ANL/EVS-17/6

BEHAVIORAL RESPONSES OF FISH TO A CURRENT-BASED HYDROKINETIC TURBINE UNDER MUTLIPLE OPERATIONAL CONDITIONS: FINAL REPORT

Environmental Science Division

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Prepared for the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy.

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1 INTRODUCTION AND PROJECT GOALS AND OBJECTIVES

There is significant interest in the interaction of aquatic organisms with current-based marine and hydrokinetic (MHK) technologies. Determining the potential impacts of MHK devices on fish behavior is critical to addressing the environmental concerns that could act as barriers to the permitting and deployment of MHK devices. To address these concerns, we use field monitoring and fish behavior models to characterize the behavioral responses of fish to MHK turbines and infer potential stimuli that may have elicited the observed behavioral changes.

Monitoring fish interactions with hydrokinetic turbines allows one to consider the magnitude and ecological significance of several potential behavioral risks that have been identified for tidal turbines including the disruption of migratory behavior and food acquisition (Boehlert and Gill, 2010; Frid et al. 2011), behavioral attraction to the device (Boehlert and Gill, 2010; Frid et al. 2011), and avoidance of preferred habitat occupied by the device (Boehlert and Gill, 2010; Polagye et al. 2010; Hammar et al. 2013; Broadhurst et al. 2014). These risks can be assumed to be minimal if the observed fish movement patterns suggest the turbine has only small and temporary effects on normal swimming patterns or fish distribution within a channel.

Blade strike has also been identified as a primary concern associated with the operation of tidal turbines (U.S. Department of Energy, 2009). There have been multiple blade strike studies conducted in laboratory settings using fish exposed to turbines in a confined channel. While these studies indicate fish can avoid blade strike if they swim through a turbine, they do not address what proportion of fish will avoid the turbine completely while swimming through a natural channel. This question is critical in assessing the actual risk of blade strike (Hammar et al. 2015). Earlier work in our study area (Viehman and Zydlewski, 2014) partially addressed this data gap using dual-frequency identification sonar (DIDSON) monitoring of fish movement within a few meters of the Ocean Renewable Power Company (ORPC) turbine generating unit (TGU). The work described in this report further expands the spatial scale of analysis by using field surveys, hydrodynamic modeling, and behavioral simulations that cover fish response to the turbine hundreds of meters upstream and downstream.

The overall goal of this project was to monitor fish movements around an ORPC TGU, use the data to characterize the magnitude and ecological significance of behavioral responses, and investigate the potential variables driving the observed behavioral responses. This multi-year project spanning fiscal years (FYs) 2013–2016 was a collaboration between Principal Investigator Mark Grippo (Argonne National Laboratory), Dr. Andrew Goodwin (U.S. Army Engineer Research and Development Center), Dr. Gayle Zydlewski (University of Maine), and Prof. Huijie Xue (University of Maine). This report describes our activities to (1) collect hydroacoustic fish survey data, (2) produce high-resolution simulated flows for Cobscook Bay for the survey period, and (3) examine whether fish responded to visual and auditory stimuli generated by the turbine as well as natural and turbine-related changes in flows within the channel.

2 METHODS

The study was conducted in Cobscook Bay, Maine (Fig. 1), which is characterized by strong currents and large, daily tidal fluctuations. Over the course of the study, two tidal turbines were deployed. The bottom-mounted ORPC TidGen® power system (TidGen) was the original focus of the study plan developed in 2013. However, following preliminary data collection, in spring 2013, the TidGen foils and generator were removed from Cobscook Bay. The study was delayed until 2014 when the TidGen was replaced with the OCGen® power system (OCGen).

The OCGen was moored to the seafloor with gravity anchors and cables, as illustrated in Figure 2. The entire OCGen system (float and foils) was 5.1 m high and 19.7 m long. The distance of the OCGen to the seafloor varied with the tidal stage, ranging from 5.9 m to 8.4 m during maximum flow. The bottom-mounted, solid steel frame of the TidGen, which was 31.2 m long and 15.2 m wide, remained on the seafloor during the OCGen survey period. The center location of the OCGen was about 100 m seaward from the center location of the TidGen bottom support frame.

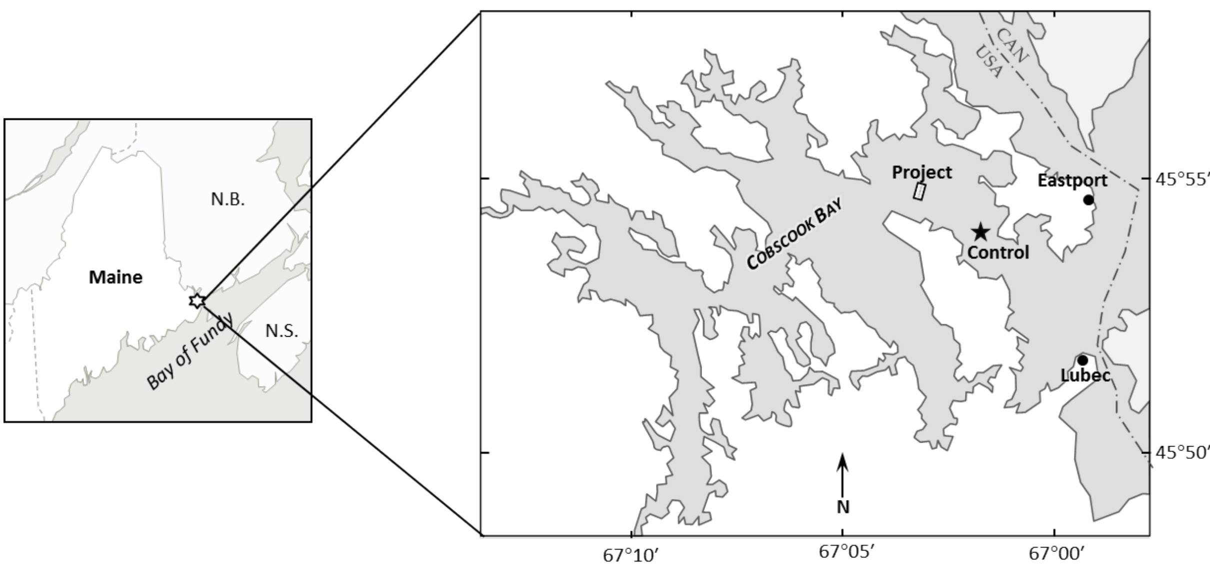


FIGURE 1 Map of Cobscook Bay, Maine, with locations of the project and control sites for fish-MHK interaction research (Source: Shen et al. 2016)

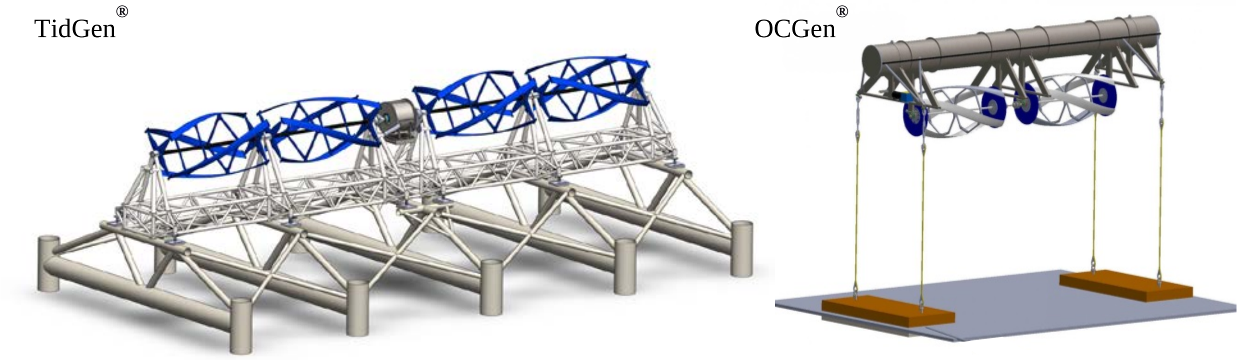


FIGURE 2 Schematic representation of the TidGen (9.5×31.2×15.2 m) and OCGen (5.1×19.7×5.3 m) power systems that ORPC installed in outer Cobscook Bay, Maine. Only the bottom mount of the TidGen system was present during the 2014 mobile hydroacoustic fish surveys over the OCGen power system (Source: Shen et al. 2016).

2.1 Mobile Hydroacoustic Fish Surveys

For the field component of this project, we conducted mobile hydroacoustic surveys to determine the position of fish in relation to the OCGen. Mobile, down-looking hydroacoustic fish surveys were initiated in late July 2014 after the OCGen was deployed (Table 1). During each survey period, the mobile hydroacoustic surveys were conducted at typically more than 100 transects covering between 200 m upstream and 200 m downstream of the OCGen, allowing the observation of fish density upstream, over, and downstream of the OCGen. Control transect surveys were also conducted on both sides of the OCGen. Only data collected during flood tides were used in the analysis (Fig. 3) because the TidGen bottom support frame could potentially affect fish behavior as the fish approached the OCGen during ebb tides. Because the seafloor sloped upward when the boat approached the device during the flood tide, fish tracks deeper than the dashed line (Fig. 3) were excluded to ensure equal amounts of water were sampled during the length of a transect.

Following hydroacoustic data collection, the data were processed into fish positions, densities, tracks, or a combination of these. Detected fish tracks were manually inspected for accuracy. A complete description of the hydroacoustic surveys and data processing is provided in Shen's et al. (2016). The survey transect was binned into 10-m segments, and the relationship between the number of fish tracks in the 10-m bin (sum of all surveys) and the distance to the turbine was determined using a simple linear regression which was fitted with the data from 10 m to 140 m upstream of the OCGen. Turbine avoidance was indicated by a decrease in the number of fish tracks with decreasing distance to the OCGen.

TABLE 1 2014 Dates and Conditions for Mobile Hydroacoustic Surveys

Start time	End time	Tidal pattern	Lunar cycle	Turbine	Number of transects
7/29/2014	7/31/2014	Flood	Neap tide	Free-spinning	100
7/29/2014	7/31/2014	Ebb	Neap tide	Free-spinning	98
7/27/2014	8/3/2014	Flood	Neap tide	Free-spinning	158
8/13/2014	8/16/2014	Flood	Spring tide	Static	128

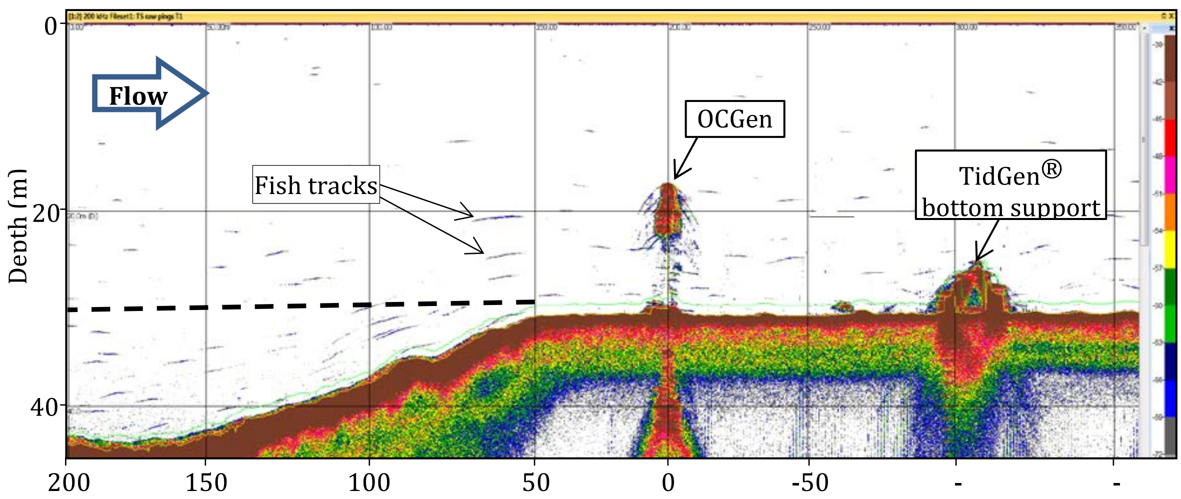


FIGURE 3 A mobile transect over the OCGen power system and the TidGen bottom support frame during a flood tide (Source: Shen et al. 2016)

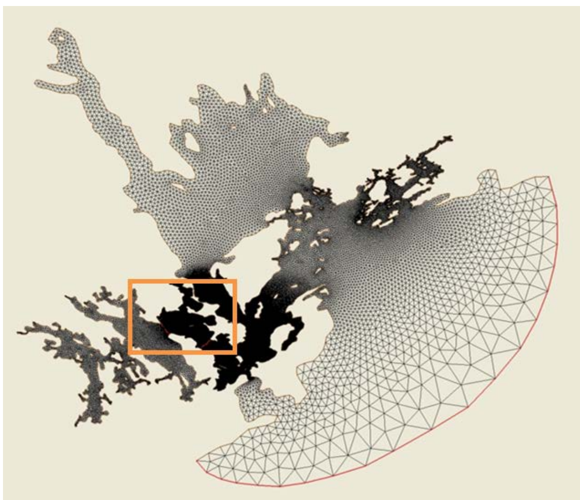
After the surveys were completed, we discovered that the OCGen was free-spinning (rotating but not generating power) during the surveys conducted from July 29 to August 3 and that during the August 13 to August 16 survey, the turbine was in a static operational condition and was not spinning (Table 1). As described in Section 2.4, this operational variation allowed us to examine the relationship between fish behavior and the operational status of the turbine.

2.2 Hydrodynamic Modeling of Flows in Cobscook Bay

Using output from two separate hydrodynamic models, flow in the study area was visually simulated to qualitatively assess the magnitude of the hydrodynamic disturbance generated by the OCGen. Using a Finite-Volume Community Ocean Model (FVCOM), high-resolution simulations of flow near the OCGen were generated for the time periods corresponding to the hydroacoustic fish surveys. The objective was to provide simulations of hydrodynamic fields with sufficient detail for the Eulerian-Lagrangian-Agent Method (ELAM) fish behavior analysis; the ELAM depends on accurately capturing not only the flow field (including flow velocities, turbulent kinetic energy), but also the derivative field (including flow velocity gradients, flow acceleration).

A high-resolution FVCOM coastal circulation model (approximately 5 m spatial resolution) was nested in the existing Cobscook-Passamaquoddy model with 20 m resolution of outer Cobscook Bay (Fig. 4a). The location of the OCGen is shown in Figure 4b. The size of the high-resolution area was based on the preliminary estimated area of flow modifications caused by the OCGen, which was estimated to reach hundreds of meters downstream as the flow field leaves the turbine, and tens of meters upstream where the flow field approaches the turbine. The high-resolution area covered the mobile hydroacoustic survey area, with the high-resolution mesh blending into the existing 20-m mesh resolution outside this region. The actual turbine dimensions and the dimensions used in the model are shown in Figure 5. All model runs were conducted on the Argonne Laboratory Computing Resource Center's Blues or Fusion computing clusters.

The FVCOM was designed to follow the operational specification of the OCGen. During the first three fish survey periods (July 29–August 10, 2014), the FVCOM simulated a fully functioning OCGen. Consequently, during slack tide models, drag reduced to 0.3701, which represents a free-spinning, non-power generating OCGen. When the water flow speed exceeded 1 m/s, the OCGen began generating power and the FVCOM drag coefficient became 2.237. The buoyancy floats above the turbine had a continuous drag coefficient of 0.776. The TidGen bottom mount was also accounted for in the model. However, after the model runs were completed, we discovered that the OCGen did not generate any power during the three fish survey periods. Instead, the OCGen was free-spinning from July 29 to August 10, at which point the OCGen blades stopped rotating and remained static. Because the OCGen was free-spinning and never generated power before August 10, the modeled drag of 2.237 was likely never realized; instead, the OCGen had a free-spinning drag coefficient of 0.3701 for all flow conditions. Therefore, the real-world wake was smaller than the FVCOM-modeled wake prior to August 10 when flow speed exceeded 1 m/s. Model runs were not conducted for the non-rotating, static condition that existed after August 10, because there was no drag coefficient available for this condition. This motionless state is not a normal operational condition, and therefore is not relevant to assessing behavioral changes in fish.



a.)

b.)

FIGURE 4 The Cobscook-Passamaquoddy model regional mesh including Cobscook Bay, Penobscot Bay, and part of the Bay of Fundy on the US-Canada border. (a) The red line on the far right represents the oceanic boundary, and the orange box represents the study area where the OCGen was deployed. (b) A high-resolution, close-up of Cobscook Bay and the location of the turbines, as shown by the orange circle. Figure provided by Shivanesh Rao, University of Maine.

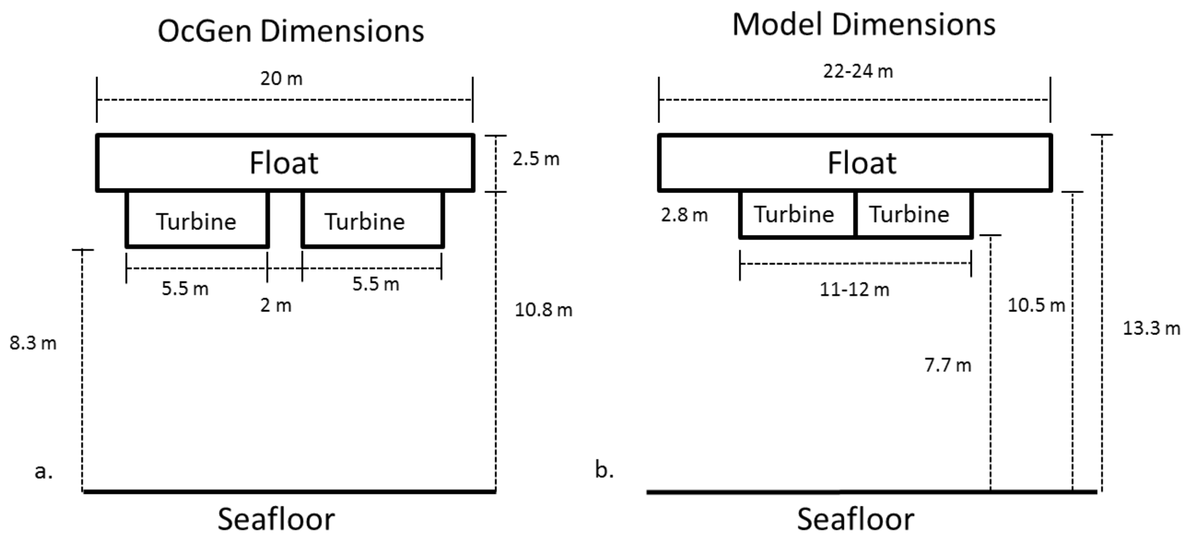


FIGURE 5 (a) The OCGen power system dimensions and location in the water column and (b) the model equivalent of the OCGen dimensions

A second hydrodynamic model for Cobscook Bay was developed by Sandia National Laboratory using its Environmental Fluid Dynamics Code (SNL-EFDC). Because different hydrodynamic models have their own strengths and weaknesses, it is advantageous to compare how different modeling methods impact ELAM analysis results. In addition, SNL-EFDC has wide familiarity within the MHK industry and is used by ORPC.

The SNL-EFDC model used a rectangular domain that extended the model's domain 830 m in the streamwise direction (or the direction of net tidal flow) and 320 m in the cross-stream direction. The domain consisted of 10,624 horizontal cells measuring 5×5 m^2 and 11 vertical layers. Turbine dimensions and thrust coefficients used in the SNL-EFDC model were the same as those used in FVCOM.

2.3 ELAM

Individual-based models (IBMs) of behavior are commonly used to assess the impacts of hydraulic modifications on fish populations. However, many existing IBMs are data-intensive and unpractical for meeting the needs of MHK developers. To address this R&D challenge, we applied the comparatively simple ELAM model to simulate fish experience in a flow field around the OCGen. The ELAM model was developed by the U.S. Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC) (Goodwin et al. 2014), and was traditionally used in environmental applications for conventional hydropower operations (Goodwin et al. 2007); this was the first application of the model to MHK technology. The ELAM model integrates the hydroacoustic fish position data (Section 2.1) with hydrodynamic modeling simulations (Section 2.2), providing a mechanistic explanation of the observed fish behavioral responses to turbine-related and natural changes in the flow field. Using this information, the ELAM model can simulate fish movement trajectories that characterize fish behavior before, during, and after they encounter a turbine.

There were four overall tasks required to develop the ELAM model: (1) collection of mobile and stationary hydroacoustic data on fish in Cobscook Bay and the processing of this data into fish tracks and/or density information (Section 2.1), (2) development of high-resolution hydrodynamic modeling for Cobscook Bay for periods when fish data are available (Section 2.2), (3) integration of hydrodynamic patterns and fish hydroacoustic data, and (4) simulation of fish movements under various behavior rules.

An ELAM analysis is executed according to the conceptual model in Figure 6. ELAM analysis begins with identifying scenarios and data integration. Scenario identification is an important step, yet is rarely straightforward. Scenarios must have sufficient real-world observations along with hydrodynamic model representations of what the field flow conditions were at the time of an observation. We then synchronized the fish tracks from the hydroacoustic monitoring within the simulated flows corresponding to that survey period. Following the conceptual model in Figure 6, we then evaluated the role of passive behavior and volitional behavior on the densities of simulated fish approaching the turbine, by comparing these simulations to the observed changes in fish track density.

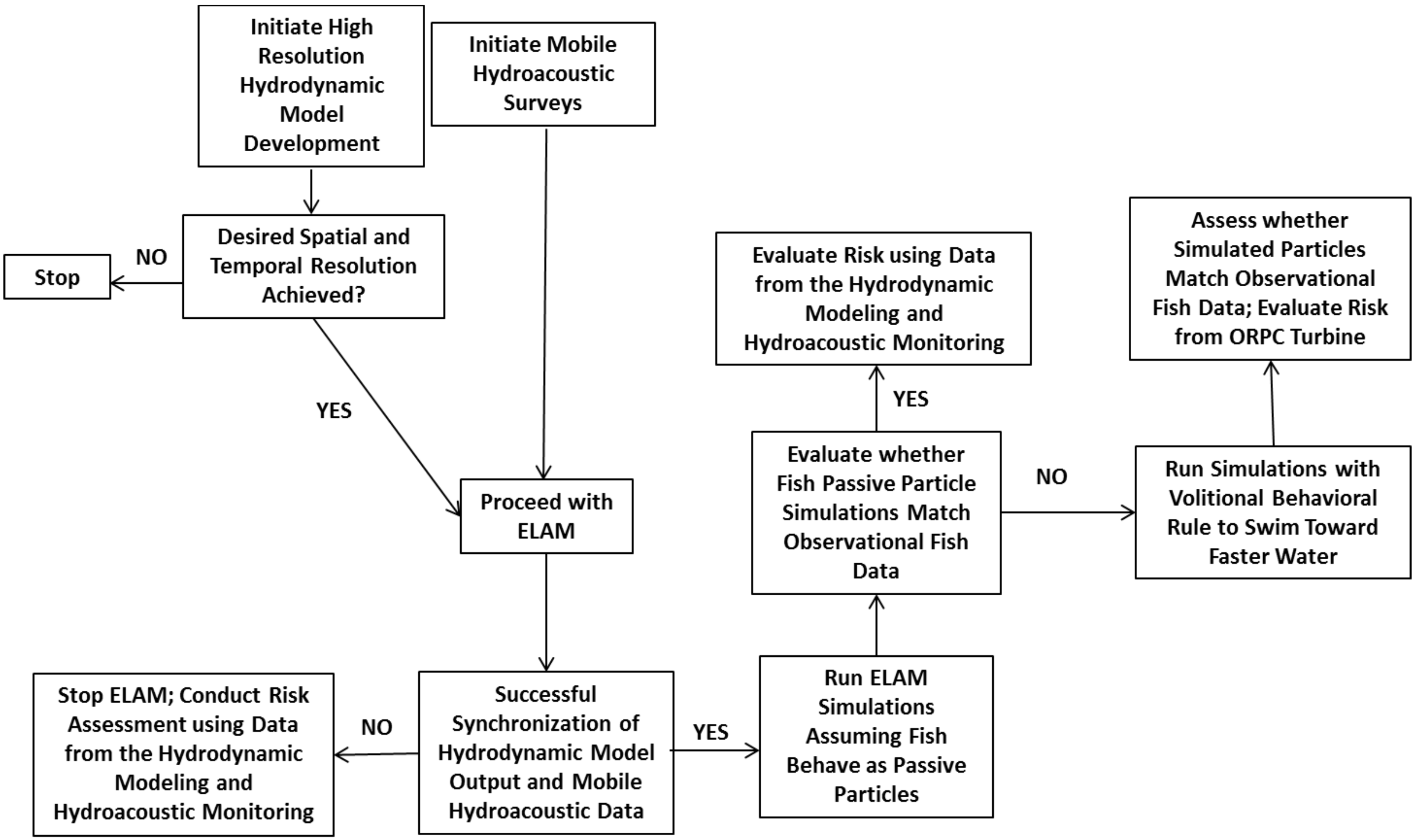


Figure 6 Conceptual model of ELAM analysis. This proposed work effort will evaluate only "direct" response behaviors to hydrodynamics.

2.4 Analysis of Mechanisms for Behavioral Changes

We investigated fish behavior under different environmental and operational conditions in order to test which stimuli were associated with observed behavioral changes. We examined fish behavior in relation to three potential stimuli: (1) natural and turbine-related flow patterns in the channel, (2) noise generated by the turbine, and (3) visual stimuli generated by the turbine. The analyses were not intended to conclusively demonstrate causation, but rather to determine whether the data supports these environmental stimuli as potential explanations for any changes in fish density along the survey transects.

The relationship between the number of fish tracks and the distance to the turbine was used as the metric of behavioral change (Section 2.1). The significance of turbine-associated visual stimuli was investigated by examining differences in fish behavior between fish survey data collected during the day and data collected at nighttime. The turbine would presumably be visible to fish at a greater distance during the daytime compared to night. Therefore, differences in avoidance behavior between the two periods would indicate a visual stimuli effect. Fish response to turbine-generated noise was investigated by examining differences in fish behavior between data collected while the turbine was freespinning (July to early August 2014) versus when it was static (mid-August 2014). Based on prior acoustic monitoring of the TidGen (ORPC, 2014), we assumed that the OCGen would produce significantly less noise when static compared to when it was freespinning. The relationship between track density and distance to the turbine was tested using regression analysis.

Fish respond to hydrodynamic forcings. Hydrodynamic stimuli in Cobscook Bay could result from not only natural flow and channel morphology, but also from disturbance to the flow field generated by the OCGen. To assess the latter, the hydrodynamic model output described in Section 2.2 was used to qualitatively assess the magnitude of the hydrodynamic disturbance generated by the OCGen. The ELAM model was used to assess whether natural flow patterns were the primary influence on fish swimming behavior. Specifically, we tested whether assigning behavioral rules in which the simulated fish followed natural velocity changes within the channel would result in fish density distributions that matched the patterns in the hydroacoustic fish track data. The analysis directly addressed the question of whether natural flows were the cause of the observed avoidance. If the fish did not display the same density patterns as in the field-based data, we would have further confirmation that the turbine itself was the source of the observed behavioral patterns.

Using the ELAM model, we released simulated particles 700 m upstream of the OCGen. Seven-hundred meters was chosen to more realistically simulate the actual experience of fish while at the same time maintaining a manageable model run time. The particles were not released from a central location, but rather randomly across the channel from bank to bank (Figure 7). The released particles were coded to follow one of two decision rules: (1) no volitional behavior (individuals resemble passive particles) and (2) volitional behavior in which fish swim toward faster water. For rule 2, multiple swim speeds ranging from 0.05 to 0.25 were evaluated. A swim speed of 0.1 m/s would best approximate the actual swimming speed of the pelagic fish in Cobscook Bay (Gayle Zydlewski, personal communication). Modeling fish with greater swimming speed allowed the greater expression of volitional behavior, because the fish is better able to resist the prevailing current if it chooses to do so.

To see how fish density distribution changed with distance from the turbine, we then quantified fish density distributions at 25m intervals within a rectangle that extended three hundred meters out from the OCGen (Figure 7). Densities were calculated for multiple rectangle widths (8, 16, 24, and 32 m) which covered the approximate width of all of the hydroacoustic field survey tracks (Figure 7). The comparison of ELAM-generated fish densities and observed fish densities was conducted qualitatively because methods are still lacking for rigorous quantitative comparisons that account for underlying idiosyncrasies between field-monitored and modeled-trajectory data.

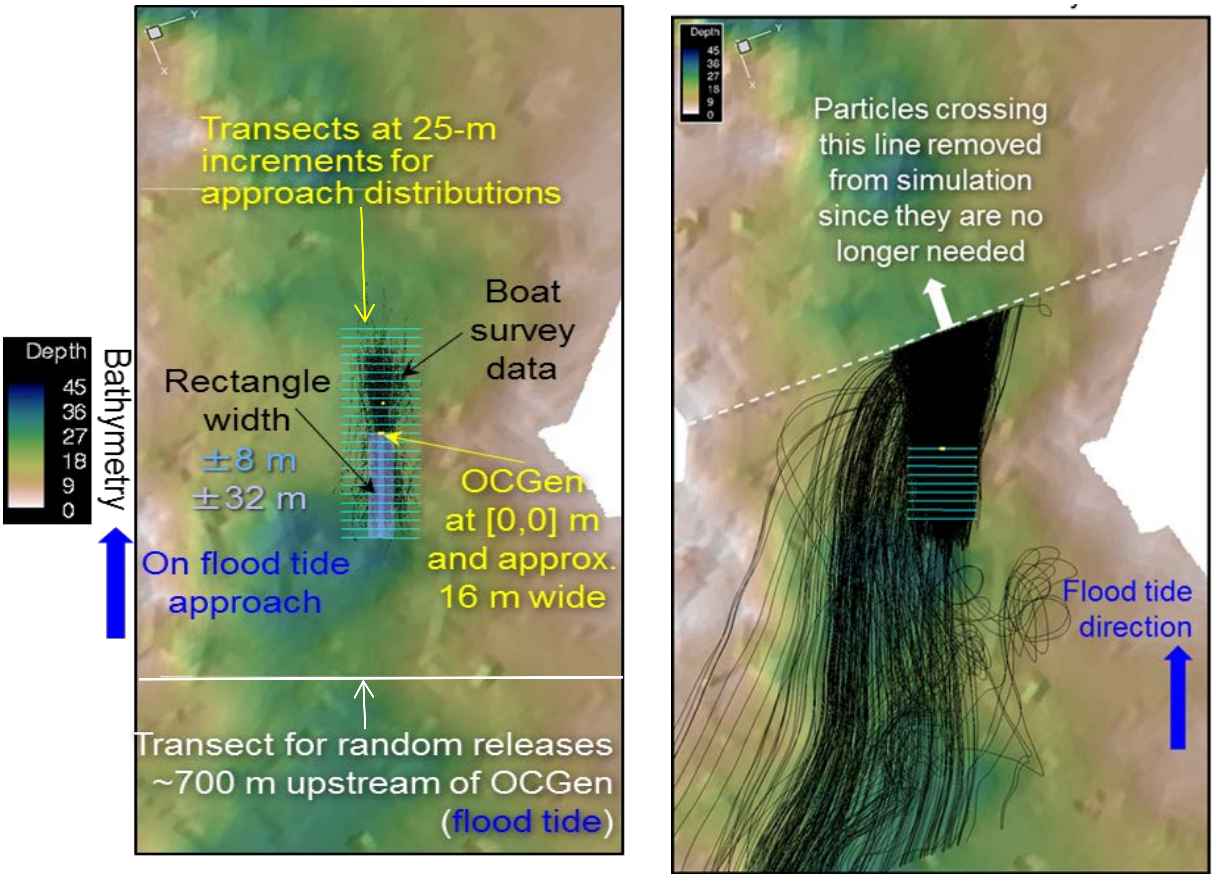


Figure 7. Location of ORPC turbines and survey transects, random fish particle releases, and the transects at which fish density distributions were calculated.

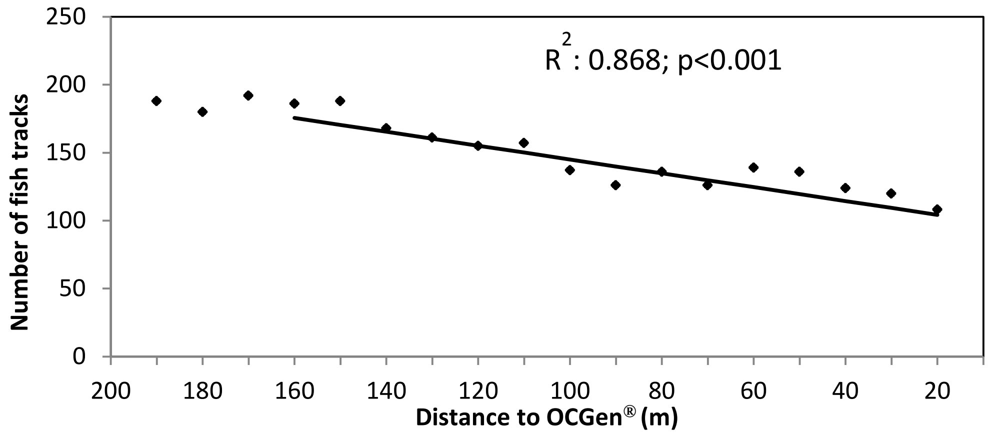
3 RESULTS

3.1 Hydroacoustic Fish Surveys

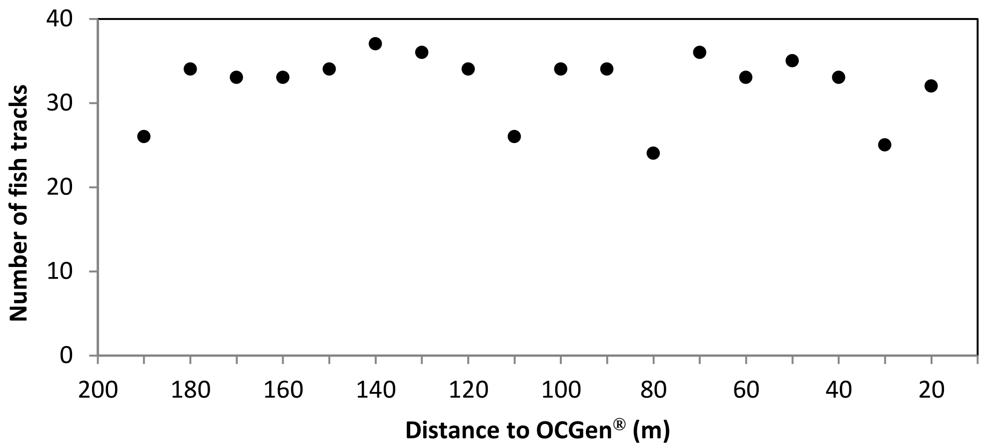
When flood tide surveys conducted under the freespinning condition were combined, there was a significant negative relationship between the number of fish tracks within the 10-m distance bins and the distance to the OCGen ($y = -0.5093x + 103.78$; $R^2 = 0.86$). The number of fish tracks began decreasing approximately 140 m upstream of the OCGen (Fig. 8a), and there was a 37.2% (95% CIs: [21.8%, 49.4%]) decrease in the number of fish between 140 m and 10 m upstream of the OCGen. The significant decrease in fish tracks approaching the spinning turbine was found for both daytime ($R^2 = 0.7402$; $p<0.001$) and nighttime ($R^2 = 0.7648$; $p<0.001$) surveys, and the decline in fish tracks began at approximately 140 m from the turbine during both day and night (Figs. 9a and 9b). No relationship between the number of fish tracks and the distance to the OCGen was found for control transects (Fig. 8b) or control transects parsed by day (Fig. 9c) or night (Fig. 9d). However, it should be noted that the number of control transect surveys was less than the number turbine surveys.

To examine whether fish avoided the turbine using vertical or horizontal movements, we examined the proportion of total fish in the water column that were located between 0 and 10 m (the approximate depth of the OCGen) (Fig. 8c). The proportion of fish near the bottom showed little variation across the survey transect indicating the decrease in the number of fish tracks between 140 and 10 m is the result of a change in horizontal rather than vertical position as they approach the device.

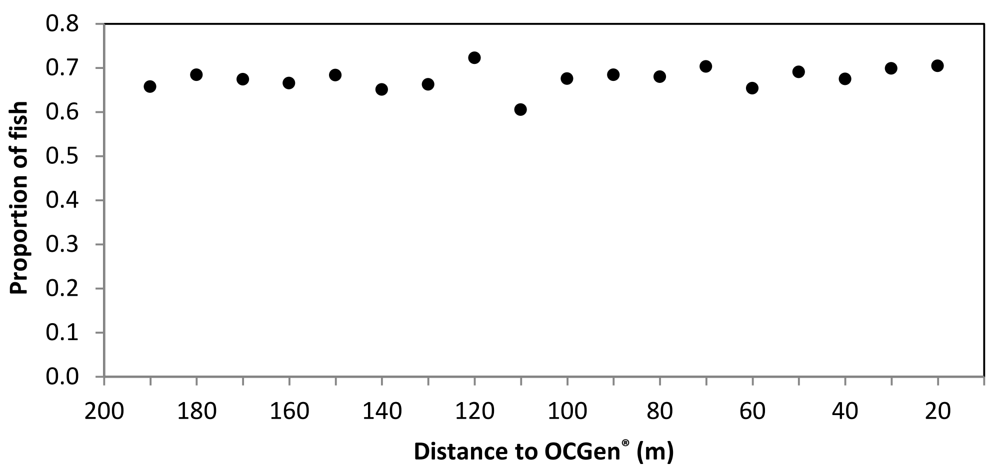
For surveys conducted in mid-August, when the turbine was static, there was a weak relationship ($p=0.0357$) between the number of fish tracks and the distance to the OCGen for all turbine transects combined (Fig. 10a). This weak relationship was present in daytime survey data ($p=0.0154$), but not for nighttime survey data (Fig. 10a). A similarly weak relationship was observed at control transect surveys conducted during the static turbine period for nighttime surveys (p=0.02557), but not daytime surveys ($p=0.3031$) (Figs. 10b and 10c).



a)

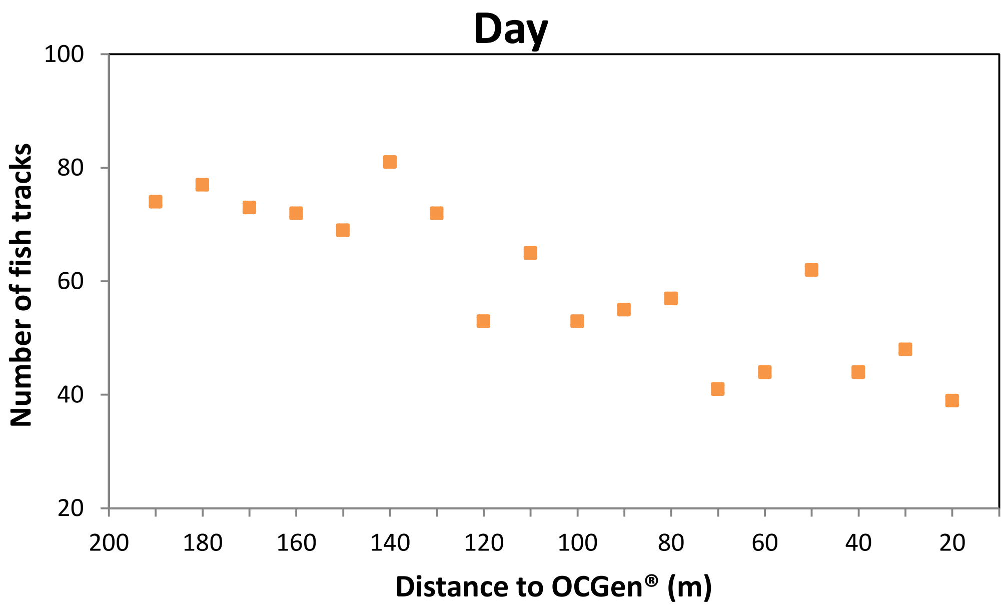


b)

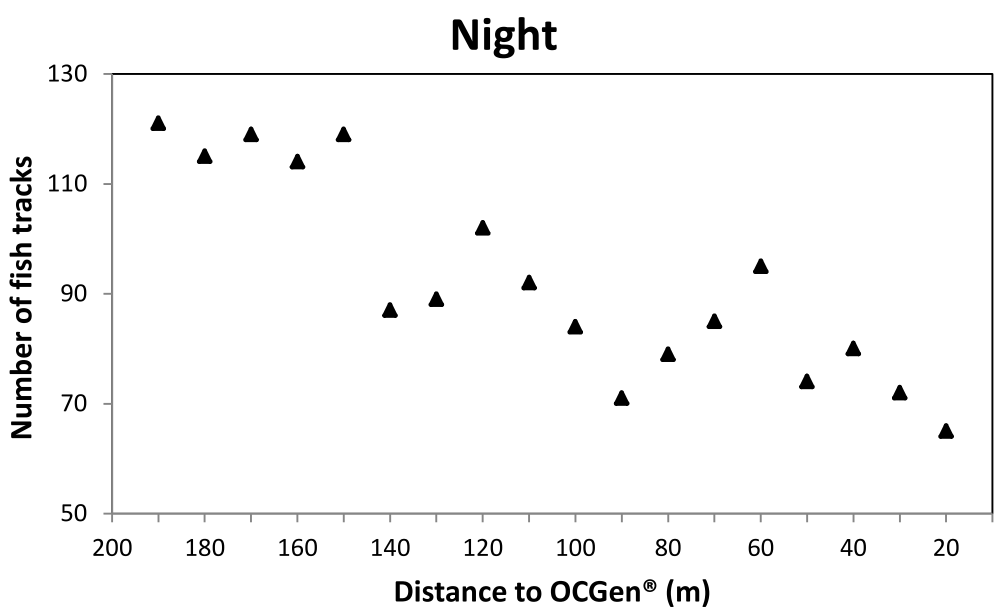


c)

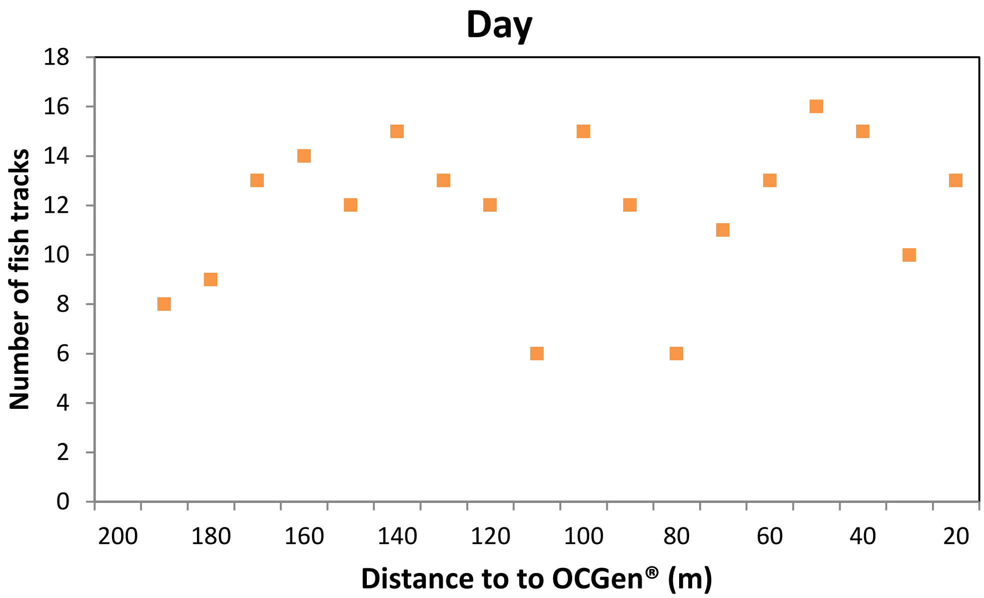
FIGURE 8 (a) The relationship between the number of fish tracks and the distance of the track to the OCGen and (b) the number of fish tracks versus the distance to the theoretical location of the OCGen at control transects. The data points represent the total number of fish tracks (sum of all surveys) in each of the 10 m distance intervals between 200 and 20 m from the OCGen. Figure 8c shows the proportion of fish at the depth of entire OCGen (0-10 m above the seafloor) relative to fish in the entire water column (Source: Shen et al. 2016).


Day
100
80
60
40
20
Number of fish tracks
200
180
160
140
120
100
80
60
40
20
Distance to OCGen® (m)

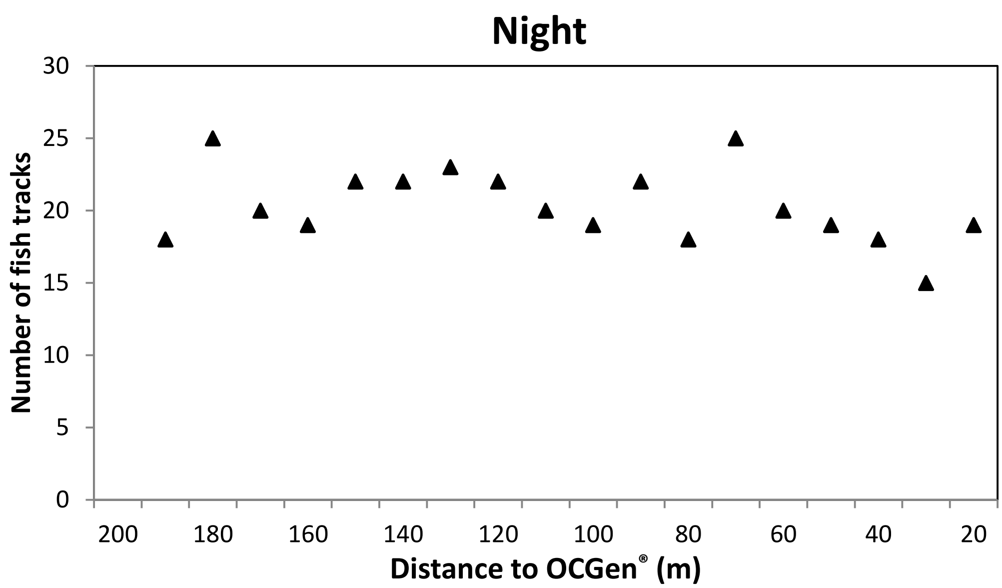
a)


Night
130
110
90
70
50
Number of fish tracks
200
180
160
140
120
100
80
60
40
20
Distance to OCGen® (m)

b)

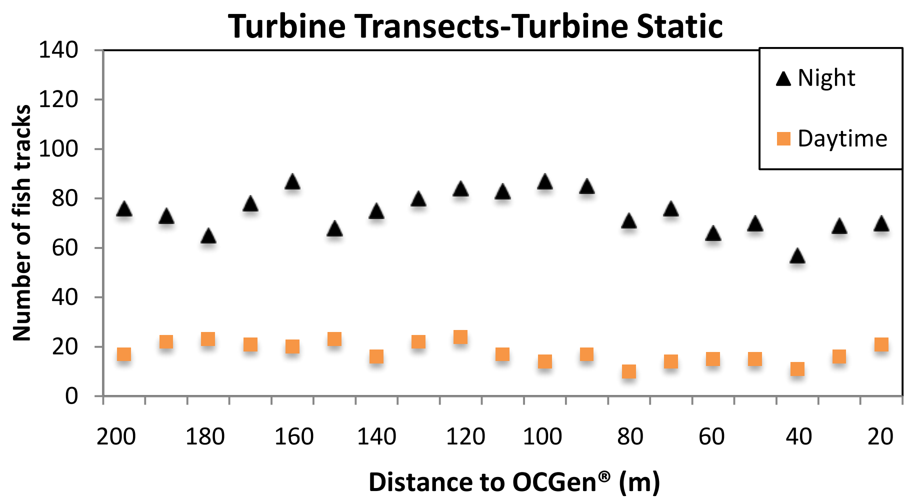


c)

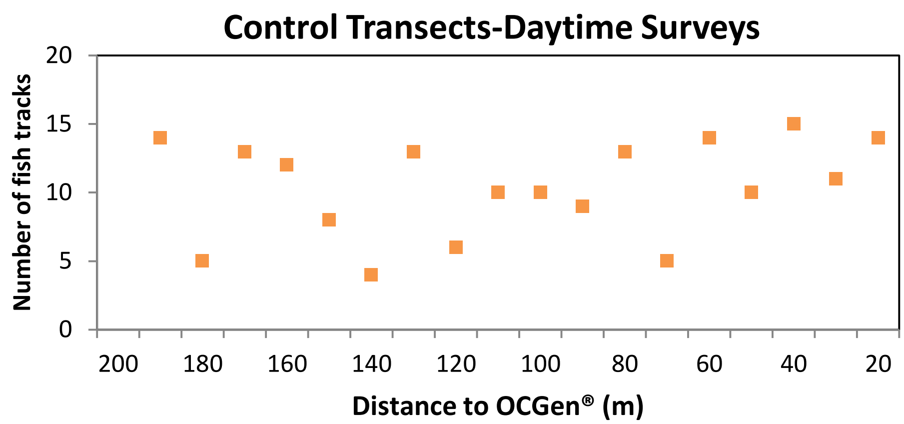


d)

FIGURE 9 The relationship between the number of fish tracks and the distance of the track to the OCGen when the turbine was spinning during (a) daytime and (b) nighttime surveys and (c and d) at control transects. The data points represent the total number of fish tracks (sum of all surveys) in each of the 10 m distance intervals between 200 and 20 m from the OCGen.



a)



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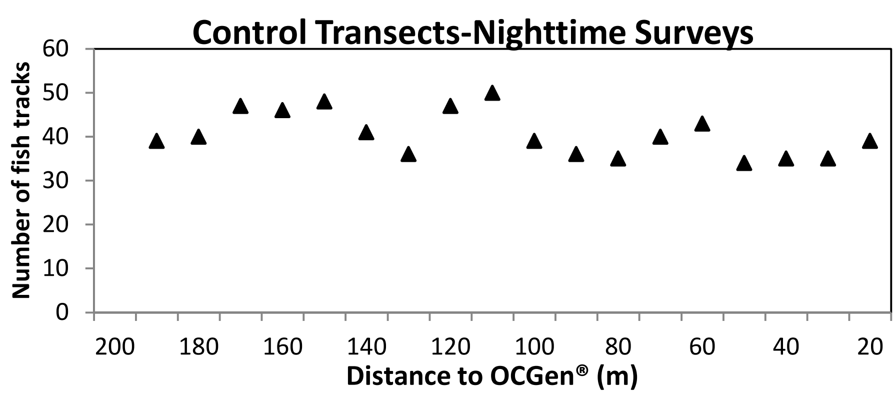


c)

FIGURE 10 The relationship between the number of fish tracks and the distance of the track to the OCGen when the turbine was static (a) during daytime and nighttime at turbine transects and (b and c) at control transects. The data points represent the total number of fish tracks (sum of all surveys) in each of the 10 m distance intervals between 200 and 20 m from the OCGen.

3.2 Hydrodynamic Modeling

3.2.1 FVCOM Model

To assess the accuracy of the FVCOM output, model results were compared to the surface elevations from two Acoustic Doppler Current Profiler (ADCP) devices latterly positioned approximately 74 m from the OCGen. The ADCP devices recorded the elevation and velocity of the flow, and surface elevations were extracted from the model cell corresponding to the ADCP locations, referred to as “Lubec” and “Goose” (Fig. 11). We also compared the model surface elevations with those recorded by the National Oceanic Atmospheric Administration (NOAA) tidal gauge at Eastport, which was located farther away from the turbine location. The modeled surface elevation and the elevation measured by the ADCPs aligned closely (Fig. 11). The modeled and NOAA tidal gauge surface elevations at Eastport also matched closely, with only a slight phase difference between the two. This comparison shows that the model reasonably approximated the volume flux entering and exiting the location of the turbine in Cobscook Bay.

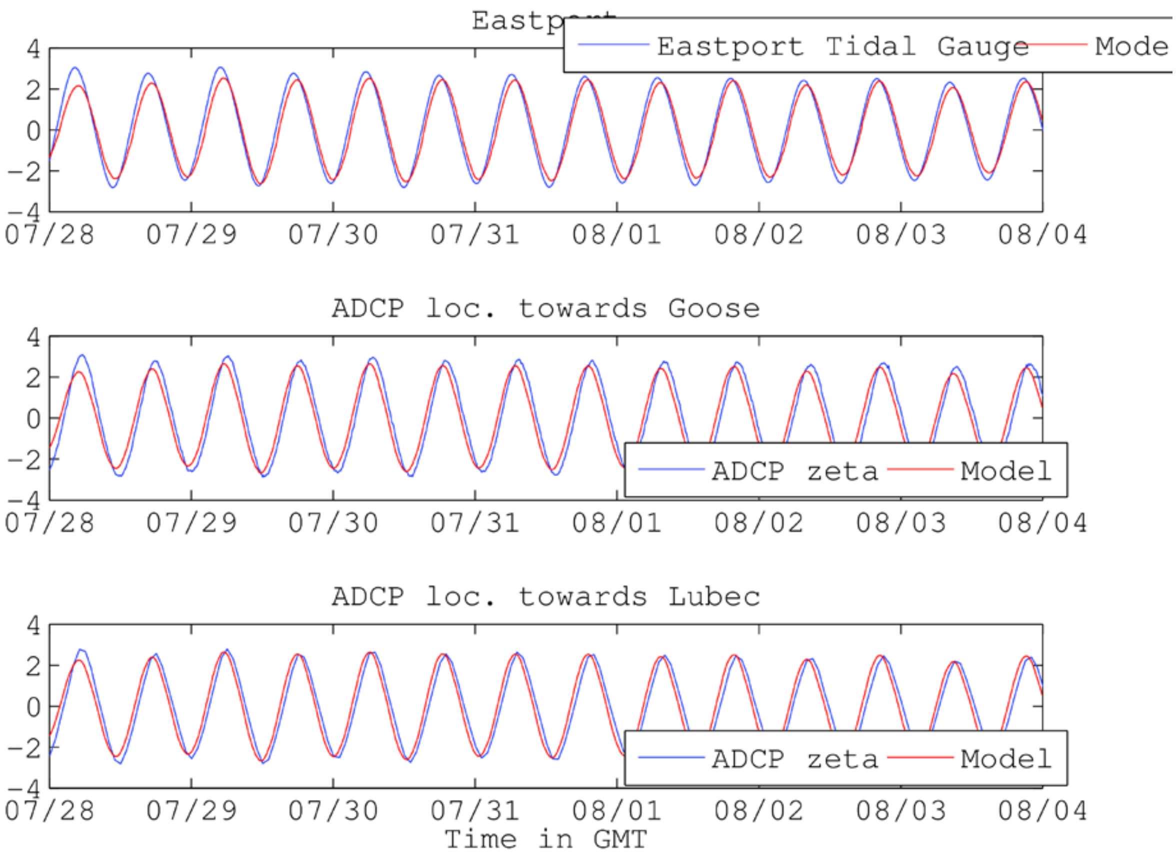


FIGURE 11 Comparison of FVCOM output and tidal elevation measured by the study's ADCP devices and a NOAA tidal gauge. The tidal elevations at the three locations closely match the measurements from the ADCP and tidal gauge.

3.2.2 SNL-EFDC Model

Water levels and depth-averaged velocity magnitudes from the calibrated model closely matched ADCP measurements (Figs. 12 and 13). Modeled depth-averaged velocity magnitudes were on average within 0.07 m/s of measured values, which is within the typical measurement errors for an ADCP.

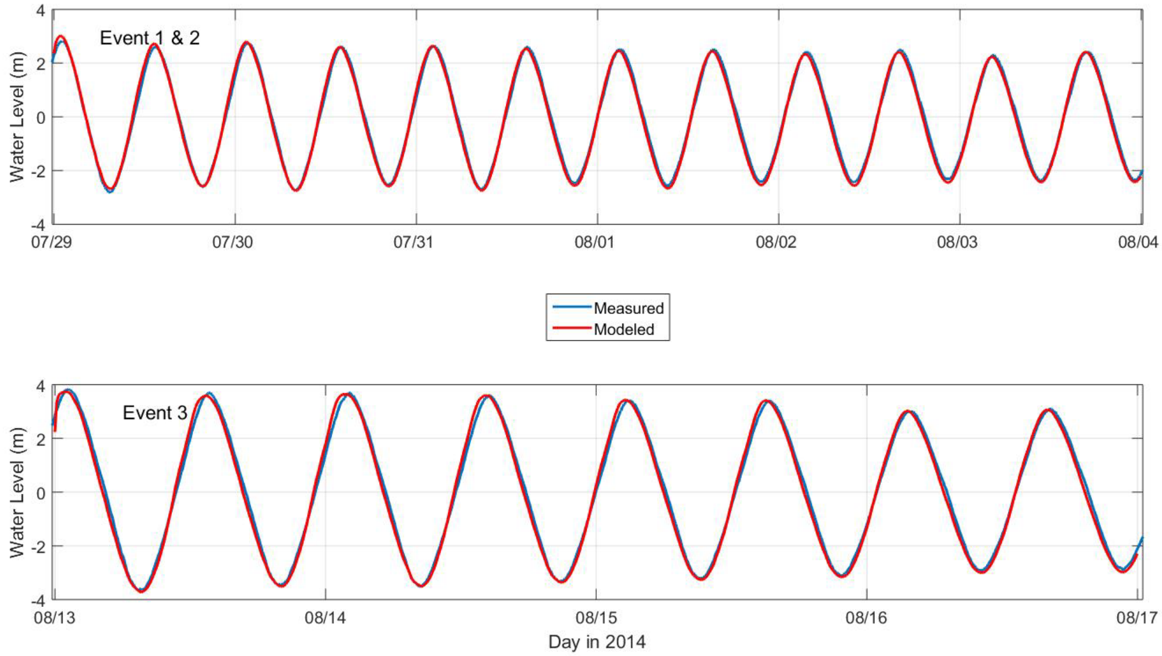


FIGURE 12 Comparison of the SNL-EFDC modeled water levels to measured water levels at the ADCP location for all sampling events

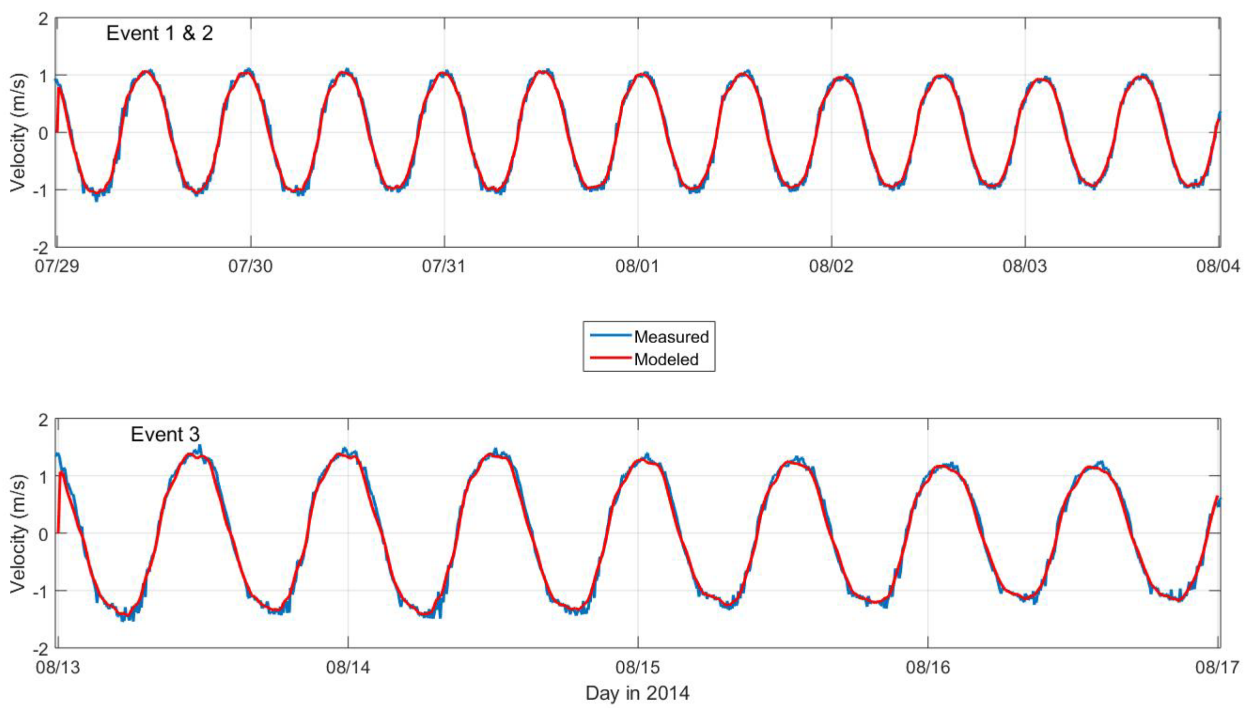
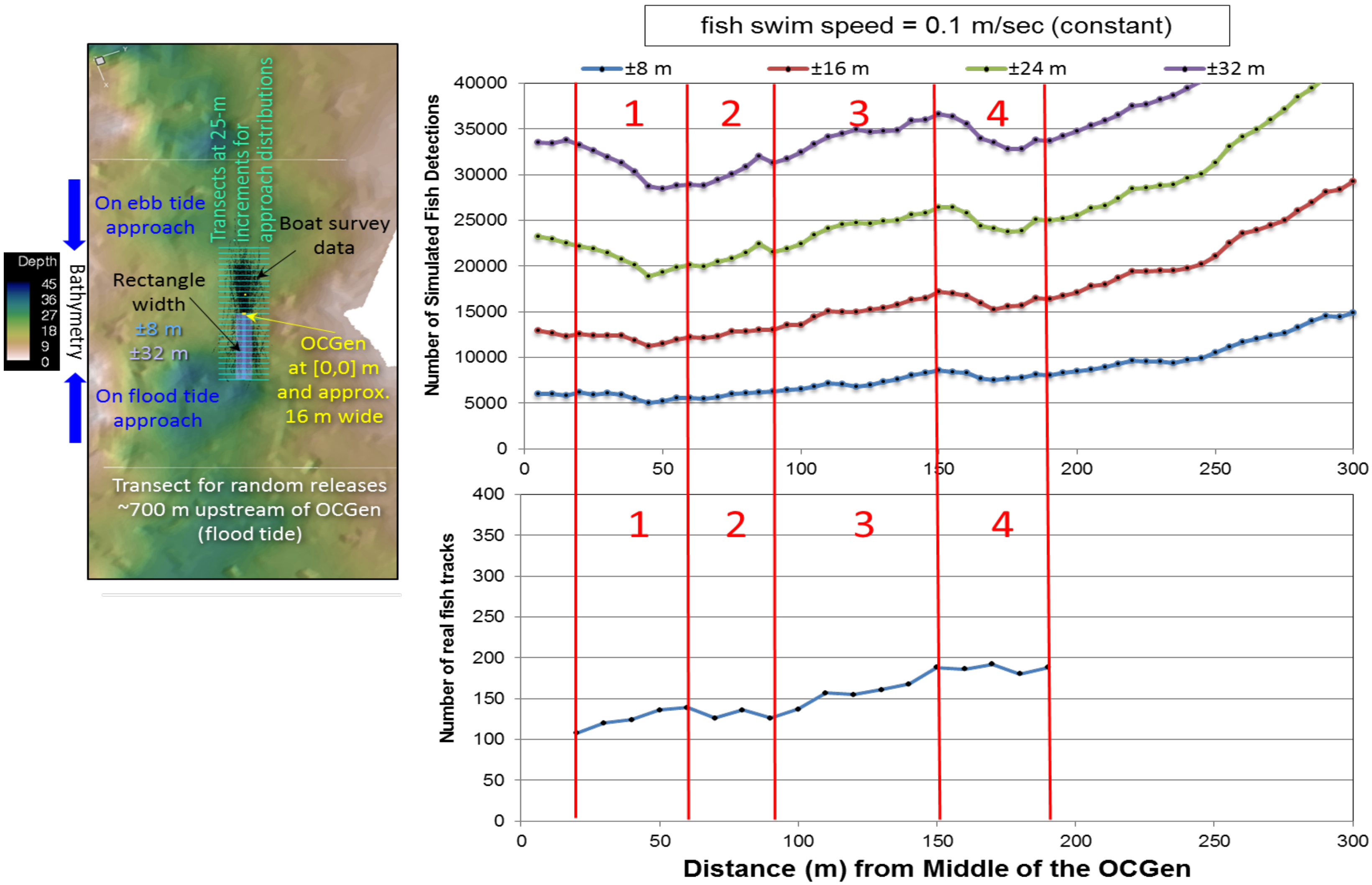


FIGURE 13 Comparison of SNL-EFDC modeled depth-averaged velocity to measured depth-averaged velocities at the ADCP location for all sampling events

Both the FVCOM and SNL-EFDC simulations suggested that the project site has very high natural turbulence as is typical of a strong tidal system. Even with the overestimated drag coefficient in the period before August 10 (due to the fact that the turbine was freespinning, not generating), the model output simulations indicate the flow field disturbance associated with the OCGen was not clearly discernable from background flow. Earlier hydrodynamic modeling of the TidGen in Western Passage showed only a 10% drop in water velocity (S. Rao, personal communication). The TidGen turbine is 3–4 m high and 25 m long, which is larger than the OCGen. Therefore, the velocity reduction due to the OCGen is likely to be smaller—10–15 cm/s at most—and difficult to identify against the high natural background turbulence. Thus the small reduction in velocity associated with the larger TidGen in Western Passage is consistent with our assessment that the hydrodynamic impact of the OCGen was minimal.

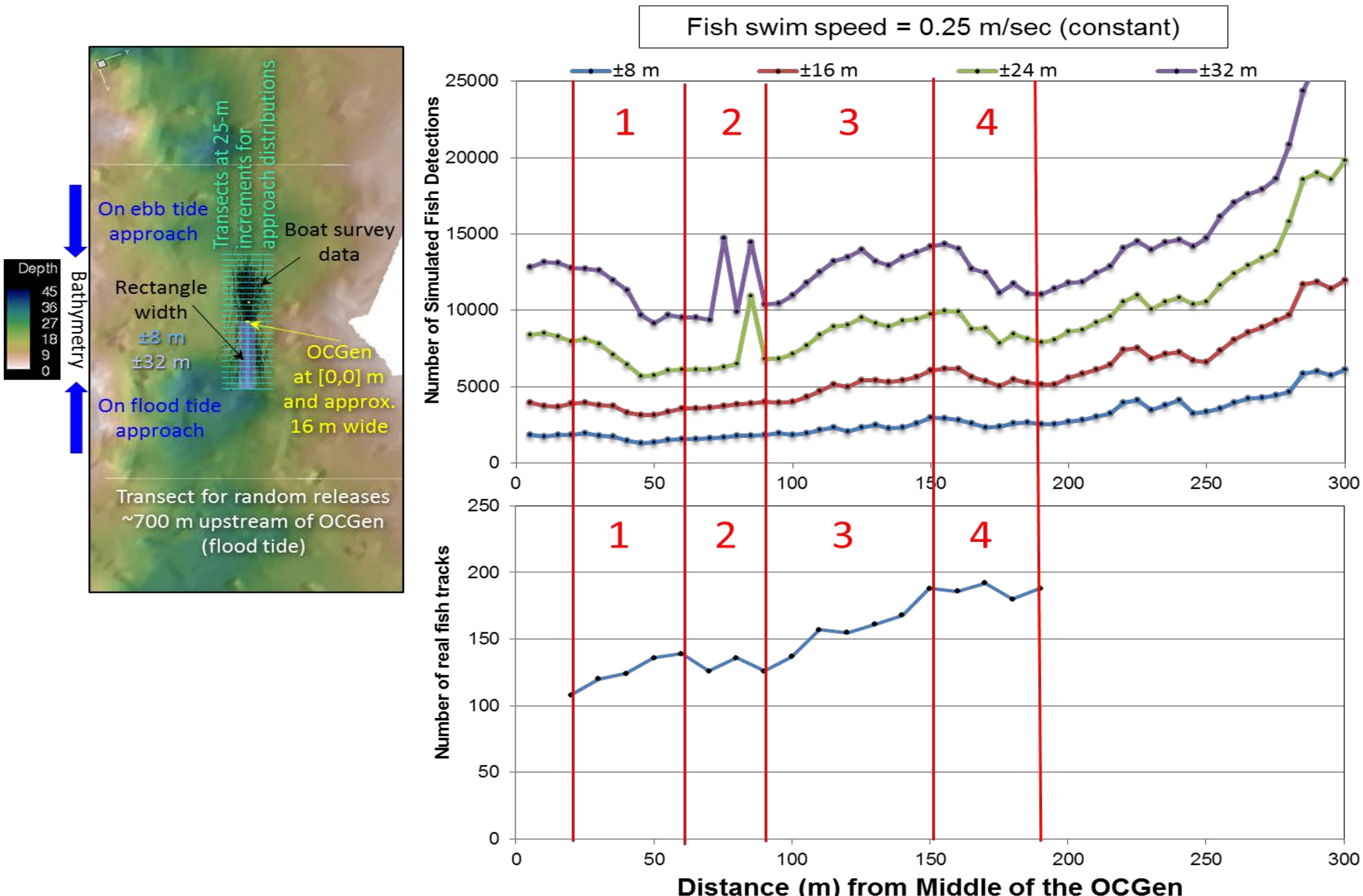
3.3 ELAM Analysis

Overall, the number of simulated fish detections decreased with decreasing distance to the OCGen, although the decline was not continuous (Figure 14). Between 175 m and 150 m, the number of fish detections increased briefly, but then generally declined again until 40 m from the OCGen, at which point the number of fish increased. Although the general trend in simulated fish detections matched the trends in the hydroacoustic fish data (i.e. a decline in fish density nearer the turbine; Figure 14), there were differences at different segments of the survey transect. The sharpest decline in simulated fish detections was between 200 and 300 m. However, no field data was collected at these distances so a comparison is not possible. Between approximately 200m and 150 m, simulated fish detection either increased or remained constant, while the number of observed fish tracks was relatively constant (Figure 14, Segment 4). The number of fish appeared to decrease between 150 and 90 m for both simulated and observed datasets (Figure 14, segment 3). However, between 20 and 60m, the simulated and observed data diverged with the former showing an increase in fish and the latter showing a decrease (Figure 14, Segment 1). These patterns were similar in simulations using fish speeds of 0.1 m/s and 0.25 m/s, and among the four rectangle widths. While the patterns were similar, the simulated fish density fluctuations along the transects increased with rectangle width and were more pronounced at 0.25 m/s and (Figure 14 a and b).



Depth
45
36
27
18
9
0
Bathymetry
On ebb tide approach
Transects at 25-m increments for approach distributions
Boat survey data
Rectangle width
±8 m
±32 m
OCGen at [0,0] m and approx. 16 m wide
On flood tide approach
Transect for random releases ~700 m upstream of OCGen (flood tide)
fish swim speed = 0.1 m/sec (constant)
±8 m
±16 m
±24 m
±32 m
Number of Simulated Fish Detections
Number of real fish tracks
1
2
3
4
Distance (m) from Middle of the OCGen

a)



b)

Figure 14. Comparison of trends between the numbers of ELAM simulated fish and the number of hydroacoustic fish tracks with distance from the OCGen. Simulations using a fish swim speed of 0.1 m/s are shown in Figure 14a and 0.25 m/s are shown in Figure 14b.

4 DISCUSSION

The key finding of the hydroacoustic surveys was that there was a significant decline in fish density with decreasing distance to the OCGen. The decline appeared to be the result of horizontal, not vertical, movements to avoid the turbine. Because of the uneven bathymetry, fish track counts excluded the bottom third of the water column between 200 and 50 m from the OCGen in order to equalize the amount of water column surveyed across the transect (Figure 3). This meant that bottom fish were not counted except in the final 50 m of the transect nearest the turbine. If bottom fish were relatively abundant compared to fish higher in the water column, this could have led to an underestimate of fish densities between 200 and 50 m. However, if this were true there would have been an increase in fish densities from 50 m to the turbine, when bottom fish were included in the fish track counts. In fact, however, the decrease in fish density continued all the way to the turbine, suggesting that excluding bottom fish did not significantly affect the results.

In contrast to surveys conducted while the turbine was freespinning, there was a weak or non-existent relationship between the number of fish tracks and the distance from the OCGen for transects surveys conducted during the static turbine condition. These results support the hypothesis that stimuli produced by the spinning turbine (e.g. noise, visual cues) could potentially explain the decrease in fish density along the survey transect when the turbine was spinning. We investigated three potential OCGen related explanations for the observed avoidance behavior: (1) noise generated by the turbine, (2) visual stimuli generated by the turbine, and (3) turbine-generated flow patterns in the channel. As an alternative explanation, natural flow patterns within the channel were also investigated using ELAM simulations. Each explanation is reviewed below.

4.1 Explanations for Avoidance Behavior

4.1.1 Noise

Noise is one possible turbine-generated stimuli. Fish density began to decline approximately 140 m from the OCGen when it was free-spinning. Therefore, if noise is the source of the avoidance behavior, the noise from the OCGen would have to be of sufficient levels to elicit avoidance at a distance of 140 m. The ability of fish to detect turbine noise is related to the hearing sensitivity of the fish, the sound produced by the MHK technology, and the ambient noise generated by existing natural processes or human activity within the area. No noise studies are available for the OCGen that could be used to determine noise levels at incremental distances from the turbine. However, ORPC has previously measured noise generated by a small, test turbine and the commercial scale TidGen system (ORPC 2011; ORPC 2014). For the test turbine, there was an increase of up to 35 dB re 1 μPa^2/Hz above the ambient background noise level 68 m from the turbine, although the turbine-generated noise level was typically only around 10 dB re 1 μPa^2/Hz above background (Table 2). Sound pressure levels from the turbine were below 100 dB re 1 μPa^2/Hz, even at the maximum rotational speed (ORPC 2011). Considering these results were for the smaller test unit, the noise levels and distance the sound travelled are likely greater for the commercial-scale OCGen.

Table 2. Comparison of ambient noise and noise measured at 68 m from the ORPC test unit under varying environmental conditions (Source: ORPC 2011).

		dB re μPa^2/Hz						
		Ambient						TGU
Current (Knots)		1.1	1.5	2.2	2.9	3.0	3.3	2.9
Third Octave Band (Hz)	80	65.3	54.8	58.3	64.6	66.7	76.9	65.3
	100	67.7	59.5	64.7	69.7	72	81.5	67.7
	125	76.7	64.7	69.2	77.4	75.4	82.9	76.7
	160	86	70.4	81.2	80.6	78.3	85.2	86
	200	89.6	70	76.8	80.4	80.7	87.8	89.6
	250	94.3	72.2	81.5	80.9	85.7	87.1	94.3
	315	94.3	70.8	85.4	90.1	85.9	96.2	94.3
	400	98.7	70.1	85.6	91	87.2	91.8	98.7
	500	101.8	71.4	83.2	90.9	91.5	91.6	101.8
	630	95.4	72.7	84.8	98.6	88.5	97.8	95.4
	800	95.9	77.1	83.8	89.1	88.7	95.3	95.9
	1000	98.9	76.1	85	91.3	80.6	96.5	98.9
	1250	104.9	76.8	87.6	89.2	81.6	92.4	104.9

In April 2013, noise measurements of the TidGen (ORPC 2014) were conducted during ambient, freewheeling, and turbine generating periods. The noise signals recorded were different for the spinning and non-spinning states. Increased sound levels were detected at certain frequencies (i.e. 105 and 210 Hz) anytime the turbine was rotating, but the peaks were higher when the turbine was freespinning (Fig. 15) suggesting greater noise was generated when the turbine was not generating power. However, at certain distances there were low frequency sound peaks while the turbine was generating that were not present when free spinning (Figure 15). Low frequency sound peaks were also detected in the non-spinning state, but these were attributed to boat noise (ORPC, 2014). Overall, the in-water sound peaks associated with the TidGen was less than 120 dB re 1 $\mu Pa^2/Hz$ at all measured frequencies (Fig. 15). This was true when the turbine generated power and when freespinning (ORPC 2014). Measurements taken at 154 m from the TidGen indicate that at frequencies around 100 Hz, the turbine generated the highest noise levels, or slightly over 100 dB re 1 $\mu Pa^2/Hz$ (Fig. 15). Although these noise levels would not be injurious to fish, multi-species studies suggest that fish would be able to detect sounds within this frequency and noise level (Popper and Hastings 2009), and 154 m is similar to the 140 m at which the avoidance behavior was observed in this study. However, the TidGen turbine is much larger than the OCGen, so the noise levels may be higher than those generated in our study by the OCGen. Also, the detection of turbine noise by fish does not mean the noise level would induce the observed turbine avoidance behaviors.

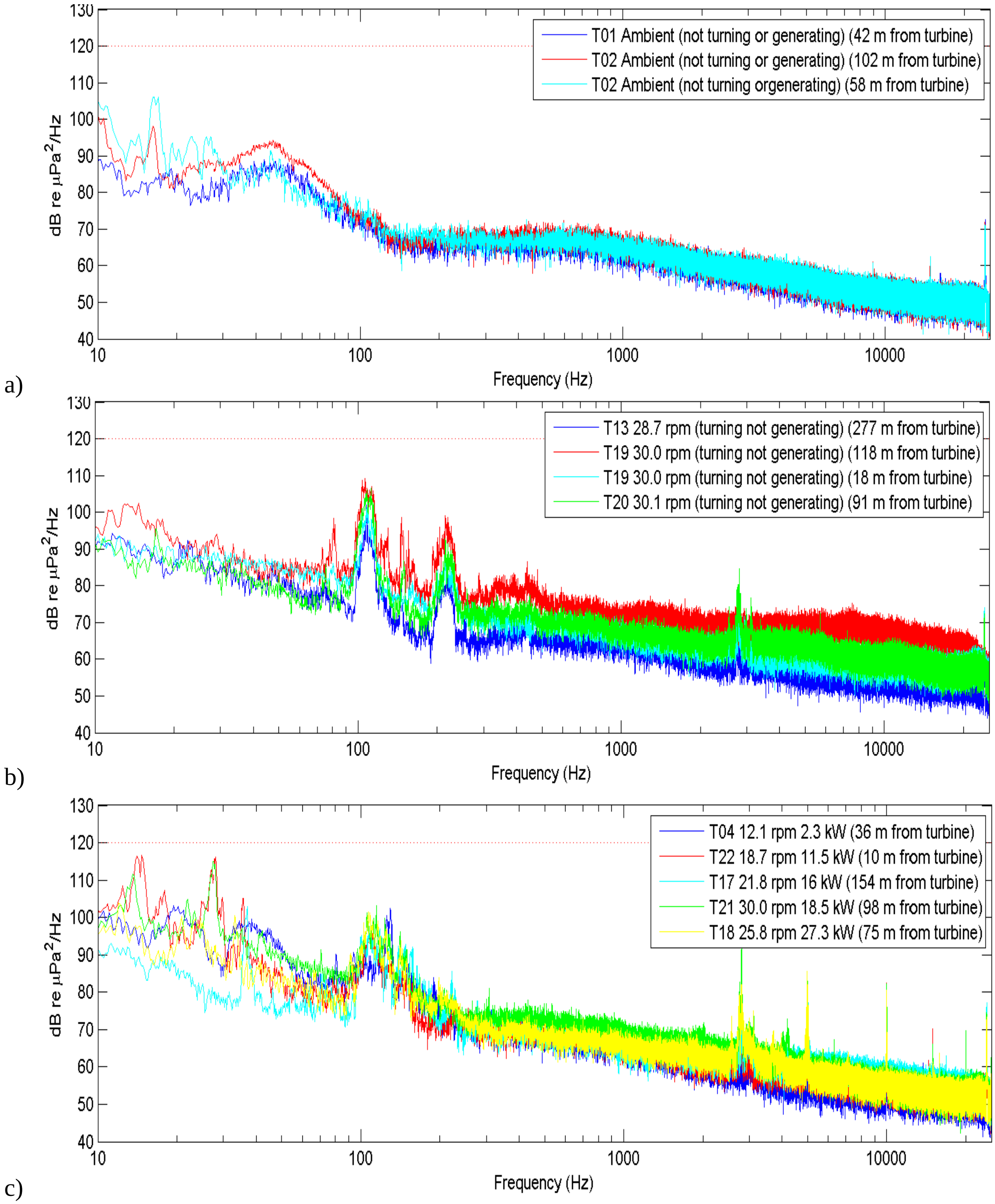


FIGURE 15 Power spectral density for the TidGen turbine during (a) ambient (not rotating), (b) free spinning, and (c) generating conditions at various frequencies and distances from the turbine on April 2-3, 2013 (Source: ORPC 2014).

Species-specific sensitivity to noise is another important consideration. Pelagic and benthic trawl samples collected during the OCGen hydroacoustic surveys indicated that Atlantic mackerel (*Scomber scombrus*) and Atlantic herring (*Clupea harengus*) were the pelagic species most likely to be interacting with the OCGen (Shen et al. 2016). Clupeids, such as the Atlantic herring, are known to be sensitive to noise (Popper and Hastings 2009), while mackerel are likely less sensitive to noise because they lack a swim bladder (Hawkins and Popper 2014). Given the economic importance of these species, more testing is needed to determine the relative sensitivity of mackerel to noise (Normandeau Associates 2012; Hawkins 2014).

By necessity, MHK devices are placed in areas like Cobscook Bay that have high flow and turbulence. This placement may reduce the ability of fish to detect noise from the turbine, because ambient noise increases with tidal flow (Willis et al. 2013). Therefore, it is difficult to evaluate with confidence the potential effects of noise generated by MHK devices on specific fish species. Other studies of MHK technology suggest that noise from vessel traffic, seismic surveys, and other existing anthropogenic noise will be more significant than noise generated by MHK devices, although the studies also suggest that turbines can increase noise levels above background levels within some distance to the devices (Verdant Power 2010; ORPC 2011; Polagye et al. 2012). For example, Verdant Power made underwater noise measurements surrounding the four operating turbines in the East River and found that turbine-generated noise was 145 dB re 1μPa at 1 m from the turbines, which would be audible to most fish species. The noise level appeared to return to background levels (~125 dB re 1μPa) less than 200 m from the turbine, meaning this turbine-generated increase in noise above background appeared to be small (Verdant Power 2010).

4.1.2 Visual Cues

Another explanation for the avoidance behavior observed near the OCGen in Cobscook Bay is that fish were able to see the turbine as they approached, and therefore changed their direction. Near-field (<5 m from the turbine) DIDSON studies of fish interaction with an ORPC TidGen found that fish that passed through the turbine generally did so at night rather than during the day (Viehman et al. 2014). These results indicate that fish behavior changed because they could see the turbine. Other field studies also suggested that near-field turbine visibility reduced fish interactions with turbines (Hammar et al. 2013).

However, while sight may have played a role in near-field studies, it is unlikely fish would be able to see the turbine from a distance of 140 m where avoidance behavior was observed. To confirm, we investigated whether there were differences in avoidance behavior between transects conducted at night versus the day, with diurnal differences indicating a visual response to the turbine. We found the decline in the number of fish tracks with decreasing distance to the turbine was significant for both day and night surveys, and, most importantly, the decline in fish tracks began at approximately 140 m from the turbine during both day and night. These results suggest that visual stimuli were not the source of the avoidance behavior at the distances examined.

4.1.3 Turbine-Related Hydrodynamic Changes

The SNL-EFDC and the FVCOM hydrodynamic simulations do not suggest that the turbines created a significant flow disturbance above background flow conditions and that the hydrodynamic disturbance would not have extended 140 m upstream of the turbine during the incoming tide. Therefore, turbine related hydrodynamic stimuli were not likely to be responsible for the observed avoidance behavior. The study area is a high-velocity system with naturally turbulent flows which may have overwhelmed the more localized disturbance to the flow field generated by the OCGen. Turbines are purposely placed in areas of high flow in order to optimize power generation. Therefore, our results may not be atypical of tidal MHK projects. If so, behavioral impacts in fish resulting from hydrodynamic alterations may be minor and localized for single MHK device deployments. However, economically viable MHK deployments will ultimately require the deployment of additional devices in an array, which would likely increase the magnitude of hydrodynamic change. If plans by ORPC to deploy a turbine array are implemented, further study would be needed to assess the nature of the hydrodynamic changes and any subsequent behavioral alterations. As described in Section 5, following additional data collection around the array, the ELAM can be used for this purpose.

4.1.4 Natural Hydrodynamic Stimuli

Channel bathymetry and morphology create flow field conditions, particularly water velocity and acceleration fields, that significantly influence fish movement decisions (Goodwin et al. 2014). The natural flow patterns visible in the Cobscook Bay flow simulations, specifically high-velocity flow in the southern portion of the channel, could have caused fish to move away from the northern bank where the OCGen is located. The high-velocity corridor was likely generated by a bathymetric change which began approximately 150 m from the OCGen (Fig. 3). Consequently, the observed avoidance response may have been related to natural flow conditions rather than the OCGen.

To test the significance of natural flow patterns on behavior, we ran ELAM simulations of fish particles that behave passively and fish particles that follow natural flow velocity changes, to see if they match the patterns found in the hydroacoustic fish track data. From approximately 50 to 200 m from the turbine, the ELAM simulations reproduced the general spatial trends in fish density observed in the hydroacoustic fish surveys. Both data sets showed a general decrease in fish density with decreasing distance to the turbine. However, from 0 to 50m from the turbine, the ELAM simulated an increase in fish densities, which was the opposite of the continued decrease in fish densities found in the hydroacoustic surveys. This suggests that additional hydrodynamic behavioral response parameters may be needed in the ELAM model to more accurately reproduce the avoidance behavior. Alternatively, it suggests that turbine related stimuli, such as noise, began to influence fish behavior closer to the turbine.

Overall, the ELAM analysis provides some support for the alternative hypothesis that fish are following the natural water flow away from the device at distances between 50-200 m from the OCGen, rather than responding to stimuli generated by the OCGen. These results correspond to the behavioral rules identified by a prior ELAM analyses of how fish navigate water currents by following accelerating water (Goodwin et al. 2014). However, while the ELAM simulations can partially reproduce the patterns in the hydroacoustic detections, the fact that the avoidance behavior was not found at control transects or when the turbine was not spinning, suggests that it was the rotating turbine that was responsible for the avoidance behavior.

4.2 Ecological Implications of Findings

As demonstrated by this study, MHK devices have the potential to alter the behavior of individual fish that move within the vicinity of the device while it is in operation. Of further interest is whether these behavioral changes could result in ecologically meaningful impacts such as the disruption of spawning and migratory runs or the avoidance by fish of their normal habitats due to the presence of the turbine. For species that do interact with an MHK device, blade strike is among the factors of concern to regulators. As described below, the results of this study suggest that the risk of significant ecological impacts is low for a single MHK device.

4.2.1 Displacement from Preferred Habitats

Fish were found to actively avoid the OCGen, which could result in displacement or avoidance of preferred habitat. To assess the potential of this impact in Cobscook Bay, one must know the relative spatial distribution of fish populations within Cobscook Bay and the vertical distribution of fish in the water column. Down-looking hydroacoustic surveys conducted during 2010–2013 in the area of the proposed TidGen deployment indicated fish density was generally highest near the sea floor and the probability of fish being present in the same location as the TidGen was between 0.5 and 0.8 for all seasons and tidal conditions (Viehman et al. 2014; Shen et al. 2016). However, these data refer to the vertical distribution of fish that are actually present at the site and not the relative abundance of fish at the TidGen site compared to other locations in Cobscook Bay. For example, if most fish prefer inshore habitat, only a small percentage of the total population may be present at the location of the TidGen, which was located more centrally in the channel.

No studies of the habitat-wide distribution of fish within Cobscook Bay were available specific to ORPC turbine deployments. However, there are studies of fish interactions with tidal MHK devices in other systems from which to glean information on the distribution of fish within high-flow channels. For example, fixed hydroacoustic studies of Verdant Power axial turbines in New York's East River indicated that, even when the turbines were not operating, there were fewer fish in the mid-channel habitat where the turbines were located compared to the slower velocity zones inshore, Although these findings may be an artifact of the weaknesses of fixed hydroacoustic devices to detect fish in high velocity conditions, they do suggest that fish are less abundant in open channels during periods of high flow. In a European Marine Energy Centre study conducted in Scotland, video recordings around an OpenHydro turbine (Broadhurst et al. 2014) showed that pollack (*Pollachius pollachius*) generally were not present around the turbine, although aggregations of fish were occasionally observed (Broadhurst et al. 2014). Tidal stage and water velocity appeared to be the primary determinant of fish presence or absence around the turbine with greater a number of fish present during slack tide.

In summary, while tidal turbine studies in Cobscook Bay and other locations indicate that turbines do elicit species-specific behavioral changes in fish, the installation of turbines in the strong current zones (consistent with energy production needs), may minimize the potential for displacing fish from areas where they are most abundant.

4.2.2 Disruption of Fish Movement

The primary goal of this study was to assess the magnitude of change in fish movement patterns upstream, over, and downstream of the OCGen. The empirical data derived from the hydroacoustic surveys suggest the fish move horizontally away from the path of the OCGen (Shen et al. 2016). Unfortunately, the presence of the TidGen bottom mount confounded the interpretation of movement patterns downstream of the OCGen. However, the lack of flow field disturbance evident in the FVCOM flow simulations suggests that it is highly unlikely that a single turbine deployment in Cobscook Bay would pose a significant fitness cost to individual fish or disrupt ecologically significant life-history activities such as migration and spawning.

Our findings are similar to those in other systems. Hammar et al. (2013) used underwater video to record fish movement through a narrow tidal channel. They found that passage through the channel was significantly lower for 6 of the 16 genera recorded when the turbine was present, compared to when it was absent from the channel. The passage rate was negatively related to water velocity, but only when the turbine was present, indicating that the decrease in passage was due to the higher rotational speeds of the turbine, not the water velocity itself (Hammar et al.

2013). However, fish that passed through the channel avoided the turbine by only 0.3 to 1.7 m, indicating minimal disruption of movement and energetic cost to the fish.

Most MHK project development plans include the deployment of an array of turbines, which increases the potential for hydrodynamic disturbance and subsequent behavioral changes over a large portion of the deployment site (Hammar et al. 2013). These impacts can be mitigated to some degree by turbine placement in areas where fish are less likely to be present. As described in Section 5, following additional data collection around the array, the ELAM can be used identify array configuration that minimize impacts to fish.

4.2.3 Blade Strike

As summarized in Table 3, existing blade strike studies do not suggest a significant risk for fish from direct blades strike. Near-field studies of fish interactions with the TidGen using a DIDSON acoustic camera indicated that few fish entered the device while it was static, and the number of fish entering the turbine decreased by 35% when the turbine was rotating (Viehman and Zydlewski 2014). For fish that do approach the device, recent studies in laboratory and natural settings suggest a low potential for injury and mortality from blade strike, except in the case of very young, larval stages of fish (Table 3). For example, in studies in a narrow tidal channel, Hammar et al. (2013) recorded only two individuals entering the turbine rotor and no individuals were observed being hit by the blade. They also found that fish passage through a tidal channel was negatively related to the rotational velocity of the turbine, which would likely reduce the probability a turbine blade actually striking a fish.

For mid-field and far-field interactions, whether the MHK device is located in the habitat preferred by the species is a significant factor in the probability of a fish-turbine encounter. Most studies suggest that a significant number of interactions is unlikely because the locations or time periods in which the turbines typical operate are generally not suitable for aquatic organisms (Section 4.2.1). As reported in Viehman et al. (2014) and Shen et al. (2016), the probability of fish being present in the same location as the proposed TidGen deployment was generally between 0.5 and 0.8 in all seasons and tidal conditions. However, the probability of the fish being at the same depth as the turbine blades was much lower, ranging from 0.079 to 0.093 (Shen et al. 2016).

TABLE 3 Summary Fish and Blade Strike Studies

Reference	Variables Measured	Results
Amaral et al. 2015	Entrainment avoidance, injury, and survival of hybrid striped bass, rainbow trout, white sturgeon	• Entrainment varied by species. • Survival rate of entrained fish exceeded 95%. • Overall survival probability was 0.95 for striped bass and >0.99 for rainbow trout and white sturgeon.
Castro-Santos and Haro 2015	Mechanical injury, avoidance behaviors, and migratory delay in Atlantic salmon smolts and adult American shad interacting with a vertical-axis turbine	• Salmon smolts did not show avoidance behavior toward the turbine and no injuries were recorded from passing through the turbine. • Survival was 98.3% for treatment smolts and 96.4% for controls. • Shad appeared to actively avoid the turbine and no injuries were observed. • Adult shad mortality was not statistically different between control and treatment groups.
Hammar et al. 2013	Field study of multi-species fish movement patterns through a narrow strait with and without a turbine	• Only one species on two occasions was detected passing through the turbine. • Reduced passage when turbine was operating, especially at higher speeds.
Jacobson et al. 2011	Injury, survival rates, and behavior of two size classes of rainbow trout and largemouth bass	• Survival was greater than 98%. • Fish that were struck were typically hit in the caudal fin, and fish were not stunned or severely injured. • Both species seem to avoid the turbine.
Normandeau Associates, Inc. 2009	Injury and mortality of five species ejected through a Hydro Green turbine	• Survival was 98% or greater for all fish, which was similar to controls. • No fish that passed through the turbine had evidence of injury or descaling, and no post-passage predation was observed.
Schweizer et al. 2012	The risk of blade strikes on four species of larval and juvenile freshwater fish	• Mean survival of one to 14 days post-hatch striped bass for fish that had passed through the blade were typically not significantly lower than control fish. • The post-blade passage survival appeared to increase with age, as older fish were able to avoid the blade. • Significant differences between blade-exposed and control groups were not observed for walleye/sauger, fathead minnows, or crappie, all of which were more than 20 days post-hatch.

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TABLE 3 (Cont.)

Reference	Variables Measured	Results
Verdant Power 2010	DIDSON imagery of fish interactions with Verdant turbines	• No blade strikes of fish were observed during turbine operation.

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This study significantly expands the range of earlier near-field blade strike and DIDSON studies by observing fish behavioral changes as they approached the device over hundreds of meters. The results of this study indicate that fish in Cobscook Bay begin to avoid the OCGen at 140 m from the device, further reducing the probability fish will physically interact with the device. Overall, the probability of fish encountering the turbine blade appears to be low, due to behavioral preferences related to natural water flow and active avoidance of the turbine. This finding combined with near-field blade-strike studies indicating low risk for juvenile and adult fish suggests that a single OCGen poses a minimal risk to pelagic fish.

5 FUTURE STUDIES

While existing data suggest small, localized ecological risk to fish from a single MHK device, the risk may increase with additional devices. This will become more relevant as commercial-scale MHK arrays come under consideration by regulators. Therefore, the ecological risks associated with commercial scale operations will ultimately have to be evaluated to fully understand the ecological impacts of MHK devices.

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In the future, the ELAM could be used to generally forecast fish behavior under alternative array configurations at commercial scales to evaluate alternatives that may minimize impacts to fish movement. Because fish response to an array could be different from their response to a single turbine, extending the ELAM to an ORPC commercial array and different array designs would require 1) the deployment of additional TGUs in Cobscook Bay, to study the unique hydrodynamic patterns generated by the hydraulic interactions between the turbines, 2) collecting fish monitoring data around the TGU array, and ,3) benchmarking the ELAM generated simulations against available monitoring data and refining the encoded behavior hypothesis as needed. Beyond assessing and improving the encoded behavior hypothesis, the ELAM requires no other refinement to be applied to a commercial array. Thus, the ELAM could help commercial developers to identify configurations that minimize impacts to the extent practicable, as required by the National Environmental Policy Act.

6 CONCLUSIONS

The key finding of the hydroacoustic surveys was that there was a significant decline in fish density beginning approximately 140 m from the free-spinning OCGen. Similar avoidance behavior was not observed at control transects or when the turbine was not spinning. Visual cues and turbine-related hydrodynamic stimuli did not appear to be detectable to fish at 140 m. Of the other potential explanations we investigated, noise and natural flow patterns appeared to be the most plausible explanations for the observed patterns in fish behavior. However, several uncertainties remain. First, we don’t have sufficient data to evaluate with confidence the distance at which noise generated by MHK devices are detected by specific fish species, nor what behavioral changes they would elicit at different noise levels. Second, while the ELAM results provide some support for the alternative hypothesis that natural hydrodynamics were responsible for the observed patterns of fish behavior, the ELAM model parameters cannot account for the decrease in fish density closer to the turbine. Therefore, it is possible that turbine related stimuli, such as noise, influenced fish behavior closer to the turbine.

Overall, this study provides additional confirmation for the idea that a single turbine is unlikely to result in more than negligible impacts to fish communities. Assuming that the observed fish avoidance behavior was related to the OCGen, the installation of turbines in the strong current zones that fish may tend to avoid, may minimize the potential for displacing fish from areas where they were most abundant. I addition, if the turbine elicited the avoidance behavior, it would minimize the already low probability of blade strike revealed in near-field laboratory studies. Alternatively, if the avoidance behavior was the result of the fish following natural flow patterns in the channel, it would confirm that turbine related disturbances are only one of a number of stimuli in the fish’s environment and that they are relatively insignificant compared to the overwhelming influence of the natural channel bathymetry and hydrodynamics.

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