A conditional probabilistic encounter-impact model for fish-turbine interactions

Jezella I. Peraza, John K. Horne

Abstract— **Knowledge gaps exist in efforts to quantify risks and impacts of fish-turbine interactions. Despite empirical data and modelling studies characterizing fish approach and pass through hydrokinetic turbines, no comprehensive model quantifies conditional occurrence probabilities of fish-turbine interactions in sequential steps. In an effort to address this gap, we combine empirical acoustic density measurements of Pacific herring (*Clupea pallasii*) in Admiralty Inlet and when data limited, literature values in an impact probability model that includes approach, entrainment, and collision of fish with axial or cross-flow tidal turbines. The model includes probabilities of active and passive avoidance and impacts of fish collisions with a device, blade strikes, and a collision followed by a blade strike. Impact probabilities vary widely from 0.00110 to 0.689, with the highest probabilities occurring for a cross-flow turbine at night with no active or passive avoidance. This generic encounter-impact probability model can be applied to any animal in any aquatic environment for any hydrokinetic device.**

Keywords— **Collisions, Encounter, Environmental Impact, Hydrokinetic Turbines**

I. INTRODUCTION

Tidal energy is at an earlier stage of development and deployment compared to wind turbines [1], but shares the common challenge of animal-device interactions with potential effects on animal growth and survival. Potential mortality from collisions and/or blade strikes is perceived as a threat to animal populations and can impede development of on- and offshore wind [2]–[4] or tidal turbine sites. Adequate baseline and post-installation monitoring data on animal-tidal device interactions are not available, resulting in uncertainty among regulators who are cautious in permitting development of full-scale Marine Renewable Energy (MRE) sites [5], [6].

Encounter and collision rates between aquatic animals and tidal turbines are not well quantified due to limited opportunities and appropriate technologies to observe, measure, and characterize interactions [7]. Worldwide, there have been few acoustic and optical technologies deployed to monitor tidal energy sites [8]. Even though stationary acoustic multibeam and multi-frequency echosounders are available, their deployment is often limited due to operational constraints including limited detection of weaker targets [9]. A supplementary approach to empirical measures when animal behaviour and hydrodynamic data are limited is the use of probability models to estimate animal-device interactions [10]. These studies include fish swimming trajectories in approaches to tidal turbines [11] or document fish interactions with a device (e.g., [12], [13]), but there remains a need for a comprehensive model that quantifies encounter probabilities as fish approach and pass through a hydrokinetic turbine.

To accurately estimate potential encounter and collision risks that influence MRE monitoring requirements and operational regulations, additional risk factors should be incorporated into a conditional encounter-impact model. Current empirical observations lack active and passive avoidance behaviours of fish approaching a tidal turbine. Additional risks such as collision with stationary components of a device are also not commonly included in published models. Collisions with stationary components could disorient fish [14] and potentially lead to a subsequent blade strike.

This study develops a conditional probabilistic model that quantifies encounters and impacts between fish and tidal turbines. The encounter-impact model estimates probabilities of approach, encounter, collision, blade strike, and collision and blade strike using acoustic data from Admiralty Inlet, WA, and literature values when empirical data are lacking. Existing data gaps are

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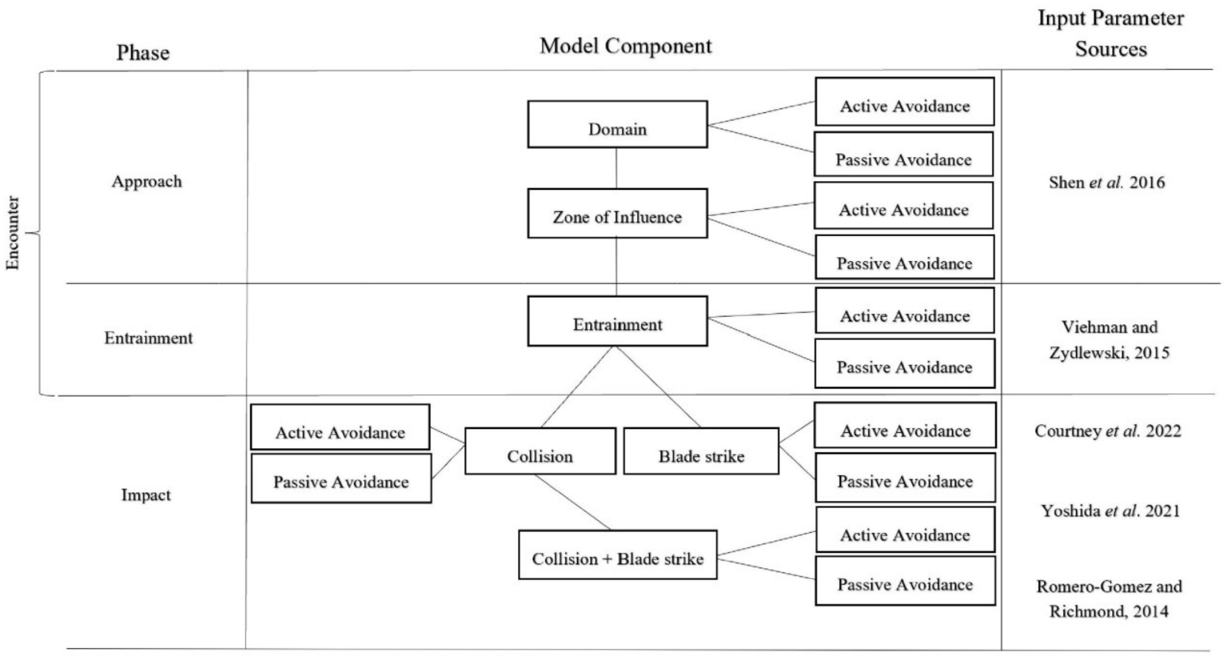

Fig. 1. A schematic of the empirical encounter-impact probability model. On the left-hand side of the figure, the model is divided into approach, entrainment, and impact phases. The center of the figure details components of the encounter-impact model. The impact component consists of collision, blade strike, and collision and blade strike. The right-hand side of the figure lists literature used as input parameter sources attributed to corresponding model components.

identified along with appropriate next steps for model application. This encounter-impact model is designed to be generic and can be applied to any potential tidal energy project site.

II. METHODS

A. Model description

The encounter-impact model includes conditional occurrence probabilities of fish approaching, being entrained, and then interacting with a tidal turbine in sequential steps (Fig. 1).

The approach phase quantifies when an animal enters the vicinity of an MRE device and includes the model domain, zone of influence, and estimates of active or passive avoidance. The model domain is comprised of the study area and estimates the probability of whether an individual fish is present within a site. If fish are present, then the domain model component is assigned a probability value of 1 (Table I). The approach phase quantifies when an animal enters the vicinity of an MRE device. As an empirical analogue, Shen *et al.* [11] used mobile hydroacoustics to track fish approaching a cross-flow tidal turbine in Cobscook Bay, ME and estimated probabilities of fish approaching and encountering an MRE device. From field studies, initial responses to a turbine by fish, measured using change in swimming direction, has been documented at hundreds of meters [11]. We define the zone of influence as the reaction distance between an animal and the turbine. In this model, the zone of influence is set to Shen *et al.'s* [11] 140 m upstream from an axial or cross-flow tidal turbine (Fig. 2a and 2b). A vertical height of 25 m above the seafloor is used to represent approximately twice the vertical footprint of a proposed turbine in Admiralty Inlet [15] and also corresponds to Shen *et al.'s* [11] range of water depths (25 m at low tide to 32 m at high tide) at their study site. The probability of being within the zone of influence is

TABLE I
PROBABILITY EQUATIONS FOR EACH COMPONENT IN THE ENCOUNTER-IMPACT MODEL

Model component	Probability Equation
Domain	Pr(Domain) = 1
Zone of Influence	Pr(Zone of Influence) = P(1 – avoid)
Entrainment	Pr(Entrainment) = P(zone of influence) * P(1 – avoid ∣ zone of influence)
Collision	Pr(Collision) = P(entrainment) * P(collide ∣ entrainment)
Blade strike	Pr(Blade strike) = P(entrainment) * P(strike ∣ entrainment)
Collision and Blade strike	Pr(Collision and Blade strike) = P(entrainment) * [P(collide) * P(strike ∣ collide)]
Overall Impact	Pr(Impact) = Pr(Collision) + Pr(Blade strike) + Pr(Collision and Blade strike)

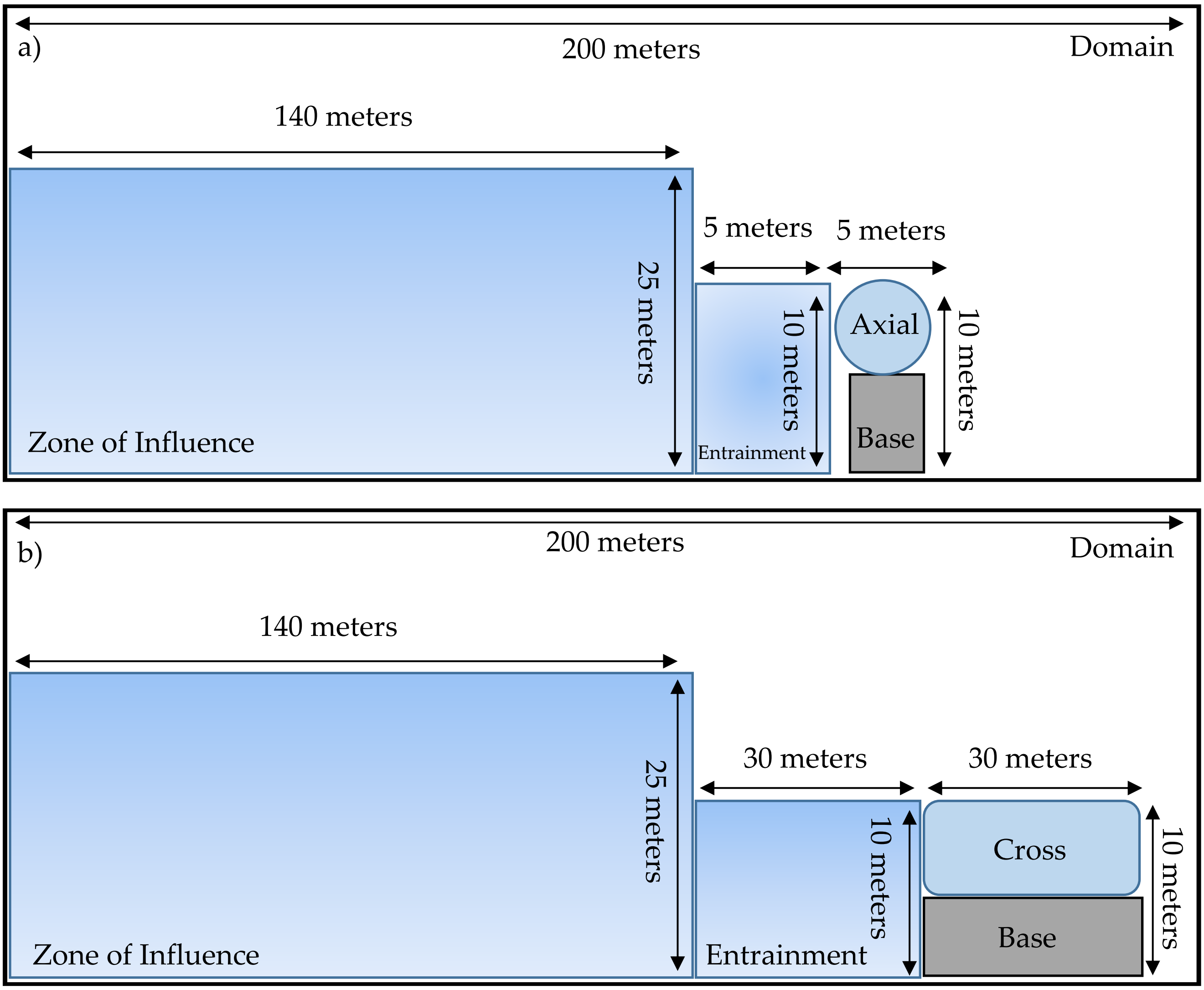

Fig. 2. A two-dimensional schematic showing dimensions of the encounter-impact model components for an a) axial and b) cross-flow turbine.

dependent on the device's shape and size, water depth, tidal current speed range, and fish swimming ability. The probability of fish being in the zone of influence is defined as the complement of the probability of avoiding the device (Table I).

The entrainment phase of the model (Fig. 1) occurs within the spatial area adjacent to a tidal turbine and includes entrainment, active avoidance, and passive avoidance. Direct interactions between fish and turbines are most commonly studied within 5 to 15 m distance of a device (e.g., [12], [13]). The horizonal distance of the entrainment area is set to approximately the width of an axial or cross-flow turbine [11], [12], with a vertical distance of 10 m to represent the height of a turbine.

Entrainment occurs when a fish is within the area adjacent to the device, normal to the device face. If an animal continues its current trajectory within the entrainment zone it will collide with the turbine base or enter the turbine. The turbine base and entry area are half of the vertical height of the turbine (Fig. 2a and 2b). The dimensions of the cross-flow turbine base are 30 m by 5 m and 30 m by 10 m for the area of turbine entry. The dimensions of the axial-flow turbine base are 5 m by 10 m and 5 m by 5 m for the area of turbine entry.

Impact is defined as one or more interactions between a fish and a tidal turbine through collision and/or blade strike(s). The impact phase of the encounter-impact model (Fig. 1) occurs at the tidal device. Laboratory and field-based experiments provide empirical data for probability estimates, with published values emphasizing blade strikes [14], [16]. In cases where empirical data are lacking, the impact phase of the model incorporates laboratory and simulation model data [17] that align with the encounter-impact collision and blade strike model components.

Interactions between a fish and a tidal turbine are composed of collisions and/or blade strikes. Collision is defined as physical contact between an animal and turbine base or a non-moving device component. A blade strike is contact between an animal and a rotating blade [18]. Collision and blade strike in the model are treated as potential sequential events. Turbine dimensions can exceed 15 to 20 m in length and width [11], [13], [14], which provides a large surface area for fish to potentially collide with a device's base or non-rotating structure. Blade strikes constitute the greatest risk to fish and are a concern among researchers and regulators [19]. The encounter-impact model estimates conditional probabilities of individual animal-device impacts, consisting of potential collisions, blade strikes, or sequential collision and blade strike (Fig. 1). The overall probability of impact combines all potential outcomes from interactions with any part of the device and/or a blade strike.

Probabilities of each subcomponent of impact are dependent on whether the animal is present within the entrainment area. The probability of occurrence for collision with a turbine is calculated as the probability of entrainment multiplied by the probability of collision given that a fish is entrained. The probability of occurrence for a blade strike is defined as the probability of entrainment multiplied by the probability of a blade strike given that a fish is entrained within the device. Lastly, the probability of occurrence for collision and blade strike is defined as the probability of entrainment, multiplied by the probability of collision, multiplied by the probability of blade strike given that a fish collided with the device (Table I).

All phases of the encounter-impact model include active and passive avoidance (Fig. 1). In behavioral studies, fish have been shown to actively evade predation and navigate around obstacles, even at long distances (e.g., [20], [21]). Tidal flow speeds often surpass fish swimming capabilities [22], [23], potentially leading to passive transport through the water column and passage around or through MRE devices. Therefore, avoidance is defined as a fish's response and movement away from a device and/or its avoidance due to hydrodynamic forces [18]. Average fish length is used to estimate the threshold between active and passive locomotion using Okubo's [23] locomotion equation:

$$S_S = 2.69 \cdot L^{0.86} \quad (1)$$

where S_s is swimming speed (ms^{-1}), and L is fish length (m). Active locomotion is assumed when the ratio of swim speed to tidal flow is greater than 1 body length per second (bls^{-1}) [22]. Passive locomotion occurs when the tidal speed exceeds 1 bls^{-1}, in this study 0.155 ms^{-1}.

B. *Arbitrary MRE devices*

When empirical data were collected in Admiralty Inlet no tidal turbine devices were present at the study site. For this study, observed hydrodynamic, fish density, and fish distribution characteristics are used in combination with dimensions from representative axial and cross-flow tidal turbine devices to calculate encounter and impact probabilities. Tidal turbine dimensions used in this study are based on an axial-flow Verdant Power Kinetic Hydropower System (KHPS) [12] (Fig. 2a) and a cross-flow Ocean Renewable Power Company (ORPC) TidGen Power System [11] (Fig. 2b). Verdant Power KHPS turbine characteristics include a three-bladed, single-rotor axial-flow turbine with a rotational speed of approximately 40 revolutions per minute. The height of the device is approximately 10 m, with a rotor-swept area of 5 m in diameter, defining an area of 5 m by 10 m. The TidGen device is a cross-flow turbine 31.2 m long and 9.5 m high with foils (i.e., rotating blades) 6.7 - 9.5 m above the seafloor, defining an area of 30 m by 10 m.

C. *Empirical data description*

Data were collected in 2011 at a site in Admiralty Inlet, Puget Sound, WA chosen by the Snohomish Public Utility District [24] for the potential deployment of two hydrokinetic turbines. The proposed site is approximately 750 m off Admiralty Head at a depth of 55 m mean tide height. Data were collected using a Simrad EK-60 echosounder operating at 120 kHz, an autonomous bottom-deployed 1MHz Nortek AWAC acoustic doppler current profiler (ADCP), and midwater trawl catches deployed from a mobile surface vessel. Acoustic and fish surveys were conducted from May 2 to May 13 and June 3 to June 14, 2011, during day and night for a combined total transect length of 28 km [15]. 324 parallel transects (0.7 to 1.5 km long) extending northwest and southeast of the proposed turbine location, were spaced 0.5 km apart (see [24] for survey details). The ADCP, deployed from May 9 until June 10, 2011, collected concurrent tide state and tidal velocity measurements for 12 minutes every two hours [15].

A Marinovich midwater trawl, a 6 m x 6 m box trawl fished with 4.6 m x 6.5 m steel V-doors, was used to capture samples to quantify species composition and length-frequencies of the fish community. Among captured species, Pacific herring (*Clupea pallasii*) represented 32% of the total catch by number. All acoustic backscatter was attributed to Pacific herring in acoustic density calculations. The average length of Pacific herring caught in the midwater trawl was 0.155 m and is used in all acoustic and swimming speed calculations. Based on similar acoustic operating frequency, sampled fish lengths, and time of year, the target strength conversion equation for Pacific herring from Thomas *et al.* [25]: $26.2 \cdot \log10(L_{cm}) - 72.5$ is used to transform acoustic-derived densities ($m^2 \cdot m^{-2}$) to fish densities ($fish \cdot m^{-2}$).

D. *Factors contributing to model component probabilities*

Since no turbine was deployed during data collection, the Admiralty Inlet dataset provides the flexibility to analyse acoustic fish densities and distributions using multiple turbine types and light regimes represented by time of day (Fig. 3). To observe how acoustic densities varied with light fluctuations, probabilities of occurrence for each model component during day or night are calculated for each turbine type. Fish densities are estimated by dividing each surveyed transect in horizontal 140 m, 30 m, or 5 m bins (corresponding to turbine type, Fig. 2a and 2b) and then grouping bins to match the size of each model component. This approach also ensures that each bin along every transect can be used as a location for sequential model components or a device.

Probability estimates in the encounter-impact model are also influenced by active and passive avoidance. The zone of influence in the model uses three avoidance scenarios to influence probability estimates. The first scenario assumes fish are unable to avoid the turbine within the zone of influence. In the second scenario, fish can avoid the turbine within the zone of influence using active and passive avoidance. Active avoidance rates are estimated from the Admiralty Inlet dataset by discounting abundance estimates of fish within model components using Shen *et al.'s* [11] avoidance rate of 0.372. Passive avoidance rates are estimated by tabulating the number of fish observed swimming above model components. The third scenario uses Shen *et al.'s* [11] active avoidance rate of 0.372 without incorporating passive avoidance. When an avoidance rate from Admiralty Inlet or Shen *et al.* [11] is incorporated into the model, estimates of fish impact are calculated using conditional probabilities from sequential model components. This approach evaluates a fish's ability to avoid a device across model components and provides insight into the likelihood of impact for each model phase and overall encounters with tidal turbines. Conversely, when an avoidance rate is not included, calculated impact probabilities are not contingent on sequential model components.

E. Quantifying impact probabilities

Occurrence of fish during day or night is determined by enumerating acoustic densities detected within bins along each mobile survey transect that are aligned with areas of each model component (Fig. 2a and 2b). These density estimates along binned cells within each transect are summed to estimate total abundance. Probabilities of occurrence for each model component are determined by dividing the number of fish detected within each cell of each model component by total fish abundance.

Since no fish-turbine interactions measurements are available from the Admiralty Inlet dataset, encounter and impact published values are used in model calculations. Blade strike probabilities are taken from field [14] and laboratory measurements [16], as well as calculated using a kinematic blade-strike model [17]. The probability kinematic blade-strike model uses the length of fish (m), tidal velocity (ms^{-1}), the number of blades, turbine

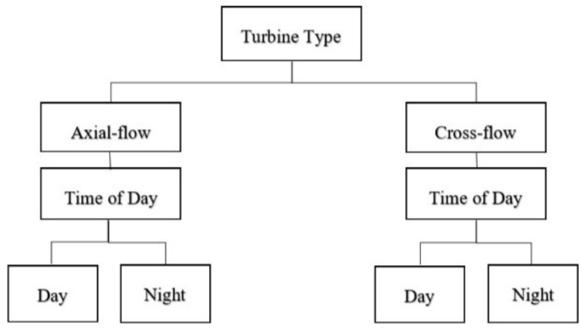

Fig. 3. Factors contributing to the encounter-impact probability model's estimates. The turbine type is axial or cross-flow. For each turbine type, probabilities of occurrence are obtained during day and night.

rotations (s^{-1}), and fish approach angle representing the angle perpendicular to the blade plane [17]. Blade strike probabilities are estimated for tidal turbine operation from approximately 1.0 ms^{-1} [12] to the maximum velocity, 3.0 ms^{-1} [24], observed in Admiralty Inlet. Tidal velocity ranges are utilized to fulfil the tidal velocity component (ms^{-1}) of the kinematic blade-strike model, where probability estimates are contingent on flow speeds. To obtain blade strike probability estimates, the kinematic blade-strike model is parameterized using empirical data from Admiralty Inlet and characteristics of the example MRE turbines (Fig. 2a and 2b).

At this time, there are no published probability estimates of collisions between fish and stationary tidal structures or collisions followed by blade strikes. Collision probabilities are estimated by calculating the complement of blade strike probabilities obtained from the literature and subsequently multiplying by avoidance rates from Viehman & Zydlewski [13]. Viehman & Zydlewski [13] categorize avoidance rates by fish size and time of day. In this study, their avoidance estimates are used in collision probability calculations as a multiplicative discount factor, for comparable fish lengths and light conditions. The sequential occurrence of collision and blade strike are determined by multiplying estimated collision and published blade strike probabilities. All probabilities of collision, blade strike, and collision and blade strike are discounted by avoidance rates in model calculations. Overall impact probabilities of occurrence are calculated by summing probabilities of each impact subcomponent (Table I).

III. RESULTS

Probabilities of impact depend on occurrences of collision, blade strike, or sequential collision and blade strike. Collision probabilities between fish and tidal devices span three orders of magnitude between 0.000364 to 0.324 for both turbine types. Probabilities of blade strike are similar, ranging between 0.000261 to 0.40 for both turbine types. As expected, probabilities of collision and blade strike are lower than either single impact, ranging

TABLE II
IMPACT PROBABILITY ESTIMATES FOR AXIAL OR CROSS-FLOW TURBINES DURING DAY OR NIGHT AND AVOIDANCE SCENARIO (I.E., NO AVOIDANCE, ADMIRALTY INLET AVOIDANCE, SHEN *ET AL*. 2016 AVOIDANCE). IF AN AVOIDANCE RATE IS APPLIED, PROBABILITIES ARE CONDITIONAL ON PRECEDING COMPONENTS OF THE ENCOUNTER-IMPACT MODEL.

		Axial-flow turbine		Cross-flow turbine	
		Day	Night	Day	Night
No avoidance	Courtney *et al.* 2022	0.172	0.455	0.172	0.455
	Yoshida *et al.* 2021	0.0928	0.353	0.0928	0.353
	Romero-Gomez and Richmond, 2014	0.436 - 0.175	0.666 - 0.171	0.337 - 0.138	0.689 - 0.423
Admiralty Inlet Avoidance	Courtney *et al.* 2022	0.00204	0.00541	0.00204	0.00541
	Yoshida *et al.* 2021	0.00110	0.00419	0.00110	0.00419
	Romero-Gomez and Richmond, 2014	0.00515 - 0.00206	0.00805 - 0.00545	0.00907 - 0.00191	0.0176 - 0.00529
Shen et al. Avoidance	Courtney *et al.* 2022	0.00687	0.0185	0.00687	0.0185
	Yoshida *et al.* 2021	0.00370	0.0144	0.00370	0.0143
	Romero-Gomez and Richmond, 2014	0.0164 - 0.00699	0.0276 - 0.0187	0.0304 - 0.00647	0.0357 - 0.0181

between 0.0000242 to 0.0678 for both turbine types. Overall impact probabilities, a combination of subcomponents, for the two turbine types are nearly identical ranging between 0.00110 to 0.666 for an axial-flow turbine and 0.00110 to 0.689 for a cross-flow turbine (Table II).

Turbine design influences impact probabilities, with an axial-flow turbine exhibiting the lowest risk of impact across contributing factors and avoidance scenarios (Table II). When comparing impact probabilities in light regimes, probabilities are higher at night than during the day for both turbine types, with probability variations up to three orders of magnitude (Table II).

As expected, probabilities of event occurrence are higher when no avoidance is applied compared to estimates when avoidance is included. When no avoidance is included, model components are not conditioned on preceding events (Fig. 1). Probabilities of occurrence are lowest when Admiralty Inlet avoidance rates are applied, reflecting the utilization of conditional probabilities. Probabilities of impact are highest by two to three orders of magnitude when no avoidance is included in the model for a cross-flow turbine (Table II).

Input parameter literature sources along with other modelling approaches are compiled to enable comparison to results in this study (Table III). Shen *et al.* [11] observed order of magnitude higher probabilities of fish approach and encounter with a tidal turbine than average approach estimates in this study. Similarly, Viehman & Zydlewski [13] report order of magnitude higher average probabilities of entrainment at night and a 0.290 probability estimate difference between day and night calculations. Wilson *et al.* [26] found lower impact probabilities on Pacific herring by two orders of magnitude in comparison to this study. Band *et al.* [27] observed order of magnitude higher probabilities of collision for Harbour seals with turbine rotors when compared to results of this study.

IV. DISCUSSION

Regardless of the combination of factors, probabilities of fish-turbine encounters and impact ranges from a minimum of 0.00110 to a maximum of 0.689. Impact probability values are particularly low when conditioned on fish occurring within a turbine's zone of influence, where subsequent entrainment may lead to an impact. All highest impact probability values occur at night with no avoidance in calculations.

Turbine design plays a role in influencing fish-turbine impact probability estimates. Larger turbine designs, exemplified by the 30 m by 10 m silhouette of the ORPC TidGen cross-flow turbine, presents a large surface area for potential collisions with the device. The cross-flow turbine is approximately six times longer than the Verdant Power KHPS axial-flow turbine used as the other turbine design example. Greater cross-flow impact probability estimates and congruent empirical blade strike estimates from Courtney *et al.* [14] demonstrate high probabilities of entrainment and collision associated with cross-flow turbines, attributable to the large size of the device.

Light and dark cycles have limited influence on empirical data-based variations in impact probabilities. A slight elevation in probability is observed during night

TABLE III
COMPARISON OF AVERAGE PROBABILITIES OF OCCURRENCE FOR EACH PHASE OF THE ENCOUNTER-IMPACT MODEL TO PUBLISHED LITERATURE

Encounter-Impact Model Phase	Encounter-Impact Model Probabilities		Baseline Reference Phase	Baseline Reference Results		Baseline References	Species
	Day	Night		Day	Night		
Approach	0.0636	0.0649		0.432		Shen *et al.* 2016	Unidentified
Entrainment	0.0200	0.0203		0.0432	0.333	Viehman and Zydlewski, 2015	Unidentified
	0.0200	0.0203		0.154		Bevelhimer *et al.* 2017	Unidentified
Collision	0.0126	0.0982	Collision	0.306		Band *et al.* 2016	Harbour seal
Blade strike	0.0567	0.0543	Encounter	0.000212		Wilson *et al.* 2006	Pacific herring
Collision and Blade strike	0.00243	0.0126	Encounter	0.000363		Wilson *et al.* 2006	Harbor porpoise

transects compared to those sampled during the day. Fish behaviour in light and dark conditions provides insight on fish-turbine detection distances where experimental studies [13], [16], [28], [29] found that light intensity affects fish distribution in the presence of MRE devices. Williamson *et al.* [29] observed a 2.63 times greater increase in fish aggregation rates around turbine structures at night compared to day, supporting previous studies that show greater probabilities of turbine entry for smaller fish at night [13]. Viehman *et al.* [28] reported that fish are more evenly distributed at night, even at dynamic tidal turbine sites, demonstrating the persistence of fish in dark conditions where turbines are present.

Overall impact probability estimates vary under different combinations of turbine type, light condition, avoidance scenario, and blade strike probability. Impact probabilities with no avoidance result in higher values by one to two orders of magnitude when compared to other impact subcomponents that include avoidance scenarios. Probability estimates assuming no avoidance are not conditioned on preceding events, as estimates are calculated directly from empirical data specific to Admiralty Inlet and the literature. The higher fish-turbine encounter probabilities reported by Wilson *et al.* [26] are based on Pacific herring but are not conditional and do not incorporate active or passive avoidance. Comparing blade strike probabilities derived from literature values, Yoshida *et al.'s* [16] probabilities result in the lowest overall impact probability estimates when combined with an avoidance scenario. These lower probability values are attributed to a lower turbine blade rotational speed to fish swimming speed ratio, resulting in greater avoidance and lower blade strike rates. In contrast, overall impact probabilities are highest when using blade strike probabilities from Romero-Gomez & Richmond's kinematic blade strike model [17] that assumes no fish avoidance. In combination, our probability estimates demonstrate that avoidance is an important factor influencing impact probability values, both as a scenario within the conditional model and experimentally with fish and turbine present.

The lack of collision and combined collision and blade strike empirical data or published values necessitated the modification of blade strike rates for model subcomponents. Parameter values for these impact subcomponents are derived by discounting blade strike probabilities from the literature with Shen *et al.'s* [11] avoidance rate of 0.372. The use of published blade strike probabilities in calculation of collision probability estimates may have increased collision probabilities. To illustrate by example, Courtney *et al.* [14] observed greater blade strike occurrences compared to other studies that found no blade strikes in natural environments (e.g., [11]–[13], [30]). Romero-Gomez & Richmond's [17] kinematic blade-strike, parameterized for Pacific herring in Admiralty Inlet, does not incorporate avoidance resulting in higher blade strike estimates. Probabilities calculated using blade strike rates from these two studies result in impact probability values that range from a factor or two to an order of magnitude higher than estimates derived from Yoshida *et al.'s* [16] blade strike estimates. The lack of data or published probability values for both collision and blade strike that also include avoidance rates illustrate a current knowledge gap.

Obtaining data on direct and delayed impacts of interactions between MRE devices and aquatic animals is essential for regulating operations and monitoring MRE sites. Direct impacts include fish colliding with device structures and/or being struck by turbine blades. Fish interacting with tidal turbines may also experience hydraulic shear stress [31] and/or barotrauma [19] that are often studied in open-channel flume experiments. It is difficult to translate shear and barotrauma laboratory results to the field when assessing whether fish are impacted directly by physical interaction with a turbine or indirectly by other factors. The encounter-impact model does not include indirect effects of fish-turbine interactions nor considers delayed impacts after turbine encounters [cf. 8].

Numerical models can be used to estimate initial values for unknown quantities of fish approach and turbine interaction to help identify empirical data gaps in MRE research [10]. Our hybrid model combines analyses of empirical data from Admiralty Inlet with literature values to estimate probabilities of device encounters and impacts on fish interacting with tidal turbine devices. Although not currently possible, a probability model based entirely on empirical data would be ideal for model parameterization and subsequent model validation. Field data are needed to quantify fish collision rates with stationary turbine components. Data that track fish through turbine encounters will enable probability estimates of avoidance, collision with turbine structures, and the combination of collision followed by blade strike. Long range fish trajectory data can be used to quantify active and passive turbine avoidance behaviours through each step of a sequential encounter model. Having complete empirical data sets would enable the validation of probability estimates and allow resource managers to investigate potential mortality of aquatic animals including species of special status, such as the threatened Puget Sound Chinook salmon *(Oncorhynchus tshawytscha)* [32]. The combination of empirical data with numerical models is a formidable tool to assess fish interactions with MRE devices and is essential for informed regulatory decision-making, conservation strategies, and sustainable development of the MRE blue economy.

Tidal energy is an emerging field that requires the filling of knowledge gaps through increased research effort and environmental monitoring. One area of uncertainty that requires additional effort is characterizing fish avoidance behaviours, including reaction distances to MRE devices. This and other knowledge gaps hinder the permitting/consenting and subsequent development of MRE projects worldwide. To facilitate progress from demonstration projects to commercial-scale sites, it is essential to implement effective risk management strategies, comprehensive environmental monitoring, and regulatory frameworks that provide clear standards for operation of tidal energy [33]. The encounter-impact empirical model in this study is designed to be adaptable to any species and location, and include a wide range of MRE devices when estimating risk probabilities. The flexible nature of this model serves as a starting point to quantify probabilities of encounter and impact across different tidal project sites and to further discussions on impact uncertainty.

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