FISH IN A TIDALLY DYNAMIC REGION IN MAINE: HYDROACOUSTIC ASSESSMENTS IN RELATION TO TIDAL POWER DEVELOPMENT

By

Haley A. Viehman

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Advisory Committee:

Gayle Zydlewski, Assistant Professor of Marine Science, Advisor

Michael Peterson, Professor of Mechanical Engineering

James McCleave, Professor Emeritus of Marine Science

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By Haley A. Viehman

Thesis Advisor: Dr. Gayle Zydlewski

An Abstract of the Thesis Presented
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Fish ecology in regions of extreme tidal flows is poorly understood, but as these areas link on- and off-shore habitats, they are important to many marine and diadromous fish species. Strong tidal currents are also being targeted for energy extraction, but the effects of tidal energy devices on fish are unknown. The probability of fish encountering a tidal energy turbine is highly dependent on the vertical distribution of fish at the project site. In extremely tidal coastal areas, fish presence and distribution is heavily influenced by tidal, diel, and seasonal cycles. Understanding the vertical distribution of fish therefore requires sampling on a fine temporal and spatial scale. Stationary hydroacoustic surveys may be used to gather these data, as part of a BACI (Before, After, Control, Impact) type study design, to predict then monitor the effects of tidal energy devices on fishes.

Starting in May 2010, a down-looking, single-beam SIMRAD echosounder and a DIDSON (Dual-frequency IDentification SONar) unit were used to document the relative density of fish throughout the water column at a targeted pilot project site and a control site in Cobscook Bay, Maine. Stationary 24-hour surveys were carried out each season to examine variation in fish density and vertical distribution. Relative fish density was highest in spring and fall, and almost always increased near the bottom, regardless of tide or time of day. Tide and day/night had some effect on the vertical distribution of fish, but the effect was not the same each month. Results from these analyses will be used to predict the likelihood of fish encountering the turbine and to create a basis for comparison of data collected after device installation.

Direct observation of fish reactions to a full-scale test device was carried out in September of 2010. A test turbine suspended below a floating research platform was monitored for 24 hours using two DIDSON units. A higher proportion of fish interacted with the device when it was still than when it was rotating. A greater portion interacted at night, and the type of interaction shifted from avoidance during the day to passing into the turbine at night. This behavioral shift was most obvious in small fish (<10 cm), nearly all of which passed through the device at night; most large fish (>20 cm) still avoided the turbine. Most fish were present at night during the slack tide.

Combining the baseline knowledge of where fish are in the water column with knowledge of how they behave in close proximity to an operating tidal device will provide a more complete picture of the potential effects these devices could have once installed.

THESIS/DISSERTATION/PROJECT

ACCEPTANCE STATEMENT

On behalf of the Graduate Committee for Haley A. Viehman I affirm that this manuscript is the final and accepted thesis. Signatures of all committee members are on file with the Graduate School at the University of Maine, 42 Stodder Hall, Orono, ME.

Dr. Gayle Zydlewski, Assistant Professor of Marine Science Date

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CHAPTER 1

AN APPROACH FOR ASSESSING FISH PRESENCE IN RELATION TO TIDAL POWER DEVELOPMENT

1.1 Abstract

This paper seeks to guide fish assessment studies related to tidal power development because the lack of installed projects to date has prevented the creation of any standard protocols. A before-after-control-impact (BACI) study design is suggested to examine changes in the presence and vertical distribution of fishes. Changes in these aspects of fish behavior occur on small (tidal) and large (seasonal) temporal scales, and sampling must occur at similar scales. Fine temporal and spatial resolution is required to characterize fish movements associated with tide or diel cycle, but surveys must be conducted across long periods of time in order to identify seasonal trends. Several tools for the collection of such data are described and discussed. One approach that provides the high-resolution data necessary for these analyses is hydroacoustics. A fish assessment study related to tidal power developments in Cobscook Bay, Maine is presented as an example. This study used stationary hydroacoustic surveys to collect baseline data on fish presence and distribution during every season over the course of two years. The methods and results of the study are discussed, and recommendations for future assessments are made.

1.2. Introduction

Little is known of fish ecology in the regions of extreme tidal flows that are currently targeted for tidal power development. These sites are often the interface between deep-ocean habitats and inshore foraging, spawning, and nursery areas essential to the life history of many marine fishes. In addition to sustaining resident fish species year-round, these areas are frequented seasonally by diadromous fishes, marine species spawning on- or off-shore and using the coastal zone as nursery grounds, and marine species making seasonal visits to the coastal zone as adults (Zijlstra 1988). Extreme tidal currents such as those sought for tidal power generation (on the order of 2.5 $m \cdot s^{-1}$; Polagye et al. 2011) have a major influence on the behavior of these species.

Currents are an integral part of a fish's environment, effecting migrations, habitat selection, foraging behaviors, and predator-prey interactions (Auster 1988, Montgomery et al. 2000). Several migratory species utilize selective tidal stream transport to move on- or off-shore (or in and out of freshwater), rising up in the water column when the current is flowing in the desired direction but moving to the bottom, where the current is slower, when it changes direction. Some examples include American eel, *Anguilla rostrata* (McCleave and Kleckner 1982); Atlantic cod, *Gadus morhua* (Arnold et al. 1994); sockeye salmon, *Oncorhynchus nerka* (Levy and Cadenhead 1995); sea trout, *Salmo trutta* (Moore et al. 1998); and plaice, *Pleuronectes platessa* (de Veen 1978, Greer Walker et al. 1978). Castonguay and Gilbert (1995) found that Atlantic mackerel (*Scomber scombrus*) avoided opposing tidal flows but moved with favorable ones as they migrated into the Gulf of St. Lawrence, though vertical migrations were not observed. Atlantic herring, *Clupea harengus*, have been found to swim with favorable tides but against opposing ones in order to maintain position (Lacoste et al. 2001), and some fish simply move back and forth with both flow directions, traversing up to several kilometers per tidal cycle (Sakabe and Lyle 2009). Sampling tidal flats, lagoons, and estuaries at slack tides has demonstrated that multiple species use the tides to gain access to intertidal foraging, spawning, and sheltering grounds (Gibson et al. 1996, Marshall and Elliott 1998, Morrison et al. 2002, Hartill et al. 2003, Krumme 2004, Ribeiro et al. 2006, Jovanovic et al. 2007).

Tidal turbines placed in the water column have the potential to affect fish using tidal currents. Potential effects of tidal devices on fish have been hypothesized by various groups (Gill 2005, DOE 2009, Polagye et al. 2011), with the highest priority concerns being fish interaction with moving parts of the device. Effects of such interactions range from mortality or injury of individuals due to direct blade strike, to interference with fish movements and migrations, whether due to strike, velocity changes, or noise generation (Polagye et al. 2011).

The quantity and magnitude of these “dynamic” effects are highly uncertain, as very few devices have been installed to enable field studies (Polagye et al. 2011).

Understanding these effects depends on understanding the movements and migrations of fish at a site, particularly of pelagic fishes, which are most likely to be within range of turbine blades. Any tidal device will be placed in a specific part of the water column, so how fish use the water column during the moving tide, specifically their vertical distribution, will greatly affect their probability of interaction with a device. Fish vertical distribution is not constant. Apart from vertical migrations linked to tidal currents, many fish species also exhibit diel vertical migrations linked to changing light intensity (Bohl 1980, Janssen and Brandt 1980, Levy 1990, Nilsson et al. 2003). Tide and diel factors together can affect fish behavior; for example, fish may wait for nightfall to travel with the rising tide into shallow intertidal foraging grounds (Morrison et al. 2002, Ribeiro et al. 2006, Jovanovic et al. 2007). These vertical movements are site- and species-specific, and may also vary with age or size class within a species (Imbrock et al. 1996, Jovanovic et al. 2007, Ellis and Bell 2008, Becker et al. 2011).

Few studies examine the vertical distribution of fish in high-velocity flows, especially those strong enough for tidal power generation. Many studies of tidally dynamic areas have focused on species composition and habitat use at low and high tides, which has shown that fish move with the tides but does not reveal anything about their use of the water column during that time (Morrison et al. 2002, Ribeiro et al. 2006, Jovanovic et al. 2007). Tracking individual fish using acoustic tags has provided detailed information on horizontal tidal migrations of individuals, and in some cases vertical distribution as well (Parker and McCleave 1997, Barbin 1998). Others provide depth information by passively sampling tidal currents with nets placed at discrete depths (McCleave and Kleckner 1982, Rijnsdorp et al. 1985), or depth and horizontal distribution by using hydroacoustics (Castonguay and Gilbert 1995, Levy and Cadenhead 1995). The vertical distribution of fish in strong tidal currents remains poorly understood for most species and locations, which increases the uncertainty surrounding the dynamic effects of tidal turbines.

As very few tidal energy devices have been installed, no standard protocols exist to guide the collection of data for effect assessment. The purpose of this chapter, therefore, is to act as a starting point for assessing the effects of a tidal power installation on fishes. General methodology is suggested, tools available for sampling tidally dynamic areas are reviewed and discussed, and a study of fish in Cobscook Bay in relation to a pilot tidal power project is presented as an example, along with recommendations for future work.

1.3. General Methodology

Any approach chosen will need to suit the location and scale of the tidal power project under investigation. For most project installations, a Before-After-Control-Impact (BACI) study design is recommended. This design reduces sampling to a limited number of points, and may be applied over a wide range of spatial and temporal scales. BACI designs are meant to quantify the effects of a change to the local environment, and has been used successfully in several offshore applications, including wind power (Carstensen et al. 2006), oil drilling (Currie and Isaacs 2005), and pipeline construction (Lewis et al. 2002). The use of a control site aids in identifying variation in the data that is not due to the "impact" and is a particularly useful aid in extremely variable environments.

Pre-deployment information ("before" data) on fish at a tidal energy site is essential, creating the baseline for comparison of post-installation ("impact") data. Pre-deployment data can also aid in predicting the effects of a tidal device. This may be useful for device placement or risk assessment involved with the permitting process. The amount of information that must be gathered as part of the "before" study of a site will depend on the amount of information already available for the location. Studies should naturally begin with a thorough literature review, focusing on the species present at the site and considering seasonal, diel, and tidal patterns in their presence and vertical distribution.

The goal for the site should then be to characterize the presence and vertical distribution of fish at project and control areas, before installation and when it is in place. It is important to survey shortly after device installation if installation-related effects are also of interest. Construction-related changes can be short-lived in marine environments and can be lost if using a temporally coarse sampling regime (Smith 2002).

Fish movements occur on a large range of time scales, from small movements that take place in a matter of minutes (vertical migration at slack tide) to large movements that take place seasonally, such as offshore migration. Surveys must sample with fine enough resolution to capture small-scale movements of fish associated with tide and diel cycles (multiple samples per tidal stage), and surveys must be spaced adequately to also capture longer-term trends associated with seasonally changing fish communities (multiple surveys per season).

1.4. Sampling Gears

A wide array of sampling gears and techniques exist for the observation and characterization of fish presence and distribution. Not all can be used successfully in the difficult working conditions often present at tidal power sites. Those that may aid the assessment of tidal energy devices are listed and discussed below. It is unlikely that any single gear will provide all the necessary information, and a combination of multiple sampling methods is likely to be the best solution.

1.4.1. Benthic and Pelagic Trawling

Physical sampling techniques such as benthic and pelagic trawls are useful for acquiring the species and size composition of a fish community. Spreader doors are useful for keeping the net open and herding fish into it. If the depth of a trawl can be known and controlled, it may also be useful for obtaining a measure of the vertical distribution of fish within the water column. The capacity in this sense is limited because the depth of a trawl can be difficult to control, and a trawl can only sample a small portion of the water column at one time. Trawls are difficult to fish in high current speeds, which can limit available sampling time in tidal channels to a small window surrounding slack tide. Gibson et al. (1996) used a beam trawl (a form of benthic trawl) to sample at slack water in a rapidly changing tidal environment, and pointed out that making repeated hauls in a short amount of time and obtaining replicates for each tidal state can be challenging. Other issues to consider include gear avoidance by fish, size selectivity of the gear, fish injury or mortality, and, in the case of benthic trawls, destruction of bottom habitat (Nielsen and Johnson 1983).

1.4.2. Seines, Fyke nets, Weirs

Seine, fyke nets, and weirs can be used effectively to characterize the components of a fish community on relatively fine temporal and spatial scales, but in limited habitats. They have been used extensively to study the use of habitats in shallow intertidal areas, including the study of behaviors related to tidal and diel cycles (Gibson et al. 1996, Morrison et al. 2002, Ribeiro et al. 2006, Jovanovic et al. 2007). However, these sampling methods are generally limited to shallow areas, and are not useful for sampling deep, fast tidal channels.

1.4.3. Acoustic Telemetry

Acoustic telemetry allows the tracking of individual fish with a great range of spatial and temporal resolution (Hartill et al. 2003). Acoustic tags have been used with success to investigate the tidal and diel movements of fish within estuaries and other coastal zones, some of which examine vertical as well as horizontal movements (Parker and McCleave 1997, Barbin 1998), and some that look only at horizontal ones (Greer Walker et al. 1978, Moore et al. 1998, Lacoste et al. 2001, Childs et al. 2008). Tagged fish can be tracked manually from a boat, or an array of acoustic receivers can be placed throughout a study area to detect tags moving within range of the receivers. The latter option is better suited to longer-term studies of a relatively limited region, such as a tidal power project site and surrounding areas. In the case of extremely tidal locations, which vary greatly in space and time, telemetry has a significant advantage over netting techniques because it provides more than just a "snapshot" of fish behavior. However, acoustic tags can be expensive, which may limit the number of individuals that may be tagged. Tagging individual fish can be logistically demanding, and fish must be large enough for the tag to be attached or implanted, which limits the species and age classes that can be studied. Battery life of tags are dependent on size, the frequency of transmission, and the amount of data that is collected (Lucas and Baras 2000, Hartill et al. 2003). Noisy underwater areas, such as those with high current speeds or complex physical structures, greatly limit the detection range of acoustic receivers (Lucas and Baras 2000), and this may make them unsuitable for monitoring tidal energy projects at close range.

1.4.4. Hydroacoustics

Hydroacoustics encompasses a broad range of methods that use active sonar to detect, identify, and quantify fish presence. Hydroacoustic surveys have been used for many purposes, including monitoring vessel avoidance by fish (Vabø et al. 2002, Draštík and Kubečka 2005), characterizing diel vertical migrations (Bohl 1980, Janssen 1980) and tidal stream transport (Levy and Cadenhead 1995), and quantifying upstream salmonid migrations (Ransom et al. 1998). Most echosounder systems used in fisheries assessments can detect objects much smaller than most fish at ranges of hundreds of meters, with resolution on the order of centimeters.

Echosounding systems range in complexity and cost and come with a wide variety of frequencies and beam widths and shapes, but there are three basic configurations: single-, dual-, split-, and multi-beam. All of them can be used to obtain the distance of sound-reflecting objects, such as fish, from the acoustic transducer, as well as volume backscattering strength, which is generally assumed to be a relative measure of fish density. This is all that the single-beam echosounder can provide directly, though additional methods such as deconvolution can be used to obtain target strength approximations (Simmonds and MacLennan 2005). Target strength is necessary to estimate the numbers of fish contributing to the acoustic signal, and to estimate the sizes of individual fish. Dual- and split-beam echo sounders provide target strength, and additional information provided by split-beam echosounders can include fish swimming speed and direction (Simmonds and MacLennan 2005).

Hydroacoustic survey sampling designs are flexible, numerous, and adaptable to a number of situations (Lucas and Beras 2000, Simmonds and MacLennan 2005). Acoustic beams can be oriented horizontally, as in shallow water (Draštík and Kubečka 2005) or in some riverine passage studies (Ransom et al. 1998), or they can be oriented vertically, as in studies of diel vertical migrations (Bohl 1980, Janssen and Brandt 1980), tidal stream transport (Levy and Cadenhead 1994), or horizontal fish distribution (Simard et al. 2002). Surveys can include mobile transects across an area of interest (Levy and Cadenhead 1994, Simard et al. 2001), or they can be stationary (Ransom et al. 1998, Krumme 2004, Chapter 2). While many surveys are carried out from the surface, it is also possible to mount hydroacoustic equipment on the sea floor. Bottom-mounted, upward-looking acoustics have been used to examine diel migrations at a site (Axenrot et al. 2004, Jensen et al. 2011) and can help to reduce effects of vessel motion or hull-induced turbulence, though sampling volume near the bottom is decreased. These types of deployments can be connected to shore via underwater cables or be completely self-contained, with batteries and data storage included in the unit.

Overall, hydroacoustics offers diverse, adaptable, and non-invasive methods to sample large volumes of water in a nearly continuous manner, regardless of current speed or light levels. This is extremely useful in highly variable tidal environments, and fish presence and vertical distribution may be studied with extremely high temporal and spatial resolution. However, external noise sources or entrained air (common in high velocity environments) can affect the quality of hydroacoustic data (Simmonds and MacLennan 2005). Additionally, sampling can be limited by acoustic "deadzones" which occur near boundaries such as the seafloor or surface, in which fish or other targets cannot be distinguished from the surface or substrate (Ona and Mitson 1996). Also, the echo strengths of fish are affected by fish physiology (with or without swim bladder) and behavior (e.g., tilt angle or dense schooling), which can influence number and size/species estimates (Simmonds and MacLennan 2005). Equipment costs can be high, especially for complex systems such as split- or multi-beam echosounders. Data storage can become an issue for long-term surveys, especially for autonomous deployments.

Data processing must be kept in mind when designing acoustic surveys. Huge volumes of data are produced by continuous sampling, and though processing can be automated to some extent, manual inspection is always required and is time consuming. Additionally, acoustics data alone are generally not enough for species identification, especially in environments with highly diverse fish communities. Surveys are usually be combined with physical sampling, such as trawling, to verify the species of fish detected (Simmonds and MacLennan 2005).

1.4.5. Acoustic Imaging: the Dual-frequency IDentification SONar (DIDSON)

DIDSON is a form of multi-beam acoustic equipment which uses the feedback from multiple stacked sound beams to construct a video-like image of a fan-shaped sampling volume. DIDSON operates in very high frequencies (1.1 or

1.8 MHz) and as such has a relatively short sampling range (approximately 40 m at 1.1 MHz and 12 m at 1.8 MHz). DIDSON data are particularly helpful for providing accurate length measurements of fish and has been used in applications such as detecting the passage of migrating salmon (Ransom et al. 1998) and characterizing the diel movements of different size classes of fish in an estuary (Becker et al. 2011). DIDSON also offers the unique opportunity to observe fish behaviors in detail and has been used to study the reactions of fish to a pelagic trawl (Rakowitz et al. 2011) and to a hydrokinetic tidal turbine (Chapter 3). As the DIDSON uses sound to create an image rather than light, it is effective in dark or turbid environments where cameras have limited utility. This is especially appealing for tidal applications, where nighttime monitoring of fish-turbine interactions is important. DIDSON could be very useful for applications such as turbine monitoring (Chapter 3) or for verification of fish targets in other acoustic data (Chapter 2). Unfortunately, DIDSON units are much more expensive than other acoustic systems, such as single- and split-beam echosounders.

1.5. Case study: Cobscook Bay

Cobscook Bay, Maine, is currently host to the largest commercial tidal energy project in the United States. In March 2012, Ocean Renewable Power Company (ORPC) started installing a pilot tidal energy device on the sea floor. This device consists of four cross-flow turbines aligned end-to-end on a horizontal axis, with a permanent magnet generator in the center. Each turbine contains four helical blades and is approximately 6 feet (1.8 m) in diameter and 20 feet (6.1 m) in length. The entire turbine structure is 102 feet (31.1 m) long, and is held approximately 24 feet (7.3 m) above the sea floor by a solid steel frame. Plans for this deployment prompted the start of the fish assessment study, and baseline data collection started in 2010, two years before the expected installation date. The literature review conducted at the outset revealed that little was known of the fishes of Cobscook Bay. Most studies had taken place in adjacent Passamaquoddy Bay and were dated (Tyler 1971, MacDonald et al. 1984). Furthermore, these studies were not always in agreement on seasonality or presence of species. While they identified several key species in the area, none of these studies considered the vertical distribution of pelagic species in relation to season, tide, or diel cycles (except for Atlantic herring in Passamaquoddy Bay; Brawn 1960a).

1.5.1 Site Considerations

Cobscook Bay is located at the mouth of the Bay of Fundy, and consists of three smaller bays joined by narrow channels. The bay’s nearly enclosed nature combines with its high tidal range (mean range of 5.7 m; Brooks 2004) to generate tidal current speeds in excess of 2.5 $m \cdot s^{-1}$ in the outer bay, the site of the pilot tidal energy project. Here, tidal mixing is very strong, resulting in nearly uniform salinity and temperature throughout the outer bay (Brooks 2004). The outer bay is the only link between deeper ocean waters and the inner bays, which have expansive intertidal zones that could serve as nurseries and feeding grounds for many species during the summer months.

Surveys were carried out at an impact site and a control site. The impact site was chosen to be as close as possible to the future pilot project, located mid-channel location at the upper end of the outer bay, where the minimum low-tide depth was 24 m and the maximum high-tide depth was 35 m. The control site was chosen to be as similar as possible in depth and flow pattern, though it was slightly deeper (31 m to 45 m, minimum and maximum) and had current speeds that were slightly less constant with depth than at the project site. Current speeds over the course of a tidal cycle were relatively well matched, however.

1.5.2 Sampling Gear

Stationary, down-looking hydroacoustic surveys were chosen as the primary means of data collection, given the desire to characterize fish present at the project site with fine vertical and temporal resolution, during all tidal stages. A wide-angle, single-beam echosounder system was used to sample as large a volume as possible, especially near the surface. Another goal of the project was to develop a cost-effective method for initial site assessments related to marine renewable energy, and single beam echo sounders were best suited for that need. A DIDSON acoustic camera was used in conjunction with the single-beam echo sounder to obtain acoustic images of the upper 10 m of the water column. Though species identification was not one of the initial goals of this project, the DIDSON provided length and behavior information that could not be extracted from single beam data and aided in distinguishing entrained air or krill from schools of fish in the upper water column (Chapter 2), all of which appear similar in the single-beam echosounder data.

Sampling was carried out at least once per season, beginning in May of 2010 (Table 1.1). Each site was surveyed continuously for 24 hours, with survey dates chosen to ensure two tidal cycles during the day and two at night. This was not always possible when nights or days were very short.

Year	Winter	Spring	Summer	Fall
2010		May	June, Aug	Sept, Oct, Nov
2011	Jan, Mar	May	June, Aug	Sept, Nov

Table 1.1. Hydroacoustic sampling schedule. Months sampled by 24-hour stationary hydroacoustic surveys at project and control sites in Cobscook Bay in 2010 and 2011.

1.5.3 Data Analysis

Volume backscatter and total area backscatter were used as relative estimates of fish density, but fish were not enumerated or sized since target strength values could not be obtained from the single beam data. Total water column backscatter was assumed proportional to overall fish abundance, and the vertical distribution of backscatter throughout the water column was assumed indicative of fish distribution. DIDSON data were primarily used to distinguish between fish and non-fish aggregations in the upper water column, but the upper 10 m of hydroacoustic data were excluded due to interference from entrained air.

Relative abundance (density) and vertical distribution of fish could be obtained for any span of time, from minutes to the entire 24 hours sampled in a survey. Distributions for ebb and flood tides during the day and night were compared, revealing distinct effects in many surveys. By examining the relative abundance of fish in each survey over time, seasonal patterns in fish presence were also apparent and were similar at both sites for both years, though overall density changed substantially between years.

1.6. Discussion

1.6.1. Sampling Schedule

The sampling schedule, involving a one-day survey at each site for 8 months of the year proved logistically simple but time intensive. Running acoustic equipment over the side of a vessel moored mid-channel required the constant presence of at least two people. This sampling scheme resulted in points of extremely high-resolution data spread across two years (Chapter 2);

however, increasing survey frequency and sampling multiple times per month would greatly increase the ability to better distinguish patterns within natural daily variability. Operation costs limited the ability to increase the temporal sampling regime. However, increased cost could be mitigated by applying those funds to deploy an autonomous acoustic system on the sea floor, programmed to record data at intervals over a longer period of time (on the order of a month or more, depending on battery life). This would spread sampling more evenly across longer time spans, increasing overall resolution without requiring as many hours of boat time and allowing time series analyses. However, autonomous systems are not readily available and are costly.

1.6.2. BACI Approach

Despite the hydrodynamic and geographic differences between the control and impact site, similar seasonal patterns in relative fish abundance were found at both locations. This pattern was the same in both years, and both sites also showed similar changes in overall fish density from 2010 to 2011. The similarity in trends at both sites supports the role of the control site for distinguishing natural variation from turbine effects, despite the highly variable environment of the bay.

1.6.3. Sampling Gear

As the project progressed, it became clear that more information on the species present was necessary. An additional study was initiated to characterize the fishes of the bay, using trawls where possible in all three bays, and extensive beach seining. This sampling effort has added greatly to what was gleaned from the literature review, revealing some species that were not expected and confirming the presence or absence of others. Though the amount of trawling that can be carried out alongside the acoustic surveys was limited, it will likely aid in verifying the species detected with down-looking hydroacoustics. However, it is suspected that some of the faster fish known to be in the area are avoiding the trawl, including Atlantic mackerel. The addition of more nighttime trawls may reduce net avoidance and allow a more complete picture of species presence.

The relative density measurements obtained with the single-beam acoustic system are useful, but it became clear that for this study, more information is required. Without reliable target strength values, it could not be certain that omitted signals were not from fish. As the reality of the tidal device deployment progressed, the focus of the fish assessments shifted toward species identification and movements of the various components of the fish community. For this, accurate target strength values are necessary. As such, a split-beam echo sounder has been purchased, and will be integrated into surveys beginning in May 2012. Changing equipment just before beginning the “impact” phase of sampling may complicate before-after comparisons. However, calibration of the two systems (single- and split-beam) and comparison of concurrent data will help mitigate any effects of equipment change. Examination of the vertical distributions of fish by size groups should reveal more species- or size-specific diel and tidal behaviors, and on- and off-shore movements, many of which are likely not discernible when species must be grouped into a single metric.

Though a split-beam system will overcome many of the analytical limits of the single-beam system currently in use, all acoustics surveys are subject to interference from a myriad of external noise sources. In Cobscook Bay, there is a significant amount of entrained air in the upper 10 m of the water column, sometimes extending nearly to the bottom in rough weather conditions. This masks a good deal of signals from fish, which can be seen amidst these clouds in the DIDSON. The upper 10 m of the water column had to be omitted from analysis of single beam data because of this (Chapter 2), which constitutes nearly half of the water column at low tide. This issue has yet to be resolved.

1.7. Recommendations

A BACI design is recommended for the assessment of tidal power devices' affects on fish, focusing on changes in fish presence and vertical distribution at project and control sites. Stationary hydroacoustic surveys can obtain data with the high temporal and spatial resolution necessary for these analyses. A split-beam echosounder should be used, if possible, due to the greater ability to identify detected fish and examine the movements of different groups. Autonomous acoustic data collection will likely allow for much more thorough sampling over a longer time frame. Acoustic surveys should be accompanied by physical sampling methods (using a trawl with spreader doors) to verify acoustic targets, but this may be difficult for most sites of interest. If concurrent fish tagging studies are ongoing in a region, at least one acoustic receiver should be deployed somewhere in the study area; however, these should not be located too near the tidal power device, as structure noise will decrease the receiver's detection range. Regardless of the methods or sampling gear chosen, high-resolution information on fish use of the water column at a tidal project site should be the result. The ability to analyze fish presence and vertical distribution on a wide range of time scales is necessary for the assessment of extremely tidal regions, where fish behavior is largely governed by cyclical environmental changes over widely different scales.

CHAPTER 2

VERTICAL DISTRIBUTION OF FISH AT A TIDALLY DYNAMIC REGION TARGETED FOR ENERGY EXTRACTION

2.1. Abstract

The use of tidal currents by fish for movements to and from onshore spawning, foraging, and nursery grounds is well documented. However, fish use of the water column in extremely tidal areas, where current speeds are frequently in excess of 1.5-2 $m{\cdot}s^{-1}$, is largely unknown. This information is necessary to determine the environmental effects of tidal energy devices, which are installed in high-current areas at fixed locations within the water column. A pilot tidal energy device will be installed in outer Cobscook Bay, Maine in 2012. To assess its effects on fish, in 2010 and 2011, down-looking hydroacoustic surveys were used to collect pre-deployment data on the presence and vertical distribution of fish at the proposed pilot project site and at a control site. Twenty-four-hour stationary surveys were conducted at each at least once every season. Relative fish density and distribution were analyzed with respect to annual, seasonal, diel, and tidal cycles. In both years and both sites, fish density increased in the spring (May) and late fall (November). Fish density nearly always increased toward the sea floor, and there was evidence of vertical movements related to diel and tidal cycles, though these were not consistent

from survey to survey. This work has established a baseline dataset for the comparison of similar acoustic data that will be collected post-deployment of the pilot tidal device.

2.2. Introduction

The importance of tidal flows to fish ecology is well documented. Several migratory species utilize selective tidal stream transport to move on- or off-shore (or in and out of freshwater), moving into the water column when the current is flowing in a favorable direction but moving to the bottom, where the current is slower, when it changes direction. Some examples include American eel, *Anguilla rostrata* (McCleave and Kleckner 1982); Atlantic cod, *Gadus morhua* (Arnold et al. 1994); sockeye salmon, *Oncorhynchus nerka* (Levy and Cadenhead 1995); sea trout, *Salmo trutta* (Moore et al. 1998); and plaice, *Pleuronectes platessa* (de Veen 1978, Greer Walker et al. 1978). Atlantic salmon, *Salmo salar,* migrating upriver (Stasko 1975) and Atlantic mackerel, *Scomber scombrus*, migrating into the Gulf of St. Lawrence (Castonguay and Gilbert 1995) have been observed moving with flood tides more than ebbs, and so may also use selective tidal stream transport, though associated vertical migrations have not been observed. Atlantic herring, *Clupea harengus*, have been found to swim with favorable tides but against opposing ones in order to maintain position (Lacoste et al. 2001), and fish have also been shown to simply move back and forth with both flow directions, traversing up to several kilometers per tidal cycle (Sakabe and Lyle 2009). Beyond the vertical migrations involved in selective tidal stream transport, fish use of the water column in extreme tidal currents remains largely unknown.

Cobscook Bay is a highly productive bay located at the mouth of the Bay of Fundy, consisting of an inner, central, and outer bay joined by narrow channels. The bay is known for its high biodiversity, which is largely due to the extreme tidal mixing that takes place there (Larsen and Campbell 2004). The mean tidal range is 5.7 meters, and current speeds in the bay can exceed 2 $m \cdot s^{-1}$ in the channel of the outer bay (Brooks 2004), making this area extremely attractive for tidal power development. In March 2012, Ocean Renewable Power Company (ORPC) began installing a pilot tidal energy device in the outer bay; however, the effects of the device on fish are unknown, and little information exists to aid in predicting these effects. The presence and composition of pelagic fishes of the bay are poorly understood because most studies of the region have focused on benthic species vulnerable to trawling. Additionally, many of these studies are dated and were conducted not in Cobscook but in the adjacent Passamaquoddy Bay (Tyler 1971, MacDonald et al. 1984). Key species in the area include alewife (*Alosa pseudoharengus*), Atlantic herring (*Clupea harengus*), blueback herring (*Alosa aestivalis*), rainbow smelt (*Osmerus mordax)*, silver hake (*Merluccius bilinearis*), white hake (*Urophycis tenuis*), and Atlantic mackerel (*Scomber scombrus*), though studies do not always agree on species seasonality (Tyler 1971, MacDonald et al. 1984, Saunders et al. 2006, Athearn and Bartlett 2008). Vertical distribution of fishes in the water column is unknown, apart from one study of the vertical distribution of Atlantic herring in Passamaquoddy Bay (Brawn 1960a). These missing data are critical to assessing the potential effects of any tidal power device on fishes.

The pilot device that will be installed in outer Cobscook Bay is ORPC's TidGen™ power system, which consists of four cross-flow turbines aligned end-to-end on a horizontal axis, with a permanent magnet generator in the center (www.orpc.co; Figure 2.1). Each turbine contains four helical blades, and is approximately 6 feet (1.8 m) in diameter and 20 feet (6.1 m) in length. The entire turbine structure is 102 feet (31.1 m) long, and is held approximately 24 feet (7.3 m) above the sea floor by a solid steel frame. The TidGen™ has a peak power output of 180 kW in a 3 $m \cdot s^{-1}$ (6 knot) current, and operates at a maximum of 40 rotations per minute, which corresponds to a tip speed of approximately 5.5 $m \cdot s^{-1}$.

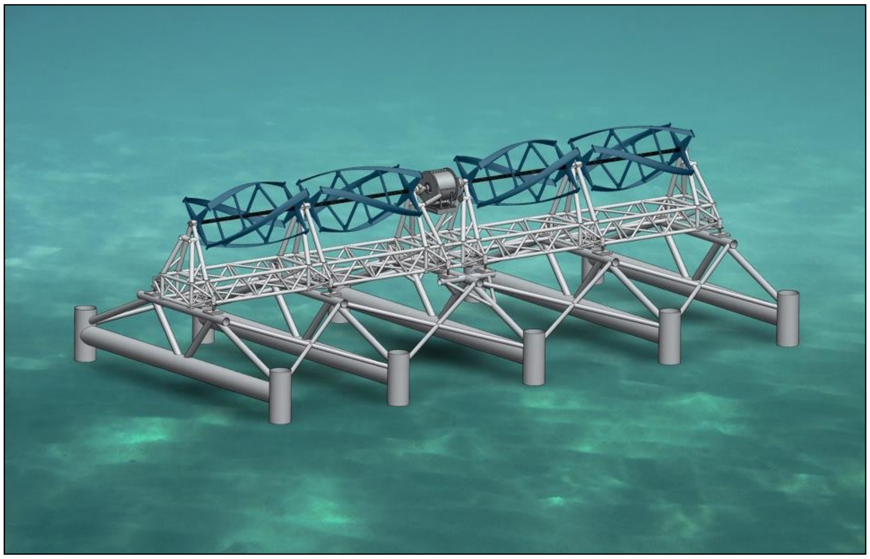

Figure 2.1. Pilot tidal energy device. Drawing of Ocean Renewable Power Company's TidGen™ Power System, the pilot project to be installed in outer Cobscook Bay.

Hydroacoustic technologies allow continuous observation of the entire water column regardless of current speed, with high spatial resolution and low disturbance to fish or other organisms (Simmonds and MacLennan 2005). A downward-looking, single beam echosounder was therefore used to examine the presence and vertical distribution of fish in the water column prior to device deployment, in order to provide a baseline for assessing the effects of the pilot tidal power device on fishes after deployment. Two years of pre-deployment data were collected at the pilot project site and at a control site nearby, addressing the following:

1. Does the density of fish in the water column vary year to year?
2. Does total water column fish density vary among months of the year?
3. Does fish density vary spatially (between sites)?
4. What is the vertical distribution of fish density in the water column?
5. Does the vertical distribution of fish density vary seasonally and annually?
6. Does the vertical distribution of fish density vary with day and night or tidal stage?

2.3. Methods

2.3.1. Site

Data were collected in outer Cobscook Bay at the future pilot project site and a control site (Figure 2.2). The future project site, CB1, was located mid-channel at 44°54.60' N, 67°2.74' W; the control site, CB2, was approximately 1.6 km farther seaward, mid-channel at 44°54.04' N, 67°1.71' W. The vessel was moored at these two sites and swung around its mooring as the direction of tidal flow changed at each slack water. This movement was minimal for most months (205 m mean difference at CB1, 147 m mean difference at CB2), though positioning of the mooring at CB1 in May and June of 2010 caused the boat to swing over a very deep region during most of the ebbing tide. Ebb tide data were subsequently omitted from analyses for these months. Under normal conditions, water depth at CB1 ranged from an average of 24.5 m at low tide to 32.3 m at high tide, and from 33.8 m to 41.3 m at CB2. At CB1, average current speed (water column mean) was 1.01 m·s^{-1} (2.0 knots), with a maximum of 2.06 m·s^{-1} (4.0 knots). At CB2, average current speed was 0.87 m·s^{-1} (1.7 knots), with a maximum of 1.78 m·s^{-1} (3.5 knots).

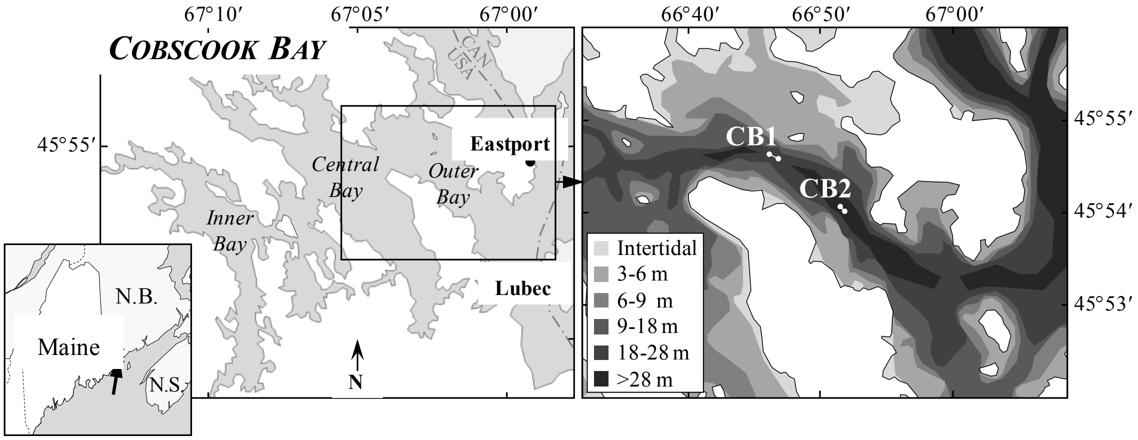

Figure 2.2. Map of Cobscook Bay and locations of hydroacoustic surveys. Left: Cobscook Bay, Maine. Right: Sampling sites in the outer bay, showing bottom depth (from Kelley and Kelley 2004). Mean ebb and flood positions are indicated by the white-filled circles.

2.3.2. Equipment

Surveys were carried out from a moored, 40-foot (12.2 m) fishing vessel (Figure 2.3). A dual-frequency (38 kHz and 200 kHz) single beam Simrad EK60 echo sounder was used with a 31° (half power beam angle) circular transducer. The echo sounder was operated at 2 pings per second with a pulse duration of 0.512 ms for all surveys except May and June 2010, when 1.024 ms and 0.256 ms pulse durations were used, respectively. The transducer insonified a 31° conical volume of water from the surface to the sea floor, though it is likely that some fish near the surface and seafloor were not detected due to the acoustic deadzones (Ona and Mitson 1996, Horne 2000). The vertical resolution of the transducer was approximately 38 cm when using the 0.512 ms pulse length (most surveys), and resolution was 19 cm and 76 cm with the 0.256 ms and 1.024 ms pulse lengths, respectively.

The Simrad echo sounder was calibrated using standard copper calibration spheres as recommended by Foote et al. (1987). In-situ on-axis calibrations were carried out at slack tide at least once during each sampling session. The position of the spheres within the beam was approximate because the water was rarely completely still. Therefore, calibration values obtained in this manner were only used to assure continued equipment functionality. To obtain accurate calibration offsets, in January 2011 and February 2012 the echo sounder was taken to a frozen lake, where the water was still, to be sure of the location of the spheres in the echosounder beam. On-axis calibrations were performed for both frequencies at all power and pulse length settings used during surveys, and corrected transducer gains and volume backscatter calibration constants were calculated for each setting. During the 2011 calibration, the beam pattern was also characterized and found similar to that provided by the manufacturer.

A DIDSON (Dual-frequency IDentification SONar) was used in conjunction with the Simrad echo sounder. The DIDSON operated at 1.8 MHz frequency and captured approximately 8 frames per second, producing video-like images of a 29°x14° sampling volume with a range of 10.8 m. Vertical resolution (along the length of the viewing window) was 2.0 cm. Horizontal resolution was 0.5 cm at the start of the viewing window (1.0 m from the DIDSON lens) and 7.0 cm at its maximum range. Both the Simrad transducer and the DIDSON were mounted 1 meter below the surface over the port side of the vessel, facing downward (Figure 2.3).

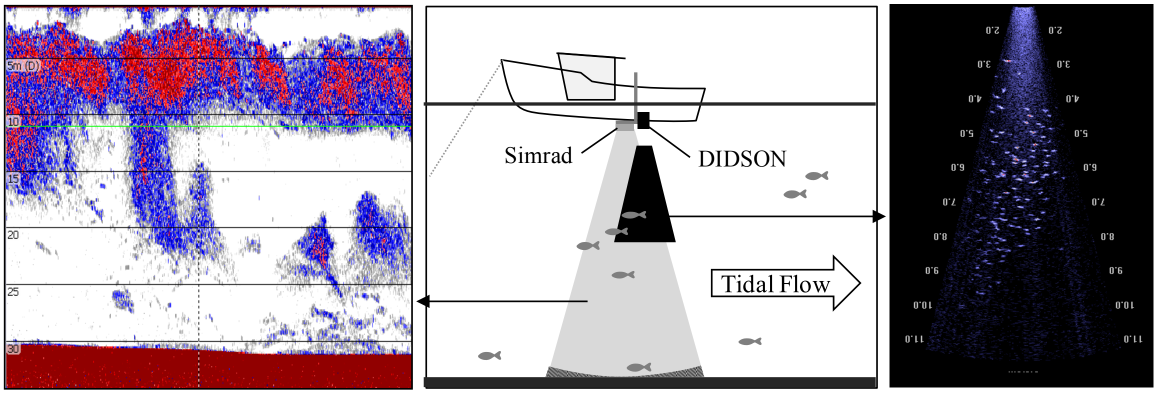

Figure 2.3. Acoustic survey setup and sample data. Stationary acoustic survey setup (center). Light grey filled area represents volume insonified by the Simrad echosounder; hatched lines indicate the acoustic deadzone. Dark grey area indicates field of view of DIDSON. Left: Sample segment of data from Simrad echosounder. Right: sample frame from DIDSON footage, showing individuals in the upper portion of the aggregation seen in the Simrad data.

Current speed readings were obtained with either a Marsh-McBirney (MM) flow meter (May 2010-May 2011) or an Acoustic Doppler Current Profiler (ADCP) (June 2011-November 2011). These were also mounted over the side of the vessel about 1 meter below the surface (MM flow meter to starboard; ADCP to port, just aft of the DIDSON and Simrad transducer). The MM flow meter recorded surface current speed only, while the ADCP recorded current speeds throughout the water column with vertical resolution of 1 m.

2.3.3. Field Sampling

Twenty-four-hour stationary surveys were carried out at the two sites at least once each season, beginning in May of 2010 (Table 2.1). Surveys were scheduled with the goal of sampling nearly two complete tidal cycles: one at night and one during the day. Depending on the time of year, this was not always possible; in May and June, nights encompassed only one tidal stage, and in March, this was true for days. Environmental data were recorded every half hour, and included cloud cover, precipitation, sun/moon visibility, qualitative wind speed and wave height, and current speed (when using the MM flow meter). When using the ADCP, current speed was automatically recorded every half hour. Salinity was 32 ± 0.45 ppt in May, June, August, and September surveys in 2011 (unpublished data), and was assumed to vary little over the course of the year in this very well-mixed area (Brooks 2004, Larsen and Campbell 2004).

2.3.4. Data Analysis

The raw data used in analyses were volume backscatter. Volume backscatter is the total contribution of acoustic backscatter from all the targets within the volume of water sampled, expressed in units of $m^2 \cdot m^{-3}$ in the linear domain or in decibels (dB) in the logarithmic domain (Simmonds and MacLennan 2005). When sampling fish, volume backscatter can generally be assumed a relative measure of fish density. It can be used to estimate the number of fish detected if combined with accurate target strength readings or detailed knowledge of the fish being sampled. This was beyond the scope of our analyses because target strength values obtained with the single-beam echo sounder could not be corrected for losses associated with beam pattern. Instead, total area backscatter was chosen to represent fish density in various layers of the water column. Total area backscatter is the summation of volume backscatter over a range of depths, and is expressed linearly in $m^2 \cdot m^{-2}$ (s_a) or in dB (s_A). Linear values were used in analyses and figures.

For each site (analyzed separately), acoustic data were processed then analyzed. Data analyses consisted of two main parts: a) analysis of the variance in total water column backscatter (i.e., fish density) in relation to year, month, and diel and tidal cycles; and b) analysis of the vertical distribution of backscatter (i.e. fish density) within the water column in relation to year, month, and diel and tidal cycles.

Year	Month	Site	Days	Start – end time	Mean surface temp. (°C)	Tidal depth range (m)	Moon phase
2010	5	CB1	19 – 20	06:30 – 06:00	7.5	25 – 49	🌒
		CB2	21 – 22	09:00 – 09:00	7.8	31 – 41	🌔
	6	CB2	13 – 14	06:40 – 07:40	9.4	33 – 40	🌑
	8	CB1	5 – 6	08:15 – 08:30	13.3	25 – 30	🌘
		CB2	4 – 5	07:45 – 08:00	13.3	35 – 40	🌘
	9	CB1	6 – 7	06:10 – 06:10	14.3	24 – 31	🌑
		CB2	7 – 8	07:00 – 07:40	13.9	34 – 45	■
	10	CB1	17 – 18	13:40 – 13:40	11.9	26 – 35	🌔
		CB2	19 – 20	17:20 – 14:00	11.7	36 – 42	🌔
	11	CB1	20	07:30 – 16:10	9.6	24 – 31	◙
		CB2	17 – 18	06:00 – 07:30	9.6	36 – 45	🌔
2011	3	CB1	15 – 16	07:00 – 06:30	2.9	25 – 30	🌔
		CB2	16 – 17	22:15 – 22:00	3.0	34 – 41	🌔
	5	CB1	28 – 29	08:00 – 08:00	7.9	24 – 30	🌘
		CB2	27 – 28	07:45 – 07:45	7.8	32 – 41	🌘
	6	CB1	26 – 27	08:00 – 08:00	10.2	24 – 30	🌘
		CB2	27 – 28	08:50 – 08:50	10.4	33 – 40	🌑
	8	CB1	22 – 23	05:45 – 05:45	13.8	25 – 30	🌗
		CB2	23 – 24	06:20 – 06:00	13.5	35 – 40	🌘
	9	CB1	22 – 23	06:20 – 06:30	13.0	24 – 29	🌘
		CB2	23 – 24	07:00 – 06:30	12.9	33 – 40	🌑
	11	CB1	16 – 17	14:00 – 14:00	10.5	24 – 30	🌖
		CB2	18 – 19	14:40 – 14:40	10.5	33 – 40	🌗

Table 2.1. Hydroacoustic survey information. Sampling dates, times, and basic environmental data.

2.3.4.1. Acoustic Data Processing

Acoustic data processing was carried out using Echoview software (5.1, Myriax Pty. Ltd., Hobart, Australia), and data values were exported for statistical analyses in MATLAB (r2011b, The MathWorks, Inc., Natick, MA, USA). In Echoview, data processing began with calibration of the data using the correct gain and volume backscatter calibration constants obtained during the winter ice calibrations (section 2.1). The volume backscatter data were then visually scrutinized, and areas of noise (for instance, from a passing boat's depth sounder) or high boat motion (for example, during slack tides, when the boat was rotating about its mooring) were identified and excluded from analyses. The upper 10 m of the water column were similarly excluded from analyses because large quantities of entrained air frequently obscured the acoustic backscatter from fish within that layer, especially during rough water. Any backscatter that showed clear evidence of entrained air that extended below 10 m was manually excluded from analyses, as were any times that indicated excessive boat movement. DIDSON footage was used to verify that excluded signals were from non-fish targets, which included entrained air as well as occasional aggregations of krill. Acoustic returns beyond the range of the DIDSON could not be verified in this way, and were not excluded unless clearly abiotic in origin (e.g., electrical interference).

A threshold was then set for the volume backscatter data, which eliminated any targets with on-axis target strengths (TS) less than -60 dB. This was done to exclude backscatter signals from non-fish targets (such as plankton, krill, and fish larvae) from analyses, while keeping signals from fish, though some fish were probably also excluded. Of fishes known to be in the region, Atlantic mackerel are among the few pelagic species lacking a swimbladder; therefore, they are likely to have some of the weakest target strengths detected. A 20-cm Atlantic mackerel (the lower size limit expected, based on local knowledge and hook-and-line sampling) would have a target strength of approximately -60 dB according to several equations converting TS to length (Foote 1980, Misund and Beltestad 1996, Simmonds and MacLennan 2005). For comparison, a 10-cm Atlantic herring, which has a swim bladder, would have a much stronger target strength of approximately -52 dB (Foote 1987). For single-beam data, setting the TS threshold at -60 dB means that a fish with TS of -60 dB is included in analyses if it swims through the central axis of the beam. However, since the acoustic beam is weaker near the edges, the same -60 dB fish swimming through the beam off-axis will appear to have a lower TS, and will be excluded from analyses. For the single-beam echosounder used in this survey, this means that Atlantic mackerel 26 cm long (TS ≈ 54 dB) are only included if swimming within 15.5° of the beam's central axis, but a herring 15 cm long would be included if within 23° of the central axis. Basically, the sampling volume is lower for fish with weaker acoustic signals than for those with stronger ones, and setting a universal threshold will exclude fishes from analyses somewhat disproportionately. Fishes that may have been present at the sampling locations and their expected minimum and maximum lengths are shown in Table 2.2, along with their theoretical target strengths.

Species	**Expected length (cm)**		**Estimated TS (dB)**		**TS-length equation source**
	Min.	**Max.**	**Min.**	**Max.**	
Atlantic herring *Clupea harengus*	10	30	-51.9	-42.4	Foote 1987
Atlantic mackerel *Scomber scombrus*	20	40	-60.3	-44.2	Foote 1980
Threespine stickleback *Gasterosteus aculeatus*	5	10	-58.5	-52.5	Jurvelius et al. 1996
Atlantic cod *Gadus morhua*	10	20	-44.8	-40.1	Foote 1987

Table 2.2. Expected fish and target strengths. Four fishes expected to be seen in the water column within the survey area, with expected lengths and target strengths calculated using equations from sources at right.

Slack tide start and end times were determined using the mean water column current speed. If current speed data were collected with the ADCP, mean water column current speed was obtained by averaging from surface to seafloor. If a survey's current speed data were surface measurements taken with the MM flow meter, a correction was applied in order to approximate the water column mean using surface measurements. This correction was obtained for each site using data collected concurrently with the ADCP and the MM flow meter in August of 2011. Slack tides were defined as periods of time when the turbine would not be rotating, beginning when the current speed fell below 0.5 $m \cdot s^{-1}$ and ending when it rose above 1.0 $m \cdot s^{-1}$. On average (± standard error), periods of slack tide were 2.9 ± 0.1 hours long at CB1 and 2.2 ± 0.1 hours at CB2. Slack tides were removed from each survey's acoustic dataset, since during these times the boat was swinging about its mooring, and the increased motion lowered the quality of the data. Also, when a turbine would not be rotating, it would pose a lesser threat to fishes encountering it.

Remaining acoustic data were divided into analysis cells spanning 30 minutes in the time dimension and 1 m in the depth dimension. Half-hour time bins were chosen in order to capture the variability in vertical distribution over time, and to assure minimal autocorrelation of successive bins and a sample size of at least 6 time bins for each tidal stage (the shortest of which was approximately 3 hours). Depth divisions were measured upward from the seafloor rather than downward from the surface because the tidal turbine will be installed at a fixed distance above the bottom (it will span the range of 7 to 9 m above the bottom). Because the depth of the water column changes with the tide, for each survey the highest layer included in analyses was determined by the water depth at low tide minus the 10 m that were excluded due to entrained air. This value was 15 m for CB1 and 27 m for CB2, and any layers that rose above this level were ignored. Echoview was used to calculate and export the total area backscatter, in units of $m^2 \cdot m^{-2}$, of each analysis cell.

2.3.4.2. Analysis of variance in total area backscatter of the entire water column

Total area backscatter, s_a, of the water column (sea floor to highest layer analyzed) was obtained for each half-hour time bin by summing the s_a values from each layer. Each time bin was associated with a site, year, month, day or night, and a tidal stage (ebb or flood). The s_a data were not normally distributed and did not meet the assumptions of the ANOVA without transformation (Box-Cox method), so permutation tests were used to confirm ANOVA p-values. If factors were found to have significant effects, Scheffe multiple comparison tests were used on transformed data to determine which groups of means, if any, were different.

2.3.4.3. Analysis of the distribution of area backscatter within the water column

The vertical distribution of backscatter (i.e., relative fish density) within the water column was obtained for multiple time spans of interest by calculating the mean backscatter for each layer of analysis cells within a time span. Time spans depended on the comparisons being made: for each survey, vertical distributions were calculated for the entire 24 hours sampled, day and night, and day ebb, day flood, night ebb, and night flood. The effects of factors such as year, month, day and night, and tidal stage on vertical distribution were determined by comparing the corresponding distributions. Comparison consisted of analyzing the similarity of the shapes of the distributions, as well as the offset between them (i.e., the difference between their means). To quantify the similarity of shape, one distribution was linearly regressed onto the other. The significance of this regression and the slope of the regression line were used as parameters indicative of shape similarity. If the fit was significant ($p \leq 0.05$) and the slope was not negative, the shapes were considered similar. If the fit was not significant or the slope was negative (which would indicate opposite trends), the shapes were considered dissimilar. In many comparisons, one stage had consistently higher backscatter throughout the water column than the other (offset). The significance of this offset was evaluated using a two-sample, two-tailed Student t-test ($p \leq 0.05$).

2.4. Results

2.4.1. Does the density of fish in the water column vary year to year?

Analysis of the water column s_a revealed that year had no significant effect on overall fish density at CB1 ($p = 0.12$), but that 2010 had significantly higher density than 2011 at CB2 ($p = 0.001$; Figure 2.4).

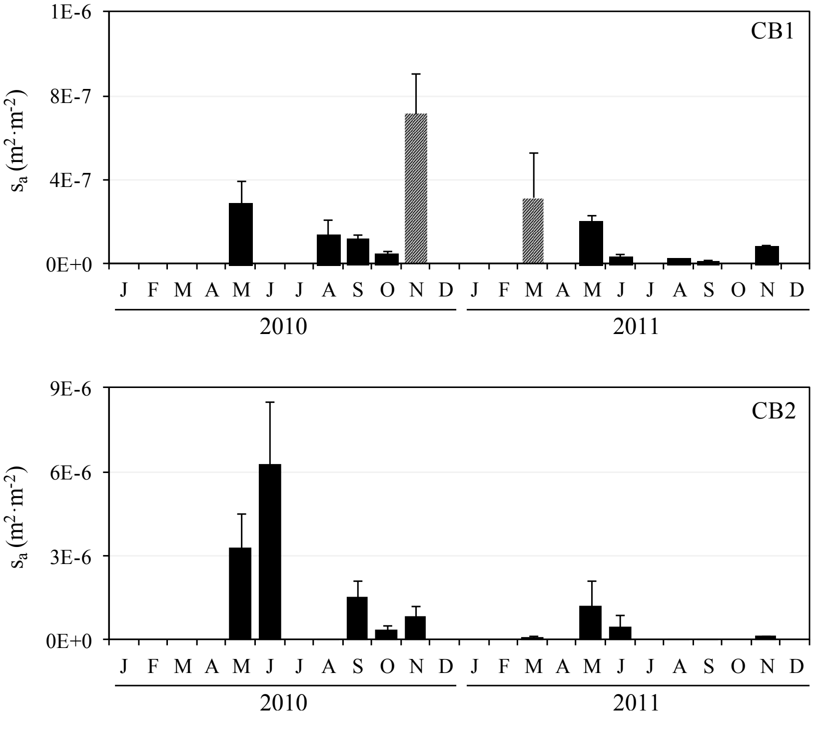

Figure 2.4. Water column total area backscatter v. sampling month. Average total area backscatter (s_a) for months in 2010 and 2011, at CB1 (top) and CB2 (bottom). Error bars are 1 standard error, crosshatched bars denote potentially abnormal values (section 4). Months lacking bars were not sampled.

2.4.2. Does total water column fish density vary among months of the year?

Relative fish density changed significantly from month to month at both sites in 2010 (CB1: $p = 0.013$, CB2: $p = 0.004$), but only at CB1 in 2011 (CB1: $p = 0.005$, CB2: $p = 0.181$) (Figure 2.4). At CB1 in 2010, November had a significantly higher fish density than the other months in multiple comparisons tests, followed by May and September, then August and October. At CB1 in 2011 , May and November had the highest densities, followed by the four other months, which were not significantly different from each other. At CB2 in 2010, there was less distinction among the months. May and June had higher densities than August, October, and November; September spanned these two groups, having greater fish density than August and October but not having significantly different density than the other months. At CB2 in 2011, the separation among months was more clear: May and November had significantly higher fish densities than all other months, followed by March, June, August, and September.

2.4.3. Does fish density vary spatially?

Relative fish density varied significantly from site to site only in 2010, when fish were an order of magnitude less dense at CB1 than at CB2 ($p = 0.001$;

CB1: $2 \cdot 10^{-7} \pm 3.5 \cdot 10^{-8}$; CB2: $2.1 \cdot 10^{-6} \pm 4.9 \cdot 10^{-7}$). In 2011, relative density was not significantly different at the two sites ($p = 0.613$).

2.4.4. What is the vertical distribution of fish density in the water column?

Backscatter from fish was observed in all parts of the water column (Figure 2.5). Fish density almost always increased with depth, except for three surveys in which fish density increased in the upper layers analyzed. These surveys included all tides in May 2011 and the daytime ebb tide in August 2010 and June 2011. Fish were sometimes concentrated in one or two layers in the middle of the water column (e.g., day flood in September 2011). These mid-column increases in density were generally associated with the passage of several small, dense schools of fish during that time span.

2.4.5. Does the vertical distribution of fish density vary seasonally and annually?

At CB1, the vertical distribution of fish varied from month to month in both years (left-hand blocks, Figure 2.5). For those months that were sampled in both years, survey distributions from 2010 were compared to the corresponding surveys in 2011. Fish had similarly shaped distributions in both years in August and November, but were distributed differently in May and September (Table 2.3). May was strongly bottom-oriented in 2010, but top-oriented in 2011 (Figure

2.5). September 2010 and 2011 were similar when compared visually, except that in 2011 there was an increase in density in the 10-11 m layer (Figure 2.5). Differences in the magnitudes of the distributions in 2010 and 2011 were more obvious, as can be clearly seen in the un-scaled distributions in the left blocks of Figure 2.5. Fish densities throughout the water column were higher in 2010 than in 2011 in all months surveyed besides May, in which magnitude did not change significantly between years (Table 2.3). These differences reflect what was shown by the analysis of total water column backscatter (section 3.2).

Month	**Distribution shape: Significance of linear fit (p-value)**	**Distribution mean: 2010 or 2011 greater?**
May	0.243	Same
Aug	0.003	2010
Sept	0.274	2010
Nov	$1.78 \cdot 10^{-5}$	2010

Table 2.3: Vertical distributions of fish at CB1, 2010 v. 2011. Similarity of 2010 and 2011 entire-survey vertical distributions of fish at CB1. Shaded cells indicate significant difference. For shape, insignificance of the linear regression ($p > 0.05$) or negative slope indicate dissimilarity.

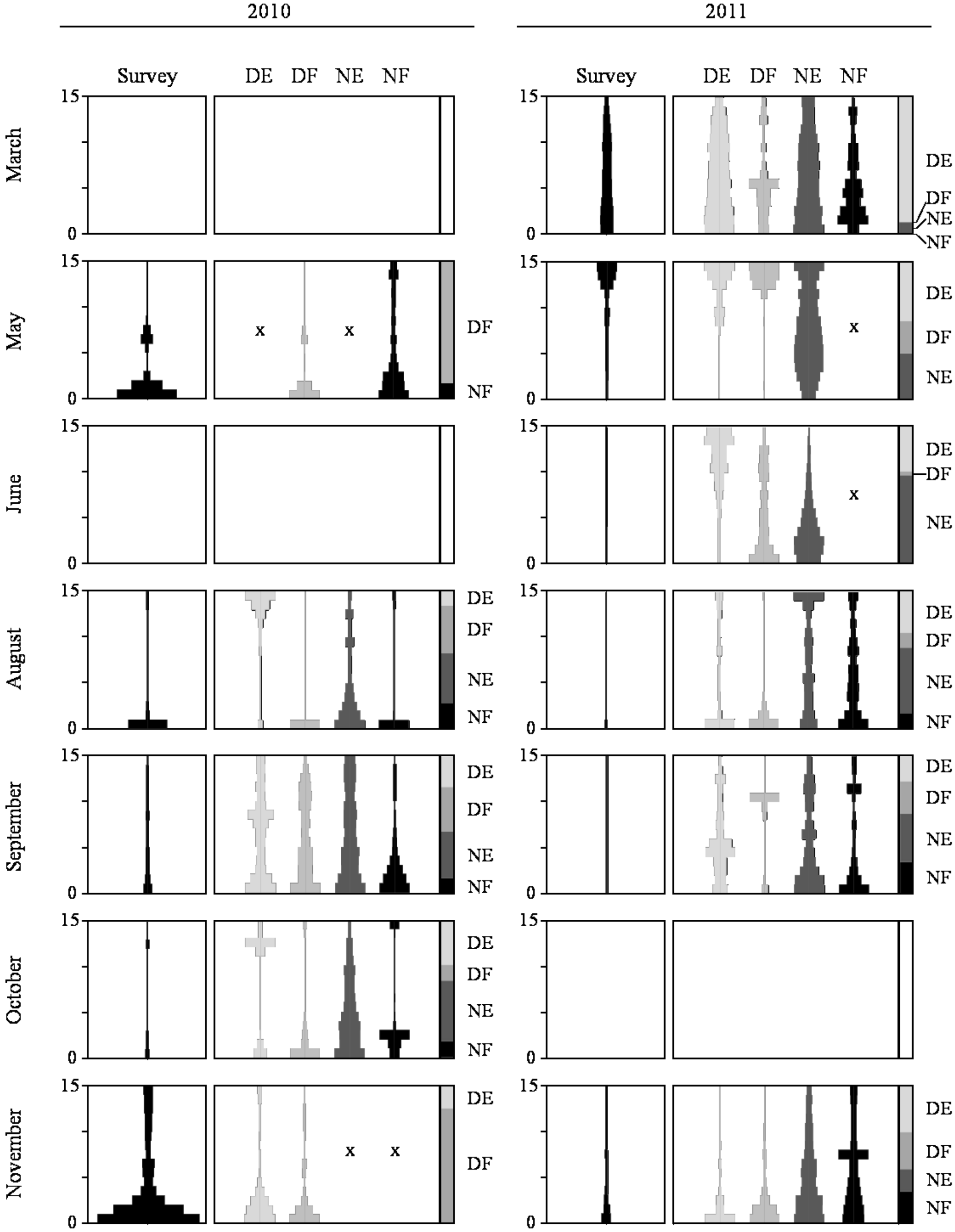

Figure 2.5. Vertical distributions of fish at CB1. Relative vertical distribution of fish within the water column at CB1 for 2010 (left column) and 2011 (right column). The vertical axes are distance from sea floor in m, the horizontal axes are relative total area backscatter (s_a), proportional to fish density. In each column, entire-survey distributions are shown in the left block, in black. These are to scale to allow visual comparison of relative density in different surveys. The right blocks contain the relative distributions for each tidal stage, separated into day ebb (DE), day flood (DF), night ebb (NE), and night flood (NF). These distributions are normalized to show small backscatter values. The vertical bar to the right shows the relative backscatter (fish density) of each stage. X's indicate unavailable data.

2.4.6. Does the vertical distribution of fish density vary with day and night or tidal stage?

Fish distributions changed shape with day and night in 4 of the 11 surveys, including October 2010 and May, June, and September of 2011. In Figure 2.5, this can be seen in general as a more filled water column during at least one of the night tides. While the shape of fish distributions differed in 4 of the surveys, overall magnitude differed in 3: fish density was less during the day than the night in August of 2010 and June of 2011, but greater during the day in March of 2011 (Table 2.4).

Year	Month	Distribution shape: significance of linear fit (p-value)	Distribution mean: day or night greater? (D/N)
2010	May	< 0.001	Same
	Aug	< 0.001	N
	Sept	< 0.001	Same
	Oct	0.689	Same
	Nov	–	–
2011	Mar	< 0.001	D
	May	0.935	Same
	June	0.002	N
	Aug	0.036	Same
	Sept	0.903	Same
	Nov	< 0.001	Same

Table 2.4. Vertical distributions of fish, day v. night. Similarity of day and night vertical distributions of fish at CB1. Shaded cells indicate significant difference. For shape, insignificance of the linear regression (p > 0.05) or negative slope indicate dissimilarity.

Fish distributions also varied with tide (Table 2.5). The shapes of the distributions were affected by tide more often during the day (August and October 2010, March, June, and September 2011) than at night (October 2010, August 2011). In 10 of the 13 instances when offsets between distributions were significant, densities were greater during the ebb tide than the flood tide.

Year	Month	Day or Night	Significance of linear fit (p-value)	Greater density in ebb or flood? (E/F)
2010	May	D	–	–
		N	–	–
	Aug	D	0.932	Same
		N	0.001	E
	Sept	D	0.039	F
		N	< 0.001	E
	Oct	D	0.373	Same
		N	0.068	E
	Nov	D	< 0.001	F
		N	–	–
2011	Mar	D	0.132	E
		N	0.006	E
	May	D	< 0.001	E
		N	–	–
	June	D	0.072	E
		N	–	–
	Aug	D	< 0.001	E
		N	0.120	E
	Sept	D	0.406	Same
		N	< 0.001	E
	Nov	D	< 0.001	Same
		N	0.016	F

Table 2.5. Vertical distributions of fish, ebb tide v. flood tide. Similarity of tidal stage vertical distributions of fish at CB1. Shaded cells indicate significant difference. For shape, insignificance of the linear regression ($p > 0.05$) or negative slope indicate dissimilarity.

2.5. Discussion

Primary features of Cobscook Bay are its high biological productivity and its extreme tidal currents (Brooks 2004, Larsen and Campbell 2004). The bay has complicated geography, which combines with its large tidal range to create high current speeds and flow that vary greatly with location and tide (Brooks 2004, Huijie Xue, unpublished data). Multiple fish species pass through the strong currents of the outer bay to move between deeper ocean habitats and the extensive inshore nurseries and foraging grounds of the inner bays. These include migratory fish species, such as alewives, blueback herring, rainbow smelt, silver hake, white hake, and Atlantic mackerel, as well as year-round residents, such as Atlantic herring and threespine stickleback (Tyler 1971, MacDonald et al. 1984, Saunders et al. 2006, Athearn and Bartlett 2008). Given the extreme variation in currents over time and space, as well as the mixed seasonal and year-round fish community, acoustic estimates of relative abundance and vertical distribution were expected to show high variation.

Though acoustic backscatter (i.e., fish density) at the control site, CB2, was an order of magnitude greater than that of the project site, CB1, similar yearly and seasonal trends were seen at both sites. At both sites, fish density increased in the spring and fall. The largest difference between the seasonal patterns at the two sites were November 2010 and March 2011, which had much higher fish densities relative to the other surveys at CB1 than at CB2 (Figure 2.4). Both instances can be linked to unusual circumstances. The November 2011 survey occurred during a storm, and fish density during the partial flood tide sampled was much greater than it was during the ebb of that survey as well as any of the other surveys at CB1. Abnormality of this high backscatter was verified by comparison with fish densities at CB2, which was sampled just two days prior but in good weather conditions. The increase in relative density was much more modest there. The storm is the best explanation for this great difference. Relative density in March 2010 was greatly affected by the passage of two large schools in an otherwise nearly empty water column. The same schools did not pass through CB2, and backscatter there was much less in March than in other months. If these two surveys are eliminated from CB1 data, CB1 and CB2 both show significantly higher fish densities in 2010 relative to 2011 ($p = 0.001$). It is beyond the scope of this study to explain this yearly variation, but the fact that both sites show similar trends on an annual and seasonal scale (despite large differences in magnitude) supports the use of CB2 as a control site, and its importance in identifying variation that may be out of the ordinary.

Given the seasonal pattern in total fish density at each site, and the seasonal variation in both species and size composition of the fish community, patterns in vertical distribution on seasonal, diel, and tidal cycles were expected.

Atlantic herring, alewives, and juvenile Atlantic cod are all species present in the area that are known to exhibit diel vertical migrations (Brawn 1960a, Janssen and Brandt 1980, Blaxter 1985, Perry and Neilson 1988, Nilsson et al. 2003), and tidal flows can be selectively used by adult and juvenile fish of many species (Stasko 1975, de Veen 1978, Greer Walker et al. 1978, Arnold et al. 1994, Castonguay and Gilbert 1995, Levy and Cadenhead 1995, Moore et al. 1998, Lacoste et al. 2001). While patterns in vertical distribution of fish associated with these factors were not consistent from survey to survey at either CB1 or CB2, there were distinct differences associated with day/night, tide, or a combination of the two factors in several surveys.

Diel changes in fish distribution were observed in several surveys, including August and October 2010 and May, June, September, and November of 2011 (Figure 2.5, Table 2.4). In these surveys, fish were more evenly distributed at night than during the day. The strongest example of diel changes in distribution was seen in May of 2011, when during the day, fish were concentrated in the upper few layers of the water column analyzed, but at night they spread throughout the water column. In this case, fish were near enough to the surface to clearly observe this behavior with the DIDSON. Almost all fish observed in the DIDSON footage were small (on the order of 5 cm) and aggregated in tight, small schools during the day that remained in the upper half or so of the water column. At night, these schools dispersed throughout the water column, extending downward from the upper layers. This is obvious in the vertical distributions, and is consistent with known diel behavioral patterns in fish (Janssen and Brandt 1980, Luecke and Wurtsbaugh 1993, Nilsson et al. 2003). These small fish are also unlikely to have much control over their horizontal movements in the strong tidal currents throughout the outer bay, which may explain why they were seen in abundance during the ebb as well as the flood tides. The unusually low variety in fish sizes in the DIDSON footage from this survey, though not necessarily representative of the entire water column, may indicate that on this day a more uniform group of fish was sampled than usual. This is perhaps one reason the diel behavior is so obvious. As many diel patterns are species- and site-specific (Weinstein et al. 1980, Levy and Cadenhead 1995, Neilson and Perry 2001), the more mixed the fish community, the less clear these patterns will appear. This is likely to be a common problem faced in Cobscook Bay, given its diverse and variable fish community. This problem is exacerbated by the inability to estimate fish size from the single-beam acoustic data; for this, a split-beam echo sounder is required.

Significant changes in distribution with tidal stage were relatively common at CB1 (Table 2.5), however, as with diel variation, differences were not consistent from one survey to another. August 2010 is one example. During the daytime ebb, fish were concentrated in the upper 4 m analyzed (though in low densities in comparison to the other stages), and during the night ebb, fish were spread throughout the water column, increasing in density in the lower 5 m. These distributions contrasted sharply with those of flood tides, in which fish were almost entirely concentrated in the lowest water layer, regardless of day or night. This could indicate that fish sought the slower-moving boundary layer near the sea floor during the inflowing tide, perhaps indicative of an offshore movement. Differences between tidal stages, such as these, were seen in multiple surveys.

Relative fish densities were not always the same during the ebb and flood tides. Of the 13 instances when densities were unequal, fish densities were higher during the ebb than the flood (Table 2.6). This difference may indicate a general outward flux of fish at CB1, which could be true without suggesting a net outward flux of fish from the inner bays. The flow in Cobscook Bay is highly variable, and the nature of its route changes with the ebb and flood tide (Brooks 2004; Huijie Xue, unpublished data). Fish carried out through CB1 on the ebb tide could easily return to locations up-bay of CB1 via a completely different route. Less than 2% of the width of the channel is sampled at the acoustic beam's greatest diameter, and variability in flow pattern likely obscured some tidally-related fish behaviors. However, the presence and behavior of fish at this particular location with reference to the pilot tidal device were the focus of this study.

In nearly every survey, there was an obvious increase in fish density in the lower layers of the water column, regardless of day/night or tidal stage. This may be attributable to demersal feeding habits of fishes, and may also be related to the decrease in current speed near the sea floor, which was evident in ADCP data. Regardless of cause, this preference for lower layers appears to outweigh the influence of tidal stage or daylight on fish distribution at CB1, as it is apparent during most surveys and other behaviors are inconsistent. Preference for the bottom-most layers is therefore likely a behavior common to multiple species and size classes. If current speed plays a role in the distribution of fish in the water column, it may be beneficial to examine fish behavior during the slack tides. With strong currents removed, certain behaviors (e.g. diel movements) and distinct groups of fish (e.g. pelagic or benthic) may become more apparent.

Observing the changes in fish presence and distribution was complicated by the properties of the acoustic system used. The use of a single-beam echo sounder has several limitations which make pattern identification within a mixed fish community difficult. First, the acoustic threshold of -60 dB target strength (TS) eliminated backscatter from most larval fish and small invertebrates, such as krill, but it also likely eliminated backscatter from some fishes, especially those lacking swimbladders, such as Atlantic mackerel (as explained in the methods). This difference could result in under-sampling certain fish species in relation to others, which may affect the behaviors seen. A further limitation of the acoustic system was the inability to correct TS values for beam pattern, therefore neither size nor number of fish detected could be estimated. Without the ability to distinguish between groups of fish, movements of the various components of the community are impossible to distinguish from each other, and instead may serve to mask each other from detection. Additionally, without the knowledge of fish size, the ability to identify differences in the fish species sampled at the ebb and flood tides is limited. With such variable flow patterns throughout the bay and the large amount of flushing that occurs with each tidal cycle (Brooks 2004), the fish within the ebb and flood tides could be very different, making a consistent effect of tide on the vertical distribution of fish unlikely.

The omission of the upper 10 m of data due to excessive acoustic interference may also have removed evidence of diel or tidal changes in the vertical distribution of fish. During low tide at CB1, the excluded layers constituted nearly the entire upper half of the water column. If fish underwent vertical migrations, a large part of the movement was likely omitted. Analyses of the DIDSON footage collected during these surveys would aid in quantifying this effect. The DIDSON footage from May 2011 has been reviewed in more detail than other surveys, and many small schools were seen in the upper 10 m during the day but spread throughout the rest of the water column at night. Future work will include quantifying fish in the omitted layers through full analyses of the DIDSON data collected at CB1 and CB2.

The timing of surveys each month likely affected the data collected. Sampling continuously for one day per month provided a wealth of information for that particular day on a fine time scale, useful for behavioral analyses. However, the data collected over 24 hours are not necessarily representative of a larger span of time, such as an entire month or season. In such a dynamic environment, there is a high degree of day-to-day variability which is difficult to identify unless multiple days are sampled. November 2010 and March 2011 surveys at CB1 provided examples of the type of error that can be introduced by sampling just one day. While sampling at a control site helped identify these two surveys as abnormal, to achieve a more accurate understanding of the patterns in vertical distribution and how they change over time would likely require sampling multiple days spread throughout the month. Continuous monitoring is probably unnecessary, and the quantity of data would be difficult to manage due to limited data storage in the field and the high level of manual processing that it must undergo. A compromise of shorter periods of continuous sampling, occurring more often over a larger time scale, would greatly improve the interpretation of patterns within the data, while remaining realistic in terms of analysis. One option for future consideration would be to deploy a bottom-mounted unit that automatically collects data on a preset, semi-continuous schedule. This would solve issues such as boat motion at slack tide, reduce the effort and cost required to collect the data, and allow high-resolution data collection over a much longer time.

Regardless of these issues, the results obtained provide valuable information for the assessment of the pilot tidal power device. While the omission of 10 m of water column and the limitations of the single-beam acoustic system may not be ideal for quantifying the drivers of biological processes, it is certainly sufficient to characterize fish use of the region that will be directly affected by the installation of a tidal turbine. The rotating foils will be located approximately 7 to 9 m above the sea floor, directly in the center of the analysis range (0-15 m). This study showed that within that range, fish were generally denser near the bottom (0-5 m). This is below the layers spanned by the rotating turbine, but these fish are likely to encounter the solid support frame and foundation. If the number and size of detected fish could be approximated, the potential rate of fish encounters with the turbine and its supporting structures, as well as the likely reactions of those fish (which have been found to be affected by fish size; Chapter 3) could be estimated.

As this study progresses, continued data collection at the pilot project and control sites will improve understanding of the seasonal movements of fish through the region, fish use of the water column during periods of high flow, and any changes associated with the introduction of the pilot device. The use of a split-beam echo sounder in place of the current single-beam system will allow estimation of fish numbers and size, as well as direction of movement. Analyzing the vertical distribution of various size groups will greatly improve knowledge of which species are present, when they are present, and which parts of the water column they utilize with respect to various environmental factors. This information is of particular interest to environmental regulators concerned for endangered species, such as Atlantic salmon, that may be present at tidal sites, and can aid in management efforts as tidal power development continues.

CHAPTER 3

FISH INTERACTIONS WITH A COMMERCIAL-SCALE TIDAL ENERGY DEVICE IN A FIELD SETTING

3.1. Abstract

Fish are a key part of the marine ecosystem likely to be affected by marine hydrokinetic tidal turbines, but little is known about fish behavior around a hydrokinetic turbine in the natural environment. In September of 2010, two DIDSON acoustic cameras were used to observe fish interactions with a test turbine mounted below a floating platform in Cobscook Bay, Maine. Twenty-four hours of footage were collected, fish behaviors were classified (e.g., avoidance, entrance, passing by), and the effects of turbine movement (rotating or still), day and night, and fish size (small, ≤ 10 cm; medium, > 10 and ≤ 20 cm; and large > 20 cm) on behaviors were analyzed. A greater proportion of fish interacted with the turbine when it was still rather than rotating, and at night rather than day. Fish reacted further away from the device during the day than at night. For small and medium fish, the type of interaction shifted from avoidance of the turbine during the day to entrance at night; large fish mainly avoided the turbine. Given the poor visibility in the bay and the need for both day and night observation, the DIDSON was a useful tool for turbine assessment.

3.2. Introduction

Tidal currents play an essential role in the life cycles of marine and diadromous fishes, but humans are increasingly interested in extracting energy from the same currents. Many fishes are known to use the tides for on- and off-shore movements related to foraging, spawning, and sheltering (Dadswell and Rulifson 1994, Hartill et al. 2003, Krumme 2004, Ribeiro et al. 2006). Several migratory species actively seek currents when the tide is flowing in their desired direction of movement, including American eel, *Anguilla rostrata* (McCleave and Kleckner 1982); Atlantic cod, *Gadus morhua* (Arnold et al. 1994); sockeye salmon, *Oncorhynchus nerka* (Levy and Cadenhead 1995); sea trout, *Salmo trutta* (Moore et al. 1998); plaice, *Pleuronectes platessa* (de Veen 1978, Greer Walker et al. 1978); Atlantic salmon, *Salmo salar* (Stasko 1975); Atlantic mackerel, *Scomber scombrus* (Castonguay and Gilbert 1995), and Atlantic herring, *Clupea harengus* (Lacoste et al. 2001). Areas of extreme tidal currents are being targeted for tidal energy development, which utilizes large, in-stream hydrokinetic (HK) turbines to extract energy from the fast, predictable flow (Charlier and Finkl 2010). Due to the spatial overlap of tidal energy devices with fish populations, interactions between the two should be expected. However, this has yet to be studied in the United States due to the lack of installed HK turbines. Most of what is known of fish interactions with turbines is from conventional hydropower plants, where water flows at high speeds through turbines installed within dams or other barrages. To move upstream past these obstacles fish must use fishways if available, or when moving downstream, pass over a spillway or (more likely) through a turbine (Čada et al. 2006). When passing through a hydropower turbine, fish are subjected to rapid pressure changes, cavitation, shear stress, and blade strike, all of which can cause injury or mortality (Dadswell and Rulifson 1994, Čada et al. 2006). At the Annapolis estuary low-head tidal barrage in the Bay of Fundy, mortality rates among fish passing through turbines were found to range from 20% to 80% (Dadswell and Rulifson 1994). HK turbines are fundamentally different from conventional hydropower designs because they do not require a barrage. Instead, HK devices are free-standing, open structures installed in areas with strong currents. Rather than being channeled through turbines, fish may be able to avoid them entirely. While studies have examined the survival of fish passing through tidal turbines in laboratory flumes (Amaral et al. 2008, Jacobson 2011), the probability of fish interactions with tidal turbines when in their natural environment is unknown.

The choices fish make when presented with a tidal energy device in the open marine environment must be examined in order to assess the potential effects of these devices on fish. To date, most tidal devices are composed of a stationary support structure and foundation, a generator, and moving turbine components. The attraction of fish to underwater anthropogenic structures is well documented, and turbine support structures and foundations have the potential to act as artificial reefs. This has been the case for the foundations of offshore wave power devices (Langhamer et al. 2009), the monopiles of offshore wind farms (Wilhelmsson et al. 2006), and decommissioned oil platforms (Soldal et al. 2002). Additionally, in high-flow channels where low-flow areas are sparse, the lower-energy area downstream of the support structure and turbine could provide refuge from the high speed currents for a number of fish species (Čada and Bevelhimer 2011). On the other hand, the turbine will be a large, moving object, and the generator will produce a certain level of noise, potentially repelling fish from the area. The ability of fish to avoid objects perceived as threatening is as well known as their attraction to solid structures: fish have shown avoidance behaviors to vessels at ranges of 100-200 m, or as far as 400 m if the vessel is particularly noisy (Mitson 1995, Vabø et al. 2002, de Robertis and Wilson 2007). Rakowitz et al. (2011) observed strong avoidance reactions of several fish species to trawls at close ranges as well, with fish darting away when as close as 1 m to the advancing net. Jacobson (2011) documented a strong aversion of fish to entering a tidal turbine in the laboratory, even when introduced at very close range.

Polagye et al. (2011) identified several potential “dynamic” effects of HK tidal turbines on fish. These are effects involving the moving portion of the turbine (the blades), including direct strike and pressure changes around the blades. These effects have been hypothesized to lead to fish death or injury, increased stress, alterations of migratory pathways, or even changes in predator-prey relationships. To evaluate the potential for any of these effects, the behavior of fish around a device in a field setting must be better understood.

This study was designed to answer that question by monitoring a test HK turbine deployed in Cobscook Bay, Maine by Ocean Renewable Power Company. Goals were to classify fish behaviors in reaction to the turbine when encountered in the natural environment, to quantify the behaviors observed, and assess the effects of day or night, fish size, and turbine movement on their behaviors.

3.3. Methods

3.3.1. Site

Cobscook Bay is the eastern-most bay of the United States, at the mouth of the Bay of Fundy, and it consists of three smaller bays joined by narrow channels (Figure 3.1). The mean tidal range is 5.7 m (Brooks 2004), and current speeds within the outer bay regularly surpass 2 $m \cdot s^{-1}$. The depth at the site of the research platform ranged from 17 m to 31 m over the course of a tidal cycle.

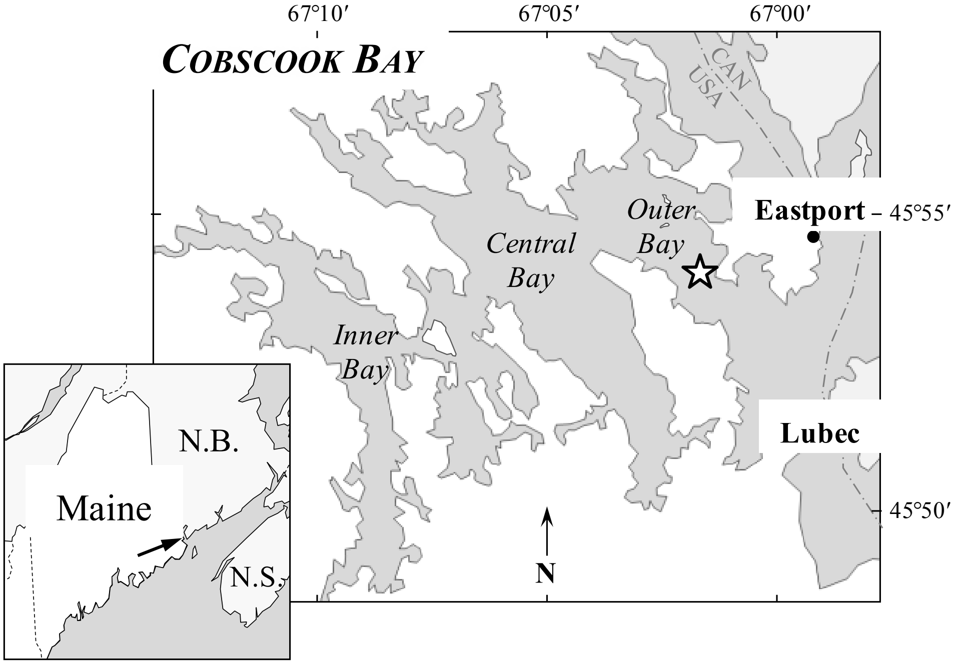

Figure 3.1. Map of Cobscook Bay. ORPC research platform, the Energy Tide II, mooring location at ☆.

3.3.2. Equipment

Two DIDSON (Dual Frequency IDentification SONar) acoustic cameras were used to observe a test turbine suspended below ORPC's research platform, the Energy Tide II (Figure 3.2). The Energy Tide II is a modified 56 ft (17 m) x 23 ft (7 m) barge, with two large, hydraulic arms that rotate 90° to suspend the turbine below at a depth of approximately 5 m (Figure 3.3). The test turbine was ORPC's basic device module, the Turbine Generator Unit (TGU), which consists of two helical-bladed, cross-flow turbines sharing a central axis with a permanent magnet generator. The turbine started to rotate when current speeds exceeded 1 $m{\cdot}s^{-1}$, and stopped rotating when current speeds fell below 0.5 $m{\cdot}s^{-1}$. The maximum rotational speed of the turbine observed during this survey was 27 rpm at a current speed of 2.8 $m{\cdot}s^{-1}$ (5.4 knots), at which point the blade tip speed was approximately 2.6 $m{\cdot}s^{-1}$ The maximum rotational speed of the turbine is 40 RPM, at which point the blade-tip speed is approximately 5.5 $m{\cdot}s^{-1}$. The research platform was moored in place, and turned on its mooring with each turn of the tide.

The two DIDSON units were mounted fore and aft of the TGU and angled in order to view a cross section of each side of the turbine and support structure (Figure 3.3). The DIDSON combines the feedback from 96 individual, high-frequency (1.8 MHz) acoustic beams, each 0.3° x 14° and divided into 512 equal range segments, to build an image of a 29° by 14° volume of water. These

Figure 3.2. Research platform. ORPC's Energy Tide II, showing test turbine in raised position.

images are produced in rapid succession, between 4 and 21 frames per second, to create "video" footage of the insonified area. The viewing windows were aligned as closely as possible with one another on each side of the turbine, each oriented with the long axis of its cross-sectional viewing area parallel to the flow. Fish swimming or drifting with the flow passed through as many of the 96 beams as possible, providing the best view of the fish's behavior as it approached and departed from the turbine. Fish swimming at an angle to the current were harder to visualize. In high-frequency (1.8 MHz) mode, each DIDSON had a range of 13.3 m. The viewing window was set to begin at 3.3 m in the fore DIDSON and 2.5 m in the aft to eliminate areas of noise due to reflection off of the support structures and to better view the turbine. The DIDSONs sampled a partial cross-section of turbine approximately 0.75 m wide at its top and 1 m wide at its base, and each captured approximately 1/3 of the turbine's cross section. The fore DIDSON's viewing window extended 2.5 m upstream of the turbine, 1 m above it, and 5 m below it. The aft DIDSON was held at more of an angle due to its mount location, and insonified a region extending approximately 3 m above, behind, and below the turbine. Vertical resolution of each DIDSON (along the length of the viewing window) was 2.0 cm. Horizontal resolution ranged from 1.3 cm at a range of 2.5 m to 8.3 cm at its maximum range. A frame rate of at least 7 frames$\cdot$s^{-1} was maintained throughout the sampling period.

Current speed was recorded using a Valeport model 803 ROV current meter attached to the support frame of the turbine.

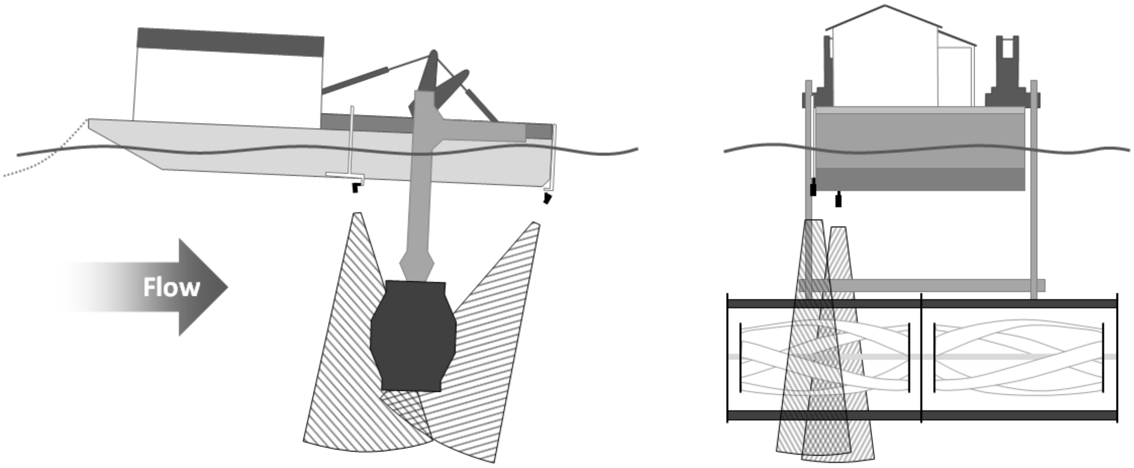

Figure 3.3. Survey setup. Schematic of the ORPC research platform, the Energy Tide II, with the test turbine suspended below (adapted from schematic provided by Ryan Beaumont, RM Beaumont Corporation, Brunswick, ME). Left: side view. Right: front view. DIDSONs are shown in survey positions by black boxes. Volume insonified by each DIDSON is indicated by hatched areas.

3.3.3. Survey Sampling

The survey began at 10 am on September 8th, and acoustic video was recorded with both DIDSONs continuously for 24 hours. Sampling included 13 hours of daylight and 11 hours of darkness, and spanned two tidal cycles. Current speed was recorded every half hour along with environmental observations that included wave height, wind speed, cloud cover, precipitation, and sun and moon visibility.

3.3.4. Data Analysis

DIDSON footage was analyzed manually using DIDSON software, which allowed frame-by-frame viewing of the footage along with measurement tools. Information was collected for each fish viewed, including time of detection, range from the DIDSON, fish length, whether the fish was part of a school (and how many individuals were in the school), turbine state (rotating or still), and fish behavior (see section 3.4.1). If fish avoided the turbine, the distance between the fish and the turbine at the time of the avoidance reaction ("reaction distance") was recorded. Often, long spans of time would pass in which same-sized fish would pass through at the same depth, showing similar behaviors and at a roughly constant frequency. At these times, the number of individual fish was estimated by multiplying the rate of fish passage by the duration of time for which that rate remained constant. Behavior, depth, and the other descriptors were then assigned to each of those fish.

3.3.4.1. Classification of Fish Behavior

Seven fish behavior categories were identified (Table 3.1 and Figure 3.4). Five of these behaviors were interactions with the turbine, and two were not. Interactions fore of the turbine were considered encounter behaviors, or initial reactions, as they occurred during a fish's first approach to the turbine.

Behaviors aft of the turbine were considered departure behavior, or secondary responses. Encounter and departure behaviors were analyzed separately.

3.3.4.2. Analysis of Factors Affecting Fish Behavior

The effects of day, night, fish size, and current speed on the proportion of fish interacting with the turbine and the type of interaction were examined. The category of day or night was assigned to each fish using its time of detection and known times of sunset and sunrise. Current speed data were interpolated to obtain the current speed at each fish's time of detection. Fish were classified by their length as small (≤ 10 cm), medium (> 10 cm and ≤ 20 cm), or large (> 20 cm). Schools in which fish were too densely packed or too numerous to be counted accurately were omitted from analyses and described qualitatively instead. Fish detected within 3.3 m of the aft DIDSON were omitted from analyses in order to assure that sampling areas fore and aft were similar.

The number of fish exhibiting each behavior (Table 3.1) was counted for each factor category or combination of categories examined (e.g., large fish avoiding the turbine at night, large fish avoiding the turbine during the day). The proportions obtained were compared using two-sample z-tests for difference of proportions. The effects of factors on reaction distance was examined using one-way ANOVA permutation tests, with a significance level (alpha) of 0.05.

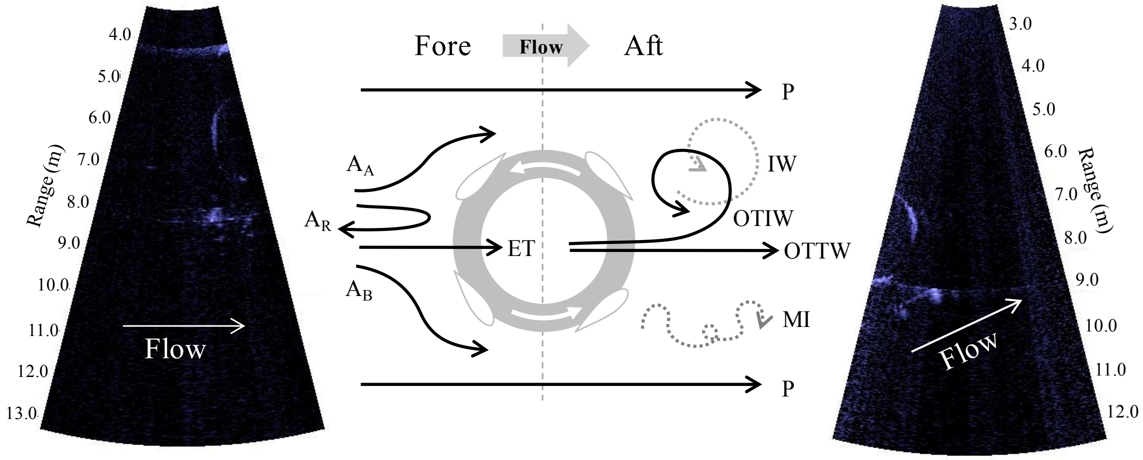

Figure 3.4. Fish reactions to test turbine. (Center) Schematic of the seven behaviors observed in DIDSON footage of ORPC test turbine. (Left) Frame from fore DIDSON. (Right) Frame from aft DIDSON. Cross-section of turbine and support frame can be seen in both frames. Flow direction is indicated is slanted in the aft view due to the tilt of the DIDSON.

Where seen	Name of Behavior	Description of behavior
In front of and behind turbine	MI	MIlling – milling occurred during slack tide, when current speed was low. Fish ceased directed movement and instead moved in short bursts in random directions.
	P	Pass by – fish entered the field of view already above or below the turbine and passed across the view without diverting course, apparently unaffected by the turbine's presence.
In front of turbine	A	Avoidance – fish noticeably altered course to avoid the turbine, swimming above or below it (A_A or A_B), or reversing direction against the current (A_R).
	ET	Enter Turbine – fish swam into the interior of the turbine. These were always fish that entered the field of view within the same depth range as the turbine.
Behind turbine	OTTW	Out of Turbine, Through Wake – fish were seen exiting the turbine, then swam directly through the wake of the turbine to re-enter the current.
	OTIW	Out of Turbine, Into Wake – fish were seen to exit the turbine and then remained in the wake, generally moving in and out of sight in a spiral pattern.
	IW	In Wake – fish appeared within the wake of the turbine and remained for several seconds, though previous location (inside the turbine or travelling above or below with the current) was unknown.

Table 3.1. Fish reactions to test turbine. Categorization and description of fish behaviors observed near ORPC test turbine in Cobscook Bay, ME.

3.4. Results

Fish were within view of the two DIDSONs during every hour of the survey, and were present 45% of the time analyzed (Figure 3.5). More fish were present aft of the turbine than fore (18,991 fore; 20,262 aft), and many more fish were present at night than during the day (4,511 day; 34,742 night). There was a large increase in numbers of fish during the nighttime slack tide (12 to 3 am), which accounted for over 77% of the total fish detected (Figure 3.5).

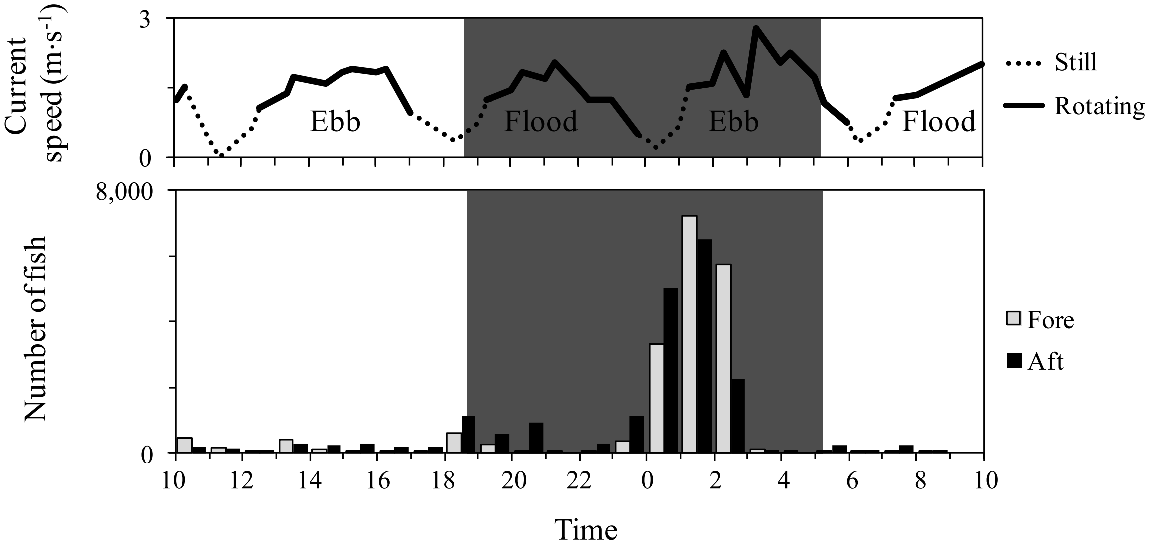

Figure 3.5. Current speed and number of fish detected v. time. Top: Surface current speed at ORPC research platform in Cobscook Bay, September 8-9, 2010. Solid lines indicate time when test turbine was rotating, dashed lines indicate time when turbine was still. Bottom: Number of fish detected at research platform per hour, fore and aft of test turbine. Shaded grey region indicates night.

Most fish were small (28,951), with fewer medium fish (9,851), and very few large fish (451). Fish aft of the turbine were slightly larger than those fore of it (permutation test p = 0.001) (Figure 3.6).

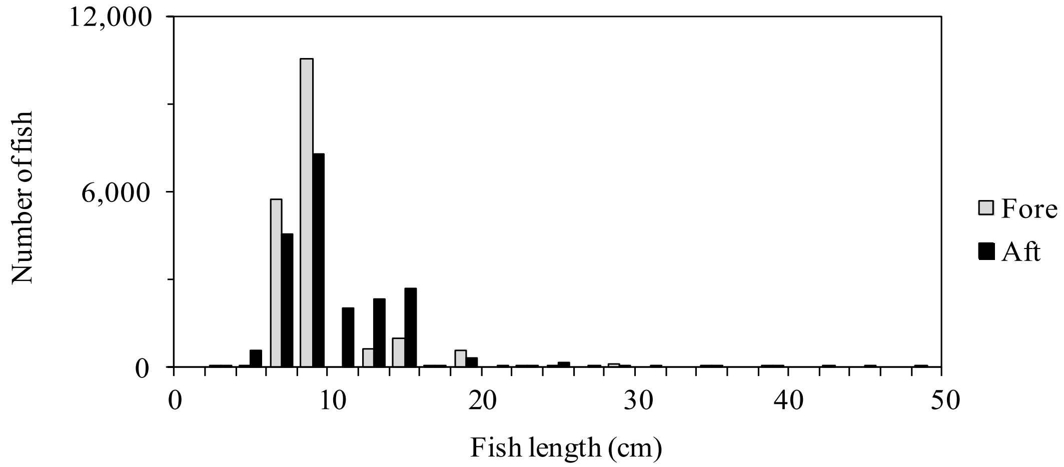

Figure 3.6. Fish size distribution. Distribution of fish sizes observed fore and aft of the ORPC test turbine in Cobscook Bay, Maine.

3.4.1. Fish Schools

Seventy schools were observed within the viewing zone of the two DIDSONs. Most schools were composed of less than 20 individuals (54 schools, 77.1%). Nine schools were estimated as having more than 50 individuals, and two had more than 100. These large schools (>50 individuals) were excluded from quantitative individual-based analyses, given the difficulty in distinguishing individual fish. When the tide was flowing, most schools (47) passed by either above or below the turbine (P), apparently unaffected. Individuals from 23 schools interacted with the turbine in some way, either avoiding it (A, 16 schools), passing into it (ET, 2 schools), passing out of it (OTTW/OTIW, 3 schools), or appearing in its wake (IW, 2 schools). When the current speed was low, schools moved slowly with no clear direction (milling behavior, MI), and did not appear to interact with the turbine (which was not rotating).

The large schools (> 50 individuals) were seen primarily during the day, with only two occurring at night. Three of the 50+ schools and both 100+ schools were seen only when the DIDSON had been temporarily switched into long-range mode in order to view them. None of these schools came within 2 m of the turbine, whether rotating or still, and only one of them needed to divert its course downward to maintain that distance. The only other sign of interaction between these large schools and the tidal turbine was at one point during the daytime slack tide, when a 100+ school approximately 7 m across gathered below the stationary turbine. This school consisted of small (≤ 10 cm), tightly-aggregated fish (most likely herring), and it rose up from the lower limits of the view, milled below the turbine for several seconds, then slowly moved out of view

Other schools did not remain near the turbine for long, and only five of the 70 entered the turbine (ET or OTTW/OTIW). Of the 16 that avoided the turbine, 14 altered course to swim below it and 2 reversed direction, swimming upstream and out of sight. The mean reaction distance for these schools was 2.52 ± 0.21 m. One school entering the turbine (15 fish, 20 cm long) swam directly in without altering course. The other (six fish, each 10 cm long) broke apart just before reaching the turbine: four individuals managed to dart upstream, while the remaining two passed into the turbine. Neither school was seen to emerge from the turbine downstream, but this is not surprising, since a small movement to either side would carry fish outside the volume sampled by the aft DIDSON. The 3 schools observed leaving the turbine on the aft side were small (three, six, and seven fish apiece), with fish lengths ranging from 10 to 15 cm. Two of these (three- and seven-fish) emerged together as a tight group and passed directly through the wake and into the current (OTTW). The other school (six fish) emerged from the turbine slightly scattered, but quickly aggregated in the wake and returned to the current together (OTIW).

3.4.2. Individual Fish

Individuals include all non-schooling fish as well as those fish in schools with fewer than 50 members, which could be counted reliably. Nearly 40% of the total fish observed interacted with the turbine, either avoiding it (A), passing into it (ET), passing out of it (OTTW/OTIW), or appearing in its wake (IW).

3.4.3. What affects fish-turbine interactions?

3.4.3.1. Turbine Rotating vs. Still:

More fish interacted with the turbine (A, ET, OTTW, OTIW, or IW) when it was still (39.2%) than when it was rotating (35.1%) (z-test $p < 0.001$). More interactions were fish passing through the turbine (ET) when it was still (91.1%) than when it was rotating (43.2%) (z-test p-value < 0.001, Figure 3.7). Whether the turbine was rotating or still also had a significant effect on the reaction distance of fish. The mean reaction distance (± standard error) while the turbine was rotating and still was 1.50 ± 0.02 m and 2.42 ± 0.07 m, respectively (permutation test $p = 0.001$).

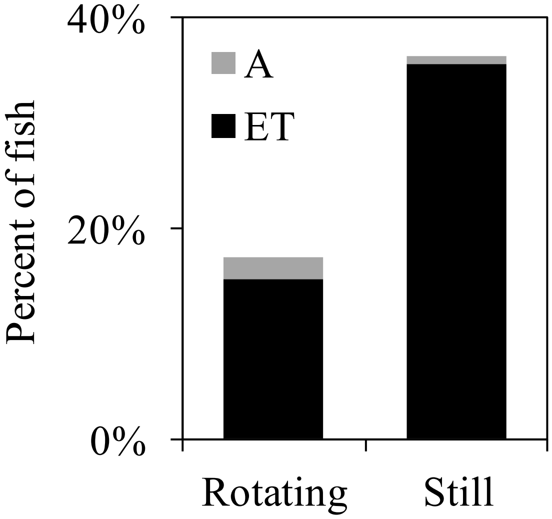

Figure 3.7. Effects of turbine state on fish behavior. Proportions of fish that interacted with the test turbine in Cobscook Bay while it was rotating and still (includes fish fore and aft of turbine). Interactions are split into proportions of fish that avoided the turbine (A) and fish that passed into it (ET).

3.4.3.2. Effects on Initial Behavioral Response to Turbine: Fish Fore of Turbine

Results from this point forward focus on times when the turbine was rotating and excludes fish in schools with 50 or more members.

A higher proportion of fish interacted with the turbine during the night than during the day (day: 20.5%; night: 35.5%; z-test $p < 0.001$). Of those fish to interact with the turbine, avoidance was higher during the day than during the night (day: 81.8%; night: 8.5%; z-test $p < 0.001$, Figure 3.8). Reaction distance was also greater during the day than during the night: 2.95 ± 0.04 m and 1.25 ± 0.02 m, respectively (permutation test $p = 0.001$).

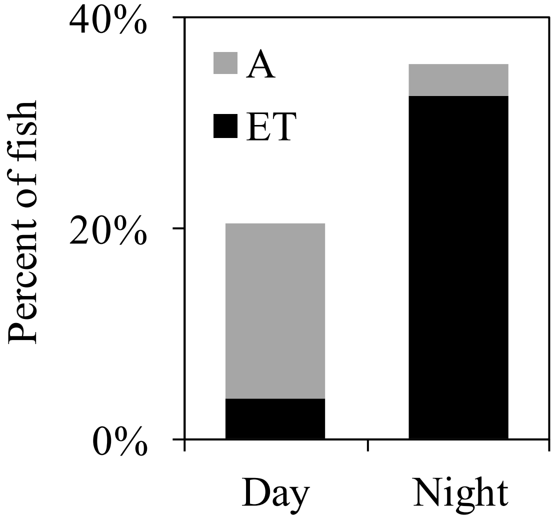

Figure 3.8. Effects of day/night on fish behavior. Proportions of fish that interacted with the test turbine in Cobscook Bay during the day and night (fore of turbine only). Interactions are split into proportions of fish that avoided the turbine (A) and fish that passed into it (ET).

The relative numbers of fish in the three size classes changed considerably between day and night. During the day, 34.8% of the fish were small, 52.5% were medium, and 12.7% were large. During the night, proportions were dominated by small fish (85.0%), followed by medium fish (14.4%), then very few large fish (0.6%).

The proportion of small fish to interact with the turbine did not change significantly between night and day (33.1% day; 33.3% night; z-test p-value = 0.969; Figure 3.9). A significantly higher proportion of medium fish interacted with the turbine at night than during the day (16.7% day; 49.2% night; z-test $p < 0.001$), and the same was true for large fish (1.9% day, 23.4% night, z-test $p < 0.001$). The type of interaction was found to change significantly for both small and medium fish, but not enough large fish interacted with the turbine to test this effect. During the day, 76.8% of small-fish interactions with the turbine were avoidance, with the remainder passing into the turbine. At night, avoidance dropped to only 5.0% (z-test p-value < 0.001). A similar pattern was seen for the medium-sized fish: during the day, 89.8% avoided the turbine instead of passing through, but at night only 20.7% avoided the turbine (z-test p-value < 0.001). Size had a significant effect on the reaction distance (permutation test $p = 0.001$). Medium fish reacted furthest from the turbine, with mean reaction distance of 3.54 ± 0.08 m during the day and 2.57 ± 0.06 m at night. Small and large fish reacted to the turbine at significantly shorter distances, during both the day and night. During the day, small fish had a mean reaction distance of 2.64 ± 0.03m. Only one large fish was detected avoiding the turbine during the day, and it did so at 0.8 m away. At night, small and large fish reaction distances were not significantly different, with a mean of 1.12 ± 0.02 m.

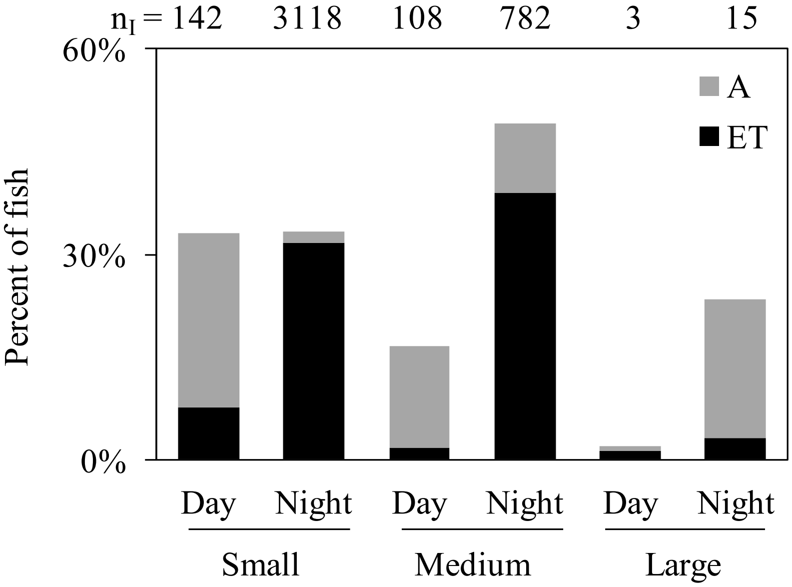

Figure 3.9. Effects of day/night on fish behaviors in front of turbine, by size class. Proportions of each fish size class that interacted with the test turbine in Cobscook Bay during the day and night (fore of turbine only). The total number of interactions is shown along the top edge of the plot area (n_I). Interactions are split into proportions of fish that avoided the turbine (A) and fish that passed into it (ET).

3.4.3.3. Departure from Turbine: Fish Aft of Turbine

Interactions aft of the turbine included passing through the wake (TW) and pausing within the wake (IW), but almost all fish (97.5%) paused in the wake. Of those that passed straight through the wake, more did so during the day than the night (4.7 % and 1.0%, respectively; z-test p < 0.001). Within each size class, there was a large difference in the proportion of fish interacting during the day and at night, though the difference was not the same for each size (Figure 3.10). During the day, most fish in the wake were medium (62.6%), followed by small (31.3%) and large (0.9%). At night, most were small (69.7%), followed by medium (29.1%), then large (0.2%). This change was independent of the overall shift in size proportions seen between night and day, when all fish (interacting and passing by) were included (z-test p-value < 0.001 for small and medium, < 0.03 for large).

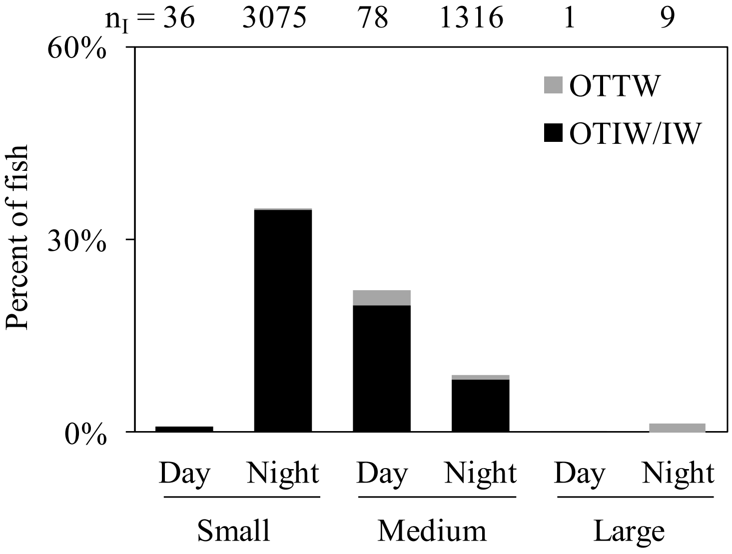

Figure 3.10. Effects of day/night on fish behaviors behind turbine, by size class. Proportions of each fish size class that interacted with the test turbine in Cobscook Bay during the day and night (aft of turbine only). The total number interactions is shown along the top edge of the plot area (n_I). Interactions are split into proportions of fish that passed directly through the wake of the turbine (OTTW) and fish that paused within the wake (OTIW/IW).

3.5. Discussion

A possible outcome from this study could have been fish avoiding the barge and turbine entirely, but they clearly did not. Thousands of fish were seen in the immediate area of the turbine, passing above, below, and through it, actively avoiding it, or pausing in its wake. Their presence does not necessarily support the attraction of fish to the turbine, but they were observed to approach it quite closely. The only potential evidence of the structure attracting fish occurred when the very large school gathered below it for several seconds during the day.

Only 5 of 70 schools entered the turbine, suggesting that schooling fish may be better able to detect and avoid it. This would be in agreement with Domenici and Batty (1997), who observed that schooling herring reacted to a sound stimulus with more consistent directional movement away from the stimulus than individuals. Rosen et al. (2012) noted that the diving speed of shoaling Atlantic cod in response to a pelagic trawl was positively correlated with shoal size. Godø et al. (1999) studied the effects of density on the catchability of Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), and American plaice (*Hippoglossoides platessoides*) using video observations and noted that individual cod and haddock swam erratically in front of the trawl, but fish that formed schools swam at a steady pace ahead of the trawl and in the same direction. Schooling fish may therefore be more capable of avoiding an obstacle such as the test turbine than individual fish.

Most fish detected were already above or below the turbine when they entered the field of view, and most of these were above the turbine. This was at least partially due to a combination of decreasing resolution with range, increasing acoustic beam attenuation with range, and the acoustic "shadow" effect below the turbine structure. These fish passed straight across the view without changing course. It is possible that they had already detected the obstacle and adjusted their trajectories farther upstream. This type of behavior was observed in bream (*Abramis brama*), bleak (*Alburnus alburnus*), and silver carp (*Hypophthalmichthys molitrix*), and others avoiding a trawl in the Czech reservoir, Želivka, where they reacted as far as 7 m away from the advancing net (Rakowitz et al. 2011). However, behavioral response at that spatial scale would not be detected in this study, since the DIDSON viewing window extended only 2.5 m upstream of the turbine.

Fish were almost always present in the wake of the turbine, but it was not always clear whether they originated from within the turbine or had diverted into the wake from the stream of fish passing above and below. Many fish were observed exiting the turbine on the downstream side, after which a small proportion (approximately 1%) passed directly back into the uninterrupted current, and most fish paused within the wake of the structure. Fish travelling straight across above or below the turbine would also sometimes depart from their trajectories to pause in the wake. This was not a frequent behavior, but there were much greater numbers of fish counted in the wake than were counted entering the turbine. This would indicate that either many more fish passed through points of the turbine beyond the section viewed, or more were entering the wake after passing the turbine, also outside the insonified volume. As less than 1 m of the total length of the turbine was insonified (Figure 3.3), both of these are likely scenarios. Fish in the turbulent waters of the wake would have a good deal of lateral movement within the eddies, and fish could have been counted multiple times as they passed back and forth through the volume sampled.

Though their origins were not clear and their numbers may be inflated, the frequent presence of fish in the wake of the turbine could indicate a preference for lower-energy regions within this high-velocity channel, a rheotactic response to a stationary reference point, or a need to rest and re-orient to the flow after passing through the turbine. Since this behavior was evident even when the turbine was still as well as moving, the former are more likely. This is consistent with results from acoustic studies carried out at a nearby site, where fish were most commonly found to be concentrated in the lower 3-4 m of the water column, where current speeds were lowest (Chapter 2). While there is not much literature on the use of low-velocity areas by marine pelagic fish, several migratory species have been found to seek out low-flow areas for rest and for more efficient progress through high-velocity periods during upriver migration, e.g. sea trout (Linnik et al. 1998); Pacific lamprey, *Lampetra tridentata* (Keefer et al. 2011); and sockeye salmon (Hinch and Rand 1998). Atlantic herring have been shown to be positively rheotactic under certain flow regimes when near a stationary reference point (Brawn 1960b), and therefore it is possible that sensing the device (either visually or through other senses, such as the lateral line system) could cause fish to swim against the current in its wake. This may be an important consideration for the design and placement of large-scale tidal turbine arrays, especially when located on migratory fish routes.

There was a marked difference between fish behavior during the day and night: fish avoided the turbine much more often during the day than at night and at a farther distance away. These results indicate that visibility may be an important factor in determining a fish's response to an obstacle. Relying on vision during the day, fish may have detected the turbine from a greater distance and adjusted their courses earlier; at night, they may have used other sensory systems to detect and avoid it, which resulted in closer-range reactions or none at all. Blaxter and Batty (1985) observed similar behaviors in herring in a tank, where objects of varying opacity were introduced with and without light. Fish did not collide with opaque obstacles in the light, only transparent ones, and at night, both transparent and opaque obstacles were hit in similarly high proportions. Rakowitz et al. (2011) also concluded that ambient light affected trawl avoidance behaviors: during the day, 44% of fish showed avoidance reactions to the trawl, whereas at night, this number dropped to only 6%.

The sizes of fish detected also varied noticeably between night and day. Many more fish were detected at night than during the day, and these were predominantly small. During the day, fish were mostly medium in length. This is likely due to a diel vertical migration of small fish from the more sheltered layers near the sea floor to the upper layers at night. This type of behavior is well documented in many fish species, including Atlantic herring, alewives (*Alosa pseudoharengus*), and juvenile Atlantic cod (Brawn 1960a, Janssen and Brandt 1980, Blaxter 1985, Perry and Neilson 1988). It is particularly prevalent among small and juvenile fish, and is usually the product of predator avoidance (i.e., seabirds) and the tracking of planktonic food sources (Bohl 1980, Levy 1990, Axenrot et al. 2004). In this case, the vertical migration was also likely related to the low current speeds of the slack tide, which are more manageable for small fish and allowed them to use the entire water column, rather than just the low-current layers near the bottom (Auster 1988). Hydroacoustic studies at a nearby site just two days prior to this study (Chapter 2) confirmed this migration, showing backscatter transfer between the deep, slow-moving layers of water and the mid-water column corresponding to the start and end of this time span (however, the upper 10 m of the water column were not sampled in that case). Vertical fish migrations such as this will greatly affect which fishes encounter a tidal energy device and when. The importance of light to obstacle avoidance is important to consider when designing and placing tidal energy devices. Most HK tidal turbines are designed to be placed in the mid-water column or to be bottom-mounted, and would therefore patterns in the number of fish encounters would be very different than in this study.

Fish size also had a significant effect on their interactions with the turbine independently of day and night. A higher proportion of medium fish avoided the turbine than the small ones. Though there were not enough large fish that interacted with the turbine to include in statistical analyses, a much higher proportion of the large fish passed by or avoided the turbine than was seen in either small or medium fish. It was apparent that larger fish were more able to avoid the turbine, most likely due to their greater maneuverability in fast currents (Auster 1988). These results are in agreement with Rakowitz et al. (2011), who found that the fish showing the least avoidance reaction to the trawl were the smallest (mean total length approximately 19 cm), swimming at low speeds and showing no change in direction. The fish that avoided the trawl the most were the largest (mean total length of approximately 42 cm, maximum near 70 cm), which showed complex swimming behaviors, faster swimming speeds, and a high average reaction distance. The distribution of fish reaction distances in Rakowitz et al. was bimodal, with the larger fish changing course 5-7 m away from the trawl and smaller fish reacting 1-2 m away. The fish observed in this study would fall mostly within the small and medium categories of Rakowitz et al., and their reaction distances agreed well with the shorter group of distances reported there. No reaction distances on the order of 5-7 m were seen in this study because the viewing window extended only 2.5 m upstream of the turbine.

If fish entered the field of view in line with the turbine, they either avoided the turbine by adjusting their course (diverting up, down, or upstream) or passed directly into it. It was not possible to determine whether fish entering the turbine were struck by the blades or not, as the resolution of the DIDSONs and a slight blurring of the moving turbine parts made anything within approximately 5 cm of the blades difficult to discern. However, if fish are known to be entering the turbine, results from laboratory studies may be applied to predict the likelihood of their survival, and their behavior upon exiting. For instance, flume studies discussed by Jacobson (2011) indicated high survival rates, on the order of 98-100%, for fish passed through a similar form of cross-flow turbine. If relative scale and turbine design are similar, laboratory and field observations may be combined for a more complete understanding of fish interactions with tidal HK turbines. This would be especially useful for improving understanding of fish behaviors near the turbine at higher current speeds, which can only be sampled in the field for the short time that they exist, at mid-tide.

The operational state of the turbine, which is closely linked to current speed, had a significant effect on fish behavior. A higher proportion of fish passed through the turbine when it was still than when it was rotating. As night and day made little difference to these proportions, this is likely related to the fish's abilities to detect moving objects via senses other than vision, such as the lateral line system. For example, Blaxter and Batty (1985) found that herring avoided vibrating objects with more success than stationary ones, in the dark as well as light. Moving objects may therefore be easier for fish to detect than still ones, and may also be perceived as a higher threat.

Another possible explanation for the increased avoidance of the rotating turbine could be its effect on the nearby flow field. Recent work by Cameron (2012) has shown that flowing water tends to be diverted around fast-spinning cross-flow turbines, flowing above and below the turbine rather than passing through. While this is not optimal for turbine performance, it may be beneficial to fish, especially those with limited maneuverability within the current. This may have been related to some of the more gradual avoidance reactions shown by fish, such as the unhurried downward movement of schools to pass below the turbine. Additionally, the very close-range flow- and pressure-fields around the blades of the turbine may have a significant effect on how fish interact with them (Amaral 2008). Some small fish appearing to enter the turbine may have shown last-minute deflection downward along the outer surface of the passing blade (within 5 cm). Again, resolution was not high enough to be certain of this effect without further processing, but this behavior is consistent with how a passive particle would travel through the flow field generated near the surface of a moving hydrofoil (Chang 1970). The flow fields around the turbine as a whole and around its individual components are important aspects of fish-turbine interaction that should be investigated in the future. The fine-scale interactions of fish, turbines, and flow fields are likely to be best understood through a combination of computer models, laboratory flume studies, and high resolution field sampling techniques.

Even given the DIDSON's limited resolution for viewing fine-scale interactions of fish with the moving blades, it is clearly a useful tool for evaluating the interactions between fish and tidal HK turbines. This is especially true when considering the need for nighttime monitoring (as there is an obvious effect of day and night on fish behavior near the turbine), and when remembering that most devices will be installed at depths with poor light, in areas that are often too turbid for light-dependent cameras to work well.

In this study, DIDSON footage could not reveal how fish were behaving further away from the research platform. Any fish avoidance of the observation area could be quantified with the addition of side-looking acoustics to the research platform, or potentially the use of DIDSON units in low-frequency mode (1.1 MHz), which increases the maximum range to 40 m but reduces resolution.

The combination of varying scales of study is crucial to understanding the effects of tidal turbines. Laboratory studies provide accurate estimates of the survival of fish when passing through HK turbines. Field observations of fish interactions with turbines, such as the one presented here, are necessary to obtain the probability of fish encountering and either passing through or avoiding the device, and how this changes with biological and environmental factors. Combining the results of both study types will allow more accurate prediction of fish survival when encountering a device in the natural environment, but this information must then be placed in the context of a project site. The horizontal and vertical movements of fishes in relation to seasonal, diel, and tidal cycles will be unique to each project site, and will determine what fish are likely to encounter the device and when this is likely to occur.

REFERENCES

Amaral SV, Hecker GE, Stacy P, Dixon DA. Effects of leading edge turbine blade thickness on fish strike survival and injury. HydroVision 2008. Paper No. 250. 14 p.

Arnold GP, Greer Walker M, Emerson LS, Holford BH. 1994. Movements of cod (*Gadus morhua* L.) in relation to the tidal streams in the southern North Sea. ICES J. Mar. Sci. 51: 207-232.

Athearn K, Bartlett C. 2008. Saltwater fishing in Cobscook Bay: Angler profile and economic impact. Marine Research in Focus. 6.

Auster PJ. 1988. A review of the present state of understanding of marine fish communities. J. Northw. Atl. Fish. Sci. 8: 67-75.

Axenrot T, Didrikas T, Danielsson C, Hansson S. 2004. Diel patterns in pelagic fish behaviour and distribution observed from a stationary, bottom-mounted, and upward-facing transducer. ICES J. Mar. Sci. 61: 1100-1104.

Barbin, GP. 1998. The role of olfaction in homing and estuarine migratory behavior of yellow-phase American eels. Can. J. Fish. Aquat. Sci. 55: 564-575.

Becker A, Cowley PD, Whitfield AK, Järnegren J, Næsje TF. 2011. Diel fish movements in the littoral zone of a temporarily closed South African estuary. J. Exp. Mar. Biol. Ecol. 406: 63-70.

Blaxter JH. 1985. The herring: a successful species? Can. J. Fish. Aquat. Sci. 42(Suppl. 1): 21-30.

Blaxter JHS, Batty RS. 1985. Herring behaviour in the dark: responses to stationary and continuously vibrating obstacles. J. Mar. Biol. Ass. U.K. 65: 1031-1049.

Bohl E. 1980. Diel pattern of pelagic distribution and feeding in planktivorous fish. Oecologia (Berl.). 44: 368-375.

Bos AR. 1999. Tidal transport of flounder larvae (*Platichthys flesus*) in the Elbe River, Germany. Arch. Fish. Mar. Res. 47(1): 47-60.

Brawn VM. 1960a. Seasonal and diurnal vertical distribution of herring (*Clupea harengus* L.) in Passamaquody Bay, N.B. J. Fish. Res. Bd. Canada. 17(5): 699-711.

Brawn VM. 1960b. Underwater television observations of the swimming speed and behaviour of captive herring. J. Fish. Res. Bd. Canada. 17(5): 689-698.

Brooks DA. 2004. Modeling tidal circulation and exchange in Cobscook Bay, Maine. Fish. Bull. 11 (Special Issue 2): 23-50.

Burke JS, Masahiro U, Tanaka Y, Walsh H, Maeda T, Kinoshita I, Seikai T, Hoss DE, Tanaka M. 1998. The influence of environmental factors on early life history patterns of flounders. J. Sea Res. 40: 19-32.

Čada G, Loar J, Garrison L, Fisher R Jr., Neitzel D. 2006. Efforts to reduce mortality to hydroelectric turbine-passed fish: locating and quantifying damaging shear stresses. Environ. Manage. 27(6): 898-906.

Čada GF, Bevelhimer MS. 2011. Attraction to and avoidance of instream hydrokinetic turbines by freshwater aquatic organisms. Oak Ridge (TN): Oak Ridge National Laboratory; Report No.: ORNL/TM-2011/131. Available from: U.S. Department of Energy Information Bridge.

Cameron MP. 2012. Flow field measurements for a cross flow turbine. [master's thesis]. [Orono, (ME)]: University of Maine.

Carstensen J, Henriksen OD, Teilmann J. 2006. Impacts of offshore wind farm construction on harbour porpoises: acoustic monitoring of echolocation activity using porpoise detectors (T-PODs). Mar. Ecol.-Prog. Ser. 321: 295-308.

Castonguay M, Gilbert D. Effects of tidal streams on migrating Atlantic mackerel, *Scomber scombrus* L. ICES J. Mar. Sci. 52(6): 941-954.

Castro-Santos T. 2011. Applied Aspects of Fish Swimming Performance. In: Farrell AP, editor-in-chief. Encyclopedia of Fish Physiology. San Diego: Academic Press, 1652-63 p.

Chang PK. 1970. Separation of flow. New York: Pergamon. 777 p.

Charlier RH, Finkl CW. 2010. Ocean energy: tide and tidal power. Berlin: Springer-Verlag. 262 p.

Childs A-R, Cowley PD, Næsje TF, Booth AJ, Potts WM, Thorstad EB, Økland F. 2008. Do environmental factors influence the movement of estuarine fish? A case study using acoustic telemetry. Estuar. Coast. Shelf S. 78: 227-236.

Crittenden RN, Thomas L, Marino DA, Bhorne RE. 1988. A weighted duration-in-beam estimator for the volume sampled by a quantitative echosounder. Can. J. Fish. Aquat. Sci. 45: 1249-1 256.

Currie DR, Isaacs LR. 2005. Impact of exploratory offshore drilling on benthic communities in the Minerva gas field, Port Campbell, Australia. Mar. Env. Res. 59: 217-233.

Dadswell MJ, Rulifson RA. 1994. Macrotidal estuaries: a region of collision between migratory marine animals and tidal power development. Biol. J. of the Linn. Soc. 51: 93-113.

de Robertis A, Wilson CD. 2006. Walleye pollock respond to trawling vessels. ICES J. Mar. Sci. 63: 514-522.

de Veen JF. 1978. On selective tidal transport in the migration of North Sea Plaice (*Pleuronectes platessa*) and other flatfish species. Netherlands J. Sea Res. 12(2): 115-147.

Domenici P, Batty RS. 1997. Escape behaviour of solitary herring (*Clupea harengus*) and comparisons with schooling individuals. Mar. Bio. 128: 29-38.

Draštík V, Kubečka J. 2005. Fish avoidance of acoustic survey boat in shallow waters. Fish. Res. 72: 219-228.

Ellis WL, Bell SS. 2008. Tidal influence on a fringing mangrove intertidal fish community as observed by in situ video recording: implications for studies of tidally migrating nekton. Mar. Ecol. Prog. Ser. 370: 207-219.

Foote KG. 1980. Importance of the swimbladder in acoustic scattering by fish: A comparison of gadoid and mackerel target strengths. J. Acoust. Soc. Am. 67(6): 2084-2089.

Foote KG. 1987. Fish target strengths for use in echo integrator surveys. J. Acoust. Soc. Am. 82(3): 981-987.

Foote KG, Knudsen HP, Vestnes G, MacLennan DN, Simmonds EJ. 1987. Calibration of acoustic instruments for fish density estimation: a practical guide. ICES Coop. Res. Rep. 144.

Forward RB, Reinsel KA, Peters DS, Tankersley RA, Churchill JH, Crowder LB, Hettler WF, Warlen SM, Green MD. 1999. Transport of fish larvae through a tidal inlet. Fish. Oceanogr. 8(Suppl. 2): 153-172.

Forward RB, Tankersley RA, Reinsel KA. 1998. Selective tidal stream transport of spot (*Leistomus xanthurus* Lacepede) and pinfish [*Lagodon rhomboids* (Linnaeus)] larvae: Contribution of circatidal rhythms in activity. J. Exp. Mar. Biol. Ecol. 226: 19-32.

Gibson RN, Robb L, Burros MT, Ansell AD. 1996. Tidal, diel and longer term changes in the distribution of fishes on a Scottish sandy beach. Mar. Ecol. Prog. Ser. 130: 1-17.

Gibson RN. 1973. Tidal and circadian activity rhythms in juvenile plaice, *Pleuronectes platessa*. Mar. Biol. 22(4): 379-386.

Gill AB. 2005. Offshore renewable energy: ecological implications of generating electricity in the coastal zone. J. Appl. Ecol. 42: 605-615.

Godø OR, Walsh SJ, Engås A. 1999. Investigating density-dependent catchability in bottom-trawl surveys. ICES J. Mar. Sci. 56: 292–298.

Graham JJ. 1972. Retention of larval herring within the Sheepscot Estuary of Maine. Fish. Bull. 70(2): 299-305.

Greer Walker M, Harden Jones FR, Arnold GP. 1978. The movements of plaice (*Pleuronectes platessa* L.) tracked in the open sea. J. Cons. Int. Explor. Mer. 38(1): 58-86.

Guillard J. 1998. Daily migration cycles of fish populations in a tropical estuary (Sine-Saloum, Senegal) using a horizontal-directed split-beam transducer and multibeam sonar. Fish. Res. 35: 23-31.

Hartill BW, Morrison MA, Smith MD, Boubée J, Parsons DM. 2003. Diurnal and tidal movements of snapper (*Pagrus auratus*, Sparidae) in an estuarine environment. Mar. Freshwater Res. 54: 931-940.

Hinch SG, Rand PS. 1998. Swim speeds and energy use of upriver-migrating sockeye salmon (*Oncorhynchus nerka*): role of local environment and fish characteristics. Can. J. Fish. Aquat. Sci. 55: 1821-1831.

Horne JK. 2000. Acoustic approaches to remote species identification: a review. Fish Oceanogr. 9(4): 356-371.

Imbrock F, Appenzeller A, Eckmann R. 1996. Diel and seasonal distribution of perch in Lake Constance: a hydroacoustic study and in situ observations. J. Fish Biol. 49: 1-13.

Jacobson P. 2011. Fish Passage Through Turbines: Applicability of Conventional Hydropower Data to Hydrokinetic Technologies. Palo Alto (CA): Electric Power Research Institute. Report No.: 1024638.

Janssen J, Brandt SB. 1980. Feeding ecology and vertical migration of adult alewives (*Alosa pseudoharengus*) in Lake Michigan. Can. J. Fish. Aquat. Sci. 37: 177-184.

Jensen OP, Hansson S, Didrikas T, Stockwell JD, Hrabik TR, Axenrot T, Kitchell JF. 2011. Foraging, bioenergetic and predation constraints on diel vertical migration: field observations and modeling of reverse migration by young-of-the-year herring *Clupea harengus*. J. Fish Bio. 78: 449-465.

Jovanovic B, Longmore C, O'Leary A, Mariani S. 2007. Fish community structure and distribution in a macro-tidal inshore habitat in the Irish Sea. Estuar. Coast. Shelf S. 75: 135-142.

Jurvelius J, Leinikki J, Mamylov V, Pushkin S. 1996. Stock assessment of pelagic three-spined stickleback (*Gasterosteus aculeatus*): A simultaneous up- and down-looking echo-sounding study. Fish. Res. 27: 227-241.

Keefer ML, Peery CA, Lee SR, Daigle WR, Johnson EL, Moser ML. 2011. Behaviour of adult Pacific lamprey in near-field flow and fishway design experiments. Fisheries Manag. Ecol. 18: 177-189.

Kelley JT, Kelley AR. 2004. Controls on surficial materials distribution in a rock-framed, glaciated, tidally dominated estuary: Cobscook Bay, Maine. Northeast. Nat. 11(Special Issue 2): 51-74.

Krumme U. 2004. Patterns in tidal migration of fish in a Brazilian mangrove channel as revealed by a split-beam echosounder. Fish. Res. 70(1): 1-15.

Lacoste KN, Munro J, Castonguay M, Saucier FJ, Gagné JA. 2001. The influence of tidal streams on the pre-spawning movements of Atlantic herring, *Clupea harengus* L., in the St Lawrence estuary. ICES J. Mar. Sci. 58: 1286-1298.

Langhamer O, Wilhelmsson D. 2009. Colonisation of fish and crabs of wave energy foundations and the effects of manufactured holes—a field experiment. Mar. Env. Res. 68: 151-157.

Larsen PF and Campbell DE. 2004. Ecosystem modeling in Cobscook Bay, Maine: a summary, perspective, and look forward. Northeast. Nat. 11(Special Issue 2): 425-438.

Levy DA. 1990. Reciprocal diel vertical migration behavior in planktivores and zooplankton in British Columbia lakes. Can. J. Fish. Aquat. Sci. 47: 1755-1764.

Levy DA and Cadenhead AD. 1995. Selective tidal stream transport of adult sockeye salmon (*Oncorhynchus nerka*) in the Fraser River Estuary. Can J. Fish. Aquat. Sci. 52: 1-12.

Lewis LJ, Davenport J, Kelly TC. 2002. A study of the impact of a pipeline construction on estuarine benthic invertebrate communities. Estuar. Coast. Shelf S. 55: 513-221.

Linnik VD, Malinin LK, Wozniewski M, Sych R, Dembowski P. 1998. Movements of adult sea trout *Salmo trutta* L. in the tailrace of a low-head dam at Włocławek hydroelectric station on the Vistula River, Poland. Hydrobiologia. 371/372: 335-337.

Lucas MC, Baras E. 2000. Methods for studying spatial behaviour of freshwater fishes in the natural environment. Fish Fish. 1: 283-316.

Luecke C, Wurtsbaugh WA. 1993. Effects of moonlight and daylight on hydroacoustic estimates of pelagic fish abundance. T. Am. Fish. Soc. 122: 112-120.

MacDonald JS, Dadswell MJ, Appy RG, Melvin GD, Methven DA. 1984. Fishes, fish assemblages, and their seasonal movements in the lower Bay of Fundy and Passamaquoddy Bay, Canada. Fish. Bull. 82(1): 121-139.

Marshall S and Elliott M. 1998. Environmental influences on the fish assemblage of the Humber Estuary, U.K. Estuar. Coast. Shelf S. 46: 175-184.

McCleave JD, Kleckner RC. 1982. Selective tidal stream transport in the estuarine migration of glass eels of the American eel (*Anguilla rostrata*). J. Cons. Int. Explor. Mer. 40: 262-271.

Metcalfe JD, Arnold GP, Webb PW. 1990. The energetics of migration by selective tidal stream transport: an analysis for plaice tracked in the southern North Sea. J. Mar. Biol. Assoc. U.K. 70: 149-162.

Misund, OA, Beltestad AK. 1996. Target-strength estimates of schooling herring and mackerel using the comparison method. ICES Mar. Sc., 53: 281–284.

Mitson RB. 1995. Underwater noise of research vessels: review and recommendations. ICES Coop. Res. Rep. 209. 61 pp.

Montgomery J, Carton G, Voigt R, Baker C, Diebel C. 2000. Sensory processing of water currents by fishes. Phil. Trans. R. Soc. Lond. B. 355: 1325-1327.

Moore A, Ives M, Scott M, Bamber S. 1998. The migratory behavior of wild sea trout (*Salmo trutta* L.) smolts in the estuary of the River Conwy, North Wales. Aquaculture. 198: 57-68.

Morrison MA, Francis MP, Hartill BW, Parkinson DM. 2002. Diurnal and tidal variation in the abundance of the fish fauna of a temperate tidal mudflat. Estuar. Coast. Shelf S. 54: 793-807.

Neilson JD, Perry RI. 2001. Fish Migration, Vertical. In: Steele JH, Thorpe SA, Turekian KK, editors. Encyclopedia of Ocean Sciences. 1st ed. Boston: Elsevier Academic Press. Vol. 2, p. 955-961.

Nielson LA, Johnson DL, editors. 1985. Fisheries techniques. 2nd ed. Blacksburg: Southern Printing Company. 468 p.

Nilsson LAF, Thygesen UH, Lundgren B, Nielsen BF, Nielsen JR, Beyer JE. 2003. Vertical migration and dispersion of sprat (*Sprattus sprattus*) and herring (*Clupea harengus*) schools at dusk in the Baltic Sea. Aquat. Living Resour. 16: 317-324.

Ona E, Mitson RB. 1996. Acoustic sampling and signal processing near the seabed: the deadzone revisited. ICES J. Mar. Sci. 53: 677-690.

Parker SJ, McCleave JD. 1997. Selective tidal stream transport by American eels during homing movements and estuarine migration. J. Mar. Biol. Ass. U.K. 77: 871-889.

Perry R I, Neilson J D. 1988. Vertical distributions and trophic interactions of age-0 Atlantic cod and haddock in mixed and stratified waters of Georges Bank. Mar. Ecol. Prog. Ser. 49: 199-214.

Polagye B, Van Cleve B, Copping A, Kirkendall K. 2010. Environmental effects of tidal energy development. U.S. Dept. Commerce, NOAA Tch. Memo. F/SPO-116. 181 p.

Rakowitz G, Tušer M, Říha M, Jůza T, Balk H, Kubečka J. 2011. Use of high-frequency imaging sonar (DIDSON) to observe fish behavior towards a surface trawl. Fish. Res. 123-124: 37-48.

Ransom BH, Johnston SV, Steig TW. 1998. Review on monitoring adult salmonid (*Oncorhynchus* and *Salmo* spp.) escapement using fixed-location split-beam hydroacoustics. Fish. Res. 35: 33-42.

Ribeiro J, Bentes L, Coelho R, Gonçalves JMS, Lino PG, Monteiro P, Erzini K. 2006. Seasonal, tidal and diurnal changes in fish assemblages in the Ria Formosa lagoon (Portugal). Estuar. Coast. Shelf S. 67: 461-474.

Rijnsdorp AD, Stralen MV, Van der Veer HW. 1985. Selective tidal transport of North Sea Plaice larvae *Pleuronectes platessa* in coastal nursery areas. T. Amer. Fish. Soc. 114(4): 461-470.

Rosen S, Engås A, Fernö A, Jörgensen T. 2012. The reactions of shoaling adult cod to a pelagic trawl: implications for commercial trawling. ICES J. Mar. Sci. 69(2): 303-312.

Rowe PM, Epifanio CE. 1994. Tidal stream transport of weakfish larvae in Delaware Bay, USA. Mar. Ecol. Prog. Ser. 110: 105-114.

Sakabe R and Lyle JM. 2010. The influence of tidal cycles and freshwater inflow on the distribution and movement of an estuarine resident fish *Acanthopagrus butcheri*. J. Fish Biol. 77(3): 643-660.

Saunders R, Hachey M, Fay CW. 2006. Maine's diadromous fish community. Fisheries. 31(11): 537-547.

Simard Y, Lavoie D, Saucier FJ. 2002. Channel head dynamics: capelin (*Mallotus villosus*) aggregation in the tidally driven upwelling system of the Saguenay – St. Lawrence Marine Park's whale feeding ground. Can. J. Fish. Aquat. Sci. 59: 197-210.

Simmonds J, MacLennan D. 2005. Fisheries Acoustics: Theory and Practice. 2nd ed. Oxford: Blackwell Science. 437 p.

Smith EP. 2002. BACI design. In: El-Shaarawi AH, Piegorsch WW, editors. Encyclopedia of environmetrics. Chichester: John Wiley & Sons. p 141-148.

Soldal AV, Svellingen I, Jørgensen T, Løkkeborg S. 2002. Rigs-to-reefs in the North Sea: hydroacoustic quantification of fish in the vicinity of a "semi-cold" platform. ICES J. Mar. Sci. 59: S281-S287.

Thorne RE. 1988. An empirical evaluation of the duration-in-beam technique for hydroacoustic estimation. Can. J. Fish. Aquat. Sci. 45: 1244-1248.

Trump CL, Leggett WC. 1980. Optimum swimming speeds in fish: the problem of currents. Can. J. Fish. Aquat. Sci. 37:1086-1092.

Tyler AV. 1971. Periodic and resident components in communities of Atlantic fishes. J. Fish. Res. Bd. Canada. 28: 935-946.

USDOE 2009. Report to Congress on the Potential Environmental Effects of Marine and Hydrokinetic Energy Technologies: Prepared in Response to the Energy Independence and Security Act of 2007, Section 633(B). Wind and Hydropower Technologies Program, Energy Efficiency and Renewable Energy, U.S. Department of Energy. December, 2009.

Vabø R, Olsen K, Huse I. 2002. The effect of vessel avoidance of wintering Norwegian spring spawning herring. Fish. Res. 58: 57-77.

Weinstein MP, Weiss SL, Hodson RG, Gerry LR. 1980. Retention of three postlarval fishes in an intensively flushed tidal estuary, Cape Fear River, North Carolina. Fish. Bull. 78(2): 419-436.

Willhelmsson D, Malm T, Öhman MC. 2006. The influence of offshore windpower on demersal fish. ICES J. Mar. Sci. 63: 775-784.

Wills JC, Bremigan MT, Hayes DB. 2004. Variable effects of habitat enhancement structures across species and habitats in Michigan reservoirs. T. Am. Fish. Soc. 133(2): 399-411.

Wilson B, Batty RS, Daunt F, Carter C. 2007. Collision risks between marine renewable energy devices and mammals, fish and diving birds. Oban (Scotland): Scottish Association for Marine Science; Report No.: PA37 1QA.

Wroblewski JS, Nolan BG, Rose GA, deYoung B. 2000. Response of individual shoaling Atlantic cod to ocean currents on the northeast Newfoundland Shelf. Fish. Res. 45: 51-59.

Zijlstra JJ. 1988. Fish migrations between coastal and offshore areas. Lect. Notes Coast. Estuar. Interact. 22: 257-272.

BIOGRAPHY OF THE AUTHOR

Haley Viehman was born in Allentown, PA in December 1987. She spent most of her childhood in Camden, ME but spent part of middle and high school in Quakertown, PA. She and her family returned to Maine in 2003, and she graduated from Camden Hills Regional High School in 2005. Haley has always loved animals, the outdoors, and building things. Her interest in marine biology began in Maine's tide pools, and in her junior year of high school she was selected to participate in the Keller Bloom Program at the Bigelow Laboratory for Ocean Sciences. She studied Civil Engineering at Cornell University, spending her junior year abroad at the University of Cantabria in Santander, Spain. During her years at Cornell, Haley became fascinated with work at the intersection of engineering, society, and the environment, particularly related to sustainable development and renewable energy. She participated in the AguaClara sustainable water treatment research project during her senior year, and in the organization Engineers for a Sustainable World. Haley graduated with a Bachelor of Science in Civil Engineering in May of 2009. Her passion for invention, the environment, and multidisciplinary work led her to a graduate position at the University of Maine the following fall, researching the effects of novel tidal energy technology on fishes. Haley is a candidate for the Master of Science degree in Marine Bioresources from the University of Maine in May, 2012.