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Towards Resolving the Risk of Turbine Collision on Fish

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Summary

The most important concern for permitting tidal and river turbines is the collision risk of marine animals with the turbine blades. Our understanding of the risk to individual fish from colliding with turbine blades is poor; if these collisions were to occur, it is unknown whether fish will sustain recoverable injuries or be killed. Equally unknown is the impact these collisions might have on populations, particularly for threatened, endangered, or commercially managed fish species. In addition to observations of interactions of fish with turbines, numerical models need to be developed or expanded to predict impacts on fish populations. These models could replace expensive and technically challenging monitoring programs in high energy, often murky, tidal or river waters.

In this project, a multi-pronged approach was taken to (1) assess the state of knowledge and key uncertainties in studies of collision risk, (2) lay out the steps needed to estimate collision risk effects on fish populations, and (3) identify knowledge gaps and the research needed to fill them. This approach included a workshop with experts, a literature review of modeling and empirical studies, the development of a research framework, and the identification of case studies to address through future work.

First, parameters needed for models for collision risk of fish and data available from empirical studies were compared. This comparison highlighted the discrepancy between parameters needed in models and available data. Empirical data are lacking for collision risk assessment, mainly due to the difficulty in monitoring encounter and collision events. Therefore, collision risk models include a large range of parameters that are mainly based on broad assumptions. Significant parameters to consider in collision risk assessment and consequences on populations were identified in this project such as fish length, detection distance of the turbine, or time the fish spends in risk area or depth.

Next, a research framework was developed using the status of key species to assess the consequences of collision on individual fish and potential impacts on listed and managed populations. The research framework highlights the priorities needed to assess fish collision risk for a tidal or river energy project development. Based on the regulatory status of fish species of interest, the framework identifies the preferred scale and type of study, including the variability among fish species of regulatory interest which can be adapted to migratory and sessile fish, pelagic or demersal fish, fish with different life histories or seasonality, and fish in temperate or tropical regions. From this framework, species were selected to pursue the further development of case studies for collision risk assessment.

Targeted research studies should be developed to fill the data gaps between parameters needed for models and data available from empirical studies. For protected species, the development and use of technologies to determine fish presence and assess their behavior in the nearfield is recommended. Long-term monitoring around deployed turbines will be needed to determine potential interactions between fish and turbines and better understand the likelihood of collisions. These data will inform encounter rate and collision risk models for fish individuals. For managed fish species, it is recommended to work with fisheries agencies that can provide stock assessments and use specific repeated protocols to collect their data. These data can then be used in a model to evaluate the potential effects of collision risk on the population.

Based on existing studies of collision risk and identified knowledge gaps, next steps to resolve the risk of turbine collision on fish were proposed. For example, comparing model results between sites and species to highlight patterns among study designs and species, and initiate a data transferability approach; or applying population-level effects to localized populations that overlap with marine energy development areas.

This project is a first step towards the future development of effective and robust numerical models for assessing the collision risk of fish around turbines. This overall effort will achieve a balanced and accurate estimate of the severity of collision risk to fish at the population scale.

Definitions

Encounter: Animal being in the nearfield of a turbine (1 to 5 device lengths)

Collision: Animal being in contact with the blade of a turbine

Exposure Time: Amount of time an animal spends at the depth and in the field of a device

Avoidance: Animal responding to and moving away from a device at a distance greater than 5 device lengths

Evasion: Animal changing its behavior to escape contact with a device within 5 device lengths (after the encounter, but before a potential collision)

1.0 Introduction

The risk of collision between marine animals and turbine blades continues to be the first question raised by regulators upon hearing of new tidal or river projects, the most significant issue that slows permitting, and in some cases, has contributed to the abandonment of projects (Copping and Hemery 2020). The greatest focus of environmental research and pre-permitting investigations for tidal and river turbine projects has been directed at collision risk (Sparling et al. 2020). However, the interaction of marine mammals, fish, and diving sea birds with devices is not understood well enough to satisfy regulators and other stakeholders that turbines will not cause harm, jeopardize threatened or endangered populations of marine animals, or impact the sustainability of important fisheries.

The challenges to understanding collision risk stem from the difficulty in observing close encounters and interactions of marine animals with turbines in fast moving tidal or river waters that are often murky, and the lack of analogous underwater structures that could provide insight into how marine animals will behave around turbines. Researchers in many nations are applying novel sensor configurations and integrated platforms to gather better data on marine mammals and fish around turbines, but there is still a need for more datasets to better characterize the interactions (Hasselman et al. 2020). Similarly, few models are used to assess collision risk with turbines (Wilson et al. 2007, Band 2012, Grant et al. 2014). These models are built on assumptions as few data are available for parameterization. Modeling approaches are needed to link datasets on collision risk and scaling effects from individuals to population (Copping et al. 2021).

This project focused on the collision risk of fish with turbines. It aimed to (1) assess the state of knowledge and key uncertainties in studies of collision risk, (2) lay out the steps needed to estimate collision risk effects on fish populations, and (3) identify knowledge gaps and the research needed to fill them. First, parameters needed for models for collision risk of fish and data available from empirical studies were compared, allowing for significant modeling parameters and gaps in knowledge to be identified. Next, a research framework was developed using the status of key species to assess the consequences of collision on individual fish and potential impacts on listed and managed populations. From this framework, species were selected to pursue the further development of case studies for collision risk assessment. This project is a first step towards the future development of effective and robust numerical models for assessing the collision risk of fish around turbines. This overall effort will achieve a balanced and accurate estimate of the severity of collision risk to fish at the population scale.

2.0 Approach

A multi-pronged approach was taken to understand the state of knowledge for collision risk of fish with turbines and to build a pathway forward. This approach included using the outcomes from a workshop, performing a literature review of modeling and empirical studies, the development of a framework, and the identification of case studies to address in future work.

2.1 Workshop

Ocean Energy Systems (OES)-Environmental and the Offshore Renewables Joint Industry Program (ORJIP) Ocean Energy held an online workshop on Tuesday 16th March 2021 titled “Collision risk to fish from tidal turbines: next steps towards understanding and retiring risk”. The purpose of the workshop was to bring together experts and marine energy practitioners for a structured discussion on the state of knowledge on the processes of avoidance, evasion, and collision. This Seedling project helped to shape the modeling aspects of the workshop and used the outcomes from the workshop to inform the state of knowledge on collision risk and path forward. Additional information on the workshop, including a recording and workshop report, is available at https://tethys.pnnl.gov/events/collision-risk-fish-tidal-turbines-next-steps-towards-understanding-retiring-risk.

2.2 Literature Review

To assess the existing information on collision risk for fish, a total of 55 modeling and empirical studies were reviewed. A full list of the studies reviewed is included in Appendix A, and additional methods for review and categorization of parameters are described in the sections below.

All papers on models relating to collision risk were gathered from the Tethys database (https://tethys.pnnl.gov) and Google Scholar. These papers were sorted to focus specifically on models for turbines and fish (or models that could be adapted to fish). Each paper was labeled as an encounter rate model, a collision risk model, or an exposure time population model (each model type is described in section 3). For each specific model/paper within each model category, the basic model parameters were identified. The type of parameter was labeled as Biology, Behavior, Environment, or Technology. Additional information was reviewed from relevant adjacent fields (hydropower, fisheries).

All papers on empirical measurements related to collision risk or fish distribution around turbines were gathered from the Tethys database. These papers were then down-selected to remove modeling studies, summary reports, review papers, and studies on hydroelectric dams, tidal barrages, and wind energy – leaving only empirical studies on tidal and river turbine devices (both field and laboratory studies). The data collected in each study were identified and categorized into Biology, Behavior, Environment, or Technology.

2.3 Research Framework

Based on workshop outcomes and literature review, a research framework was developed to address the collision risk of fish in tidal and river energy projects. The development of this framework was based on regulatory criteria, describing the different levels of information that are needed to understand the risk of collision.

2.4 Case Studies

Six preliminary examples of protected, managed, and other species of fish were identified from project environmental assessments in the U.S. These examples were down-selected based on data availability and relevance to MRE sites to two key examples, Sockeye Salmon and Atlantic Sturgeon, that were studied and refined to present as case studies for the development of future collision risk models that can be applied to populations.

3.0 Parameters of Interest for Collision Risk

3.1 Modeling Studies of Collision Risk

3.1.1 Type of Models

The purpose of a collision model is to estimate the likelihood of an encounter or contact (collision) between an animal and a device. The rates of encounter and/or collision depend on several parameters such as the size and location of the device, as well as the animal's behavior and ability to detect the device. The outcomes of a collision model are the probabilities of encounter and/or collision. If the survival rate of the animal after a collision is included in the model, the potential effects on the population can be assessed.

There are three main types of collision models that are currently used in collision risk studies. At the individual scale, two models can be used to estimate the interactions (i.e., encounter or collision) between animals and devices: an *encounter rate model* or a *collision risk model*. At the population scale, an *exposure time population model* can be used. Each model is described below.

Encounter rate model

An encounter rate model is an analytical model that has a similar structure to that of a predator-prey model, with the predator being the blade of a turbine and the prey being the animal (Wilson et al. 2007). Parameters included in an encounter rate model are the volume of water swept by a predator, the size of the prey, the prey density, and the relative swimming speeds of both predator and prey. In an encounter rate model, the turbine blade, viewed from the side, sweeps a certain volume of water in a unit of time that an animal has some probability of occupying. The outcomes are the likelihood of encounter between the animal and the turbine blade.

Collision risk model

Collision risk models are based on the Band (2012) model developed to assess the collision risk of birds with wind turbines. The analytical approach of a collision risk model integrates the area covered by the turbine rotor, the size of the animal, its transit time across the plane of the rotor, its behavior, and its density. Analytical collision risk models are sensitive to assumptions about avoidance rate; however, studies rarely include avoidance or evasion behavior within a collision risk model. Spatial simulations are another approach to assess collision risk with the representation of an animal and a device in 3D over time (Rossington and Benson, 2020). Spatial simulations for collision risk integrate the shape and movement of a device, the animal's behavior, and size.

Exposure time population model

The exposure time population model approaches collision risk from the perspective of populations. This model was developed by Grant et al. (2014) for assessing the collision of diving birds with tidal turbines but can be applied to other species. It integrates two models: a population model and an exposure time model. The population model estimates the amount of additional mortality caused by collisions that would not decrease the population growth rate. The exposure time model estimates a collision probability from the number of time animals spend at the depth of the device and the proportion of that depth occupied by the device. The combination of both models estimates the collision risk per unit of time based on existing data for the population size and the individual exposure time. All the collision events are assumed to be fatal, and the animal's behavior is not included – both of which can result in an overestimation of the risk.

3.1.2 Parameters from Modeling Studies

Models developed to assess fish collision risk use a large range of parameters as inputs. Four categories of parameters were defined: Biology, Behavior, Environment, and Technology. Biological parameters relate to the morphology and physical characteristics of the animal, such as the length of individuals or the size of a population. Behavioral parameters include animal attributes such as swimming speed and preferred depth as well as sensory capabilities and response. Environmental parameters relate to the physical environment surrounding the animal and include water temperature, tidal current speed, or bathymetry. Technological parameters describe the shape and characteristics (e.g., blade width, rotational speed) of a device.

The parameters included in models applied to the collision risk of fish are summarized in Figure 1. Each parameter is associated with a category and the stage at which it is used in collision risk assessment. Here, the assessment of collision risk is defined by six stages, based on the studies reviewed: encounter/avoidance, evasion, collision, injury, population effects, and regulatory concerns.

All these categories of parameters included in collision risk models for fish are used in most assessment stages. Models for encounter/avoidance are used most often and therefore the literature includes a large range of parameters on fish behavior, the physical environment, and the device itself. To estimate the probability of encounter/avoidance between a fish and a device, important parameters to consider are fish length, fish swimming behavior, and flow velocities.

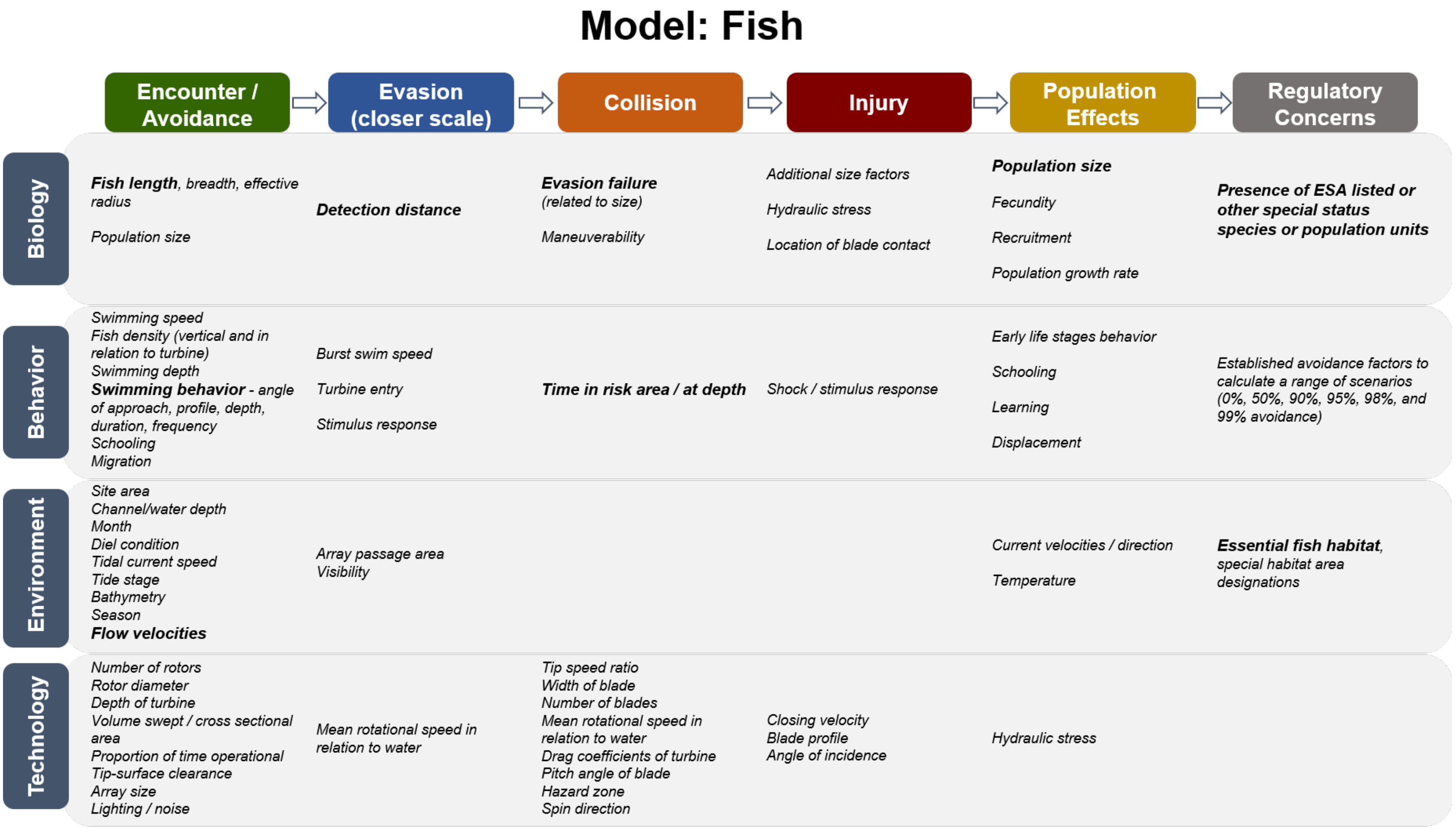
To study fish evasion behavior at a closer spatial scale, models include the distance of detection from a device, and the ability of the fish to swim and maneuver next to a device. At the evasion stage, the distance at which a fish can detect a device has a large effect on its ability to evade the device.

When a fish fails to evade a device, the probability of collision increases. In the collision stage, models include new biological parameters such as an evasion failure related to the size of the individual and the maneuverability of the fish around a device (i.e., ability to turn in a small radius). The time spent in the risk area or depth (i.e., area or depth of the device) is also considered in the behavior category. Both evasion failure and time in risk area or depth can have a large effect on the probability of collision. At the collision stage, several parameters are also included in the models to describe the shape and speed of the turbine blades (e.g., mean rotational speed, blade width, pitch angle, and spin direction).

When a collision occurs, models used for the injury stage include injury rates related to the size of the individual, the location of blade contact, and additional parameters to describe the blade interaction such as the angle of incidence. Although shock or stimulus response (e.g., noise; Rossington and Benson, 2020) can be included to describe fish behavior, the consequences of these additional stimuli on the incidence of injury as it affects the survival rate of the individuals are unknown.

Models used to assess population effects of collision risk assume the mortality of the fish after a collision. Although these models can address risk at different biological processes (e.g., fecundity, recruitment) and behavior (e.g., schooling, migration), defining the size and structure of the population is key to assessing the consequences of individual mortality on the population dynamics.

In several studies reviewed on collision models for fish, the model was applied to species of regulatory concern, such as managed or protected species (e.g., KHPS Fish Interaction Model, Bevelhimer et al. 2016). In this case, additional important parameters need to be considered such as the fish presence and distribution (category: Biology) and the presence of essential fish habitats such as spawning or feeding habitat (category: Environment).



Model: Fish

	Encounter / Avoidance	Evasion (closer scale)	Collision	Injury	Population Effects	Regulatory Concerns
Biology	**Fish length**, breadth, effective radius Population size	**Detection distance**	**Evasion failure** (related to size) Maneuverability	Additional size factors Hydraulic stress Location of blade contact	**Population size** Fecundity Recruitment Population growth rate	**Presence of ESA listed or other special status species or population units**
Behavior	Swimming speed Fish density (vertical and in relation to turbine) Swimming depth **Swimming behavior** - angle of approach, profile, depth, duration, frequency Schooling Migration	Burst swim speed Turbine entry Stimulus response	**Time in risk area / at depth**	Shock / stimulus response	Early life stages behavior Schooling Learning Displacement	Established avoidance factors to calculate a range of scenarios (0%, 50%, 90%, 95%, 98%, and 99% avoidance)
Environment	Site area Channel/water depth Month Diel condition Tidal current speed Tide stage Bathymetry Season **Flow velocities**	Array passage area Visibility			Current velocities / direction Temperature	**Essential fish habitat**, special habitat area designations
Technology	Number of rotors Rotor diameter Depth of turbine Volume swept / cross sectional area Proportion of time operational Tip-surface clearance Array size Lighting / noise	Mean rotational speed in relation to water	Tip speed ratio Width of blade Number of blades Mean rotational speed in relation to water Drag coefficients of turbine Pitch angle of blade Hazard zone Spin direction	Closing velocity Blade profile Angle of incidence	Hydraulic stress	

Figure 1. Specific parameters identified from the literature review of collision models for fish. Parameters identified to be the most significant in each stage of collision risk assessment are in bold.

3.2 Empirical Studies of Collision Risk

3.2.1 Application of Empirical Studies

Most empirical studies on collision risk of fish have assessed the likelihood of encounter between a fish and a device, and the animal's behavior (evasion or avoidance). Only a few studies assessed collision events between fish and a turbine through laboratory experiments (Berry et al. 2019, Amaral et al. 2015, Schweizer et al. 2012, Amaral et al. 2011). Few studies of collision risk used the information assessed from empirical research as model parameters. Bevelhimer et al. (2016) included fish behavior (position in the water column, swimming direction, and speed) in a probability model used to determine the overall risk of a turbine blade striking a fish. Shen et al. (2016) used vertical distribution data of fish in an encounter rate model to estimate the probability that fish would be at the depth of a device. Empirical data on fish abundance, vertical distribution, and behavior were also used in an encounter rate model by Zydlewski et al. (2016). Hammar et al. (2015) simulated avoidance and evasion failure by using behavioral observations of fish interacting with fishing gear in a collision risk model. Finally, McIlvenny et al. (2021) included acoustic tracking data on fish presence and swimming depth in a particle tracking model.

3.2.2 Data from Empirical Studies

Data collected from empirical studies on collision risk of fish with turbines can describe the morphology of a fish, its behavior, or the device characteristics. Few data are available from empirical studies, particularly from the collision stage (Figure 2).

Empirical studies addressing encounter and avoidance often describe the species of fish observed/studied, the fish life stage and length, its behavior, and how these characteristics relate to environmental variables such as time of day or season if the study is conducted in the field. At closer scales in empirical studies on evasion, detailed information on the behavior of fish can be added such as their mode of swimming or direction of turns. Because few empirical studies address the collision stage due to the difficulty of observing such rare events, the only additional parameters identified at this stage are fish routes around the turbine and migratory status.

Once a rare collision event between a fish and a turbine is observed, the injury rate, mortality rate, and potential population effects need to be assessed. The only existing empirical data for injury and population impacts of collision are from hydropower studies (Bevelhimer et al. 2017, Hou et al 2018), which incorporate substantially different dynamics from those of turbines.

Observations: Fish

	Encounter / Avoidance	Evasion (closer scale)	Collision	Injury	Population Effects	Regulatory Concerns
Biology	*Species* *Fish length* *Hearing sensitivity* *Lifestage* *Individual vs. school*	*Body shape*		*Injury rates** *Survival/mortality rates**		*Endangered status*
Behavior	*Swim depth, speed* *Direction of swim* *Swim tracks* *Distance from turbine* *Behavior (passive, avoidance)* *Vertical distribution* *Diel vertical migration* *School behavior* *Fish density* *Passage count rate*	*Fish movement* *Mode of swimming* *Direction of track turns* *Horizontal and vertical swim speed evasion*	*Route around turbine* *Migratory status*			
Environment	*Time of day* *Season* *Tidal cycle* *Diurnal phase* *Flow velocity* *Seabed composition* *Ambient noise* *Temperatures* *Turbidity*	*Depth*				
Technology	*Mooring,* *Position in water column* *Sound produced* *Turbine speed*	*Dimensions*		*Blade profile** *Rotor height** *Rotational speed**		

*from hydropower studies

Figure 2. Data identified during literature review of empirical studies informing collision risk of fish with turbines.

3.3 Knowledge on Collision Risk from Surrogate Industries

3.3.1 Hydropower

A lot of research has been done in the hydropower industry to make hydropower turbines more fish-friendly and improve fish passage in regulated rivers. Bevelhimer et al. (2017) reviewed experimental research performed to understand the mechanisms of fish harm from hydropower turbines, including biological, behavioral, and technological parameters. The HydroPASSAGE project has been developing tools to mitigate the environmental impacts of dam passage on fish such as an autonomous sensor package to quantify the stressors fish may experience during their passage through a hydropower turbine (Sensor Fish; Deng et al. 2014), the Biological Performance Assessment (BioPA) to estimate the likelihood a fish will be exposed to a stressor (Richmond et al. 2014), and the Hydropower Biological Evaluation Toolset (HBET) to predict the stressors and the magnitudes to which fish may be exposed (Hou et al. 2018). The BioPA and HBET tools are used to predict the injury and mortality of fish from interactions with hydropower turbines (Pflugrath et al. 2020). The interactions considered between the hydropower turbines and the fish are collision, rapid decompression, and fluid shear. Only the collision interaction is an analogous risk to fish between hydropower and marine energy turbines, but most of the information available in these studies does not apply to marine energy due to engineering differences between the devices.

A report by the Electric Power Research Institute (Jacobson et al. 2012) summarizes some of these differences between hydropower and marine energy turbines specific to collision. Hydropower turbines operate in a closed system, with no opportunity for evasion or avoidance. They also spin much faster than marine energy turbines and have higher strike velocities, with different blade technology. Lastly, fish passing through a hydropower turbine experience high flow velocity, significant changes in pressure and flow direction, and encounter many other structures that can contribute to overall injury or mortality rates.

The most relevant information from hydropower studies that can potentially be applied to marine energy turbines is the translation of injury and mortality rates (dose-response data) to population impacts. Algera et al. (2020) reviewed population level consequences of collision for hydropower but indicated that the evidence base for population impacts is rather small, and that they were unable to estimate the impacts of hydropower dams on the fish population. It may be possible to use data from hydropower studies in the parameterization of future population models, but the differences noted previously between the rates of injury and mortality from hydropower turbines compared to marine energy will need to be strongly considered.

3.3.2 Fisheries

Although collision risk is not a stressor present in the fisheries industry, some knowledge on the consequences of individual fish mortality from harvest or bycatch on population dynamics can be transferred to the marine energy industry. Population dynamics describe the changes in a population throughout time related to recruitment, growth, mortality, or spatial distribution (Quinn and Deriso, 1999). These dynamics are represented in population models and are used for fisheries management (Hilborn and Walters, 1992).

Population models applied to fisheries management are used to ensure sustainable harvest practices and define the maximum sustainable yield, the largest average catch that can be captured from a stock over an indefinite period. Populations in fisheries management are defined by three components:

- Recruitment: age or size at which a fish reaches a reproductive stage
- Growth: related to biomass (size and length of individuals)
- Mortality: natural and harvested

The assessment of recruitment, growth, and mortality rates that drive the dynamics of a population is key to assessing its sustainability over time (White et al. 2014). Studies assessing spatial scales of fisheries management also found that models should consider spatial variations in demographic patterns (Burgess et al. 2014, Garavelli et al. 2018).

Population models used for fisheries management could be modified and applied to collision risk studies to determine acceptable levels of mortality for a sustainable fish population. However, the processes affecting population dynamics likely differ when focusing on collision risk with turbines, as compared to fisheries harvests. In fisheries management studies, mortality of early life stages (i.e., eggs and larvae) usually has high impacts on the sustainability of a population (e.g., Berkeley et al. 2011), but the risk of early life stages mortality from collision with a turbine is likely low due to the small size of the individuals. Knowledge on the effects of juvenile (i.e., post-larvae stage, after recruitment) and adult mortality on the population sustainability from fisheries management studies could inform collision risk for turbines. Due to their larger size and potential migration patterns, juvenile and adults are more susceptible to collision risk. Mortality of adults will also drive the reproductive potential of a population, thus affecting its sustainability over time.

In the case of a tidal/river energy project developed in an area where commercial or recreational fish species are present, multiple stressors need to be considered: natural mortality, harvest mortality, and collision risk mortality. Existing population models for fisheries management would need to be applied carefully and in the context of multiple stressors.

3.4 Knowledge Gaps

The data available from empirical studies were compared to the parameters used in collision risk modeling to identify knowledge gaps. We found that, in many cases, model inputs were not informed by data collected in the field and instead relied on multiple assumptions about fish characteristics, such as their behavior.

Parameters needed in models and available empirical data were compared at each stage of collision risk identified in Figures 1 and 2. At the collision stage, there are very little empirical data. Biological parameters that need to be studied empirically to eliminate modeling assumptions are evasion failure rates and fish maneuverability. Behavioral parameters needed are detection distance of the turbine and time spent in the risk area/depth. These parameters are considered to be some of the most important missing pieces of information in assessing collision risk of fish with turbines.

There are also no available data on injury from a turbine blade strike outside of the information from hydropower studies previously described. Key parameters to measure include impacts of the location of blade contact, injury/survival rates specific to marine energy devices, and other injury outcomes and long-term impacts on the population outside of mortality.

At present, understanding the population effects of turbine collision risk is not supported by any empirical data, though there may be knowledge from fisheries studies that could be leveraged if appropriately considered. Key parameters that are needed to make this step toward population level impacts are understanding the size of a population (i.e., number of individuals), the consequences of collision (similar to injury risk), fecundity and growth rates, as well as behavioral data, including schooling and learning.

Knowledge gaps relating to the understanding of collision risk effects on populations were also identified by experts in the collision risk workshop. These include:

- A need to define a population (i.e., ecological vs. evolutionary context), relative to the scale of each project site and expected effects.
- The lack of models that can predict the outcomes of a collision, limiting the application of existing models.

4.0 Framework for Assessing Collision Risk

Based on inputs from the workshop and the literature review, a research framework was developed for addressing the collision risk of fish with a turbine (Figure 3). This framework is based on the status of the fish species of interest and defines the first steps to consider when assessing collision risk: the potential effect of collision based on the species status and the data availability. It then identifies the preferred scale and type of study for each species' status. Each step is described below.

1. Status	**Protected Species**	**Managed Species**		**Other Species**
2. Definition	These species may be designated as endangered or threatened, and are carefully regulated to ensure survival of the species or population.	These species are considered culturally, commercially, or recreationally important, and are closely monitored to ensure sustainability.		These species are not closely managed or regulated due to a lack of economic or cultural value and/or high abundance.
3. Potential effect of collision	The mortality of a small number of animals could affect the population.	Mortality of an individual is unlikely to negatively impact the population. High rate of mortality could have population level effects.		Mortality of an individual is unlikely to negatively impact the population.
4. Data availability	Few datasets	Existing datasets from fisheries (e.g., catch rates)		Likely few datasets available
5. Scale of study	Nearfield	Midfield	Farfield	NA
6. Type of study	Observations: acoustic telemetry, acoustic cameras, and video cameras to track encounter/ collision Modeling: encounter rate/ collision risk models	Observations: echosounders for presence/ absence, distribution	Modeling: population models more efficient than observations	NA

Figure 3. Framework for assessing collision risk of fish with a turbine. NA = no study needed.

The first step in this collision risk framework is to define the status of the fish species of interest. This designation drives the path forward for assessment.

Protected fish species or populations have some level of legal protection afforded to them due to their status as endangered or threatened. A collision for a small number of individuals that results in mortality (considered “take” under the Endangered Species Act [ESA]) could impact the survivability of the population (with some exceptions based on the life stage of the individual). Few data are available on the species or populations. For collision risk assessment, nearfield studies are needed. Using acoustic telemetry and/or acoustic/video cameras on a device will improve the likelihood of tracking potential encounter and collision events. Encounter events can be informed by the assessment of the horizontal and vertical distribution of fish in the water column. Species identification is necessary when focusing on protected species and collecting enough data for analysis may be a limitation. Preliminary encounter rate and collision risk models can also be developed to understand if the level of risk is acceptable to site a project in an area with protected species present.

Managed fish species are often highly regulated and considered to be included in culturally, recreationally, or commercially important fisheries. Significant amounts of data are often available on these species' abundance and population structure for fisheries management purposes. The mortality of a few individuals is unlikely to significantly impact the population but should be monitored to ensure sustainability for all users and parties interested in the species. Monitoring collision risk for managed species could include performing midfield studies with echosounders to determine presence and distribution at a project site, which could supplement existing fishery stock assessments and refine them on a spatial scale relevant to the tidal or river energy project. Developing population models in the farfield scale would help predict overall potential impacts on a population. Using this type of models for managed species in locations where lots of data are available is the most efficient way to assess the effects of collision risk on fish populations.

Other species include species or populations that are not considered particularly culturally important or commercially/recreationally valuable. This may be due to a high abundance of individuals, poor quality for human uses, lack of fisheries pressure, or little information about the species. The mortality of an individual is unlikely to impact the population, though relatively fewer data are likely to be available compared to managed species. Regulators are unlikely to require monitoring or assessment of collision risk for these species.

For each of the species' status, potential case studies were identified that could be pursued further in testing out the framework and developing collision risk models at the population scale.

5.0 Case Studies

Several species were selected to initiate future case studies for each species status defined in the framework. These species, their characteristics, distribution, and the associated tidal/river energy sites are described in Table 1.

Table 1. Species selected for potential case studies on collision risk assessment. Regions of interest, relevant information, and associated tidal/river energy sites are mentioned.

Status	Species	Characteristics	Distribution	Tidal/river energy sites
Protected	**Atlantic Sturgeon** *Acipenser oxyrhynchus oxyrhynchus*	Slow-growing and late-maturing	New England/Mid-Atlantic, Southeast of U.S.	East River, New York Minas Passage, Canada
	Chinook Salmon *Oncorhynchus tshawytscha*	Major prey for orcas	West Coast of U.S. and Alaska	Admiralty Inlet, Washington
Managed	**Pacific Herring** *Clupea pallasii*	Forage fish, regulated fishery	West Coast of U.S. and Alaska	Admiralty Inlet, Washington
	Sockeye Salmon *Oncorhynchus nerka*	Regulated fishery	West Coast of U.S. and Alaska	Igiugig, Alaska
Other	**Surfperch**	Minimally regulated recreational fishery	West Coast of U.S.	Admiralty Inlet, Washington
	Northern Pike *Esox lucius*	Invasive	West Coast of U.S. and Alaska	Igiugig, Alaska

Atlantic Sturgeon and Sockeye Salmon were chosen out of these examples to pursue further development of case studies for collision risk assessment due to the amount of information available and clear connection to marine energy project sites.

5.1 Atlantic Sturgeon

Atlantic Sturgeon can weigh up to 363 kg, measure up to 4.3 m, and live up to 60 years (Figure 4). They are anadromous fish; they are born in freshwater and the juveniles migrate to the sea to mature. Adults migrate back to their birthplace in freshwater to spawn. They are distributed in rivers and coastal waters along the U.S. East Coast, from Maine to Florida. Atlantic Sturgeon are listed as endangered under the ESA in the Carolina, Chesapeake Bay, New York Bight, and South Atlantic Distinct Population Segments (DPSs); they are listed as threatened under the ESA in the Gulf of Maine.

Habitat degradation and impediments to passage are the main significant threats to Atlantic Sturgeon. Critical habitat is designated in all DPSs. In the New York Bight DPS, critical habitat includes the vicinity of the Roosevelt Island Tidal Energy (RITE) project developed by Verdant Power. Regulatory requirements for this project include ongoing monitoring of the presence and distribution of Atlantic Sturgeon in the area, previous analysis of fish behavior around turbines by video, and a collision risk model developed for estimating the probability of blade strike (Tomichek et al. 2015, Bevelhimer et al. 2016). Knowledge gaps identified in preliminary research include fish behavior around the turbine (avoidance/evasion), outcomes of potential blade strike, and population size. This case study provides an opportunity to determine further monitoring and modeling recommendations for a protected species.

Figure 4. Atlantic Sturgeon (NOAA Fisheries)

5.2 Sockeye Salmon

Sockeye Salmon is one of the smaller species of Pacific salmon, measuring 50 to 70 cm in length and weighing 1.8 to 6.8 kg. They occur from Northwest Alaska to the Deschutes River in Oregon. Sockeye Salmon is sustainably managed and responsibly harvested under U.S. regulations. Commercial, recreational, and tribal fisheries are managed in ocean and inland waters of the West Coast and Alaska.

In Alaska, no population of Sockeye Salmon is listed under the ESA and the fishery is managed under the Fisheries Management Plan for Salmon Fisheries. Several monitoring and modeling studies have been conducted on Sockeye Salmon present in the Kvichak River, where a hydrokinetic turbine has been deployed by Ocean Renewable Power Company (ORPC) at Igiugig. These studies include life stages information, historic stock data, video of fish presence near the turbine, and existing population models for fisheries management (e.g., Nemeth et al. 2014, Cunningham et al. 2018). This case study provides an opportunity to use fisheries management data and practices to develop a population model and estimate the potential effects of collision risk on populations.

Figure 5. Sockeye Salmon (NOAA Fisheries)

6.0 Conclusion and Next Steps

The comparison of modeling and empirical studies applied to the assessment of collision risk of fish with tidal turbines highlighted the discrepancy between parameters needed in models and available data. Empirical data are lacking for collision risk assessment, mainly due to the difficulty in monitoring encounter and collision events. Therefore, collision risk models include a large range of parameters that are mainly based on broad assumptions. The most significant parameters to consider in collision risk assessment and consequences on population were identified in this project: fish length, detection distance of the turbine, time the fish spends in risk area or depth, evasion failure, population size, and presence of listed species or essential fish habitat.

To date, models used to determine collision risk were developed for fisheries (e.g., predator-prey model), hydropower, or adapted from bird collisions with wind turbines, thus limiting their use for collision risk assessment for fish with tidal or river turbines. Models adapted to the life cycle of fish are needed for a better assessment of collision risk. For example, specific parameters needed are species-specific behavior, injury outcomes, and consequences of collision (e.g., on reproduction).

The research framework highlights the priorities needed to assess fish collision risk for a tidal or river energy project development. Based on the regulatory status of fish species of interest, the framework identifies the preferred scale and type of study, including the variability among fish species of regulatory interest which can be adapted to migratory and sessile fish, pelagic or demersal fish, fish with different life histories or seasonality, and fish in temperate or tropical regions.

Targeted research studies should be developed to fill the data gaps between the parameters needed for models and data available from empirical studies. For protected species, the development and use of technologies to determine fish presence and assess their behavior in the nearfield is recommended. Long-term monitoring around deployed turbines will be needed to determine potential interactions between fish and turbines and better understand the likelihood of collisions. These data will inform encounter rate and collision risk models for fish individuals. For managed fish species, it is recommended to work with fisheries agencies that can provide stock assessments and use specific repeated protocols to collect their data. These data can then be used in a model to evaluate the potential effects of collision risk on the population.

Based on existing studies of collision risk and identified knowledge gaps, recommended next steps to resolve the risk of turbine collision on fish are:

- Understand the role of turbine technologies in collision risk;
- Apply population-level effects to localized populations that overlap with marine energy development areas;
- Compare model results between sites and species to highlight patterns among study designs and species, and initiate a data transferability approach;
- Identify the existing models used to assess population effects in a variety of applications; and
- Explore the collaborative opportunities between fisheries management and marine energy regulatory processes for managed fish populations.

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Appendix A. Literature Review

Table A1. Modeling studies relevant to collision risk of fish.

Reference	Type of Model
ABP Marine Environmental Research (2010). Collision Risk of Fish with Wave and Tidal Devices (Report No. R.1516). https://tethys.pnnl.gov/publications/collision-risk-fish-wave-tidal-devices	Encounter Rate Model, Collision Risk Model
Bevelhimer, M.; Colby, J.; Adonizio, M.; Tomichek, C.; Scherelis, C. (2016). Informing a Tidal Turbine Strike Probability Model through Characterization of Fish Behavioral Response using Multibeam Sonar Output (Report No. ORNL/TM-2016-219). https://tethys.pnnl.gov/publications/informing-tidal-turbine-strike-probability-model-through-characterization-fish	Collision Risk Model
Copping, A.; Grear, M. (2018). Applying a simple model for estimating the likelihood of collision of marine mammals with tidal turbines. *International Marine Energy Journal,* 1(1), 27-33. DOI: 10.36688/imej.1.27-33. https://tethys.pnnl.gov/publications/applying-simple-model-estimating-likelihood-collision-marine-mammals-tidal-turbines	Collision Risk Model
Grant, M.; Trinder, M.; Harding, N. (2014). A Diving Bird Collision Risk Assessment Framework for Tidal Turbines (Report No. 773). https://tethys.pnnl.gov/publications/diving-bird-collision-risk-assessment-framework-tidal-turbines	Exposure Time Population Model
Hammar, L.; Eggertsen, L.; Andersson, S.; Ehnberg, J.; Arvidsson, R.; Gullström, M.; Molander, S. (2015). A Probabilistic Model for Hydrokinetic Turbine Collision Risks: Exploring Impacts on Fish. *PLoS ONE,* 10(3), 1-25. DOI: 10.1371/journal.pone.0117756 https://tethys.pnnl.gov/publications/probabilistic-model-hydrokinetic-turbine-collision-risks-exploring-impacts-fish	Collision Risk Model
Horne, N.; Culloch, R.; Schmitt, P.; Lieber, L.; Wilson, B.; Dale, A.; Houghton, J.; Kregting, L. (2021). Collision risk modelling for tidal energy devices: A flexible simulation-based approach. *Journal of Environmental Management,* 278(Part 1), 111484. DOI: 10.1016/j.jenvman.2020.111484 https://tethys.pnnl.gov/publications/collision-risk-modelling-tidal-energy-devices-flexible-simulation-based-approach	Collision Risk Model
Romero-Gomez, P.; Richmond, M. (2014). Simulating Blade-Strike on Fish Passing Through Marine Hydrokinetic Turbines. Renewable Energy, 71, 401-413. DOI: 10.1016/j.renene.2014.05.051 https://tethys.pnnl.gov/publications/simulating-blade-strike-fish-passing-through-marine-hydrokinetic-turbines	Collision Risk Model
Rossington, K.; Benson, T. (2019). An agent-based model to predict fish collisions with tidal stream turbines. Renewable Energy, 151, 1220-1229. DOI: 10.1016/j.renene.2019.11.127 https://tethys.pnnl.gov/publications/agent-based-model-predict-fish-collisions-tidal-stream-turbines	Collision Risk Model
Schmitt, P.; Culloch, R.; Lieber, L.; Molander, S.; Hammar, L.; Kregting, L. (2017). A Tool for Simulating Collision Probabilities of Animals with Marine Renewable Energy Devices. Plos One, 12(11), e0188780. DOI: 10.1371/journal.pone.0188780 https://tethys.pnnl.gov/publications/tool-simulating-collision-probabilities-animals-marine-renewable-energy-devices	Collision Risk Model
Scottish Natural Heritage. (2016). Assessing collision risk between underwater turbines and marine wildlife. SNH guidance note. https://tethys.pnnl.gov/publications/assessing-collision-risk-between-underwater-turbines-marine-wildlife	Encounter Rate Model, Collision Risk Model, Exposure Time Population Model
Shen, H.; Zydlewski, G.; Viehman, H.; Staines, G. (2016). Estimating the probability of fish encountering a marine hydrokinetic device. Renewable Energy 97, 746-756. DOI: 10.1016/j.renene.2016.06.026 https://tethys.pnnl.gov/publications/estimating-probability-fish-encountering-marine-hydrokinetic-device	Encounter Rate Model

Tomichek, C.; Colby, J.; Adonizio, M. (2015). Improvements to Probabilistic Tidal Turbine-Fish Interaction Model Parameters, paper presented at 3rd Annual Marine Energy Technology Symposium (METS), Washington DC, USA. https://tethys.pnnl.gov/publications/improvements-probabilistic-tidal-turbine-fish-interaction-model-parameters	Collision Risk Model
Wilson, B.; Batty, R.; Daunt, F.; Carter, C. (2007). Collision Risks Between Marine Renewable Energy Devices and Mammals, Fish and Diving Birds. https://tethys.pnnl.gov/publications/collision-risks-between-marine-renewable-energy-devices-mammals-fish-diving-birds	Encounter Rate Model, Collision Risk Model
Xodus Group (2016). Brims Tidal Array Collision Risk Modelling - Atlantic Salmon (Report No. A-100242-S02-TECH-001). https://tethys.pnnl.gov/publications/brims-tidal-array-collision-risk-modelling-atlantic-salmon	Collision Risk Model

Table A2. Empirical studies relevant to collision risk of fish.

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