of Fundy, Canada.

2. Materials and Methods

This paper addresses the development and application of a conceptual probabilistic framework for the collision risk of marine animals, particularly marine mammals and fish, and demonstrates the initial steps in the framework using a case study.

2.1. Conceptual Probabilistic Framework

We conceptualize collision risk as a series of seven sequential events (i.e., steps) that must each occur for a marine animal to approach an operational turbine, be struck by a turbine blade, and be harmed (i.e., suffer a critical injury or mortality) (Figure 1). Descriptions of these seven events are outlined in the Results section. Each of these events has an associated probability of occurring, and the likelihood of harm is ultimately a product of these dependent probabilities. Consequently, if any of the probabilities in this sequence of events is small (near-zero) or zero, then the overall probability of harm is similarly low and unlikely.

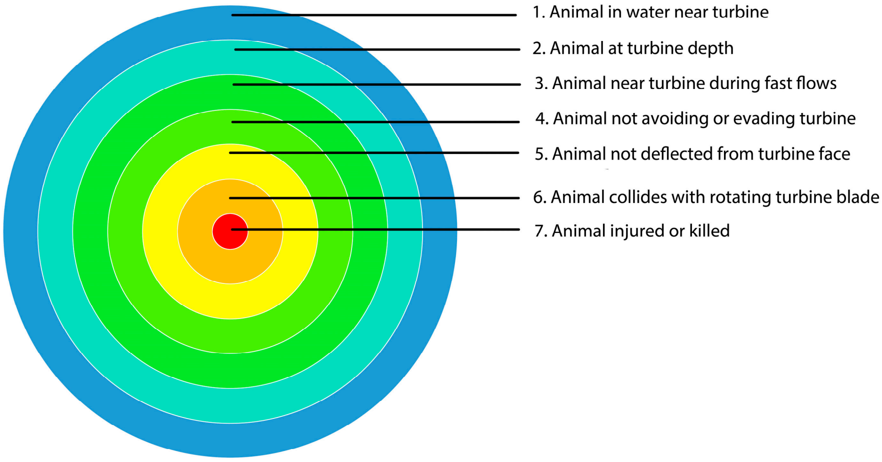

Figure 1. Conceptual probabilistic framework for quantifying the likelihood of collision risk for marine animals and operational tidal energy turbines. The framework outlines a series of sequential steps that must take place, each with an associated probability, for a marine animal to approach an operational turbine, be struck by a turbine blade and be harmed (i.e., suffer a critical injury or mortality). Adapted from Copping et al. [39].

Evidence that supports a risk assessment for each of the seven events was acquired through a search of the literature that included peer-reviewed articles in scientific journals (Web of Science and Tethys knowledge base—a database devoted to compiling information about the environmental effects of MRE—https://tethys.pnnl.gov accessed 1 May 2023) as well as the additional grey literature found on Tethys [40] to contextualize the probability of each event occurring. Although the peer-reviewed scientific literature was the primary base of evidence, the MRE industry is still in the early stages of development, and some key findings are documented in environmental monitoring reports and permitting/consenting documents that are not available in the peer-reviewed literature or found in associated databases. While the value of the non-peer-reviewed reports cannot be weighed as heavily as those in the scientific literature, each has been scrutinized by governmental bodies as evidence to support regulatory processes. We reference these materials judiciously.

2.2. Case Study

We demonstrate an application for a subset of the proposed framework (i.e., steps 1–3; see below) using striped bass (*Morone saxatilis*) in the Minas Passage, Bay of Fundy, Canada, based on the work of Bangley et al. [41]. Bangley et al. [41] used a combination of acoustic tag detection data (2017–2020) for adult striped bass (i.e., >60 cm fork length) from the Shubenacadie River, Nova Scotia, and associated environmental variables at specific locations in the Minas Passage to develop species distribution models and predictive spatiotemporal maps (i.e., 150 m $\times$ 150 m grid cells) to determine the presence probabilities of striped bass by season and tidal stage. The species' vertical distribution throughout the water column was incorporated into the approach using data from depth sensors included for a subset of the acoustic tags; we include additional depth distribution data from tagged individuals detected during 2009–2013 to more fully account for the species' vertical distribution in the Minas Passage. Because the detection probability for acoustic tags in tidal channels can be impacted by local hydrodynamics [42], the modeled presence probability of striped bass used here is adjusted using a scaling function adapted from MacKenzie et al. [43] that weights acoustic tag detections during hydrodynamic conditions that are associated with poor detection efficiency [44].

Although the results of this demonstration are specific to adult striped bass from the Shubenacadie River, these factors do not preclude the value of Bangley et al. [41] for demonstrating an application of the framework developed herein. Indeed, the results of Bangley et al. [41] are particularly relevant for understanding the probabilities associated with the presence of striped bass in the vicinity of an operational turbine (step 1), their presence at the depth of the turbine rotor (step 2), and their presence at tidal flow rates greater than the 'cut in' speed of a turbine (step 3). The probabilities associated with steps 4–7 in the framework are not available from Bangley et al. [41], but may be inferred (conservatively) from other studies on collision risk for striped bass in controlled laboratory conditions (e.g., [22,45]), modelling studies for fish based on computational fluid dynamics and finite element analysis (e.g., [46]), and other relevant sources.

Bangley et al. [41] identified the late ebb tidal stage during October as the period of the greatest presence probability of striped bass in the Minas Passage. To demonstrate a conservative application of the framework, we selected the 150 m × 150 m grid cell with the highest predicted scaled presence probability of striped bass under these conditions as the site where a tidal stream turbine might be deployed (Figure 2). The hypothetical tidal stream device can be described as: a floating horizontal-axis technology with a single rotor at 8 m depth, three blades each with a length of 2 m (rotor diameter 4 m), and a rotor swept area of 12.56 m^2. These measurements allow us to establish a vertical depth of encounter with the turbine blades between 6 and 10 m depth. The turbine would operate from a cut-in speed of 1.0 m/s, up to a speed of 5.0 m/s, with a rotational speed of 65 rpm at a tidal velocity of 3.0 m/s. Following the hierarchy of collision risk proposed in this paper, the probability of species presence within the turbine vicinity (step 1) was measured as the scaled presence probability from the species distribution model, the probability of presence at the turbine depth (step 2) was measured as the proportion of depth sensor measurements falling within the depth of encounter, and the probability of presence between the cut-in and cut-out speeds (step 3) was measured as the proportion of hourly presence records within that current speed range.

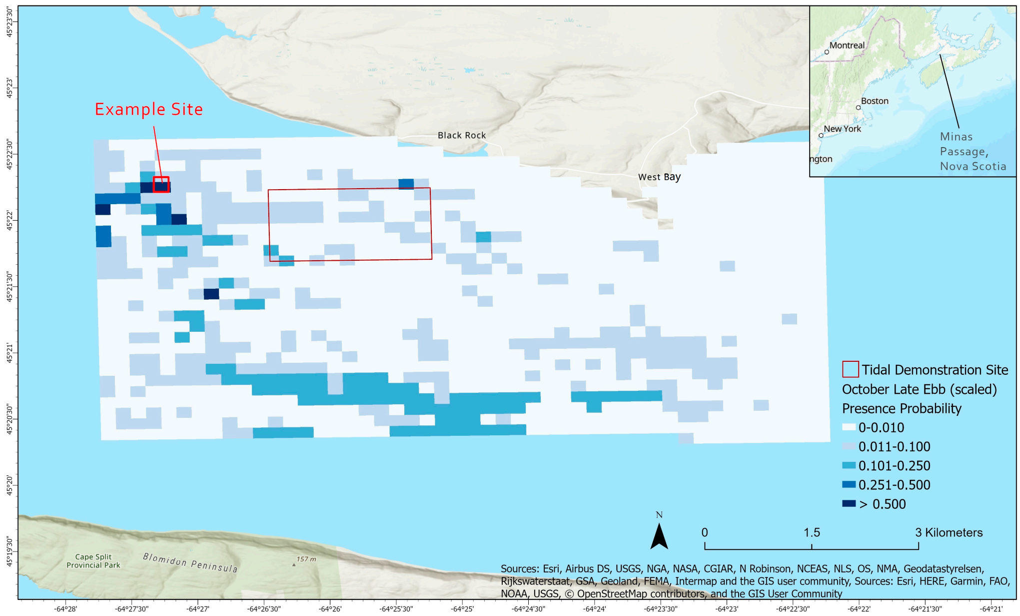

Figure 2. Grid cells (150 m × 150 m) are mapped for the probable presence of striped bass in the Minas Passage, predicted using average environmental conditions during a late ebb tide stage in October. The Fundy Ocean Research Center for Energy tidal demonstration site is delineated by the large red rectangle, while the example site used for the case study (longitude −64.45447, latitude 45.37068) is highlighted to the left.

3. Results

Descriptions for each of the seven events outlined in Figure 1 are provided below. To increase understanding of the likelihood of each event occurring, we identify the factors that need to be considered in determining the risk of each event and synthesize the existing relevant literature. We then examine the framework as it applies to the striped bass case study. Throughout this section, it is important to recognize that collision risk is most likely to be assessed for a species of interest—those of conservation concern that are afforded legal protection in various jurisdictions, species of commercial or recreational value, or those of cultural relevance. The amount and suitability of available data that can be used in the framework for assessing collision risk will vary by species and may need to be supplemented with additional data collection. Ideally, in situ data collection would be conducted multiple times throughout the year, allowing for variation in species presence, life history, and behavior to be incorporated into the risk assessment. The probability of occurrence of each event should be considered individually; however, few quantitative probabilities are available in the literature for each step in the framework. Our results focus on providing a description of the elements that would drive an estimate of the probability at each ring made from the existing literature.

3.1. Probability of Being Present in the Water Column and in Vicinity of the Turbine

An animal must be present around an operational turbine for a collision to occur. An assessment of which marine animals are present in the waters near a tidal turbine and understanding their spatial and temporal distributions (e.g., resident or migratory species, areas of occupancy, frequency of presence), prior to device installation, is the first component required to estimate the risk of collision. This information can be determined through the development of species distribution models [47] that can link species presence in tidal channels with habitat variables and environmental heterogeneity (e.g., [41,48–50]). Although the spatiotemporal distribution for each species must be assessed separately, existing information may be available from prior monitoring activities to assist in this effort. Species that are resident to an area where tidal turbine installations are planned may be at higher risk of collision, due to their increased spatial and temporal overlap with devices (i.e., increased exposure), than migratory species that may only move through the area occasionally. Species presence and collision risk may also vary by life history stage, with spatiotemporal distributions of juveniles differing from adult animals (e.g., Atlantic salmon (*Salmo salar*) post-smolts vs. kelts); [51,52] and may also vary by population [53].

Assessments of the presence, abundance, and movement of animals are the most common types of data collected in association with marine energy monitoring and are a vital part of an analysis of potential collision risk. This information is gathered using a variety of methods and monitoring instruments, depending on the site conditions and the species of interest. Marine mammals are most often assessed as individuals or pods. Their presence is commonly observed using passive acoustics for vocalizing cetaceans [54,55], active acoustics such as imaging sonars [56–58], underwater optical cameras (still or video) [59,60], and observations made from vessels, aircraft, or land [61]. Fish are commonly assessed as individuals or schools (depending on the species) using various active acoustic instruments like single beam or split beam echosounders [62–64], multibeam acoustic cameras [32,65,66] and multibeam imaging sonars [26,67], acoustic telemetry [41,42,68], and with underwater optical cameras [25,69]. Other marine animals such as sea turtles and diving sea birds may be assessed in conjunction with marine mammal surveys, or from other dedicated monitoring campaigns [70] using some of the approaches mentioned above.

3.2. Probability of Being Present at the Depth of the Turbine Rotor

Animals must be present at the depth of the swept area of an operating turbine for a collision to occur. The amount of time that an animal is present at the depth of the turbine swept area, and therefore its exposure to collision risk, will vary by species, life history, and behavior. For marine mammals, species depth distributions may vary widely over a relatively short period of time. For instance, if marine mammals are transiting through an area to reach important resources (e.g., foraging or breeding habitats) they may primarily be located in the upper portions of the water column ('cruising' or 'porpoising'; [71,72]), and may not be found in the swept area of bottom-mounted devices. However, if foraging for food, marine mammals may make frequent transits between the mid-water column or seafloor and the surface (to breathe) over protracted periods of time (e.g., [30,73,74]), exhibiting a bimodal depth distribution pattern [75], and may be exposed to risk for both bottom-mounted and surface deployed technologies. The depth distribution of fish species is dependent on life stage, life history and behavior (e.g., species that utilize the entire water column, demersal species that tend to be oriented towards benthic habitats, or pelagic species that tend to be found higher in the water column), and may be influenced by diel migrations (i.e., deeper during the day, shallower at night) and the confounding effects of water temperature and tidal stage [76–79].

Data about species depth distributions are often more challenging to collect than data about their spatial (in the horizontal plane) and temporal distributions. Often the presence of animals is deduced from population estimates at a site and from the assumed depth distribution throughout the water column [28,80]. Marine mammals may be tagged with D-tags that record the depths of dives and allow for estimates of depth distributions at a site (e.g., [73]), but these studies are relatively rare as permission to tag marine mammals is often difficult to acquire [81,82]. Individual fish may be tagged using acoustic tags equipped with depth sensors that record species depth distributions (e.g., [41,83]) that are detected by lines of acoustic receivers [84,85]. The depth distribution of fish populations can also be determined directly with the use of multiple opening nets such as MOCNESS (Multiple Opening/Closing Net and Environmental Sensing System) or bongo nets that can be operated in the water column by remotely opening and closing at specific depths to ascertain which fish or portion of a population are caught at various depth strata [86]. However, nets are seldom employed for monitoring in tidal channels because of the inherent difficulties with successfully utilizing this sampling equipment in areas that are frequently characterized by complex and turbulent hydrodynamics (e.g., [87,88]). Active acoustic (i.e., echosounder) surveys may target different depths, allowing for some estimation of fish biomass at specific depths [89], but correctly delineating species is difficult without ground truthing acoustic targets using accompanying trawl surveys that can be difficult to conduct in these environments [87]. Moreover, tidal channels and their complex hydrodynamics can entrain air in the water column that can obfuscate the use of this approach for collecting accurate depth distribution data [90].

Most commonly, the depth distribution of marine animals is extrapolated from small numbers of behavioral studies that tag or follow specific individuals, but seldom in locations of interest for tidal energy development [30]. The depth distributions of fish are often assumed from associations with physical features and processes such as tidal stage, season, and diel movement [91]. Additionally, fish and other marine animal depth distributions may be determined with the use of underwater optical cameras deployed at a depth around tidal turbines; however, these surveys are still relatively rare, difficult to carry out in turbid waters, and are generally insufficient to determine species depth distributions [92].

3.3. Probability of Being Present at Flow Rates Greater Than the 'Cut in' Speed of the Turbine

Tidal turbines are designed to begin rotating when the flow rate reaches a speed at which power generation becomes viable; often referred to as the 'cut in' speed of the device. The cut in speed will vary with the particular turbine design, but for turbines that can generate utility scale energy, is unlikely to be less than 1.0–1.5 m/s [93,94]. If marine animals are present in the immediate vicinity of the device, or within the turbine swept area, they are not at risk of collision when tidal flows are less than the cut in speed of the turbine. Once a turbine begins to rotate, the rotational speed will be proportional to the speed of the tidal flow, increasing the tip speed of the blade with increasing flow rates. At low flow rates leading up to and just past the cut in speed, the rotational speed of the turbine blades will be low and less risky to marine animals than at the greater flow rates that are optimal for power generation.

Underwater video has captured a phenomenon that shows fish present around the turbine rotor, nacelle, and blades during low flow conditions, but leaving the camera field of view as flow rates increase [95–97]; possibly descending to the seafloor where they can use the boundary layer, substrate coupling strategies, and rheotaxis to hold station and prevent downstream displacement [98], and associated flow refugia to conserve energy [99]. These species may be at lower risk of collision than those that may be transiting through a tidal channel during seasonal migrations and using selective tidal stream transport to conserve energy [100–102]. Similar evidence shows the presence of marine mammals around tidal turbines at slack tide, followed by avoidance of the rotor area as tidal currents increase and the turbine blades rotate [103].

Information about the movement of species through a tidal channel can be acquired using acoustic telemetry and strategically deployed lines of acoustic receivers that are appropriately spaced [42,53] to account for variation in acoustic signal detection with current speed.

3.4. Probability of Not Exhibiting Avoidance or Evasion Behavior

Behavioral studies of marine animals do not report collisions with underwater objects, with the exception of large masses such as ships that can move at relatively high speed (e.g., [104]). There are few studies that focus on marine animals in close proximity to marine energy devices, partly due to the difficulty of observing interactions in fast flowing, often turbid, waters. Based on observations of marine mammals and fish in their natural habitats, it is likely that they will sense the presence of a turbine underwater at some distance and avoid the obstacle, or may approach out of curiosity and evade the moving parts at closer ranges [30,31].

Marine animals have developed a suite of sensory systems that permit them to accurately perceive their environments and respond appropriately to stimuli by exhibiting a range of behaviors. This includes the ability to detect operational turbines and exhibit avoidance and evasion behaviors to prevent being struck by turbine blades at varying distances from a device that may span up to 100 m or more (e.g., [29,32,62,105]). Despite these intrinsic abilities, there is some potential for collision with a turbine blade to occur under adverse environmental conditions (i.e., turbid, noisy, and turbulent fast-flowing tidal currents) that may prevent detection of the device or where the reaction time between device detection and expression of behaviors to prevent a collision is insufficient.

Empirical in situ evidence for avoidance and evasion behavior has been observed for marine mammals (e.g., [29,105]) and fish (e.g., [26,32,62]), and there is some evidence that diving seabirds avoid areas with fast tidal currents [106]. Numerous laboratory-based studies provide empirical observations of avoidance and evasion by fish in controlled settings, which consistently show similar responses for a variety of species under differing flow regimes, up to approx. 2.5 m/s (e.g., [107–109]).

While fish have been observed to avoid or evade an operational turbine, some have been observed to pass through the rotor swept area [25,110]. Flume studies and a small number of field studies show that fish that pass through a rotating turbine may become disoriented but do not appear to suffer harm [22,24,25,66]. The relative size of the turbine, the design and solidity of the rotor swept area, and the species present near an operational device, are all likely to affect the ability of marine animals to detect and avoid or evade the rotating blades.

The limited observations available cannot be used to definitively determine that fish and other marine animals will always avoid a rotating turbine, or emerge unscathed, but the preponderance of evidence suggests that the sensory capabilities of marine animals are likely to alert them to the presence of a hazard and allow greater than 90% survival [111–113].

3.5. Probability of Not Being Deflected by the Pressure Generated by the Turbine

A turbine that operates near the Betz limit (or the limit of energy extraction) diverts about one-third of the upstream flow, which, since avoidance and evasion is separately considered, provides a purely physics-based discounting factor on overall collision risk [114,115]. This blocking effect can be generalized to turbine arrays to determine the fraction of incoming flow, and hence passively moving marine life, that will bypass the array. There are two scales of flow diversion: at the array scale, a fraction of flow is diverted as though the array is a single, large turbine, and at the turbine scale, involving interactions among neighboring turbines [116]. Optimizing a multi-row turbine farm for power extraction requires a staggered arrangement (as is common in wind farms) such that flow bypassing one row is met by turbines in the subsequent row [117]. This may be at odds with minimizing collision risk, and both factors should be considered in turbine placement [118]. For small marine organisms such as plankton, including larval fish and invertebrates, and perhaps some small fish, which effectively act as tracers, the probability of not bypassing the turbine/turbine array can be applied with a high degree of certainty towards evaluating collision risk. Larger marine animals, which are apt to travel across streamlines and even against the flow, would not be nearly as predictable, and may be subject to increased risk of collision.

3.6. Probability of a Physical Strike with a Turbine Blade

Should a marine animal enter the rotor swept area of a tidal turbine, the probability of collision with a rotor blade will depend on several factors. Most turbine swept areas are not highly solid, such that the animal may traverse the turbine swept area without experiencing a collision. The rotational speed of the turbine, the particular part of the blade closest to the animal (as the tip of a blade moves much faster than positions closer to the turbine hub), the rotor diameter, and the size and length and swimming speed of the marine animal [119] will affect the likelihood of a collision.

Tip speed is an important parameter in determining marine animal survival after a collision. The rotational speed of a turbine is not a determining factor as larger turbines rotate at a speed proportionally slower than smaller turbines, while the tip speed remains the same [120] at a specific tidal flow speed.

Studies of fish swimming in high flow indicate that they swim into the flow (i.e., exhibit rheotaxis) at most times, at speeds where they can maintain or gain on the current [121,122], and swim only occasionally with current flows, at lower speeds [123,124]. Marine mammals also most commonly swim into the current although some seals have been shown to ride tidal current in pursuit of prey [30]. This behavior suggests that fish and marine mammals may most commonly approach a turbine so they can see and detect its presence and will only occasionally be "overtaken" by a turbine and inadvertently pass through the rotor swept area.

3.7. Probability That Collision Results in Harm (i.e., Critical Injury or Mortality)

If a marine animal were to enter the rotor swept area of a tidal turbine and collide with a blade, the consequences of such a collision could be a minor recoverable injury, immediate mortality, or a critical injury that results in permanent disability or death at a later time (i.e., latent mortality). There has never been an observation of a marine mammal struck by a turbine, and while there is video evidence of fish coming very close to a turbine [66], no harm has been observed. There are few studies that provide definitive information on what the consequences of a strike from a tidal turbine might be, although studies of equivalent forces on marine mammal tissue have shown that damage to skin, blubber, and muscle are likely recoverable from a typical tidal blade strike [39,119]. While no equivalent tests have been carried out for fish, Hecker and Amaral [125] show that survival rate after being struck depends on two variables: strike velocity and the ratio of fish length to blade thickness. Simulations indicate that the speed of the turbine is the factor most likely to determine the impact to the fish [46].

3.8. Case Study Results

Based on species distribution model results from Bangley et al. [41], the scaled probability of striped bass presence at the example site is 0.812 during the late ebb tide stage in October. The proportion of depth sensor measurements falling within the depth of encounter is 0.350. The proportion of striped bass hourly presence records occurring during ebb tide in October at current velocities between the cut-in and cut-out speeds is 0.729. This gives an overall probability of encounter with the turbine through the first three steps of collision risk framework of 0.207 (0.812 × 0.350 × 0.729) during the late ebb tide stage in October (Figure 3).

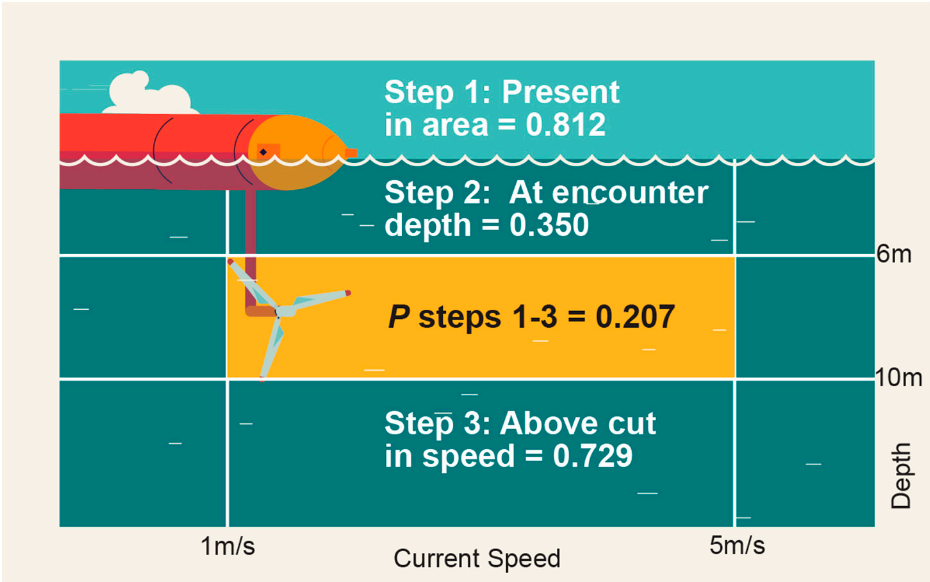

Figure 3. Probability (*P*) based on case study data from striped bass acoustic tag detections of each of the first three collision risk steps. Each step occurs independently (steps 1–3). The central probability (P steps 1–3) indicates the combined probability of all three steps occurring at once. Illustration by Stephanie King.

These results suggest that approximately one out of five adult striped bass of Shubenacadie River origin passing through the Minas Passage will fulfill the first three steps of collision risk. This means that these fish may simultaneously occur (1) in the general vicinity of the turbine, (2) at the depth range of the swept area of the device, and (3) at current velocities under which the turbine is operational. As described above, estimation of the probability of the further steps of collision risk will require data beyond those available to this study.

There are no results available from the case study that apply to the subsequent steps (4–7) in the collision risk assessment framework. The data collection methods needed to address these steps are under development with multiple research groups worldwide working to develop and deploy instrumentation that will collect appropriate data.

4. Discussion

Understanding the mechanics and the spatiotemporal distribution of a marine animal in relation to a rotating tidal turbine is essential for estimating the probability of a collision occurring. Similarly, understanding the forces that may cause an animal to collide with a turbine blade, and the resistance of the tissues, organs, and bones of a marine animal will lead to an assessment of the consequences of collisions. Together, the probability of occurrence and potential consequences can provide a first order estimate for the risk of collision. The assessment framework outlined in this paper steps through the circumstances that must come into play in order to estimate the outcome of a collision. By examining each step in the process that must take place to result in a deleterious outcome, it is possible to get a sense of the risk that might be incurred by a marine animal in the presence of an operational turbine. If any one of the steps in the framework presents a near zero probability of occurrence, the overall probability, and therefore the risk, must be considered near zero as well. Conversely, if collision risk is assessed as considerably greater than 'near zero', then this methodology allows for the identification of the best step at which to apply mitigation measures. Although the peer-reviewed literature does not often provide specific probabilities for the various events in the proposed framework, a general indication about the likelihood for a specific event occurring may be gleaned, and the general shape of a reaction curve determined from Monte Carlo simulations may provide valuable insight [126]. Conducting such simulations is beyond the scope of this paper but warrants further consideration in subsequent work. Early estimates of the probability of collision are being determined [127]. There is an ongoing need for additional research and monitoring around operational tidal turbines to elucidate the risk of collision. It is important to ensure that each step in the sequential approach to collision risk is considered as monitoring programs and data collection efforts are designed.

It is important to note that, while the steps in the framework presented here involve the potential risk for individual marine animals, it is the potential effect on populations that is of greatest concern. The ability to use outcomes of risk to individual animals to assess population-level risk is a commonly used technique by fisheries and wildlife regulators. Each of the events (steps) presented in Figure 1 represents a conditional probability that could lead to a collision for an individual animal. The resulting probability of a collision, and the potential consequences of such a collision (step 7) for an individual animal, must be used to inform population models that assess whether an adverse impact on a population is likely.

The first three steps in the framework presented here are driven by the presence of animals in time and space that might overlap with rotating turbine blades (presence of animals in the channel; presence of animals at the operating depth of the turbine; presence of animals when flows are above the cut-in speed of the device). The overlap of animals with the turbines in these three steps will require gathering data for any species that might be at risk at a project site, with the characteristics of the site taken into consideration, as illustrated by the case study on striped bass. At this point in the risk profile, animals might choose to be present in the area of a turbine, or they might be present as a necessary part of a migratory pathway, a movement corridor, or taking advantage of an essential habitat for feeding, reproduction, rearing, or avoiding predators. The knowledge base to determine risks for the initial three steps in the framework will continue to be built through data collection from the required monitoring programs around demonstration-, pilot-, and commercial-scale tidal deployments. The risk to species of concern should be examined for any prospective tidal project site and for a specific type of turbine; often these assessments can be satisfied with stock assessments for fish of commercial or conservation concern, or population assessments for marine mammals under conservation regulations. Once the presence of the species of concern is understood, further assessments may not be necessary at those locations. Underwater passive acoustic monitoring systems can be deployed to detect and locate vocalizing marine mammals, while a range of active acoustic instruments like single-beam or split-beam echosounders, multibeam acoustic cameras and multibeam imaging sonars and acoustic cameras can all be used to assess the location of marine animals. Underwater video is often very useful in identifying species but collects large amounts of data for analysis and may be prone to failure [66].

The next step in the process (avoiding or taking evasive action) is dependent on the ability of the animal to detect the operating turbine and its ability to maneuver and swim away from the moving parts of the device. Without detailed behavioral studies of marine animals in the vicinity of a turbine, it is difficult to determine at what distance, and under what environmental conditions (extent of turbidity, ambient noise level, tidal flow rate) each species might detect and avoid a turbine, or whether they will approach until forced to evade the blades just prior to collision. Laboratory and flume studies indicate that most fish will evade a turbine blade if possible, with virtually all fish surviving close encounters with turbines and/or traversing the rotor swept area alive. Understanding the behavioral aspects of marine animals around turbines is the most costly and least understood research area in the chain of risk (step 4). While some behaviors can be extrapolated from other structures in the ocean, there are no direct surrogates. However, marine animals do not generally collide with objects underwater and have the ability to detect new objects in their environment. Behavioral studies around turbines are likely to continue but due to high costs, safety concerns for researchers working in proximity to high tidal flows, and the degree of variability of behaviors among individuals and within populations, these studies are unlikely to reach consensus about how animals interact with turbines. Behavioral studies may use a combination of boat- and remote-based observers, underwater active acoustics, and underwater video. All these techniques are expensive, potentially cause safety concerns in fast flowing tidal waters, and produce vast amounts of data that are often hard to interpret.

For those marine animals that do not avoid or take evasive action near a turbine, the hydrodynamic forces generated at the face of the rotor area may deflect the animal (step 5), decreasing the probability of a collision occurring. The hydrodynamic forces generated from the blades and rotor assembly are likely to deflect only small fish and planktonic organisms like larval fish and eggs, while larger nektonic organisms will be capable of swimming against the forces. These forces are small, particularly in comparison to those from conventional hydropower turbines, and can be calculated using numerical models. Focused research studies on these interactions would help to determine the threshold size of fish that might be subject to the deflection forces at the face of a turbine.

If a marine animal reaches the face of a turbine and continues through the rotor swept area (step 6), there is a probability that the animal may be stuck by a rotating blade. Species with greater body lengths will be more at risk of collision, although many of these larger species also have greater swimming speeds allowing them to clear the rotor swept area before encountering a blade, which may mitigate the probability of an adverse outcome. Numerical models can predict the potential risk to a fish or marine mammal of a collision with a blade, while crossing through the rotor swept area. These models could be validated using continuous underwater video focused on the face of the turbine. This methodology is expensive and prone to failure and is most applicable in clear, relatively shallow waters during daylight hours. More turbid water, greater depths, and the dark portions of the day will require artificial illumination which may change the behavior of some marine animals, and potentially attract additional species that might not otherwise be at risk of collision. Excessively turbid waters make underwater video recordings challenging.

The consequences of a collision between a marine animal and a turbine blade are the least well-defined aspect of the framework (step 7). The only studies of comparable forces to blade collisions on marine animal tissue have been for a small number of marine mammal species. Evidence for the deleterious effects of fish colliding with a rotating turbine are not comparable to the much higher velocity conventional hydropower turbines, nor are propeller strikes from ships of the same nature and severity of what can be expected from tidal turbines [128]. Further studies of additional marine animal tissues are needed, particularly for fish that are considered at risk, to determine if a collision with a tidal blade is likely to cause serious injury or death [46].

The assessment of risk for a marine animal colliding with a tidal turbine must consider the behavior of the particular species at the location in question. Animal behavior is complex and difficult to assess, particularly in the fast-moving and often murky waters where tidal power is sited. This paper attempts to assess a reasonable, if conservative, estimate of collision risk, largely without taking the avoidance and evasion behavior of marine animals into account. The assessment framework outlined in this paper will provide an additional margin of safety for marine animals as well as providing a simple means for tidal developers to progress with confidence.

5. Conclusions

There are significant challenges to developing and operating tidal turbines that range from technical engineering questions, financing options, to the uncertainty of potential harm to marine animals from the devices deployed in the ocean. The risk of marine animals colliding with rotating turbine blades continues to be the most daunting challenge for the permitting/consenting and licensing of tidal energy around the world. The study of collision risk to marine animals continues to be a high priority within the marine energy community, as it continues to slow and hinder deployments, which, in turn, limits the information available on the interaction. Device and project developers, researchers, regulators and scientific advisers, and other stakeholders need to collaborate to define and implement the most appropriate studies and monitoring programs to better understand the risks, and to ensure that knowledge gained is shared and applied appropriately in deploying and monitoring tidal turbines.

Providing a simple means to apply the accumulated knowledge of collision risk for device and project developers, with sufficient scientific evidence to convince regulators and stakeholders, could be an important step towards normalizing the deployment of tidal turbines and further expanding the knowledge base of its potential effects. The authors have put forward this assessment framework as a pathway to thinking about the risk of collision with a tidal turbine and considering the possibility of an encounter causing definitive and serious harm to marine animals. This methodology suggests that the potential risk to a marine mammal or fish from a tidal turbine is likely small and seeks to clarify the steps that must be taken to collect the necessary data required to validate this supposition.

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