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IMPROVEMENTS TO PROBABILISTIC TIDAL TURBINE - FISH INTERACTION MODEL PARAMETERS

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INTRODUCTION

Atlantic sturgeon (*Acipenser oxyrinchus*) are a protected species that are known to traverse the area occupied by Verdant Power's Roosevelt Island Tidal Energy (RITE) Project in the East Channel of the East River, New York City (NYC). To acquire regulatory permits for the installation and operation of the project, it was required to determine the likelihood of a kinetic hydropower system (KHPS) turbine strike on these species. A probability based model, known as the KHPS-Fish Interaction Model was developed to quantify the risk of the turbine striking these fish and used for the Federal permitting process [1].

The methodology, original assumptions and associated probability estimates behind the model are presented, along with parameter updates based on recently collected data. At RITE, the model quantifies the risk to Atlantic sturgeon by the Verdant Power horizontal axis, 3-bladed open-rotor turbines. Although the primary focus of the model was turbine interaction with Atlantic sturgeon in the East River, NYC, it was developed so that it could be used and updated at various sites where KHPS are considered as part of a project's environmental compatibility evaluations.

Research conducted by Verdant Power since 2011 in collaboration with the Atlantic Cooperative Telemetry (ACT) Network detecting previously tagged Atlantic sturgeon has shed insight into some of the parameter values [2]. As information is learned from the results of the adaptive management monitoring plans, modeling parameters have been modified based on actual data. Three of the seven model parameters have been recently updated from a basis of best assumptions to be a determination from data collected in situ, as discussed in this paper.

SITE CHARACTERIZATION

The East River is a 27 km long tidal strait connecting the waters of the Long Island Sound with those of the Atlantic Ocean in New York Harbor. It separates the New York City Boroughs of Manhattan and the Bronx from Brooklyn and Queens and is a saltwater conveyance passage for tidal flows. Roosevelt Island splits the East River in to two channels, the West Channel, the primary navigation channel, and the East Channel, where the RITE project is located (Figure 1). Atlantic sturgeon are long lived species known to occur in the Hudson River and Long Island Sound. Atlantic sturgeon tagged along the eastern seaboard and in Long Island Sound have been detected traversing the project vicinity. The introduction of Marine Hydrokinetic technologies into the East River poses a new and somewhat unknown blade strike risk to fish populations. To characterize this risk, a basic understanding of the technologies involved, typical environmental conditions and target species are factored into the analysis.

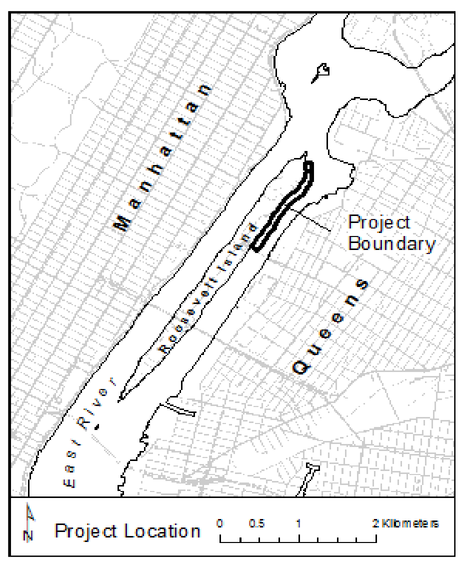

FIGURE 1. LOCATION OF VERDANT POWER RITE PROJECT IN THE EAST RIVER, NEW YORK CITY.

TECHNOLOGY

Marine Hydrokinetic technologies refer to a group of devices that extract energy directly from the kinetic energy present in moving water. Some devices, such as the turbine developed by Verdant, are designed to extract energy from tidal flows in a manner similar to the way a typical wind turbine operates. The Verdant turbine is an open bladed horizontal axis, downstream rotor type whose design is such that as the flow direction changes from flood to ebb tide, the turbine passively yaws to align with the flow. The Verdant turbine, as applied to RITE, features a 5 m diameter rotor and operates at a fixed speed of 40 rpm. As such, the tip speed ratio varies from 10.5 (water velocity (V_W) = 1 m/s) to 4.2 (V_W = 2.5 m/s) and the tip speed at rated power is 5 (V_W = 2.1 m/s) which is the design tip speed ratio. Since the turbine rotates at a fixed speed, the nominal tip speed is 10.5 m/s (23.5 mph).

DATA COLLECTION AT RITE

As part of the Tagged Species Detection Plan [1], Verdant Power installed three (3) VEMCO VR2W receivers in and around the RITE Project, as shown in Figure 2. Two of the receivers, VR2W RITE N and VR2W RITE S, were deployed in May 2011 in the East Channel of the East River from existing buoys at the current RITE Project site. The third receiver, VR2W-W, was deployed in August 2011 in the West Channel of the East River. Range testing conducted by Verdant confirmed a receiver detection range of 400m, greater than either channel width, ensuring the detection of all fish traveling through each channel. Test tags were also deployed to ensure the receivers were functioning properly. From initial deployment in May 2011 to July 2014, 27 tagged Atlantic sturgeon have been detected traversing the East River (Table 1). Verdant KHPS were not operating during this time period except for a 2-week test in September, 2012.

KHPS-FISH INTERACTION MODEL

A 2-Dimensional (2D) probabilistic approach was developed to support the Verdant Power License [1] to determine the overall risk of strike by using a product of independent sub-probabilities. The model considers a 2D lateral cross section of the channel at the location of the turbine and comprises seven major parameters: Probability of Blade Rotation (P1), Distribution of Water Velocity over the Tidal Cycle (P2), Fish

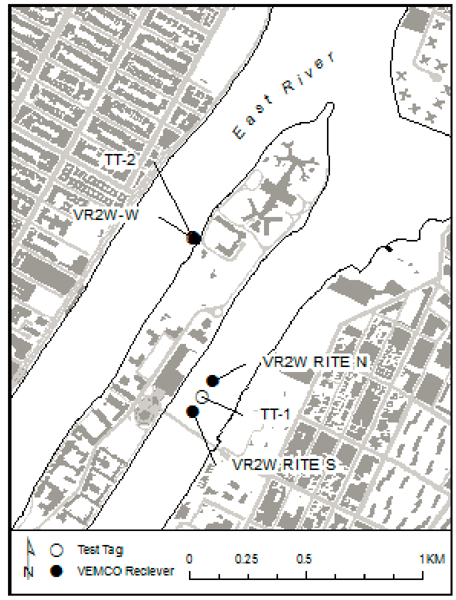

FIGURE 2. RITE VEMCO RECEIVER (3) AND TEST TAG (2) DEPLOYMENTS

TABLE 1. ATLANTIC STURGEON DETECTIONS FROM MAY 2011 THROUGH JULY 2014 IN THE EAST RIVER, NYC.

Date	East Channel	West Channel	Total Detections
6/6/2011	1		1
10/19/2011		1	1
3/18/2012		1	1
5/5/2012	1	1	2
6/15/2012		1	1
6/19/2012		1	1
6/23/2012		1	1
10/10/2012	1		1
10/11/2012		1	1
4/7/2013		1	1
6/1/2013		1	1
6/20/2013		1	1
6/21/2013		1	1
7/7/2013		1	1
4/29/2014	1	1	2
5/9/2014	1		1
5/15/2014		1	1
5/23/2014		1	1
6/5/2014		1	1
6/8/2014		1	1
6/12/2014		1	1
6/17/2014		1	1
6/18/2014		1	1
6/19/2014		1	1
6/21/2014	1		1
Total	6	21	27

Distribution (P3), Turbine Rotor Area (P4), Blade Interaction with Fish (P5), Fish Distribution (P6) and Avoidance Behavior (P7). These parameters are combined to provide the total probability of strike as shown in Equation 1.

$$P_{Strike} = \sum_{V_W=0}^{V_{W,Max}} P1 \cdot P2 \cdot P3 \cdot P4 \cdot P5 \cdot P6 \cdot P7 \quad (1)$$

Most of these parameters will vary as a function of water velocity and are summed across all water velocities up to the maximum tidal flow ($V_{W,\ Max}$). The following section describes the individual parameter values used in the 2010 License Application. Additional discussion on parameters that have been updated based on the results of the Tagged Species Detection Plan conducted at the RITE site in the 2011-2014 period is provided. The collection of this ongoing data is funded in part by grants from the New York State Energy Research and Development Authority (NYSERDA), who has supported Verdant Power's efforts at RITE since 2005.

P1: Probability of Blade Rotation

A unique characteristic of the Verdant KHPS design is that for the water velocities present at the site, the rotor will turn at a near constant speed of 40 rpm independent of the water velocity. In addition, the turbine features an automatically operated brake that will stop the turbine from rotating when water velocities are too low to generate power. This means that during times when the flow is below 1 m/s the turbine will not be rotating and will therefore not pose a risk to fish. This is illustrated in Figure 3 which shows the probability of rotation as a function of water velocity. Parameter P1 remains unchanged from the original model.

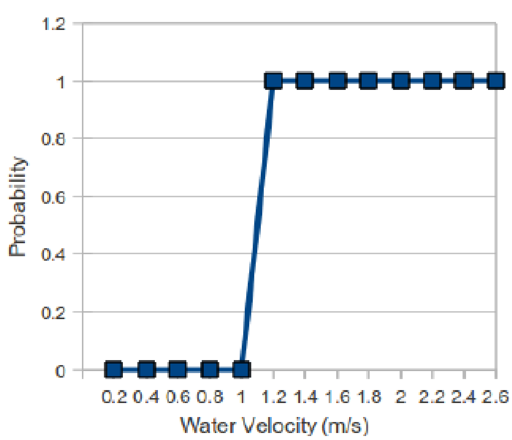

FIGURE 3. PROBABILITY OF BLADE ROTATION (P1).

P2: Distribution of Water Velocity over the Tidal Cycle

The environment in the East River provides for a predictable, but constantly changing, flow profile. The speed at which the water moves has a significant impact upon the risk of the fish being struck. As the turbine rotor will turn at a constant rate, faster water flows will incur a lower chance of strike as the fish will be carried through the rotor disk faster. The parameter P2 remains unchanged and is shown in Figure 4.

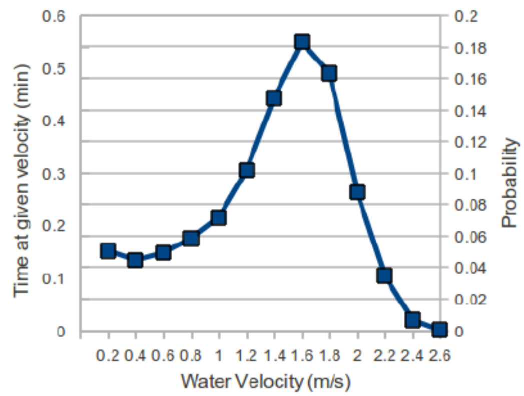

FIGURE 4. RITE SITE VELOCITY DISTRIBUTION (P2).

P3: Fish Distribution (East vs. West Channel)

The East River bifurcates around Roosevelt Island, forming the East and West Channels. The cross sectional area of the channels is roughly equal (both channels have a similar width of approximately 240m and depth of 10m). The West Channel has a slightly higher average flow speed and the volume of water passing through both channels is equal to within approximately 5%. It reasonably follows that half of any fish present will transit via the West Channel and will therefore not be affected by the turbines present in the East Channel. Parameter P3 was originally assumed to be 0.5 (i.e. Atlantic sturgeon had an equal probability of using the East and West Channel). However, results from the tagged species detection effort underway at the RITE suggest a change to this parameter is appropriate. From May, 2011 to July, 2014, 27 unique detections of Atlantic Sturgeon transiting the area occurred. Of those 27, only 6 were detected in the East Channel. As such, the probability of occurrence in the East Channel is 22% based on data collected thus far and this parameter can be updated from P3 = 0.5 to P3 = 0.22.

P4: Turbine Rotor Area

With a 2D model the turbine(s) will occupy a certain percentage of the cross sectional area of the river, therefore the probability that a fish will transit through the turbine area will be given by the ratio of overall channel cross sectional area to turbine area.

While the turbine disk area can be given by a standard calculation of area, hydrodynamic theory states there will be a volume of water incident on the disk that will be ejected due to the energy extraction. Figure 5 shows this effect in profile and illustrates this ejection zone. Any fish present in this zone will be moved away from the rotor. The existence of this effect has been acknowledged in the literature [3, 4].

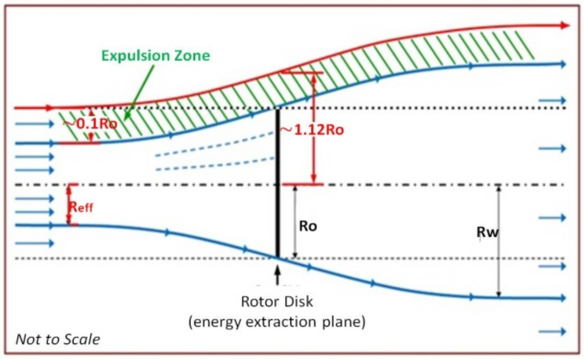

FIGURE 5. DIAGRAM SHOWING ROTOR EJECTION ZONE.

The cross sectional area of Verdant's 5m diameter turbine is $19.63m^2$, while the ejection zone has been calculated at $3.7m^2$. This gives an effective turbine area of $15.93m^2$. The profile of the East Channel of the East River is well known and for the purposes of this model is approximated to be a square channel with a constant width of 240m and an average depth of 10m.

This ratio is a constant value and does not vary with water velocity. Parameter P4 is unchanged as the turbine diameter remains 5 m. Including the rotor ejection zone, P4 = 0.0066 for the Verdant 5 m rotor in the East Channel of the East River.

P5: Blade Interaction with Fish

For fish that will be incident upon the rotor, parameter P5 provides the probability of the blade impacting the fish (at any point on its body). This quantity is determined by the speed of the fish approaching the turbine, the length of the fish, the rotational speed of the turbine blades and the angle that the fish is approaching the turbine.

The primary assumption included in this parameter is that a fish will try to avoid the turbine blades by swimming at its maximum burst speed through the rotor. Based upon the body of data collected during the RITE demonstration, it may be possible to justify some additional spatial or zonal avoidance behavior, however because there is no specific data available on the sturgeon species of interest no additional avoidance behavior is accounted for in the present model. The speed of the fish through the rotor will therefore be given only by the species maximum burst speed plus the water velocity.

Fish likely swim through the East Channel in both directions, upstream and downstream. Verdant has collected hydroacoustic data on fish movements at the RITE East Channel site which support the assumption that fish will typically be swimming with the current, especially at times of high current. From this data we have made the assumption that when the water velocity is less than the regular endurance speed for a particular species during any day, then 80% of fish will be swimming with the current and 20% against. For times when the water velocity is greater than the regular endurance speed, all fish will be swimming with the current.

While the speed of the fish approaching the turbine, the rotational speed of the turbine blades and the angle that the fish is approaching the turbine remain as originally assumed, the four years of data collected as part of the Tagged Species Monitoring plan reveals that the known lengths of tagged (likely adult) Atlantic sturgeon transiting the area range from 72 to 160 cm with an average length at tagging of 122 cm. Parameter P5 was updated from the original common length based on the literature [5] of 104 cm to 122 cm.

Swim velocities can be categorized into endurance swimming speeds and burst swimming speeds. Unfortunately swim speeds for these species are not well determined; although it can be supported that a good approximation for the burst swim speed may be taken as 4 (four) times the nominal length per second [6]. Endurance swim speed is typically assumed to be half of the burst swim speed [6]. Based on the new average length of 122 cm, an updated burst swim speed of 4.88 m/s and the associated endurance swim speed of 2.44 m/s were calculated.

P6: Fish Distribution (At Different V_W)

In the 2010 license application parameter, P6 was assumed to be P6 = 1 for all water velocities. Due to the lack of information, the model assumed an even distribution of Atlantic sturgeon at all water velocities. Based on the tagged species detections thus far, 22% of all fish detections (6 of 27) occurred completely within 45 minutes of slack tide (44% occurred completely within one hour of slack tide). As such, the water velocity was below the turbine cut-in velocity of 1 m/s for these fish and they are not at risk of blade interaction. Since the specific water velocity at every detection timestamp is not known, a conservative assumption is made that $V_W > 1$ m/s 45 minutes after all slack tides and that P6 is constant for all water velocities above 1 m/s. Evidence does suggest that very few (1 of 27) sturgeon were detected at the peak of the tide cycle ($V_W \sim 2.5$ m/s), however, P6 will be held constant for all $V_W > 1$ m/s until additional research can confirm this. These results enable this parameter to be updated from P6 = 1 to P6 = 0.78.

P7: Avoidance Behavior

Parameter 7, Avoidance Behavior, was set at P7 = 1; meaning no avoidance behavior by fish of any size at any water velocity. While it is likely that some avoidance could be appropriately included in the absence of any data, a conservative assumption for all species and size ranges was made.

Further refinements to determine avoidance behavior and angle of incidence (P5) are currently being conducted as part of a DOE funded grant to Oak Ridge National Laboratory (ORNL): *Informing a Tidal Turbine Strike Probability Model through Characterization of Fish Behavioral Response using Multibeam Sonar Output.* The study uses unique data collected by Verdant in September, 2012 as part of the Seasonal DIDSON Observation Monitoring to quantify the distribution, behavioral response, and general patterns of fish movement around an operating horizontal axis tidal turbine through computer analysis of individual fish movement. The study will quantify the number and sizes of fish as they pass through the cone of detection and encountered a single operating KHPS turbine during the period when the turbine was deployed (224 hr). ORNL will examine consecutive detections in nearly the same location that will be identified as a track of an individual fish and each track will be evaluated for general trajectory in three dimensional space (x, y, z coordinates), change in direction that result in avoidance of the turbine (i.e., change in compass direction and depth), passage through the swept area of the turbine, and swimming velocity. The objective of this study is to provide additional information to refine model parameters P5 and P7 which will be updated as appropriate.

CONCLUSIONS

This paper outlines the KHPS-Fish Interaction Model and provides a summary of the assumptions used, the methods applied, and recent monitoring data collected to calculate the probability of a blade strike with respect to a single turbine operating at the RITE Project on the Endangered Species Act listed species Atlantic sturgeon in the East River, New York. While the investigation of fish interactions with operating KHPS turbines in terms of temporal and spatial abundance has been underway at the RITE site since 2007, the assumptions used in this model have attempted to take a conservative view. Data collected from environmental monitoring studies conducted by Verdant has as intended been used to refine the body of knowledge in this area and improve the predictions made by this model.

Three of the seven KHPS-Fish Interaction Model parameters, P3: Fish Distribution (East vs. West Channel), P5: Blade Interaction with Fish and P6: Fish Distribution (At Different V_W) have been updated based on data collected at RITE from tagged Atlantic sturgeon. Initially, based mostly on literature and assumptions, Verdant originally estimated the probability of an Atlantic sturgeon getting struck by a turbine blade to be less than 0.1% (P_{Strike} = 0.086%). Using updated parameter values based on data collected at the site from 2011 to 2014, the probability of a turbine-sturgeon interaction is still below 0.1% and is actually lower using recently collected data (P_{Strike} = 0.032%).

Furthermore, the method of establishing a KHPS-Fish Interaction Model using conservative assumptions, and updating the model parameters with collected monitoring data is a sound adaptive management approach for the evolving marine renewable energy industry to confirm environmental compatibility.

ACKNOWLEDGEMENTS

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