Potential Environmental Effects of the Leading Edge Hydrokinetic Energy Technology

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CHANGING WHAT'S POSSIBLE

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13. ABSTRACT (Maximum 200 words)

The Volpe Center evaluated potential environmental challenges and benefits of the ARPA-E funded research project, Marine Hydrokinetic Energy Harvesting Using Cyber-Physical Systems, led by Brown University. The “Leading Edge” research team developed and tested an innovative hydrofoil-type power conversion device to capture energy from flowing water. The technology could provide low-carbon energy to power remote homes/businesses, port and marine facilities, or other coastal facilities, among other uses. This primary aim of this study was to assess which potential environmental impacts of the Leading Edge technology are similar to other tidal energy devices and which might be unique. This report identifies best practices and mitigation measures that could minimize environmental risk during design and deployment of hydrokinetic energy devices. To support future permitting processes, this report includes a summary of NEPA requirements and information that could contribute to a site-specific environmental impact assessment. Volpe also collected environmental data during Leading Edge prototype testing and found that for a vessel-mounted stationary deployment, alteration of water currents and acoustic impacts are likely to be at the lower range of possible impacts.

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Acronyms and Abbreviations

Abbreviation	Term or description
µT	100 microTesla = 1 Gauss, G
AC	alternating current
ACHP	Advisory Council on Historic Preservation
ADCP	Acoustic Doppler current profiler
AMD	acoustic mitigation device
Annex IV	International collaborative to examine environmental effects of marine energy.
ARPA-E	Advanced Research Projects Agency - Energy
B-field	magnetic field
BIA	Bureau of Indian Affairs
BLM	Bureau of Land Management
BOEM	Bureau of Ocean Energy Management
CATEX	Categorical Exclusion
CEQ	White House Council on Environmental Quality
cm	centimeter
dB	decibel
DOC	dissolved oxygen content
DOE	U.S. Department of Energy
DON	U.S. Department of the Navy
DOT	U.S. Department of Transportation
DIDSON	High definition sonar technology
E	electrical field
EA	Environmental Assessment
E-field	electric field
EIS	Environmental Impact Statement
EISA	Energy Independence and Security Act of 2007 (Public Law 110-140)
EMF	electromagnetic radiation
EPA	Environmental Protection Agency
EPCRA	Emergency Planning and Community Right-to-Know Act
FAD	fish aggregation device
FERC	Federal Energy Regulatory Commission
FONSI	Finding of No Significant Impact
GHG	Greenhouse gas
GIS	Geographic information system
H-ADCP	Horizontal acoustic Doppler current profiler
iE-field	induced electrical field
km	kilometer
kW	kilowatt
M	meter
micro-Pa	micropascal
MLLW	mean lower low water
m/s	meters per second
MMA	Massachusetts Maritime Academy
MMS	Minerals Management Service
MREC	Marine Renewable Energy Center of the University of Massachusetts Dartmouth

Abbreviation	Term or description
mT	milliTesla (1 x 10^{-3} T)
MW	megawatt
NEPA	National Environmental Policy Act
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NOI	Notice of Intent
NPS	National Park Service
nT	nanoTesla (1 x $10^{-9\ T}$)
nV/m	nanoVolt per meter
OCS	Outer Continental Shelf
ONMS	Office of National Marine Sanctuaries
OPT	Ocean Power Technologies, Inc.
ORPC	Ocean Renewable Power Company
OTEC	Ocean Thermal Energy Conversion
P	pressure
PATON	Private Aid to Navigation
PDEIS	Programmatic Draft Environmental Impact Statement
PMMS Ltd.	Project Management Support Services Limited
PNNL	Pacific Northwest National Laboratory
ROD	Record of Decision
rpm	rotations per minute
s	seconds
SEL	sound exposure level
SPL	sound pressure level
TWh/yr	terawatt hour per year
USACE	United States Army Core of Engineers
USCG	United States Coast Guard
USFS	United States Forest Service
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
V	volt
Volpe	The John A. Volpe National Transportation Systems Center
WEC	Wave energy converter
WSR	National Wild and Scenic Rivers

Executive Summary

Introduction

The U.S. Department of Energy has placed a high priority on hydrokinetic energy systems due to the scale, reliability, and predictability of this type of technology, as well as its potential environmental benefits. The Volpe Center evaluated potential environmental challenges and benefits of the ARPA-E funded research project, *Marine Hydrokinetic Energy Harvesting Using Cyber-Physical Systems* (hereafter referred to as the "Leading Edge" tidal energy project) led by Brown University. The Leading Edge research team developed and tested an innovative hydrofoil-type power conversion device to capture energy from flowing water in rivers and tidal basins with an efficient and low-cost system.

The Leading Edge technology could provide low-carbon energy to power remote homes/businesses, port and marine facilities, or other coastal facilities, or can be fed into the electrical grid to power vehicles, among other uses. Ports in particular have shown interest in opportunities to reduce emissions and improve facilities through electrification. However, such tidal energy projects will inherently be deployed in environmentally sensitive areas (river beds and tidal basins) and could affect wildlife and marine habitats, and may also have implications for shipping lanes and activity. Structures placed in near-shore regions could lead to changes in water flows and sedimentation, affecting shoreline scour and infrastructure such as bridges. The Volpe Center team evaluated whether potential environmental impacts of the hydrofoil-type power conversion device could prevent it from advancing as a viable technology in the energy market.

This report synthesizes available information relevant to the potential effects on the natural environment and the potential benefits of the hydrofoil device under continuing development by the Leading Edge team, led by Brown University. Recent reports from the Annex IV collaborative project (operated by the U.S. Department of Energy), the Bureau of Ocean Energy Management, and a U.S. Department of Energy report to Congress in response to the Energy Independence and Security Act of 2007 (Section 633b) have thoroughly reviewed available information related to environmental effects of tidal turbine technologies. Here we present a summary of key findings from these reports, and integrate additional recently available literature. *The primary focus of this report is to assess which potential environmental impacts of the Leading Edge power conversion device are similar to other tidal energy devices and which potential impacts might be unique to the Leading Edge hydrofoil-type design.*

Potential Environmental Effects

Potential areas of environmental concern common to all hydrokinetic energy devices and those that may be unique to hydrofoil technology are summarized in Table ES-1. Volpe's assessments identified alteration of waves and currents, interference with animal movements, and risk of animal strikes as the most distinct potential environmental effects of hydrofoil compared to rotary-turbine hydrokinetic energy technologies. Overall, the slower device speed is expected to reduce the environmental effects of the Leading Edge hydrofoil device compared to rotary turbines.

Table ES-1. Potential environmental effects of hydrokinetic energy technologies.

	Hydrofoil: unique effects	Effects common among technologies
Alteration of currents and waves	Wake effects on currents will vary over time and likely be more turbulent, with no "dead zone" like behind the hub of traditional turbines (when on or off). Hydrofoil support structures could introduce static dead zones in the wake, but they are avoided to minimize drag. Hydrofoils (single or arrays) could conceivably span an entire channel and extract a significant portion of the current/wave energy.	Devices will alter currents/waves with localized effects in open ocean sites, which can affect ecosystem structure by altering sediment and nutrient transport patterns, leading to changes in benthic and near-shore habitat as well as alterations in beach formation patterns, navigation, and recreational suitability (e.g., for surfing, boating, fishing). All devices can potentially remove a significant portion of current/wave energy, depending on the configuration of units.
Alteration of bottom substrates, sediment transport, sediment deposition, and benthic habitats.	Unique effects may be observed if hydrofoils are able to extract a more significant portion of the current and wave energy at a site. Ability to operate more closely to the bottom compared to turbines could lead to greater effects on bottom substrates and benthic habitats due to change in currents, waves, and water quality.	Effects will depend on proportion of energy removed from a site. Slower currents and smaller waves due to energy removal may increase sediment deposition/scour and affect bottom substrates, displacing benthic organisms and altering animal behavior. Bottom substrate and fixed structure effects depend on anchoring mechanisms (weighted structures, piles, floating, barge-mounted, guy wire arrangements) and pelagic structures.
Noise	Device wing will move at slower speeds (max speed is similar to current speed), and the acoustic signature will be unique. Noise level during operation is predicted to be lower than for turbines, but may be more pulsed (data required).	Animals may avoid areas with high noise levels that can mask communications and echo-location, changing behavior and/or migratory patterns or hindering hunting behavior in some species. Pile-driving during project installation or operational noise may damage marine animal hearing or result in death of nearby organisms.
EMF	Depends on power take-off mechanism; signal could be more pulsed or multiple devices linked to a single generator may produce steady EMF signals.	EMF in the water near devices and cables can alter feeding behavior, migration, reproduction, or susceptibility to predation near the project. Effects are limited to species that use the earth's magnetic field as a navigation aid and electrosensitive species such as sharks and eels.
Chemical toxicity	No unique aspects: similar materials, anti-fouling compounds, lubricants, and hydraulic fluids are utilized in other hydrokinetic technologies.	Coatings, lubricants, paints, biocides, or other chemicals used in, on, or as part of maintenance of the devices can cause toxic effects on wildlife and humans.
Interference with animal movement or migration	The static elements of the hydrofoil device will be similar as for other hydrokinetic technologies, but the dynamic elements will differ. Slower movement and the wider span of the device may make it easier for animals to detect and avoid; can swim around or past. Wider span of a single device or arrays that block a channel may deter wildlife and block migratory paths. Ability to locate devices closer together can minimize the footprint for a given number of devices in an array.	Static elements (cables, anchors, etc.) or dynamic elements of devices can change migration, aggregation, and foraging behaviors due to artificial reef formation and potential attraction to new habitat. Can also cause injury/mortality due to entanglement and/or increased predator activity. Anchoring systems can block channel access and prevent movement and/or migration of animals through the installation area. Fishing activity may be reduced (structures will prevent commercial trawling) or increased (artificial reef formation may increase recreational fishing activity).
Strike	Slower movement of hydrofoils for a given current speed compared to turbine blades could be easier for wildlife to avoid, reducing the risk for injury and mortality due to strike; slower speed minimizes risk of cavitation exposure.	Fast movements of turbine blades pose risk of animal injury and mortality due to strike, although studies to date have found little evidence of animal strikes with any hydrokinetic technology.

Suggested Mitigation Measures

A variety of best practices and mitigation measures have been identified to minimize environmental risk during design and deployment of hydrokinetic energy devices. A few key mitigation measures identified for different elements of the device include: using blunt hydrofoil edges, limiting hydrofoil speed to below 4.5 m/s, considering acoustic and EMF signatures in relation to local species of concern, minimizing and/or using non-toxic coatings and paints, minimizing anchoring wires and keeping them taut to reduce entanglement risk, consider layout, footprint, maintenance schedules, lighting, and other features to minimize disruption of animal movement and migration patterns, and avoid critical habitats.

Environmental Permitting

The Leading Edge project focuses on the development of a commercial hydrokinetic power conversion device to harness energy from natural water flows in tidal areas and rivers. While the Leading Edge device prototype testing completed to date has not required permits from the Federal Energy Regulatory Commission (FERC), future grid-connected stages likely will. Before issuing approval and permits for testing and device deployment when required, FERC must comply with the National Environmental Policy Act (NEPA) and will likely require environmental impact analyses for prospective projects. While the prototype testing was not subject to FERC permits and NEPA, available environmental information for the first Leading Edge prototype testing site in Rhode Island is reviewed. This section provides a detailed example of the type of site-specific information required to support the permitting process for future deployments. We also present a brief summary of potential environmental benefits of the Leading Edge hydrofoil technology. Potential benefits include reduction in environmental impacts (namely air quality and water quality) at shoreline facilities and ports should the generated energy be used locally, and reduction in carbon intensity of overall electricity generation. To support future permitting processes, the Volpe team compiled a summary of NEPA requirements and information that could contribute to a site-specific environmental impact assessment for deployment locations (Section 10). In addition, we summarize the key environmental effects analyzed in existing NEPA-type analyses completed for related technologies. We also provide recommendations for data that could be collected during ongoing testing of Leading Edge hydrokinetic energy prototypes to inform future NEPA analyses.

Environmental Measurements

Volpe's assessment of potential environmental effects (Section 3) and of which information would inform future NEPA analyses (Section 10), along with feedback from the Leading Edge team and ARPA-E, informed the environmental data collection efforts during testing pf the second Leading Edge prototype. Preliminary environmental measurements completed during the Leading Edge prototype testing periods included biofouling experiments assessing opportunities to use various surfaces to limit device hindrance by biocolonization, characterization of water currents at the testing site, assessment of current flows and changes caused by the prototype to downstream current speed and directions, and evaluation of underwater noise effects of the prototype (Section 14).

The growth of marine life on structures exposed to seawater (biofouling) is typically addressed by the application of anti-biofouling coatings. To identify effective but less toxic coatings, the Volpe team compared biofouling on different device materials. Anti-biofouling treatments with low environmental toxicity were highly effective at reducing accumulation of algal communities. Notably, for components made of aluminum, the anti-biofouling compound Trilux, which does not contain copper, was highly effective. For components made of fiberglass, any of the three paint treatments achieved similar reductions in biofouling accumulation; the fewer total toxic components of International VC Offshore recommend it for use on fiberglass-substrate components. Despite the effectiveness in reducing biotic growth, the anti-fouling treatments did not eliminate all growth on the test plates. For long-term deployment, periodic maintenance and cleaning of the submerged components of the device will be required. However, depending on the deployment locations, anti-fouling treatments should reduce biotic growth sufficiently to support less frequent maintenance cycles.

Water current impacts of the Leading Edge prototype demonstrated small, but observable effects on the flow field in the very near-field vicinity of the hydrofoils. These effects consist of a slight slowing of the flow in the upper 2m for the ebb tides that were monitored during device operation, on the order of 0.25 m/s. This is less than measured velocity reductions of ca. 0.5 m/s in other hydrodynamic energy projects such as the Stingray (The Engineering Business Ltd. 2005), but greater than the velocity reduction of 0.05 m/s for the Muscaget Tidal Energy Project. While wave velocity reductions were only notable at upper levels of the channel, it is possible that a slight acceleration of the flow may be occurring beneath the device. Thus it is likely that sediment accretion will not be strongly altered as a result from the Leading Edge device as tested. If full-scale version of the hydrofoil device is able to extract a more significant portion of the current and wave energy at a site, greater effects on bottom substrates and benthic habitats due to change in currents, waves, and water quality. Acoustic impacts were similarly moderate for the Leading Edge prototype. The device hydrofoils move at slower speeds than other hydrokinetic energy devices, as max speed is similar to current speed.

While the environmental measurements were limited by the amount of time that both sets of Leading Edge hydrofoils were being tested, the results provide a preliminary picture of noise and current impacts. The effort also produced established methods and equipment requirements to enable future expanded measurements during longer-term Leading Edge device testing phases.

Conclusions

Overall, the environmental measurements thus far suggest that for the prototype device with vessel-mounted, stationary deployment, current alteration and acoustic impacts are likely to be on the lower side compared with other underwater hydrokinetic energy devices, and that there are opportunities to enhance efficiency and reduce noise and current alterations. However, the final design, size, and installation techniques (e.g., single devices versus arrays) used for the commercial deployment of the Leading Edge hydrokinetic energy technology, as well as site-specific conditions related to current, sediment, and ambient sound, will determine how commercial installations affect current flows and acoustic conditions. The Volpe team has identified research priorities for environmental measurements and evaluation during either future long-term testing of a full-scale Leading Edge device or initial commercialization efforts. These recommendations could provide baseline data that could be used in NEPA environmental impact analyses, permitting, or other environmental evaluations.

1 Introduction

1.1 Tidal Energy Project Motivation

Due to fluctuations in and anticipated long-term rise of oil prices as well as environmental impacts associated with the extraction and burning of fossil fuels, research is underway to identify, develop, evaluate, and deploy a variety of alternative energy technologies that are less environmentally damaging than fossil fuels and associated climate change (Allison et al. 2014). The energy associated with tides and fast-moving currents is seen as a source of renewable, environmentally friendly energy, provided a suitably efficient and environmentally-benign harvesting mechanism can be developed. The U.S Department of Energy's (DOE) Advanced Research Projects Agency-Energy (ARPA-E) funded a research project at Brown University entitled, "Marine Hydrokinetic Energy Harvesting Using Cyber-Physical Systems." The research, which is being performed by the "Leading Edge" tidal energy project team (Brown University and Blue Source Energy), is pursuing the objective of developing an innovative hydrofoil-type power conversion device to maximize power production and reduce costs to capture energy from flowing water in rivers and tidal basins ARPA-E provided funding to the Volpe National Transportation Systems Center (Volpe) to evaluate the potential environmental risks and benefits of Leading Edge tidal energy technology.

Hydrokinetic energy harvesting systems are being examined with interest by DOE due to the large amount of energy available from such systems. Researchers at the Electric Power Research Institute estimate that by harvesting 15% of in-stream current and tidal energy, up to 140 TWh/yr of electricity could be generated, and even greater power would be available from wave energy (Bedard et al. 2007). Furthermore, tidal energy in particular is more reliable and predictable than solar or wind energy and can be used to generate distributed energy supplies without reliance on fossil fuels (Bedard et al. 2007). As for all renewable energy collection devices for which available energy varies with time, overall system reliability and predictability will increase when paired with an energy storage device. In-stream applications of hydrokinetic technology may provide rural development economic opportunities. As long as the emissions associated with device production and installation are small, harvesting of hydrokinetic energy can provide life cycle greenhouse gas emissions benefits as well as energy security advantages. For these reasons, DOE has put a high priority on supporting projects to cost-effectively harvest renewable hydrokinetic energy as "an important part of our all-of-the-above energy strategy" (Danielson 2013).

While hydrofoil devices may be uniquely suited for in-stream applications because of their profile, (they can operate in shallow waters, with a wide profile), they are also well-suited for coastal areas. Coastal areas tend to be highly developed and heavily populated, thus hydrokinetic energy harvesting in tidal areas may provide opportunities for generating clean energy near areas of heavy energy consumption. The proposed technology will provide low-carbon energy that could be used locally to power port and marine facilities, island homes/businesses, or other coastal facilities. The energy could also be fed into the electrical grid to power vehicles, among other uses. Ports in particular have shown interest in opportunities to reduce emissions and improve facilities through port electrification. Electrification can be used for shore powering of ships when in port ("cold ironing") to reduce ship emissions relating to lighting, heating/refrigeration, and hot water. Electrification of cranes, short-haul trucks, forklifts, and other small vehicles can also substantially reduce port emissions (Theodoros 2012). Currently there is global interest in cold ironing, but cost effectiveness is substantially affected by the need to invest in transformer infrastructure, often related to distance to the power source (Theodoros 2012). Thus, a local source of power such as a tidal energy project may provide a unique opportunity to aid port electrification.

While there are clear benefits to the low-carbon energy that could be provided by the hydrofoil technology under development by the Leading Edge team, such tidal energy projects will inherently be deployed in environmentally sensitive areas such as river beds and tidal basins. Hydrokinetic projects may affect local flora, fauna, and ecosystem structure, and may also have implications for shipping lanes and recreational activities. Structures placed in near-shore regions could lead to changes in water flows and sedimentation, affecting shoreline scour and infrastructure such as bridges. Volpe is collaborating with the Leading Edge tidal energy team under ARPA-E funding to evaluate potential environmental challenges and benefits of the proposed hydrofoil power conversion device. The primary objective is to understand if potential environmental impacts of the device technology could prevent it from advancing as a viable technology in the energy market.

1.2 Key Environmental Concerns Associated with Tidal Energy Technologies

Tidal energy technologies are intended to address a key environmental challenge – limiting the use of fossil/non-renewable resources for power generation and/or fuel production. Tidal energy systems also provide the opportunity for local/distributed energy production in certain settings and can improve energy security by reducing dependence on finite fossil fuel resources. However, potential environmental risks associated with the installation and operation of tidal energy devices must be evaluated to ensure that addressing one problem does not introduce or exacerbate other environmental concerns. Key environmental risks associated with tidal energy harvesting devices and arrays, include:

- Alteration of waves and currents: physical devices and energy extraction can alter flows and wave height and power, which can affect ecosystem structure by altering sediment and nutrient transport patterns, leading to changes in benthic and near-shore habitat as well as alterations in beach formation patterns, navigation, and recreational suitability (e.g., for surfing, boating, etc.).
- Noise emissions: noise may affect wildlife, changing behavior and/or migratory patterns or hindering hunting behavior in some species.
- Electromagnetic fields: effects of EMF are poorly understood, but may have impacts on wildlife, particularly electrosensitive species such as sharks, eels, and others, which may confuse power transmission lines with prey, and species that use the earth's magnetic field as a navigation aid.
- Chemical toxicity: the use of coatings, lubricants, paints, biocides, or other chemicals for operation and maintenance of the devices may have toxic effects on wildlife and humans.
- Formation of physical barriers: the device and associated anchoring systems can block channel access and prevent movement and/or migration of animals through the installation area. Also the device can result in creation of new or expanded habitat associated with fixed structures in open water areas and potential changes in species composition and density associated with the changes

- Wildlife strike: moving parts of the device (i.e., hydrofoil wings) may strike animals, leading to injury or death.

This report describes the Leading Edge hydrofoil technology, summarizes key potential environmental risks of hydrokinetic energy, identifies the risks that are uniquely associated with hydrofoil-style devices, and summarizes key mitigation measures and/or best practices that can reduce environmental risks during development and implementation of the proposed technology. A case study of site specific considerations for one testing location is also presented, along with a summary of potential environmental benefits associated with the technology. To further support future permitting processes, the Volpe team compiled a summary of NEPA requirements and information that could contribute to a site-specific environmental impact assessment. In addition, the key environmental effects analyzed in existing NEPA-type analyses completed for related technologies are summarized. We also provide recommendations for data that could be collected during ongoing testing of the Leading Edge hydrokinetic device to inform future NEPA analyses. The Volpe team completed preliminary environmental measurements during prototype testing of the Leading Edge device, included biofouling experiments, characterization of water currents at the testing site, assessment of current flows and changes caused by the prototype device to downstream current speed and directions, and evaluation of underwater noise effects of the prototype. The report ends with conclusions and recommendations for future environmental monitoring to consider during Leading Edge device field testing.

2 Technical background

2.1 General Features of Hydrokinetic Energy Technologies

Hydrokinetic technologies convert the movements of river and ocean currents or waves into electricity. Wave energy technologies extract energy as waves pass using differential movement of horizontal and vertical parts or moving and stationary parts, differential pressures driven by wave action, or capture and controlled release of water. Many of the wave energy technologies utilize hydraulic power take-off systems. Ocean thermal energy conversion technologies extract energy from pressure driven vaporization and condensation of fluids using the temperature differential in the water column. Due to need for at least a 20 degree C temperature differential for operation, this technology is mainly restricted to tropical deep water locations. Many current devices are turbine-style rotating machines with a rotational speed proportional to the velocity of the fluid (DOE 2009). Turbines types include horizontal axis turbines and vertical axis turbines, which may have enclosures or ducts to concentrate flow past the turbine. A key characteristic of turbine-style devices is that the linear speed of the blades increases with distance from the center of rotation, resulting in high linear speeds near the tips of the blades. A predominant environmental concern of rotating machines is that the high linear speeds potentially pose threats of wildlife strike.

2.2 Description of the Leading Edge Hydrofoil Technology

The Leading Edge hydrokinetic energy harvesting device employs an oscillating hydrofoil (wing-shaped structure), coupled with an active system for motion control. As the current flows past the device the hydrofoils move slowly up and down along the vertical axis, driving a belt linked to a generator to produce energy (Figure 1).

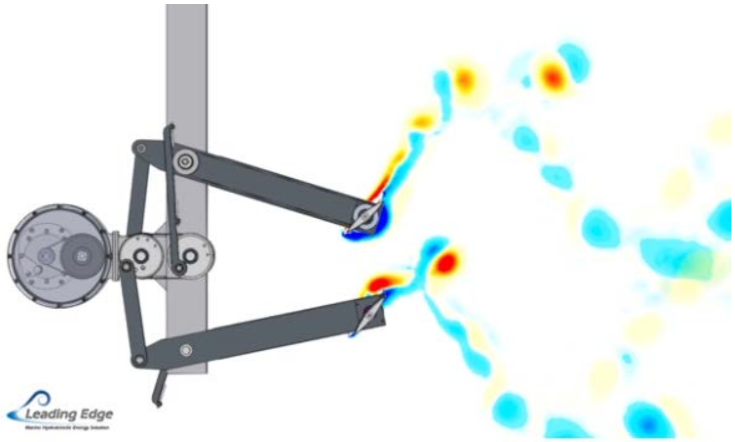


Figure 1. Conceptual rendering of the Leading Edge hydrofoil technology, showing simulated images of the vortices shed as the device operates.

The initial device design utilized a hydraulic generator, but the hydraulics were eliminated after a thorough analysis of potential failure modes and environmental risks. The first prototype is a single-arm device with two rows of hydrofoils (Figure 2). The device functions bi-directionally, to extract energy during both rising and falling tides. The frequency of the hydrofoil oscillations can be actively controlled and constantly adapted by the software control system. The hydrofoil length and pitch can be modified to optimize energy extraction at different installation locations.

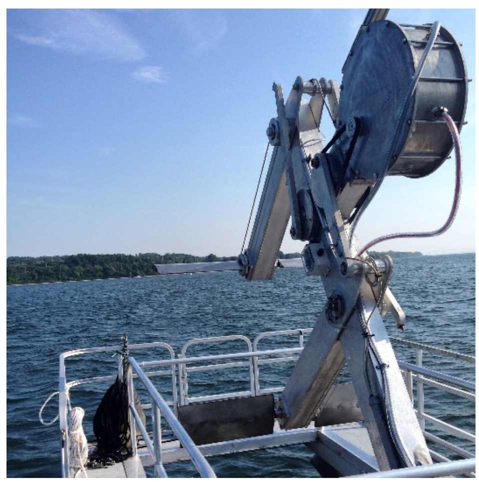


Figure 2. The first Leading Edge prototype with two rows of hydrofoils, shown in a raised position during field testing.

In addition to the active system for motion control, the two hydrofoils operate out of phase to drive the opposing foil through the direction reversal. This design also has the added benefit of reducing variation in torque during the device operation. After successful testing of the first prototype, the Leading Edge team designed the second prototype to test the operation of multiple devices operating in close proximity. The second Leading Edge prototype consists of a custom designed pontoon boat with two Leading Edge Oscillating Wings mounted along the centerline (Figure 3).

Figure 3. Schematic and photo of the second Leading Edge prototype with two devices, each with two rows of hydrofoils. Photo credit Michael Miller.

A fundamental difference between the Leading Edge hydrofoil devices and turbine-style devices is they move with an oscillating vertical motion, rather than a rotary motion. The hydrofoils also move much more slowly than rotary hydrokinetic turbines for the same water flow speed. The fastest speed of the hydrofoils is similar to the flow rate of the water, and the evidence to date shows they present a low risk of strike for fish and other wildlife. As with all hydrokinetic energy technologies, the environmental risks posed by the Leading Edge hydrofoil technology will vary depending on site-specific characteristics of the aquatic environment as well as the installation configuration (e.g., the arrangement of multiple foils and devices).

3 Potential environmental effects of tidal energy devices

Most available assessments of the environmental effects of hydrokinetic energy technology focus on rotary turbine devices, as these are the primary types of large-scale devices that have been deployed to date. While some potential environmental impacts of the Leading Edge hydrofoil technology will be similar to other hydrokinetic energy technologies, some unique design features of the hydrofoil device are likely to result in different environmental effects. DOE reviewed the general patterns of potential impacts on the aquatic environment from installation and operation of hydrokinetic technologies in a U.S. DOE report to Congress in response to the Energy Independence and Security Act of 2007, Section 633b (DOE 2009). Additional recent reports from the Annex IV collaborative project, operated by the U.S. Department of Energy (Copping et al. 2013a), and the Bureau of Ocean Energy Management (McCann 2012), also reviewed available information related to environmental effects hydrokinetic technologies. Here we utilize these published resources and other available literature to assess the potential similar and distinct environmental effects of the Leading Edge hydrofoil device.

3.1 Alteration of Waves and Currents

Alterations of currents and waves occur when tidal energy conversion devices block regular wind patterns or extract energy from the underlying current. Wave height reduction can affect the environmental, navigational, and recreational conditions (e.g., surfing and fishing) within meters to kilometers of a site, depending on the size of a project (Michel and Burkhard 2007). Alterations in wave and/or current energy may be beneficial for certain situations by reducing erosion along beaches or under bridges. The level of change caused by implementing tidal energy devices is predicted to vary with the amount of energy extracted from the ocean by each device and by the number and spacing of devices in an array (DOE 2009). Field measurements of wave height reduction as a result of tidal energy technology are limited, but several modeled results and predictions of height reductions are reviewed in Table 1. Predicted effects on wave height. In modeling scenarios, wave distance was predicted either at the shoreline, near the device, or both (Boehlert et al. 2008). At the pilot and very small commercial scale levels the alteration of waves and currents is expected to be minimal.

Table 1. Predicted effects of wave energy devices on wave height

Scenario	Device Distance from Shore	Location of predicted reduction	Wave Reduction	Notes	Reference
Halcrow study of wave energy conversion (WEC) devices near the coast of Cornwall, UK (at Wave Hub*)	5 to 20 km	Shoreline	3 to 13 %	Combinations of WEC devices were tested	South West of England Regional Development Agency, 2006
Six 20kW (avg) "OPT PowerBuoys" operating in Hawaii	1.22 km	Shoreline	0.3 to 0.5% for wave periods of 9s and 15s	Buoys are 4.5 m in diameter and spaced 51.5 m apart	Office of Naval Research, 2003
Estimate for a commercial-scale wave energy facility in the 2007 MMS' PDEIS for Alternative Energy	N/A	2 km (from device)	10 to 15 %		Michel & Burkhard, 2007
Array of WEC devices Spanning a 1x3 km area	20 km	20 km (from device)	1 to 2 cm (1%)		Millar et. al, 2007
A 2.25 x 1.11 km cluster of Pelamis Devices	N/A	N/A	12% behind wave and 5-10% at shoreline		Bedard et. al, 2007

*Wave Hub, located on the North Coast of Cornwall, UK, is a site for the testing and development of offshore renewable energy technology

The Stingray demonstrator, constructed in 2002 by The Engineering Business Ltd, is an energy generator that utilizes oscillating hydroplanes to generate electricity using the motion of tidal waves and therefore has some similarities to the Leading Edge tidal energy device. The device has a maximum height of 23.6 m, a maximum width of 15.5 m, an 11 m hydraulic arm, and a single hydroplane with a chord length of 3 m. At tidal velocities of approximately 1.5 m/s and above, Stingray has a rated power of 150 kW. Field tests were conducted in Yell Sound off the coast of the Scottish Shetlands Islands in order to measure changes in tidal flow velocity caused by the 180 ton device. Results were deemed inconclusive due to a lack of repeatable measurements but they suggested that in tidal currents between 1.5 and 2.0 m/s, the device could reduce flow velocity by up to 0.5 m/s. The test measured velocity forward of, at, and aft of the Stingray prototype at depths of 33.5 m, 31.4 m, and 30.1 m respectively. Figure 4 shows the difference between flow velocity forward of and aft of the Stingray prototype while it is and is not operational (The Engineering Business Ltd. 2005).

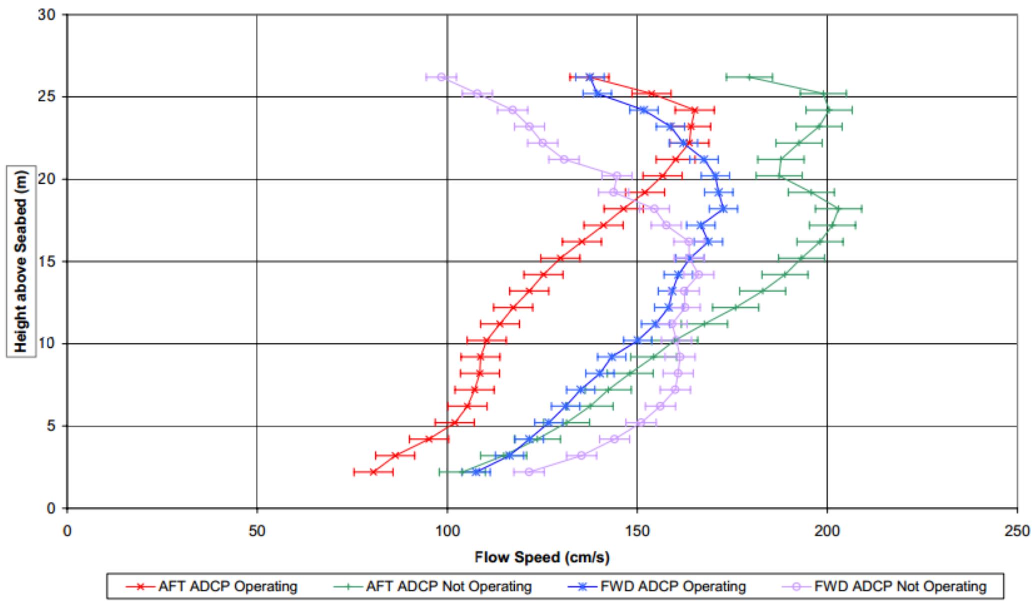


Figure 4. Average flow speed for a 30 minute period while the Stingray device is both operating and not-operating. Figure from The Engineering Business Ltd., 2005.

Velocity reduction information can help to determine the spacing requirements between hydrofoil devices required to minimize power loss in a network of devices. At Wave Hub, simulations showed that four Westward facing Wave Dragon overtopping WEC devices could cause a wave velocity reduction of up to 0.8 m/s forward of and aft of the device, but also a simultaneous increase of 0.6 m/s in bands outside the area of decreased flow (Figure 3; South West of England Regional Development Agency 2006). In addition, the models predict that the installations would have only minimal effects on wave period and height, with a maximum potential reduction in wave height of 1-2 cm difference for most beaches in the region (Millar et al. 2007). Similarly, a study comparing the effects of high and low power extraction scenarios using a high-resolution model of Ria de Ribadeo (NW Spain) concluded that water velocity would be reduced upstream and downstream of the farm, and increased beside it. The effects were higher in the higher power extraction scenario. Furthermore, modifications of the flow pattern reduced the available energy density at the tidal turbine by 21% for the high scenario and 12% for low scenario (Ramos et al. 2013). Wave energy converter devices above the surface are predicted to have less of an effect on tidal velocity than submerged rotor systems (DOE 2009).

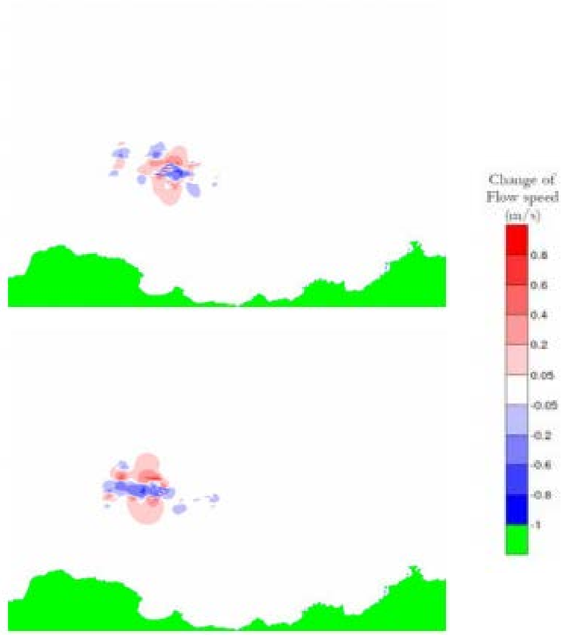


Figure 5. Changes under the worst case WEC layout scenario to flood tidal flow speed (top) and ebb tidal flow speed (bottom). Figure from South West of England Regional Development Agency, 2006)

Mitigation: Waves and Currents

As tidal energy devices move from prototype and test phase to implemented technology, the need for measured reductions in wave height and tidal velocity to confirm modeled and preliminary field data will become more significant. Currently, effective mitigation practices could include limiting the number and size of devices and siting projects away from marine protected areas, sensitive habitats, popular recreational areas, and fishing sites. Reducing drag by streamlining the shape of components (burying cables, altering spacing, and reducing non-energy generating surface area), could also have a significant effect on decreasing the amount of energy removed from the current. Drag reduction both increases the amount of energy used to generate electricity and reduces the amount of energy removed from the environment.

3.2 Alteration of Sediment Dynamics, Bottom Substrates, and Benthic Habitats

Tidal energy devices utilize the kinetic energy of water movement, reducing wave height and current velocity. This change in energy distribution in ocean tides, marine channels, and rivers can alter sediment transport and deposition, affecting the composition and dynamics of bottom substrates (DOE 2009). While effects on water flow are more pronounced during device operation, supporting structures can also significantly alter local flow patterns, affecting sediment dynamics. Fast currents frequently scour the bottom, preventing the built-up of sediments, while areas with slow currents can have high rates of sediment deposition, generating fine-grained muddy substrates. Tidal energy extraction can increase local sediment deposition, resulting in shoaling and a decrease in sediment grain size on the lee side of energy arrays (Boehlert et al. 2008). However, observations of sediment type and bathymetry, utilized in high resolution morphodynamic and spectral wave models to evaluate potential effects of a

Tidal Energy Converter installation (less than 50 MW) in the Irish Sea, found that the sedimentary impacts were within the bounds of natural variability (Robins et al. 2014).

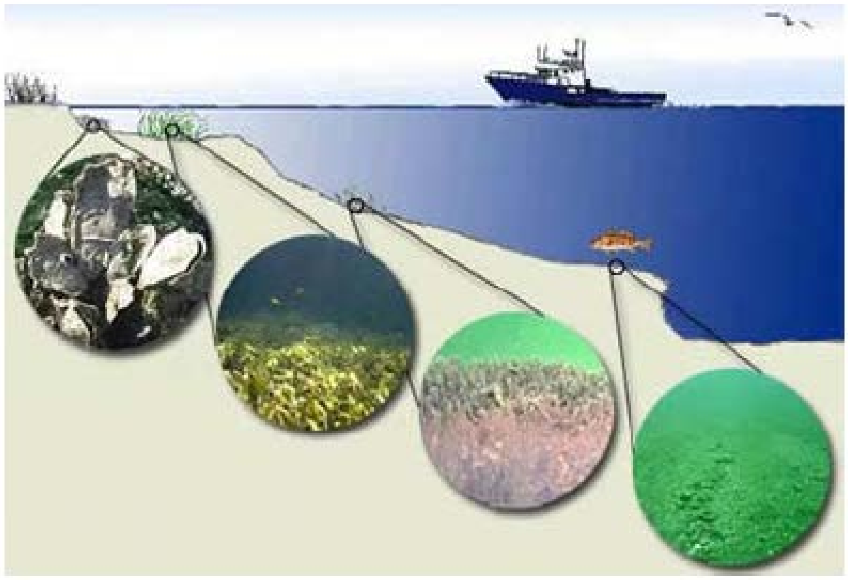


Figure 6. Examples of different benthic habitats (oyster bed, seagrass meadow, amphipod tube mat, and sandflat (DOE 2009).

The distinct physical and geochemical characteristics of bottom substrates (benthic habitats) determine the suitability for bottom-dwelling organisms (Figure 6). Deposition of sand will increase mortality and decrease growth rate of plant shoots (Craig et al. 2008). However, deposition of organic matter can increase benthic invertebrate communities that adapt to the substrate present. Excessive deposition of organic matter can result in locally anoxic sediments and adverse effects on the benthos. Economically important bottom-dwelling sessile organisms such as mussels, clams, and oysters may be particularly vulnerable to changes in sediments dynamics, requiring evaluation during site selection. Tidal energy installations also have the potential to significantly benefit benthic communities by preventing commercial fishing activities in the area. Cessation of towed-gear fishing increased total richness and biomass of benthic communities (Blyth et al. 2004). In addition, the tidal energy device structures are likely to serve as artificial reefs, with rapid colonization by sessile organisms, and utilization by consumer and predatory fish species (see Section 3.6).

The installation process of bottom-mounted marine hydrokinetic devices may significantly disturb bottom substrates, potentially releasing contaminants previously adsorbed by the sediments. Species that spawn in benthic habitats will be particularly vulnerable during the installation process. Once construction is complete, the benthic species are likely to recolonize if the bottom substrates remain relatively unaltered, with most species returning to the area (Wilber and Clarke 2001), although effects may still be observed up to two years after installation (DONG Energy 2006). Cables required to transfer energy to shore also have the potential to affect bottom substrates. A study of cable effects on rocky seafloor in Half Moon Bay, California showed that in near shore areas with high wave energy, cable strumming caused incisions in rocky substrates (Kogan et al. 2006). In areas where the seafloor is dominated by sediment, the cable became covered by sediment in near-shore areas but remained exposed further from shore. Epifaunal biota abundance increased slightly, and some species preferentially colonized the cable surface; in fact, lines of anemones were used to find cable that had been buried by sediment (Kogan et al. 2006). Installation and initial operation of tidal technologies will also frequently affect water quality. Temporary effects from construction may include a localized decline in dissolved oxygen content (DOC) from anoxic sediments (DOE 2009).

Mitigation: Sediment Dynamics, Bottom Substrates, and Benthic Habitats

Effects of tidal energy structures on bottom substrates can be reduced by altering the design of the devices and supporting structures. Careful site selection, streamlining component shapes, reducing the surface area, and adjusting the spacing between individual devices can minimize seafloor disturbance and sediment dynamics alterations (Copping et al. 2013a). Understanding the hydrodynamics of the area will assist in assessing the size and orientation of a hydrokinetic installation that will minimize alterations to the environment. Orientation of structures and components, such as routing cables to avoid sensitive substrates (e.g., live coral, seagrass beds, productive rocky habits) can reduce impacts. Dynamic positioning on a vessel in sensitive areas can replace the need for anchors. In terms of design, a mooring system can be designed to a minimum anchor size, seafloor footprint, and chain/cable sweeping of seafloor (Michel and Burkhard 2007). Before construction occurs, completing pre-construction surveys will prepare construction teams on possibilities for and avoidance of contamination.

3.3 Noise Produced by Hydrokinetic Energy Technologies

Throughout the life of a device or an array of devices there are several sound sources that can potentially affect the organisms in the surrounding environment. Noise from activities including construction, maintenance, noise-based fish deterrent systems, and hydro-acoustic environmental monitoring tend to be temporary but also the most abrasive to wildlife. Noise produced by hydrokinetic energy devices can elicit stressful startle responses in marine animals, or longer term avoidance of a given area. Pile-driving activities associated with the installation of bottom-mounted devices can generate sufficient noise to cause hearing damage and even mortality in nearby marine animals (Copping et al. 2013a). Operational noise can potentially interfere with animal communication and echolocation, and may affect wildlife movements if animals avoid areas with high sound levels. There are minimal data available on the long terms effect of the noise produced by tidal energy projects.

Several fundamental properties of underwater sound transmission are relevant for understanding potential effects of noise on animals (DOE 2009). The intensity of underwater noise, measured in the basic unit of sound pressure level (SPL), given in decibels (dB) can be calculated by: $SPL\ (dB) = 20\ log_{10}(P/P_o)$, where P is the pressure fluctuation caused by sound and P_o is the reference pressure, defined in underwater acoustics as 1 µPa at 1 meter from the source. Doubling the pressure of a sound, P, results in a 6 dB increase in SPL. Sound intensity decreases with distance from the sound source. Note that dB levels in water cannot be compared to dB levels in air as the reference pressure used in water is 1 µPa and the reference pressure used in air is 20 µPa. An approximation can be made between dB in air and dB in water by subtracting 62 dB from the SPL in water to get the SPL in air (OGP-IAGC 2008). Noise can also be measured in Sound Exposure Level (SEL) which takes into account both intensity and duration, normalizing the time of the acoustic event to 1 second. This is useful when comparing different acoustic sources that occur over varying periods of time.

The free-field transmission distance of sound in seawater is determined by a combination of geometric spreading loss and an absorptive loss that is proportional to the sound frequency. The transmission loss of energy (intensity) due to spherical spreading in deep water is estimated by 20 $\log_{10}r$, where r is the distance in m from the source. Attenuation (weakening) of sound also increases as its frequency increases. In shallow settings, the shape and material of the sea floor or river bed will affect transmission distance as well due to absorption. The speed of a sound wave in water is proportional to the temperature, moving faster in warmer water.

Audiograms measure the normal range of hearing and can be used to assess the potential sensitivity of marine animals to sound frequency and intensity (Figure 7). For aquatic animals, normal hearing ranges from a sound intensity of 10 dB to almost 170 dB, across a wide range of frequencies.

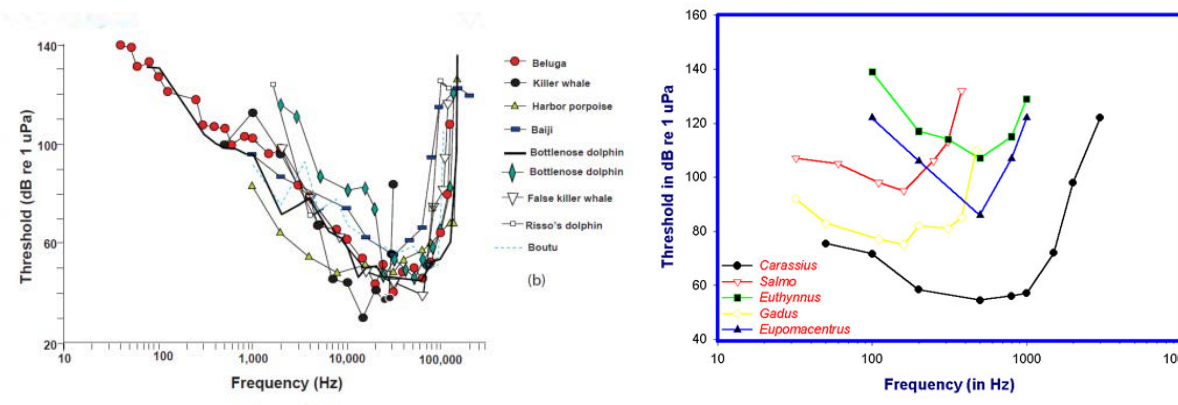


Figure 7. Examples of audiograms for a) marine mammals (from Reynolds and Rommel, 1999), and b) teleost fish (from Mann et al. 1997).

Table 2 details sound pressure levels of several common man-made sources that potentially affect underwater life (Thomsen et al. 2006). Based on this table, man-made devices commonly introduce external noise at frequencies and intensities that would fall within the hearing spectrum of aquatic animals and possibly alter their behavior. The lower limits for the concern about temporary or permanent hearing loss in cetaceans (whales, dolphins, and porpoises) and pinnipeds (seals) are 180 and 190 dB re 1 µPa, respectively (NMFS 2003, Southall et al. 2008). Pile driving and shipping activities will be required for the installation of many underwater, bottom-mounted tidal energy devices. Pile-driving activities generate noise levels well above the lower limits for concern of hearing loss in cetaceans and pinnipeds. These highly mobile organisms may leave the area during active construction, affecting their access to the habitat.

Ongoing operational noise specific to tidal energy technology is not yet well characterized. The

Table 2. Frequencies and intensities of some anthropogenic sounds (from Thompsen et al. 2006, modified from NRC (2000).

Source	Frequency at the highest level 1/3-octave band (Hz)	Source level at the highest level 1/3-octave band (dB re 1 µPa at 1 m)
5-m Zodiac inflatable boat	6,300	152
Bell 212 helicopter	16	159
Large tanker	100 + 125	177
Icebreaker	100	183
Medium-sized support/supply ships[b]	10-20	130-160
Acoustic Thermometry of Ocean Climate (ATOC)[a]	75	195
Air gun array	50	210
Heard Island Feasibility Test (HIST; research device)	50 + 63	221
Military search sonar	2,000-5,000	230+
Pile-driving (Sweden; 30 m from source)[b]	250	140->180
Pile-driving (UK; 1 m from source)[b]	200 + 800 + 1,600	262
Pile-driving (Germany; 400 m from source)[b] See Figure C-1 for frequency spectrum	125 + 315 + 1,100	180

[a] scientific research device
[b] from Thomsen et al. (2006)

Department of the Navy predicts that OPT Powerbuoys, which have been implemented in Oahu, Hawaii, operate between 75 and 80 dB re *1* µPa (Office of Naval Research 2003) and that hydraulic drilling to install mooring OPT Powerbuoys would range between 120 and 170 dB at 15 to 39 kHz within 40m of the drilling site. Wave Dragon Waves Ltd. predicted that their overtopping, pre-commercial WEC device had an operational SPL of 143 dB re *1* µPa and that hydraulic drilling for mooring installation would range from 159 to 181 dB re 1 µPa, which is similar to DON SPL predictions for hydraulic drilling (PMSS Ltd. 2007).

Mitigation: Sounds and Noise

Acoustic Deterrent Systems are being developed that use sonar to detect when animals move into a range where they may be affected by noise generated from a marine hydrokinetic installation. These devices could be used to detect large animals and determine if a device can be temporarily disabled until that animal has passed. However, these devices add noise to the environment and are not capable of detecting smaller animals. Another approach to mitigation is to avoid or reduce noise in sensitive areas. Sound insulation can be implemented in the form of bubble screens on the water's surface or as noise barriers placed around WEC devices or installation machinery. In shallow water, Wursig et al. (2000) measured a 3 to 5 dB (pulse level) reduction in sound produced by pile-driving activities.

However, Nehls and colleagues (2007) determined, from review, that bubble screens would not be effective in deep water or strong tidal currents and that foam or inflatable insulated sleeves around piles would be more effective in reducing noise.

Acoustic Mitigation Devices (AMDs) and similar devices create noise that is intended to deter aquatic animals from approaching technology. Wilson and Dill (2002) found that noises that are "sufficiently frightening" (particularly noises that replicate the acoustic signature of predators) are the most effective deterrents. These devices, ironically, add noise to the environment with the intention of forcing wildlife to avoid a noisy environment. Some studies, including Weilgart et al. (2007) and Simmonds et al. (2004), have concluded that the problem of predicting and controlling noise in underwater environments is currently too complicated and that avoiding inhabited areas or controlling operation times is the best means of mitigation.

3.4 Electromagnetic fields (EMF)

The transmission of power generated by hydrokinetic devices through offshore networks of submarine cables to shore-side facilities produces EMF: an electric field (E field) and an induced magnetic field (B field). In addition, a secondary induced electrical field (iE-field) may be generated as water or animals move through the magnetic field (CMACS 2003, Cada et al. 2011, Tricas and Gill 2011). The strength of a typical magnetic field generated outside a standard buried cable is shown in Figure 8. EMF can attract electro-sensitive species that might be confused into thinking cables or other elements are prey species (McCann 2012).

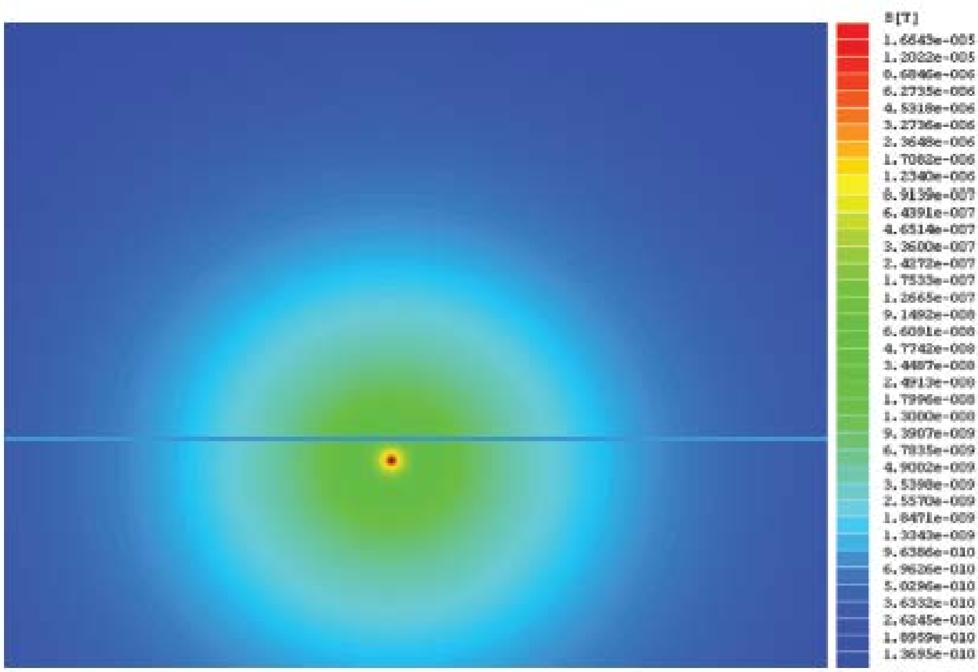


Figure 8. The magnetic field (Teslas) outside an industry standard 13 kV sub-sea cable buried to 1m. The seabed surface is shown as the horizontal blue line. Source: Boehlert, 2010, referenced within to the Centre for Intelligent Monitoring Systems, University of Liverpool, UK.

Anthropogenic sources of EMF have the potential to alter the feeding behavior, reproduction, and migration behavior of marine organisms. Elasmobranch species (e.g., sharks, rays, skates) gain heightened awareness of spatial information by detecting fields from movements in ocean currents and fish movements through Earth's magnetic field (Öhman et al. 2007). Skates and stingrays may be sensitive to electric fields as low as 1 nV/m (Fisher and Slater 2010), exhibiting cardiac responses (Kalmijn 1966) and an ability to orient relative to uniform electric fields similar to those produced by ocean currents (Kalmijn 1982). Sharks have shown extremely sensitivity to low frequency (1/8th to 8 Hz) AC electric fields (Kalmijn 2000, Walker et al. 2003), but there is no evidence of magnetic field sensitivity (Fisher and Slater 2010). Salmonids and other species of teleost fish are an order of magnitude less sensitive to electric fields than sharks (Fisher and Slater 2010). Environmental effects and behavioral responses of fish may differ for DC power transmission systems and AC systems (Woodruff et al. 2013).

There is evidence that some marine mammals and benthic species are affected by magnetic fields, but not electric fields (Fisher and Slater 2010). The most sensitive species to magnetic fields appear to be eels, which can respond to signals as low as a few µT (Fisher and Slater 2010). The heartrate of *Anguilla japonica* (Japanese eel) was shown to decrease after continued exposure from classical conditioning-induced experiments in which 10-40 trials of exposure to magnetic fields were run. Extended exposure to magnetic fields in early life elicited a conditioned response (i.e., slowing of the heartbeat), that may have altered migratory behavior as an adult (Nishi et al. 2004). A tank study of behavioral effects of EMF on ecologically and economically important species, including the Atlantic halibut *(Hippoglossus hippoglossus*), Dungeness crab (*Metacarcinus magister*), and American lobster (*Homarus americanus*) conducted by Pacific Northwest National Laboratory (PNNL) found minimal changes in behavior that would suggest the species explicitly avoided or sought an approximate 1.1 mT DC EMF intensity. However, the authors noted some differences in movement frequency and patterns between the Control and Exposure treatments in specific areas of the tank. Contact with magnetic fields resulted in modified hormone levels (brook trout), decreased embryonic development (trout and rainbow trout), altered circulation motions in embryos (trout and larvae in pike), and decreased biomass/mortality (European catfish) (Öhman et al. 2007). Some species of fish and sea urchins have shown cellular-level alterations including circulation, gas exchange, and embryotic development rates (Fisher and Slater 2010).

No studies to date have confirmed whether EMF sources will significantly alter navigation or feeding in seasonal migrants or in species such as Dungeness crab and American lobster, which migrate between on-shore and off-shore habitats (Tricas and Gill 2011, Woodruff et al. 2013). However, a recent study found that migrating sockeye salmon can be redirected to different routes of return to spawning rivers when natural shifts in local geomagnetic fields occur (Putman et al. 2013). Further field studies are required to understand how anthropogenic EMF generated by a network of transmission cables associated with hydrokinetic energy installations will affect broader-scale patterns of coastal migration and onshore-offshore migration in species of particular concern for a given site.

Mitigation: EMF

Current evidence suggests that effects from EMF magnetic emissions should be evaluated on a site-specific and species by species basis. The intensity of EMF levels is highest in close proximity to a hydrokinetic energy system, therefore the bottom region near benthic communities will be affected rather than the upper water column (Fisher and Slater 2010). Monitoring systems with sufficient sensitivity to detect EMF levels shown to effect marine animals should be utilized. Options to mitigate potential EMF effects include siting the installation away from migratory paths of species of particular ecological or economic concern. Additional field studies may also lead to specific recommendations for routing cables either perpendicular or parallel to migratory routes to control cumulative exposure and effects of migratory routes for specific species (Woodruff et al. 2013).

3.5 Chemical toxicity

Marine hydrokinetic energy installations may present risks of both acute and chronic chemical exposure. Acute chemical exposure will occur in the event of an accidental release of oils and other operating fluids, including hydraulic fluids (DOE 2009). Collision of vessels with an installation may also lead to the accidental release of fuel or other contaminants. Chronic exposure is caused by the slow release of anti-fouling compounds, paints, lubricants, and other chemicals utilized for device operation and maintenance (Boehlert and Gill 2010). Encrustation by barnacles and other marine organisms (biofouling) can increase corrosion and decrease electrical generation efficiency of systems (Copping et al. 2013a). The dissolved metals or organic compounds typically used to control biofouling in marine applications can produce low-level chronic contamination over time. In addition, paint flaked off could be ingested by filter-feeders and then consumed by other species (Cada et al. 2007). Even at sub-lethal concentrations, some contaminants can affect sensory systems, growth, and behavior of individual animals. There is also the potential for bioaccumulation of metals and other compounds for plants and animals that reside in the vicinity of the device. Individual toxicity effects may reduce the population densities of sensitive species, ultimately affecting local communities and ecosystems (DOE 2009). Particularly for device arrays, cumulative impacts from toxic compound exposure could result in significant ecological effects on local ecosystems. The life cycle of the devices and potential release of fluids, paints or other toxins during demolition should be considered. While potential environmental impacts due to chemical toxicity are important to consider for hydrokinetic installations, the risks will be similar to those for all marine construction projects (Boehlert and Gill 2010).

Mitigation: Chemical toxicity

The risks of acute chemical exposure due to accidental fluid releases can be minimized by utilizing standard safety practices and spill-mitigation plans utilized for other marine construction and end-of-life demolition projects. For emergency management practices, estimating the potential chemical concentrations that could be released under routine and accident situations is important to understand and mitigate potential contamination levels (DOE 2009). In addition, the use of environmentally-friendly lubricants and hydraulic fluids that are inert or break down rapidly to inert components will minimize risks posed by tidal energy devices. For example, Panolin offers bio-hydraulic fluids (HLS SYNTH) that they report have extended oil drain intervals, are readily biodegradable, with low toxicity (> 100 mg/l for algae, daphnia, and fish), and are "not bioaccumulative" according to OECD 107/117 methods (Panolin accessed 2015). While the engineering team eliminated the hydraulic generator in the final design of the Leading Edge device, existing assessments of the risks and mitigation strategies for the hydraulic systems utilized in wave energy technologies could inform the team if hydraulics are reintroduced for much larger versions in the future. Chronic exposure risk may also be minimized by utilizing bio-based paints and lubricants. In addition, non-toxic antifouling coatings under development may reduce biological growth on the device by providing low-friction, smooth surfaces (Magin et al. 2010, Epstein et al. 2012). Additional required cleaning can be accomplished in situ using high pressure jet spray, or by removing the device from water to clean on floating platform or onshore. However, manual device cleaning to minimize device coatings involves more service trips that could increase the potential for collision and spills. Careful control of releases during maintenance/cleaning and end-of-life demolition should be considered as part of hydrokinetic device development.

3.6 Interference with animal movements and migrations

A tidal energy device and/or array can affect animal movements and migration through direct physical barriers and effects, through secondary effects on movement and migration due to noise and EMF (described above), or through changes in ecosystem habitat and population distributions that affect the location and concentrations of food sources/prey, or predators.

Physical interference with animal movements and migrations may result from either static elements of the tidal energy device (e.g., cables, anchors, monopoles, etc.) or dynamic elements (e.g., the hydrofoil, belt-drive system, linkage arms, etc.) (DOE 2009). Static structure effects can include changes in hydrodynamics, currents, sediments/scour, and also can alter habitat and ecosystem structure (DOE 2009). Mooring lines, in particular, may be the most challenging physical element to limit, as they are necessary to properly secure devices, yet can cause entanglement and entrapment. Lines that are thin and loose are particularly problematic, as these are less noticeable to swimming animals. These lines can inhibit individual movements but also affect larger migratory movements of groups of animals. The effects may be exacerbated by existing migration patterns through areas of interest for hydrokinetic energy installations. For example, gray whales (*Eschrichtius robustus)* migrate within 2.8 km of the shoreline along the Pacific Coast (Hagerman and Bedard 2004), which may coincide with prime candidate locations for hydrokinetic energy projects. Site-specific evaluation of migration patterns can inform the site selection process to avoid key migratory routes.

Other changes in community structure and ecosystem services related to the physical device can result in changes in species behavior and therefore their movements and migrations through an area. Hydrokinetic devices, anchoring, cables, mooring lines, transmission lines, and associated generators may attract or repel aquatic organisms (DOE 2009). Surface piercing structures are likely to become seabird roosts and/or marine mammal haul out locations (Polagye et al. 2011a), and as such can alter movement and aggregation of these species.[1]

[1] It should also be noted that large-scale surface-piercing structures may affect viewscapes for humans and animals. Such issues have been major concerns for offshore and near-shore windfarms.

Underwater man-made structures tend to rapidly form artificial reefs, particular large and complex structures. Hydrokinetic devices are likely to be colonized quickly by sessile species such as mussels, hydroids, anemones, algae, and barnacles (Langhamer et al. 2009), concentrating potential food sources for other species around the device, increasing habitat heterogeneity (Linley et al. 2007, Polagye et al. 2011a), and potentially altering local population distribution patterns and nutrient flow through local food webs (Gill et al. 2005). These reefs can act as Fish Attraction/Aggregation Devices (FADs) that provide shelter and food (DOE 2009). Attractiveness of artificial reef structures will depend on the identity of the local species and whether they are habitat limited and are strongly reef-dependent species (Bohnsack 1989). In some cases the aggregation may represent actual population augmentation by increasing foraging and reproductive success while in other cases it appears that artificial reefs may act as sinks for nearby populations of fish (Grossman et al. 1997). This "attraction versus production" debate has gone on for decades (Bohnsack 1989, Grossman et al. 1997, Pickering and Whitmarsh 1997, Brickhill et al. 2005), but at a minimum it is well known that submerged structures can alter local species distributions and modify local habitats. Whether an artificial reef actually increases population sizes for a given species will likely depend on the shape, size, material, and complexity of the artificial (Pickering and Whitmarsh 1997). Artificial reef studies completed elsewhere indicate that fish rapidly occupy new reef structures, sometimes within hours of completion (Turner et al. 1969). The overall effect on population is difficult to determine, as energy conversion sites could attract smaller fish which could in turn attract prey which could in turn attract fishermen, whose efforts may be limited by the presence of tidal energy devices or their mooring and anchoring systems (DOE 2009). Wave-energy extracting buoys and foundations have also been found to form artificial reefs, with vertical structures experiencing heavy colonization dominated by blue mussels (*M. edulis*) (Langhamer et al. 2009).

Construction and installation of hydrokinetic devices can have long-lasting impacts on benthic flora and fauna, such that local habitat may be altered not only for these organisms, but for those that utilize them. At least one study showed that macro algae and benthic invertebrates took more than two years to recover from the physical disturbances of pile driving and cable laying (DONG Energy 2006). Dynamic effects are mostly related to strike and/or entrainment of organisms (eggs, juveniles, adults) during the normal functioning of the device. However, particularly with turbines, dynamic effects can also relate to changes in "pressure and velocity gradients" and turbidity downstream due to functioning of device. The functioning of the device may change upwelling, aggregation of prey, and currents, and therefore change migratory and behavioral patterns of birds and sea mammals (Polagye et al. 2011a). At least one study on turbines for the "OpenHydro" project showed that fish tended to move close to the downstream side of the turbines in certain conditions, but it is unclear whether the behavior was due to changes in current speed or the presence and functioning of the turbine per se (Polagye et al. 2011a). Other dynamic effects include maintenance activities – for example, removal and cleaning of components can release biocides to the local environment and will temporarily displace attracted/resident fish and other animals using device for support, as shelter, or as feeding or breeding locations.

While any single element of a hydrokinetic energy device (cables, anchors, movement of hydrofoils) may have limited effects on local populations, any environmental evaluation must also include the cumulative effects of multiple stressors/environmental changes. Cumulative stressors can affect animal and plant communities, populations, and ecosystem structure even when each effect individually is minor. Such cumulative stressors may lead to "top-down" ecosystem effects where predators and availability of prey change substantially. Energy removal from the current itself can also lead to systemic changes in local ecosystem function by affecting mixing rates, hydrology/hydrography, and water chemistry. It is not yet understood what constitutes an ecologically significant amount of energy to remove from a system (Polagye et al. 2011a). Furthermore, large arrays will have greater effects than single or a few devices, and therefore the scale of any given installation will be an important determinant of the scale of artificial reef formation, blockage of movement, change in population distribution patterns and behavior, and ecosystem impacts.

Mitigation: Animal movement and migration

The most important mitigation action associated with animal movements is to avoid sensitive habitats and migration paths, especially for larger fish, marine mammals, and sea turtles. Devices should be spaced so as to allow passage and cables laid along the surface of the seabed should be flexible enough to conform to the surface floor but with enough tension to avoid looping. Depending on the species in question, acoustic deterring devices and visual cues, such as highly visible paint, can help to avoid entanglement and collision. Structures should also have minimal horizontal surface area, so as to deter marine mammals, sea turtles, and birds from utilizing them as a resting habitats or sites with easily accessible prey.

3.7 Potential for marine animal strikes

A strike or collision is considered to be a physical contact between an organism and a device or its pressure field that causes harm to that organism (Wilson 2007). A tidal energy device and/or array will be composed of stationary and moving components that both present a risk of wildlife collisions. Some authors have suggested that strikes and collisions between marine animals and man-made structures, both on and beneath the ocean or river surface, may be underestimated, underreported and more diverse than generally thought (Wilson 2007). An assessment of the potential impacts of a tidal energy device or array can be made by examining how birds and marine animals interact with similar moving and stationary objects. Wilson (2007) takes the approach of modeling the probability of a species encountering a device and then assessing each species' capability for avoidance in a field of 100 2-bladed, 16 meter diameter turbines. Encounter rates were found to be highly dependent on animal density and the size of the animal, with larger marine animals having a higher probability of encounter. For example, model results showed that 2% of the predicted population of 1,590 million herring living off of the Scottish West Coast, an area of 90,828 km^2, would encounter a device whereas 3.6 to 10.7% of the predicted porpoise population of 12,076 in a 30,650 km^2 area would encounter a device. Encounter, however, does not equate to contact and the likelihood of collision will depend on visibility and turbidity around the device, water velocity, the size and number of moving parts on a device (i.e., blades, arms), and the swimming ability of the species in question (Wilson 2007). The limited empirical data for wildlife encounters with *in situ* tidal energy devices suggests that major effects of tidal turbines on marine animals are not expected (Viehmann 2012, Copping et al. 2013a).

Stationary Components

In most cases, structures, cabling, anchored barges, and other stationary objects pose little threat to cause injury or mortality to birds and marine life, even in the case of collision. However, increased turbidity in high velocity flows coupled with current alterations caused by the removal of tidal energy could increase the potential for injury, both for visual predators and for fish or schools of fish that may have trouble with avoidance during high velocity approaches with shortened response times. Smaller animals have shown a preference for areas of increased turbidity as they can be effective areas to forage and take refuge from predators. Larger predators, often visually dependent, and their prey may have an increased risk of collision in the low visibility conditions created by increased turbidity (Wilson 2007). Floating surfaces and Sections of tidal energy devices that breach the surface can be collision risks for birds (especially diving birds), near surface marine animals, and animals that may haul-out or search for prey around devices. Devices can act as fish aggregating devices (FADs) and in low visibility conditions, near-surface birds and marine animals, particularly those searching for prey, that are not familiar with the area may collide with devices while in pursuit. Cables and chains for mooring have the potential to cause lacerations upon impact if they are too taut or entanglement if they are too loose, but impact with mooring structures is not predicted to be common (Boehlert et al. 2008).

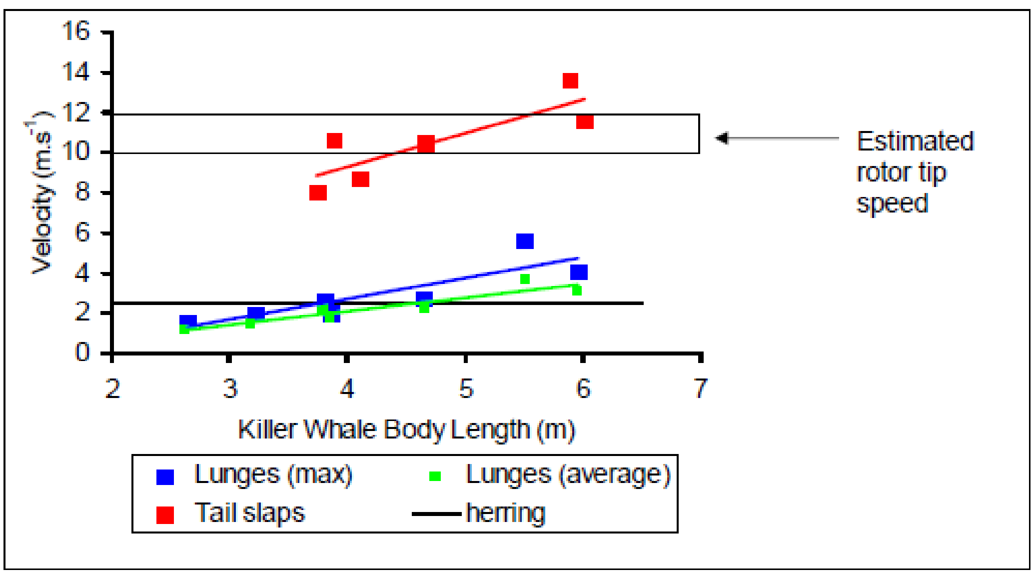


Figure 9. Lunging, tail slap velocities and the predicted burst speed of herring are compared to the predicted marine energy device rotor tip speed. From Wilson et al. 2007; adapted from Domenici 2001.

Moving Components

Marine life can collide with any tidal energy device, but those that move independent of the motion of the tidal flow are the primary concern when it comes to significant strikes. For a hydrofoil or turbine blade, the velocity of the blade and/or hydraulic arms will increase with their distance from the rotating axis, also increasing the impact of a strike. Rotating blades also introduce the potential for cavitation, the collapsing of low pressure cavities that form from a sudden change in pressure. The collapse of cavitation bubbles can reach pressures of tens of thousands of kilopascals which can reduce device efficiency and cause damage to both blades and organisms (Sinclair and Rodrigue 1986, Cada et al. 1997). In particular, fish with swim bladders are prone to pressure-related injuries (barotrauma). Decompression during fish passage through hydroturbines can cause rapid swim bladder expansion and result in injury or death (Carlson 2012). Wilson et. al (2007) states that most turbine blades will operate below a tip velocity of 12 m/s to avoid cavitation and compares this limit on blade velocity to an example from nature. While hunting herring, killer whales (*Orcinus orca*) strike their prey with their tails with enough force to stun the fish. As seen in Figure 9, tail swipe speeds of 8 to 13.6 m/s coincide with rotor tip speeds of 10 to 12 m/s, both of which far exceed 2.5 m/s the predicted burst speed velocity of herring. The maximum burst speed of a fish has been predicted to be roughly 10 body lengths per second (Videler and Wardle 1991).

Experimental analyses corroborating this result showed that that fish length to blade thickness (L/t) ratios were important determinants of the likelihood of damage at speeds above 4.57 m/s, and suggested that speeds lower than turbine blade speeds 4.57 m/s should cause “minimal or no injury to all species and life stages (except possibly early larval fish)” (Jacobson et al. 2012). For the current design, the Leading Edge hydrofoils are expected to move at a similar speed as the current, or ~2.5m/s for the targeted sites.

Mitigation: Animal Strikes

Siting according to the design of a tidal energy device will be important in protecting wildlife against collisions. Ideally, a device should be installed so that its vicinity to the topography and to other devices provides sufficient space for passage, dependent on the species of concern at a given site. Modifying blade structure for wide spacing between blades, blunt/thick leading edges, and low rotation rates are likely to reduce injury and mortality. Placing project sites in less populated areas is ideal but not always possible as narrow straights with high velocity water, which are ideal for tidal energy projects, are often densely populated. Properly designed blades should not cause cavitation and efficient operation at lower velocities decreases the chance of a collision being harmful. If floating surfaces or structures that extend above the water’s surface are necessary, visual cues such as bright paint or lighting could be helpful for birds and near surface animals or animals that traverse between land and water.

A safe velocity at which moving parts of tidal energy devices can operate has not been determined definitively. In many cases the size and design of a tidal energy device greatly influence an organism’s ability to avoid collision with moving components upon encounter. Figure 10 provides an example in which the “predicted zone of potentially damaging strike” is determined by calculating the region of a 5 meter unducted turbine in which the blades are moving fast enough to cause injury or mortality and animals do not have ample space to avoid collision (Coutant and Cada 2005, Aubry 2009).

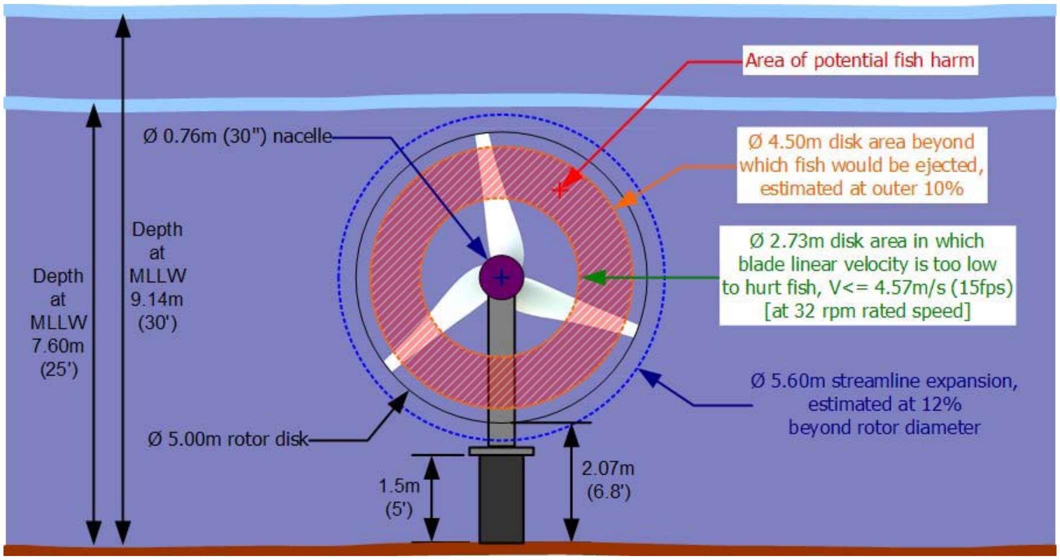


Figure 10. Predicted zone of potentially damaging strike associated with an unducted horizontal axis turbine. Source: Coutant and Cada (2005) from Department of Energy's "Report to Congress on the Potential Environmental Effects of Marine and Hydrokinetic Energy Technologies" (2009).

In this model, 4.57 m/s is designated as a blade velocity not harmful to fish. An increase in the blade length, number of blades, rpm, or a reduction in the blade spacing is likely to increase the predicted strike zone. It should also be noted that the work described in Coutant and Cada (2005), focuses on hydropower turbines, which are much faster and cause more shear and pressure changes compared to hydrokinetic turbines or hydrofoils (Jacobson et al. 2012). In a series of flume studies designed to compare the effects of different HK turbines on juvenile hybrid Striped Bass, Rainbow Trout, and White Sturgeon, Bass were most likely to be entrained, but even entrained fish had greater than 0.95 probability of survival (Amaral et al. 2015).

4 Potential environmental effects unique to hydrofoil technologies[2].

Many environmental effects will be common to all types of hydrokinetic technologies, however the unique features of the hydrofoil technology may result in some distinct effects (Table 3). In this Section the environmental issues reviewed in Section 5 for hydrokinetic technologies in general are addressed, with a particular focus on the unique aspects of hydrofoil technologies. Available literature and knowledge of the current hydrofoil device design, based on extensive meetings with the Leading Edge engineering team (Brown University and Blue Source Energy) are utilized to assess the potential environmental effects of the hydrofoil device.

[2]The potential environmental effects of the hydrofoil technology were assessed for this draft report based on the details of the preliminary device design. The report will be updated at the end of Q4 to reflect changes in the device design during the development and testing phases.

Table 3. Potential environmental effects of hydrokinetic energy technologies.

	Hydrofoil technology: unique effects	Effects common among technologies[3]
Alteration of currents and waves	Wake effects on currents will vary over time and will likely be more turbulent, without the "dead zone" behind the hub of traditional turbines (when on or off). Hydrofoil support structures may introduce static dead zones in the wake, but they are avoided to minimize drag. Hydrofoils (single or arrays) could conceivably span an entire channel and extract a significant portion of the current/wave energy.	Devices will alter currents/waves but only localized effects in open ocean sites. In contained regions all devices could remove significant current/wave energy, depending on the configuration of units. Devices may affect mixing, circulation, and water quality (site-dependent). Reduced velocities potentially could potentially cause alterations in sediment/plankton transport and bottom/coastal habitats.
Alteration of bottom substrates, sediment transport, and sediment deposition, and benthic habitats.	Unique effects may be observed if hydrofoils are able to extract a more significant portion of the current and wave energy at a site. Ability to operate more closely to the bottom compared to turbines could lead to greater effects on bottom substrates and benthic habitats due to change in currents, waves, and water quality.	Effects will depend on the proportion of energy removed from a site and the type/size of structures. Slower currents and smaller waves due to energy removal may increase sediment deposition/scour and affect bottom substrates, displacing benthic organisms and altering animal behavior. Bottom substrate effects depend on anchoring mechanisms (weighted structures, piles, floating, barge-mounted, guy wire arrangements).
Noise	Device wing will move at slower speeds (max speed is similar to current speed), and the acoustic signature will be unique. Noise level during operation is predicted to be lower than for turbines, but may be more pulsed (data required).	Animals may avoid areas with high noise levels that can mask animal communications and echolocation. Pile-driving during project installation or operational noise may damage marine animal hearing or result in death of nearby organisms.
EMF	Depends on power take-off mechanism; signal could be more pulsed or multiple devices linked to a single generator may produce steady EMF signals.	EMF in the water near devices and cables can alter animal feeding behavior, migration, reproduction, or susceptibility to predation near the project.
Chemical toxicity	No unique aspects: similar materials, anti-fouling compounds, and lubricants are utilized in other hydrokinetic technologies.	Coatings, lubricants, paints, biocides, or other chemicals used in, on, or as part of maintenance of the devices can cause toxic effects on nearby organisms.

[3] Summarized from table ES-1 in EISA 633b document. In all cases, potential impacts on animal habitat due to alteration of waves and currents, along with direct impacts on animal behavior or individual injury/mortality are predicted to also affect plant and animal populations, with resulting community and ecosystem-level effects. The population, community, and ecosystem effects are implicit, and not specifically referenced in this summary.

	Hydrofoil technology: unique effects	Effects common among technologies[3]
Interference with animal movement/migration	The static elements of the hydrofoil device will be similar as for other hydrokinetic technologies, but the dynamic elements will differ. Slower movement and the wider span of the device may make it easier for animals to detect and avoid; can swim around or past. Wider span of a single device or arrays that block a channel may scare wildlife and block migratory paths. Above-surface structures are anticipated to be minimal.	Static elements (cables, anchors, etc.) or dynamic elements of devices can change migration, aggregation, and foraging behaviors due to artificial reef formation and potential attraction to new habitat. May cause injury/mortality from entanglement and/or increased predation. Surface-piercing structures may affect haul-out/roosting locations for wildlife and/or affect viewscapes. Fishing activity may be reduced (structures will prevent commercial trawling) or increased (artificial reef formation may increase recreational fishing activity).
Strike	Slower movement of hydrofoils for a given current speed compared to turbine blades could be easier for wildlife to avoid, reducing the risk for injury and mortality due to strike; slower speed minimizes risk of cavitation exposure.	Fast movements of turbine blades pose risk of animal injury and mortality due to strike.

The localized effects of hydrofoils and turbines may differ substantially, with the potential for very different effects on marine animals. For example, the physical structure of the hydrofoil technologies will generate distinct wake structures compared to turbines. The wake structure of a rotary turbine is relatively steady over time (Figure 11), with three distinct regions including an out layer with the spiral blade tip vortices rotating in the same direction as the blades, an inner layer rotating counter to the spiral tip vortices, and a central core layer of zero to low flow, rotating in the same direction as the spiral-tip vortices (Kang et al. 2012). The core layer is created by the blockage of the central rotor of a turbine, providing a resting area in high currents where fish may congregate (Polagye et al. 2011a). Both small and large fish were observed to remain in the wake after interacting with a helical cross-flow turbine (Peterson et al. 2014). In contrast, the oscillating vertical motion of the hydrofoil creates a wake structure that varies through space and time (Figure 11). The wake structure is more turbulent, and is not likely to provide a resting area for fish. This may reduce the attraction of smaller fish to the device, and therefore, their larger predators. In addition, although cavitation exposure is possible, it is less likely given the slower speed of the hydrofoils. For both types of devices, the stationary supporting structures may produce low velocity wake regions, but engineers will seek to minimize these regions, as they increase drag and reduce device efficiency.

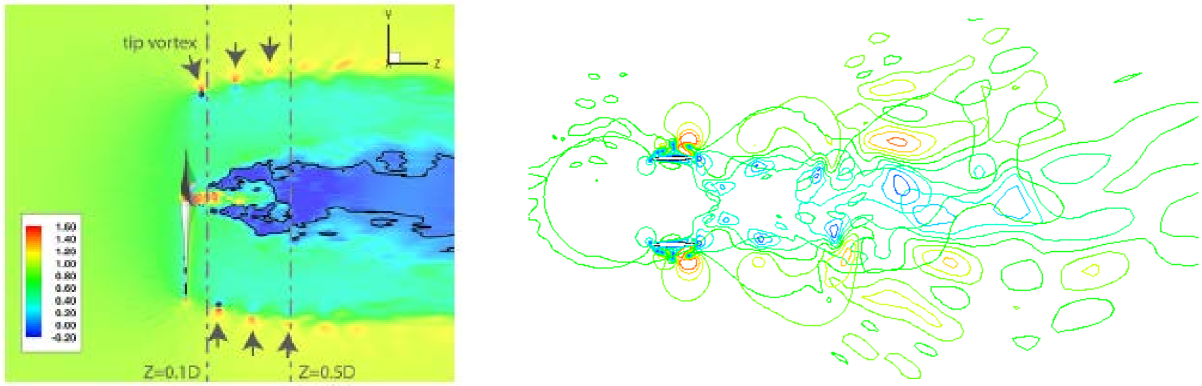


Figure 11. Contour plots represented the modeled wake structures of a rotary turbine and a hydrofoil device. a) a vertical axis rotary turbine, with stream velocity non-dimensionalized by U1=2.0 m/s (figure from Kang et al. 2012) and b) a hydrofoil device showing an overlay of the top and bottom points of the stroke to visualize the entire area impacted over time (unpublished figure based on single-foil device design provided by the Leading Edge research team.

Noise and EMF

The hydrofoil device is likely to generate unique noise and potentially unique EMF signals compared to turbines and wave generators. The number and phasing of the hydrofoils during operation (whether they are moving in parallel or out of synch) for a particular installation will determine the noise signature of the device. The slower speed of the hydrofoil technology, (the maximum foil speed is similar to the speed of the current), is predicted to result in lower sound levels compared to turbines. However, the signal may be more variable through time, producing a pulsed acoustic signature. Likewise, the EMF signals produced by the device may be pulsed, depending on the power take-off mechanism utilized. If multiple hydrofoils operate out of phase and are linked to a single generator, steady EMF signals may be produced. The EMF signature may also depend on the location of the power conditioning systems in the final hydrofoil technology design. If the system is located underwater, onboard the device, then the voltage, current, frequency, and power quality (all of which contribute to EMF) will be more consistent between the device and shore. If, however, the power conditioning is on shore, then these same parameters may change dramatically with time over the device-to-shore cable. For all ocean energy devices, transmission lines to transfer the power produced to the electric grid will generate EMF signals. EMF in the water near devices and cables can alter animal feeding behavior, migration, reproduction, or susceptibility to predation near the project, as discussed in Section 3.4.

Chemical toxicity

For all type of ocean energy technologies, the coatings, lubricants, paints, biocides, or other chemicals used in, on, or as part of maintenance of the devices can cause toxic effects on nearby organisms. The hydrofoil technology is not expected to pose any unique risks of chemical toxicity compared to other technologies. Similar construction materials, anti-fouling compounds, and lubricants are utilized in other hydrokinetic technologies. The primary distinction may be the potential for hydrofoil installations to be sited in near-shore and inlet locations, where fluid leaks could pose a greater risk to animals in the area. Site-specific details such as the current speed and the number of devices utilized in an array will determine the total volume of fluids for a given installation. Hydrofoil device life-span compared to a turbine device may also affect life cycle toxic release risk (shorter life-spans would lead to more frequent installation, repair, and demolition, which could lead to greater release risk), and should be evaluated. The use of non-toxic fluids will reduce the risks posed by the hydrofoil device.

Interference with animal movement and strike risk

The dynamic, moving elements of the hydrofoil technology are likely to have different effects than other hydrokinetic technologies. The slower movement and the wider span of the device may make it easier for animals to detect and avoid, so they can swim around or past it. However, the wider span of a single device or arrays that block a channel may scare wildlife and block migratory paths. For fish and marine mammals, the slower movement of the hydrofoils for a given current speed compared to turbine blades will likely be easier for fish and other wildlife to avoid, reducing the risk for injury and mortality due to strike. The structure of the device, with the broad, flat hydrofoil surfaces moving at slower speeds compared to turbine blades may encourage more biotic growth, which could lead to attraction of fish species and, as a consequence, larger fish, birds, and/or marine mammals. The horizontal surfaces of the device may also provide resting surfaces when stationary. The device could potentially be more attractive to animals compared to turbines, but observational data will be required during device testing to assess animal behavior. The final design of the Leading Edge hydrofoil device will be evaluated for potential pressure changes associated with device action that could lead to barotrauma risks for fish species with swim bladders, and further information will be provided in the final version of this report.

The static, supporting elements (cables, piles, anchors, etc.) of the hydrofoil device are expected to have similar environmental effects as other hydrokinetic technologies. Installed units or arrays may affect migration, aggregation, and foraging behaviors due to potential attraction to new habitat. They can also cause injury/mortality due to entanglement and/or increased predator activity. As with any device installed in the water, there may be significant reef effects of the device. Biotic growth on the surfaces of the device attracts small consumers, which in turn attract larger predator species. Mammals in particular may be curious and approach the device, however little risk of strike is expected for hydrofoil technology. In the vicinity of all hydrokinetic energy installations, fishing activity may be reduced (the structures will prevent commercial trawling), or increased (artificial reef formation may increase recreational fishing activity).

Summary

An overall assessment of the potential risks unique to the Leading Edge hydrofoil device will depend on the final design. Further analysis and discussion will be included in the final version of this report. Currently the environmental risks of the Leading Edge device with regard to wildlife strike and hindrance of animal movement and migration appear likely to be less than those of existing hydrokinetic turbine installations. Furthermore, due to a design that utilizes a greater cross-Sectional area of the flowing current, the Leading Edge team anticipates that the hydrofoil will show five-fold greater energy harvesting efficiency per unit area. This feature could reduce the environmental footprint of a hydrofoil installation compared to a turbine installation of a similar power generating capacity. Risk evaluation for other environmental considerations such as EMF, noise, toxicity, etc. will be further expanded with final information on device size, energy harvesting efficiency, structural design, and EMF and noise signatures. However, as with any device installed in a natural area, the actual impacts of a given installation will depend on site-specific features that would be assessed either as part of site screening criteria or prior to installation at a selected site. Site-specific risks are considered in Section 6.2.

5 Consideration of potential impacts of device arrays

In most hydrokinetic energy harvesting sites, particularly in tidal areas, arrays of multiple devices are used to maximize the extraction of energy from a given site. The potential environmental effects associated with a single device will obviously be compounded by deployment in arrays, and both the number and arrangement of the devices in the array will contribute to environmental effects. The current design of the Leading Edge hydrofoil device is a floating, pontoon-mounted device. The pontoons provide a flexible mounting option that can be modified to maximize energy extraction and minimize inter-device interference and the number of placement of anchoring lines in the array. The second Leading Edge 2 kW prototype consisted of two sets of hydrofoils, with the limited field data suggesting that there were very small device effects on water currents. Additional modeling work is required to understand the likely characteristics of current flows and energy extraction around larger arrays.

6 Addressing Environmental Risks: Design and Implementation

6.1 Mitigation of Potential Environmental Effects and Best Practices

In the Potential Environmental Effects Section (Section 3), general mitigation and best practice approaches to preventing impacts from hydrokinetic energy devices were summarized for each resource area. Table 4 highlights specific concrete actions that can be implemented during design and installation of the Leading Edge hydrofoil device to reduce the risk of potential environmental impacts based on the existing literature. The mitigation measures and best practices are broken down by resource category (e.g., alteration of waves and currents, noise, etc.) and by the aspect of design and installation (i.e., hydrofoil arm design, anchoring/base design, etc.). In many cases, appropriate mitigation and best practices will be determined by site type or site-specific characteristics, as discussed in Section 6.2.

6.2 Siting Considerations Relating to Environmental Impacts

The environmental resources outlined above are potential issues for all tidal energy projects. However, actual risks will vary based on the location of the device, whether in a river channel, a near-shore site, or an off-shore site, as well as specific aspects of a particular site, such as the presence of key conservation targets (biodiversity, endangered and threatened species) or other factors that may exacerbate environmental impacts. Key environmental considerations that should be addressed for all tidal energy projects and for rivers, near-shore, and off-shore site types are listed below.

General consideration for all tidal energy installations

- Presence of endangered/threatened species: the presence of such species can restrict activities in particular areas.

- Unique habitats/biodiversity hotspots: critical habitats and biodiversity hotspots may or may not be regulated, but should be avoided to minimize undue impacts on biodiversity; may be regulated under the National Marine Sanctuaries Act of 1972 (U.S. Congress 2000).
- Underwater archaeological resources (shipwrecks, ruins, flooded prehistoric sites): these sites are regulated in US lands and waters by a variety of Federal Acts and State laws (summarized in Aubry 2009). Many of these are applicable in internal waters and territorial seas (out to 12 nautical miles from shore) but some apply to areas further offshore as well.
- Critical wildlife migration routes: marine mammal or other wildlife migration routes may be a consideration for siting, particularly if natural or manmade features constrain migration routes along particular paths with which the device/array would interfere.
- Swimming/ boating/ surfing/ fishing, other recreation: not be strictly environmental features but are often considered as part of protection of natural areas and therefore may fall under the same regulations or agency oversight (e.g., State Departments of Conservation and Recreation).

Table 4. Recommendations for each hydrofoil design elements to mitigate each potential impacts listed in the first column.

Potential Impact	Hydrofoil arms	Anchoring/Base	Electricity transport lines	Array Design
Alteration of currents and waves	Limit the total energy extracted from a channel to avoid disruptions of physical processes	Limit above surface structures that can block regular wind patterns		Limit above surface structures that can block regular wind patterns and affect viewscapes
Alteration of bottom substrates and benthic habitats	Measure substrate/ sediment as inputs to models of regional sediment dynamics, evaluate slip-stream to estimate localized effects.	Minimize non-generating support structures	Loose enough to conform to surface but taut enough not to curl, loop, or scour. Avoid disturbing contaminated sediment	Site installations to avoid critical habitat and minimize bottom disturbance.
Noise	Depends on acoustic signature: use field measurements/models to determine for different size devices.	Limit pile driving to non-migratory seasons, utilize sound dampening measures to limit noise below dangerous levels away from the installation site.		Evaluate sound levels and frequencies produced by installation configurations (fewer large devices vs. more small devices). Select final design for each site based on species of greatest concern at installation sites.

Potential Impact	Hydrofoil arms	Anchoring/Base	Electricity transport lines	Array Design
EMF			Standard use of shielded cables. Consider local and transient elasmobranchs, benthic species, mammals, and other EMF-sensitive species when developing layout and shielding of cables.	Minimize number of cables required for array (e.g., by installing fewer, but larger devices).
Chemical toxicity	Utilize non-toxic anti-fouling coating and mechanical removal when required.			Minimize use of toxic paints, lubricants, other substances that can leak into the environment.
Interference with animal movement or migration	Allow space around the device for animal movement.	Minimize number of guy wires/ anchor lines, consider local species of concern to inform cable thickness for visual detection		Minimize extraneous lighting, work periods outside spawning or migration periods for wildlife[4]
Strike	Hydrofoil speed below 4.5 m/s.* Maximize blade edge thickness. Modify leading edge foil thickness to match body length dimensions for species of concern. Evaluate use of warning sounds prior to device movement.	Floating structures pose threat to predatory birds and near surface animals, especially in low visibility conditions	Space lines in order to allow adequate passage. Overly taut lines can cause laceration and loose lines can cause entanglement upon collision.	Allow space around the array for animal movement around or under the installation.

*(Cada et al. 1997)

River sites

- Anadromous fish species: fish that live in the open ocean but return to freshwater rivers to spawn may be at risk for disrupted reproduction if upstream paths are blocked or hindered
- Wild and scenic rivers: rivers may be designated for use restrictions under the Wild and Scenic Rivers Act of 1968 (16 USC 1271-1287), under which rivers possessing "outstandingly remarkable scenic, recreational, geological, fish and wildlife, historic, cultural or other similar

[4] (Polagye et al. 2011b)

values, shall be preserved in free-flowing conditions and… their immediate environments shall be protected...” (90th U.S. Congress 1968).

Near-shore sites

- Beach formation/erosion: wave height and power determine the formation and erosion of shorelines due to movement of sediments across the sea floor. Many communities already invest substantial resources into the maintenance or management of beach formation and erosion, and modified patterns of sediment transport and deposition can have substantial impacts on ecosystem structure and habitat for local species.
- Surfing/wave-related recreation: often regulated under similar regulations and/or agencies as conservation-related concerns. Reduction in wave height and/or strength may affect the frequency and quality of recreational opportunities related to wave action, such as surfing.
- Pipeline presence: Pipelines are commonly used under water bodies to move natural gas and other materials; damage to such pipelines can affect water quality, air quality, and marine life. Sea-bed installation will need to avoid pipelines to reduce the risk of pipeline structural damage and leakage of materials into the environment
- Small marine mammals: in shallow, near-shore areas, small marine mammals are likely to be more of an issue than very large mammals. Such species may use platforms and horizontal structures as haul-out locations or may experience interference with movement and migration near large arrays of devices.

Off-shore sites

- Shipping lanes/freight: large shipping vessels may pose issues for siting at offshore locations, depending on vessel draft.
- Large marine mammals: in deeper marine environment, larger mammals such as whales are more likely to be present than in near shore areas, may have more difficulty avoiding large arrays or complex structures (e.g., many guy wires/anchor lines).
- Off-shore pipelines: sea-bed installation will need to avoid pipelines to reduce the risk of pipeline structural damage and leakage of materials into the environment.

Commercialization of this technology will likely involved detailed site screening criteria that will take into account technical constraints (current speeds, depth, grid connection, etc.) as well as environmental siting considerations.

7 Case study: potential environmental effects for proposed testing site

7.1 Site description

For the initial device testing, the Leading Edge tidal energy team completed a “tug-test” of a small unit attached to a pontoon boat, driven at speeds to simulate a 4 knot current near the Sakonnet River Rail Bridge site in Rhode Island. Consultations with the RI Department of Environmental Management, the RI Coastal Resource Management Center, the Coast Guard, and the Army Core of Engineers established that permits were not required for testing the device mounted to a boat. However, longer term stationary testing of the Leading Edge device will likely be subject to permitting requirements. This Section provides a case study of the types of environmental considerations that could be taken into account for any given testing location.

Site Background

The Sakonnet River is a 23 km long tidal strait connecting Rhode Island Sound to Mount Hope Bay, through which it is connected to the larger Narragansett Bay to the west. The proposed testing site is at the narrowing of the Sakonnet River between Tiverton and Portsmouth, RI (Figure 12). The area of proposed testing is approximately 360 feet wide occurring between the causeway ends of a former railroad bridge, with a channel of approximately 40 feet in depth. At the shallow edges, the substrate is composed of rock, primarily related to the original causeway construction, whereas at depths of 40 feet below mean low water and deeper, the bottom is primarily composed of fine sediments except where currents are strong. The area is heavily used for boating, recreational fishing, and waterfront commercial activities, and is designated for Intensive Use in the Portsmouth Harbor Management Plan (Portsmouth Harbor Commission 2014) .

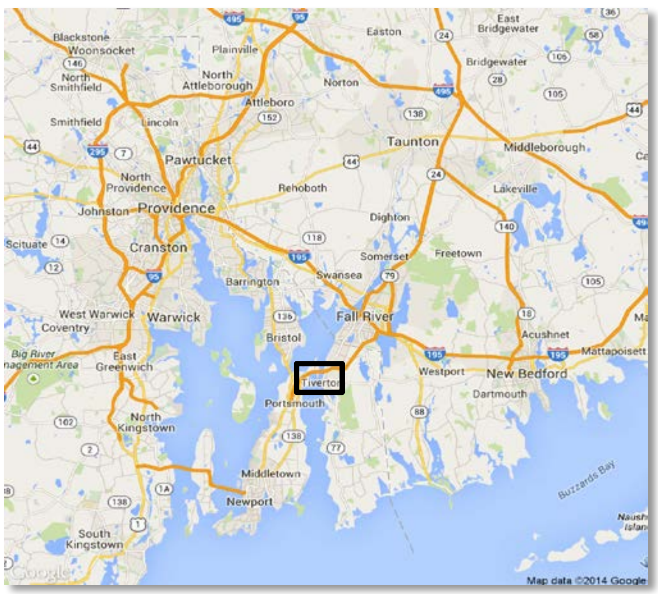


Figure 12. Location of the field testing of the first Leading Edge technology prototype. The testing was completed near the Sakonnet River Bridge connecting Portsmouth and Tiverton, RI.

The Coastal Resources Management Council (CRMC) has designated the area as Category 3, allowing high intensity boating (CRMC and DEM 2007). The water quality of the area is categorized as “SB” salt waters, “designated for primary and secondary contact recreational activities; shellfish harvesting for controlled relay and depuration; and fish and wildlife habitat. They shall be suitable for aquacultural uses, navigation, and industrial cooling. These waters shall have good aesthetic value.” Commercial barges and other large boats tend to use the East Passage of Narragansett Bay rather than the Sakonnet

River. Draft and Final Environmental Impact Statements (DEIS and FEIS, respectively),[5] as well as an associated fisheries study, were completed for a replacement of the Sakonnet River highway bridge adjacent to the old railroad bridge site, and as such provide a great deal of site specific information that is unlikely to have change since the FEIS was published in 2002 (FHWA et al.).

As the proposed testing would occur in the water with no intended interaction with the land other than at the launch site of the barge, the most likely resource to be affected by the project is wildlife, specifically birds and aquatic species (fish, shellfish, etc.), and associated resources such as Endangered and Threatened Species. Therefore, this site-specific case study focuses on these resources.

Table 5. Status of birds in the Sakonnet River Bridge area.

Bird status in study area	Common Name	*Scientific Name*
Identified species in study area	Great blue heron	*Ardea herodias*
	Great egret	*Casmerodius albus*
	Mute swan	*Cygus olor*
	Robin	*Turdus migratorius*
	Mourning dove	*Zenaida macroura*
	Red-winged blackbird	*Agelaius phoeniceus*
	Common crow	*Corvus brachyrynchos*
	Goldfinch	*Carduelis tristis*
	Red-breasted merganser	*Mergus serrator*
	Herring gull	*Larus argentatus*
	Black-backed gull	*Larus marinus*
	Sparrow spp.	Genera not specified
	Finch spp.	Genera not specified
Potential users of study area	Red-tailed hawk	*Buteo jamaicensis*
	Osprey	*Pantion haliaetus*
	Ducks	*Anas* spp.

7.2 *Wildlife Resources: Birds*

The preparers of the Sakonnet River Bridge Rehabilitation Project Draft EIS recorded eleven specific bird species "plus numerous sparrow and finch species" as occurring in the site area, all of which were characterized as species tolerant to human-influenced environments and disturbance (Table 5). They also suggested that several birds of prey as well as ducks might use the area based on available habitat.

7.3 *Wildlife Resources: Fish*

The fisheries study associated with the Sakonnet River Draft EIS draws upon a number of different fish studies performed in the area of the proposed testing site, although many of the existing studies focus on Mount Hope or Narragansett Bays. Nevertheless, such studies provide an indication of the species that may use the Sakonnet River. The RI Division of Fish and Wildlife conducts spring, fall, and monthly trawl surveys in Narragansett Bay, and additional year-round monthly trawl surveys were done for Brayton Point power plant studies. Diver studies were also performed to evaluate specific aquatic

[5] The Sakonnet River FEIS refers extensively back to the DEIS for descriptions of the site and affected environment. Therefore, the remainder of this Section draws on data presented in the DEIS (Source: FHWA).

species' presence near the rail bridge footings. According to the diver study, the pilings of the highway bridge support blue mussels (*Mytilus edulis*), hydroids, anemones and starfish. Quahogs (*Mercenaria mercenaria)* were also found in the intertidal areas near the bridge. Sessile species such as shellfish represent a "fouling community" that may be anticipated to colonize any installed device in the area, although actual colonization rate and extent will depend on larval presence during testing, depth of the device, food supply, and environmental conditions (Joschko et al. 2007). Previous studies have shown extensive colonization of offshore constructed substrates by *Mytilus edulis* particular at depths from zero to 2 meters from the surface (Joschko et al. 2007, Langhamer et al. 2009).

Based on existing studies, 118 fish species are likely to occur in the Sakonnet River; particular species of recreational and/or commercial value include tautog *(Tautuga oniitis*), winter flounder (*Pleuronectes americanus*), alewives (*Alosa pseudoharengus*), blueback herring (*Alosa aestivalis*), American shad (*Alosa sapadissima*), rainbow smelt (*Osmerus mordax*), striped bass *(Morone saxatilis*), and bluefish (*Peprilus triacanthus)*. Other species of note include cunner (*Tautogolabrus adspersus*), black sea bass (*Centropristis striata*), scup (*Stenotomus chrysops*), Atlantic silverside (*Menidia menidia*), Atlantic menhaden (*Brevoortia tyrannus*), and crevalle jack (*Caranx hippos*)" (FHWA et al. 2001).

The area around the highway bridge at this site is popular for recreational fishing from shore and from small boats. The DEIS for the Sakonnet River Bridge project states that the National Marine Fisheries Service estimates that between 10 and 78 fishermen fish in local waters on a daily basis throughout the summer months (FHWA et al. 2001). Fishing in the area is largely focused on tautog, also known as blackfish, but also on striped bass, bluefish, scup, and black seabass. Juvenile tautog prefer vegetated habitats, whereas larger juveniles and adults prefer rocky habitats, often areas where pilings, jetties or other bottom features can provide shelter from predation (Olla et al. 1974, Olla and Studholme 1975, Olla et al. 1975) and substrate for mussels, their primary food source (Olla et al. 1974), which are found around the rocky bottom, piles, and bridge supports in the Sakonnet (FHWA et al. 2001). Similarly, black seabass and scup tend to be found over rocky-bottomed areas including piling artificial reefs, as motile epibenthic invertebrates such as mollusks, crustaceans, polychaetes and small fish are important food sources for these species (Sedberry 1988, Steimle et al. 1999, NOAA FishWatch 2014). All of these species may move among locations and water depths based on temperature. In summer, tautog seek cooler, deeper waters, come inshore in fall, and adult tautog tend to move offshore in winter, whereas younger fish stay in inshore areas but are torpid (Olla et al. 1974). The fisheries study suggest that these fish are abundant around the Sakonnet River highway and railroad bridges because fast currents maintain water quality and there is abundant cover from the man-made structures that provide protection, relief from currents, and feeding areas.

Winter flounder (*Pleuronectes americanus*) are believed to spawn in the Sakonnet River at night between February and April, and tend to migrate from cool deep water in the summer to warmer inshore areas in fall. Counts of winter flounder in Narragansett Bay and the Sakonnet River tend to be highest in the fall, winter and spring and lowest in the summer. Larval counts suggest that adults spawn in the Sakonnet River (Gray n.d.).

Anadromous species (alewife, blueback herring, American shad, rainbow smelt) do use the Taunton River at the head of Mount Hope Bay as a spawning ground and habitat, and significant non-governmental and governmental activity has focused on developing, restocking, and/or enhancing anadromous fish runs to the Taunton River Basin. These species are likely to move upstream through the Sakonnet River from February to June (FHWA et al. 2001). Overall, fish eggs and larvae studies suggest that these icthyoplankton are least abundant November through January, with the lowest number of species occurring in January and the highest in July, and the highest densities occurring in June and July (FHWA et al. 2001).

Submerged structures tend to form artificial reefs through colonization by benthic organisms that then attract fish who feed on the fouling organisms. Even a device left for a few months at the Sakonnet River bridge site is likely to be colonized by mussels and other sessile species and could form a very small artificial reef.

At the time of the EIS completion, US Fish and Wildlife Service had stated in a letter (April 13, 2000) that no threatened or endangered species were known to occur at the site. However, both species of river herring (alewife and blueback herring) are species of special concern for the National Marine Fisheries Service, and there is an ongoing active effort to manage and conserve these species (NOAA Fisheries Greater Atlantic Region 2013).

7.4 Short-term tests: potential environmental effects

The short-term pontoon boat tests are essentially the same as any boating activity, with a device of approximately 1.5 meters in total depth from the bottom of the boat (Figure 13). As these test activities are temporary (up to a few hours per day for approximately five days) and are likely well within the range of normal boating activity in the area, little environmental risk is foreseen.

Figure 13. Images of the first Leading Edge prototype device.
a) Schematic of the modular pontoon boat design illustrating the configuration of the boat and hydrofoil device for the short-term pontoon boat test of the device. b) Photograph of the completed small-unit device mounted to the pontoon boat. c) Photograph of the small device raised in the moon pool of the pontoon boat.

In corroboration of this, the team has received a letter from the State of Rhode Island Coastal Resources Management Council, supported by the Department of Environmental Management indicating they have no concerns regarding this phase of testing. In addition, the Conservation Commission of the Town of Somerset, MA has provided a letter approving the small unit prototype pontoon boat testing in the Somerset River. APRAe also granted a NEPA categorical exclusion (CatEX) for the short-term testing.

7.5 Long-term testing: potential environmental effects

The original plan for the Leading Edge technology development included a long-term test of the device operation. After the first prototype test was completed, the development plan was modified to focus on testing the operation of a second prototype with two in-line devices, to assess hypothesized “constructive interference”. Future testing will include longer periods of operation. For longer-term testing, the elements that could pose environmental risks are most likely to be:

- Stationary surface structures (i.e., the barge/pontoon boat) that would provide potential perching and roosting (birds), or haul out locations (marine mammals).
- Larger hydrofoils in shallow or narrow areas could pose strike or deterrence risk for fish during periods of operation.
- Anchors may disrupt bottom substrate, and anchor lines could pose risk of entanglement or obstruction to movement for fish and other organisms.
- Underwater surfaces may develop colonies of fouling organisms, affecting local habitat, resource availability, and wildlife behavior (e.g., fish foraging behavior and locations).

Surface-breaking structures and/or watercraft may offer temporary perches for bird species. In areas heavily used for boating, the Leading Edge pontoon vessels are unlikely to alter the habitat for these bird species. For longer-term stationary testing, provision of perching opportunities on the vessels may need to be considered and bird deterrents (e.g., perch preventers) may be advisable. Strike or movement deterrence for fish from the actual device or its operation are likely to be minimal. The hydrofoil blade movements will be approximately 2.4 m/s, well below the “safe” speed of 4.57 m/s estimated for turbines (Cada et al. 1997, Jacobson et al. 2012). Anchor lines may pose a potential risk of entanglement and inhibition of movement of fish and other organisms (as well as boats). This risk can be mitigated by weighting the anchor lines to create a steep angle down to the river floor, limiting interference with other vessels. Such weighting should also keep the lines taut in the water column and along the river bed, limiting risk of entanglement and of scouring movement along the river bed.

8 Potential environmental benefits of the technology

Hydrokinetic technologies may have numerous environmental benefits, in addition to the potential risks discussed above. They provide a clean source of renewable energy that may substantially reduce the carbon footprint of off-grid locations, particularly those that rely on diesel fuel transported by air. Reductions in fossil fuel combustion due to local availability of hydrokinetic energy may reduce releases of criteria air pollutants (nitrogen oxides, particulates, etc.) associated with fossil-fuel generated power. Under specific conditions, rotors of turbines and foils could have a positive effect by increasing sediment mixing in specific, desirable conditions. Alterations in wave and/or current energy may be beneficial for certain situations by reducing erosion along beaches or under bridges. In certain settings it may also be possible to use characteristics of the device to encourage artificial reef formation to support particular local species of concern (Langhamer et al. 2009) the potential for such synergistic environmental effects will depend on site-specific constraints and the final device design. The devices have the potential to cause significant environmental impacts, but appropriate mitigation strategies can reduce the risk. The hydrofoil technology may provide several unique benefits compared to other technologies[6]. The devices can be utilized in shallow water and at lower speed currents, providing a substantial number of potential installation sites. The slower speeds of the device may pose less danger to animals passing by. The scalability of the device may allow fewer devices for a given array installation, reducing the total number of supporting structures and cables required. The benefits compared to alternative technologies and energy sources will generally be site-specific and depend on the particular deployment scenario.

9 Hydrokinetic energy permitting requirements and NEPA

The *Leading Edge* project focuses on the development of a hydrokinetic power conversion device to harness energy from natural water flows in tidal areas and rivers. The Federal Energy Regulatory Commission (FERC) is the lead Federal agency authorized by the Energy Policy Act of 2005 (EPAct) to issue preliminary permits and licenses for hydrokinetic energy projects (109th U.S. Congress 2005). For projects located on the Outer Continental Shelf (OCS), FERC has the authority to issue project licenses while the Minerals Management Service (MMS) has the authority to issue leases and easements. Authorization from the U.S. Army Core of Engineers (USACE) is required for siting both grid and non-grid connected projects (Pacific Energy Ventures 2009, Baysinger 2011). Before issuing approval and permits for testing and device deployment, FERC, the Bureau of Ocean Energy Management (BOEM) and/or the USACE, along with other agencies that have jurisdiction in the selected installation site (e.g., MMS), must comply with the National Environmental Policy Act (NEPA) and will likely require environmental impact analyses for prospective projects. NEPA requires federal agencies to carefully evaluate the likelihood that any major actions (project, plan, regulation, policy, or issued permits) will cause an impact on natural or built environmental resources (Maughan 2014). Based on a description of the proposed action, a federal agency will determine if environmental impact analysis is required for NEPA compliance or if the specific project is exempt.

This Section describes the key elements of a NEPA environmental analysis document (either an EA or an EIS) and provides suggestions for the types of data that might be used to evaluate potential impacts for a given project. The types of data that could be collected during the Leading Edge prototype testing to provide background/preliminary data to guide future NEPA evaluations are highlighted[7]. Specific NEPA and environmental permitting considerations for hydrokinetic energy projects are highlighted in Section 10.

[6] The tidal energy project includes TEM/TEA analysis that will be considered for the final report, to be submitted at the end of the fourth quarter of the project.

[7] This document is not intended to provide legal advice or prescriptive guidance on preparation of an EA or EIS, but rather provides a summary to highlight key components of an EA or EIS. For actual EA/EIS preparation, project proponents should follow the specific guidance of the regulatory agency approving the project (e.g., FERC, BOEM).

9.1 Overview of the NEPA process

Environmental impact analysis documents prepared under NEPA may be an Environmental Assessment (EA), which is a smaller, simpler document, or a larger, more complex Environmental Impact Statement (EIS). EAs and EISs cover the same general topic areas; the difference is in the level of detail and potentially the level of public outreach, consultation and requirements for evaluation of alternatives; an EIS may be triggered by an EA finding of significant adverse impacts or may be undertaken initially for large, complex projects or when required by agency regulations. FERC defines an Environmental Assessment as "a concise public document that briefly provides sufficient evidence and analysis for determining whether to prepare an environmental impact statement or a finding of no significant impact" and aids the Commission's compliance with NEPA when no environmental impact statement is necessary (Federal Energy Regulatory Commission 2012 18 CFR 380 2012.2).

FERC regulations describe specific cases in which an EA would be prepared first, and an EIS prepared only in the event of a finding of adverse effects, whereas in other cases an EIS is always prepared (Federal Energy Regulatory Commission 2012 18 CFR 380). In certain cases, some activities may be eligible for a Categorical Exclusion (CATEX). CATEX is a streamlining procedure that allows agencies to perform actions that are commonly implemented as part of normal operating procedures based on previous analyses that have determined the environmental impacts are not significant (Maughan 2014). Hydrokinetic energy projects are not included on the standard list of CATEX eligible projects in FERC regulations (Federal Energy Regulatory Commission 2012 18 CFR 380). However certain experimental hydrokinetic projects may not require FERC permits, determined on a case by case basis based on an evaluation of environmental risks (see Section 11 below).

If a FERC license is required, an EA or EIS must be prepared. In the case of an EA, after review FERC will issue either a formal Finding of No Significant Impact (FONSI) if no significant environmental impact is expected, or the process will move to the preparation of a draft EIS if there is significant impact identified. The draft EIS must meet all procedural requirements for an EIS. The draft EIS is released for comment from other federal agencies, state and local agencies, Indian tribes that could be affected by the proposed action, and the public (Maughan 2014). In order to identify and address concerns of the public and agencies up front, a scoping exercise can be completed during the initial phases of the project. Public comments can then be fully addressed in the draft EA/EIS, to avoid substantial amendment of the draft document. The process could include public meetings to solicit comments and meetings with agencies that have jurisdiction for the project. A web page and/or newsletter with instructions on how to submit comments and concerns can also be included. This process can result in a scoping report to document all the comments and suggestions received, and explain how they were addressed in the draft EA/EIS document or if they were not addressed, why not. Often this information is incorporated into the EA/EIS as well.

In addition to the requirements for an EIS prescribed in 40 CFR 1502.10 of the regulations of CEQ, an EIS prepared by FERC includes a staff conclusion Section. The staff conclusion Section includes summaries of significant environmental impacts of the proposed action, alternatives that would have a less severe environmental impact or impacts and the action preferred by the staff, proposed mitigation measures, significant environmental impacts that cannot be mitigated; and references to any pending, completed, or recommended studies that might provide baseline data or additional data on the proposed action (Federal Energy Regulatory Commission 2012 18 CFR 380.7).After a minimum 45 day comment period, the lead agency proposing the action prepares a final EIS that includes response to comment and clearly identifies changes made since the draft EIS was issued. Following the release of the final EIS, NEPA compliance concludes with the issuance of a final Record of Decision (ROD).

10 Summary of NEPA document requirements

Below is a summary of required elements for an Environmental Assessment (EA) or an Environmental Impact Statement (EIS) (91st U.S. Congress 1969, Federal Energy Regulatory Commission 2012 18 CFR 380 2012).

10.1 General Project Description

This Section focuses on details of the site, location, topography, and proposed project scope. These data will always be site specific and testing data might only be relevant if pilot projects and full scale deployments are planned for the same location. If future installations are planned for alternate locations, information gathered at the testing stage could be used to define siting criteria.

10.2 Purpose and Need

This Section provides a description of the reason for the proposed action (project) and the need that it will fulfill. This is likely to focus on particular power needs in a given location and/or particular opportunities for improving environmental footprint of power generation for the site, project area, or utility portfolio.

10.3 Description of Alternatives

The National Environmental Policy Act (NEPA) requires agencies to consider a “no action” alternative for either an EA or an EIS as a baseline against which to demonstrate and compare the environmental effects of reasonable action alternatives. For an EIS, typically at least two action alternatives are also considered (e.g., two ways to accomplish the proposed project that would meet the purpose and need; variants could include differences in technology, siting, size, and/or components of the project). One of these is usually designated as the Preferred Alternative in the Draft EIS and always in the Final EIS. If other alternatives were considered for the project but deemed inviable, this is also summarized in the document. For an EA, the same approach can be followed for alternatives, but given the smaller scope of an EA, it is also frequently possible to just address the Preferred Alternative and the No Action alternative.

10.4 Scope of Analysis

The project scope is addressed under the general project description. The scope of analysis Section outlies the key areas of concern for the project, the overall boundaries and assumptions of the analysis, and any key concerns raised during public outreach in the scoping phase of the EA/EIS development that are addressed by the analyses in the document.

10.5 Summary of Public Outreach and Public Comments

There are several mandatory public notification and public comment period requirements for NEPA documents. Typically, a Notice of Intent (NOI) to prepare an EIS is published in the Federal Register with a request for public comments on the scope of the analysis and the potential for significant environmental issues. For contentious projects or projects with extensive consultation requirements with tribal groups, local agencies, etc., additional public meetings and/or educational sessions may be undertaken during EA/EIS development to gather stakeholder input on siting, specific aspects of alternatives development, etc. For EIS documents, the White House Council on Environmental Quality (CEQ) requires that a Notice of Availability is published in the Federal Register, followed by a public comment period. The Draft and Final EIS must include summaries of the public outreach and public comments to date for each phase of public review and provide responses to the comments. Responses to comments may accept or refute different elements of a comment and may also point to existing or updated analyses to address particular concerns. Once the Final EIS is prepared, a Notice of Availability is issued, followed by a public Record of Decision on the finding of significant or non-significant impacts. There is no CEQ requirement to publish EA information in the Federal Register, but agencies can always choose to publish the information.

10.6 Affected Environment and Environmental Consequences

In this Section, the resources present in the project area are identified, including resources important for the natural and human environment. The description of the affected environment is prepared based on available information to the extent possible and supplemented with data collected specifically for the project if necessary. An evaluation of the potential for impacts on resources from either the “no action” alternative or the “action” alternatives are presented. In some cases, there are resources for which the action alternatives are predicted to be inapplicable; in such cases, the resources are acknowledged and a justification is provided for omitting analysis of these impacts. The remaining categories are analyzed and quantified to the level of detail appropriate for an EA or EIS.

10.7 Example List of Resources Described and Impacts Considered

There are many types of resources and issues that are considered in a standard EA or EIS, however only certain aspects are likely to require a detailed analysis for a hydrokinetic energy project. The following is a list of commonly considered resources that are described in the Affected Environment Section and evaluated for impacts in the Environmental Consequences Section of an EA or EIS. Resources that are likely to be a major focus of NEPA analyses for the Leading Edge technology are described in more detail, and potential opportunities for data collection during prototype testing are highlighted. Note that this document is not exhaustive – other issues may arise during actual siting, scoping, public outreach, and evaluation of particular projects. The information below highlights key areas where analyses are likely to be required.

10.7.1 Topography, Geology, and Soils

This is a general description of the site of installation, and will likely vary substantially among proposed installation sites. For the purposes of a hydrokinetic energy installation, this Section would cover both underwater topography and geology, as well as adjacent surface areas that might be affected by project components such as transmission lines or power substations. Effects of the project on water energy would also be included. Impact considerations might include potential for stream-/sea-bed disturbance and erosion, need for stabilization, blasting, pile driving, changes in habitat structure, shoreline erosion and disturbance.

Current data collection opportunities:

- Identify siting criteria based on topography, geology, soils to reduce potential environmental impacts (e.g., on water quality, sediment transport, and animal movement).

10.7.2 Air Quality and Climate

Criteria air pollutants under the Clean Air Act include particulates (categorized by size), ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide, and lead (99th U.S. Congress 1963). States are required to enforce plans to achieve and maintain air quality, and areas that exceed designated thresholds are considered in "non-attainment," resulting in restrictions on activities that may increase air pollution. Ozone-destroying pollutants and hazardous or toxic air pollutant emissions also need to be addressed (U.S. Environmental Protection Agency 2013). The CEQ has also released final guidance that requires agencies to incorporate estimates of project GHG emissions or sequestration and associated climate change impacts as well as potential impacts of future climate conditions on the proposed action into NEPA documentation (Council of Environmental Quality 2014).

This Section of a NEPA document would describe the existing air quality in the project area, any designation of non-attainment under the Clean Air Act for the region (for criteria pollutants), restrictions on activities in the area due to non-attainment, and potential for the installation or operation of the technology to emit air pollutants and greenhouse gases (e.g., CO_2, CH_4, NOx). In the case of hydrokinetic energy projects, the NEPA document will need to report the potential for air quality pollutant emissions and GHG emissions from the specific project, if any. If the project will replace some amount of local power generation, the analysis may also compare GHG emissions of power generation in the region compared to that of the hydrokinetic energy project. In regions where hydrokinetic energy will replace electricity produced by diesel flown in to fuel generators (e.g., in Alaska), there is potential for significant reduction in GHG emissions and particulates. However, it should be understood that capacity may not equal actual production, and therefore production capacity of the hydrokinetic energy project only indicates the upper bound of potential displacement) of other local power generation sources (Miller 2014). Furthermore, energy consumption has been found to expand in the face of additional supply and therefore renewable power generation may only replace a small fraction (e.g., 10%) of dirtier local power generation (York 2012). In addition to evaluating the effects (positive or negative) of the proposed hydrokinetic energy project on GHG emissions and climate change, there must also be an evaluation of how future climate conditions (e.g., altered water levels, etc.) would affect the project, and such future conditions should be considered during project siting.

Current data collection opportunities:

- Calculate criteria air pollutant and GHG emissions associated with installation and operation of the prototype and anticipated scaling with device size.
- Consider potential benefits or increases in emissions as an aspect of installation requirements for target market sites, noting limitations described above.

10.7.3 Water Resources (including Wetlands and Floodplains, Coastal Zone Management Act)

Similarly to air quality pollutants, water quality pollutants are regulated under the Clean Water Act, as is the protection of wetlands. Any discharges into waters and wetlands of the United States are subject to regulation and permitting (U.S. Army Corps of Engineers 2015 , U.S. Environmental Protection Agency 2015b). The Coastal Zone Management Act of 1972 requires states to manage coastal waters to "preserve, protect, develop, and where possible, to restore or enhance the resources of the nation's coastal zone." (National Oceanic and Atmospheric Administration 2005). States are required to define what constitutes a permissible land or water use in the coastal zone and which shall be subject to management program terms depending on the likelihood of direct and significant impacts on coastal waters or areas affected by current or potential sea level rise (Title 15 Commerce and Foreign Trade 1996). The EA or EIS for any federal project in the coastal zone must explicitly demonstrate compliance with the Coastal Zone Management Plan for the specific area of the project.

For hydrokinetic energy projects, a NEPA document will need to report any anticipated water pollutant releases, intake and discharges of water, anticipated installation impacts on water quality (e.g., sediment disturbance and associated release of silt/dredged material and possible contaminants), and anticipated long-term impacts on water quality due to changes in flow, sediment transport, turbidity, dissolved oxygen content, and biological oxygen demand.

Current data collection opportunities:

- Calculate any anticipated water or water pollutant discharge from the installation and operation of the prototype and anticipated scaling with device size or number.
- Evaluate change in water flows, turbidity, chlorophyll content, and oxygen content downstream of prototype device and estimate potential sediment disturbance for scaled up device(s).
- Evaluate potential for sessile species colonization using growth plates to assess potential for biofouling and associated creation of anoxic zone beneath the device due to sloughing off, deposition, and decomposition of biological material (e.g., utilize growth plate experiments).
- Consider disturbance of sediments (and potentially pollutants) as an aspect of installation requirements/best practices.

10.7.4 Wild and Scenic Rivers and National Marine Sanctuaries

The National Wild and Scenic Rivers (WSR) System was created by Congress in 1968 to protect rivers with "outstandingly remarkable scenic, recreational, geologic, fish and wildlife, historic, cultural, or other similar values" in "free flow condition" and protecting water quality and adjacent areas. Rivers can be designated WSR in their entirety or only along portions of the river. The Act prohibits FERC from issuing licenses for construction of power-related elements (including transmission lines) in these rivers. Siting criteria for Leading Edge hydrokinetic energy projects should therefore avoid WSR (90th U.S. Congress 1968). National Marine Sanctuaries would also be eliminated from consideration for potential project sites. The Office of National Marine Sanctuaries (ONMS) regulations (codified at 15 CFR Part 922 National Oceanic and Atmospheric Administration 1995), prohibit among other activities, the disturbance of, construction on, or alteration of the seabed and the discharging of material or other matter into the sanctuary. Consideration of WSR and National Marine Sanctuaries will inherently be site specific; thus, no data collection is suggested during the experimental/pilot testing phase, although such considerations should be added to any development of siting criteria.

10.7.5 Wildlife, Vegetation, and Habitats

There are a number of aspects of flora, fauna, and habitat that should be described for a proposed installation site and addressed in the NEPA documentation, including the presence of particular species or habitats and potential positive and negative impacts. These include:

- General flora, fauna, and habitat.
- Endangered, threatened species, species of special concern (regulated at the Federal level by the Endangered Species Act and at the State level through the natural heritage or conservation agencies), and their critical habitat.
- Biodiversity hotspots, protected areas, critical habitats.
- Specific flora and fauna groups that may be affected (e.g., marine mammals, benthic habitats).
- Invasive species concerns.
- Essential Fish Habitat.

For hydrokinetic energy projects, potential impacts on wildlife include physical contact as well as creation or destruction of habitat, impedance of movement and migration, and changes in foraging / feeding opportunities, among others. Also of potential concern is the impact of underwater noise on marine mammals and other organisms which communicate, locate, or forage by use of sound. Potential impacts on aquatic vegetation may occur due to changes in sedimentation, nutrient flows, water quality, and attraction of herbivores. Potential effects of hydrokinetic devices on wildlife, flora, and habitats are summarized in Section 3.

Current data collection opportunities:

- Evaluate potential for fish strikes using flume and field analyses (e.g., video monitoring of wildlife approach and strike).
- Evaluate potential for biofilm and sessile species colonization using growth plates.
- Develop site screening criteria for Leading Edge projects that include avoidance of key habitats, biodiversity hotspots, and endangered and threatened species.
- Consider avoidance of potential impacts on fish, mammals, and other wildlife as an aspect of device and anchoring design and siting criteria.

10.7.6 Noise

Noise and soundscape issues are important for both humans and animals, and in extreme cases can result in vibrational impacts on sensitive geological or structural formations. A NEPA document would describe the existing noise conditions both at the surface and underwater, and would evaluate the potential for changes to those conditions from the proposed device or array. Both installation and long-term noise impacts should be examined to evaluate potential effects on natural soundscapes (Fristrup 2012) and community noise levels (ANSI 12.9 series) for nearby populations.

Current data collection opportunities:

- Measure sounds associated with test device operation.

- Evaluate predictive models and/or use design data (e.g., motor specifications) for estimating sound levels associated with scaled-up device(s).
- Consider noise impacts, and appropriate mitigation, if necessary, in design of device and installation protocol.

10.7.7 Electromagnetic fields

Electromagnetic fields (EMF) associated with transmission lines and other electrically charged objects can have important physiological and behavioral effects on animals (Section 3.6). For NEPA analysis, the current and anticipated EMF conditions should be analyzed for the site. The NEPA document would analyze the potential change in EMF conditions, the presence of vulnerable species that might be affected by a change in EMF, and the potential impacts associated with the expected level of EMF that will be generated.

Current data collection opportunities:

- Evaluate potential EMF associated with main electromechanical systems of the hydrofoil, including hydrofoil arms and generator.
- Estimate EMF associated with scaled up device based on design plans, components, etc.
- Estimate potential EMF associated with future power line transmission associated with a scaled up device.

10.7.8 Visual resources, viewscapes, and aesthetics

Visual resources are part of the human environment, and include line of sight concerns for specific types of facilities (e.g., airports, watch towers) as well as aesthetics. For a project in which significant surface structures will be visible, an analysis should be undertaken to determine any key viewscapes or critical functional visual needs in the adjacent areas with which the project may interfere. If visual resource issues are identified, mitigation measures to reduce surface components or adjust size, shape and visibility may be undertaken, and public consultation is likely to be needed. The Federal Land Management Agencies (BLM, Forest Service) and other researchers have developed protocols for studying and managing visual resources that may be useful for such purposes (Whitmore et al. 1995, Manning and Freimund 2004, Bureau of Land Management 2009, Bowers et al. 2010). As visual resources and impacts are likely to be site specific, and as the hydrokinetic energy devices are likely to have a very small surface visual footprint, extensive data collection is not recommended at this time.

Current data collection opportunities:

- Design consideration to minimize surface facilities will aid in reducing future potential visual impacts.

10.7.9 Hazardous Materials, Hazardous Waste, and Solid Waste

The hazardous materials and wastes Section of the NEPA document covers both existing conditions (e.g., toxic materials adsorbed onto seabed or riverbed sediments, buried hazards, etc.) as well as the potential toxicants, hazardous materials and wastes associated with the project itself and/or potential release due to disturbance during installation or operation. End-of-life wastes may also be included in this analysis. The NEPA documentation would assess potential changes in hazardous materials and wastes conditions and future generation of such materials to assess potential impacts on health, safety, water quality, air quality, and impacts on flora, fauna, and habitats.

Current data collection opportunities:

- Assess potential toxic and hazardous materials associated with design and installation of devices.
- Avoid potential toxic and hazardous materials and minimize waste as part of design process (e.g., use non-toxic antifouling mechanisms, select components that do not require oils and other hazardous materials).
- Consider existing sediment contaminants as part of siting criteria.

10.7.10 Protection of Specific Land Types and Associated Resources

A variety of laws, requirements and standard practices that address protections related to particular types of land and societal resources, including recreational resources, historical and cultural resources, parks and public lands, and navigation in US waters. For example:

- Historical and Archeological Resources (Section 106 of National Historic Preservation Act) (89th U.S. Congress 1966)
- Farmland Resources
- Parks, Public Lands, and Recreational Resources
- Navigation in US waters (includes wetlands) as regulated by the US Army Corps of Engineers under the Rivers & Harbors Appropriation Act of 1899
- Tribal Lands and resources supporting tribal substance hunting and fishing

A NEPA document would assess the presence of such resources at or near the project site and would assess potential impacts, including direct impacts (use of such lands for the project) and induced effects (affecting quality, erosion, viewscapes, etc.). Effects on such resources often would lead to significant agency and public consultation to avoid impacts and address concerns. However, such impacts are site-specific for particular projects. Therefore, no particular data collection opportunities are available during testing to facilitate future NEPA assessments for these resources.

10.7.11 Socioeconomics and Environmental Justice

Socioeconomics and environmental justice analyses are intended to avert significant impacts on communities that are disproportionately vulnerable to or affected by environmental impacts. EPA describes environmental justice as “the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies” (U.S. Environmental Protection Agency 2015a). Executive Order 12898 requires Federal agencies to assess and address the disproportionate environmental, health, and safety impacts of Federal actions on minority and low income populations (Exec. Order 12898 1994). A NEPA document typically analyzes the presence of Environmental Justice communities in the project area and, if such communities are identified, evaluates the potential for disproportionate impacts on such groups based on the project alternatives. As socioeconomics and environmental justice issues are site specific for particular projects, no particular data collection opportunities are available during testing to facilitate future NEPA assessments for such issues.

10.7.12 Health and safety

The NEPA analysis addresses the potential for changes in public health and safety related to the execution of the proposed action. Public health and safety threats could include potential for releases of toxicants, radioactive materials, or other materials that could cause health and safety impacts or affect air and water quality, soil quality, or food contamination risks. Public safety threats could include physical dangers related to installation, operation, or failure modes of the device (e.g., presence of explosives, risk of electrical shock to people not directly involved in operation or use of the equipment, etc.). In addition, public health and safety can include effects on transportation access and safety, effects on emergency response systems, and other considerations related to the built environment (CDC National Center for Environmental Health 2008). Risks are likely to be site specific and depend on the proximity of populations to the proposed device; however, avoidance of hazardous materials and dangerous failure modes should be considered during prototype development.

Current data collection opportunities:

- Integrate failure mode analysis into device development and assess potential failure modes for commercial-scale devices.

10.7.13 Cumulative Impacts

Cumulative impacts analyses are intended to address the potential aggregate effects of many smaller, seemingly unrelated projects on a project area or region and over an extended period of time. Cumulative effects analyses under NEPA take into account other projects that are ongoing, planned, or “reasonably foreseeable” in the same project area that might have impacts on similar resources to those affected by the proposed action in order to assess the potential for significant impacts related to multiple smaller projects. For example, if multiple shoreline development, navigation enhancement, and hydrokinetic projects are planned for an area, the cumulative impacts may significantly affect water flow even if each individual project has minimal impact. In the case of hydrokinetic energy projects, cumulative effects on ecosystem function, fisheries, or other resources may result from many small hydrokinetic project installations combined with offshore wind projects and other planned development in the coastal zone or along the shore (Hydropower Reform Coalition 2015), or in riverine environments may result from multiple planned uses along the river or when combined with shoreline activities in the adjacent area, such as increased land development and runoff, changes in water use in the area, etc. Cumulative impact analysis is inherently site/project area specific and incorporates project impacts relating to specific resources; therefore, no data collection/modeling opportunities are identified for execution during the testing phase.

10.7.14 Induced Impacts

Induced and cumulative effects are related to each other but distinct. Induced effects are related to projects or actions that are enabled by the proposed action but are not direct impacts of the proposed action. For example, while installation and operation of the a hydrokinetic energy project in a riverine environment might have minor direct effects on water quality, the resulting power generation in a remote area may enable greater settlement/development and associated construction, thus increasing effects on local habitat, erosion, water quality, etc. In cases where existing power generation capacity is available, while the project itself may offer lower carbon power than other regional power sources, there is no guarantee that power from the hydrokinetic energy project will actually displace that higher carbon electricity source, but rather may simply enable additional power consumption without affecting current or anticipated growth of conventional power sources, enabling greater development, industrial activity, etc. Induced effects are site specific, and the potential for displacement or expansion of power generation capacity is site specific as well.

10.8 Comparison of Alternatives

After the alternatives have been developed and the consequences of each are described they are compared in the EA or EIS. The environmental impacts of each are contrasted and compared as are the costs, benefits, implementation potential, schedule, etc. Based on this process the Preferred Alternative is identified and an explanation is provided as to why it is preferred. For and EIS the "environmentally preferable alternative" must be identified and if it is not the preferred one, an explanation of why not must be provided. Based on the complexity of the project and the anticipated impacts, the comparison process can be qualitative or quantitative, simple or complex.

11 Special considerations for experimental and pilot hydrokinetic energy projects

As described in Section 1, all major federal actions are subject to NEPA regulations. For commercial installations, environmental impact analysis will be required to comply with FERC regulations. To support technology development, FERC has provided guidance to speed up permitting processes for experimental and pilot projects that are not anticipated to have significant impacts (U.S. Department of Energy 2008). Recent legal interpretation has determined that the Federal Power Act can be implemented in a flexible manner to allow experimental projects to proceed without licenses if the technology is experimental, the project is of short duration and removable on short notice, is in an area deemed environmentally non-sensitive, power will not be transmitted to or displace power from the national grid, and will be removed and the site restored to original condition upon completion of the project (Federal Energy Regulatory Commission 2012). Eligibility is determined on a case-by-case basis, and both experimental and pilot projects are subject to an evaluation of environmental risks. Pilot project proposals are reviewed by FERC, with input from federal, state, and local resource agencies, Indian tribes, non-governmental organizations, and members of the public. Pilot projects could allow transmission if licensed later, but do not require the intention to pursue a standard license after the pilot period (U.S. Department of Energy 2008). The agency's goal is to license hydrokinetic pilot projects in as little as six months after application filing (U.S. Department of Energy 2008).

Available information from environmental studies conducted for ongoing hydrokinetic projects can contribute to an evaluation of the environmental risks of new hydrokinetic technologies. Ocean Renewable Power Company (ORPC) has conducted extensive environmental tests of their horizontal-axis turbine technology in tidal and river systems, and to date, "no known adverse impacts" have been observed in fisheries and marine life interactions (ORPC Maine LCC accessed May 2015). The environmental studies include acoustic monitoring, benthic and biofouling studies, extensive hydroacoustic assessments of fisheries and marine life interactions, hydraulic modeling, and marine mammal and bird monitoring, all of which contribute to their adaptive management plan (ORPC Maine LCC 2014). ORPC suggests that the substantial amount of video monitoring they have done has essentially “retired the risk” of fish and marine mammal strike by their horizontal-axis hydrokinetic technology (Personal Comment, Nathan Johnson, Director of Environmental Affairs, ORPC), although whether these data are sufficient for risk assessment for the Leading Edge hydrokinetic technology remains to be determined.

12 List of frequently required environmental permits

A report prepared by Pacific Energy Ventures, LLC on behalf of the U.S. Department of Energy presents an overview of the regulatory frameworks other than NEPA that apply to hydrokinetic energy projects (Pacific Energy Ventures 2009). A Clean Water Act § 401 (water quality certification) and § 404 permit (for any discharge of dredged or fill material) is required for any dredging associated with a hydrokinetic project installation. A USACE authorization under the Rivers and Harbors Act § 10 permit for all structures placed in navigable waters and a Private Aid to Navigation (PATON) permit from the U.S. Coast are also required. Many other Federal requirements and siting restrictions also apply to hydrokinetic projects (Gaffney and O'Connell 2008). As mentioned in Section 2.7.4, the Wild and Scenic Rivers Act prohibits FERC from issuing licenses for construction of power-related elements (including transmission lines) in designated rivers.

Table 6 provides a summary of the Federal Authorizations that may apply to hydrokinetic energy installations (Adapted from Aubry 2009, Pacific Energy Ventures 2009). This list is provided as a general overview only, and federal and state rules, statutes, and regulations should be consulted for official guidance.

Table 6. Frequently required permits for hydrokinetic energy projects; adapted from (Aubry 2009, Pacific Energy Ventures 2009).

Permit/Approval	Primary Legal Authority	Lead Agency	Other Agencies	Anticipated Process Time	Relevant For
Federal Hydroelectric License	Federal Power Act 16 U.S.C. § 803(a)(1)) Section 10, Section 27; Energy Policy Act of 2005	FERC	USACE, MMS, USFWS, NOAA, USCG, BIA, EPA, NPS, USFS, ACHP, USGS, BLM; tribal governments; other relevant federal, state, local agencies	1-4 years	All sites
Preliminary Permit	Same as above	FERC	Same as above	At least 60 days	All sites
CWA §404 Permit	§404 Clean Water Act	USACE	EPA, USFWS, NMFS	60-120 days, more if EIS needed	All sites
CWA §401 Water Quality Certification	§ 401 Clean Water Act	Designated State Agency	Relevant federal and state agencies	1 year	All
COE §10 Permit	§10 Rivers & Harbors Act	USACE	USFWS, NMFS	60-120 days, more if EIS needed	Internal navigable waters affected by dredge/ fill
Private Aids to Navigation Permit	Coast Guard Regulations	USCG	USACE, state resource agencies	Average 3 months	Navigable Waters
NEPA Analysis *(ROD, FONSI, Categorical Exclusion)*	National Environmental Policy Act	FERC	EPA, NOAA, other relevant federal and state agencies	2-6 months EA, 1 year EIS	Pilot and commercial projects
§7 ESA Consultation	Endangered Species Act	NMFS, USFWS	FERC, USACE, USCG, NMFS	135+ days	All
Marine Mammal Consultation	Marine Mammal Protection Act	NMFS, USFWS	None specified	120 days or 6-24 months	All
Essential Fish Habitat Assessment	Magnuson-Stevens Act	NMFS	Regional Fisheries Management Council	30-60 days	All
Fish and Wildlife Coordination Act Consultation	Fish and Wildlife Coordination Act	USFWS	FERC, NMFS, others	Varies	All
Migratory Bird Consultation	Migratory Bird Treaty Act	USFWS	FERC, COE, state resource agencies	Varies	All
§ 106 NHPA Consultation	National Historic Preservation Act	Advisory Council on Historic Preservation	FERC, USACE, state resource agencies	At least 30 days for each stage of consultation	Sites that meet National Register of Historic Places criteria
CZMA Federal Consistency Determination	§ 307 Coastal Zone Management Act	Designated State Agency	Relevant federal and state agencies	Up to 6 months	Coastal zones in 35 eligible states and U.S. territories
Archaeological Resources Consultation	Archaeological Resources Protection Act	Secretary of the Interior	Relevant federal and state agencies; tribal governments	Varies	Archeological resources on Federal or Tribal lands
NPS consultation if Shipwreck Encountered	Abandoned Shipwreck Act of 1987	NPS	Relevant State or Federal Agencies	Varies	Abandoned shipwrecks beneath navigable waters

13 Summary of NEPA analyses for related technologies

Section 10 presents a list of NEPA requirements that may be relevant for future pilot or full-scale deployments of the Leading Edge hydrokinetic energy technology. Several hydrokinetic energy projects are currently at various stages of development in the US. As part of the permitting process, some of these projects have conducted extensive pre-deployment and in some cases, post-deployment environmental monitoring. Completed environmental studies and proposed monitoring plans for other US hydrokinetic energy projects are summarized in Table 7 and Table 8. Key results that are most relevant for the Leading Edge project are also included. Results from pre- and post-deployment monitoring completed by Ocean Renewable Power Company (ORPC) are presented in greater detail, as the ORPC devices are currently undergoing testing and post-deployment monitoring results continue to be made available. In addition, the published findings described in detail in Section 3 of this report are also summarized in Table 9 to highlight the specific NEPA resource elements they could inform for an EA or EIS. The environmental monitoring plans and research methods developed to support the permitting process for other hydrokinetic energy devices could substantially inform environmental studies that may be useful for long-term testing and commercial-scale installation of Leading Edge devices.

13.1 Verdant Power Roosevelt Island Tidal Energy Project (RITE), East River NY

Table 7 provides a summary of the environmental studies and proposed monitoring plans completed by Verdant Power for turbine testing in their Roosevelt Island Tidal Energy Project (RITE) located in the East River, NY. The project demonstrations were completed, but no additional field testing has been implemented, reportedly due to funding and device reliability issues. However, the existing project reports and FERC applications include detailed methodology for environmental monitoring activities that could inform monitoring plans for longer-term Leading Edge device testing. The proposed monitoring activities included seasonal fixed hydroacoustics, seasonal DIDSON (high definition sonar) observation monitoring, seasonal species characterization netting, tagged species detection, seasonal bird observation, and underwater noise monitoring and evaluation. Verdant power also developed a fish movement and protection plan. These activities were approved by FERC and other relevant local, state, and state agencies, providing guidance for what type of information is required by these agencies. For Leading Edge device testing, the precise requirements will vary depending on the mode and length of testing, along with the key environmental aspects of concern for the specific project site.

13.2 Muskeget Tidal Energy Project

The Muskeget Tidal Energy Project is led by the town of Edgartown, MA, working with government and academic partners. They have proposed a 5MW pilot project. The project is unique in that a municipality holds the development rights rather than a commercial entity. In addition, the University of Massachusetts at Dartmouth Marine Renewable Energy Center (MREC) has proposed to establish a research and development testing facility to support the development of tidal energy technology (MREC accessed 2015). As of January 2015, the Muskeget Channel Tidal Energy Project is the only project in Massachusetts state waters that had met the FERC-specified schedule of activities, target dates, and reporting on the status of studies (MA Executive Office of Energy and Environmental Affairs 2015).

Table 7. Summary of environmental assessments and monitoring studies completed for the Verdant Power RITE project in the East River, NY (device testing is currently suspended at this location).

Environmental Monitoring Studies	Key findings
Essential Fish Habitat (EFH) assessment	• Variety of resident and migrating aquatic fish and bird species present • Two federally-listed endangered fish species are known to traverse the area and three threatened turtle species may be present • Water pressure differences were deemed insufficient to cause cavitation concerns for fish
Draft Biological Assessment (BA) on potential impacts on marine mammals (harbor seals)	• None expected
Side-scan sonar and video field surveys to characterize bathymetry, seabed substrates, archeological site presence, vegetative cover	• Channel floor dominated by boulder/cobble substrates (no sediment concerns) • Water quality analysis not required: no re-suspendible sediment is present at site • Little to no vegetation present • No archeological sites identified
East River Hydrodynamic Survey o Single day pre- and post-deployment Acoustic Doppler Current Profiler (ADCP) measurements of flow and velocity in and around 4 demonstration units (plus 2 failed) o Empirical model of macro-scale effects Long-term ADCP data recorded at the project site	• Regions of turbine mixing and flow disturbance above river bottom; pile wake impacts reduced by natural turbulent boundary layer • Macroscale model for a 30-turbine array extracting 1MW of usable power estimated a water level increase of 0.08% and water velocity reduction of 3% (below the estimated 7% detection limit for flow change measurement) • Estimates of total kinetic energy extraction that will not result in significant environmental effects varies from 10% to 15% to 20%[8]
Evaluated fish interactions with operating turbines o Fixed hydroacoustic arrays (24 split-beam transducers) o Experimental DIDSON (high definition sonar) o Mobile hydroacoustic transects	• Fish (large and small) not present in the high current zones; localized velocity decreases deemed unlikely to affect predator-prey relationships • Fish prefer bottom or surface of water, away from turbine locations • DIDSON observations show fish avoidance; promising technology for monitoring fish in turbid water • Limited likelihood for fish harm or mortality due to turbine operations (slow speed, lack of ducted pinch points, opportunity to move away) • Sound pressure levels increased above fish hearing thresholds but well below hearing damage levels (estimates vary by species) • Installations produced noise levels on par with subway tunnel traffic (effects on species not addressed)

[8] From the following study referenced in the Verdant Power Report: In-stream feasibility demonstration project, EPRI – TP - 001 NA Rev 3 by George Hagerman, Brian Polagye, Roger Bedard, and Mirko Previsic, September 29, 2006.

Studies that were completed to support the Muskeget Channel project application for a FERC license are shown in Table 8 and include hydrodynamic characterizations, bathymetry analysis, geomorphology, and a modeling study of potential effects of a tidal energy installation on sediments. For the sediment transport modeling work, ORPC conducted a preliminary assessment for tidal energy and proposed various effective configurations for their crossflow turbines in the Muskeget Channel. No systematic survey efforts on marine megavertebrates and fishery resources, including seals, cetaceans, seals, turtles, basking sharks and ocean sunfish, in the Nantucket sound – Muskeget Channel area have been completed (Leeney et al. 2010), suggesting additional studies are required to document and appropriately monitor marine megavertebrate species if hydrokinetic devices are installed in the channel. The environmental studies completed for the Muskeget Channel provides examples of the types of pre-deployment studies that may be required to support an application for a FERC license to deploy a hydrokinetic energy project.

Table 8. Summary of environment characterization for the Edgartown Muskeget Channel tidal energy project.

Environmental Monitoring Studies	Key findings
ADCP current velocity measurements o Ship based ADCP along multiple transects o Long-term current profiling using bottom mounted ADCP	• Intersecting tidal ellipses lead to regional tidal delays, producing locally high tidal velocities • Due to channel characteristics, velocities are higher on the ebb vs flood tide by ~10-20% and reach ~3.5 knots locally
Scour experiment (Downward acoustic velocity meter) o Near bottom current measurements for documenting scouring and sediment grain size around concrete mooring (Figure 14).	• Scour around test cylinder caused sinking in sand to stable cobble layer within 48 hours • Grain sizes shifted to courser material, leading to accretion of cobble layer around base
Swath bathymetry survey and analysis o Obtain baseline high resolution bathymetry dataset for proposed installation site o Characterize large scale bedforms in channel surroundings and potential cable routes	• Deepest area contains series of rolling bedforms of 5-m height and 100-m wavelength • Large amplitude sandwaves have average wavelength of 225m and height of 4.5m
Impact modeling studies[9] o Hydrodynamic modeling o Coupled hydro-sediment model with 8 grain sizes used for impact experiments for various configurations of the ORPC crossflow turbines (Harris 2010)	• Modeled velocity fields compare well to ADCP measured tidal currents in the channel • Modeled turbine-induced modification to the sea level is quite small and localized (3mm, on par with local 15 knot wind in 30-m water) • Velocity reduction associated with turbine energy extraction are small (~ 0.05 m/s reduction) compared to background flow (~2 m/s) • Model predicts ~ 15% accretion of sediment bed (5-10cm over 30 days) due to reduced energy transporting sediments with turbine installations compared to evolution of bed in natural conditions *assuming invariant bed topography*

[9] The effect of tidal power generation on sediment transport in Muskeget channel.

Monitoring methods may include visual surveys (aerial and boat-based) and static acoustic monitoring (SAM). SAM at tidal energy sites presents many challenges including resilient mooring and noise modelling requirements and equipment calibration for comparison among sites (Leeney et al. 2010). Recommended methodology for detection and monitoring of marine megavertebrates in the region, based on accepted survey and mitigation techniques was developed for each element of concern, including equipment requirements, challenges, and safety concerns (Leeney et al. 2010). These methods may provide guidance for monitoring if the Leading Edge team pursues device testing in ocean environments.

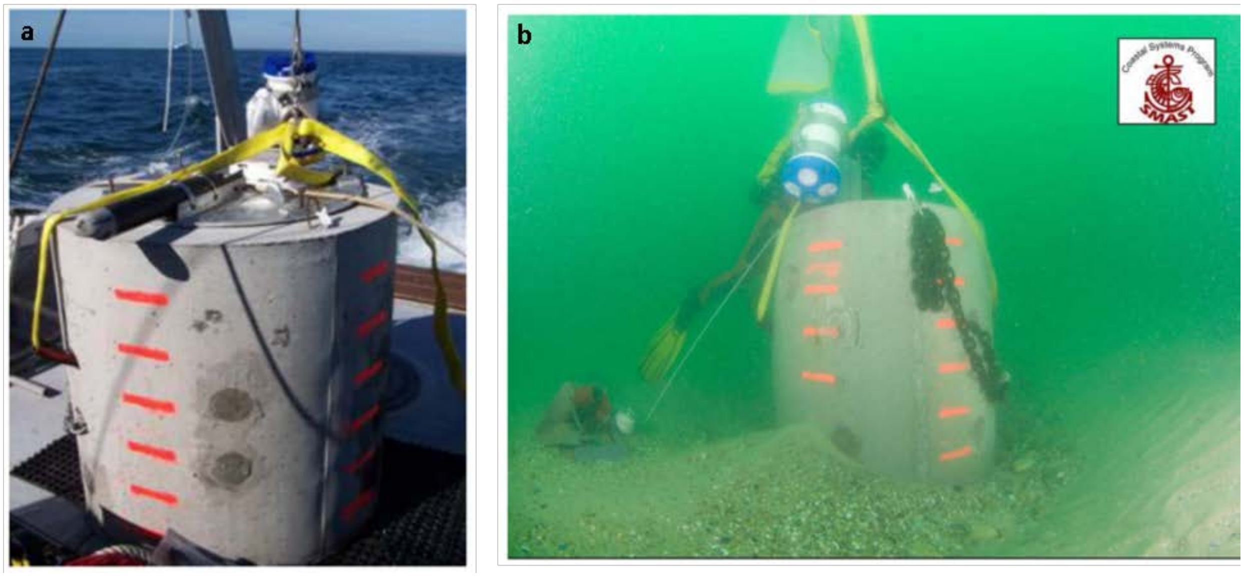


Figure 14. Images of experimental set-up for testing sediment scour in Muskeget Channel.
a) Concrete cylinder used to investigate sediment scour and settling for proposed turbine moorings in Muskeget Channel. b) Observed sediment scouring and accretion around the base of the concrete cylinder. Figures from Barrett et al. 2012 report.

13.3 Admiralty Inlet Pilot Tidal Project

The Admiral Inlet Pilot Tidal Project was designed to be the first grid-connected array of large-scale (300 kW) tidal energy turbines in the world. The project led by the Snohomish County Public Utility District was granted a FERC license in March, 2014. However the project was cancelled in September 2014 due to rising costs of construction and a decision by DOE to not contribute additional project costs (PUD 2014). During the eight years of project development, partners at the University of Washington developed underwater monitoring devices and conducted extensive surveys to understand baseline sea floor conditions and usage by fish and marine mammals (Table 9, adapted from http://tethys.pnnl.gov/annex-iv-sites/admiralty-inlet-pilot-tidal-project). Monitoring plans developed (Whiting 2015) included:

- Remotely Operated Vehicle (ROV) observations of benthic habitat and fish abundance and size at six sampling sites plus the two proposed turbine sites
- Additional assessment of noise impacts on other fish species that live in close proximity to the turbine sites

- Post-deployment monitoring of marine mammal and fisheries interactions using multi-beam acoustic camera and lighted video and a digital broadband hydrophone that allows real-time measurement of turbine noise and collection of marine mammal use of project area
- Measurements of water quality (turbidity, spills, leaching, conductivity, temperature, dissolved oxygen, and pH) during all stages of construction and operation.

Table 9. Summary of environmental monitoring studies completed during the permitting process for the Admiral Inlet Pilot Tidal Project (suspended as of September 2014).

Environmental Monitoring Studies	Key findings
Underwater noise studies o Modeling of anticipated underwater noise effects using ambient data collected from project site together with noise outputs of a similar Open Hydro turbines to determine anticipated pilot project acoustic effects on marine mammals	• In context of pre-installation ambient noise, turbine operation noise is not likely to be routinely detected by marine animals at distances greater than a few hundred meters from the project
Characterization of benthic substrate and habitats o Observations made aboard the support vessel and barge using Global Diving's Remotely Operated Vehicle (ROV)	• Turbine site can be characterized as a coarse-grained, cobble, pebble, boulder habitat for encrusting organisms and sculpin, ratfish, sunfish, urchin and some rockfish
Trawling studies (invertebrates and fish) o From 1987-2008, Washington DFW conducted 50 trawls in Admiralty Inlet within the depth range of 31-60m, depths within which the turbines would be deployed	• Existing surveys documented pre-installation benthic and fish community composition and abundance, including crustaceans, echinoderms, mollusks, other invertebrates, ratfish, sole, sculpin, rockfish, and other fish species
Hydro-acoustic fisheries investigations o Mobile hydro-acoustic surveys to determine fish densities in deployment area. Also deployed acoustic tag receiver on the seabed to collect information on presence and use of the project area by federally listed tagged species	• Preliminary results indicate minimal to moderate use of deployment area by fish; however, methods do not allow determination of use by species
Effects of turbine noise on Chinook Salmon o Test organisms were collected and exposed to a range of sounds associated with turbine noise. Fish were assessed at four different time points for tissue damage and changes in hearing sensitivity	• Results show that extreme noise exposure may cause low levels of tissue injury for Chinook salmon; no effects observed on hearing.

13.3.1 Environmental Monitoring by ORPC

Ocean Renewable Power Company (ORPC) has developed axial turbine systems to capture the kinetic energy of ocean and river currents (Figure 15). The TidGen® Power System can be secured to the ocean floor using a fixed bottom support frame or a buoyant tensioned mooring system, permitting the device to be deployed in deep water. The OCGen® device is designed for unidirectional deep water offshore currents, incorporating a buoyant tensioned mooring system. ORPC was granted a pilot project license in February of 2012 from FERC to evaluate their TidGen® Power System renewable energy device in Cobscook Bay, a large bay that opens into Passamaquoddy Bay within the Bay of Fundy in Maine. ORPC

Figure 15. Images of the ORPC hydrokinetic energy devices.
a) ORPC's TidGen® Power System deployed in Cobscook Bay, Maine in 2012-2013 and b) RivGen® Power System deployed in 2014 in Iniugig, Alaska (Figures from ORPC 2014 Environmental Monitoring Report submitted to FERC on March 17th, 2015).

has developed and implemented an adaptive management plan (AMP) to provide a strategy for evaluating monitoring data and modifying monitoring as necessary based on data collected. This approach supports the development of appropriate and cost effective environmental studies and monitoring plans. ORPC has developed new methods for environmental studies, providing tools to address permitting requirements. This Section provides a summary of the monitoring plans to investigate environmental effects of ORPC tidal energy devices, the results that may inform pilot testing and deployment of the Leading Edge hydrokinetic device. Information provided in the Section is summarized from the Cobscook Bay Tidal Energy Project (P-12711-005) 2014 Environmental Monitoring Report provided to Volpe by Nathan Johnston, Director of Environmental Affairs for ORPC (ORPC Maine LCC 2015).

Benthic and Biofouling Monitoring

ORPC developed the Benthic and Biofouling monitoring plan to evaluate whether biofouling accumulation on the tidal energy device structure may alter the benthic habitat within the deployment area. Studies were developed to characterize the existing benthic community prior to device deployment, to examine the recovery of benthic resources that were disturbed during the subsea cable installation, to examine the presence and extent coverage of biofouling organisms on the TidGen® system, and to examine the benthic community near the system. Consistent with observations for other subsea structures, artificial reef effects were observed with significant growth of mussels (5 to 6 in. thick layers of mussels over 75% of the support structures), in addition to an abundance of sea urchins and sea stars (Figure 16). A reduction in dragging activity around the project was suggested as one factor contributing to the high level of growth (ORPC Maine LCC accessed May 2015). While the high levels of growth have not yet been observed to affect the mooring and anchoring system of the TidGen® device (ORPC Maine LCC 2015), over time growth could result in structural degradation that could affect the system integrity.

Figure 16. Blue mussels on steel pile of the TidGen mooring structures (ORPC Maine LCC 2015).

Fisheries and Marine Life Interactions

The fisheries and marine life interaction plan was developed by ORPC to provide an initial description of fish populations in the pilot test area, along with post-deployment information such as tidal, seasonal, and spatial variability around the device testing sites. Downward-looking hydroacoustic surveys were completed for several months of the year for 2.5 years prior to deployment and for a year after deployment at the test location and a control site. Side-looking hydroacoustic monitoring was also completed to assess potential changes in the behavior of fish and other marine life in the vicinity of the device. The control and project sites were observed to have similar patterns of aquatic animal relative abundance, except during the installation period when lower densities at the project site were observed. There does not appear to be differences in the vertical distribution of fish during device operation. In near-field region, larger fish avoided the turbine and smaller fish passed through with no adverse effects observed (ORPC Maine LCC 2014). Fish have also been observed to congregate behind the buoyancy pod of the OCGen® device. OCGen® scour monitoring determined that there was only minimal horizontal movement of the anchors deployed to retrain the system (3-4” max), with localized scour approximately 1’ in depth observed at one corner location. Data were not available to determine if the scour occurred quickly after installation or slowly over time.

In 2014 and 2015, ORPC began testing a hydrokinetic generator unit designed to operate in rivers in Alaska. Environmental monitoring efforts during device testing included significant monitoring of fish activity around the device. ORPC’s RivGen® Power System consists of a two-turbine TGU supported by a chassis with a pontoon support structure used to deploy the system on the riverbed. ORPC completed a successful demonstration project for a 25 kW RivGen® turbine in the Kvichak River, southwest of Anchorage, Alaska. In July, 2015 ORPC’s RivGen® system began delivering power to the grid of the remote Alaskan village grid (LCC accessed 2015). During the 2014 testing, fish and wildlife were monitored near the RivGen® device (Nemeth et al. 2014). Wildlife (birds and mammals) were monitored using shore-based surveys by trained personnel each day that the device was operational. Each visual survey included 10 minutes of continuous observation using 7x50 binoculars (proceeded by a 5-minute calming period to offset unintentional disturbance due to personnel movement) with animal species, count, sighting cue, behavior, and location recorded for each sighting. The clear river environment in Alaska permitted the use of video monitoring of fish interactions with the device. Five cameras and two lights were deployed, and video monitoring was scheduled during device operation, which included all or parts of 17 days from August 14th through Sept 10th 2014. Cameras could detect fish within 10-15 feet of the device, with lights placed nearby allowing video recording at night. Ten-minute subsamples of from each hour of video collecting during periods when the device was submerged and operating, submerged and not operating, and on the surface and not operating were reviewed, for a total of 555 hours of reviewed video documenting 0.09 fish per hourly block (after standardization for effort) (Nemeth et al. 2014). Fish were found to be present at each device, travelling both directions in the stream and milling freely around the device. Salmon were clearly less abundant in the higher-speed Sections of the river compared to the slower-moving edges of the river nearby, regardless of the device presence. No contact between fish and the turbine structure were documented. The video and wildlife observation data to date have not identified any negative interactions between birds or fish and the RivGen® device (Nemeth et al. 2014). Recommendations for future fish monitoring include using a fixed mounting system for cameras and lights and monitoring fish during periods of higher abundance to understand and differences in behavior among seasons.

13.4 Environmental Studies for Related Technologies That Could Inform NEPA Analyses

As described in Section 10.7, there are many types of resources and issues that may be considered in a standard NEPA Environmental Assessment (EA) or Environmental Impact Statement (EIS) for a hydrokinetic energy project, depending on the actual installation site (refer to Table 1 for summary of commonly evaluated resource impacts). For several commonly evaluated resources, the required information is very site specific (e.g., Wild and Scenic Rivers and National Marine Sanctuaries, Socioeconomics and Environmental Justice, Protection of Specific Land Types and Associated Resources, Air Quality and Climate, Cumulative Impacts, and Induced Impacts); thus studies for related technologies will only be relevant if the same study sites are utilized.

Table 10. Summary of published findings described in detail in Section 3 of this report, highlighting the specific NEPA resource elements they could inform for an EA or EIS.

Resource element addressed	Related findings
Topography, Geology, and Soils	Changes in wave and/or current energy affecting sediment transport will vary with the amount of energy extracted. Few experimental data are available, but one study suggested an oscillating 15m wide hydroplane device could reduce current speeds by 25-30% locally around the device (The Engineering Business 2005).
Water Resources (including Wetlands and Floodplains, Coastal Zone Management Act)	Modeling results suggest minimal effects of the deployment of tidal stream turbine arrays on sediment dynamics and seabed morphology in the Pentland Firth, Scotland (Fairley et al. 2015). For installation in rivers and smaller channels, effects may be larger. No relevant experimental data showing the in situ effects of operating hydrokinetic energy devices on sediment transport were found.
Wildlife, Vegetation, and Habitats	The installation process may significantly disturb sediments and bottom substrates, but most species have been observed to return if bottom substrates remain relatively unaltered (Wilber and Clarke 2001). All hydrokinetic energy installation are likely to form artificial reefs and be colonized quickly by sessile species such as mussels, hydroids, anemones, algae, and barnacles (Langhamer et al. 2009), concentrating potential food sources for other species around the device, increasing habitat heterogeneity (Linley et al. 2007, Polagye et al. 2011b), and

Resource element addressed	Related findings
	potentially altering local population distribution patterns and nutrient flow through local food webs (Gill et al. 2005). The limited empirical data for wildlife encounters with *in situ* tidal energy devices suggests that major effects of tidal turbines on marine animals are not expected (Viehmann 2012, Copping et al. 2013b)
Noise	Pile-driving activities associated with the installation of bottom-mounted devices can generate sufficient noise to cause hearing damage in nearby marine animals (Copping et al. 2013b). Operational noise can potentially interfere with animal communication and echolocation, and may affect movements if animals avoid areas with high sound levels. For related wave energy devices, noise from pile-driving activities (Office of Naval Research 2003) is expected to remain slightly below the limits for the concern about hearing loss in whales, dolphins, porpoises and seals (NMFS 2003, Southall et al. 2008). There are minimal data available on the long terms effect of the noise produced by tidal energy projects.
Electromagnetic fields	Anthropogenic sources of EMF have the potential to alter the feeding behavior, reproduction, and migration behavior of marine organisms. While many studies have identified sensitivity of marine organisms to electric and/or magnetic fields, further field studies are required to understand how anthropogenic EMF generated by a network of transmission cables associated with hydrokinetic energy installations will affect broader-scale patterns of coastal migration and onshore-offshore migration in species of particular concern for a given site.
Hazardous Materials, Hazardous Waste, and Solid Waste	Hydrokinetic energy installations may present risks of both acute and chronic chemical exposure. Utilizing standard safety practices and spill-mitigation plans along with environmentally-friendly lubricants and hydraulic fluids that are inert or break down rapidly to inert components will minimize risks posed by tidal energy devices. The installation process of bottom-mounted marine hydrokinetic devices may significantly disturb bottom substrates, potentially releasing contaminants previously adsorbed by the sediments. Sediments with suspected contamination should be tested to develop a mitigation plan during installation.
Visual resources, viewscapes, and aesthetics	Concerns will vary by site, but limiting above surface structures that can block regular wind patterns will also minimize effects on viewscapes.

14 Environmental research on the Leading Edge prototype

Section 10.7 of this report describes the types of resources that are evaluated for potential impacts in a NEPA environmental impact analysis (either an EA or EIS). Each subsection lists potential types of analyses and experiments that can be performed during prototype testing to aid in evaluating and predicting impacts from a scaled up device or array. A subset of these measurements were completed during the testing phases of the first and second Leading Edge technology prototypes, including biofouling control, alteration of water flow, and acoustics. This type of early testing can help to identify and minimize environmental risks posed by the hydrofoil device and provide opportunities to incorporate recommendations for design, installation and operation.

14.1 Leading Edge Prototype Environmental Studies

Testing of two Leading Edge hydrokinetic energy device prototypes was completed in 2015 and 2016. The first phase focused on tug-testing of a prototype device in the Sakonnet River in summer 2015, and the second entailed stationary testing of two prototype devices mounted on a pontoon vessel. The stationary testing was completed in collaboration with the Massachusetts Maritime Academy (MMA) located at the Western end of the Cape Cod Canal, in summer 2016 (Figure 17). Water speeds in the canal at MMA reach 4-5 m/s during peak ebb tides, providing a strong tidal current for device testing.

Figure 17. Location of the phase 2 Leading Edge device field tests, at Massachusetts Maritime Academy.

Based on expert opinion, ARPA-E feedback, more specific aspects of data collection opportunities, and budgetary considerations, four studies were undertaken during the Leading Edge prototype testing phases to assess: risk of fish strike (performed by Ellerby et al.), surface coating effects on biofouling of the device, effects of the device on water currents, and effects of the device on underwater acoustics. Assessing the device effects on air quality and EMF radiation will require longer-term operation of the device, and were not completed during the first two testing phases.

14.2 Fish strike studies

ARPA-E expressed specific concern about the issue of fish and other wildlife strike in the initial phases of environmental risk analysis for this technology. Therefore, assessing fish behavior and strike risk was a high priority for the Leading Edge team. Flume studies were performed to understand potential strike risk and avoidance behavior by fish in a situation in which they are forced to encounter the hydrofoil device. Tests of fish interactions in the experimental flume found no detectable changes in blood cortisol levels, (an index of stress), associated with the presence of the hydrofoil. In addition, no startle responses, collisions, or obvious changes in behavior were observed (Dave Ellerby, personal comment). The results of this work are reported elsewhere by Ellerby and colleagues.

14.3 Biofouling

Systems such as the Leading Edge prototype will be exposed to the marine tidal environment for extended periods of time, and thus will be susceptible to growth of marine organisms on surfaces, known as biofouling, which potentially may reduce efficiency of the hydrofoil system. Biofouling occurs because of an initial colonization of algae, followed by settling of barnacles, limpets, mussels, and other organisms. Such growth creates significant drag on surfaces moving through water. Growth of barnacles and other marine organisms (biofouling) can increase corrosion and decrease electrical generation efficiency of hydrokinetic energy devices over time. Biofouling and colonization can also lead to artificial reef formation and potential creation of an anoxic zone beneath the device due to sloughing off, deposition, and decomposition of biological matter. Thus, early evaluation of device surface material options are likely to be highly valuable. To mitigate potential chronic contamination, the Leading Edge research team seeks to minimize the use of traditional anti-fouling compounds and utilize recently developed non-toxic coatings. In this report, we present results from an experimental test of several materials and coatings to assess how to best avoid such biofouling. The tests were completed in summer 2015, a year prior to the stationary testing of the Leading Edge device.

Often the metals and organic compounds used to minimize biofouling on these devices can cause chronic environmental contamination. Traditional anti-fouling coatings used copper as a biocide, with hard or eroding (ablative) coatings that work by directly leaching biocides to the surface or by gradually exposing new surface of the biocide-containing paint, respectively. The metals and organic compounds used to minimize biofouling on these devices are biocidal, and thus excessive exposure to the environment may lead to significant toxic effects to non-target organisms. To mitigate potential contamination, this research tests both traditional copper-containing anti-fouling compounds and recently developed coatings without copper.

The objective of this experiment was to test the efficacy of the anti-biofouling coatings used in the hydrofoil-type power conversion device to assess the susceptibility of different hydrofoil materials and coatings to biofouling in Narragansett Bay, the site of the initial Leading Edge prototype tug testing. The research focuses on the seasonal development of biofouling communities that could cause harmful corrosion or loss of efficiency to the device, as well as balancing the need to reduce exposure of workers and the environment to materials with high toxicity. This experiment includes evaluation of six replicate growth plates of eight different surfaces (aluminum, stainless steel, fiberglass, and fiberglass coated with a novel antifouling slip coating, and several antifouling paint options).

14.3.1 Methods

Coatings were tested on two substrates, aluminum and fiberglass, using replicate plates (51.6 cm^2), compared with bare substrates and bare stainless steel. For comparison purposes, growth rates on bare stainless steel were also compared to bare aluminum. The second set of comparisons was between bare fiberglass and coatings on fiberglass. Tested coatings included commonly-used traditional anti-biofouling coatings as well as newer anti-biofouling coatings without copper (Table 11). Coatings were donated by two boat yards: Bristol Marine and New England Boatworks.

Table 11. Experimental materials and coatings for biofouling test.

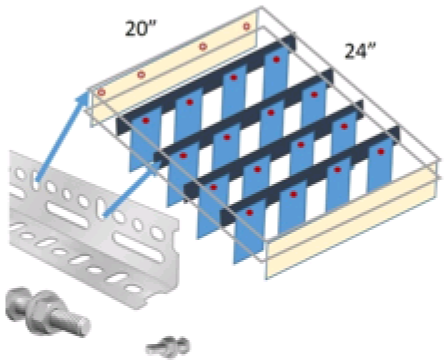
Environmental toxicity is assessed through two regulatory frameworks, the Emergency Planning and Community Right-to-Know Act (EPCRA) and the Department of Transportation Marine Pollutant list.

Substrate	Coating	EPCRA 313 Pollutants	DOT Marine Pollutants 10%
Aluminum	Bare 5086 Aluminum (Bare Al)	N/A	N/A
	Bare Stainless steel (Bare Stain)	N/A	N/A
	Anodized Aluminum (Anod Al)	None	None
	Interlux Trilux 33 (Trilux 33)	Cumene, ethyl benzene, pseudocumene, xylenes, zinc oxide, zinc pyrlthione	Pseudocumene
Fiberglass	Bare G10 Fiberglass		
	International VC Offshore Blue (VC Off)	Copper, ethyl benzene, xylenes	None
	International Baltoplate (Balto)	Barium sulfate, copper, copper oxide, copper(+1) oxide, ethyl benzene, xylenes	None
	International Micron Extra Blue (MicX)	Copper, copper oxide, copper(+1) oxide, cumene, ethyl benzene, pseudocumene, xyenes, zinc oxide	None

Toxicity of the coatings can be assessed using reported content of chemicals required to be listed under the Emergency Planning and Community Right-to-Know Act (EPCRA), namely Section 302, Extremely Hazardous Substances (EPCRA 302) and Section 313, Toxic Chemical Release Reporting (EPCRA 313). Additional toxicity information can be assessed from the marine pollutants list of the Hazardous Materials Regulations of the Department of Transportation (DOT), which requires listing of hazardous materials when constituting 10% by weight (DOT Marine Pollutant 10%) or listing of extremely hazardous materials when constituting 1% by weight (DOT Marine Pollutant 1%). None of the products tested with available material safety data sheets had components listed under EPCRA 302 or DOT Marine Transport 1%.

Test plates were attached to a galvanized steel frame assembled using zinc-plated steel fasteners. Two replicates of most material and coating combinations were placed in each frame; with 10 material x coating combinations and 16 locations within each frame, it was not possible to use two replicates of all combinations. The plates were then randomized within each of the three frames and attached to the frame using the silicone washers and nylon nuts and bolts (Figure 18). The silicone washers provided electronic insulation and prevented the passage of charge from the frame to the plates in accordance with the ASTM D3623-78A (Standard Test Method for Testing Antifouling Panels in Shallow Submergence).

A. Frame schematic



B. Example treatment assignment

Test Coating	G10 MicX	G10 Balto	G10 VC Off
Trilux 33	G10 VC Off	Bare Al	Bare Stain
G10 Balto	Trilux 33	Test Coating	Anod. Al
Bare Stain	Bare Al	Anod. Al	G10 MicX

Figure 18. Schematic (A) of 16-panel frame to test combinations of materials and coatings for growth of biofouling communities.

Example (B) of one of the three frames used for the experimental test of biofouling growth. Each frame contained the complete set of material and coating treatments, randomly assigned to locations within the frame. Shaded cells indicate treatments on G10 fiberglass; additional bare fiberglass material was placed outside the frames. An experimental coating was applied to two of the 16 plates. See Table 11 for explanation of material and treatment codes.

These frames were hung from a commercial dock in the Sakonnet River, RI, near the site of initial Leading Edge prototype tug-testing. Flexible polypropylene rope was used to attach the frames to the cleats on the dock. The rope knots were secured using waterproof electrical tape. During testing, the frames were pulled out of the water and the plates were detached. The biofouling community that developed was weighed every 3-6 weeks throughout the summer and into the fall, with photographs taken to serve as additional documentation of community growth. A tent-like structure was used to shade the plates to provide the same light exposure as the photos are taken. The plated were then photographed every 3-6 weeks through the summer and fall to assess the rates of marine life growth.

14.3.2 Data Analysis

Each of the plates was weighed to provide further data of biofouling community growth. Mass of biofouling was tracked within each plate, in each frame, over the course of the 21-week experiment. The three frames provide a blocking design for a mixed-effect analysis, using each frame as a component of the random effects. As plates were repeatedly re-measured over time, the analysis used a repeated-measures mixed effect model, in the form:

$$\text{Mass} = \text{Normal}(\text{Treatment}_{\text{Frame}} \times \text{Day}, \sigma_{\text{Frame}}),$$

where *Mass* is the wet mass of the biotic growth on the plate, *Treatment* is the material and coating combination, *Day* is the number of days after the plates were submerged, and σ_{Frame} is the pooled variance of the treatment across the frames.

Analysis was performed using the *lme4* package in the statistical programming environment R.

14.3.3 Results

Untreated substrates showed rapid and significant accumulation of biofouling communities, with up to 369 g of biofouling accumulating over the 21 weeks. Photographs demonstrated high diversity of marine algal communities, with no clearly-visible mollusk presence over the course of the experiment (Figure 19).

Figure 19. Example photographs documenting growth of biofouling communities on combinations of base materials and coatings, at different times in the experiment.
The top row of shows growth of biofouling communities on A. Bare aluminum and B. Aluminum coated with Interlux Trilux 33 after three weeks in July 2015. Bottom row shows growth of biofouling communities on C. Bare fiberglass after 15 weeks and D. Fiberglass coated with Baltoplate after 21 weeks.

Treatment with antifouling coatings resulted in significant reductions in accumulation of biofouling communities. For fiberglass substrates, the treatments with Baltoplate, Micron Extra, and VC Offshore both reduced accumulation of biofouling communities by 1 g / day over the 108 days for this subset of the experiment, for a total reduction of approximately from 118.8 g on bare fiberglass to a mean of 16.9 g on the three treatments with fiberglass (Figure 20, Table 12).

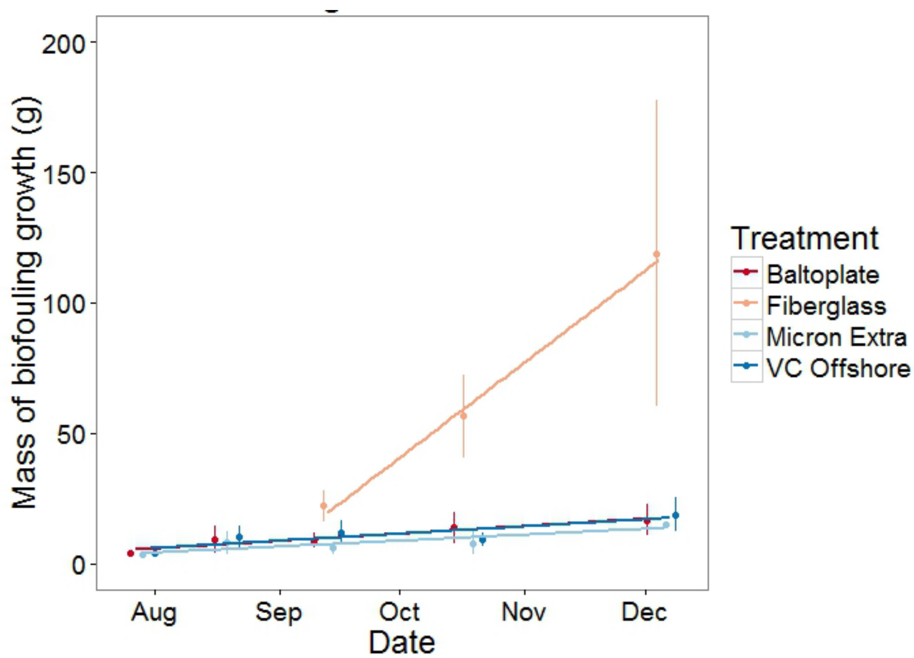


Figure 20. Growth of biofouling communities on bare fiberglass and fiberglass with antifouling coatings.

Model Summary	Effect on mass of biofouling		
	B	*CI*	*p*
Fixed Effects			
Bare Fiberglass (Intercept)	-258.62	-295.84 – -221.40	**<.001**
Baltoplate	240.59	197.32 – 283.86	**<.001**
Micron Extra	243.95	200.74 – 287.17	**<.001**
VC Offshore	240.80	197.58 – 284.02	**<.001**
Day	1.10	0.97 – 1.23	**<.001**
Baltoplate × Day	-1.00	-1.15 – -0.84	**<.001**
Micron Extra × Day	-1.02	-1.18 – -0.86	**<.001**
VC Offshore × Day	-1.00	-1.15 – -0.84	**<.001**
Random Effects			
N_{Frame}	3		
Observations	131		
R^2	0.798		

Table 12. Summary of mixed-effect repeated measure analysis of anti-biofouling coatings on fiberglass. Fixed effects show the accumulation of biofouling communities by the interaction between the treatment coatings and day of experiment; negative values for the effect size *B* indicate reductions in the pace of biofouling community accumulation compared to the reference treatment, bare fiberglass. Confidence intervals (CI) show the modeled range in effect sizes. Significant effects are indicated by the p-value (p) at α = 0.05.

For the aluminum substrate, all treatments resulted in significant reductions in accumulation of biofouling communities as well. Total growth of biofouling was greater on aluminum compared to fiberglass, and the alternative substrate bare stainless steel had the largest accumulation of biofouling, up to 162 g by the end of the experiment. The Trilux treatment reduced growth of biofouling by 0.81 g / day over the 150 days of this subset of the experiment, for a total reduction from 150 g to 19.2 g (Figure 21, Table 13).

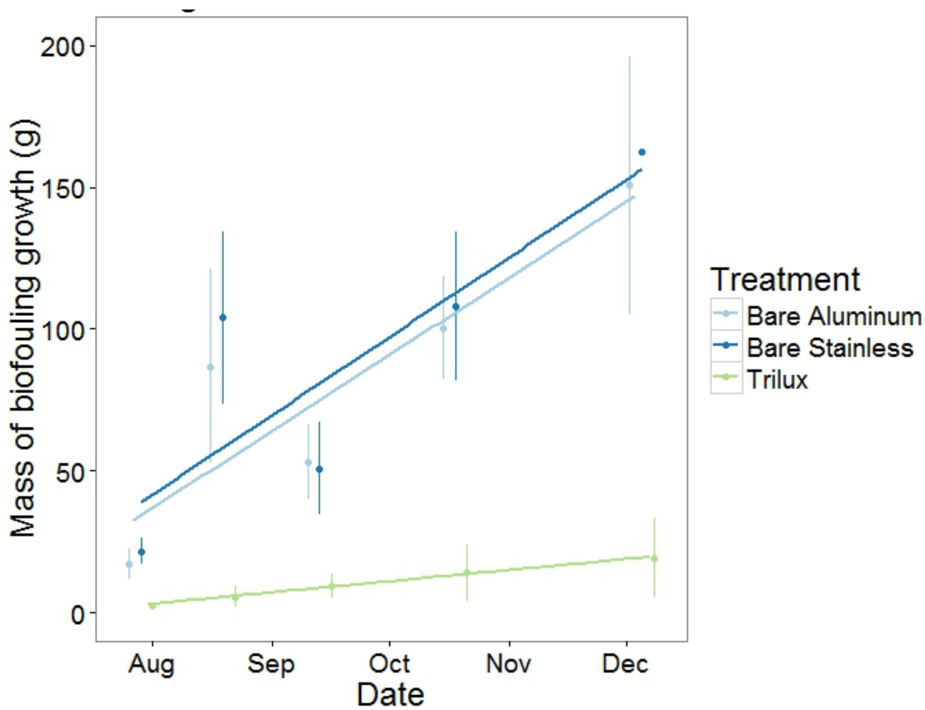


Figure 21. Growth of biofouling communities on bare aluminum, bare stainless steel, and aluminum with antifouling coatings.

Table 13. Summary of mixed-effect repeated measure analysis of anti-biofouling coatings on aluminum and stainless steel. See Table 11 for details.

	Effect on mass of biofouling		
	B	*CI*	*p*
Fixed Effects			
Bare Aluminum (Intercept)	-170.22	-227.14 – -113.30	**<.001**
Bare Stainless	-6.02	-86.08 – 74.04	0.883
Trilux	145.78	65.71 – 225.84	**0.001**
Day	0.94	0.72 – 1.16	**<.001**
Bare Stainless × Day	0.05	-0.26 – 0.36	0.755
Trilux × Day	-0.81	-1.12 – -0.50	**<.001**
Random Effects			
N_{Frame}		3	
Observations		144	
R^2		0.648	

For the bare aluminum and bare stainless steel, a transitory peak in algal biomass was measured in the second sampling period in August 2015. This may reflect a temporary peak in temperatures or other conditions conducive to algae which are particularly prone to settling on aluminum or stainless steel substrates. Fiberglass substrates and Trilux-treated aluminum did not show such peaks.

14.3.4 Summary

Anti-biofouling treatments are highly effective at reducing accumulation of algal biofouling communities on all of the substrates tested. The high effectiveness is combined with lower toxicity for Trilux, which does not contain copper, promoting this as a suitable treatment for aluminum-substrate components of the Leading Edge system. For components that must be made of fiberglass, any of the three treatments would achieve similar reductions in biofouling accumulation. With limited information about toxicity, the fewer total toxic components of International VC Offshore recommend it for use on fiberglass-substrate components of the Leading Edge system. Note that despite the effectiveness in reducing biotic growth, the anti-fouling treatments did not eliminate all growth on the test plates. For long-term deployment, periodic maintenance and cleaning of the submerged components of the device will be required. However, flume testing completed by the Leading Edge team had shown that the performance of their hydrofoil device does not depend on the shape of the hydrofoil. Therefore, depending on the deployment locations, anti-fouling treatments should reduce biotic growth sufficiently to support less frequent maintenance cycles.

14.4 Water current impacts

In order to assess how the Leading Edge stationary prototype device affects water flow and velocity, acoustic Doppler current profile (ADCP) measurements were made prior to and during the second phase of Leading Edge prototype testing at MMA in spring and summer, 2016. Figure 22 shows the location of the ADCP data collection, and the direction of the ebb and flood tides in the Cape Cod Canal. Volpe contracted Ocean Data Technologies, Inc. (Ocean Data) to support ADCP measurements. The text and figures in this section are excerpts from the full report from Ocean Data Technologies (Wood 2016).

Figure 22. Satellite image of the testing location showing the direction of the flood and ebb tides.

The first set of measurements characterized water flow in the Cape Cod Canal prior to the prototype testing. During testing of the Leading Edge prototype (the Joule), Ocean Data collected ADCP data using Aquadopp devices mounted to the Joule, and using a boat to survey the flow field behind the Joule. Measurements of water currents were targeted for the “steady-state” phases of prototype testing, when both devices were scheduled to operate. However, challenges with the device testing and operation prevented the Leading Edge team from testing both device arms during most of the ADCP data collection periods. The results presented here represent the best available assessment of how the Leading Edge technology could affect local water flow.

14.4.1 Measurement Approach

Water flow and velocity are typically measured utilizing an Acoustic Doppler Current Profiler (ADCP). The following summary of ADCP principles from the Woods Hole website (Woods Hole Oceanographic Institute) provides an explanation of the technology:

> *The ADCP works by transmitting "pings" of sound at a constant frequency into the water. As the sound waves travel, they ricochet off particles suspended in the moving water, and reflect back to the instrument. Due to the Doppler Effect, sound waves bounced back from a particle moving away from the profiler have a slightly lowered frequency when they return. Particles moving toward the instrument send back higher frequency waves. The difference in frequency between the waves the profiler sends out and the waves it receives is called the Doppler shift. The instrument uses this shift to calculate how fast the particle and the water around it are moving. Sound waves that hit particles far from the profiler take longer to come back than waves that strike close by. By measuring the time it takes for the waves to bounce back and the Doppler shift, the profiler can measure current speed at many different depths with each series of pings.*

ADCP measurements can be made at different frequencies, with higher frequency measurements offering higher resolution measurements over more limited spatial and temporal extents. Low frequency ADCP instruments were used for characterization of water currents across the canal channel at the MMA testing location. High frequency ADCP measurements were used to monitor effects of the Leading Edge prototype device on water currents at smaller spatial scales.

ADCP data were collected for two different measurement periods:

a) Site measurements to characterize variability in water current around the proposed testing location, during high tidal cycles. These data were collected from March 11th-28th, 2016.
b) Device measurements to monitor the effects of the Leading Edge prototype device (the Joule) on water flow and velocity from August 3rd-5th, at the end of the Summer 2016 testing period.

14.4.2 Cape Cod Canal Water Current Assessment

Ocean Data facilitated the equipment installation and completed the analysis of the collected data. An Aquadopp profiler mounted to the hull of a MMA training vessel was used to monitor a vertical profile of tidal currents from March 11th-13th. A side-looking ADCP mounted to the dock at MMA was used to monitor a horizontal profile of tidal currents from March 11th-March 28th.

Vertical Current Profiles: Installation Details

The Aquadopp Profiler (2 MHz acoustic Doppler current profiler) was installed at approximately 1600 hours on March 11th 2016. The unit operated until approximately 0839 hours on March 13th 2016 when battery power was depleted. The profiler was deployed along the pier at MMA towards the eastern end of the pier, 9.75m outboard of the pier face, and 1m outboard of the M/V Ranger hull. The transducer head was placed approximately 0.40m below the water surface (Figure 23).

Figure 23. Vertical water current profile measurement.

a) Photograph of the MMA M/V Ranger with pole mount off outboard rail, looking eastward. The Aquadopp profiler transducers were positioned approximately 16" below the surface. Stabilizers lines ran fore and aft to minimize vibrations. This photo was taken Saturday afternoon during strong westerly winds. b) Close-up of the Aquadopp profiler mounting. This photo was taken during an ebb (westerly) tide March 11, 2016 approximately 16:04 hours, just after installation. Note the strong wake coming off the instrument and mounting pole. Surface currents were measured to be 1.33 meters/second at this time (2.6 knots). Also note the relatively calm water surface reflecting calm wind conditions, in contrast to the brisk winds that occurred during portions of the testing period.

Horizontal Current Profiles: Installation Details

The horizontal acoustic Doppler current profiler (H-ADCP, Teledyne RD Instruments 300 kHz Narrowband) was installed at approximately 1200 hours on March 11th 2016. The unit was recovered March 28th 2016. The profiler was fixed in place along the pier at MMA towards the eastern end of the pier, facing outboard of the pier face, about -1.05m elevation (relative to mean lower low water (MLLW) datum). See Figure 24 for the H-ADCP mounting orientation. The H-ADCP looked outward into the canal flows, oriented normal to the pier face. The H-ADCP measures at fixed elevation, so the depth of the measurement relative to the water surface changed with tidal height. At high water, the depth of the currents measurements will be the deepest; at low water, the measurement depth will be the shallowest.

The measurement depths of the Aquadopp Profiler were not fixed however, but rather were relative to the water surface. Since the Aquadopp was mounted to the M/V Ranger, which rises and falls according to water level, the absolute elevation of the vertical 'bins' changed with the rise/fall of the water surface. So when comparing the H-ADCP data to observations made with the Aquadopp profiler, the depth of the two observations must be made consistent. To do this, NOAA tidal elevations (6-minute predictions) were downloaded and used to establish the fixed – absolute - elevations of the Aquadopp bins. A comparison of current velocity between the two sensors were then possible based on the absolute elevation of each measurement.

Figure 24. Horizontal water current profile measurement.

a) Photograph looking eastward at the corner of the MMA pier, showing the H-ADCP (far right) mounted at the bottom of the mounting structure. The white canister (blue caps) is the external battery housing used to power the H-ADCP. The canniest top was a distance 1.98m above the H-ADCP. The H-ADCP was installed at an elevation approximately -1.05m below the MLLW tidal datum. b) Photograph of the H-ADCP as installed. The battery canister is the only component visible. This photo was taken during slack tides on Thursday, March 17. The mounting structure was reasonably secure, assisted by using tensioning lines fore and aft. The H-ADCP measures orthogonal flow vectors - parallel to and normal to the pier face.

Current Profiles: Results

For vertical profile, the easterly flow was less than westerly flow – likely due to flow sheltering caused by presence of large tugboats forward of Ranger and upstream of the current meter. On the flood tides (flow towards the east), bottom flow appears stronger than near-surface flow, likely because flow beneath the tugboats at the near-bottom is less affected by sheltering than surface and mid-depth layers. On one of the measurement days, peak ebb was weaker than other ebbs, due probably to strong westerly winds blowing against the surface, applying an eastward-directed surface wind stress to retard near-surface flow. Peak flow during this tide was in mid-depth layers (Figure 25 and Figure 26).

For the horizontal profile, differences in the intensity of flood/ebb currents nearest to the MMA pier were observed, particularly on the easterly-running tide, which was slower than westerly currents. Asymmetry near the pier face may be due to flow blocking effects of the tugboats, which seem to have a downstream effect. On the westerly tide, flow very close to the pier is slowed, presumably by frictional effects of the pier itself, but this effect appears to vanish 6-8m away.

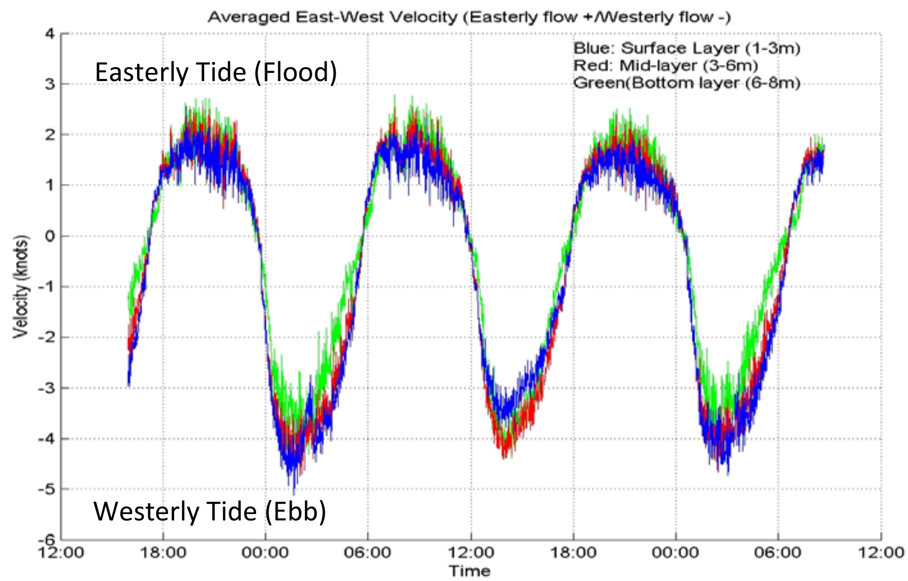


Figure 25. Averaged east-west velocity component for three depth layers.
These velocities resulted from an average of all bins between 1m to 3 m (surface layer, blue), 3m to 6m (mid-depth layer, red), and the bottom layer (6m to 8m, green). Positive-valued flow was eastward (flood); negatively-valued velocities were westward (ebb). This shows the relative strength of the westward tides versus eastward, as well as the relative noise levels between the opposing phases. Noise refers to the signal processing definition: any unwanted static or uncertainty that interferes with or obfuscates the underlying signal. Peak eastward flow showed higher variability (noise) than peak westward flow.

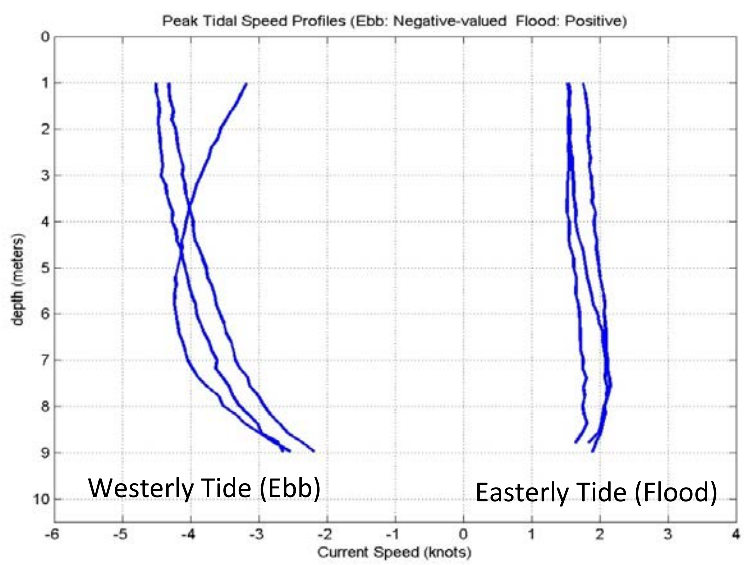


Figure 26. Average vertical profiles surrounding peak ebb and flood tides for the three complete tidal phases.
These average profiles resulted from a 30-minute temporal average (+/-15 minutes) around the time of peak flow. Note the difference in the ebb profiles (negatively-valued) where one profile shows higher speeds mid-depth versus near the surface. This particular curve is likely due to wind stress retarding near-surface currents. Flood (positively-valued) currents show higher speeds also in the lower water column, again likely due to flow shading from tugboats docked upstream of the current meter.

There remains a flow asymmetry between the flood and ebb, even in the center of the channel, with the westerly-flowing currents slightly faster than the easterly tides. Comparison of the H-ADCP measurements to the Aquadopp Profiler, once these data were normalized and referenced properly, showed excellent agreement (Figure 27). The data were compared 'as is'; no averaging or other manipulations were performed. The Aquadopp data appeared more variable than the ADCP results, but this could be due to the smaller sampling volume of the Aquadopp (20 cm vertical resolution) versus the larger sampling volume of the H-ADCP (2-meter horizontal resolution). Larger sampling volume is, in effect, a form of spatial averaging, so would smooth out variability due to small-scale turbulence.

Overlaying the flow speeds with NOAA tidal elevations, it appears the times of slack currents do not coincide with the time of high or low water, as would be typical for ocean tides. Instead, slack currents were found at the mid-tide elevations. This is characteristic of a progressive traveling wave; not the more common standing tidal wave found in open ocean areas.

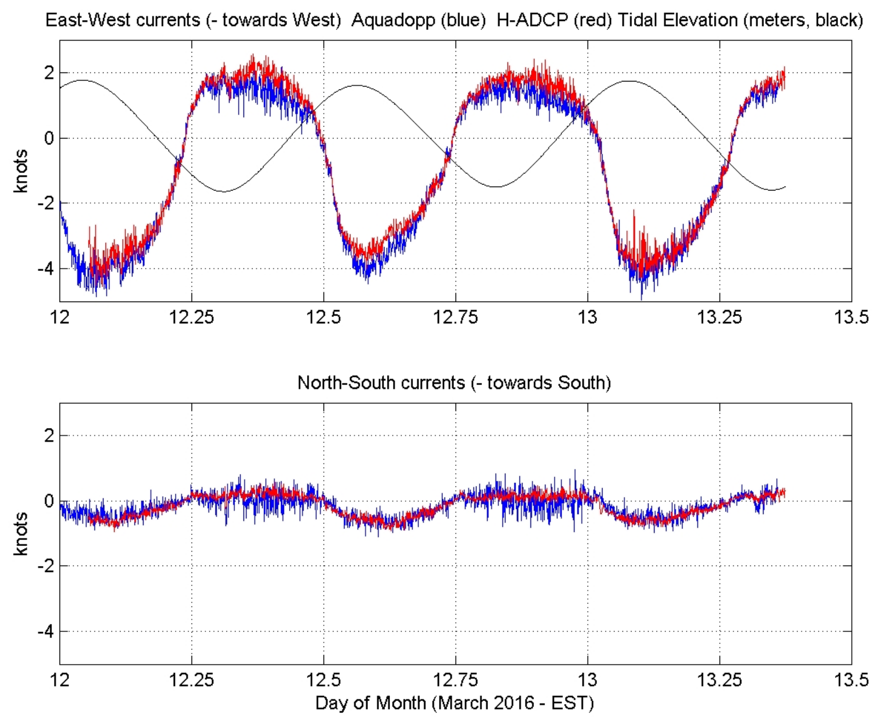


Figure 27. Comparison of the Canal currents from the Aquadopp Profiler (blue lines) to the H-ADCP measurements (red lines).

The top plot represents the along-channel (or east-west) flow while the bottom plot represents the north-south (cross-channel) flow. The different measurements – after reconciling changes in measurement elevation and coordinate systems – agree quite well with each other during the overlap times. The Aquadopp (blue) appears to have a noisier signal than the H-ADCP. The black line in the top plot represents mean tidal elevations (from NOAA). Note that slack water does not occur during high or low tide, rather, slack water appears to coincide with mid-tide. This is evidence that the tides in the Canal are progressive traveling waves (versus standing waves).

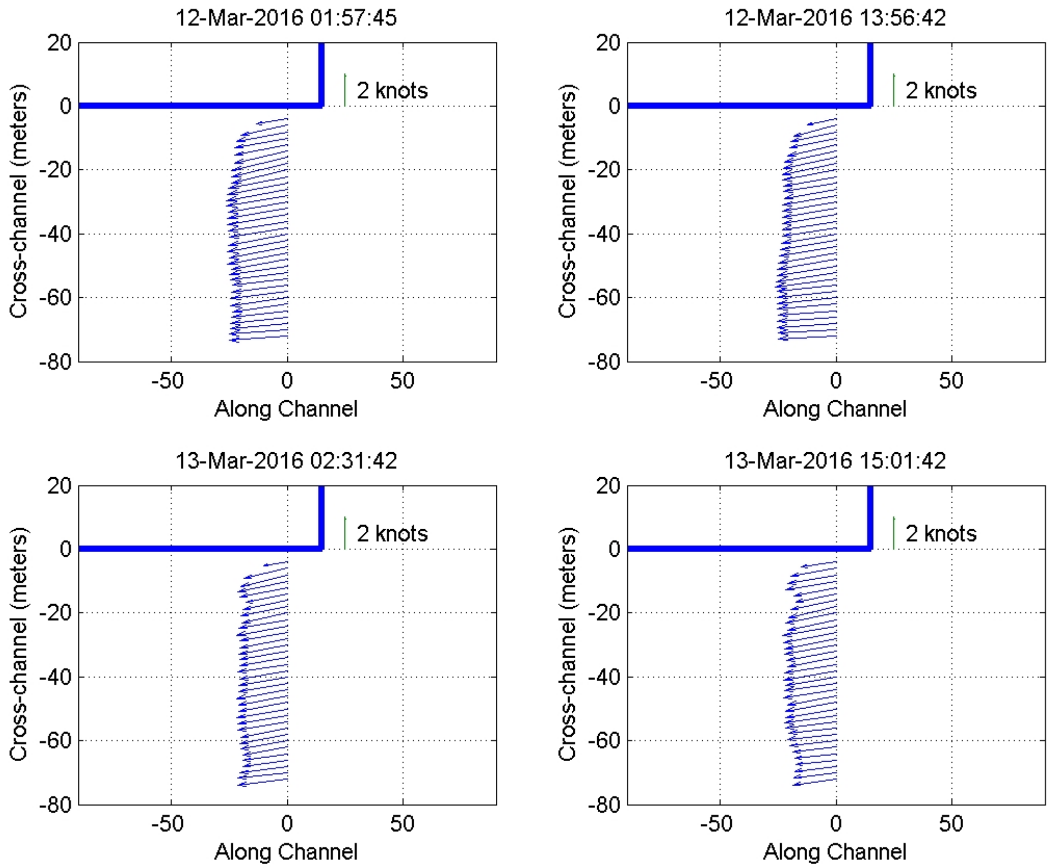


Figure 28. Instantaneous flow vectors during four consecutive peak westerly (ebb) tides.
These are the original 1-minute samples; no averaging was performed. The heavy blue line represents the MMA pier, with the measured flow vectors depicted by arrows. A 2-knot scale arrow is shown. There is a flow gradient in the immediate vicinity of the pier face, but this seems to vanish at distances of ~6-8m.

The horizontal ADCP measurements recorded the magnitude of the flow gradient moving away from the face of the pier (Figure 28). The results of the water current measurements at MA were utilized by the Leading Edge team to verify the expected water speeds with in situ measurements at the precise device test location, to inform the design process.

14.4.3 Leading Edge Device: Effects on Water Flow

The purpose of the current measurements was to quantify both incoming and exit flow through the Leading Edge device for purposes of identifying effects on the native flow field. Current measurements were collected from device-mounted Nortek Aquadopp acoustic Profilers from Wednesday, August 3 until late Thursday, August 4. The instruments were re-deployed with different sampling parameters again Friday August 5 for a simultaneous wake survey. The wake survey consisted of a vessel-mounted acoustic current meter measuring flow through several cross sections downstream of the device, as well as occupying two fixed stations, at consistent time intervals throughout the afternoon. These synoptic measurements provided a sense of the spatial variability of downstream flow. In total, data collection spanned four ebb cycles under a variety of conditions: both devices operating (Wednesday afternoon), one device operating (Thursday and Friday afternoons), and no devices operating (Thursday morning). These ebb cycles provided an opportunity to assess how the device may have affected the flow field.

Sample rates varied from 1-minute averages to short-burst 2 Hz high-frequency samples. The high frequency bursts were designed to capture higher resolution effects of the Joule operation on water flow. Vertical surface-to-seabed profiles were recorded below the device in both the forward- and aft-looking directions. Horizontal profiles were recorded in the immediate wake of the device. The intent of the wake survey was to measure the downstream flow effects of the Joule device (Figure 29). Measuring vertical velocity profiles at several downstream locations throughout a portion of a tidal cycle could determine how velocity varies with increasing downstream distance. To determine the spatial extent of such effects, two measurements of current velocity were made simultaneously. A moving-vessel survey was conducted in conjunction with fixed, Aquadopp Profilers attached to the pontoon barge in the same manner as the August 03-04 data collection described previously. Currents profiles were gathered in both near-field and far-field regions of the device. In all, currents were sampled with reasonable spatial and temporal resolution under a variety of device operating conditions. Detailed data collection methods and results for the flow observations are presented in the full report summarizing the ADCP methods and results (Wood 2016).

Figure 29. The MMA pier and Joule test device on August 5, the day of the survey.
Note the tugboat docked along the pier to the left of the photo, about 35-40 meters downstream of the pontoon barge (for scale, the pontoon barge is 35 feet in length). In the foreground is the GPS antenna.

Flow Observation Results

The intent of the measurement program was to compare incoming flow to exiting flow while the Leading Edge device was operating. This approach was presumed to be the most direct method of evaluating the effect of the Joule device. Several problems with the instrumentation were encountered, however the observed data support the conclusions drawn from the study.

The data set spanned just 3 ebb cycles when the device was operating – not enough observation cycles to make conclusive statements about device effects on the flow regime. Further, the native flow field is extremely turbulent and noisy itself, and so the data required significant smoothing to reduce measurement noise and clarify the underlying signal. Yet these brief observations suggest the Joule device may cause a slowing of flow in the upper layer where the device is located, about the upper 2m, and a corresponding acceleration of flow beneath the device. The flow effects appear to occur over short temporal and spatial scales, dissolving quickly in the otherwise-turbulent flow regime in the Canal.

A comparison of water velocity at a depth of 1.2m below the water surface shows that there are only a few noticeable differences in the normal flow components (Figure 30). Observations from both the fixed Aquadopp sensors and the two independent current meters used during the wake survey suggests the device has small, but observable effects on the flow field in the very near-field vicinity of the Joule foils. These effects consist of a slight slowing of the flow in the very upper layer – roughly the upper 2m – for the ebb tides that were monitored during device operation. This slowing of the flow in the upper layer may also result in a slight acceleration of flow beneath the device. These effects are quite local, and do not extend much below the device implying the Joule has only limited effects on water flow.

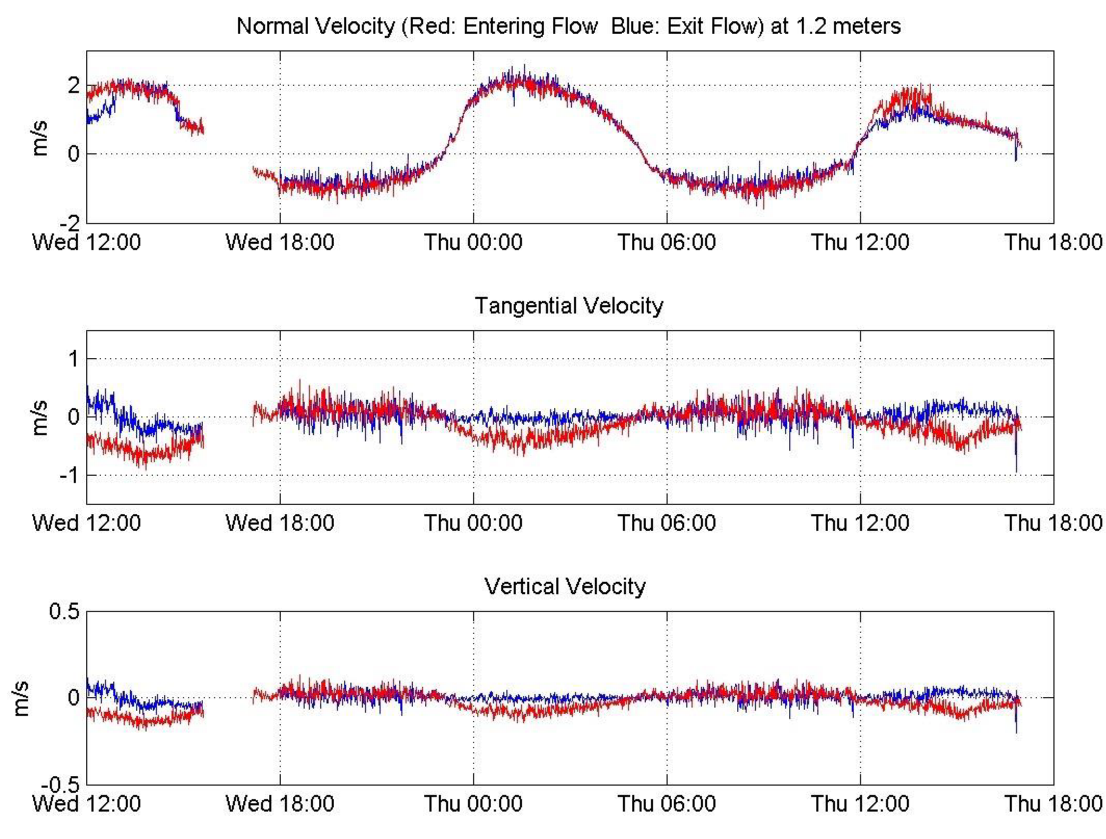


Figure 30. Time series of in-coming and exiting water flow past the Leading Edge prototype.
The normal (top), tangential (middle), and vertical (bottom) velocity components for the both the in-coming flow (denoted by the red line) and the exiting flow (blue line) at a depth of 1.2 meter (below the surface) for the time period Wednesday, August 3 to Thursday August 4 are shown. Note the discrepancies in the velocity signals during the Wednesday and Thursday afternoon ebb tides. Differences were greatest during the Wednesday ebb tide when both devices were operating. Note the scale differences (Y-axis) between the various velocity plots.

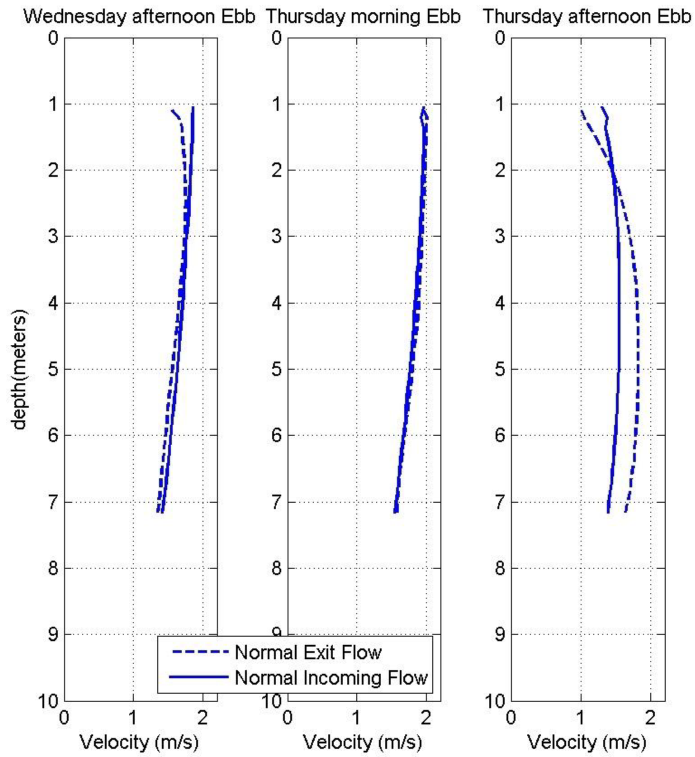


Figure 31. Mean normal velocity profiles during peak ebb tides.
Profiles from Wednesday afternoon to Thursday afternoon comparing the incoming flow (solid line) to the exit flow (dashed line) are shown. The 2m depth seems a critical depth signaling transition of the flow.

The mean velocities calculated over each ebb cycle were also compared to assess the general flow characteristics (Figure 31). The calculation was performed over an approximate 2.7-hour time period surrounding the peak velocity. The *Joule* device was operating during all afternoon ebbs, but was not in the water during the Thursday morning tide. There was a small difference in the mean velocity Wednesday afternoon, most notably above the 2m depth. Deeper flows appeared equivalent. The Thursday morning tide – when no devices were present – showed near equivalence of the incoming and exiting flows. The mean profiles varied considerably for the Thursday and Friday afternoon ebbs. Above 2m the exit flow slowed relative to the incoming flow, but appeared to be stronger below this depth.

Since only a few ebb cycles were measured during these tests, and the variability between cycles difficult to grasp with such thin evidence, we include here a repeat of baseline results gathered in March 2016. These measurements were obtained with a similar Aquadopp profiler installed about 10m outboard of the MMA pier. These profiles also showed significant cycle-to-cycle variability. At the time, our assessment was that changes in surface wind intensity – calm days versus windy days – increases the surface wind stress and altered the shape of the mean velocity profile. Westerly surface winds blowing opposite the ebb flow weaken near-surface velocity and strengthen deeper velocities (Figure 32). The different shapes of the velocity curve for the Thursday and Friday afternoon ebbs appears similar to profiles measured previously during strong winds.

Note that the Cape Cod Canal flow regime is extremely turbulent, especially close to shoreline structures such as the MMA pier where the testing was conducted. Turbulence causes quite erratic and noisy velocity measurements. By noise, we refer to the signal processing definition: any unwanted static or uncertainty that interferes with or obfuscates the underlying signal. The way to reduce noise is to average over longer periods of time, longer than 1 minute, but this noise-reduction technique is counterproductive to the goals of this particular project. Here we want to assess how the device affects flow. We suspect those effects would be at time scales of the MHK device motions, time scales of ~seconds. So averaging across these motion time scales – in an effort to reduce uncertainty - loses any hope of quantifying the device effects. In other words, the genuine turbulence that exists naturally in the Cape Cod Canal – and resulting noise contained the measured signal – may be on the same scale (or greater) as the device effects.

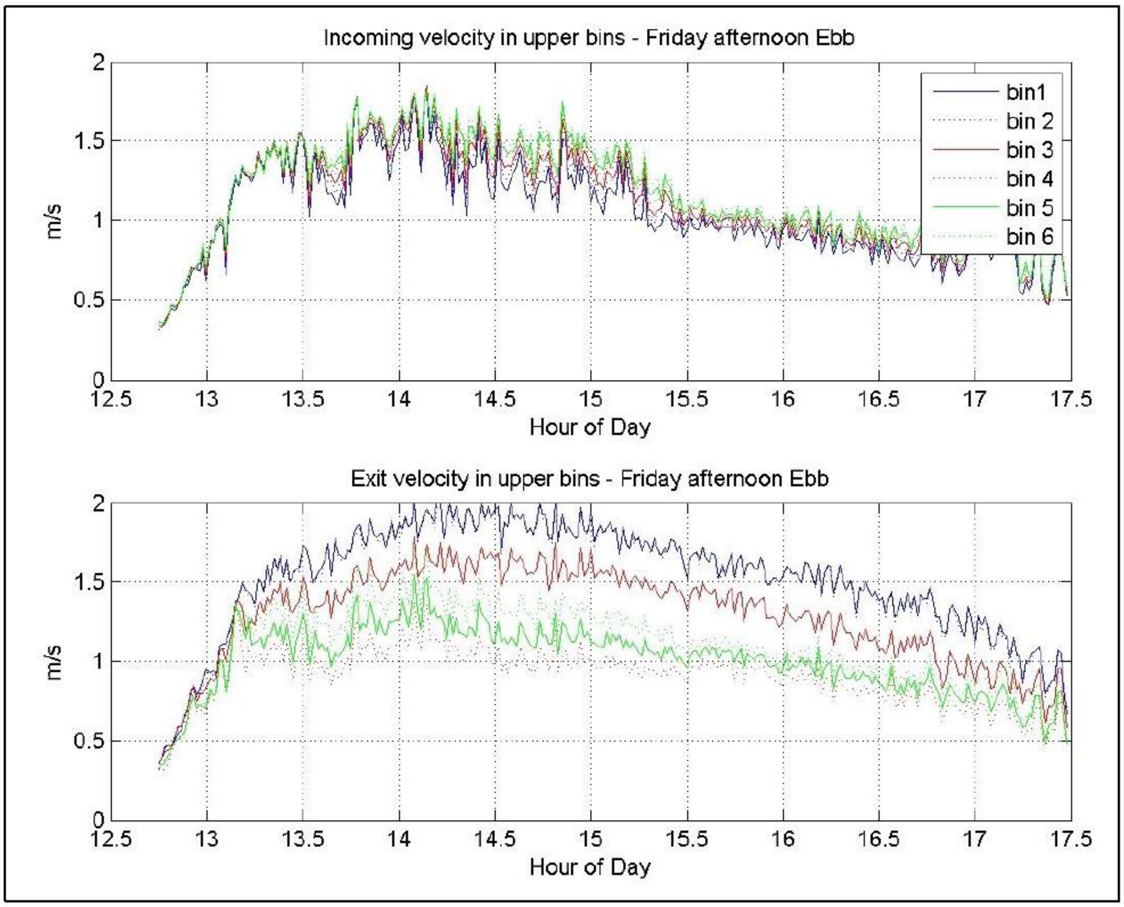


Figure 32. Comparison of velocity time series in the upper 6 range bins (1.2m to 2.8m depth) for the incoming flow (top) and exit flow (bottom) during operation of a single prototype device.
These are 1-minute averages computed from the original 1-second samples. Bins 1-3 have questionable echo amplitude levels and are therefore ignored. Bin 4 is valid – and shows a considerable sag in velocity magnitude after the device was installed (about 1315 hours).

In summary, observations from both the fixed Aquadopp sensors and the two independent current meters used during the wake survey suggests the device has small, but observable affects the flow field in the very near-field vicinity of the Joule foils. These effects consist of a slight slowing of the flow in the

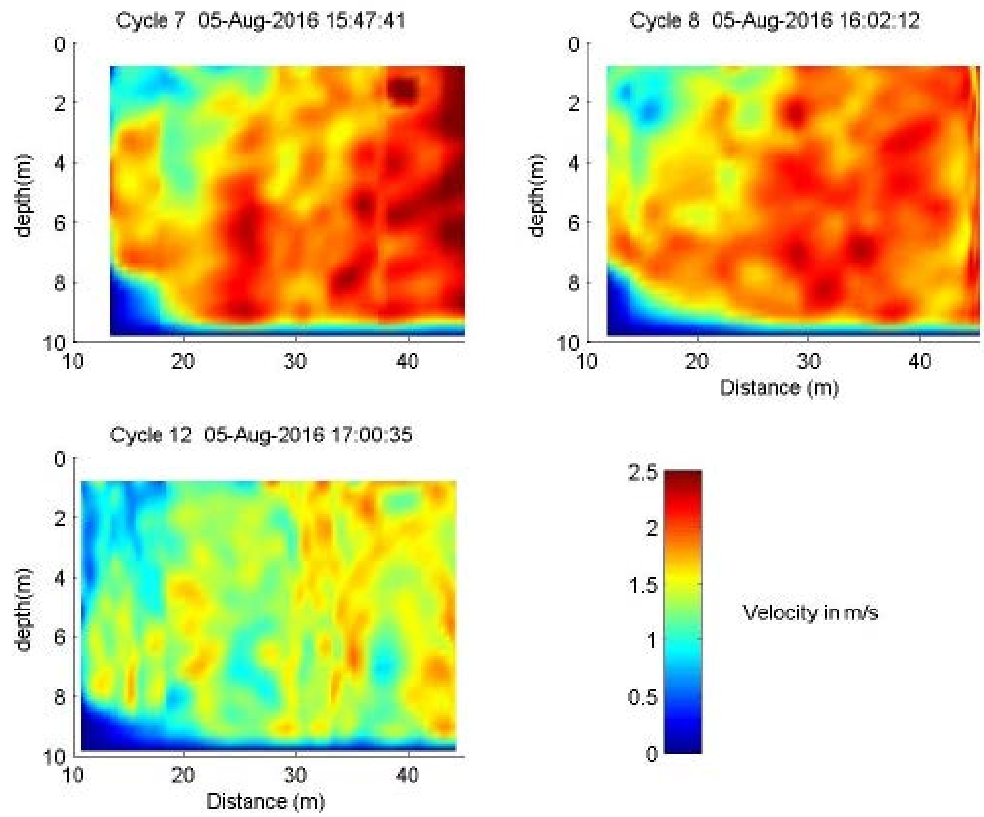


Figure 33. Color-contour panels of downstream velocity along an ADCP transect behind the *Joule*.
Color represents the strength of the current – red and orange are the strongest currents and blue are weak currents. Note the color bar to the lower right. The vertical axis is depth and the horizontal axis represents distance away from an arbitrary pier-based reference point. These contour plots represent a cross-section of the exit flow from the pier (on the left) toward the Canal channel to the right. The deep blue in the lower left corner of each plot represents the sea bottom at the toe of the pier. These profiles have undergone some smoothing to improve the presentation. The patches of light blue in the upper left represent weak flow behind the device.

very upper layer – roughly the upper 2m – for the ebb tides that were monitored during device operation. This slowing of the flow in the upper layer may also result in a slight acceleration of flow beneath the device. Accelerated flow in the lower layers was observed during the wake survey as far as 16-22m downstream (Figure 33), which was as far downstream as could be measured due to the presence of docked tugboats in the test vicinity. The downstream horizontal profiles, as well as the fixed station profiles, suggest downstream flow may be slowed relative to flow in deeper layers and flow away from the pier nearer the shipping channel. It should be noted, however, that there were other objects in the vicinity such as tugboats, the MMA pontoon barge, and the Joule test pontoon barge, that may also cause flow disturbances independent of the Joule device. Statistically, velocity spectra comparisons for the three ebb tides showed increased spectral energy for wave bursts when the device was operating versus significantly decreased energy when the device was not in the water. Three ebb cycles are insufficient to conclude that the device caused such differences, as such differences may have resulted simply from calmer wave conditions during the Thursday morning ebb tide.

For context, these effects appear similar to previous flow measurements behind the tugboats along the MMA pier in March when Joule was not present – weaker flow in the upper-layer with a corresponding increase in flow speed below the tugboat hull. We suspect the downstream effects on the flow would be similar had the Joule device been simply a boat or other floating object docked along the pier. Further, we also observed that westerly winds can also affect the mean current profiles in a similar way – a slowing of near-surface currents and corresponding increase in deeper flow. So to the extent Joule may have affected the flow field, and these effects appeared small and over short spatial scales, they were no greater or more significant than what may result from other watercraft or even a strong breeze.

14.5 Acoustic impacts

The Leading Edge prototype was assessed for acoustic impacts on the surrounding environment, with the two following key questions:

1. Are noise levels significantly elevated in the area outside the operation of the device?
2. Does the noise profile indicate potential for interference with hearing/performance of wildlife in the vicinity?

14.5.1 Methods

Two types of acoustic monitoring are typically undertaken in the vicinity of hydrokinetic energy projects. The first type is a hydroacoustic study in which acoustic detectors are used to detect presence, movements, and interactions of fish and other wildlife with the device. These may use split-beam transducers and/or hydrophones to detect and track the movements and behavior of aquatic wildlife (Verdant Power New York LLC 2010, Polagye et al. 2014, Johnson 2015). Ongoing flume and observational studies by the Leading Edge team are characterizing the extent of interaction of fish with the Leading Edge device, and therefore this type of acoustic measurement was deemed unnecessary for the prototype testing phase.

The second type is focused on understanding the underwater acoustic sound levels and sound profile characteristics of the device. These tend to use broadband hydrophones to measure sound pressure levels (SPL) of the device in three different ways:

- Near-field stationary – hydrophone is placed at the point of operation to evaluate dominant components of the noise profile and measure highest level impacts (Verdant Power New York LLC 2010)
- Far-field stationary – hydrophone is placed in one or several stationary locations at least twice the length of the device from the center of the device or array in order to be able to treat the device(s) as a point source (Verdant Power New York LLC 2010, Tougaard 2015)
- Far-field drifting – hydrophone is placed on a float or in a "drogue" that maintains specific depth positioning of the device and then allowed to float past the device/array from a distance far upstream to far downstream (Wilson et al. 2014). This eliminates broadband noise associated with water movement, which can interfere with stationary hydrophone positions, but is more complicated to control positional sampling and requires multiple units and/or multiple passes to

accurately characterize the noise levels along specific transects, as position of the instrument cannot be controlled to achieve spatially representative sampling.

After careful evaluation of the challenges of deploying acoustics equipment in the high-speed and turbulent currents at the MMA testing location, Volpe developed a sampling protocol to deploy a high-quality broadband hydrophone on the bottom of the canal, beneath the Leading Edge prototype. Just before the hydrophone was deployed, the Leading Edge prototype suffered a mechanical failure that required repair. Volpe had to return the rental hydrophone equipment without completing the planned acoustic measurements. As a backup, the Volpe team borrowed a teaching quality hydrophone (Cetacean Research sq26-h1b) from Professor James Miller at the University of Rhode Island. This hydrophone was used to complete some basic far-field monitoring of noise levels before the Joule was deployed and during select days of Joule testing (Figure 34).

On July 6th, 2016, several hours of acoustic data were collected prior to the deployment of Joule. The hydrophone was deployed at 1200 hours at slack tide and data were collected over an ebb tide (high tide was 4.2' at 1200 hours and low tide was 0.0' at 1850 hours). During the data collection, passing boats were logged and photographed during select time periods. The Cetacean Research hydrophone was deployed again on July 18th, 2016 when the rear device on the Joule was the operating. Acoustic data were recorded over an ebb tide (high tide was 3.3' at 0915 hours and low tide was 0.3' at 1630 hours). The hydrophone was deployed around 1000 hours during slack tide and removed around 1400 hours. For both time periods, the hydrophone was suspended approximately 2 feet below the water surface and was approximately 12 feet away from the nearest point on the adjacent Joule.

Figure 34. Photograph of the hydrophone mounting location.
The hydrophone was mounted on a pole to the back of the MMA barge between the pier and the Leading Edge prototype (the Joule), submerged ~1.5-2 feet below the surface of the water.

14.5.2 Data Analysis

Volpe analyzed the far-field acoustics data and used GoPro video data collected by the Leading Edge team as a proxy for near-field measurements, to evaluate the noise level and sound profile emitted by the device during operation. The second acoustic source was from an underwater video recording of the device while operating. Analysis consisted of: acoustic auditioning of data from both the hydrophone and audio extracted from the video recording in order to develop qualitative descriptions of the acoustic environment with and without the device installed; comparison of time signals and spectra from the hydrophone data; and comparison of noise sources from the audio extracted from the video recording.

Listening to the hydrophone recordings, the dominant sound, with and without the device present, is the sound of water lapping at the surface. This sound occurs often and in random patterns. During some measurement periods, passing boats were logged in the event log. The sound of the engines from these passing boats can also be heard in the hydrophone recordings. When the device is operating, mechanical sounds from the device can be faintly heard in the hydrophone recording. They are easiest to detect when the audio recording has been filtered with a 1000 Hz low pass filter. The sounds heard in the hydrophone recording are mostly due to the sound of loads changing on mechanical linkages in the device. Comparing the video to the audio recording confirms that the "clunking" sound heard faintly in the hydrophone recordings is due to changes in the loading of the device's linkages. Additional sound characteristics are also audible in this recording. These include: a tonal character that proceeds a "clunk" in each oscillation of the device and a "buzzing" sound that is relatively constant. When the device is not moving, the "buzzing" sound can still be heard. It is not known if the "buzzing" sound is due to a component of the device that continues to operate even when the linkages are motionless (such as the compressor used to keep the generator chamber dry), or if the "buzzing" sound is due to an external source. More detailed acoustics monitoring of various parts of the Joule was be required to identify its source.

The hydrophone was calibrated based on the specified sensitivity of -169 dB reference 1 V/micro-Pa[10]. Given that the sound pressure level (SPL) reference in water is 1 micro-Pa, this results in a gain of 1e-6 x $10^{(169/20)}$, approximately 281.8383, that needs to be applied to the recorder's input voltage in order to convert the measured signal from voltage to pascals. It should be noted that the recorder has an input gain that can range from 0 to 39 dB[11]. It is assumed that 0 gain was applied during the recordings, but the teaching quality hydrophone and audio-recorder may apply an automatic gain that could alter the recorded sound level by as much as 39 dB. For future monitoring during longer-term Leading Edge prototype testing, a scientific quality hydrophone will provide more accurate data.

14.5.3 Results

Hydrophone data analysis began by examining the time signals of time periods with and without the device. Figure 35 shows a sample of ambient noise with no identifiable anthropogenic noise sources. Figure 36 shows data from the same day with boat noise audible in the recording. Figure 37 shows data from a time period where the device was operating at about 17 rpm[12], or approximately 30% of full speed. Comparing these three time signatures, it is difficult to identify unique characteristics that would allow one to determine if the device were operating, in the absence of additional information. Overall, the device does not appear to elevate noise levels above the ambient conditions at the test location. The primary noise source in all cases during the peak tidal flow periods analyzed is the sound of water

[10] http://www.cetaceanresearch.com/hydrophones/sq26-h1b/index.html#
[11] https://www.zoom-na.com/products/field-video-recording/field-recording/zoom-h1-handy-recorder#specs
[12] Device speed was determined using data from the Leading Edge team.

movement. It is very challenging to separate sounds form the Joule from the water noise, as the speed of the tidal currents determines the speed of the device hydrofoil movement.

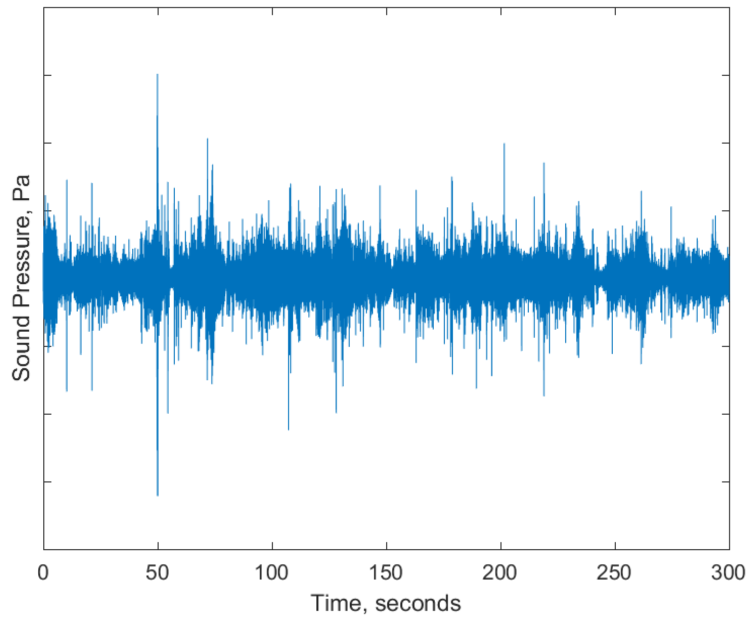


Figure 35. Sample time signature of hydrophone data without device in the water.

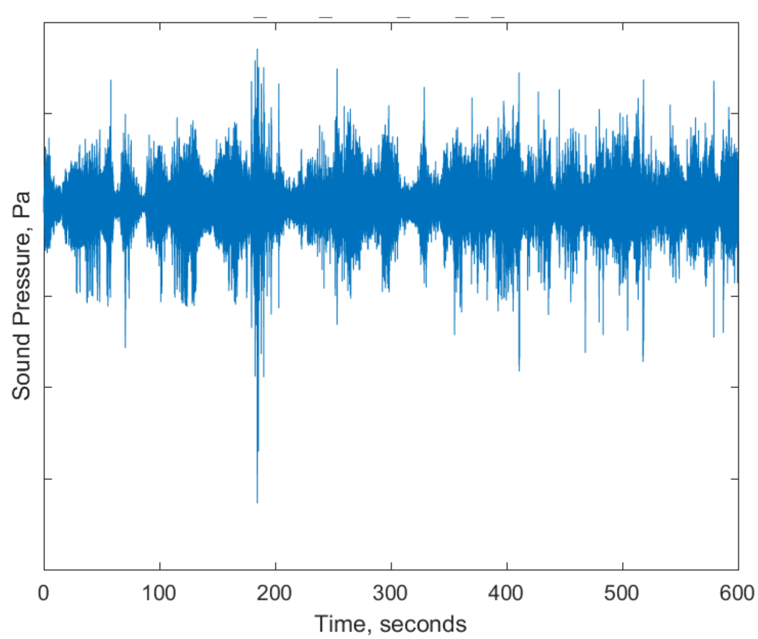


Figure 36. Sample time signature of hydrophone data without device in the water and boat noise audible.

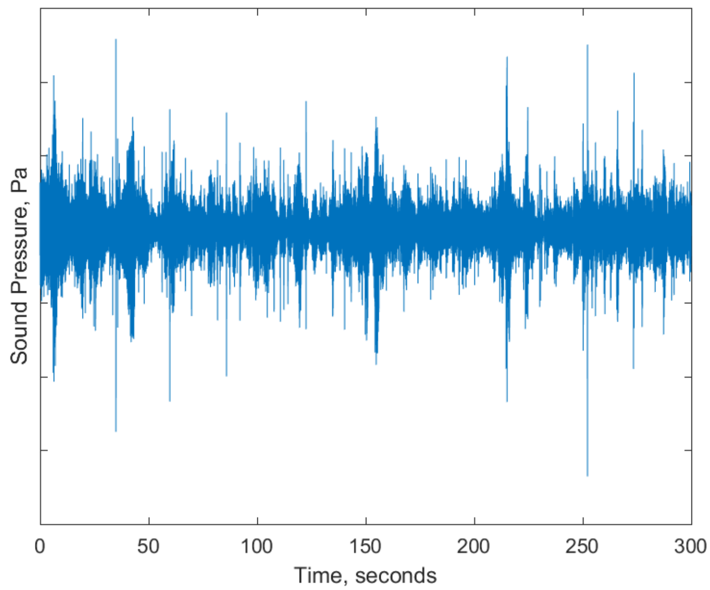


Figure 37. Sample time signature of hydrophone data with device in the water operating at approximately 17 rpm.

In order to provide the best opportunity to identify differences between ambient conditions and noise under device operating conditions, a spectral analysis was performed on samples with maximum water flow, in this case maximum ebb flow. Figure 38 shows this comparison. There is a slight offset between the two curves is observed across the entire spectrum, which may be due to differences in tidal current speeds on the two days, or to different automatic gains applied by the hydrophone recording equipment. Regardless of the offset, there is a peak for both the "with" and "without device" cases around 20 Hz. Because this is present in both cases it is most likely due solely to the ambient conditions even though the "with device" case has a more pronounced peak[13]. The overall profile of both are also similar with the exception of a slight negative bias for the "with device" case, which could be explained by the fact that the measurements occurred on different days. The most significant difference then is the presence of spectral peaks for the "with device" case between about 100 Hz and 1000 kHz. It is likely that these peaks represent a contribution to the acoustic environment due to the device. Additional analysis of other time periods of device activity were examined, including periods with different device speeds; however, although spectral peaks in this region were often observed, no consistent pattern was found. This may be due to poor signal-to-noise ratio, which could be improved by a different placement of the hydrophone, but it could also indicate that additional indicators may be needed, e.g. positional sensors to identify when the linkage loadings of the Joule device change as the hydrofoils move up and down.

[13] The two measurements occurred on different days, so even though both represent maximum ebb flow, it should be expected that the ambient contribution will vary somewhat from day to day.

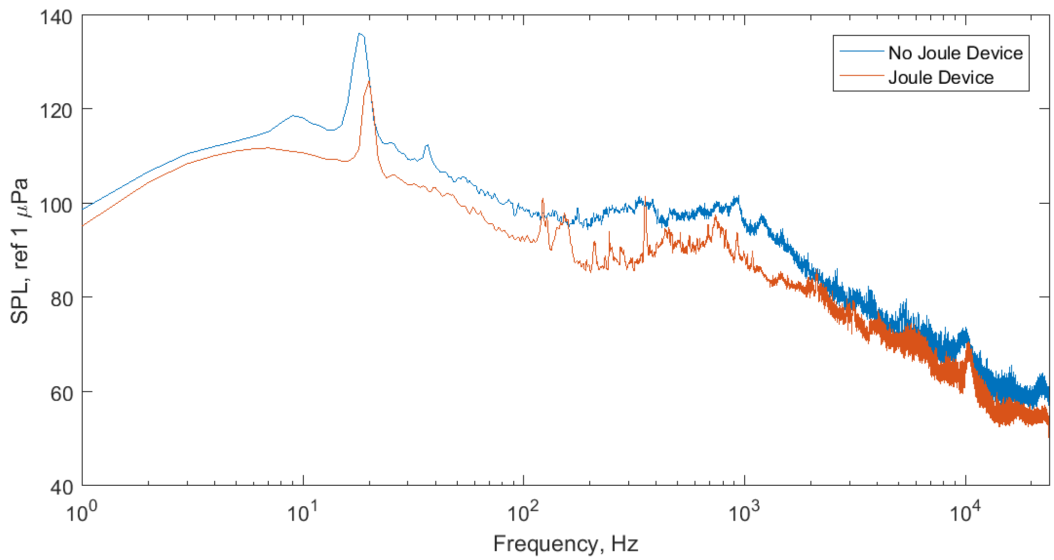


Figure 38. Comparison of acoustic character with and without the device.

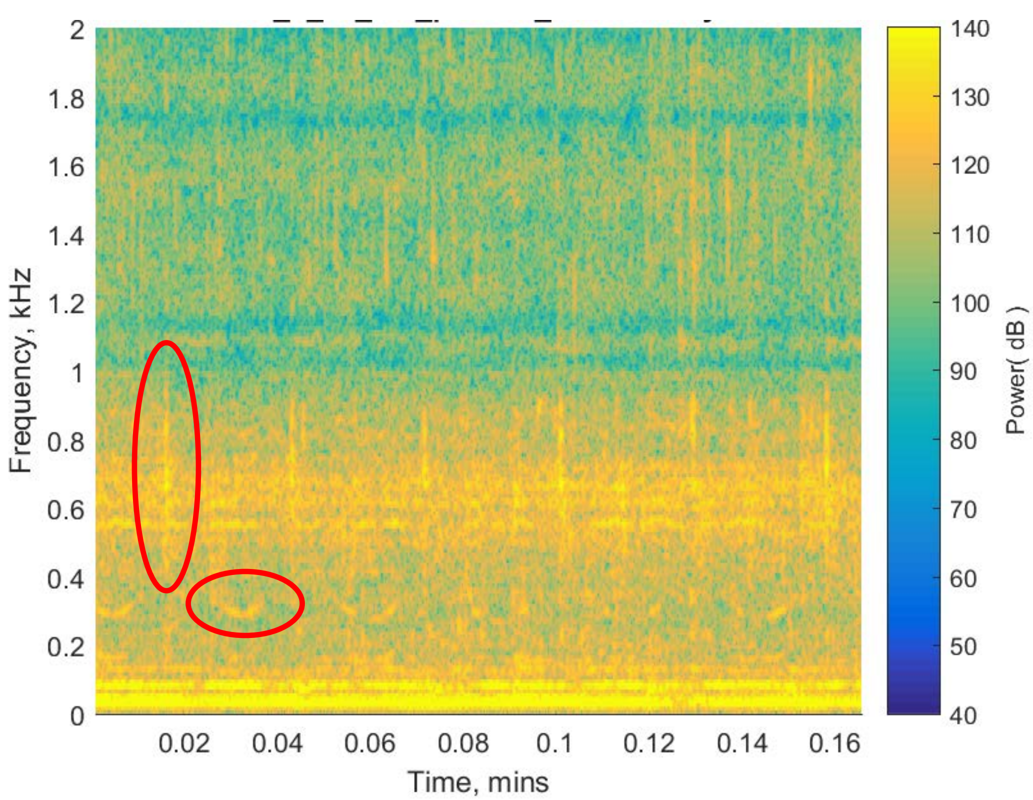


Figure 39. Spectrogram of device at moderate operating speeds.

Although the hydrophone provides long periods of calibrated data, it was difficult to correlate device sound events to specific characteristics in the analyzed data. This was due in part to the poor signal-to-noise ratio (water lapping compared to device operation) but also due in part because it was not clear exactly how the device was behaving at any particular moment[14]. The video footage, although not calibrated, did provide some additional clues. This was in part because its placement provided better signal-to-noise ratios, but also because one could see the stage of operation of the device when a particular sound such as the clunk attributed to changes in load linkages, or the tonal sounds observed. Figure 39 shows a spectrogram of the device under moderate activity. A vertical red ellipse indicates where a “clunk” occurred due the linkage loading. The horizontal red ellipse indicates where the tone that was heard proceeding the “clunk” occurred. This result indicates that with sufficiently clean measurements, device acoustic characteristics could be identified and monitored over longer testing periods.

14.5.4 Acoustic Measurements: Summary

The underwater acoustic impacts of the Leading Edge prototype were limited. Noise levels were not significantly elevated in the area outside the operation of the device. The noise profile does not indicate potential for interference with fish or other wildlife in the vicinity, according to the measurements made.

In order to obtain acoustic data that can be used to effectively monitor the device in future work, a higher quality hydrophone should be located closer to the device and further from the water’s surface or any other potentially contaminating sound sources. Most of the sounds observed were transient such as the “clunk” due to changes in the linkage loading and the tone that follows. A method to track the position of the devices linkages could be used to increase the correlation between device operation and acoustic environment. The linkage loading sounds heard during the testing of the Joule could be addressed with additional design features in future prototypes. Reducing these sounds where feasible would further decrease the overall impacts of the Leading Edge devices on the ambient acoustic environment.

15 Recommended longer-term testing research priorities

The Volpe team has identified research priorities for environmental measurements and evaluation during either future long-term testing of a full-scale Leading Edge device or initial commercialization efforts. These recommendations are described below and would provide additional baseline data that could be used in NEPA environmental impact analyses, permitting, or other environmental evaluations.

The Volpe team suggests two distinct but complementary approaches to research during future development and deployment of the Leading Edge device. The first option focuses on stationary device testing and would continue and expand on the prototype environmental studies with more data and using these to predict environmental impacts from scaled up devices or arrays. The second area of future environmental research focused on identifying screening criteria for project siting that would aid in future deployments of the device/array based on the final implementation strategy.

[14] Although device speed could be determined from the frequency data provided by the Leading Edge team, one could not determine what stage of operation was occurring at the same time as a particular sound.

15.1 Future Research Area 1: Continued and Expanded Device Measurement and Scale-up Impact Modeling

If longer-term testing is undertaken with individual devices or arrays that are placed *in situ* for several weeks to months at a time and include all elements of installation (e.g., transmission lines, etc.), it would be possible to collect key data to assess or predict impacts for particular environmental resources.

1) Continuing fish and other wildlife strike studies in situ

Based on the results of Dr. Dave Ellerby's team regarding fish interactions with the prototype device and the risk of wildlife strike, and depending on the environment in which future demonstration or commercial scale deployments occur, the Leading Edge Team should undertake additional data collection, including sonar and high-speed video monitoring of hydrofoil blades to identify if fish or other wildlife are attracted to the device and the likelihood of strike.

2) Biofouling / sessile organism colonization (continued)

A future stationary prototype or full-scale commercial device could be constructed with one or several surface materials/coatings that demonstrate reduced colonization. During stationary testing, surfaces would be visually evaluated for colonization periodically during testing and if feasible, by mass at the end-of-test device removal. In addition to these continuation studies, if longer-term installation is planned, further recommended experiments and analyses include period monitoring of biofouling growth using remote camera or diving operations, as well as data collection when device components are retrieved for maintenance or repair. These data would inform recommendations for the timing of maintenance cycles.

3) Noise

A fully installed testing device will enable more detailed measurements of noise during installation and operation to evaluate potential for impacts on wildlife, structures and soils, and humans near the installation. These data could be used to develop predictive models in combination with design data (e.g., motor specifications) for estimating sound levels associated with a scaled-up device or array. Measurements could include drifting hydrophone techniques to avoid interference from surface friction and turbulence around the measurement device and associated cables or moorings (Polagye et al. 2011b).

4) EMF

A fully installed testing device that includes transmission lines and other power generation and transmission elements would enable the measurement of EMF associated with main electromechanical systems of the hydrofoil, including hydrofoil arms and generator. EMF would be measured near device and along transmission lines at anticipated power levels. Similarly to the noise measurement, these data could be used to estimate EMF associated with a scaled up device and associated power generation and transmission based on design plans and components.

5) Installation and Operational Design Elements to Minimize Impacts

Experience with installation and operation will enable the team to identify improvement opportunities and employ and evaluate best practices, which can become part of the installation guidance and design for the fully scaled up device or array.

15.2 Future Research Area 2: Focus on Deployment Siting Criteria Development

Once more is known about the potential effects of the device and the device installation and design is finalized for commercial deployment, the identification of siting criteria that can be used as a screening approach to identify potential areas for installation would be a critical part of installation guidance and design.

Depending on final design, siting criteria can be developed that can be used along with engineering criteria to help minimize potential environmental risks of installation. Development of siting criteria for new projects can include identification or development of GIS layers that can be overlain to exclude certain sites and identify candidate sites that then could be screened in more detail.

The Volpe team envisions three potential screening levels to identify candidate locations.

i. Engineering / Design Requirements – These layers would identify potential sites based on purely technical criteria for installing the device or array, potentially including:
   a. Current/flow requirements
   b. Channel /site size requirements
   c. Depth requirements
   d. Topography, geology, and river bed conditions
   e. Census data
   f. Infrastructure requirements (utilities, access, etc.)
   g. Navigation activity level and/or vessel types in the area (e.g., estimated draw)
   h. Disputed territories
ii. General Environmental Risk Screening – The second phase of analysis would include GIS screening of critical impact areas that would affect consideration for hydrokinetic energy projects and for which screening-level (national or regional) mapped data are likely to be available, such as:
   a. Wild and Scenic Rivers
   b. Protected areas (e.g., marine sanctuaries)
   c. Biodiversity hot spots
   d. Tribal lands, recreational areas, parklands
   e. Known archaeological and historical resources
iii. Detailed Environmental Risk Screening – The third phase of analysis would evaluate particular sites (rather than a broad scale approach) and would focus on environmental considerations that may depend on specific details of the site and installation plan and would likely require State or local agency consultation to acquire appropriate data
   a. Endangered and threatened species (Federal and State)
   b. Critical habitats and migration pathways

c. Sediment contaminants and pollutant disturbance
d. Potential archaeological and historical resources

During further device development, it would be possible to develop screening tools to assess Phases i and ii depending on data availability at the national and regional level that provide appropriate levels of detail for project-specific conditions and requirements. Phase iii screening would most likely not be possible to prepare in advance of specific site identification but could be outlined in more detail. In addition to leveraging GIS to aid with site screening, additional criteria and methodologies could potentially be developed to facilitate rapid evaluation of new sites (e.g., list of key resources or agencies to consult, lists and instructions for key site evaluation diagnostics such as soil / sediment tests).

Note that this type of siting analysis would help identify candidate sites and reduce environmental risks, but it would not take the place of an appropriate NEPA analysis, permitting, and coordination with Federal, State, and local agencies with jurisdiction over the resources in the area.

16 Summary and Conclusions

In this report we assessed the potential environmental risks associated with the specific and unique Leading Edge hydrokinetic energy device. While a variety of potential risks exist, those highlighted herein include potential fish and other wildlife impacts, changes to currents that may affect sediment transport, nutrient cycling and flora and fauna in the benthic environment, potential effects on noise in the underwater environment, electromagnetic field effects, and chemical toxicity. The unique effects that might be associated with the Leading Edge hydrofoil technology were identified and summarized in Table 3, including the hydrofoil's unique potential placement (near the bottom of a river) and profile across the current (i.e., possibly spanning the entire width of a channel and/or greater energy extraction from the current). We include recommendations of design elements that could reduce environmental risk, including impact minimization approaches for the device design, installation setup, electricity transport lines, and array deployment (Table 4).

Section 9 provides a summary of the key requirements for the preparation of an environmental impact analysis document (Environmental Assessment or Environmental Impact Statement) under the National Environmental Policy Act, and provides some of the background information to draft the Affected Environment section of such documents. Well-designed siting criteria could include screening for a number of factors (e.g., Wild and Scenic Rivers, archaeological and historical resources, benthic conditions, endangered and threatened species, etc.) that would reduce the risks for those resources and minimize potential impacts overall.

Based on Volpe's analysis, the current design of the Leading Edge prototype presents similar or reduced environmental impacts compared with other hydrokinetic devices. While many impacts are similar, the reduced speed of the hydrofoil design may reduce risk of fish or other wildlife strike and reduce effects on water currents. The comparisons presented rely on the field testing for a subset of the potential environmental effects, namely current dynamics, noise, and chemical toxicity, and on comparisons with the overall design features of the Leading Edge prototype with comparable devices for other potential environmental effects.

Hydrokinetic devices which convert tidal or wave energy into electrical energy by definition all remove some amount of energy from the natural system. Such alterations of water currents are of environmental concern principally for how benthic habitats may be impacted. The field testing by the Volpe team showed that the Leading Edge prototype demonstrated small, but observable effects on the water flow in the very near-field vicinity of the hydrofoils. These effects consist of a slight slowing of the flow in the upper 2m for the ebb tides that were monitored during device operation, on the order of 0.25 m/s. This velocity reduction is less than the reductions of ca. 0.5 m/s in other hydrodynamic energy projects such as the Stingray (The Engineering Business Ltd. 2005), but greater than the velocity reduction of 0.05 m/s for the Muscaget Tidal Energy Project. While wave velocity reductions were only notable at upper levels of the channel, it is possible that a slight acceleration of the flow may be occurring beneath the device. The modest current reduction on the upper layers and acceleration below the prototype device together likely result in no substantial modification to sediment accretion. However, effects of marine renewable energy installations on sediment accretion are highly site-specific (Cada et al. 2007), and assessments of the Leading Edge would need to be made at each potential installation. If a full-scale version of the hydrofoil device is able to extract a more significant portion of the current and wave energy at a site, greater effects on bottom substrates and benthic habitats may be expected due to change in currents, waves, and water quality.

Submerged marine renewable energy installations such as the Leading Edge prototype all involve some increased underwater noise. Knowing the frequencies and magnitudes of sound produced by a device is important to assess the species-specific impacts. Marine mammals have the lowest threshold of sound detection (greatest sensitivity) at higher frequencies, around 10,000 Hz, while fish show lowest threshold at lower frequencies, near 500 Hz. The field testing conducted by the Volpe team found the stationary prototype tested showed quite limited acoustic impact at both high and low frequencies, with some indications of increased noise mostly between 100 and 1000 Hz, in the range of fish but not marine mammal sensitivities. However, the increased noise was minimal; while other hydrokinetic devices have maximum SPL of 75-143 dB re 1 μPa, the Leading Edge device showed SPL nearly equivalent to the background noise level. Given the field testing done, the acoustic impacts of the Leading Edge device are minimal.

Considering chemical toxicity, the Leading Edge prototype is likely similar to other technologies in the environmental impact. Any hydrokinetic energy installation needs to consider the growth of marine flora and fauna on surfaces; such biofouling it typically addressed by the application of anti-biofouling coatings. The materials used in Leading Edge prototype were similarly susceptible to biofouling, but anti-biofouling treatments with low environmental toxicity were highly effective at reducing accumulation of algal communities. Notably, for components made of aluminum, the anti-biofouling compound Trilux, which does not contain copper, was highly effective. For components made of fiberglass, any of the three treatments would achieve similar reductions in biofouling accumulation; the fewer total toxic components of International VC Offshore recommend it for use on fiberglass-substrate components.

Finally, collision or entanglement is a major concern for marine renewable energy installations, in particular with wind power installations potentially impacting bird life. All hydrokinetic devices which do not have an above water component avoid this impact (Inger et al. 2009). The lack of rotating turbines on the Leading Edge prototype will reduce marine animal impacts. However, the extent to which the Leading Edge prototype will require free-moving cables, chains, and power lines in the installation will present similar potential collision risks for marine organisms (Wilson et al. 2007).

Overall, the environmental measurements thus far suggest that for the prototype device with vessel-mounted, stationary deployment, current alteration and acoustic impacts are likely to be at the lower range of possible impacts compared with other underwater hydrokinetic energy devices, and that there are opportunities to enhance efficiency and reduce noise and current alterations. However, the final design, size, and installation techniques (e.g., single devices versus arrays) used for the commercial deployment of the Leading Edge device, as well as site-specific conditions related to current, sediment, and ambient sound, will determine how commercial installations affect current flows and acoustic conditions.

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18 Appendix A

Tidal Current Measurements in the Cape Cod Canal in support of Marine Hydrokinetic Energy Device Development

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Appendix A: Table of Contents

Introduction

This report presents observations of current flow during testing of Leading Edge/Brown University's marine hydrokinetic energy device, *Joule*. The purpose of the current measurements was to quantify both incoming and exit flow through the device for purposes of identifying effects on the native flow field. We provide details on the instrumentation: set-up, mounting, sampling parameters, as well as results of the data collection. Also included is an analysis of the observations and assessment of how the device may have affected flow characteristics.

Current measurements were collected from device-mounted Nortek Aquadopp acoustic Profilers from Wednesday, August 3 until late Thursday, August 4. The instruments were re-deployed with different sampling parameters again Friday August 5 for a simultaneous wake survey. The wake survey consisted of a vessel-mounted acoustic current meter measuring flow through several cross sections downstream of the device, as well as occupying two fixed stations, at consistent time intervals throughout the afternoon. These synoptic measurements provided a sense of the spatial variability of downstream flow. In total, data collection spanned four ebb cycles under a variety of conditions: both devices operating (Wednesday afternoon), one device operating (Thursday and Friday afternoons), and no devices operating (Thursday morning). These ebb cycles provided t opportunity to assess how the device may have affected the flow field.

Sample rates varied from 1-minute averages to short-burst 2 Hz high-frequency samples. Vertical surface-to-seabed profiles were recorded below the device in both the forward- and aft-looking directions. Horizontal profiles were recorded in the immediate wake of the device. Current profiles were gathered in both near-field and far-field regions of the device. In all, currents were sampled with reasonable spatial and temporal resolution under a variety of device operating conditions.

Several problems with the instrumentation were encountered, and while unfortunate, these problems did not seriously compromise the observations or conclusions drawn from the study.

The data set spanned just 3 ebb cycles when the device was operating – not enough observation cycles to make conclusive statements about device effects on the flow regime. Further, the native flow field is extremely turbulent and noisy itself, and so the data required significant smoothing to reduce measurement noise and clarify the underlying signal. Yet these brief observations suggest the *Joule* device may cause a slowing of flow in the upper layer where the device is located, about the upper 2m, and a corresponding acceleration of flow beneath the device. The flow effects appear to occur over short temporal and spatial scales, dissolving quickly in the otherwise-turbulent flow regime in the Canal.

Also included in this report is a description of preliminary tidal current measurements collected in the Canal during a brief time period in March-April 2016. The purpose of these measurements was to observe the ambient tidal flow characteristics in the vicinity of the testing area when no device was in place. These results are presented in the accompanying Appendix A located at the end of this report.

Fixed Sensor Measurements - Data Collection Chronology

The sensors were deployed on the *Joule* device during the first round of testing on Wednesday morning, August 03. They remained installed until the end of testing the following day, Thursday August 04, except for brief interruptions when the sensors were rotated out of the water for simple cleaning or maintenance. Gaps in the data set(s) occurred Wednesday from about 15:30 hours to 18:00 hours, and again Thursday at about 11:30 AM (for about 5 minutes) and again about 5 PM. This first data set was continuous other than these short interruptions.

The units were recovered following the Thursday afternoon ebb cycle, as planned, for data download. Both sensors were re-installed for the ebb tide cycle early Friday, August 5, to coincide with additional current data collection during the moving-vessel wake current survey. The units collected continuous current profile data Friday from 12:45 to 17:30 hours.

Four tidal ebb cycles were observed during this initial test phase. According to *Joule* test personnel notes, the MHK devices were operational for the first portion of the ebb cycle on Wednesday before a mechanical failure occurred to the forward device. [Note: there are two MHK devices on the *Joule* platform, a forward device and an aft device]. The forward device failed early in the Wednesday ebb cycle testing but remained in the water until recovery during the next slack tide. To the best of our knowledge, this forward device was not re-installed for the remainder of subsequent testing. The aft device was fully functional for both ebb cycles on Thursday and Friday. The devices were pulled from the water during the overnight ebb tide cycle early Thursday morning, so we able to collect data under a variety of conditions:

- Both devices operating (Wednesday afternoon ebb),
- One device operating (Thursday and Friday afternoon ebbs), and
- No devices operating (Thursday morning ebb).

These ebb cycles provide the best opportunity to assess how the device may have affected the flow field.

Description of Instrumentation and Installation Details

Nortek Aqaudopp acoustic Current Profilers (2 MHz) were fixed to the device to measure currents. These sensors provide profiles of velocity along each of its three directional acoustic beams (Figure 1).

Figure 1. Beam geometry of Aquadopp Profiler used during the tests (courtesy of nortek.com).

Each beam measures the flow velocity along the beam axis (i.e. in-and-out of the beam face). Beam velocities are positively valued for flow pointing in the direction of the beam; negatively valued when flow is running into the beam. The three beams are separated by 120° in the vertical plane; and angled 25° from the vertical axis. These 'beam' velocity measurements can be rotated into an orthogonal x-y-z coordinate system relative to the instrument axes (shown to the right) using the instrument's rotational matrix. Also, with knowledge of the instrument heading (compass) and tilt axes, the flow vectors can be rotated further into an earth-referenced coordinate system east-north-vertical.

In an attempt to measure a broader spatial region, we chose to orient the Aquadopp profiler at an angle (see Figure 2). Since the beams were angled 25° from the vertical axis, we mounted the unit at a 65° angle such that Beam 1 was horizontal and pointed directly into oncoming flow, providing a direct measure of velocity normal to the device. Beams 2 and 3 pointed downward at an oblique angle.

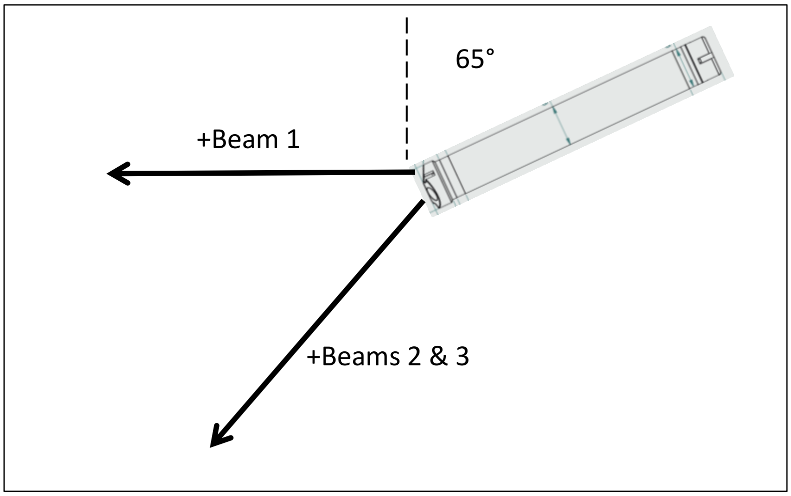


Figure 2: Orientation of the Aquadopp current profiler as installed. The instrument was tilted at a 65° angle such that Beam 1 (x-axis) pointed horizontally into the flow (or away from the flow depending on tidal phase). Beams 2 and 3 were pointed downward at compound, oblique angles. In this orientation Beam 1 provides a direct measure of the horizontal flow normal to the device.

The idea of this orientation was to provide both horizontal as well as vertical profiles, i.e. measurements downstream of the device as well as at sequential depths beneath the device. In theory, this would provide a broader region of measurement than simply a downward-looking or a side-looking configuration, providing measurements of the orthogonal velocity vector field : normal component of the flow (along the centerline of the device), as well as the tangential (i.e. cross-flow) and vertical velocity components. Since the combination of the three acoustic beams introduces spatial averaging – i.e. taking beam velocity measurements from three separate water volumes and combining to a single, centered measurement – the measurement of velocities along the horizontal beam provides a direct measure of the flow field at increasing ranges from the device.

The Aquadopps were mounted on vertical struts (see Figure 3) located on the bow and stern of the *Joule* device at a depth of about 0.76 m below the surface. One Aquadopp looked forward from the bow, or into oncoming flow, and the other unit looked aft, pointed in the direction of outgoing flow. The vertical struts were located along the centerline of the device. The mounting struts were rotated out of the water for instrument access, then reset into the water and locked into position.

Figure 3: The Aquadopp Profiler is shown (white arrow) strapped to the strut mounting bar on the bow of the *Joule* device. The strut was in the upright position at the time of this photograph – it was then rotated into the water such that the strut was oriented vertically, and the Aquadopp inclined at a 65° angle from the vertical.

Instrument Sampling, Problems, and Data Processing – Fixed Sensor Tests

The sampling program for this initial Wednesday-Thursday test consisted of data collection in beam coordinates, with a 10-second average recorded every 1 minute. The 10-second window occurred at the beginning of each minute (i.e. an average from :00 to :10 seconds every minute). This sampling mode is termed Averaging Mode. Bin spacing was set to 0.25m. The two instrument clocks were synchronized to local time (EDT) prior to deployment.

While the 1-minute average may resolve the general flow regime it would be insufficient to resolve any higher-frequency effects the *Joule* device might cause. So in addition to 1-minute samples, we programmed the Aquadopps to operate also in Burst Mode. Burst Mode allows for periodic rapid sampling and is usually done for wave measurements – in this case the sensor would sample/record beam velocities at 2 Hz for 17 minutes (2048 samples). Bursts occurred every 1 hour. This form of sampling was done to observe high-frequency response of flow to the devices when operating. However, the problem with Burst Mode sampling is the Aquadopp can only sample one mode at a time – either Burst Mode or Averaging Mode – it cannot operate in both modes simultaneously. Further, Burst Mode records only one range, not the multiple range bins that make up a vertical profile in Averaging Mode. So the resulting data files for this two-day time period consisted of 1-minute averages at 40 depth bins spaced 0.25m apart, interrupted every hour for 2 Hz sampling at only a single bin (located at a range of 0.64m). So the time series at distal bins have 17-minute gaps every hour. The range bin at 0.64m is continuous (after performing the same 1-minute averaging on the 2 Hz data).

The Aquadopps were scheduled to burst sample every hour, on the hour, for simultaneous data collection. The incoming flow sensor adhered to this schedule, with the burst occurring from :00 minutes to :17 minutes each hour. For an as-yet unexplained cause, the exit-flow sensor delayed each burst until :38 of each hour; the bursts were not synchronized. In hindsight, using Burst Mode was probably a poor decision because of the data gaps created in deeper range bins. Burst Mode was not used for the Friday survey.

A sensor problem was discovered during data processing, and which plagued both the Wednesday-Thursday data collection as well as the Friday survey data set. Beam 1 of the forward Aquadopp unit, the unit facing the oncoming ebb flow, did not operate properly. Velocity data were recorded for that beam, but upon inspection those data did not exceed the transducer noise floor. This was evident in the mean profiles of the Aquadopp echo amplitude presented as Figure 4, calculated from all valid vertical profiles recorded when the sensor was in the water. These data represent the echo amplitude, or loudness, of the returning acoustic signal used to calculate the Doppler shift. Normally, the signal is loudest in the near bins (i.e. close to the instrument) and decreases with increasing distance due to signal attenuation, scattering and absorption. A 'normal' curve looks like the left-hand traces – amplitudes of ~140 in the short range, and decreasing to ~30-40 counts at a range of 10m. The limit of usable data is at a range where the signal dips below about 30 counts, the sensor noise floor. The right-side plot of SN 039, the incoming flow sensor – show expected echo amplitude from beams 2 and 3, but beam 1 (blue trace) is ~25-30 counts. The beam basically recorded only noise, no signal, and the resulting data therefore invalid and unusable.

The same sensors were used for the Friday wake survey in the exact same mounting locations. The aft-facing Aquadopp Profiler – which operated normally the previous two days - showed a curious minima in mean velocity at a depth of 2 meters, along with a sharp increase in speed above 2 meters. This shape of the mean velocity curve was much different than previous results and so required investigation, specifically, the echo amplitude curves for this unit. Figure 5 presents vertical profiles of the Aquadopp signal strength for both instruments, the incoming instrument (SN 039, right-hand plot) and the exit sensor (SN 379, the left plot). Signal strength was quite low in the upper ranges, although still above the noise floor of 30 counts, rebounded to normal levels below 2m, then fell off in an expected manner at deeper ranges. Importantly, the echo amplitude was very low for bins 1 and 2, improved at bin 3, and was normal for bins 4 and below. This was extremely unusual behavior that was referred back to the manufacturer for explanation; their response: "Three of our experts in Norway have looked at your data, and unfortunately have no explanation for this strange behavior." This problem affected the upper 3 bins, which subsequently were treated with suspicion in the subsequent analysis. Data within bins 4 and below were valid.

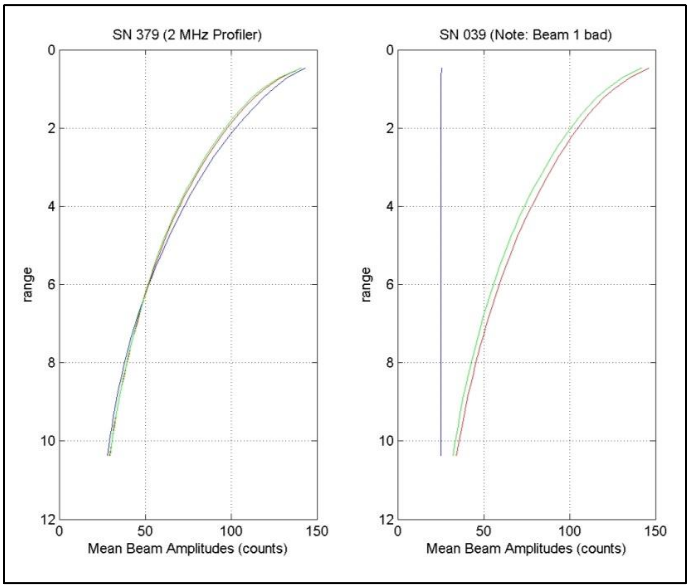


Figure 4: Mean echo amplitude for both Aquadopp Profilers for the Wednesday-Thursday ebb tides. The left curves represent the exit sensor, the right the incoming flow sensor. The blue trace is beam 1.

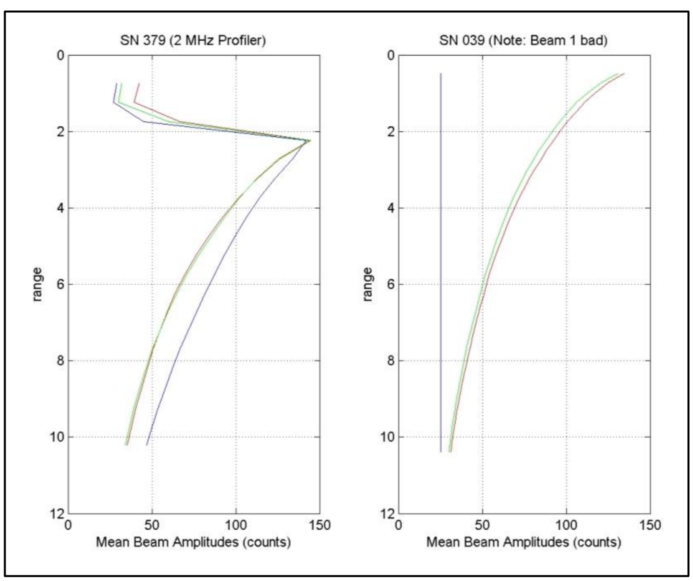


Figure 5: Echo amplitude signals for each of the three beams for the Friday ebb tide during the wake survey. The left-hand plot shows echo amplitude for SN 379 – facing aft and measuring downstream flow. The right-hand plot represents SN 039, measuring the incoming flow.

Our intent was to use the horizontal beam 1 to provide measurement of the incoming flow out to 10m in front of the device. Fortunately, of the two Aquadopps, it was far more important to measure the downstream horizontal profile than the incoming horizontal profile. So we did not utilize the incoming horizontal profile in any analysis. Instead, incoming horizontal velocities were derived using only beams 2 and beam 3, which were facing forward/downward into the flow, and result from the projection of horizontal (and vertical) flow onto those beam axes.

For the aft-facing Aquadopp Profiler, beam data were transformed from instrument beam coordinates to a coordinate system relative to the *Joule* device – velocities normal to the device , i.e. flowing between the pontoons down the centerline of the barge, tangential to the device (or cross-flow) and vertical. Some averaging of the Aquadopp data was performed for certain graphics, especially when attempting to compare velocities obtained during the survey to velocities obtained the previous few days (which were 1-minute averages). We note the averaging interval used for each set of graphics. We also calculated mean profiles over longer time scales, for example over the course of peak ebb tide (about 2.7 hours), to better compare flow behavior for successive tide phases.

Description of Wake Survey – August 05, 2016

The intent of the wake survey was to measure the downstream flow effects of the *Joule* device. Measuring vertical velocity profiles at several downstream locations throughout a portion of a tidal cycle would determine how velocity varies with increasing downstream distance. To determine the spatial extent of such effects, two measurements of current velocity were made simultaneously. A moving-vessel survey was conducted in conjunction with fixed, Aquadopp Profilers attached to the pontoon barge in the same manner as the August 03-04 data collection described previously.

The moving boat survey used a Teledyne/RDI ADCP (RiverRay 600 kHz acoustic Doppler current profiler) and GPS (Leica) mounted on a 27' Parker outboard. The ADCP was mounted to a rigid pole, looking downward, along the starboard side of the vessel, and programmed to record a vertical profile every 1 second. The vertical resolution of each profile was set to 0.25m. A GPS antenna was fixed to the top of the pole, also recording every second, to geo-locate the position of each vertical current profile. Both the ADCP and GPS signals were cabled back to the laptop PC running TRDI's proprietary WinRiver II data acquisition and display software. The RiverRay ADCP was configured with the 'Bottom Track' feature. Bottom track allows the ADCP to bounce a separate acoustic ping off the seabed to measure the speed of the vessel over ground. Assuming the seabed is stationary, this bottom track velocity is then used to correct the velocity profile for speed of the vessel (sensor) itself. Bottom track methods are superior to GPS fixes to correct for vessel motion.

The survey was designed to repeat transects downstream of the device during the afternoon ebb tide when the device was operational. ADCP data collection occurred from 14:48 to 17:20 hours. Three (3) transect lines were run cross-current, and located at increasing distances downstream – nominal distances behind the pontoon barge were ~8m, ~20m, and ~30m. The exact distance downstream would vary slightly, but were as precise as boat-handling conditions would allow. The same three lines were repeated about every ~15-20 minutes throughout the tide. The three transects were performed in immediate succession – which together formed a single transect cycle. Each cycle was run in the same order, closest line first and furthest line last. Each line began near the canal shipping lane and proceeded towards the MMA pier face. Thirteen (13) cycles were completed in total. Despite technical issues that delayed the start of the survey, data from every line were recorded successfully.

In addition to the moving transects, the vessel also occupied two fixed stations centered behind the device – distanced approximately 8m and 16m, respectively. The near-field station was recorded first followed immediate by occupation of the far-field station. Profiles were recorded for approximately 2 minutes each, a sufficient duration to calculate a reasonable average profile. Five (5) sets of stations were performed during the survey.

Note that the approximate position of the pontoon barge was recorded during the survey so the collected ADCP profiles could be geo-referenced relative to the device.

Prior to the survey, Nortek Aquadopp Profilers were again mounted to the *Joule* test device in the same manner as described in Section 1, i.e. both forward and aft-facing, at a 65° angle from the vertical at a nominal depth of 0.76m. For this survey the Aquadopps were programmed to record profiles at 1 Hz. The data record was continuous; wave data bursts were not collected. The Aquadopp was removed at the completion of the survey, and after the *Joule* device was removed from the water for the evening.

Sea conditions during the survey were challenging for several reasons. The primary reason was the presence of tugboats along the MMA pier (see Figure 6). Tugboats tied up along the pier prevented the ADCP vessel from measuring more than about 30-35m behind the *Joule* device. In addition, docking lines used to keep the *Joule* in place also prevented the vessel from approaching too close to the pontoon barge. Lastly, canal vessel traffic created –at times – significant standing waves along the MMA pier face, which made navigating close to the pier/tugboat/pontoon barge particularly challenging. Fortunately there were no collisions or other unintended contact. From a data quality perspective, the standing waves created in the survey region also caused significant sensor motion. This sensor motion cannot be distinguished from real geophysical turbulence in the data record, and so added additional noise to the data set. In this already-turbulent environment, this added noise was not helpful.

Figure 6: The MMA pier and *Joule* test device (far right side of the photo) on the day of the survey. Note the tugboat docked along the pier to the left of the photo, about 35-40 meters downstream of the pontoon barge (for scale, the pontoon barge is 35 feet in length). The dock lines, tugboats, and standing waves due to passing vessel wakes made it challenging to get close to the device without risk of collision. In the foreground is the GPS antenna.

Survey Data Processing

ADCP data processing consisted of organizing and displaying the survey data. Each transect was recorded as a single data file, and so the data files had to be grouped according each respective cycle. The ADCP data were read from native TRDI file formats into Matlab, along with GPS latitude/longitude positions.

Latitude/Longitude pairs were transformed into UTM northing-easting pairs (for convenience in plotting). To aid in visualizing the flow vectors relative to the device – a map was developed with the position of pontoon barge overlaid (along with the MMA pier wall) with the flow vectors for each cycle.

Since single ADCP profiles are instantaneous, and therefore quite noisy (erratic), we averaged the velocity data as minimally as possible to reduce this noise but still retain some semblance of true flow variability. For the synoptic vector maps, all bins above 5m were averaged together, as were every 6 profiles along the survey transect. This degree of averaging produced reasonably neat graphics; otherwise the graphics results were deemed too confusing for presentation when averaging fewer profiles or a thinner vertical layer.

As a note on data quality: there were many individual profiles measured where the data were invalid, likely due to loss of bottom track or possibly fish interference. When bottom track is lost, the cause can be as simple as excessive vessel pitching/rolling, or values outside of pre-programmed threshold due to moving objects along the bottom, it invalidates the entire profile. These profiles were discarded from further consideration.

Discussion

The intent of the measurement program was to compare incoming flow to exiting flow – this approach was presumed to be the most direct method of evaluating the effect of the *Joule* device. We present the collected data in numerous different formats at the end of this report to illustrate flow field variability during the tests: time series comparisons, calculation of mean flow(s), spectral analysis, geo-referenced flow vectors, as well as three-dimensional contours. Each of these graphics formats offers a different perspective, the sum of which we hope provides some understanding of *Joule* device effects.

Direct comparisons are presented using the 1-minute averaged time series. Figures 10 through 14 compare time series of the normal, tangential (cross-flow), and vertical velocity components for both the incoming and outgoing flow vectors from Wednesday noon to late Thursday afternoon. This time period encompassed the three ebb tide cycles when the either both devices were operating (first ebb cycle Wednesday afternoon), only one device was operating (Thursday afternoon), or no devices were operating (early Thursday morning). Each figure represents one discrete depth from 1.2m below the surface to 6.5m below the surface. Note the data gaps due to interruptions when the sensor switched to Burst Mode for high-frequency sampling (again, Burst Mode collects high frequency data at a 1.2m only, no profiles are collected).

Figure 10 compares velocity at a depth of 1.2m below the water surface. There are a few noticeable differences in the normal flow components, particularly during the onset of the first ebb cycle Wednesday afternoon, as well as smaller differences occurring during the onset of the Thursday afternoon ebb. Incoming velocities of ~2 m/s slowed to ~1 m/s on the exit side for a short period of time Wednesday; this was when both devices were in the water and operating, prior to the forward device failure. Differences appear less pronounced during the Thursday afternoon ebb cycle. The vertical velocity components differ on Wednesday also. During the onset of the ebb, incoming vertical velocities are negative (downward), perhaps flow subduction due to the presence of the forward device. In contrast, the exit vertical velocity is upward during this initial onset of the tide, when the normal components differed the most, and then turned negative (downward). Failure of the forward device during the Wednesday ebb appeared to occur when the vertical exit component turned negative and the differences between the normal components vanished. We note further that differences between the incoming and exit flow seemed to disappear at a depth of 2m and below (Figures 12-14).

We compared the differences between the incoming and exit velocity components at this upper depth with the other ebb cycles – noting smaller differences Thursday afternoon (one device operating) and zero differences Thursday morning (no device operating). We also note very little differences in velocity during the opposite-running flood tides – also when no devices were installed.

We also present a time series comparison of the raw beam velocities at the 1.2 m depth (Figure 15), comparing the starboard and port-side beams (i.e. beam 2 of the incoming sensor matches up with beam 3 of the exit sensor, and vice versa). These data are direct measurements and have no dependence on any coordinate transformation. There are similar – albeit small - differences between the incoming/exit flow during the onset of the Wednesday afternoon and the Thursday afternoon ebb.

Color-contoured panels of the normal velocity profiles are presented as Figures 16 through 18, one panel for each of the ebb tide cycles. The broad swaths of white space represent temporal gaps in profiling during the wave bursts (we said Burst Mode was probably not a good decision!). These color contours present the entire flow field in the terms of depth (vertical axis) and time (horizontal axis). Color represents the magnitude of the flow, with deep reds/orange the strongest velocity and dark blue the weakest flow. Again, Figure 16 shows some differences at the early onset of the Wednesday ebb, when both devices were installed, but only in the very upper layers, above about 2 meters. No significant differences in the flow were observed at depth. Figure 17 shows the Thursday morning ebb – when no device was in the water operating - both incoming and exit flows appear equivalent. Small differences were noted again for the Thursday afternoon ebb (Figure 18), mostly at the surface. We also observed modest strengthening in the deeper exit flow, below about 3m, versus the incoming side.

These figures show some flow differences during the Wednesday and Thursday afternoon ebb cycles; but not much difference during the early Thursday morning ebb cycle. Differences were greater for the Wednesday ebb – when two devices were operating for a time, and less so for the Thursday ebb when only one device was in the water. The differences tend to wash out in deeper layers, suggesting flow disturbances may be most significant in the immediate upper layers of the water column and closest to the device, but appear to decay rapidly with depth beneath the device. Mean velocities calculated over each ebb cycle were also compared to assess the general flow characteristics (Figure 7 below). The calculation was performed over an approximate 2.7-hour time period surrounding the peak velocity. The *Joule* device operated during all afternoon ebbs, but was not in the water during the Thursday morning tide. There was a small difference in the mean velocity Wednesday afternoon, most notably above the 2m depth. Deeper flows appeared equivalent. The Thursday morning tide – when no devices were present – showed near equivalence of the incoming and exiting flows. The mean profiles varied considerably for the Thursday Friday afternoon ebbs. Above 2m the exit flow slowed relative to the incoming flow, but appeared to be stronger below this depth.

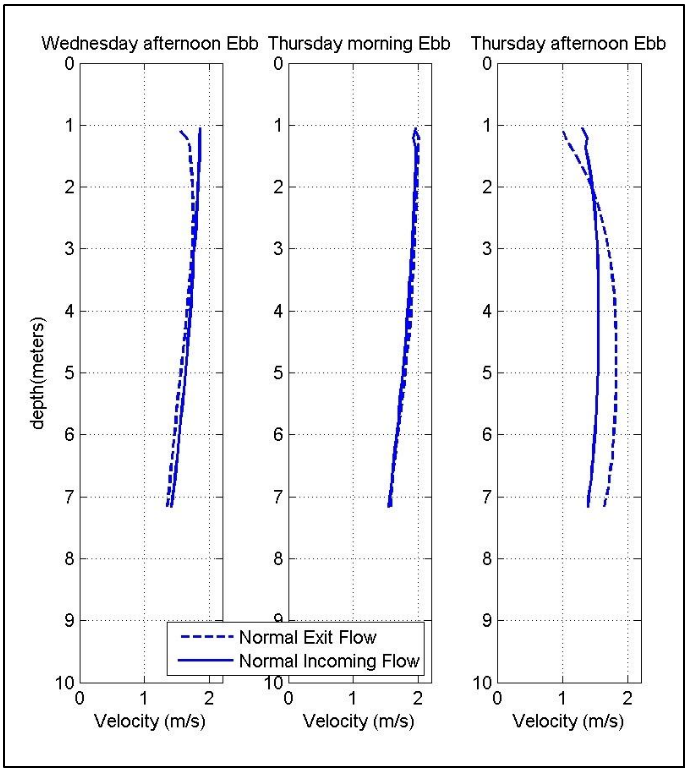


Figure7: Mean normal velocity profiles during peak ebb tides Wednesday afternoon to Thursday afternoon comparing the incoming flow (solid line) to the exit flow (dashed line). The 2m depth seems a critical depth signaling transition of the flow.

Since only a few ebb cycles were measured during these tests, and the variability between cycles difficult to grasp with such thin evidence, we include here a repeat of baseline results gathered in March 2016. These measurements were obtained with a similar Aquadopp profiler installed about 10m outboard of the MMA pier (see Appendix A). These profiles also showed significant cycle-to-cycle variability (Figure 8). At the time, our assessment was that changes in surface wind intensity – calm days versus windy days – increases the surface wind stress and altered the shape of the mean velocity profile. Westerly surface winds blowing opposite the ebb flow weaken near-surface velocity and strengthen deeper velocities. The different shapes of the velocity curve for the Thursday and Friday afternoon ebbs appears similar to profiles measured previously during strong winds.

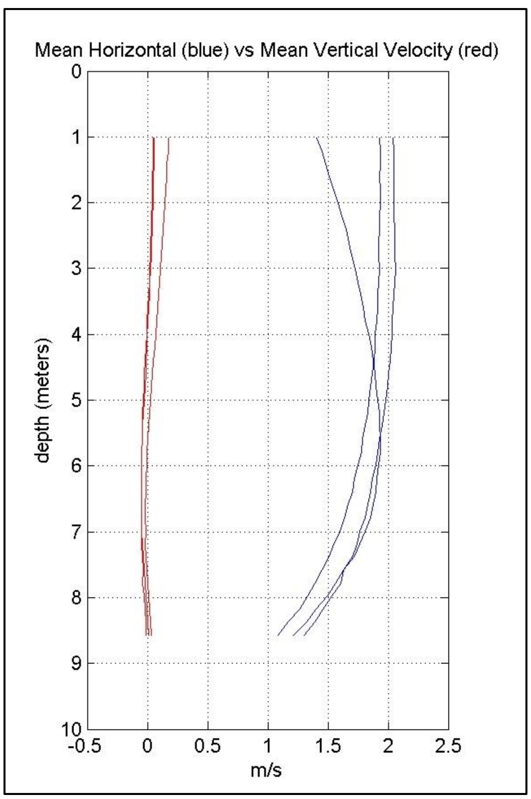


Figure 8: Vertical profiles of mean horizontal velocity (blue) and mean vertical velocity (red) for the three ebb tides measured in March 2016. These mean profiles were calculated over a 200-minute duration at the time of peak velocity.

We must comment on velocity noise levels and overall turbulence. The Cape Cod Canal flow regime is extremely turbulent, especially close to shoreline structures such as the MMA pier where the testing was conducted. Turbulence causes quite erratic and noisy velocity measurements. By noise, we refer to the signal processing definition: any unwanted static or uncertainty that interferes with or obfuscates the underlying signal. The way to reduce noise is to average over longer periods of time, longer than 1 minute, but this noise-reduction technique is counterproductive to the goals of this particular project. Here we want to assess how the device affects flow. We suspect those effects would be at time scales of the MHK device motions, time scales of ~seconds. So averaging across these motion time scales – in an effort to reduce uncertainty - loses any hope of quantifying the device effects. In other words, the genuine turbulence that exists naturally in the Cape Cod Canal – and resulting noise contained the measured signal – may be on the same scale (or greater) as the device effects.

The high-frequency velocity measurements obtained during hourly wave bursts were processed statistically to determine spectral energy content. Wave bursts were collected for the Wednesday and Thursday tests: 2048 samples at 2 Hz (the fastest the Aquadopp can operate). Four hourly velocity spectra were plotted around the time of each peak ebb cycle (Figures 19 through 21). These spectra show that when the device was out of the water –early Thursday morning –little energy was present. But when the device was in the water and operating, the spectral energy levels increased noticeably, especially for the exit flow device (blue line). Again, this is hardly conclusive given only one ebb tide when the device was not operating. Differences could be due to the local wave climate also – calm at night but more energetic due to afternoon sea breezes (especially in Buzzards Bay). There does not appear to be any preferred frequency, so we suspect that perhaps the signals sampled at 2 Hz was not fast enough to prevent signal aliasing and folding that high-frequency energy into false bands of the resulting spectrum. Sampling at a faster rate – say 10 Hz - may provide better results.

Fixed-sensor Aquadopp measurements of the Friday afternoon ebb began about 12:45. The intensity of the tide increased through the early afternoon (Figure 22); peak speeds were reached between about 2-2:30 PM (1400-1430 hours). Incoming speeds at the surface were about 1.75 m/s. The tide gradually waned throughout the afternoon, falling to 1 m/s by 1530 hours and 0.75 m/s by 1700 hours. We are not certain when the device began operating but the data suggests the device began operating (or was at least in the water) by about 1315 hours that afternoon. While both velocities were equivalent prior to ~1315 hours, after this time the signals diverged – incoming velocities were higher than the exit velocity, at least at this upper depth, while vertical and tangential components also diverged.

The spatial flow vectors in the upper layer measured by the mobile ADCP (Figure 23) provide synoptic visualization of the flow field. Recall that to improve the visual display we averaged every 6 profiles along the transect and within the upper 5m of the water column. These observations show flow vectors close to the pier were weaker relative to current vectors measured closer to the main channel. Previous measurements with a horizontal H-ADCP made in March indicated the same – friction along the pier slowed currents, but this frictional effect faded closer to mid-channel. The same appears to hold here – during the ebb tide slower currents were observed between the barge and (downstream) tugboat relative to flow vectors closer to mid-channel. We also noticed a slowing of flow immediately downstream of the device; vectors were weaker behind the device relative to vectors further downstream. This was especially true for survey cycles 7, 8, 10, and 12 which occurred as the tide was waning.

The fixed station profiles (Figures 24 to 28) showed good agreement between the two fixed station locations, both speed and direction throughout the water column appeared similar. This suggests no discernible flow differences existed over that downstream distance interval. It is interesting that flows were weaker at the surface than at depth. Peak speeds in the uppermost bins, about 1-2m deep, had magnitudes of order ~1-1.2 m/s at peak tide (see Stations 17-18, Figure 24). Speeds below 5m had magnitudes of order ~2 m/s. Also plotted on these profiles are velocity measurements obtained from the Aquadopp profilers. The Aquadopp data were averaged over the same time increment as the fixed station profiles. These data showed relatively weaker flow at the surface and stronger flow in deeper layers. Weakening of the surface flow may have been due to the presence of the *Joule* device. If the *Joule* device presented a flow obstruction, one might expect localized flow acceleration above, below and/or around the obstruction. In the absence of obstructions, such as observations obtained last March when no device was present, the vertical profile showed stronger flow in the upper layers relative to deeper layers. So these fixed station profiles do suggest some effect of the device on the downstream flow.

The mean downstream velocities were calculated and presented in Figure 29. These mean profiles resulted from the horizontal-looking beam 1 of the Aquadopp Profiler mounted on the exit side of the device, with the means corresponding to the 2.7-hour window during the time of peak ebb velocity. These velocity measurements were centered at a depth of 0.76m, so measuring the very upper layer. These downstream profiles show a relative minimum speeds nearest the device (a range of 0.6m) accelerating to a relative maximum about 5-7m downstream, then weakening at ranges out to 10m. The profiles are reasonably similar in shape for all ebb tides. Velocities observed during the Thursday morning ebb, when no devices were installed, were by far the strongest speeds measured at nearly 2 m/s. The Thursday and Friday afternoon tides were the weakest, less than 1.2-1.3 m/s. These mean downstream profiles suggest the near-surface velocities vary in the downstream direction. Whether this downstream variability was due to the device or other factors is unclear.

We return to mean depth profile of the downstream-looking Aquadopp. Figure 9 shows the mean velocity profiles for the Friday afternoon ebb tide. The incoming tide (solid line) shows an expected result – strong currents in the upper layers with a slight weakening with depth. However, the exit flow denoted by the dash line showed a strange inflection at the 2m depth level, the depth of the slowest currents. Current speeds increased above 2 m and in deeper layers. In fact, if correct, this suggests that currents on the exit side of the device, above about 1.5m and below about 3.5m, were faster than the incoming flow. We consider these results with some skepticism. Recall also the echo amplitude profiles of Figure 5. Bins 1 to 3 were lower than usual, just above the noise level, but bin 4 had an expected signal of ~140 counts, suggesting reasonably good data quality. Yet velocity magnitude for bin 4– where the inflection point is located - was significantly less than adjacent bins. The observation of slower currents in the upper layer – see Figure 29 which shows mean currents at 0.76m were ~0.9 m/s during the Friday ebb – is evidence that flow near the surface is less than flow at depth, thus we conclude data quality for these upper 3 bins is suspect.

Color-contour plots of the Aquadopp (at the original 1-second sample interval) were created to compare the normal (horizontal) velocities during the survey (Figure 30) in three-dimensional format. It shows a horizontal band of slower flow about 2m deep, which we deem good quality data, with accelerated flow below. This horizontal band was not noticeable before about 1300 hours, and became wider as the ebb tide slowed. This plot of the incoming and exit velocities suggests flow obstruction in the upper 2m. This obstruction may have caused localized flow acceleration below the device.

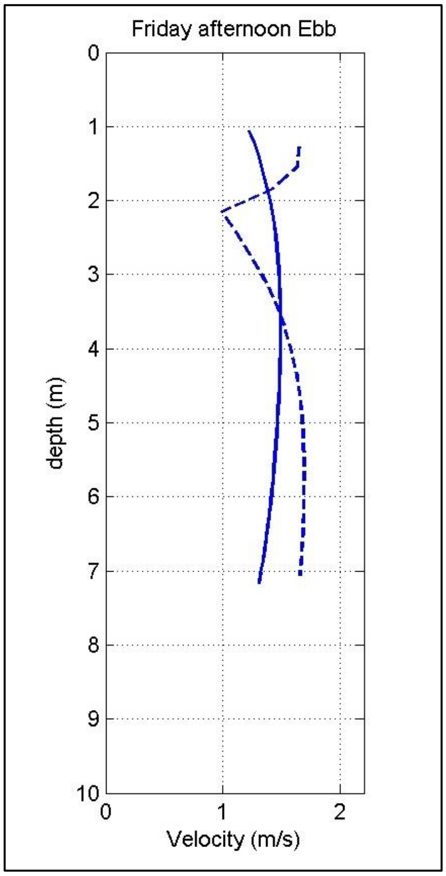


Figure 9: Mean velocity profile for the incoming flow (solid line) versus the exit flow (dashed line) during the Friday ebb tide. These averages were computed for an approximate 2.7-hour period surrounding the time of peak flow. The strange inflection point at 2m happens to be the approximate depth of the *Joule* device.

We also looked at the moving survey transects, particularly transect lines running close to the device. If indeed the device was causing some flow disturbance, perhaps it would be evident when looking at cross-sections of velocity as the survey boat moved from mid-channel, where currents would be unobstructed, to near the device, where some obstruction was suspected. So similar color-contoured plots were produced of selected transects to investigate if this were the case (Figure 31). For this figure, instead of plotting time across the horizontal axis these plots use distance as the x-axis. Essentially, the colors represent a cross section of surface-to-seafloor downstream velocity variability from the pier out toward the Canal channel. The left side of the contour plot is flow nearest the pier; the right side contours represent flow closer to the Canal channel. Notice that in each contour plot a patch of light blue (weak flow of ~1 m/s) is present in the upper left corner, evidence of weaker currents found in the upper layer close to the pier (as close as the ADCP could get given the obstacles). There are also deeper reds (strong flow of ~2+ m/s) toward the right-hand side of the plot, showing that currents well outboard of the device were much stronger. Weaker flow in the upper layer near the device suggests also some sort of flow obstruction near the surface.

So what does this flow obstruction actually look like? We plot the individual range bins comparing the incoming flow to the exit flow during the survey (Figure 32). For the incoming flow (the upper plot), we saw velocities in the upper 6 range bins were quite similar – not much variability from 1.2m deep to 2.8m deep. Incoming velocities appeared to be roughly equivalent in these depth ranges. In contrast, exit flows at the same depths were quite disparate. Bins 1 and 2 (the blue solid and dashed lines) were almost identical. Bin 3 (solid red) began to weaken slightly. However, velocity in Bin 4 – where the echo amplitude levels were in normal range and indicative of valid data - was much weaker than the upper 3 bins. Velocities in Bins 5 and 6 began to increase gradually from the local minima at Bin 4. We already determined that velocities in the upper 3 bins were suspect, but from bin 4 and deeper velocities were valid. Bin 4 represents slowed flow, likely due to device obstruction.

Looking further at Figure 32, we see that the incoming and exit velocities were similar at the start of the ebb tide, before 1300 hours. This may have been because the *Joule* device was out of the water, therefore no obstruction. We suspect the *Joule* device was deployed sometime around 1315 hours as the tide increased, and about the time that the exit velocity signals begin to diverge, suggesting presence of an obstruction.

In summary, observations from both the fixed Aquadopp sensors and the two independent current meters used during the wake survey suggests the device has small, but observable affects the flow field in the very near-field vicinity of the *Joule* foils. These effects consist of a slight slowing of the flow in the very upper layer – roughly the upper 2m – for the ebb tides that were monitored during device operation. This slowing of the flow in the upper layer may also result in a slight acceleration of flow beneath the device. Accelerated flow in the lower layers was observed during the wake survey as far as 16-22m downstream, which was as far downstream as could be measured due to the presence of docked tugboats in the test vicinity. The downstream horizontal profiles, as well as the fixed station profiles, suggest downstream flow may be slowed relative to flow in deeper layers and flow away from the pier nearer the shipping channel. Keep in mind however that there were other objects in the vicinity such as tugboats, the MMA pontoon barge, and the *Joule* test pontoon barge, that may also cause flow disturbances independent of the *Joule* device. Statistically, we compared velocity spectra for the three ebb tides and noticed increased spectral energy for wave bursts when the device was operating versus significantly decreased energy when the device was not in the water. Three ebb cycles are insufficient to conclude that the device caused such differences, as such differences may have resulted simply from calmer wave conditions during the Thursday morning ebb tide.

For context, these effects appear similar to previous flow measurements behind the tugboats along the MMA pier this past March when *Joule* was not present – weaker flow in the upper-layer with a corresponding increase in flow speed below the tugboat hull. We suspect the downstream effects on the flow would be similar had the *Joule* device been simply a boat or other floating object docked along the pier. Further, we also observed that westerly winds can also affect the mean current profiles in a similar way – a slowing of near-surface currents and corresponding increase in deeper flow. So to the extent *Joule* may have affected the flow field, and these effects appeared small and over short spatial scales, they were no greater or more significant than what may result from other watercraft or even a strong breeze.

Fixed Sensor Graphics

August 3-4, 2016

Current Profile Sample Rate: 1 minute
17-minute Wave Bursts every 1 hour (2048 samples at 2 Hz)

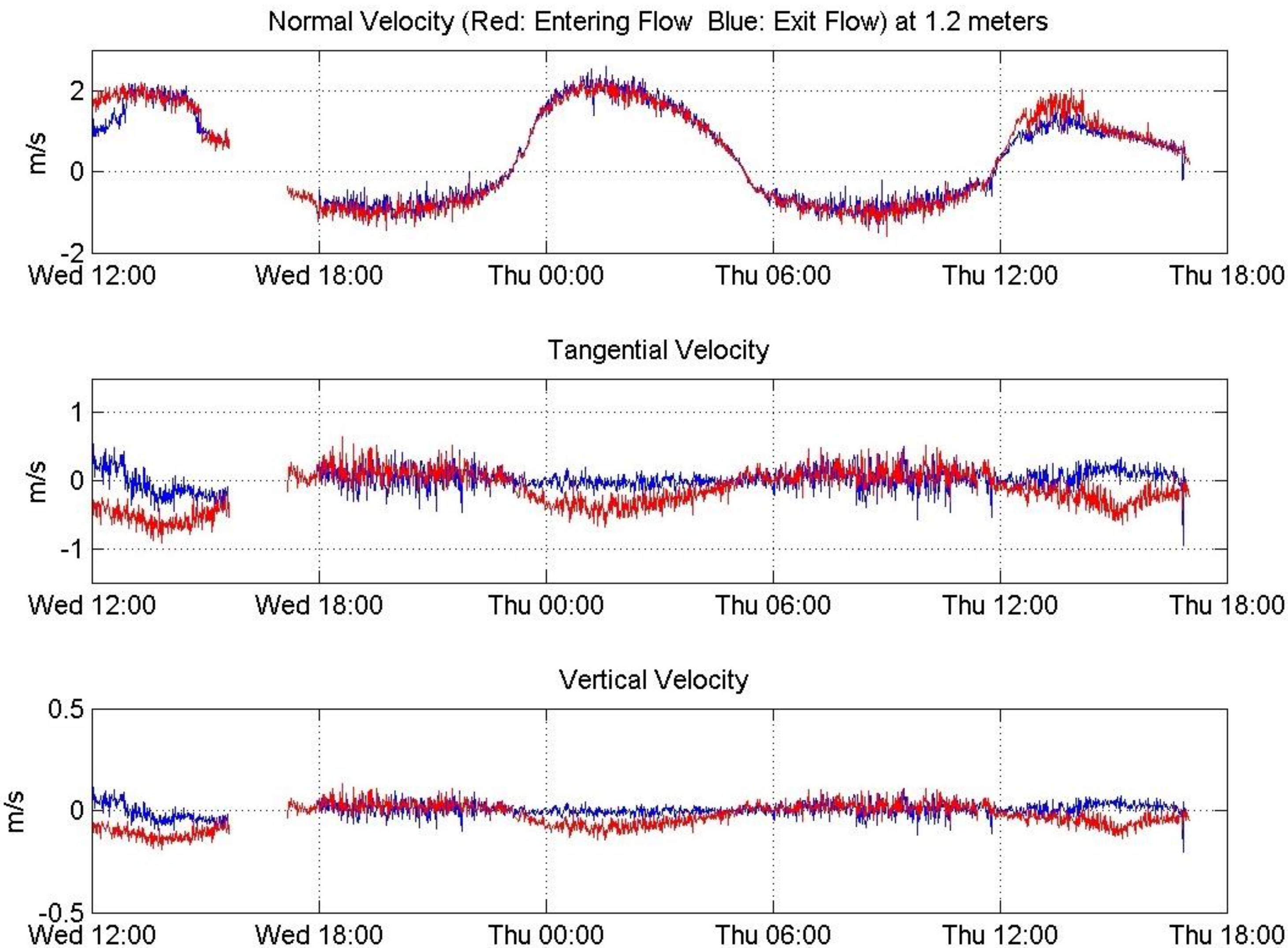


Figure 10: Time series of the normal (top), tangential (middle), and vertical (bottom) velocity components for the both the in-coming flow (denoted by the red line) and the exiting flow (blue line) at a depth of 1.2 meter (below the surface) for the time period Wednesday, August 3 to Thursday August 4. Note the discrepancies in the velocity signals during the Wednesday and Thursday afternoon ebb tides. Differences were greatest during the Wednesday ebb tide when both devices were operating. Note the scale differences (Y-axis) between the various velocity plots.

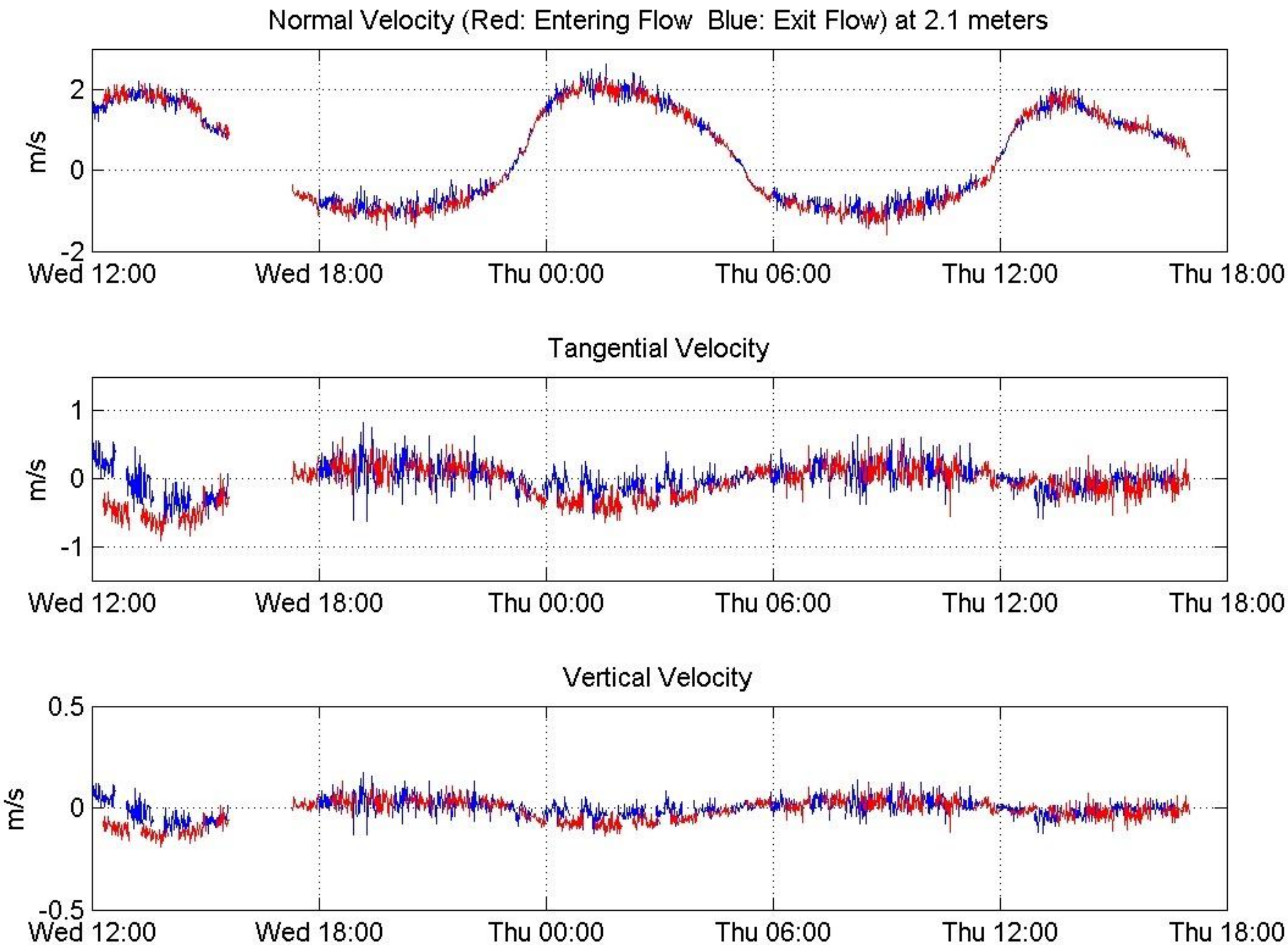


Figure 11: Time series of the normal (top), tangential (middle), and vertical (bottom) velocity components for the both the in-coming flow (denoted by the red line) and the exiting flow (blue line) at a depth of 2.1 meters (below the surface) for the time period Wednesday, August 3 to Thursday August 4. The data gaps in each series were due to interruptions while in Burst Sampling Mode. Note the scale differences (Y-axis) between the various velocity plots.

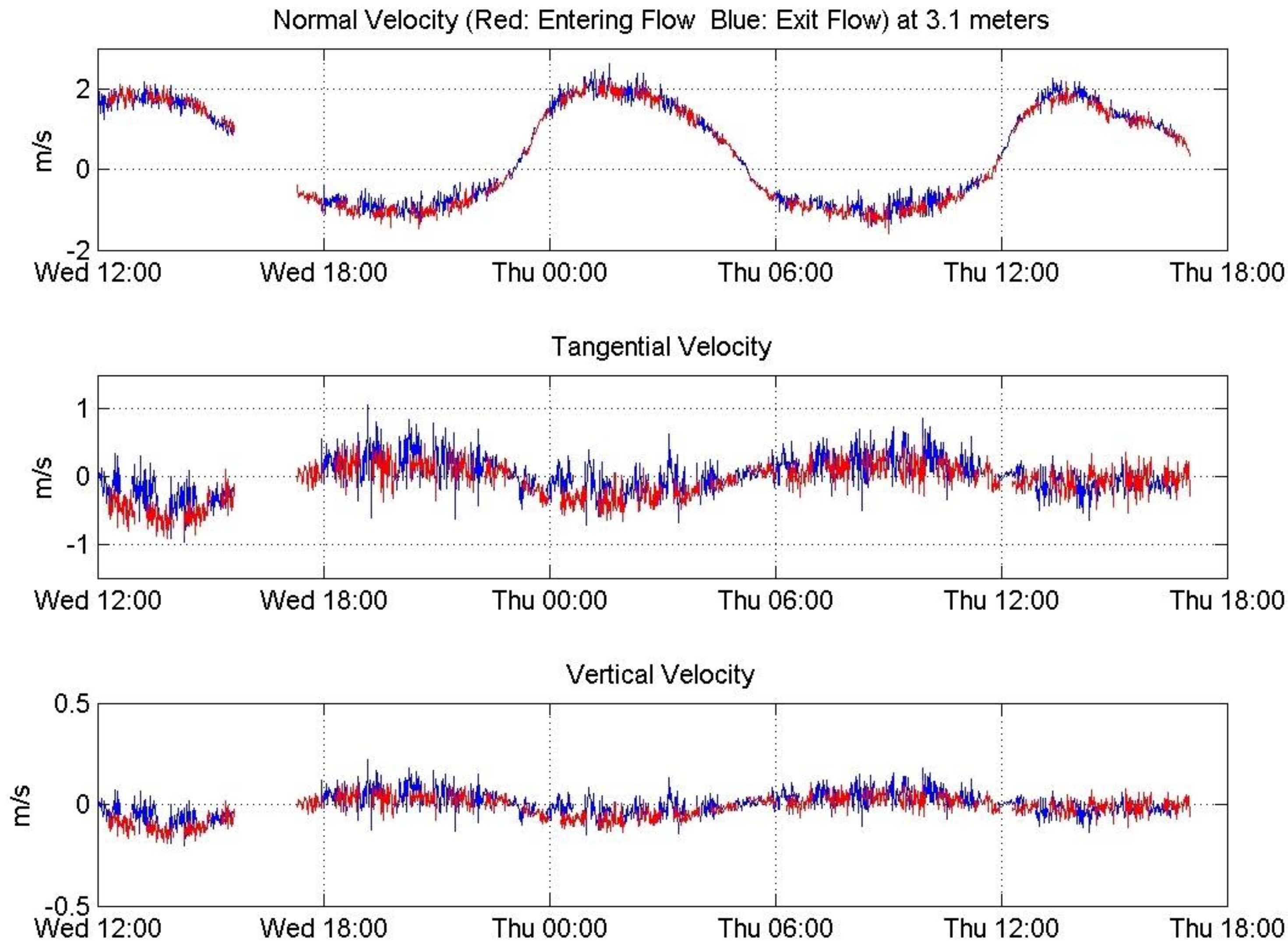


Figure 12: Time series of the normal (top), tangential (middle), and vertical (bottom) velocity components for the both the in-coming flow (denoted by the red line) and the exiting flow (blue line) at a depth of 3.1 meters (below the surface) for the time period Wednesday, August 3 to Thursday August 4. Note the scale differences (Y-axis) between the various velocity plots.

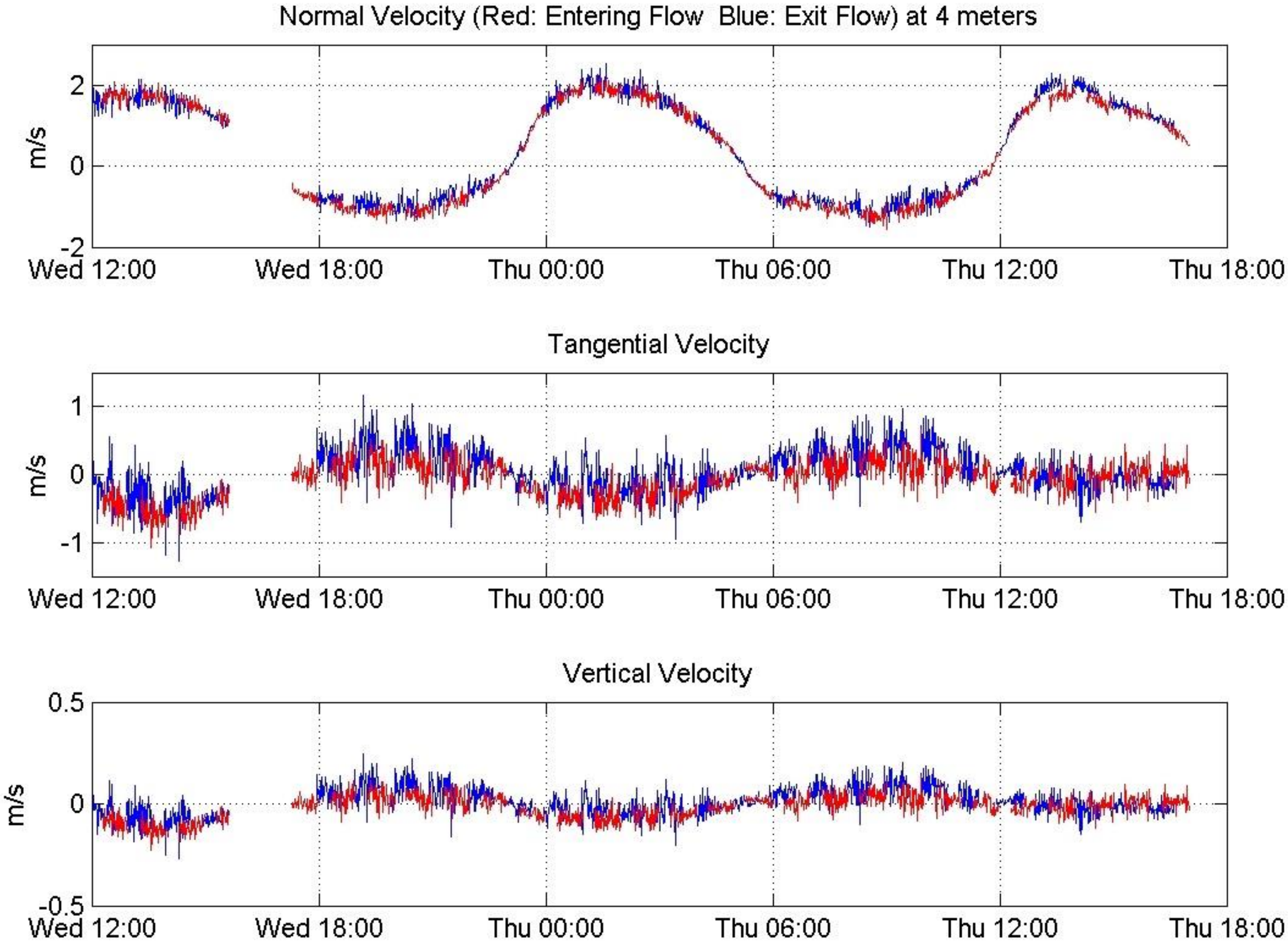


Figure 13: Time series of the normal (top), tangential (middle), and vertical (bottom) velocity components for the both the in-coming flow (denoted by the red line) and the exiting flow (blue line) at a depth of 4 meters (below the surface) for the time period Wednesday, August 3 to Thursday August 4. Note the scale differences (Y-axis) between the various velocity plots.

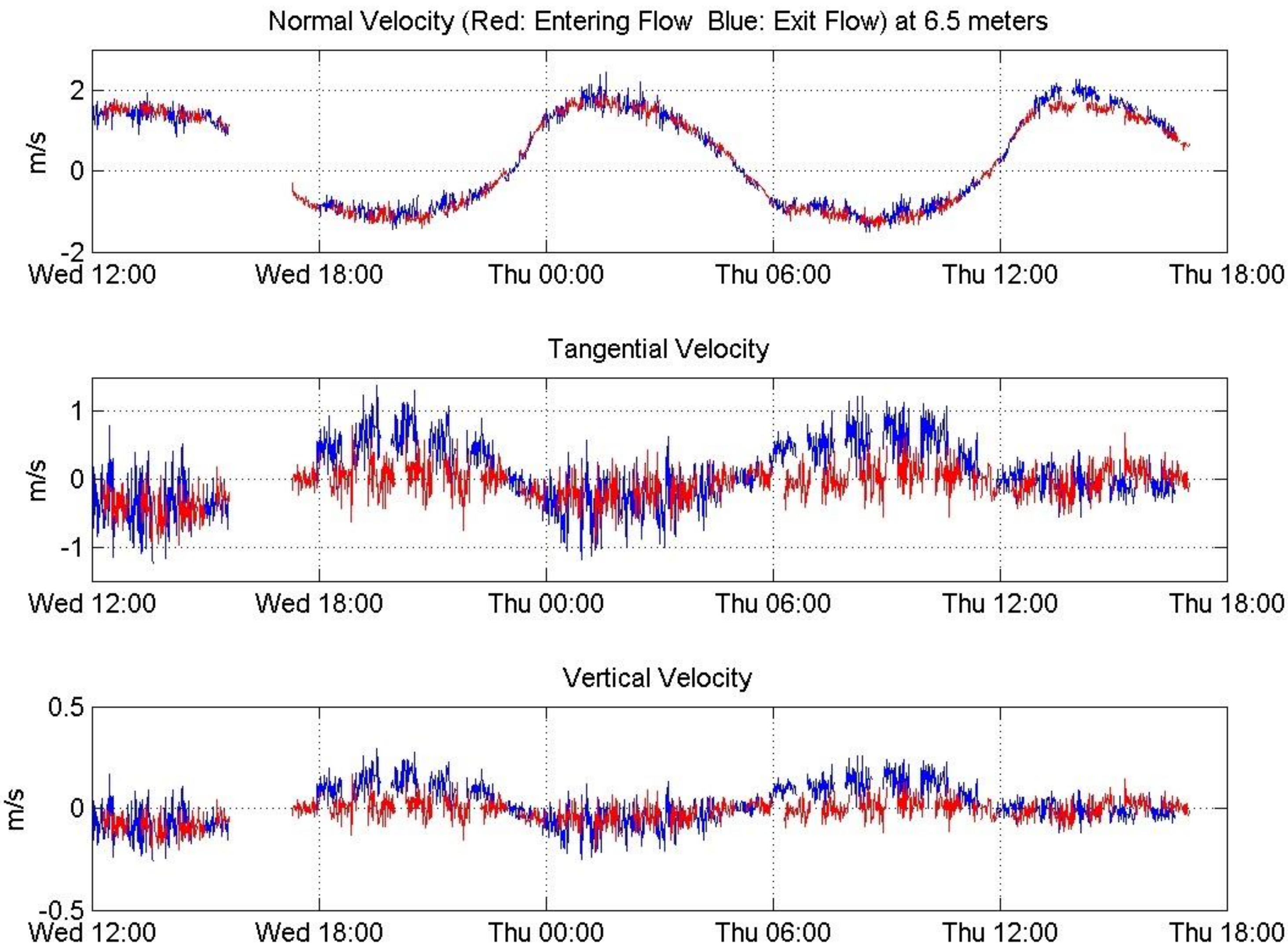


Figure 14: Time series of the normal (top), tangential (middle), and vertical (bottom) velocity components for the both the in-coming flow (denoted by the red line) and the exiting flow (blue line) at a depth of 6.5 meters (below the surface) for the time period Wednesday, August 3 to Thursday August 4. Note the scale differences (Y-axis) between the various velocity plots.

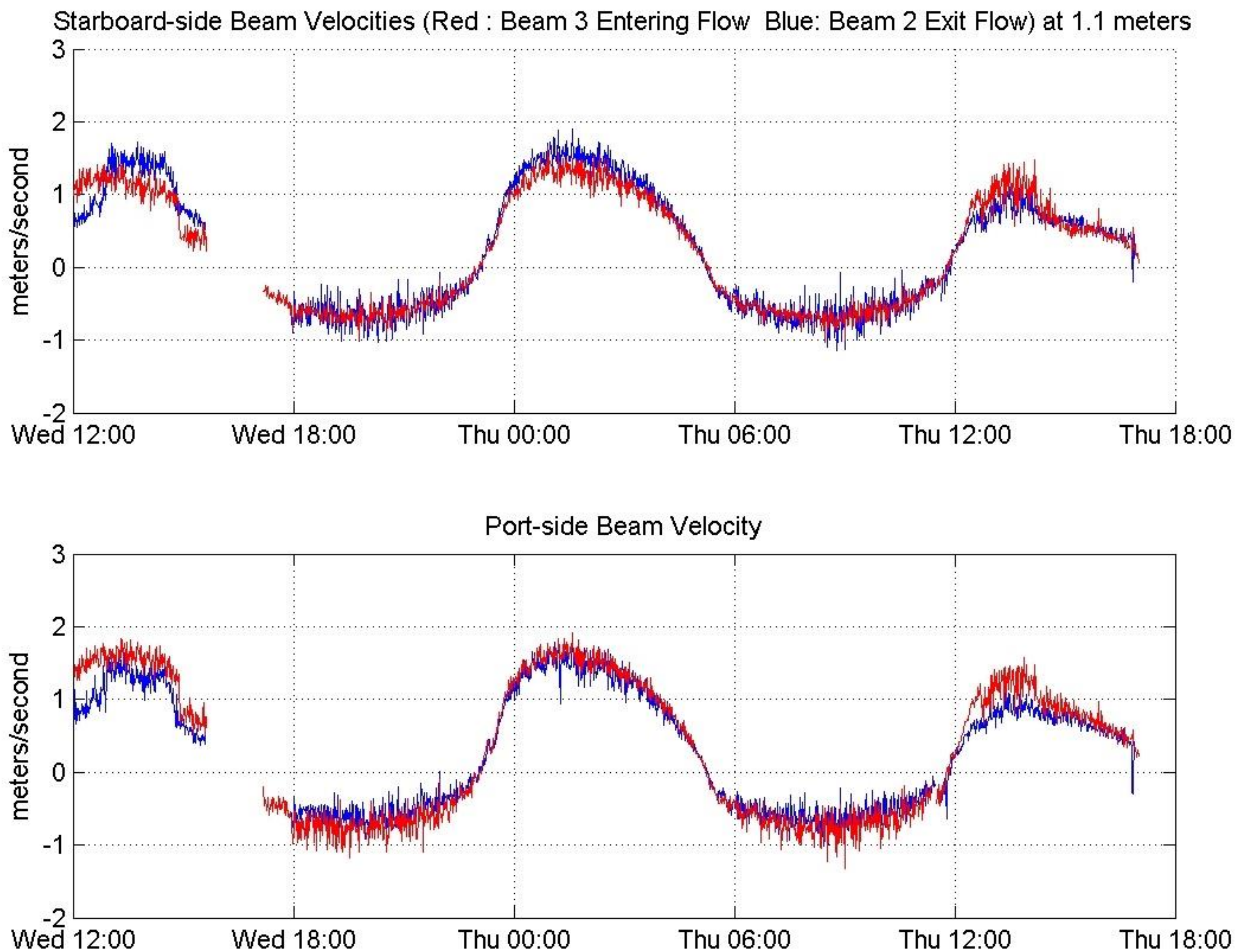


Figure 15:

Comparison of the original beam velocities 1.1m deep on the starboard side (top plot) and port side (bottom plot) of the *Joule* device. The in-coming flow is red; the exit flow is blue. These signals are direct measurements – not derived from assumptions regarding vertical velocity due to failure of beam 1. Note the starboard side of the *Joule* device is outboard (closest to the canal) and the port side is inboard, closest to the MMA pier.

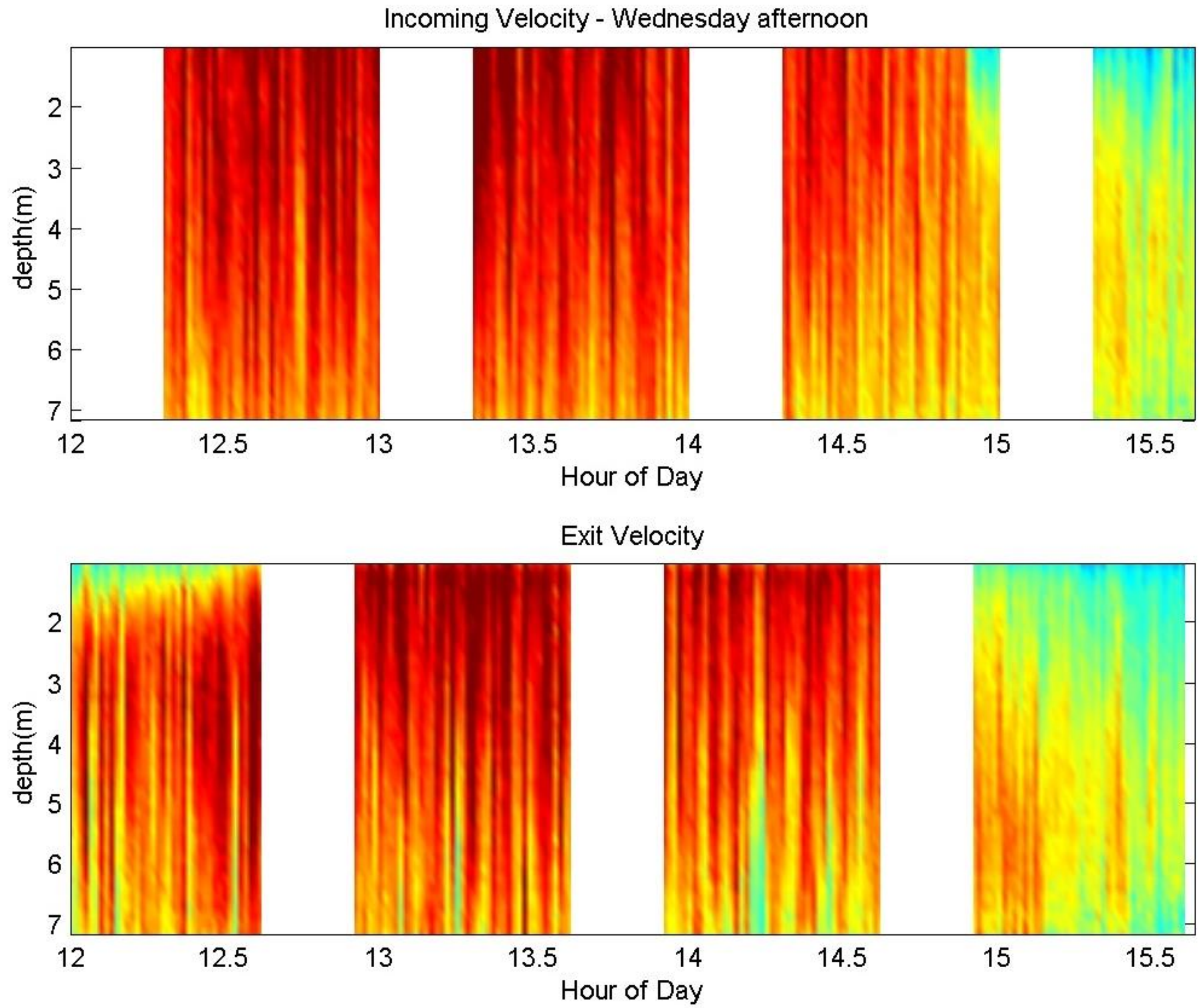


Figure 16: These color-contour plots compare the incoming (horizontal) velocity with the exit velocity for a single ebb cycle. The white spaces represent time of wave bursts. Wave bursts were 17 minutes in length; no current profiles are collected during that time. Bursts were scheduled for the same time between the two units, but for inexplicable reasons one burst was offset by 38 minutes. During simultaneous recording of current profiles, there appears to be some slowing of very upper layer currents on the exit side, especially early in the ebb cycle (about 12:30) when both devices were in the water.

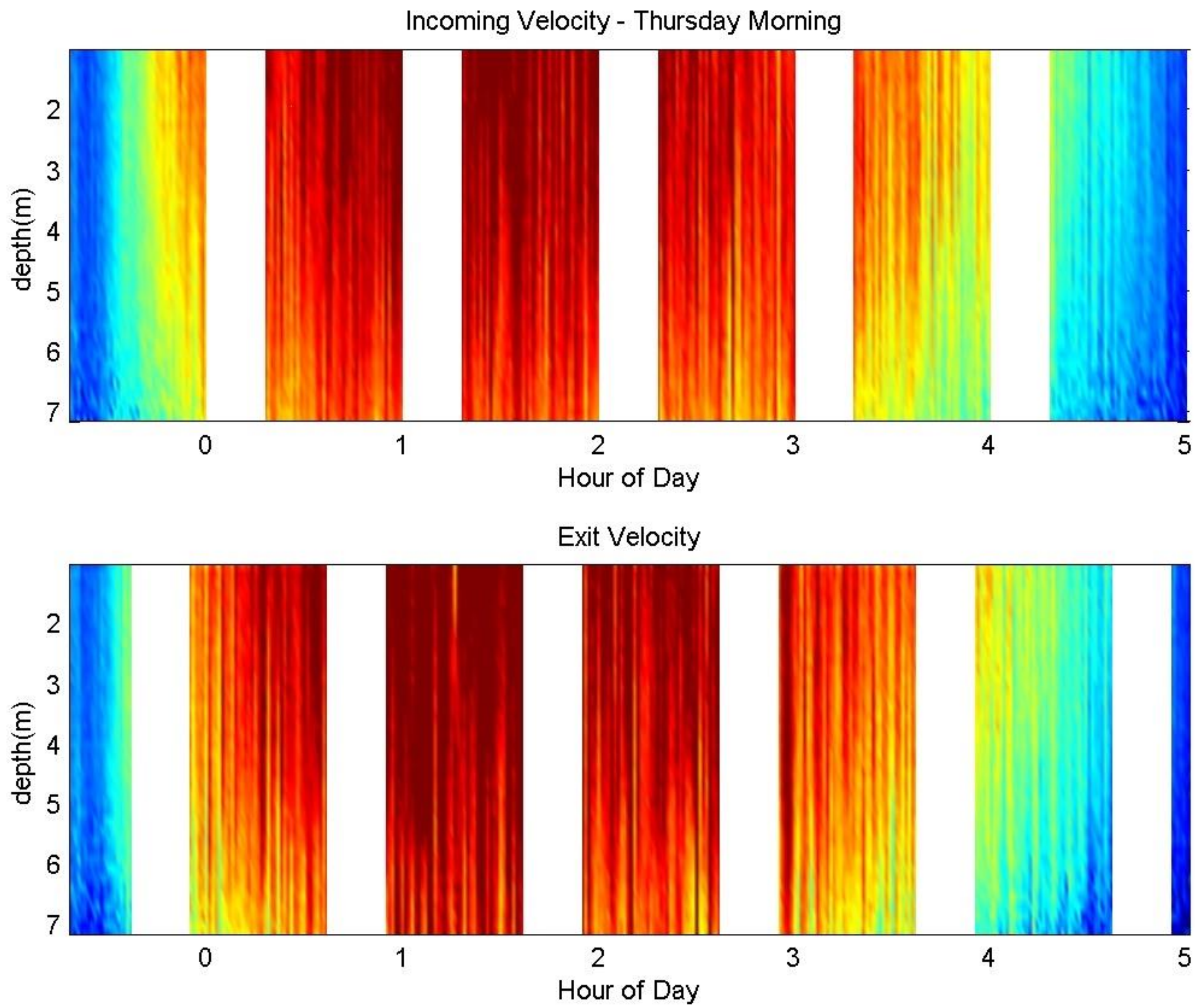


Figure 17: The Thursday morning ebb occurred when no device was installed. There is little difference between the incoming and exit velocity.

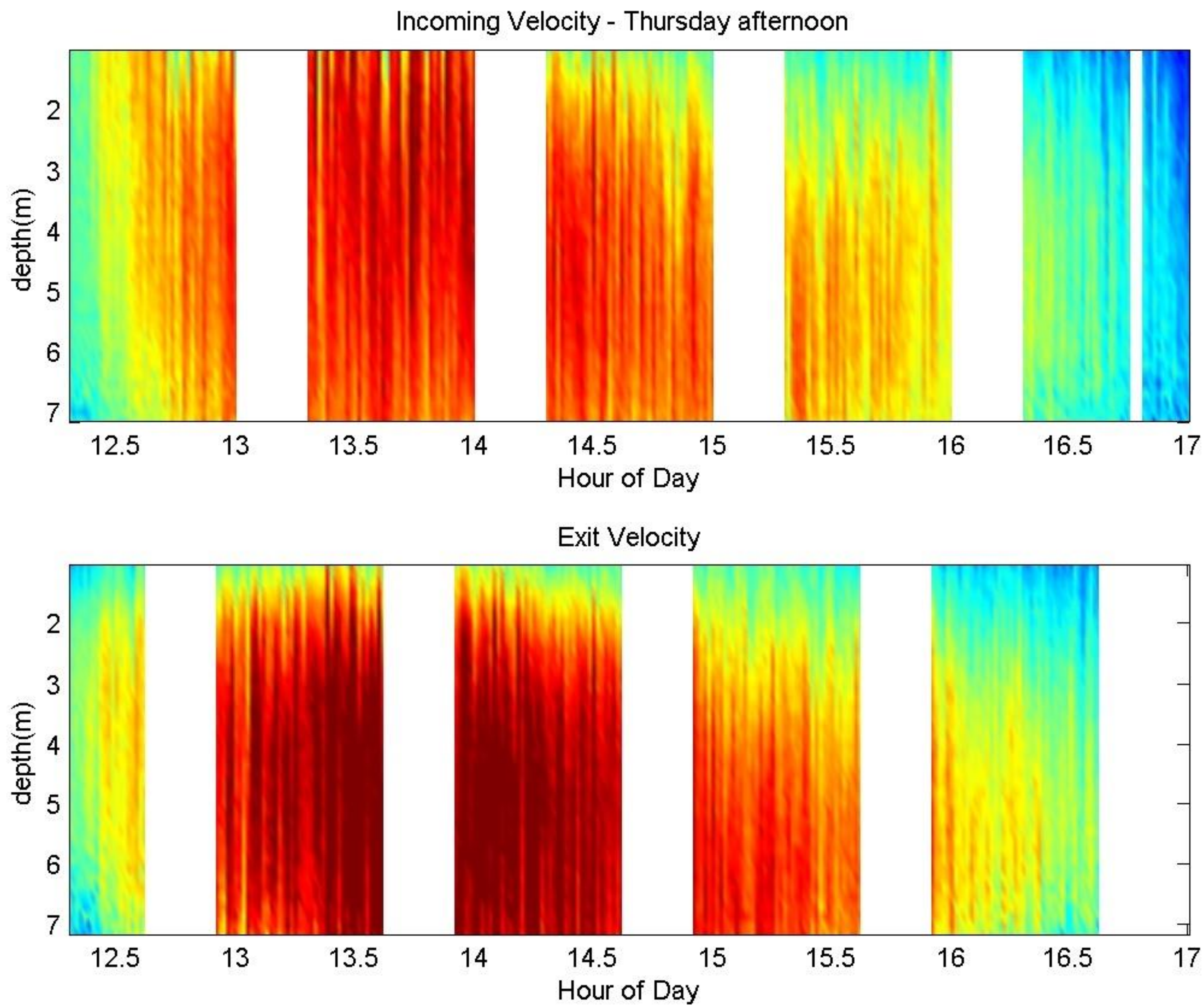


Figure 18: Some evidence of slowing flow on the exit side about 13-13.5 hours Thursday afternoon when one device was operating. There is also evidence of flow acceleration in the deeper layers between 13.5 hours to 14.5 hours.

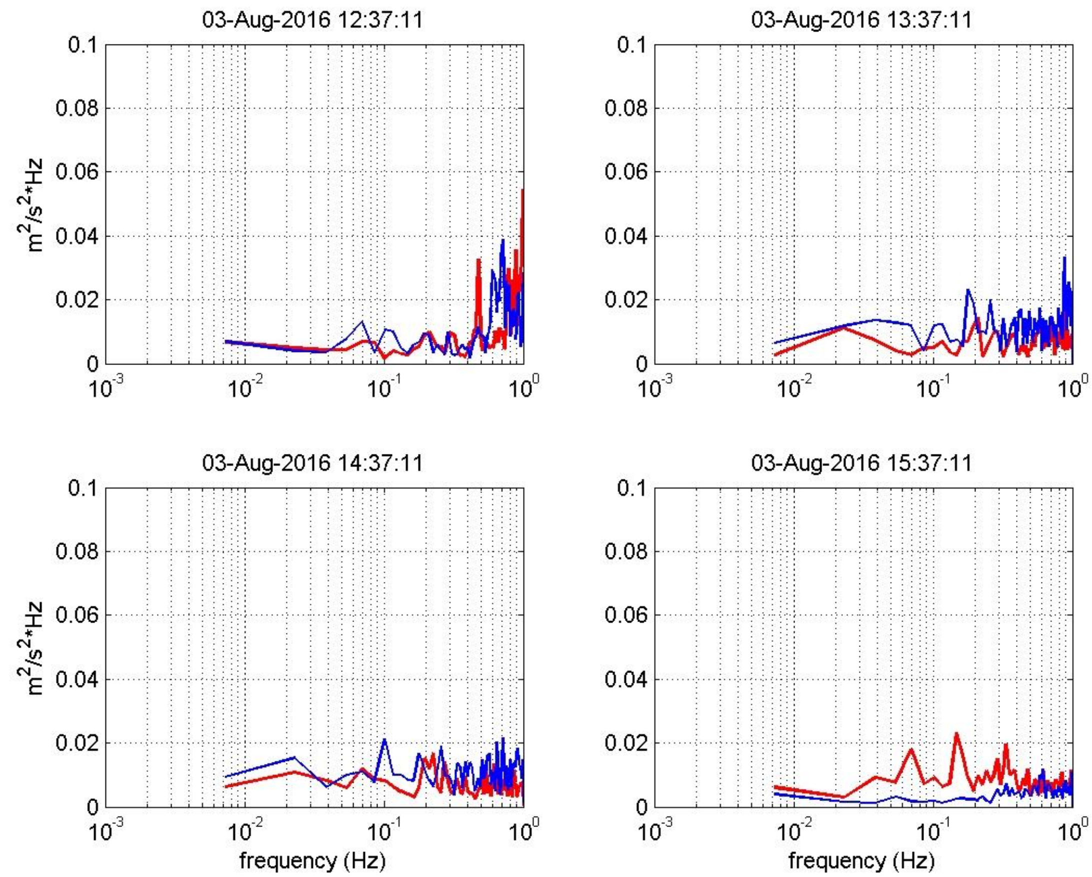


Figure 19: These figures are variance-preserving spectra of hourly wave bursts around the time of peak ebb tide on Wednesday 03-August. The blue line is the exit (horizontal velocity) while the red line is the incoming flow. These resulted from 2048 points sampled at 2 Hz. 16 blocks were used in the spectral smoothing. Shown here is the Wednesday afternoon ebb.

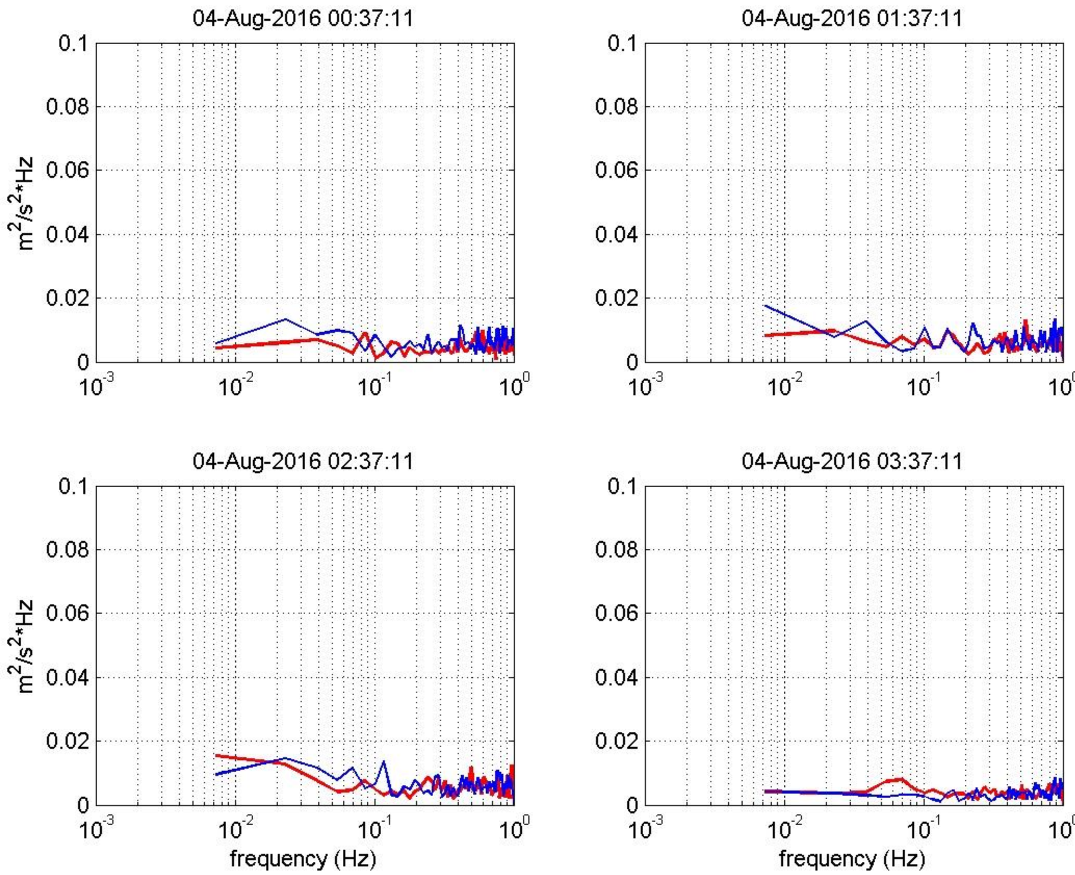


Figure 20: These figures are variance-preserving spectra of hourly wave bursts around the time of peak ebb tide early August 4. The blue line is the exit (horizontal velocity) while the red line is the incoming flow. These resulted from 2048 points sampled at 2 Hz. 16 blocks were used in the spectral smoothing. Shown here is the Thursday morning ebb when no devices were operating. Variance (energy) is much less than the previous ebb, although this could be due to calmer surface wave conditions.

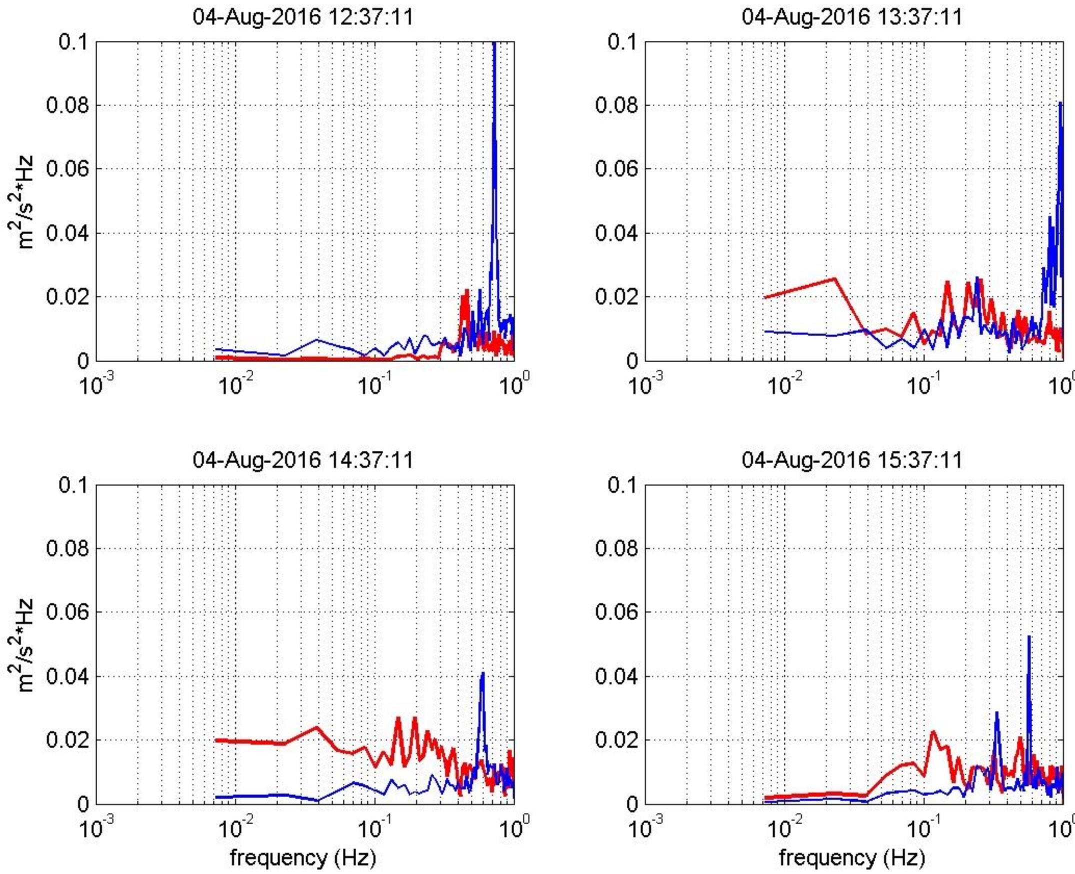


Figure 21: These figures are variance-preserving spectra of hourly wave bursts around the time of peak ebb tide during the afternoon of August 4. The blue line is the exit (horizontal velocity) while the red line is the incoming flow. These resulted from 2048 points sampled at 2 Hz. 16 blocks were used in the spectral smoothing. Shown here is the Thursday afternoon ebb when one device was operating. The increased energy may be due to building wave conditions.

Wake Survey Graphics

August 5, 2016

<u>Fixed Aquadopp Sensors</u>

1-second sample rate

No wave bursts

<u>Mobile 600 kHz ADCP</u>

1-second profiles

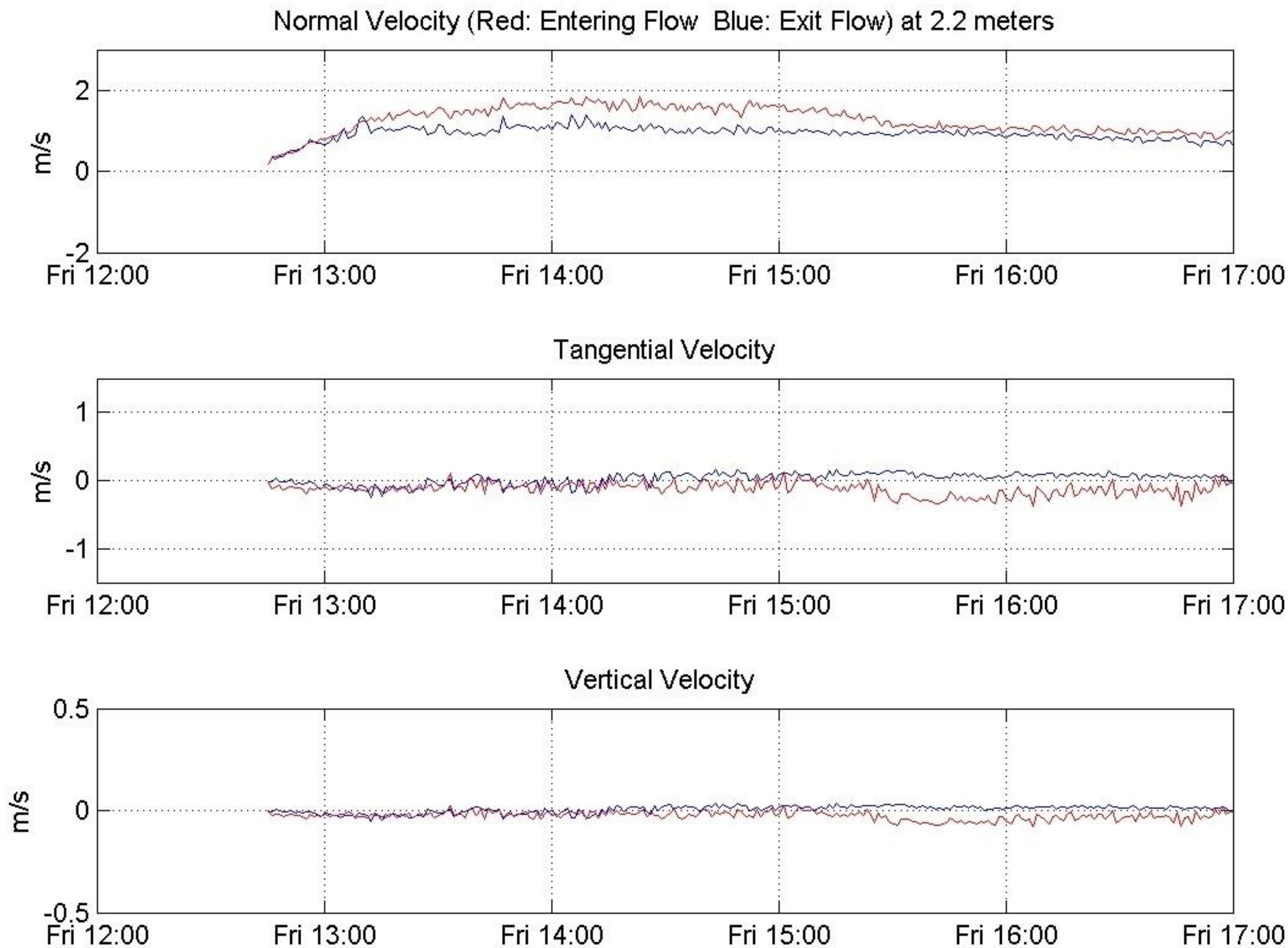
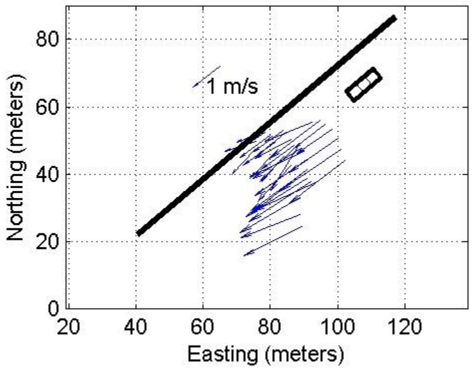
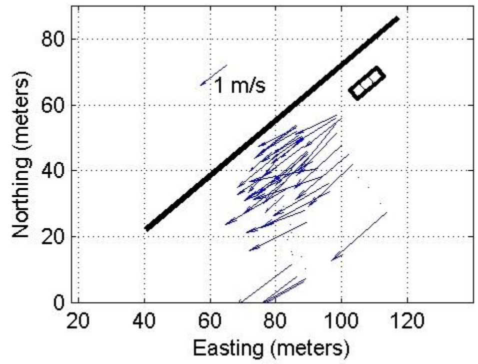


Figure 22: Time series comparing the incoming flow to the exit flow 2.2m deep for the Friday afternoon ebb tide. These velocities were valid according to echo amplitude signals. Differences between the incoming and exit flow were significant, with incoming flow stronger than the exit flow.

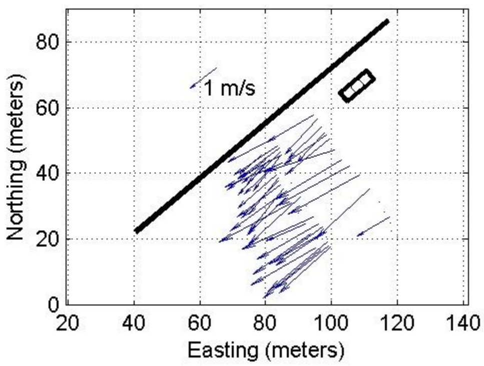
Cycle #1 14:24-14:28 hours



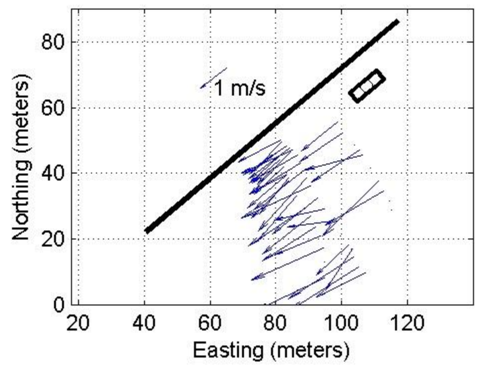
Cycle #2 14:29-14:38 hours



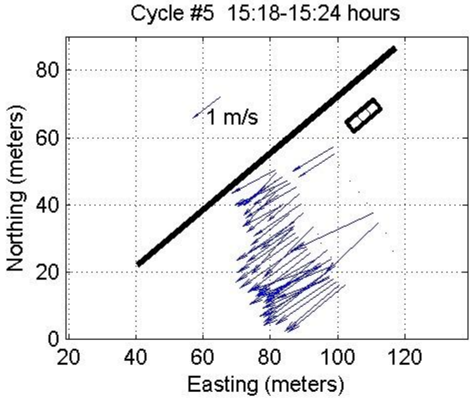
Cycle #3 14:41-14:48 hours



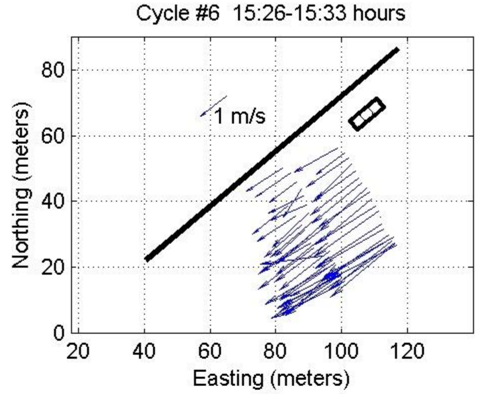
Cycle #4 14:50-14:56 hours



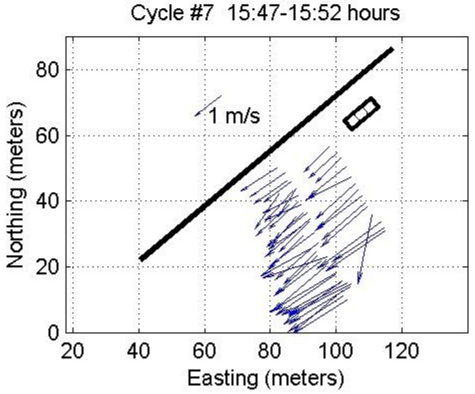
Cycle #5 15:18-15:24 hours



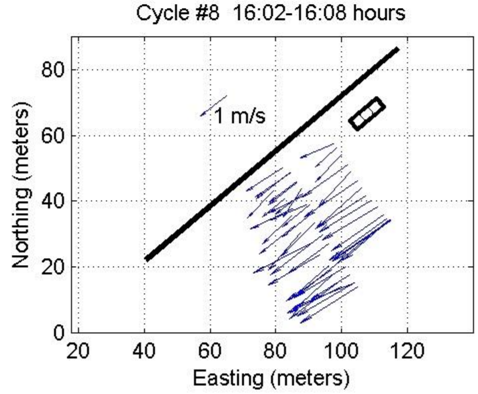
Cycle #6 15:26-15:33 hours



Cycle #7 15:47-15:52 hours



Cycle #8 16:02-16:08 hours



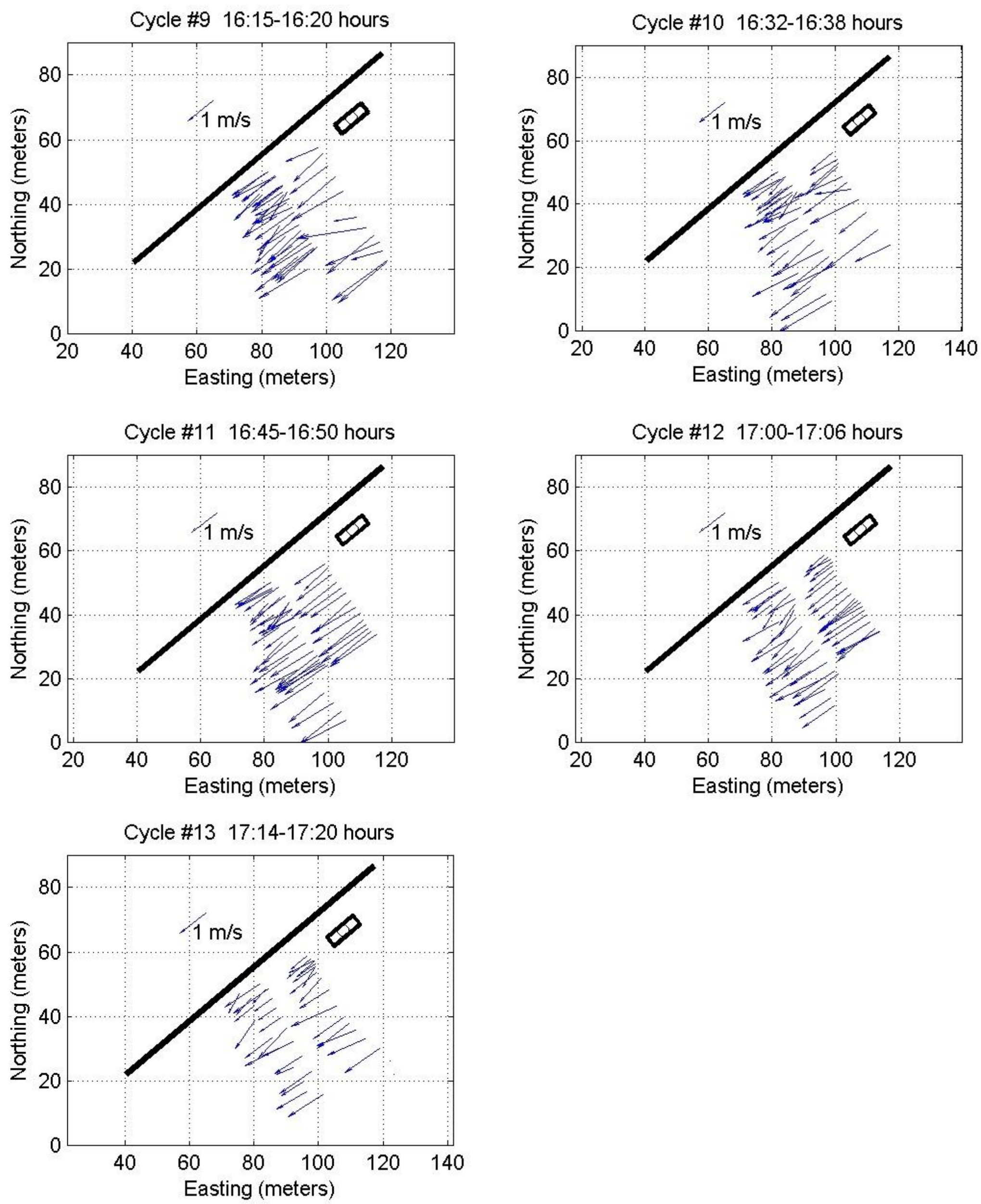


Figure 23: Synoptic vector plots for the wake survey on August 5, 2016. The heavy black line represents the approximate location of the MMA pier face. The black rectangle represents the approximate position of the *Joule* device pontoon barge. The position of the actual flow measurement is the base of each arrow. Flow vectors have been averaged to reduce scatter. A scale vector (1 m/s) is also shown. The y- and x-axes are labeled in Northing-Easting (in meters). While the X-Y positons were output in UTM (Zone 19 North), the 6- and 7-digit values were too large for the plots, so the positions were referenced to an arbitrary local origin for clarity.

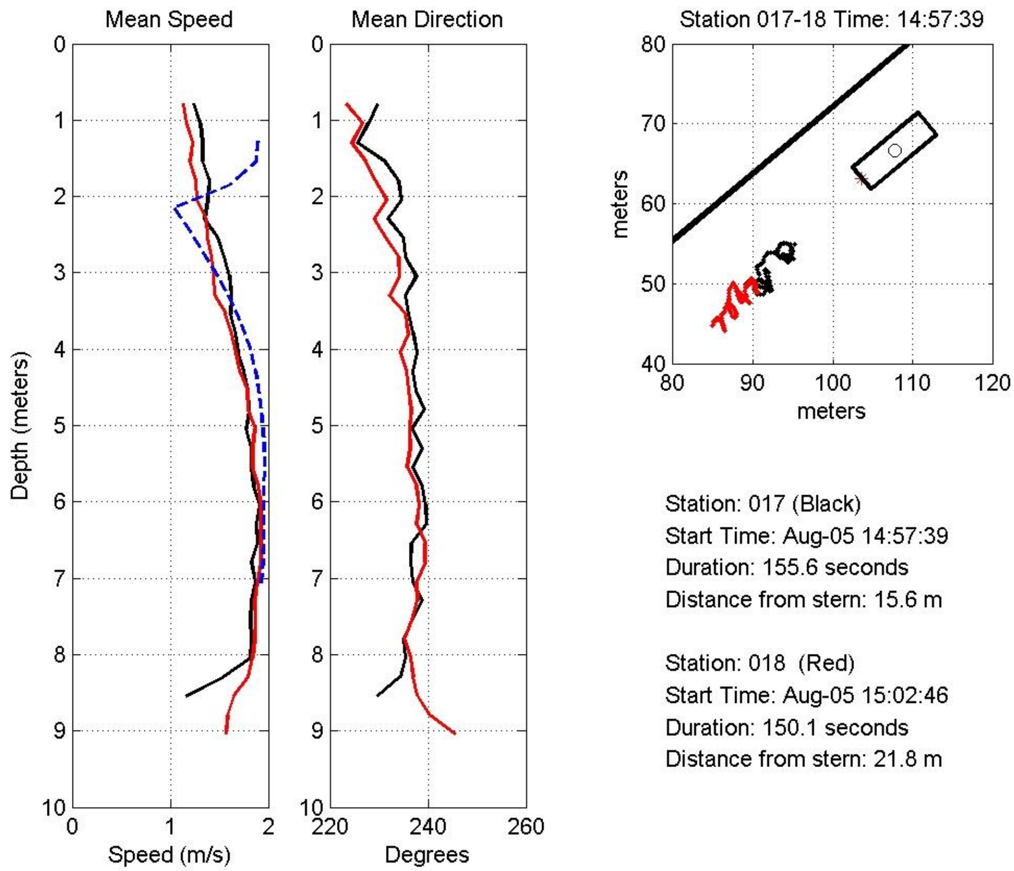


Figure 24: Fixed Stations 017-018. The profile plots include the mean speeds and directions calculated for each fixed station. The red profile is the far-field station and corresponds to the red-colored position fixes on the map; the black profile represents the near-field station. The blue dashed line is the Aquadopp profile averaged over the same time period as the fixed stations (ignore the blue dashed line above 2m). Below the map lists the meta-data associated with each station: start time, duration of the occupation, and mean distance from the stern of the *Joule* barge. Note the relative agreement between independent sensor results.

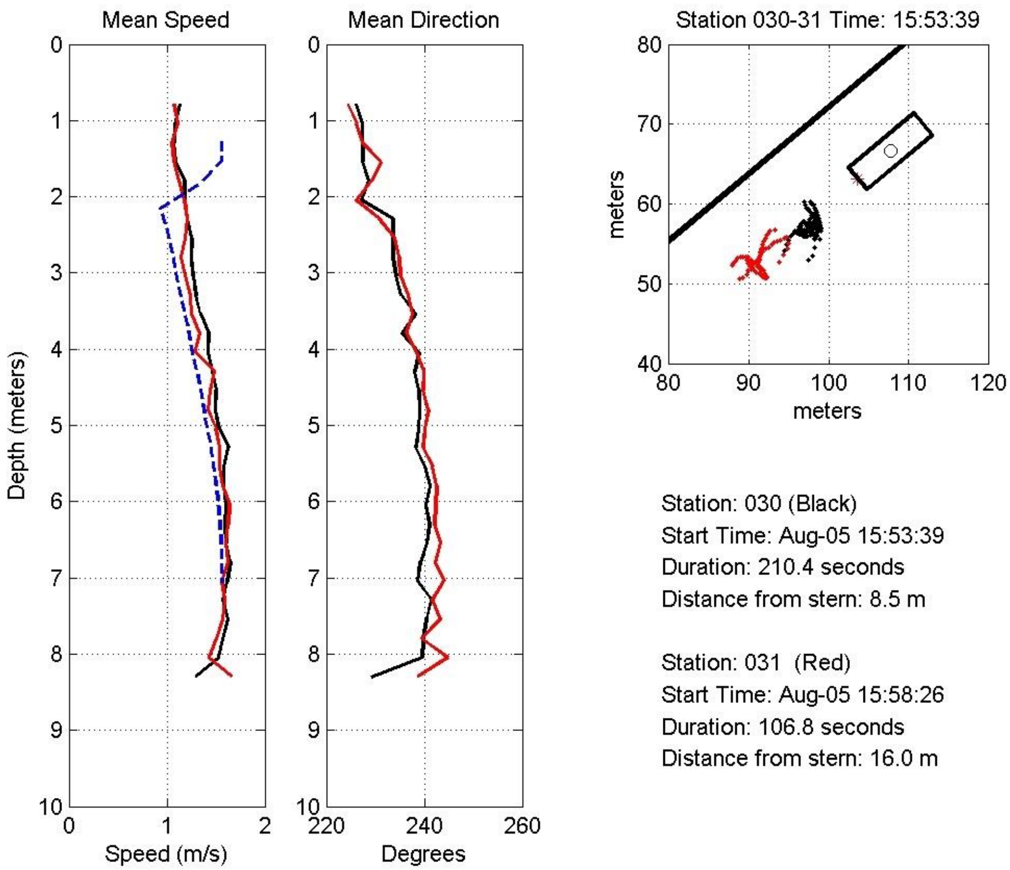


Figure 25: Fixed Stations 030-031. The red profile is the far-field station; the black profile the near-field station. The blue dashed line is the Aquadopp profile averaged over the same time period as the fixed stations (ignore the blue dashed line above 2m). Stronger flow was observed in deeper layers relative to upper layers.

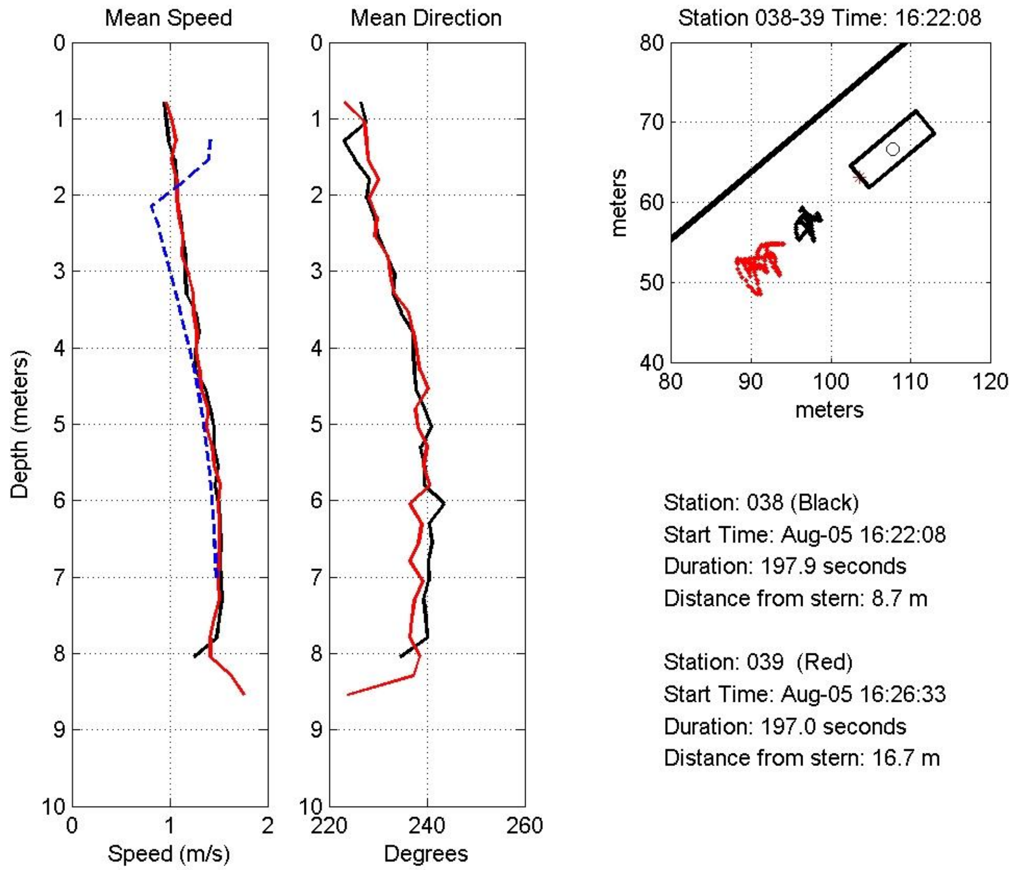


Figure 26: Fixed Stations 038-039. The red profile is the far-field station; the black profile the near-field station. The blue dashed line is the Aquadopp profile averaged over the same time period as the fixed stations (ignore the blue dashed line above 2m). Stronger flow was observed in deeper layers relative to upper layers.

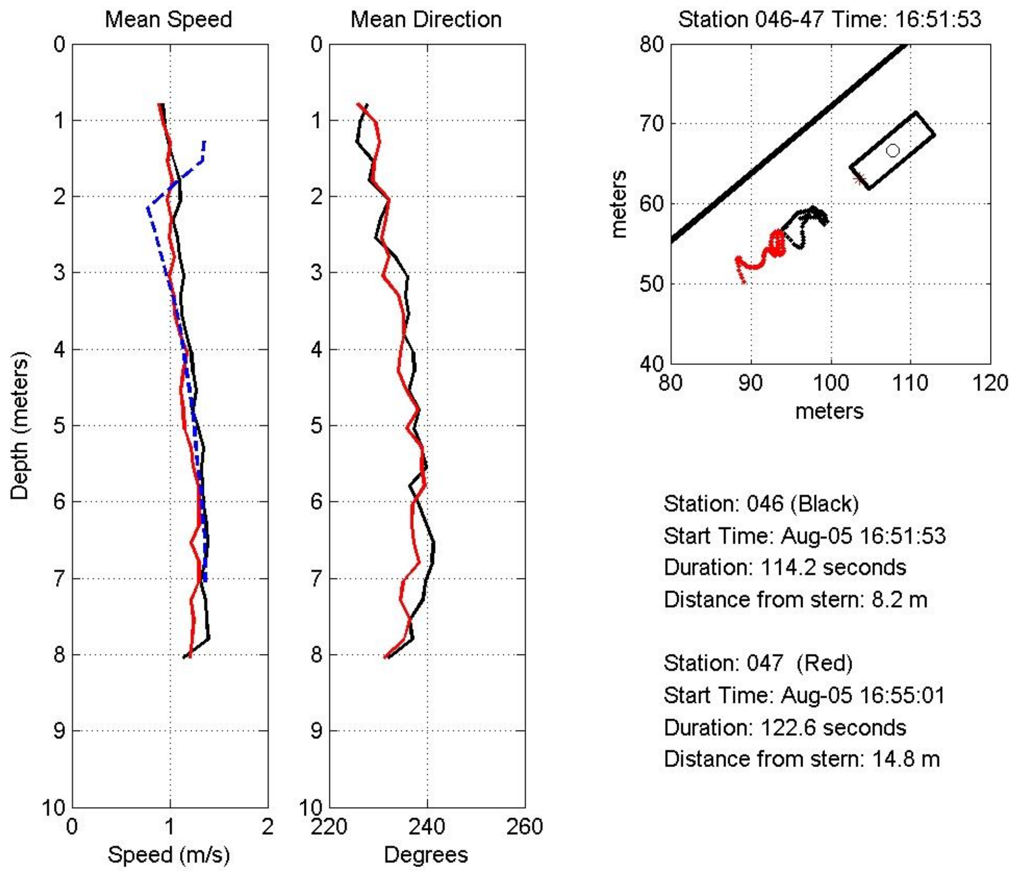


Figure 27: Fixed Stations 046-047. The red profile is the far-field station; the black profile the near-field station. The blue dashed line is the Aquadopp profile averaged over the same time period as the fixed stations (ignore the blue dashed line above 2m). Stronger flow was observed in deeper layers relative to upper layers.

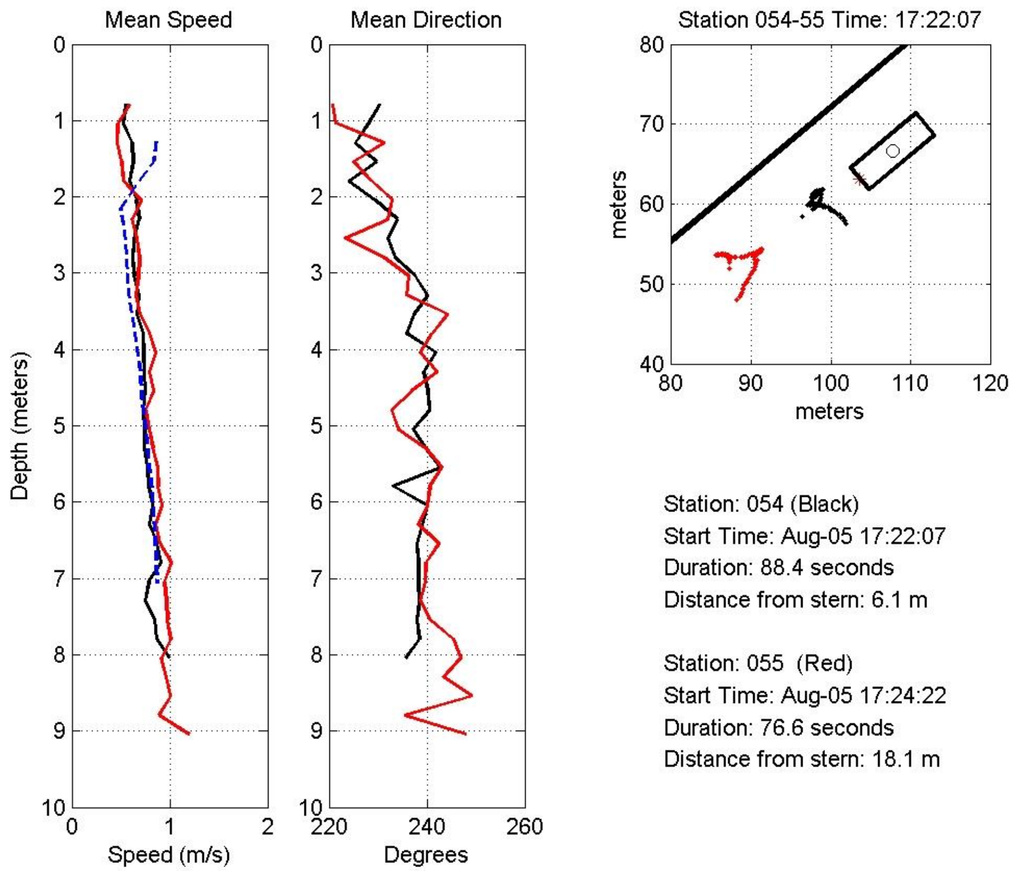


Figure 28: Fixed Stations 054-055. The red profile is the far-field station; the black profile the near-field station. The blue dashed line is the Aquadopp profile averaged over the same time period as the fixed stations (ignore the blue dashed line above 2m). Stronger flow was observed in deeper layers relative to upper layers.

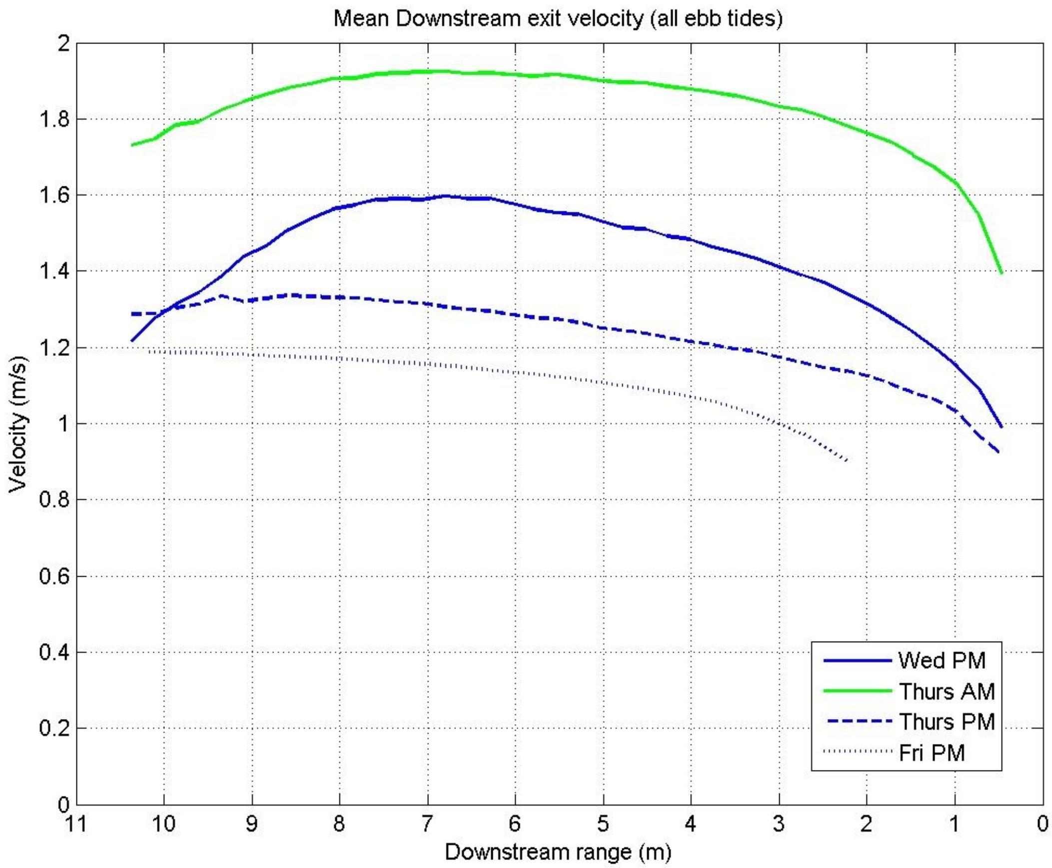


Figure 29: *__Horizontal__* profile of mean downstream velocities behind the device for the four ebb tide phases. These velocities were measured at a depth of 0.76m below the surface, so representative of flow in the very upper layer. The shape of these downstream profiles are similar – weakest near the device (range of 0-1m) growing in strength at ranges of 5-7m, and then weakening at ranges 10m+. Downstream flow was strongest for the Thursday morning ebb when no devices were in the water. The weakest flows were measured during the Thursday and Friday ebbs when one device was in the water.

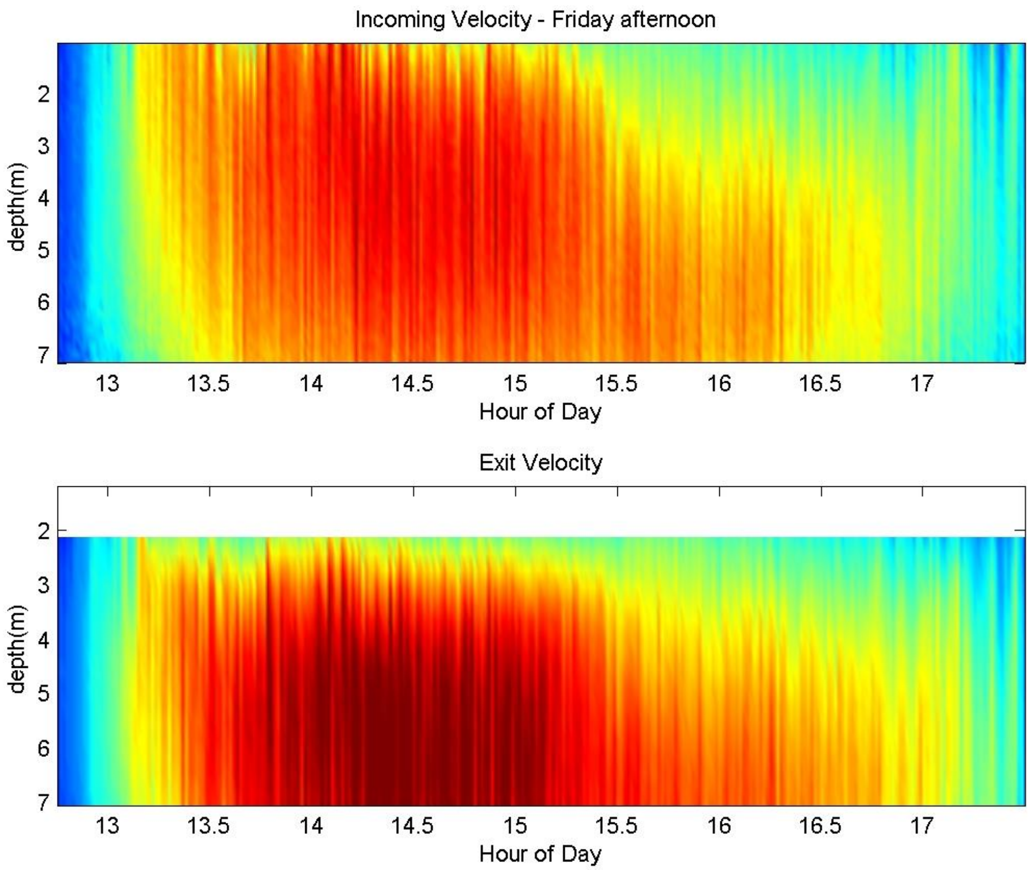


Figure 30: Color-contoured plot of the incoming and exit flows during the Friday survey. Time is the horizontal axis (time of day in hours), depth is the vertical axis, and color denotes velocity magnitude. Deep red and orange colors indicate strong flows; blue colors indicate weaker flows. The 1-second velocity data were averaged into 1-minute samples to reduce noise. Note the slower flow of exit velocities above ~3m but a corresponding increase in flow velocity below about 4m. The upper 3 bins of the exit velocity profiles were excluded from display due to suspect data quality.

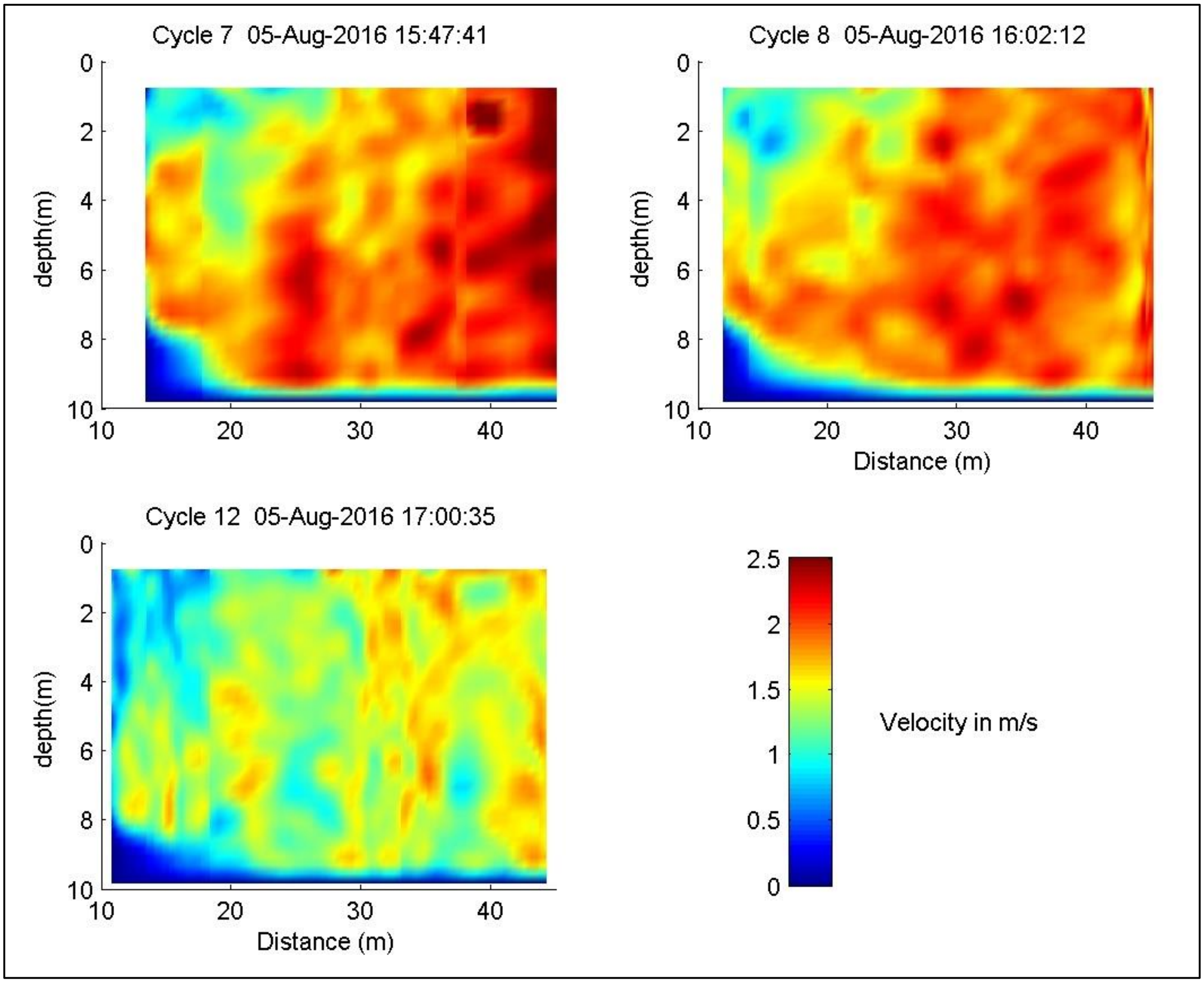


Figure 31: Color-contour panels of downstream velocity along an ADCP transect behind the *Joule* device. Color represents the strength of the current – red and orange are the strongest currents and blue are weak currents. Note the color bar to the lower right. The vertical axis is depth and the horizontal axis represents distance away from an arbitrary pier-based reference point. These contour plots represent a cross-section of the exit flow from the pier (on the left) toward the Canal channel to the right. The deep blue in the lower left corner of each plot represents the sea bottom at the toe of the pier. These profiles have undergone some smoothing to improve the presentation. The patches of light blue in the upper left represent weak flow behind the device.

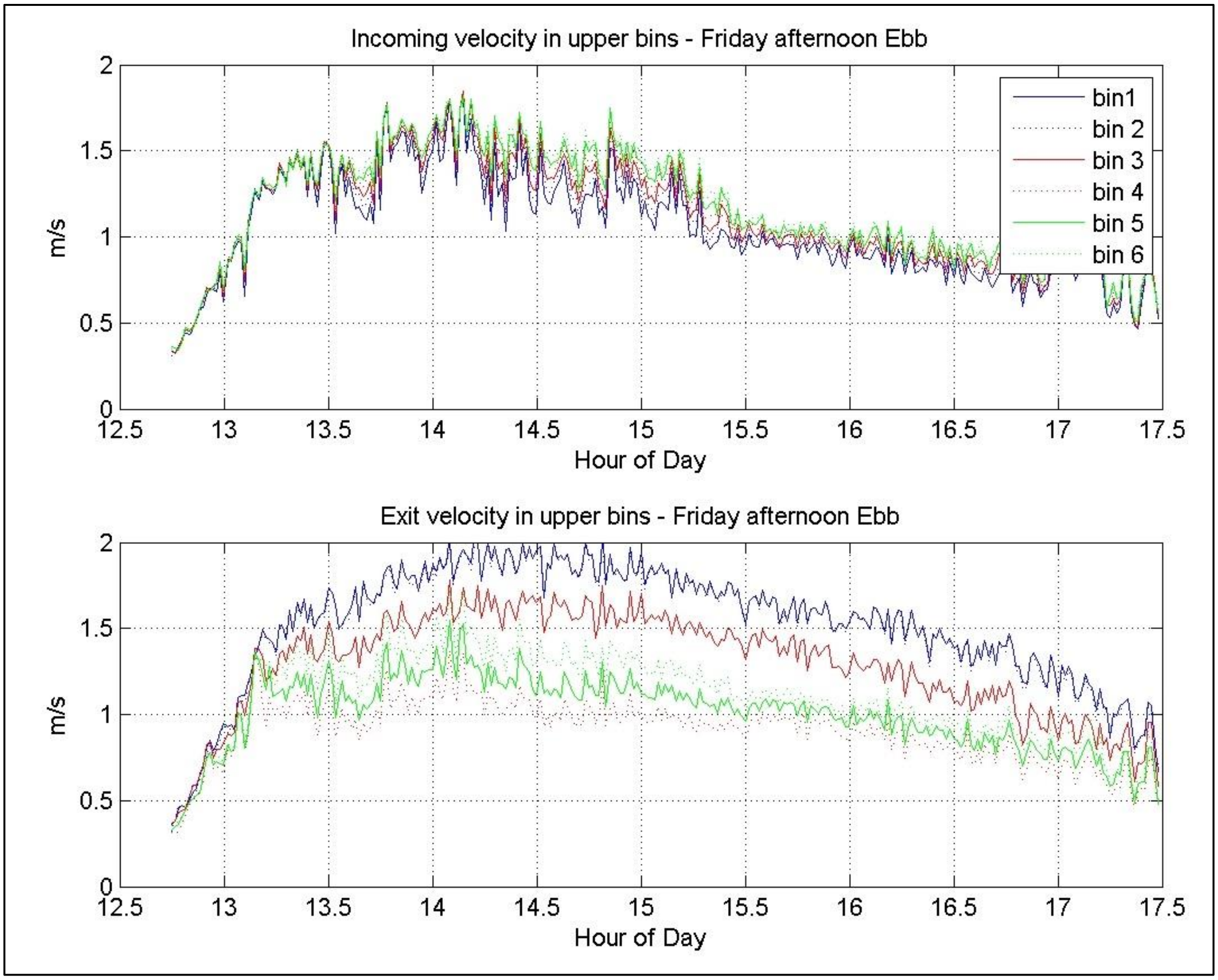


Figure 32: Comparison of velocity time series in the upper 6 range bins (1.2m to 2.8m depth) for the incoming flow (top) and exit flow (bottom). These are 1-minute averages computed from the original 1-second samples. Bins 1-3 of the exit velocity have questionable echo amplitude levels and are therefore ignored. Bin 4 (dotted red) is valid – and shows a considerable sag in velocity magnitude after the device was installed (about 1315 hours).

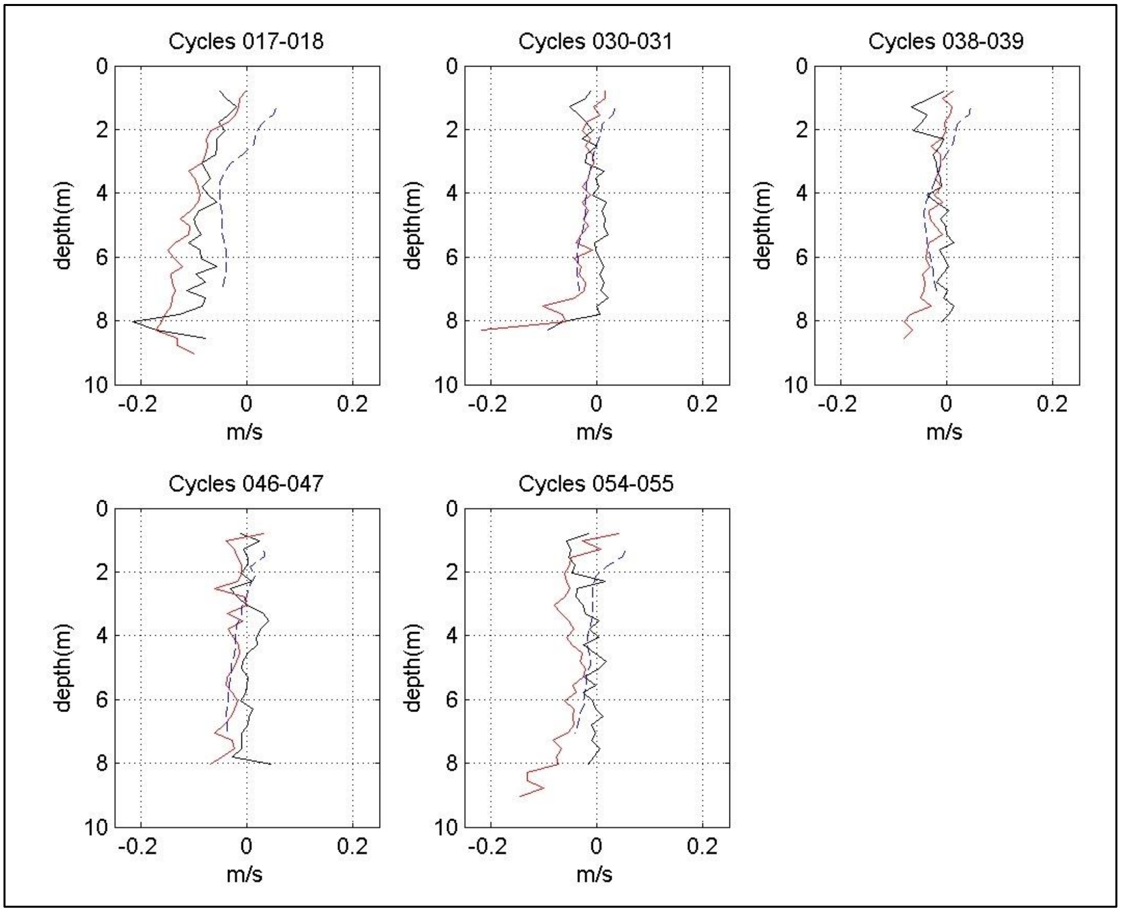


Figure 33: Mean vertical velocities measured by the ADCP during the fixed stations. The black line represents the near-field station; the red line the far-field stations, and the dashed blue line represents the vertical profile measured by the Aquadopp profiler mounted on the exit-side of the device. For the Aqaudopp profiles (blue line), please ignore all velocities above 2m.

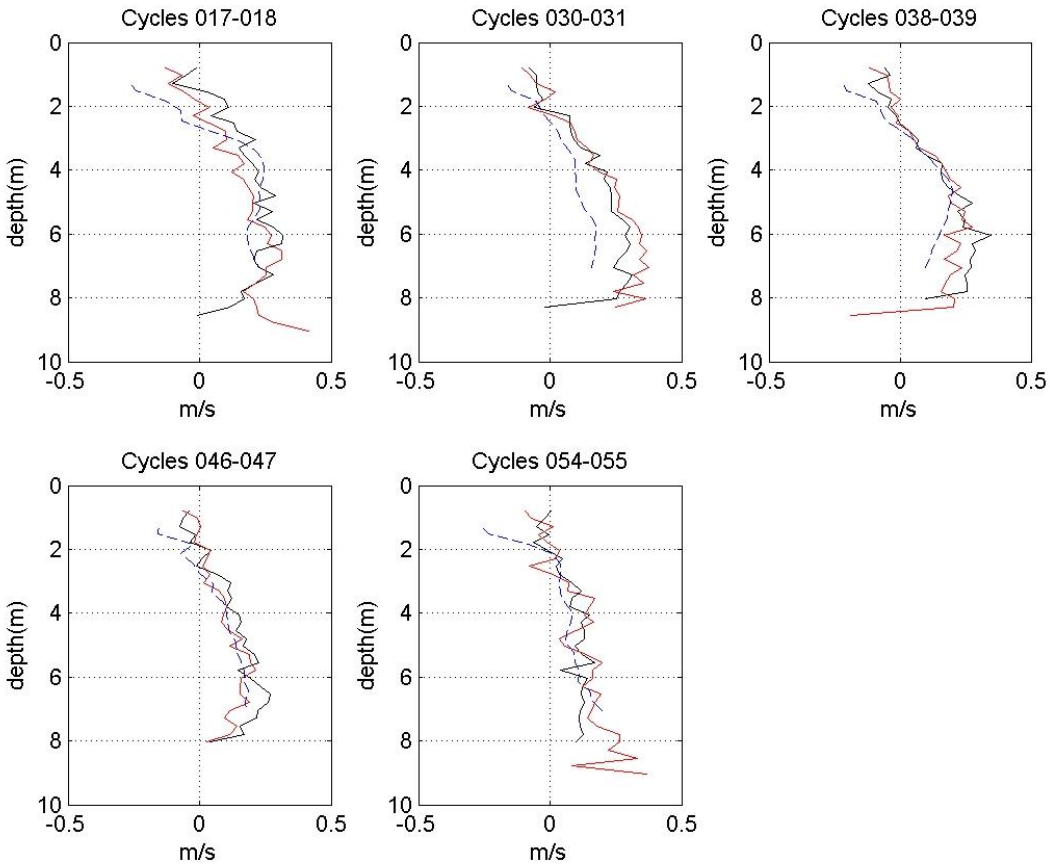


Figure 34: Mean tangential velocities measured by the ADCP during the fixed stations. The black line represents the near-field station; the red line the far-field stations, and the dashed blue line represents the profile measured by the Aquadopp profiler mounted on the exit-side of the device line), please ignore all Aquadopp velocities above 2m.

Appendix A1

Preliminary Current Measurements in the Cape Cod Canal Using an Aquadopp Vertical Profiler and Horizontal Acoustic Doppler Current Profiler (ADCP)

March-April 2016

The following section provides details of the installation of an Aqaudopp acoustic vertical profiling current meter and a horizontally-looking acoustic Doppler current meter. These instruments were installed along the pier at Massachusetts Maritime Academy (MMA) to measure the ambient flow field in the vicinity of the intended marine hydrokinetic device tests scheduled for the summer of 2016. This section also includes some general observations of the resulting measurements.

These brief observations suggest tidal velocities along the MMA pier can be affected by several factors:

- Strong surface winds which slow near-surface currents but strengthen mid- and bottom layer currents
- Large objects (tugboats docked to the pier) upstream of the flow path appear to slow eastward-running tidal currents
- Natural modulation of the tidal constituents on alternating phases

Aquadopp Vertical Profiler Installation Details

The Aquadopp Profiler (2 MHz acoustic Doppler current profiler) was installed approximately 1600 hours 11-March-2016. The unit operated until approximately 0839 hours 13-March-2016 when battery power was depleted. The profiler was deployed along the pier at the Massachusetts Maritime Academy (MMA) towards the eastern end of the pier, 9.75m outboard of the pier face, and 1m outboard of the M/V Ranger hull. The transducer head was placed approximately 0.40m below the water surface. See Figures A-1 through A-3 for the Aquadopp mounting orientation.

Because of the proximity of the Aquadopp to the steel hull of the M/V Ranger, the compass readings may be biased. Note that the compass was fixed for the duration of data collection, so the bias would be a constant – and likely small - offset. The unit was set such that beam #1 (denoted by the forward arrow marked X) pointed forward (relative to the M/V Ranger), or approximately westward. [Note: compass readings when X points towards due west would be 270°]. If looking downward, Beam #2 pointed 120° counter-clockwise, or towards the south-southeast (150°), outboard of the vessel. Beam #3 pointed 120° further counter-clockwise, or towards the north-northeast (30°), beneath the vessel. The beams angled 30° from the vertical.

Assessment of the acoustic amplitude data showed no acoustic interference for beams 1 and 2; however, beam 3 found interference at depths ranging from 8m to 9.5m, depending on tidal elevation. This interference was likely a sediment mound, or perhaps riprap, at the foot of the pier face. Velocity data in these distal bins showing acoustic interference are invalid, and hence removed from the following graphics.

<u>Aquadopp Profiler Sampling Set-up</u>

(From the set-up file CLAQDp01.hdr)

Profile interval	60 sec
Number of cells	50
Cell size	20 cm
Average interval	30 sec
Number of pings per burst	15
Transmit pulse length	0.20 m

Blanking distance	0.20 m
Compass update rate	60 sec
Powerlevel	HIGH
Coordinate system	ENU
Sound speed	MEASURED
Salinity	35.0 ppt
Number of beams	3
Software version	1.37.04
Deployment name	CLAQDp
Deployment time	3/11/2016 11:00:00 AM

Time Standard: All times reported in Eastern Standard Time

Horizontal ADCP Installation Details

The H-ADCP (Teledyne RD Instruments 300 kHz Narrowband) was installed approximately 1200 hours 11-March-2016. The unit was recovered 28-March-2016. The profiler was fixed in place along the pier at the Massachusetts Maritime Academy (MMA) towards the eastern end of the pier, facing outboard of the pier face, about -1.05m elevation (relative to MLLW datum). See Figures A-8 through A-10 for the H-ADCP mounting orientation.

The H-ADCP looked outward into the Canal flows – oriented normal to the pier face. The H-ADCP measures at fixed elevation, so the depth of the measurement relative to the water surface changes with tidal height. At high water, the depth of the currents measurements will be the deepest; at low water, the measurement depth will be the shallowest.

The measurement depths of the Aquadopp Profiler were not fixed however, rather relative to the water surface. Since it was mounted to the M/V Ranger, which rises and falls according to water level, the absolute elevation of the vertical 'bins' changed with the rise/fall of the water surface. So when comparing the H-ADCP data to observations made with the Aquadopp profiler, the depth of the two observations must be made consistent. To do this, NOAA tidal elevations (6-minute predictions) were downloaded and used to establish the fixed – absolute - elevations of the Aquadopp bins. A comparison of current velocity between the two sensors were then possible based on the absolute elevation of each measurement.

Also, the H-ADCP was configured for X-Y-Z coordinates (i.e. normal to and parallel to the pier face). The orientation of the X-axis was parallel to the pier face, with +values running left-to right (i.e. towards the west). The Y direction was normal to the pier face, with positive values running outward of the pier. The Aquadopp, on the other hand, measured in earth coordinates (east-north-up) since movement of the vessel (sensor) during the averaging interval may produce errors if not related to a fixed reference frame. When comparing the H-ADCP to Aquadopp current measurements, both data sets were rotated into the geographic, fixed-frame coordinate system.

The H-ADCP sampling parameters were:

Ensemble interval: 1 minute
Pings/ensemble: 30
Time between pings: 2 seconds
Bin size: 2 meters

Distance to first bin: 4 meters
Standard deviation (accuracy): 1.17 cm/sec

Regarding data completeness – there were problems with the H-ADCP memory card. These problems occur when the data are being written, with the unit essentially 'timing out' when trying to write data to memory, and are well-known to users of ADCPs. I've experienced this same problem numerous times, and is related to the ADCP firmware and certain types of memory cards. This problem causes the unit to suspend recording for a short time interval before resuming. Once resumed, a new data file is opened. This occurred 22 times during the deployment. In most cases the data gap was only a few minutes and could be interpolated through easily; however, on two occasions the gap was ~12 hours. It is unclear why. Unfortunately, the first 12-hour gap occurred during the weekend test with the Aquadopp, resuming data recording 12-March 01:20 hours. This resulted in approximately 31+ hours of over-lapping data for comparison.

Discussion

The graphics produced in this Appendix were intended to provide a quick look at the measured velocities. No editing or manipulation of the data were performed other than to remove invalid data before/after deployment (when the unit was out of the water), or removal of contaminated data due to acoustic reflection, mentioned above. Description of each graphic is included in the figure caption(s).

There were several interesting observations that resulted from the Aquadopp data set:

- Easterly flow was weaker than westerly flow – likely due to flow sheltering caused by presence of large tugboats forward of Ranger and upstream of the current meter. On the flood tides (flow towards the east) you can see from the vertical profiles (Figure A-7) that bottom flow appears stronger than near-surface flow, likely because flow beneath the tugs – at the near-bottom - is less affected by sheltering than surface and mid-depth layers.
- Saturday peak ebb was weaker than other ebbs, due probably to strong westerly winds blowing against the surface, applying an eastward-directed surface wind stress to retard near-surface flow. Peak flow during this tide was in mid-depth layers.
- Relative strength of consecutive tidal phases – a weaker tide surrounded by stronger tides – is due to natural tidal modulation of the principal lunar and solar semi-diurnal tidal constituents.
- Mean water temperature during the deployment was 4.9°C, and ranged from a high of 5.5°C to a low of 4.3°C.

We do see differences in the intensity of flood/ebb currents nearest to the MMA pier, particularly so on the easterly-running tide, which was slower than westerly currents. We presume the asymmetry near the pier face is due to flow blocking effects of the tugboats, which seems to have a downstream effect. On the westerly tide, flow very close to the pier was slowed significantly, presumably by frictional effects of the pier itself, but this effect appears to vanish 6-8m away.

There remains flow asymmetry between the flood and ebb, even in the center of the channel, with the westerly-flowing currents slightly faster than the easterly tides.

Comparison of the H-ADCP measurements to the Aquadopp Profiler (Figure A-13) – once these data were normalized and referenced properly – showed excellent agreement. The data were compared 'as is', no averaging or other manipulations were performed. The Aquadopp data appeared noisier/more variable than the ADCP results, but this could be due to the smaller sampling volume of the Aquadopp (20 cm vertical resolution) versus the larger sampling volume of the H-ADCP (2-meter horizontal resolution). Larger sampling volume is – in effect - a form of spatial averaging, so would smooth out variability due to small-scale turbulence.

Overlaying the flow speeds with NOAA tidal elevations we note an interesting thing – the time of slack currents do not coincide with the time of high or low water, which is a typical result for ocean tides. Instead, slack currents were found at the mid-tide elevations. This is characteristic of a progressive traveling wave; not the more-common standing tidal waves found in open ocean areas.

Figure A-1: Photograph looking eastward of the MMA M/V Ranger with pole mount off outboard rail. The Aquadopp profiler transducers were positioned approximately 16" below the surface. Stabilizer lines ran fore and aft to minimize vibrations. This photo was taken Saturday afternoon during strong westerly winds.

Figure A-2: Close-up of the Aquadopp profiler mounting. This photo was taken during an ebb (westerly) tide March 11, 2016 approximately 16:04 hours, just after installation. Note the strong wake coming off the instrument and mounting pole. Surface currents were measured to be 1.33 meters/second at this time (2.6 knots). Also note the relatively smooth water surface reflecting calm wind conditions, in contrast to the brisk winds of Figure A-1.

Figure A-3: Approximate location of the Aquadopp Profiler location relative to the MMA pier. Please note that the tugboats shown in this GoogleEarth image were in different positions during data collection; the M/V Ranger was docked in the approximate location of the larger tug in this picture. The larger tug was docked at the west end of the pier during data collection. The middle tug was in the approximate same location as shown.

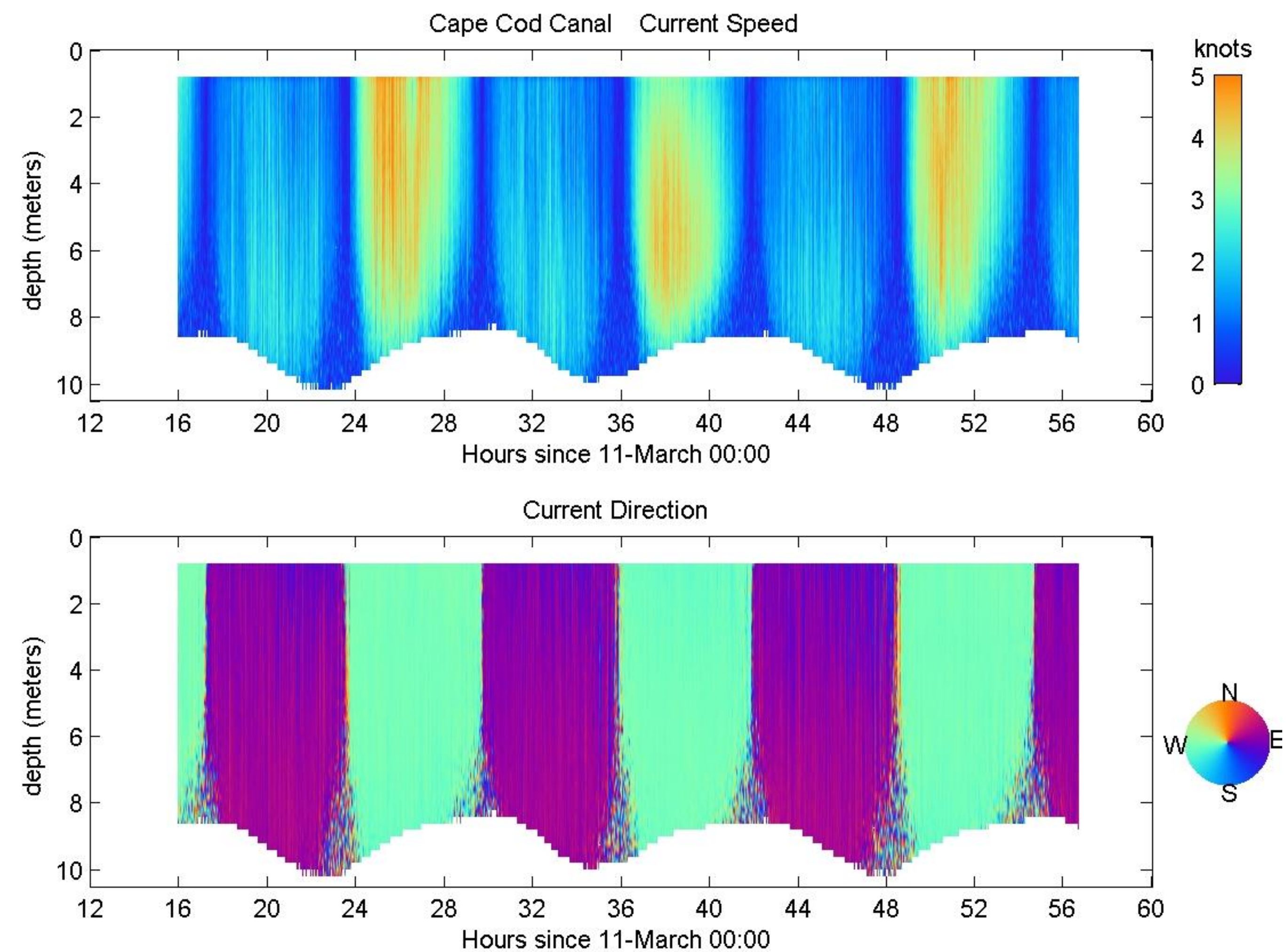


Figure A-4: Color-contours of current speed and direction during the Aquadopp deployment. The vertical axis of each plot represents depth below the surface. The horizontal axis represents time, in units of hours after 11-March 00:00 hours. For example, 36 hours would refer to March 12 at noontime. The magnitude of the signal is represented by color (speed in knots, and direction in degrees magnetic). The strongest currents were found during westerly (ebb) flow. Easterly flood currents were not as strong, possibly due to flow sheltering caused by large tugboats docked along the pier forward of the Ranger (to the west). The white spaces to the bottom of each plot represent acoustic interference with the seabed during the rise and fall of the tide.

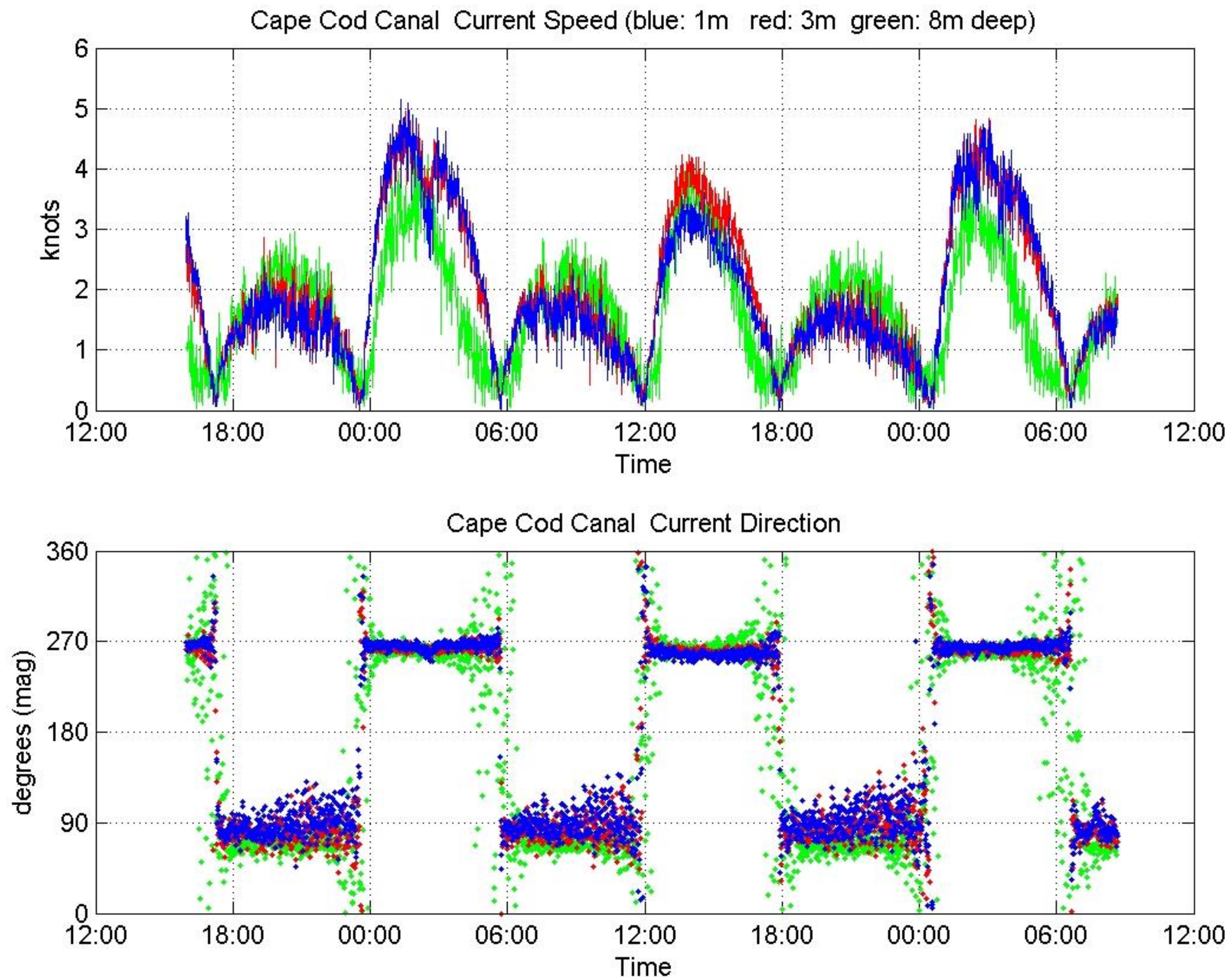


Figure A-5: Time series of current speed and direction from the Aquadopp at three (3) discrete depths: 1m deep (blue line), 3m deep (red line), and 8m deep (green). On the ebbing/westerly tides, the near-surface currents were strongest, exceeding 5 knots early Saturday morning (about 0200 hours). This was not the case for the mid-day ebb tide (about 1400 hours) – for this tide the mid-depth layer (3m) was stronger than the surface flow. The reason was likely wind stress from strong westerly winds slowing surface speeds. Flood – or easterly – tides were much weaker than westerly tides, again, likely caused by flow shading effects of the tugboats. Current direction was much noisier on the flood than on the ebb.

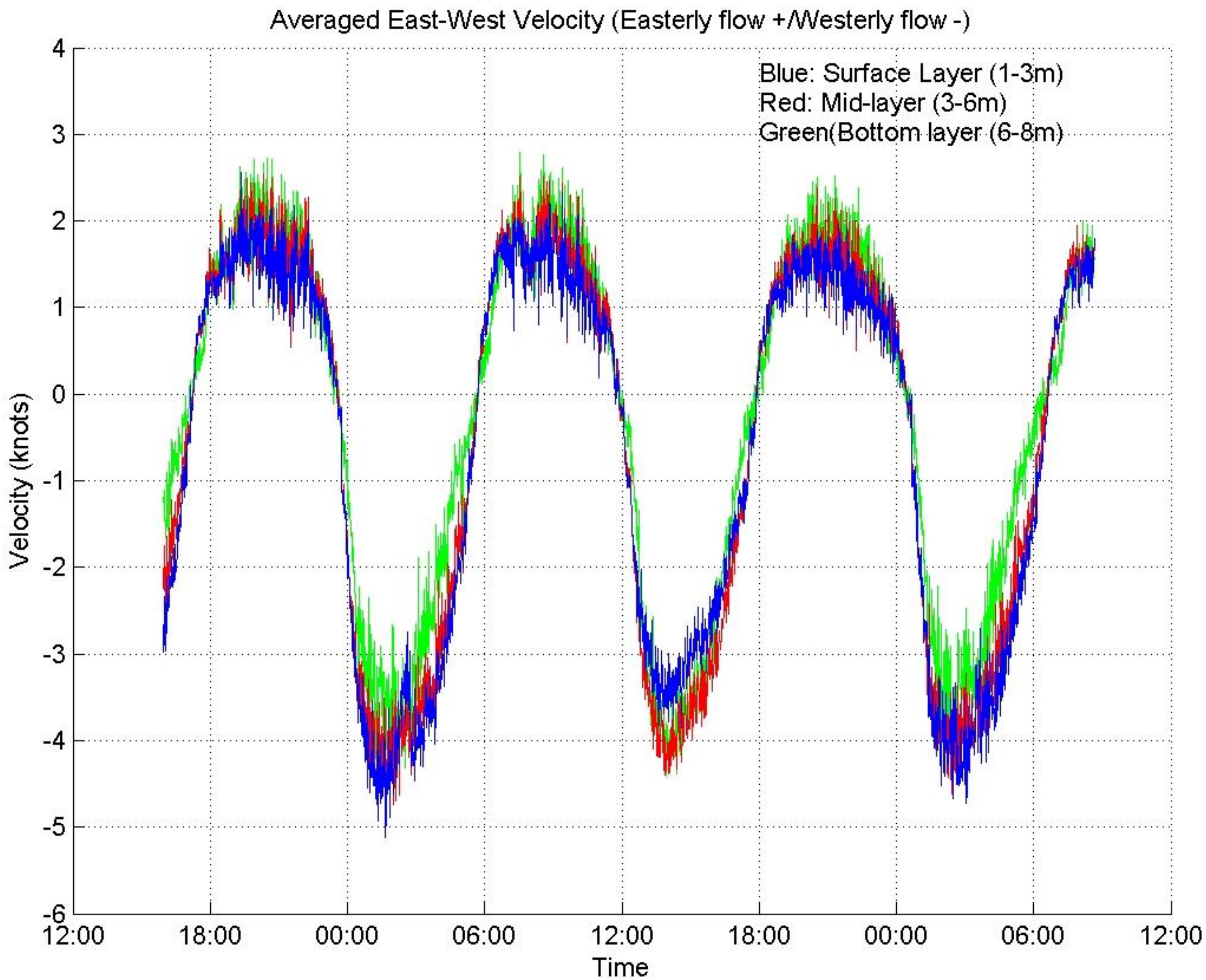


Figure A-6: Averaged east-west velocity component for three depth layers. These velocities resulted from an average of all bins between 1m to 3 m (surface layer, blue), 3m to 6m (mid-depth layer, red), and the bottom layer (6m to 8m, green). Positive-valued flow was eastward (flood); negatively-valued velocities were westward (ebb). This shows the relative strength of the westward tides versus eastward, as well as the relative noise levels between the opposing phases. Peak eastward flow showed higher variability (noise) than peak westward flow.

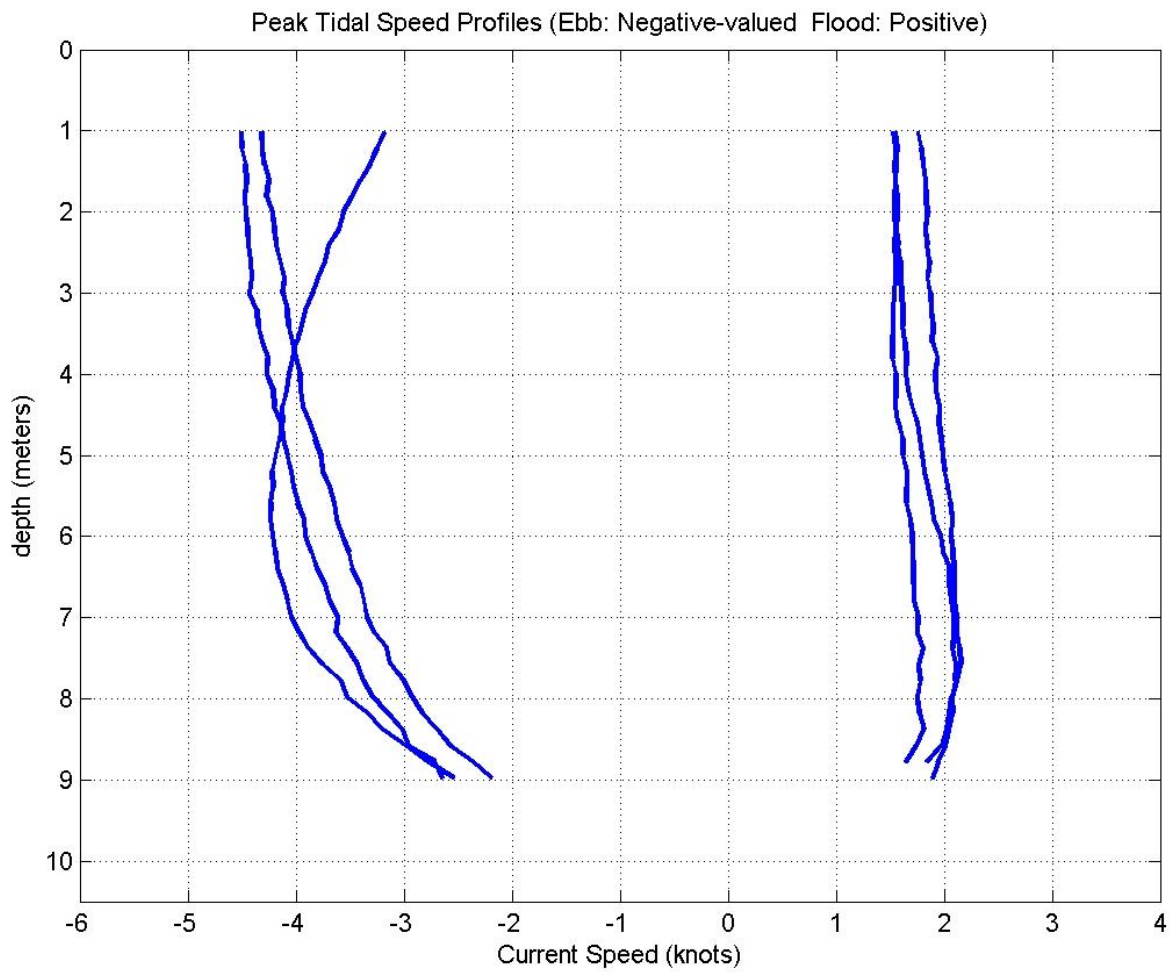


Figure A-7: Average vertical profiles surrounding peak ebb and flood tides for the three complete tidal phases. These average profiles resulted from a 30-minute temporal average (+/-15 minutes) around the time of peak flow. Note the difference in the ebb profiles (negatively-valued) where one profile shows higher speeds mid-depth versus near the surface. This particular curve is likely due to wind stress retarding near-surface currents. Flood (positively-valued) currents show higher speeds also in the lower water column, again likely due to flow shading from tugboats docked upstream of the current meter.

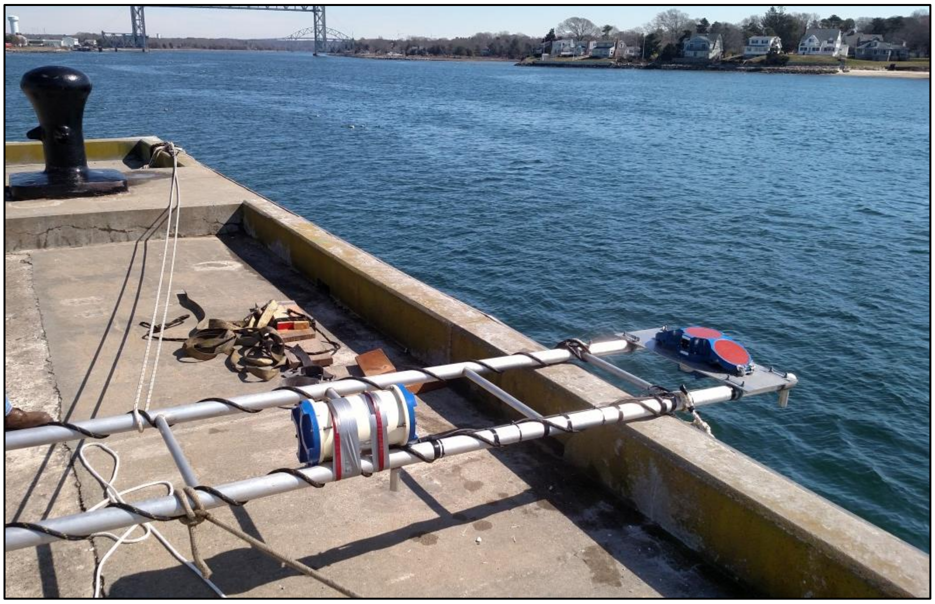


Figure A-8: Photograph looking eastward at the corner of the MMA pier, showing the H-ADCP (far right) mounted at the bottom of the mounting structure. The white canister (blue caps) is the external battery housing used to power the H-ADCP. The canister top was a distance 1.98m above the H-ADCP. The H-ADCP was installed at an elevation approximately -1.05m below the MLLW tidal datum.

Figure A-9: Photograph of the H-ADCP as installed. The battery canister is the only component visible. This photo was taken during slack tides on Thursday, March 17. The mounting structure was reasonably secure, assisted by using tensioning lines fore and aft. The H-ADCP measures orthogonal flow vectors - parallel to and normal to the pier face.

Figure A-10: Photograph of the H-ADCP mounting structure relative to the M/V Ranger following installation of both systems. The Aquadopp Profiler was mounted outboard of the vessel about midships (blocked from view, see Aquadopp report dated March 16). The H-ADCP was mounted at a distance of about 20m-25m laterally along the pier from the Aquadopp.

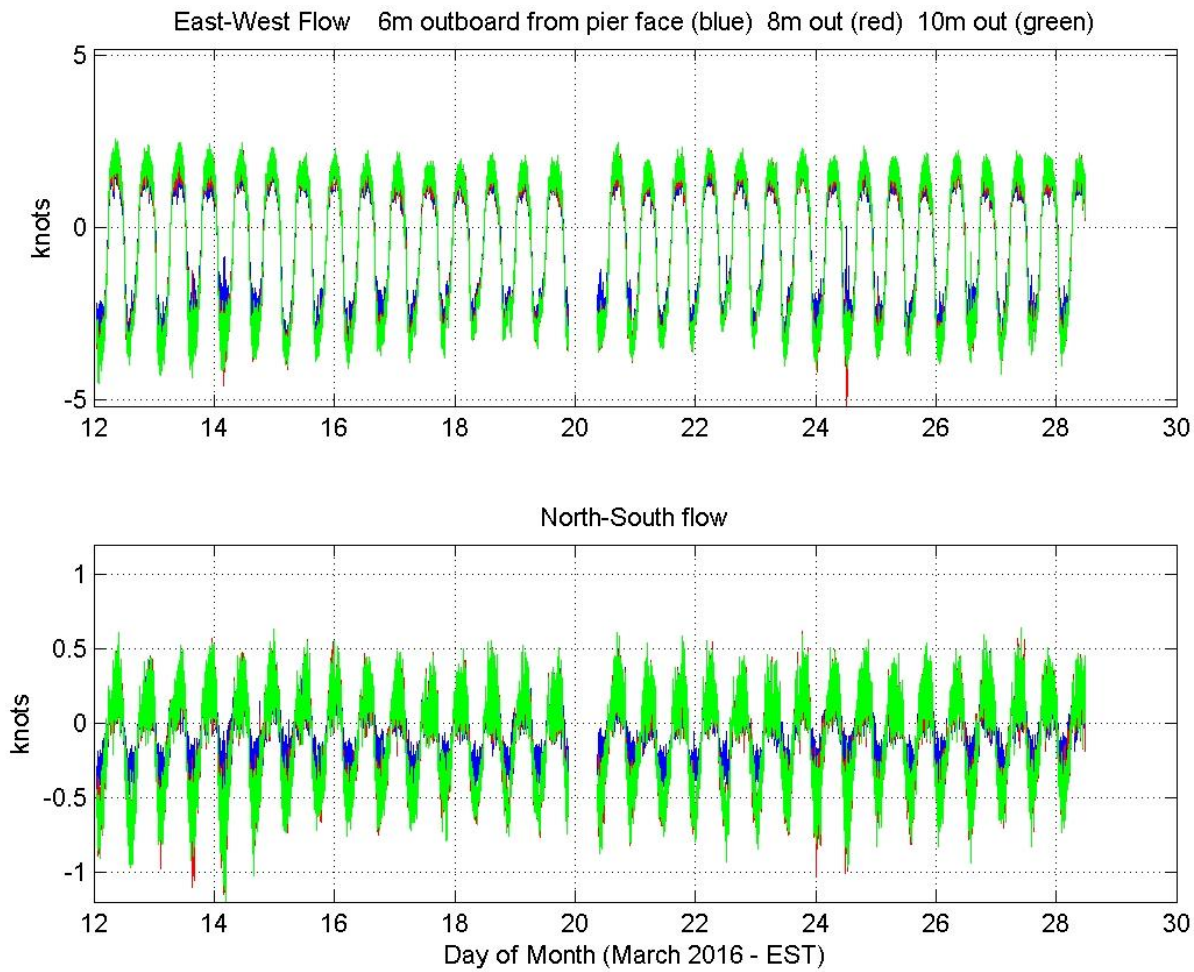


Figure A-11: Time series of current speed and direction at three (3) discrete distances outboard of the pier face: 6m deep (blue line), 8m deep (red line), and 10m (green). The bottom horizontal axis represents days in March 2016 (beginning March 12). The top plot represents flow east-west, or along-channel flow approximately parallel to the pier, where easterly-running currents are positive and westerly-running currents are negatively-valued. The bottom plot represents north-south flow, or approximately cross-channel. Positive-valued flows are north; negative flows are southerly. Note that currents appear to strengthen with increasing distance away from the pier face, (presumably) as frictional effects lessen. The gap in the middle of the plot represents data loss due to memory/recording problems of the H-ADCP electronics.

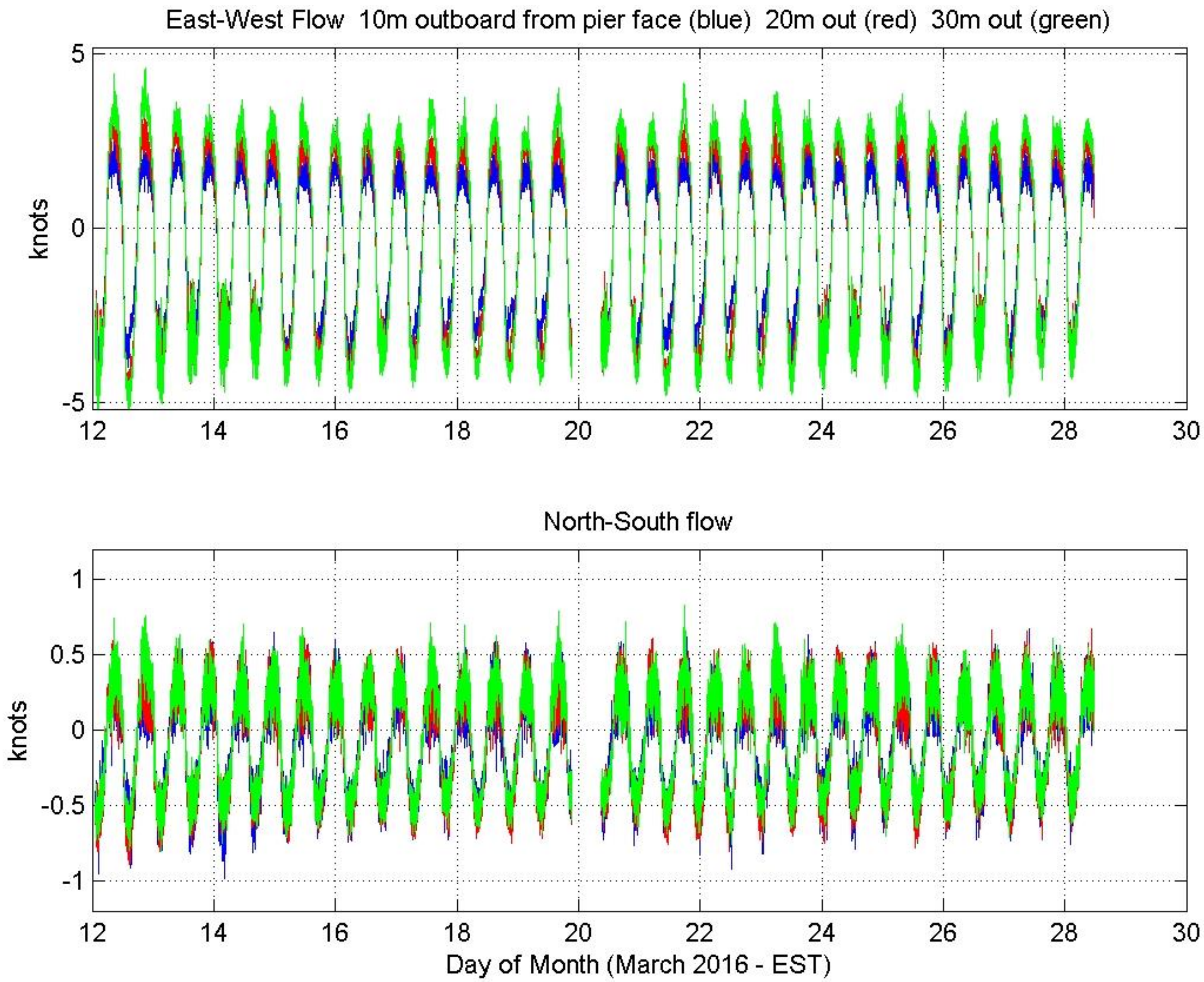


Figure A-12: Similar to Figure A-11 - time series of current speed and direction at three (3) discrete distances outboard of the pier face: 10m deep (blue line), 20m deep (red line), and 30m (green), illustrating the far-field flow variability. Note that currents appear to strengthen considerably with increasing distance away from the pier face, especially on the easterly tide. There was speculation, based on near-field current measurements, that tugboats along the pier blocked upstream flow, while westerly flows were not affected. Currents measured 30m away from the pier, presumably removed from the tugboat obstacles, approach the 5 knot threshold.

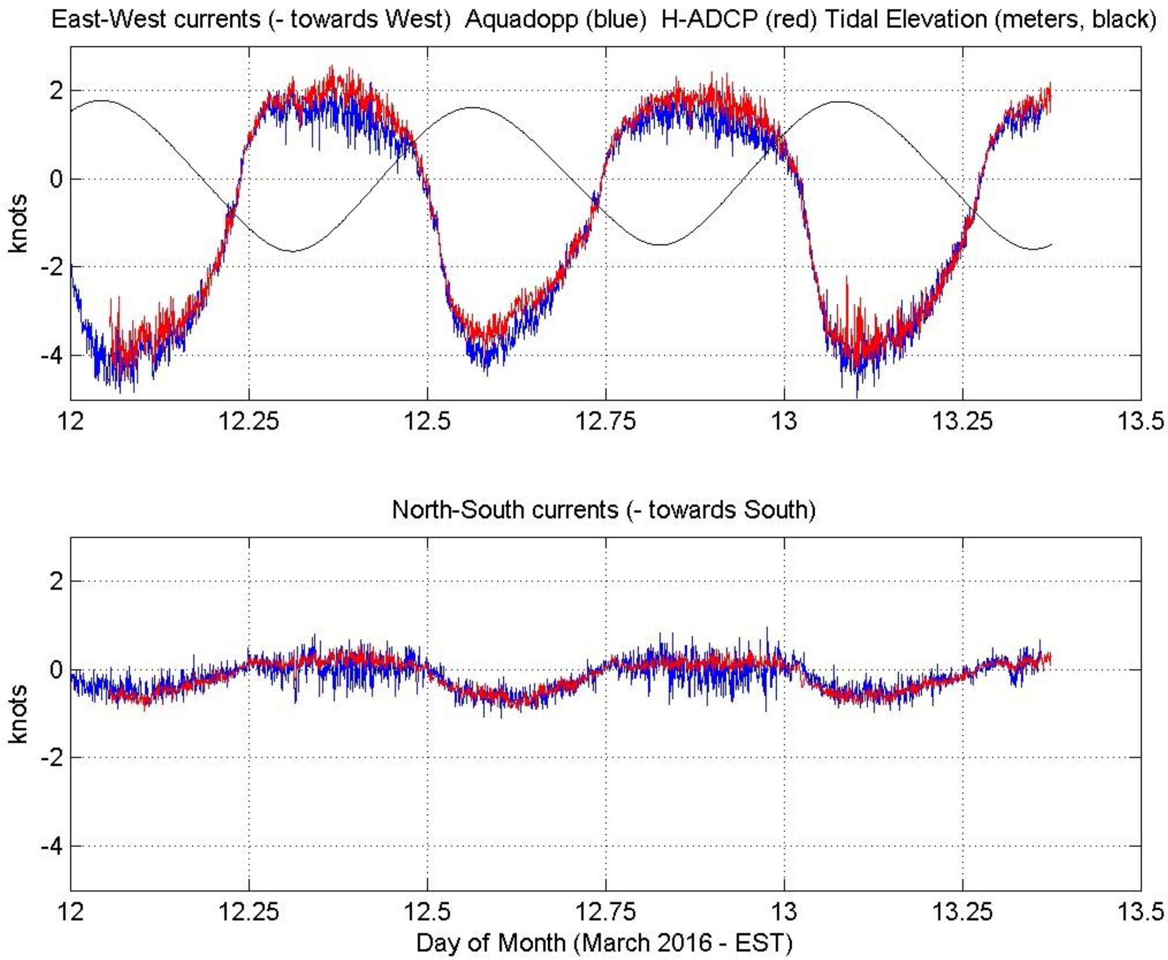


Figure A-13: Comparison of the Canal currents from the Aquadopp Profiler (blue lines) to the H-ADCP measurements (red lines). The top plot represents the along-channel (or east-west) flow while the bottom plot represents the north-south (cross-channel) flow. The different measurements – after reconciling changes in measurement elevation and coordinate systems – agree quite well with each other during the overlap times. The Aquadopp (blue) appears to have a noisier signal than the H-ADCP. The black line in the top plot represents mean tidal elevations (from NOAA). Note that slack water does not occur during high or low tide, rather, slack water appears to coincide with mid-tide. This is evidence that the tides in the Canal are progressive traveling waves (versus standing waves).

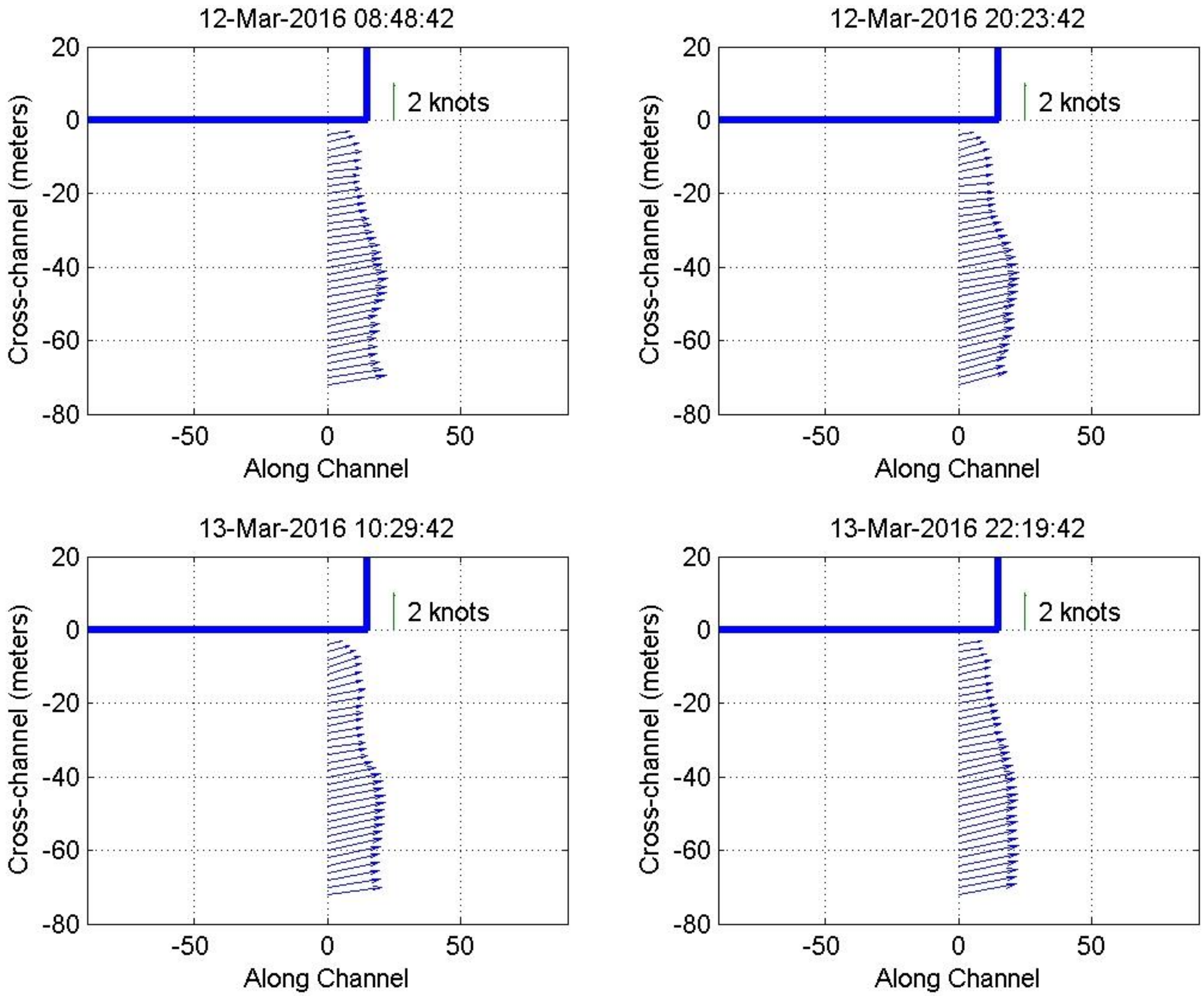


Figure A-14: Instantaneous flow vectors during four consecutive peak <u>easterly</u> tides. These are the original 1-minute samples; no averaging was performed. The heavy blue line represents the MMA pier, with the measured flow vectors depicted by arrows. A 2-knot scale arrow is shown. Note the flow gradient in the immediate vicinity of the pier face, which we surmise might be due to flow blockage from the tugboats.

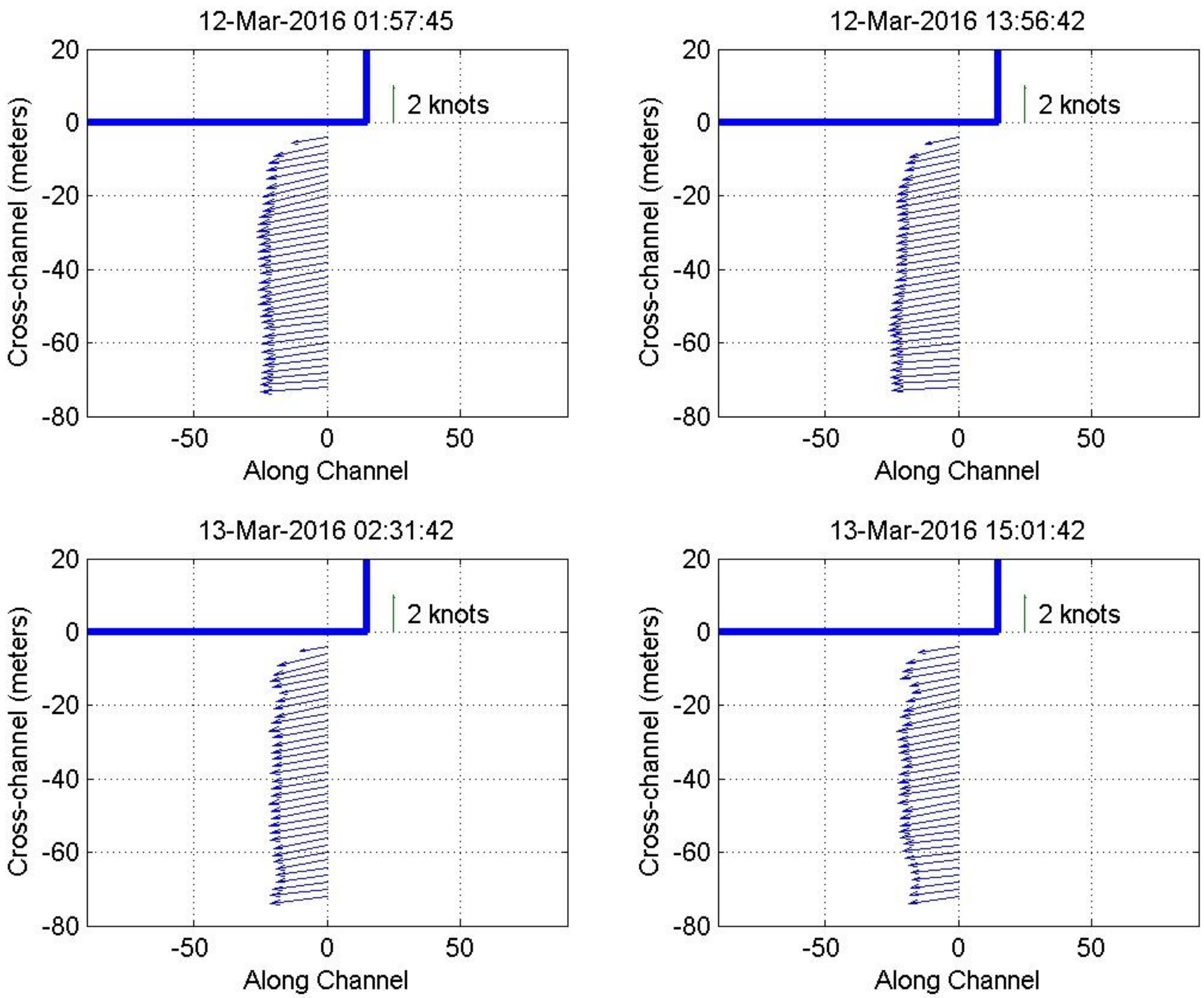


Figure A-15: Instantaneous flow vectors during four consecutive peak westerly tides. These are the original 1-minute samples; no averaging was performed. The heavy blue line represents the MMA pier, with the measured flow vectors depicted by arrows. A 2-knot scale arrow is shown. There is a flow gradient in the immediate vicinity of the pier face, but this seems to vanish at distances of ~6-8m.