Environmental Effects of Tidal Energy Development

Proceedings of a Scientific Workshop

March 22-25, 2010

Brian Polagye, Brie Van Cleve, Andrea Copping, and Keith Kirkendall, editors

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Marine Fisheries Service

NOAA Technical Memorandum NMFS F/SPO - 116

Environmental Effects of Tidal Energy Development

Proceedings of a Scientific Workshop

March 22-25, 2010

Editors: Brian Polagye[1], Brie Van Cleve[2], Andrea Copping[2], and Keith Kirkendall[3]

[1]University of Washington, Northwest National Marine Renewable Energy Center,
Box 352600, Seattle, Washington 98195

[2]Pacific Northwest National Laboratory, Marine Sciences Laboratory,
1100 Dexter Ave. N, Seattle, Washington 98109

[3]NOAA Fisheries, Northwest Region, Hydropower Division, 1201 NE Lloyd Blvd., Portland, Oregon 97232

U.S. Department of Commerce
Gary Locke, Secretary of Commerce

National Oceanic and Atmospheric Administration
Jane Lubchenco, Ph.D., Administrator of NOAA

National Marine Fisheries Service
Eric C. Schwaab, Assistant Administrator for Fisheries

April 2011

NOAA technical memorandum
NMFS F/SPO-116

Suggested citation:

Polagye, B., B. Van Cleve, A. Copping, and K. Kirkendall (editors). 2011. Environmental effects of tidal energy development. U.S. Dept. Commerce, NOAA Tech. Memo. NMFS F/SPO-116, 186 p.

A copy of this report may be obtained from:

Northwest Fisheries Science Center
NMFS, NOAA
2725 Montlake Boulevard East
Seattle, Washington 98112

Online at: *http://spo.nmfs.noaa.gov/tm/*

Table of Contents

List of Figures

List of Tables

Executive Summary

Tidal hydrokinetic energy has the potential to provide clean, reliable power, and emerging turbine designs are making production of electricity from ocean energy technologically and economically feasible. Tidal energy projects could be a viable renewable energy source, displacing fossil fuel-based energy resources, providing benefits to the marine environment through the mitigation of carbon dioxide production (which can lead to ocean acidification and climate change) and a reduction in the risk of catastrophic spills associated with fossil fuel extraction and transportation. However, the risk to the marine environment and marine organisms from tidal energy generation is not well known.

In order to appropriately site and operate tidal power installations and explore the potential contribution tidal power can make to a renewable energy portfolio, the environmental risks of the technology must be better understood. In doing so, it is important to distinguish between environmental effects and environmental impacts. *Environmental effects* are the broad range of potential measurable interactions between tidal energy devices and the marine environment. *Environmental impacts* are effects that, with high certainty, rise to the level of deleterious ecological significance.

This report summarizes the outcomes of a March 22-25, 2010, workshop in Seattle, Washington, on the environmental effects of tidal energy development. The workshop focused on building capabilities to evaluate the environmental effects of tidal energy from turbines placed in the water column throughout the United States. However, it did not address policy issues, details of technology engineering, or the socio-economic impacts of tidal energy development. The goals of the two-day meeting were to:

- Develop an initial assessment of the environmental effects of installation, operation, decommissioning, and maintenance of tidal power generating devices;
- Determine the specific marine organisms and system components that may be affected; and
- Develop a general framework of interactions against which specific tidal generation projects might plan their environmental assessments and monitoring programs.

Workshop participants were chosen from a representative cross-section of academia, research groups, regulatory agencies, and industry. These participants discussed the environmental effects of tidal energy development in the context of stressors (e.g., noise generated by device operation) and receptors (e.g., marine mammals in a project area). Stressor groups focused on attributes of one of the following stressors:

- Presence of devices: static effects;
- Presence of devices: dynamic effects;
- Chemical effects;
- Acoustic effects;
- Electromagnetic effects;
- Energy removal; and
- Cumulative effects.

Receptor groups focused on attributes of one of the following receptors:

- Physical environment: near-field;
- Physical environment: far-field;
- Habitat;
- Invertebrates;
- Migratory fish;
- Resident fish;
- Marine mammals;
- Seabirds; and
- Ecosystem interactions.

For both stressors and receptors, breakout groups evaluated the potential significance of stressor/receptor interactions and the uncertainty around each interaction. This evaluation was performed for pilot-scale deployments to identify critical gaps that should be resolved in the near-term, as well as for commercial-scale deployments to identify areas of long-term concern. In addition, each group called out a few high priority interactions and recommended approaches to monitoring stressor/receptor interactions and to mitigating environmental impacts.

Workshop participants identified a number of common challenges:

- Critical knowledge gaps hinder evaluation of environmental impacts.
- A lack of clearly identified research priorities leaves researchers and developers with little guidance about the most pressing stressor/receptor interactions.
- Technologies required to monitor high priority stressor/receptor interactions are underdeveloped and costly.
- Appropriate mitigation strategies for unavoidable environmental impacts are not well developed.

Workshop participants also made a number of recommendations to reduce critical uncertainties, mitigate for environmental effects, or develop strategic and coordinated technologies and capabilities:

- Understanding of many environmental impacts can be achieved only through careful monitoring of pilot-scale deployments.
- Priority research areas should be established for stressor/receptor interactions.
- The public sector must play a role in funding the study of high-priority stressor/receptor interactions, particularly for baseline assessments.
- The effort to share relevant marine energy information through the International Energy Agency's Ocean Energy System Implementing Agreement Annex IV should be continued, and other strategies to share data, while protecting intellectual property and proprietary information, should be developed.
- Analogous and existing data should be compiled and reviewed to avoid duplication of data collection and monitoring efforts, particularly for baseline monitoring.
- Project and device developers should work with oceanographers and other researchers to share and discuss monitoring data collection, modeling methodologies, and study results.
- Mitigation strategies may be used to reduce impacts to an acceptable level.
- Consistent, clear monitoring protocols should be developed and used by those conducting environmental research.
- Innovative approaches to monitoring instrumentation should be developed by partnerships among research institutions, industry, and funding agencies.
- Validated and calibrated ocean and hydrodynamic models can effectively address some critical uncertainties. Models are needed, both at the scale of a few turbines to address potential near-field effects and at regional scales to address potential far-field effects.
- Expanded opportunities for interdisciplinary collaboration are needed to promote improved experimental design and data collection.

Two overarching conclusions were identified. First, given the number of potential stressor/receptor interactions, research efforts must be prioritized and leveraged in order to effectively direct limited research dollars and resolve key uncertainties in a timely manner. Second, the next step to reducing critical uncertainties is careful monitoring of pilot-scale device deployments.

Participants found the structure of this workshop useful for eliciting and organizing potential environmental effects of tidal energy development and associated uncertainties. Future workshops on specific stressor or receptor topics were suggested, as the industry moves forward and the need to understand and mitigate environmental impacts becomes more important. Participants also suggested that additional workshops focused on policy and management issues associated with tidal energy development may be useful. Nearly 80% of participants agreed to a moderate or great degree that the workshop increased their understanding of the potential environmental effects of tidal energy.

This report contains recommendations relevant to tidal energy device and project developers, monitoring instrumentation developers, scientists, and regulatory agencies.

Acknowledgements

These proceedings describe the discussions and outcomes of a workshop modeled after a similar-workshop entitled Wave Energy Ecological Effects, held in Newport, Oregon, in 2007, and led by George Boehlert of Oregon State University. During that workshop, participants developed an initial assessment of the potential environmental effects of wave energy development off Oregon's coast.

The 2010 tidal energy workshop was organized by a steering committee of seven people: Brian Polagye, Research Assistant Professor, Department of Mechanical Engineering, Northwest National Marine Renewable Energy Center, University of Washington; Andrea Copping, Senior Program Manager, Marine Sciences Laboratory, Pacific Northwest National Laboratory; Keith Kirkendall, Chief of the FERC and Water Diversions Branch, NOAA Fisheries Northwest Region; George Boehlert, Director of the Hatfield Marine Science Center, Oregon State University; Sue Walker, Hydropower Coordinator, Alaska Region, NOAA Fisheries; Michelle Wainstein, Senior Program Coordinator, Washington Sea Grant, University of Washington; and Brie Van Cleve, Science and Marine Policy Analyst, Marine Sciences Laboratory, Pacific Northwest National Laboratory. George Boehlert participated in both the Oregon wave energy workshop and tidal energy workshop as a member of the steering committee. Keith Kirkendall also served on the steering committee and as a facilitator at the Oregon wave energy workshop.

The steering committee is grateful for the time and effort contributed by participants and, in particular, the workshop's 14 session chairs. Many thanks are also extended to the student note takers, who captured the details of free-flowing discussions in the breakout groups.

Thanks also to technical editor David G. Gordon of Washington Sea Grant, who applied the final polish to the report's text, and to graphic designer Robyn Ricks, also with Washington Sea Grant, who helped shape the report's design.

This workshop was made possible by generous support by NOAA Fisheries and the U.S. Department of Energy.

The conclusions and views expressed in this technical report are a synthesis of discussions that took place during the tidal energy workshop. The steering committee members summarized these discussions for the purpose of this report. The conclusions and views do not necessarily reflect those of the sponsoring agencies or the individual members of the steering committee. No endorsement of any tidal turbine or other technology is implied.

1. Introduction

The generation of power from the rise and fall of the tides dates back to at least the Middle Ages and, possibly, to the early Roman period (Charlier and Finkl 2009). A tide mill consisted of a storage pond, filled by the incoming tide through a sluice and emptied by the outgoing tide through a water wheel. The modern version of this technology is a tidal barrage, in which the waters of an estuary are impounded behind a dam in a manner analogous to conventional hydropower. Tidal barrages enjoyed substantial interest in the middle of the 20th century although, globally, only three sites are operational, because of the environmental impacts and high capital costs associated with this technology. More recently, development interest has focused on harnessing the kinetic energy in swift-moving tidal currents. This approach has the potential to generate power from the tides with fewer environmental impacts or economic challenges. Tidal power is the only form of energy that is derived directly from the gravitational interaction between the moon and sun and the earth's oceans. Because the gravitational forces depend on the predictable alignments of the celestial bodies, tidal power is also predictable to the first order (Polagye et al. 2010).

Currently, nearly 70% of the U.S. demand for electricity is met by burning fossil fuels, which are widely known for contributing to environmental impacts including degraded air quality, acid rain, ocean acidification, and global climate change. Over the past half-decade, the federal government has moved to align taxes, markets, incentives, and research funding to support development and use of renewable energy technologies. States have also played key roles in advancing policy to shift towards renewable energy. Twenty-nine states plus the District of Columbia have enacted renewable portfolio standards or renewable electricity standards requiring utilities to obtain a minimum percentage of their power from renewable sources by a given date. To satisfy this growing demand for renewable energy, utilities are pursuing a broad range of technologies. Over the past 10 years, land-based wind power has been the dominant technology, but utilities, regulators, and entrepreneurs are increasingly looking towards emerging technologies. These include attempts to harvest the power of the ocean.

Renewable ocean energy, which includes tidal current, ocean current, wave, ocean thermal energy conversion (OTEC), osmotic pressure, and offshore wind power, represents a significant resource for clean renewable electricity generation. The worldwide natural tidal dissipation is 3.7 terrawatts (TW), which is small in comparison to the 15 TW of global power consumption (Arbic and Garrett 2010). Because harnessing more than a fraction of this natural dissipation for electricity production would have profound consequences for regional tides, tidal energy should not be viewed as a "silver bullet" for global power generation needs. However, in comparison to the 0.3 TW of power produced by worldwide hydroelectric installations, the tidal resource potential is significant, particularly on a regional basis. Estimates of the practically recoverable tidal resource are limited to a few sites (e.g., Karsten et al. 2008 for Minas Passage, NS, Canada), and assessing the globally recoverable resource is an active area of academic research.

Hydrokinetic tidal power generation is geographically limited to those areas where tidal currents flow fast enough for generation. For semidiurnal tidal regimes, peak currents of 2 m/s may be sufficient for economic power generation. However, for mixed, mainly semidiurnal tidal regimes, peak currents of 3 m/s or greater are required to compensate for the diurnal inequality. In the U.S., some potential sites occur close to urban centers – in Washington's Puget Sound, the Gulf of Maine, especially near the Bay of Fundy, and Alaska's Cook Inlet near Anchorage. This proximity may enable tidal power to be the first of the new ocean energy technologies to be commercialized.

Tidal energy can provide clean, reliable power, and emerging turbine designs are making production of electricity from ocean energy technologically and economically feasible Tidal energy projects could be a viable renewable energy source, displacing fossil fuel-based energy resources, providing benefits to the marine environment through the mitigation of carbon dioxide production (which can lead to ocean acidification, climate change) and a reduction in the risk of catastrophic spills associated with fossil fuel extraction and transportation. However, the risk to the marine environment and marine organisms from tidal energy generation is not well known. In order to appropriately site and operate tidal power installations and explore the potential contribution tidal power can make to a renewable energy portfolio, a better understand of the risks of the technology will be required. Despite a positive policy environment and modest government investment in tidal power research and development, permitting of tidal device deployment remains a considerable barrier to advancement. The tidal power industry and regulators have identified poorly understood environmental effects as one of three top barriers to getting tidal devices in the water (Bedard 2008).

1.1 Workshop Overview

This report summarizes the outcomes of a March 22-25, 2010, workshop in Seattle, Washington, about the environmental effects of tidal energy development.

As tidal energy development is still in its early stages, there have not been sufficient data collected to predict the effects that pilot- and commercial-scale tidal projects will have on the marine environment. Until such data exist, the most promising method to address priorities for regulatory and research attention is to rely on the expertise and judgment of scientists and engineers with experience in various aspects of the technology, biota and habitats, and appropriate analogue industries. This workshop was designed to bring together that expertise from several nations and to address environmental effects through a structured process. As data become available to describe these effects in the future, the judgments and uncertainties recorded in this report can be replaced with better predictions and lower uncertainty.

The workshop followed the successful model used to address the environmental effects of wave energy development, held in 2007 in Newport, Oregon (described in Boehlert et al. 2008). It focused on building capabilities to evaluate the environmental effects of tidal energy from turbines placed in the water column throughout the U.S. The workshop did not address policy issues, details of technology engineering, or the socioeconomic impacts of tidal energy development; however separate meetings to address these topics were among the recommended next steps to come out of the workshop.

The goals of the two-day meeting were to:

- Develop an initial assessment of the environmental effects of installation, operation, maintenance, and decommissioning of tidal power generating devices;
- Determine the specific marine organisms and system components that may be affected; and
- Develop a general framework of interactions against which specific tidal generation projects might plan their environmental assessments and monitoring programs.

Workshop participants shared their understanding of tidal system effects, discussed the latest research in their areas of expertise, and contributed to a broad discussion of the environmental effects of tidal energy. The workshop format combined plenary talks and breakout groups targeting specific stressors (i.e., those factors that may occur as hydrokinetic tidal energy systems are installed, operated, or decommissioned) and marine receptors (i.e., those elements of the marine environment that may be affected by stressors). From their discussions, breakout groups generated summary papers for compilation into this report. These discussions incorporated knowledge acquired from better-understood analogues, such as ocean wind and undersea cable projects. These existing ocean technologies have established bodies of literature on environmental impacts that may be applicable to tidal generation installations.

Building on the workshop outcomes, this report provides an assessment of environmental effects on the marine systems in which tidal power may be generated, estimates risks to marine organisms and communities, estimates the uncertainties associated with our knowledge base, and provides recommendations for future research and monitoring needs. The workshop took a first step to systematically address the issues of concern and will help frame future discussions about the impact that tidal energy may have on the marine environment and marine organisms.

Workshop participants were drawn from a representative cross-section of universities, regulatory agencies, research laboratories, and industry. As shown in Figure 1, all groups were well-represented.

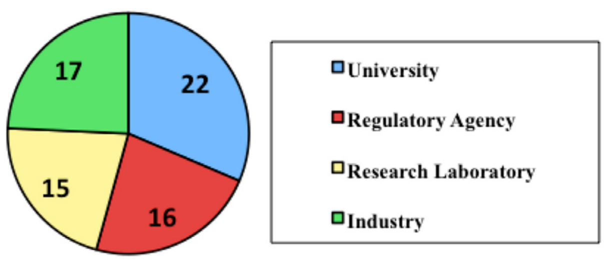


Figure 1 – Workshop participant affiliations.

As the outcomes of this workshop are intended to be broadly representative of tidal energy development in the U.S., it was important to have participants from a variety of regions with experience with or interest in tidal energy. As shown in Figure 2, a variety of regions were represented, although the majority of the participants were drawn from the U.S. West Coast (California, Oregon, Washington, and Alaska). This was a consequence of travel logistics, rather than an intentional geographic emphasis.

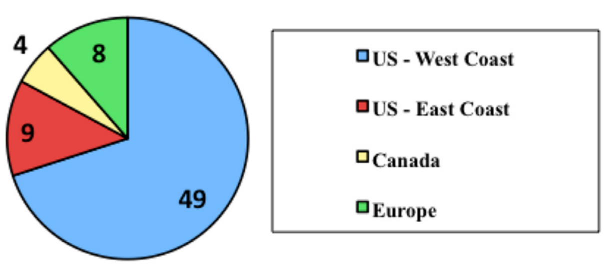


Figure 2 – Workshop participant geographic distributions.

The workshop was well-received by participants, as indicated by the results of a survey distributed to all participants. Complete results are included in Appendix E. Highlights include:

- 85% of participants rated the overall quality of the workshop as "very good" or "excellent";
- 75% of participants indicated the workshop increased their understanding of the environmental effects of tidal energy to a moderate or great degree; and
- 90% of participants indicated they were "somewhat likely" or "very likely" to apply the information learned at the workshop to tidal energy-related projects.

A complete list of participants and affiliations is included as Appendix C, and details of the workshop agenda are included as Appendix D.

1.2 Report Structure and Content

The report structure and content reflects input from a number of sources before, during, and after the workshop.

Section 1 provides background information on the regulatory framework for tidal energy projects and the technical aspects of tidal energy power generation, including engineering details on devices, site requirements, and summaries of device tests conducted to date. This section was written by the editors, with key narrative and device specifications provided by the profiled device developers.

Section 2 lays out the framework for evaluating environmental effects, including the distinction between impacts and effects and stressor/receptor organization. An overview of the type of environmental effects associated with tidal energy projects is given. Qualitative definitions of pilot and commercial deployments are also provided. This section was included in the original workshop briefing document but further modified by the editors after the workshop and, consequently, the narratives in Sections 3 and 4 do not universally adopt the described framework.

Sections 3 and 4 are the reports from each of the workshop's stressor and receptor breakout groups. Each subsection includes matrices describing the significance of and uncertainty around stressor/receptor interactions at the pilot and commercial scale. These matrices are augmented by narrative discussion and a more detailed consideration of high-priority stressor/receptor interactions. These sections were drafted by the session chairs with input from group participants. In places, the editors have inserted additional, clarifying narrative but deferred, whenever possible, to the original text. Because the breakout group discussions varied with participant expertise, allocated time, and the discretion of the group chair, the reported content also varies by subsection.

Section 5 describes common challenges for closing information gaps for environmental effects, and Section 6 presents recommendations for addressing these challenges and mitigating potential environmental impacts. These sections were written by the editors, based on the breakout group reports and further discussion with group chairs.

Section 7 concludes by providing a few final thoughts from the editors on the workshop and possible next steps.

1.3 Planning and Regulatory Context

The regulatory context for tidal power is complex and evolving. The Federal Energy Regulatory Commission (FERC) has the authority to issue licenses (both commercial and pilot) for all wave and tidal projects located on the outer continental shelf (OCS) and in state waters, while the Bureau of Ocean Energy Management Regulation and Enforcement (BOEMRE, formerly the Minerals Management Service) has the authority to issue leases, easements, and right-of-ways for wave and tidal projects located on the OCS. Because most tidal energy installations are likely to occur in state waters (within 3 miles of shore), FERC is the federal permitting agency. State resource management agencies and local governments play important roles through Coastal Zone Management Act consistency review, Clean Water Act consistency review, review under state codes, and leasing of state-owned bottom lands.

As part of the federal licensing process, the National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NOAA Fisheries), the U.S. Fish and Wildlife Service (USFWS), and the U.S. Army Corps of Engineers (USACE) consult with FERC under the authority of the Federal Power Act, Endangered Species Act, Magnuson-Stevens Fishery Conservation and Management Act, Migratory Bird Treaty Act, Fish and Wildlife Conservation Act, Marine Mammal Protection Act, National Environmental Policy Act, and Coastal Zone Management Act. The fact that multiple federal and state agencies are involved in permitting and regulating tidal power make for a complex leasing and licensing process. Uncertainty regarding potential environmental impacts of tidal energy development and impacts to other ocean uses further complicates the permitting process and may hamper expansion of the ocean energy industry.

There is a very strong need for integrated management at federal and state levels, as sectoral management continually fails to address the broad perspective needed for ecosystem-based management. Strategic Environmental Assessments (SEAs) have been used to good effect in Europe (e.g., SEA for marine renewables in Scotland) and Canada (e.g., SEA for development of tidal test facilities in the Bay of Fundy) to facilitate the siting and development of pilot and commercial-scale marine energy projects. The SEA provides a mechanism by which all environmental considerations for particular uses/programs (e.g., marine renewables) are integrated into policies at a regional or national level and directs public funding to regional scale baseline assessments. While no direct analogue exists in the U.S., the goal of ecosystem-based management is being pursued through a combination of marine spatial planning and adaptive management.

In response to concerns about environmental and competing ocean uses, in 2009 the Obama Administration initiated the development of a comprehensive ocean planning framework, Coastal and Marine Spatial Planning (CMSP). CMSP is seen by many in academia, the policy world, and stakeholders as a roadmap towards careful consideration of the tradeoffs among emerging ocean uses, existing uses, ecosystem protection, and a mechanism to provide regulatory certainty for ocean energy development. Spatial planning consists of two distinct phases: analysis of spatially referenced ocean data including resources and human uses, and a planning process to determine placement of various ocean uses (energy exploration, fishing, shipping, etc.). Several states, in coordination with federal agencies, have already developed marine spatial plans for state waters and, in some cases, beyond. A Presidential task force composed of the heads of multiple federal agencies released its *Interim Framework for Effective Coastal and Marine Spatial Planning in December 2009.* This framework, if expanded nationally, may help address management uncertainties and will provide a mechanism to resolve competing or incompatible ocean uses transparently and systematically.

Adaptive management may also be an effective tool for facilitating responsible project development. In the context of tidal energy generation, adaptive management should be a process that allows stakeholders to set goals and thresholds, and oversee and transparently evaluate results of pre-installation and monitoring studies. The results could be used in combination with information from other relevant sources to make adjustments to pre- and post-installation monitoring methods, as appropriate, and to manage or change aspects of the project operation, siting, scale-up, and goods and services trade-offs. This is intended to avoid or minimize unexpected or undesirable impacts on resources. The adaptive management process could allow for immediate action, if necessary to address critical environmental impacts of a project, should they occur. Environmental studies should focus on very explicit questions about the potential impacts and support addressing management issues within the adaptive management realm.

1.4 Tidal Power Technology Overview

Hydrokinetic tidal power is derived from the conversion of the kinetic power in moving water to electricity and depends on the area of water intercepted by the device (a circular area for a horizontal axis rotor, rectangular area for a vertical axis rotor), the *cube* of the water velocity, and the efficiency at which the device extracts the power in the water and converts it to electricity. Mathematically this is described as $P = \frac{1}{2}\rho U^3 A\eta$

where P is the power generated by the turbine, ρ is the density of seawater (nominally 1,024 kg/m3), U is the current velocity, A is the area of water intercepted by the device, and η is the water-to-wire efficiency of the device. Values for these parameters for a few devices installed to date are described in the following sections.

1.4.1 Device Components

Although there are a multitude of tidal energy devices under development, all hydrokinetic turbines include a set of common components: rotors, power train, mooring, and foundation. Additionally, all devices or arrays require electrical transmission to shore and protection against biological fouling. In most cases, devices are assembled on land to the extent possible (to minimize at-sea operations) and transported to the site by boat or barge (in some cases, purpose-built for device installation).

The following sections summarize information from a recent report to the U.S. Department of Energy (DOE) (Polagye and Previsic 2010).

1.4.2 Rotor

As with wind turbines, the rotor extracts the energy in tidal currents and converts it to rotating, mechanical energy. The axis of rotation may either be parallel to the flow direction (horizontal axis turbine) or perpendicular to the flow direction (cross-flow or vertical axis turbine). In both instances, the rotors typically have aerofoil cross-sections and operate on the principle of hydrodynamic lift. Drag-style devices are also possible but inherently less efficient.

There are a number of rotor variations that generally trade-off efficiency against simplicity and capital cost, including variable fixed pitch, asymmetric fixed pitch, and symmetric fixed pitch. Depending on the site characteristics, a horizontal axis turbine may incorporate a yaw control mechanism (active or passive) to keep the rotor aligned with the flow direction. Cross-flow turbines do not require yaw control.

For both horizontal axis and cross-flow turbines, it is theoretically possible to increase device efficiency by incorporating a diffusing duct downstream of the rotor. However, there are two potential complications. First, in practice, it is very difficult to design a functional diffusing duct, as evidenced by the fact that no commercial wind turbines incorporate diffusers. Second, because of the technical challenge of rotating the diffuser during slack water, separate diffusers are required both upstream and downstream of the rotor.

The rotational speeds of turbine rotors are limited by efficiency and cavitation considerations. Ideally, a rotation rate is achieved that allows an optimal tip speed ratio (the ratio of rotor tip velocity to current velocity). Depending on the rotor design, the optimal tip speed ratio may vary from 4 to 8. However, if the rotor tip speed is too fast, cavitation bubbles may form. Strong cavitation is undesirable because it reduces hydrodynamic performance, erodes the blade surfaces, and generates additional noise. While depth dependent, one rule of thumb is that tip speeds should be limited to 12 m/s (27 mph). For a 10 m-diameter turbine, this corresponds to approximately 20 rpm. Most devices proposed to date rotate at between 10 and 40 RPM.

1.4.3 Power train

Once the rotor has converted the kinetic power in the currents into mechanical rotation, a power train is required to further convert rotation to electrical energy. At a high level, power trains can be separated into those incorporating a gearbox speed increaser between the rotor shaft and electrical generator, those in which the rotor shaft is directly coupled to a generator, and those in which the connection between rotor shaft and generator is hydraulic. When gearboxes are used, the tonal frequency of the high-speed shaft may present a distinctive acoustic signature. The drive train configuration selected by a device developer must balance cost against reliability and efficiency. In nearly all cases, power electronics are required to condition the power output before interconnection with the grid. For example, the voltage may be stepped up from a few hundred volts at the device to 11-35 kV for transmission to shore.

1.4.4 Mooring

The rotor and power train must be moored to a foundation that resists the forces generated by the rotor. This mooring will either be rigid or flexible. Examples of rigid connections include piles similar to those used in the offshore wind industry or tubular truss structures. Because the amount of material required for a rigid mooring increases as the turbine moves up in the water column, the maximum hub height for a rigid mooring is limited by economic considerations (Kawase et al. 2010). Flexible moorings, consisting of cable or chain, have much lower material costs and do not limit hub height. However, a device with a flexible mooring must incorporate buoyancy control to offset the downward force generated by the device mass and variable tension on the mooring line during periods of device operation.

1.4.5 Foundation

Whether flexible or rigid, the mooring must be anchored to the seabed in a way that secures both the turbine and mooring against movement. One option is a penetrating anchor, such as a driven or drilled pile, that is secured in the seabed. For consolidated sediments or rocky seabeds, a penetrating anchor provides the most holding power for the smallest area disturbed. However, because the anchor is generally driven or drilled from the surface, installation in water deeper than 50-60 m may be uneconomical for a large-diameter pile. In contrast, a gravity foundation does not significantly penetrate the seabed but is held in place by its friction alone. Gravity foundations are lowered into position by a surface vessel and have a greater range of feasible deployment depths. However, for an equivalent resistive load, the footprint of a gravity foundation on the seabed is greater than a penetrating foundation. For either foundation variant, some seabed types may be susceptible to scour. This can be mitigated, for example by scour mats, but may increase the seabed area disturbed by installation.

Depending on the number of devices installed and the type of foundation, installation may require anywhere from a few hours (single device, gravity foundation) to longer than a year (large array, pile foundation).

1.4.6 Electrical Transmission

Electrical transmission from devices to shore is an integral aspect of any tidal energy project. The near-shore area adjacent to a tidal energy project may contain particularly sensitive ecology that could be disturbed by trenching a cable into the seabed. For example, in unconsolidated sediments, trenching involves burying cables to a depth of 1 to 3 m beneath the seabed, using a jet-plow technique. For tidal energy projects, the preferred option is to utilize horizontal directional drilling (HDD) from the on-shore cable termination point (i.e., substation) seaward beyond the nearshore region (i.e., the cable will exit onto seabed at the 15 to 20 m isobath). The feasibility of directional drilling is site-dependent, not appropriate in all sediment types, and requires a careful geotechnical evaluation. Currently, maximum conduit length is limited to a few hundred meters.

The portion of the subsea cable crossing the seabed may be trenched, weighted, or bolted down (depending on the type of substrate) to prevent movement. In some cases, the weight of the cable alone may be sufficient to accomplish this. A similar approach is used to secure the cable between devices. The umbilical cables required to connect turbines to shore are comparable to those used in the offshore oil and gas industry and for the inter-connection of different locations or islands.

1.4.7 Fouling and Corrosion Protection

Fouling from biological growth on devices is a significant performance risk (Orme et al. 2001) and structural risk. Turbines operating below the photic zone may be at lesser risk; however, fouling by barnacles, algae, and other organisms remains an issue for any deployment with a long maintenance interval. Working surfaces are generally treated with an anti-fouling or foul-release coating. Possible coatings include conventional biocide paints and inert, low-friction coatings. For economic or environmental reasons, other components of the foundation and support may remain uncoated, with sacrificial anodes providing corrosion protection.

1.5 Tidal Power Siting

Although each tidal energy site is unique, there are a number of common features that will affect deployment. New approaches to power extraction and device anchoring may expand the range of operationally feasible sites.

1.5.1 Tidal Resource

The tidal current speed that will support economically viable development depends on site and device-specific characteristics, but, generally, current velocities should be greater than 2.5 m/s (5 knots) on ebb and flood. Devices generally begin to generate power around 0.8 m/s (1.5 knots), but, because kinetic power depends on the *cube* of velocity, most power generation occurs closer to peak currents. Although faster currents are desirable, high-speed flows in very narrow channels (e.g., < 100 m width) are often accompanied by high levels of turbulence. Wind energy analogues indicate that power production will decrease under strongly turbulent conditions and device lifetimes will be shortened by increased fatigue. Because of irregularities in topography and bathymetry, high-speed flows tend to be localized and occur with significant spatial variability (e.g., 0.5 km). This is in sharp contrast to wave energy, where more uniform, energetic resources occur over a broad geographic extent. Other aspects of tidal resource characteristics of significance for siting are discussed in Gooch et al. (2009).

1.5.2 Deployment Depth

Because the tidal current boundary layer adjacent to the seabed is less energetic than the surrounding current, devices should be positioned far enough above the seabed to avoid this layer. The boundary layer profile is site dependent, but, generally, the device should not be placed in the bottom quarter of the water column. Devices deployed higher in the water column are able to generate more power, but foundation costs are also higher (Kawase et al. 2010). Deployment depths for pile-anchored foundations are currently limited by economic considerations to 50 m (164 ft) water depth. In theory, gravity-anchored foundations have no maximum deployment depth, but, to date, device developers have not recommended deployments deeper than 80 m (263 ft) for operational reasons. Turbine hub height is also limited for gravity foundations because of the difficulty in resisting overturning moments for devices high in the water column. The shallowest sites that have been considered for development are approximately 10 m (33 ft) in depth, which can accommodate turbines up to 5 m (16 ft) in diameter. Shallower sites simplify installation and maintenance activities but increase the risk of biological fouling of the device due to proximity to the photic zone and may pose a hazard to vessel traffic. If devices are to be sited below a commercial shipping lane, overhead clearance of 15 to 25 m (49-82 ft) will be required, at a minimum.

1.5.3 Commercial Arrays

To date, most tidal energy installations have been single devices, used to prove the technical readiness and assess environmental effects of a particular design concept. The sole exception, to date, is the Verdant Power RITE project, which involved an array of six devices arranged in three rows of two (Note: because of the size and short duration of this project it is still considered a pilot deployment, rather than a commercial deployment). Without experimental data, optimum array layouts at commercial scale are speculative and derived primarily from wind energy analogues. As a consequence of kinetic power extraction, a low-speed wake will occur downstream of each device. At some distance downstream of the device, the wake will mix with the bulk flow, restoring homogeneous conditions. The distance depends on the rotor size, device efficiency, and background turbulence. A tidal energy device deployed directly in the wake of another device will suffer significant performance loss, and, consequently, wake persistence is a significant factor in device spacing for commercial arrays. Downstream device spacing of 5-10 rotor diameters has been suggested as the minimum required to prevent wake interactions. The minimum lateral spacing is shorter, perhaps as little as half the rotor diameter. It is theoretically possible to reduce the downstream spacing by staggering successive rows of devices, but this has not been demonstrated in practice for either wind turbines or tidal turbines. Colby and Adonizio (2009) provide an overview of numerical and experimental efforts by Verdant Power to characterize the hydrodynamic disturbance from turbines in an array and highlight the challenges of both methods.

Commercial feasibility studies (e.g., Polagye and Previsic 2010) have proposed array layouts consisting of regular rows of turbines with uniform lateral and longitudinal spacing. Devices are assumed to be spread across a channel to the extent permitted by the tidal current resource, bathymetry, rotor diameter, and allowances for navigation. From a resource extraction standpoint, arrangements that maximize the blockage ratio of an array (the ratio of device swept area to channel cross-sectional area) are desirable, as high blockage ratios enhance turbine performance (Garrett and Cummins 2007). However, this arrangement may not be desirable from the standpoint of environmental risk due to both a greater risk of strike to fish and marine mammals and elevated energy removal effects due to higher losses when the wake mixes with the free stream (Garrett and Cummins 2007). Conversely, isolated clusters of turbines may be desirable environmentally, but, at commercial scale, would reduce the power-generation potential as high-speed flows are diverted around the cluster. Similarly, increasing the lateral and longitudinal separation between devices could reduce environmental risks but lead to inefficient resource utilization.

Without further studies to understand these environmental and performance trade-offs, these issues cannot be definitively resolved and are presented here as examples of the challenges associated with commercial array siting. Of particular concern are environmental risks that may not be significant at the pilot scale but could be substantial for a commercial installation. For example, the effects of noise generated from tidal energy devices may have minimal, site-specific impacts at the pilot-scale, but noise produced from a 100-trubine tidal energy park may be loud enough over a large enough area to alter migration patterns of marine fish, invertebrates, and mammals (DOE 2009).

1.6 Tidal Energy Devices

As of March 2010, there are over 60 distinct technologies included in DOE's Energy Efficiency and Renewable Energy (EERE) hydrokinetics database. However, only a handful of these have been deployed at sea for extended durations. These devices are discussed in more detail in the following sections. They remain under active development, and the specifications for these demonstrations should not be inferred to be applicable to all possible site developments. In addition to technical enhancements, site-specific factors are likely to be incorporated into device designs. In order to simplify the comparisons between different installations, the approximate power output of each device is given at a reference speed (2.5 m/s). Not included is the Marine Current Turbines SeaFlow device, which has been superseded by the larger SeaGen project.

1.6.1 Clean Current – Race Rocks (Race Rocks, British Columbia)

The Clean Current turbine is a horizontal axis rotor enclosed by a diffusing duct (Figure 3). The power train is a direct-drive permanent magnet generator around the open-center rotor hub. A 6 m diameter prototype unit has been intermittently operated at Race Rocks, British Columbia, in cooperation with Pearson College. This prototype is secured to the seabed by a rigid, penetrating monopile. A larger commercial prototype planned for installation in the Bay of Fundy in 2012 will utilize a gravity foundation. Environmental studies associated with this project have focused on disturbances associated with device installation (e.g., seabed disturbance associated with foundation and cabling, noise from drilling) are available through the project Web site. Clean Current is based in Canada.

Figure 3 – Clean Current Turbine, Clean Current Power (Source: EERE 2010)

1.6.2 Hammerfest-Strom – Tidal Stream Turbine (Hammerfest, Norway)

The Hammerfest-Strom Tidal Stream Turbine is a three-bladed horizontal axis rotor with pitch control (Figure 4). The alignment of the rotor to the flow is fixed (no yaw control), but the rotor pitch is changed by 180 degrees during slack water to accommodate bi-directional tidal flows. The device was installed in 2003 at a depth of 50 m in Kvalsundet, Norway, off Hammerfest and has been operational since 2003. Virtually no information (device specifications or environmental monitoring) regarding this project is in the public domain. Hammerfest-Strom is based in the United Kingdom.

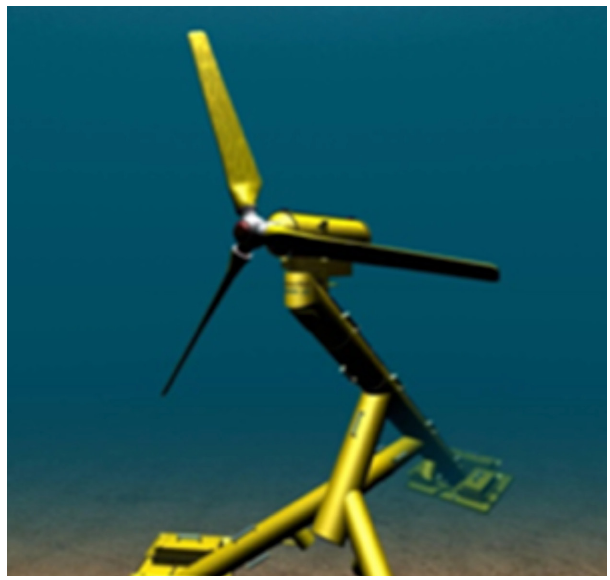


Figure 4 – Tidal Stream Turbine, Hammerfest Strom UK (Source: EERE 2010)

1.6.3 Marine Current Turbines – SeaGen (Stranford Lough, Northern Ireland)

The Marine Current Turbines' SeaGen is a two-bladed horizontal axis rotor with pitch control (Figure 5). The alignment of the rotor to the flow is fixed (no yaw control), but the rotor pitch is changed by 180 degrees during slack water to accommodate bi-directional tidal flows. The power train is a variable speed gearbox coupled to an induction generator. Each device consists of two rotors connected to a monopile foundation by a wing-shaped crossbeam. The monopile is surface-piercing and the above-water structure houses power electronics and an integrated lift mechanism to raise the rotors out of the water for routine inspection and maintenance. Marine Current Turbines Ltd. is based in the United Kingdom.

For the Strangford Lough project, the monopile is secured to the seabed by a pin-piled quadrapod. Specifications for the device deployed in Strangford Lough are given in Table 1. Per the requirements of its operating permit, Marine Current Turbines Ltd. and its partners are carrying out environmental monitoring of project effects, including: porpoise behavioral changes, using passive acoustics (echolocation hydrophones); seal behavioral changes, using telemetry tags; changes in marine mammal and bird presence, using shore-based observers; noise generated by turbine operation and installation; and disturbances to the benthos from the physical presence of the device. Some of the information being collected is proprietary to Marine Current Turbines Ltd., but some is also in the public domain.

Because of the potential for a protected population of harbor seals to be affected by turbine operation, a mitigation plan was enacted within an adaptive management framework by MCT and Irish regulators. This has proceeded through three phases.

During the first phase, from June 2008 to August 2009, turbine operation was restricted to daylight hours. A marine mammal observer stationed atop the monopole identified seals approaching the turbine and initiated device shutdown when a seal was within a specified distance. Initially, this shutdown distance was set at 200 m, but once the capability for rapid shutdown was well-established (e.g., from full power to full stop within several seconds), the shutdown distance decreased to 100 m in December 2008 and to 50 m in April 2009. During this period, a scanning active sonar (Tritech Super SeaKing DST) was validated as an alternative tool for detecting harbor seals in the vicinity of the turbine.

During the second phase, from August 2009 to April 2010, the marine mammal observer on the pile was replaced by an active sonar operator on shore (the effectiveness of the active sonar having been evaluated during the first phase of operation). Although operation continued to be restricted to daylight hours, the sonar was used to assess differences in harbor seal activity between day and night, with approximately 200 hours of nighttime activity analyzed. In January 2010, the operational window increased from the five-day work week to seven days per week and an additional hour of operation allowed before sunrise and after sunset.

The third phase began in April 2010 and is the current operational state, as of late 2010. During this phase, operation 24 hours a day, 7 days a week is permitted. Shutdown distance, as informed by the active sonar, also decreased from 50 m to 30 m. Because of the mitigation requirement for temporary shutdown when seals may be at risk, this approach does not monitor for blade strike.

MCT is currently working with regulators to remove the sonar requirement, using statistical analyses of data collected to date.

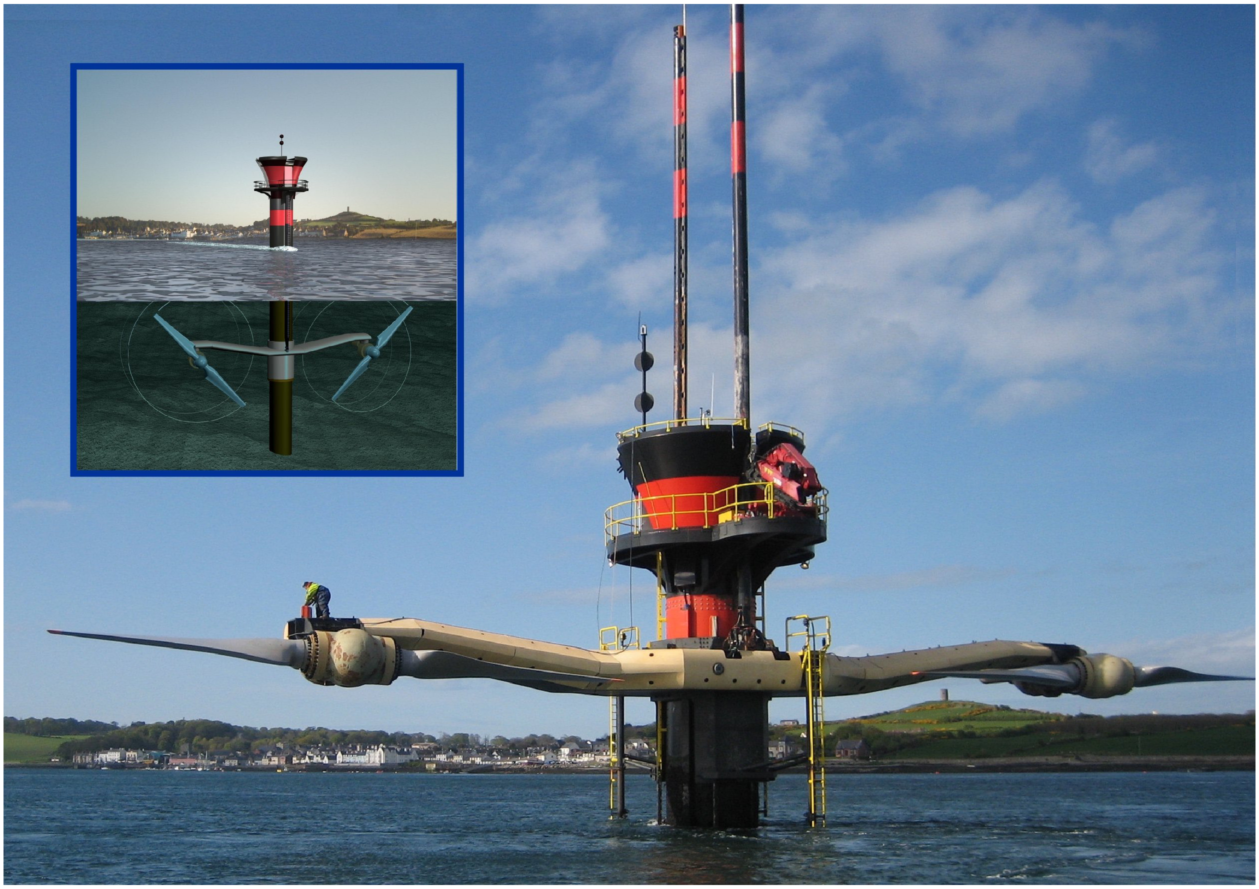


Figure 5 – SeaGen, Marine Current Turbines (Source: Marine Current Turbines)

Table 1 – Marine Current Turbines device specifications (Strangford Lough demonstration)

Specification	**Value**
Rotors per foundation	2
Rotor diameter	16 m
Rotor swept area (rotor area *x* rotors per foundation)	402 m^2
Water-to-wire efficiency	50%
Cut-in speed	0.7 m/s
Approximate power output at 2.5 m/s	1600 kW
Maximum operating rotation rate	14.3 rpm
Hub height (relative to the surface)	11 m
Hydraulic fluids or lubricants	110 L (gearbox lubricant)
Total device weight	900 tonnes (in air)
Footprint on seabed (direct contact area)	3 m^2
Estimated maintenance interval	24 months
Component design life	20+ years

1.6.4 Ocean Renewable Power Company – OCGen TGU (Eastport, Maine)

The Ocean Renewable Power Company (ORPC) Turbine Generator Unit (TGU) is a cross-flow turbine (Figure 6). Power generation is accomplished by a variable speed, direct-drive generator. ORPC's TidGen device consists of a single TGU anchored to the seabed by a gravity support frame (Figure 7). ORPC is also developing a larger OCGen module in which individual TGUs are attached together and float in the water column secured to a seafloor foundation by compliant mooring cables. Specifications for the TidGen device are given in Table 2. ORPC is based in the United States and is developing projects in Maine and Alaska.

Figure 6 – ORPC Beta TGU (Source: Ocean Renewable Power Company)

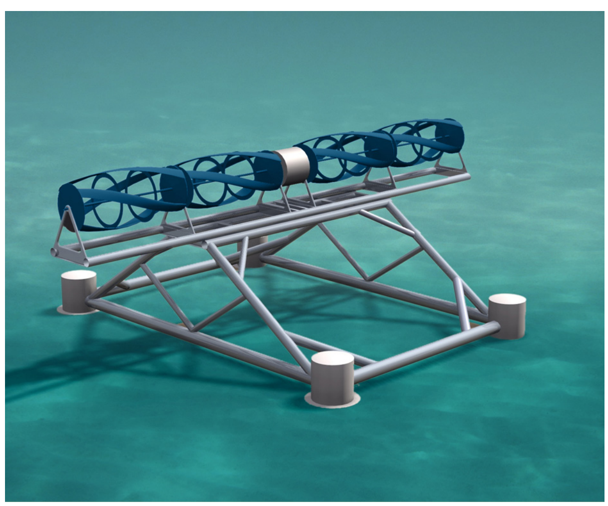


Figure 7 – ORPC TidGen (Source: Ocean Renewable Power Company)

Table 2 – ORPC device specifications

Specification	Value
Rotors per foundation	4
Rotor length	5.6 m
Rotor diameter	2.6 m
Rotor swept area (rotor area *x* rotors per foundation)	58 m^2
Water-to-wire efficiency	30%
Cut-in speed	1 m/s
Approximate power output at 2.5 m/s	140 kW
Maximum operating rotation rate	40 rpm (at 3 m/s)
Hub height (relative to the seabed)	10 m
Hydraulic fluids or lubricants	0 L (3 oz of bearing grease)
Total device weight (including foundation)	60 tonnes (in air)
Footprint on seabed (direct contact area)	11 m^2
Estimated maintenance interval	12 months
Component design life	15 years

1.6.5 OpenHydro – Fundy Demonstration (Minas Passage, Nova Scotia)

The OpenHydro turbine is a high-solidity horizontal axis rotor with symmetric, fixed-pitch blades. The alignment of the rotor to the flow is fixed (no yaw control). Power generation is accomplished by a variable speed, direct-drive permanent-magnet generator incorporated into the enclosing shroud. The center section of the rotor is open. The turbine is secured to the seabed by a tripod gravity base. Specifications for the 10 m (1 MW peak power) device recently deployed in the Bay of Fundy (Figure 8) are given in Table 3. Environmental monitoring of this device is being conducted as an independent activity by the Fundy Ocean Research Centre for Energy (FORCE), a non-profit institute that owns and operates a facility where tidal turbines are tested and demonstrated. OpenHydro also operates a grid-connected test facility at the European Marine Energy Centre (EMEC) in Orkney, Scotland, where it tests its turbine technology at 6 m (250 kW) scale for performance and environmental effects. Environmental monitoring results are proprietary to OpenHydro, which is based in Ireland.

Figure 8 – OpenHydro 10 m (1 MW peak power) Bay of Fund Turbine (Source: OpenHydro)

Table 3 – OpenHydro device specifications (Bay of Fundy demonstration)

Specification	**Value**
Rotors per foundation	1
Rotor diameter	10 m
Rotor swept area (rotor area *x* rotors per foundation)	78 m^2
Cut-in speed	0.7 m/s
Approximate power output at 2.5 m/s	200 kW
Maximum operating rotation rate	12 rpm
Hub height (relative to the seabed)	10 m
Hydraulic fluids or lubricants	0 L
Total device weight (including foundation)	360 tonnes (in air)
Footprint on seabed (direct contact area)	10 m^2
Planned installation period	2 years (Fundy Demonstration specific)
Component design life	25 years

1.6.6 Verdant Power – RITE (East River, New York)

The Verdant Power Kinetic Hydropower System (KHPS) is a three-bladed horizontal axis rotor that passively yaws to keep the rotor aligned with the mean flow direction on ebb and flood (Figure 9). For the Roosevelt Island Tidal Experiment (RITE), six turbines were supported by streamlined monopile foundations that were drilled into the seabed. For economic reasons and depending on water depth and seabed composition, future deployments will likely be anchored by gravity foundations; either in a single or triframe (three turbines per foundation) configuration. The six-turbine array installed for the RITE project is the only demonstration of a tidal turbine array in the world. Specifications for the RITE devices (Gen4), as well as specifications for the next generation (Gen5) machines, which are undergoing final design, are given in Table 4. The Gen5 machines will be installed as part of the next phase of the RITE project (30 KHPS for 1 MW-rated capacity; estimated in 2012) and other sites. The RITE project included extensive environmental monitoring, such as the use of hydroacoustic arrays to monitor fish presence, abundance, behavior, and potential interaction with KHPS turbines. Data from this monitoring effort is presented in regulatory documents filed for the next phase of the RITE project (available at *www.theriteproject.com)*. Verdant Power is based in the United States.

The permitting requirements for the RITE project included an extensive effort to characterize the risk of strike, aggregation, and avoidance posed to fish by an array of turbines. To this end, Verdant Power and its consultants deployed four types of hydroacoustic instrumentation:

- A fixed array of 24 split-beam transducers providing coverage of the turbines and near-field (out to 12 rotor diameters). Significant post-processing was required and this technique could not distinguish between species, only target size.

Figure 9 – Free Flow Kinetic Hydropower System (Source: Verdant Power)

Table 4 – Verdant Power KHPS device specifications

Specification	Gen4 RITE (2006-2008)	Gen5 >2009
Rotors per foundation	1	1-3
Rotor diameter	5 m	5-11 m
Rotor swept area (rotor area *x* rotors per foundation)	20 m^2	20-285 m^2
Water-to-wire efficiency	35%	35%
Cut-in speed	0.8 m/s	0.8-1 m/s
Approximate power output at 2.5 m/s	56 kW	56-272 kW per turbine
Maximum operating rotation rate	35 rpm	≤ 40 rpm
Hub height (relative to the seabed)	5 m	5-15 m
Hydraulic fluids or lubricants	~20 L (gearbox lubricant – contained within nacelle)	~30 L (each KHPS, gearbox lubricant – dual-sealed within nacelle)
Total device weight	~7 tons (KHPS only, in air)	~4 tons (each KHPS only, in air) for 5m diameter turbine
Footprint on seabed (direct contact area)	0.3 m^2	12-30 m^2
Estimated maintenance interval	Not applicable (prototype)	3-5 years
Component design life	Not applicable (prototype)	20 years

- A ship-mounted split-beam transducer running mobile surveys over the turbine near-field and beyond. As with the fixed array, this could not distinguish between species.
- A fixed near-video hydroacoustic sonar (DIDSON) providing coverage of the turbine and immediate vicinity (less coverage than the split beam array). Significant post-processing was required and instrumentation deployments longer than 2-3 weeks were not feasible. Species-specific identification was possible.
- A ship-mounted hybrid system consisting of a split-beam and DIDSON sonar deployed in a targeted manner to monitor for strike on a species-specific basis.

As this was the first study investigating the potential for fish strike, aggregation, or avoidance associated with the operation of a hydrokinetic turbine, several important lessons were learned:

- The fixed array of split-beam transducers indicated that fish behavior is influenced predominantly by natural tidal currents, with the presence of rotating KHPS units acting as a secondary effect. Fish were observed to be active at slack water, when the machines are not operating, and relatively inactive during ebb and flood, when the machines are operating.
- Although ship-mounted split-beam hydroacoustics provides abundance and distribution of fish over a wide area, it does not provide enough temporal or species resolution, in proportion to the cost of the surveys, to be used to assess behavioral changes and was mutually abandoned by Verdant Power and regulatory agencies.
- DIDSON sonars are effective for short-term, species-specific monitoring and did observe one fish passing around an operating turbine, along hydrodynamic streamlines. However, the cost of marine operations and instrumentation precludes anything other than short-term, targeted deployments.

Verdant Power also conducted a number of before and after controlled impact (BACI) studies related to hydrodynamics, fish presence/abundance, underwater noise, water quality, and benthic habitat. These were generally inconclusive due to the scale of the pilot project in comparison to existing variability (from both natural and other anthropogenic sources). Observations that contrasted periods in which the turbine array was in operation versus not operating were considered to be more productive for assessing key stressor/receptor relationships.

1.7 References

Arbic, B. and Garrett, C. 2010. A coupled oscillator model of shelf and ocean tides. *Continental Shelf Research*, 30(6): 564-574.

Bedard, R. 2008. *Prioritized Research, Development, Deployment and Demonstration (RDD&D) Needs: Marine and Other Hydrokinetic Renewable Energy.* Electric Power Research Institute. December 2008.

Boehlert, G.W., McMurray, G.R. and Tortorici, C.E. (Eds.). 2008. *Ecological Effects of Wave Energy Development in the Pacific Northwest*. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-F/SPO-92.

Charlier, R.H. and Finkl, C.W. 2009. Section 2: *Medieval Engineering that Lasted. In Ocean Energy: Tide and Tidal Power*. New York, NY: Springer. 29-64.

DOE (U.S. Department of Energy Energy). 2010. *Marine and Hydrokinetic Technology Database*. Wind & Water Power Program, Energy Efficiency and Renewable Energy, U.S. Department of Energy. Available from *http://www1.eere.energy.gov/windandhydro/hydrokinetic/default.aspx.*

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

Garrett, C. and Cummins, P. 2007. The efficiency of a turbine in a tidal channel. *J. Fluid Mechanics*, 588: 243-251.

Gooch, S. Thomson, J., Polagye, B. and Meggitt, D. Site characterization for tidal power. *MTS/IEEE Oceans 2009*. Biloxi, MI, October 26-29, 2009.

Karsten, R., McMillan, M., Lickley, M. and Haynes R. 2008. Assessment of tidal current energy in the Minas Passage, Bay of Fundy. *Proceedings of the IMechE, Part A: J. Power Energy*, 222(5): 493-507.

Kawase, M., Beba, P. and Fabien, B. 2010. Depth dependence of harvestable power in an energetic, baroclinic tidal channel. *Renewable Energy. Article under review.*

Orme, J., Masters, I. and Griffiths, R. 2001. Investigation of the effect of biofouling on the efficiency of marine current turbines. In C. French (Ed.) *Proceedings of MAREC 2001* (Institution of Marine Engineers, 2001). 91-99.

Polagye, B., Epler, J. and Thomson, J. Limits to the predictability of tidal current energy. *MTS/IEEE Oceans 2010.* Seattle, WA, September 20-23, 2010.

Polagye, B. and Previsic, M. 2010. *Scenario Based Analysis of Environmental and Navigation Impacts: Tidal Power Scenario Descriptions.* Technical Report to the U.S. Department of Energy by RE Vision Consulting, LLC, Sacramento, CA.

2. Environmental Effects of Tidal Power

It is important to distinguish between environmental effects and environmental impacts. *Environmental effects* are the broad range of potential measurable interactions between tidal energy devices and the marine environment. *Environmental impacts* are effects that, with high certainty, rise to the level of deleterious ecological significance (Boehlert and Gill 2010). A further distinction is made with respect to potential effects or impacts with *potential* denoting a moderate to high level of uncertainty. For effects, this uncertainty describes the fundamental nature of whether such interactions can occur. For impacts, the uncertainty describes the details of the interaction (e.g., frequency, species-specific response) that would elevate the effect to the level of environmental significance.

Little is known about the potential environmental impacts from ocean energy devices and systems (DOE 2009). Tidal power technology is building on lessons learned from conventional hydropower and the wind industry. However, only a limited number of devices have been tested at sea, and the industry has yet to settle on a clear preferred technology.

Research into device performance, environmental effects, and siting considerations for tidal power has been largely concentrated in the European Union. To date, most research has been industry-driven and concerned with technological innovation, but recent peer-reviewed literature has investigated strategies to assess environmental effects as well (Shields et al. 2009). There are some similarities between tidal power and more mature technologies such as offshore wind, and, thus, an investigation of the offshore wind environmental impact and monitoring literature (e.g., Carstensen et al. 2006, Nunneri et al. 2008) is useful to anticipate research needed for tidal power environmental effects assessment and siting.

Recent reviews of the potential environmental impacts of tidal power technologies have been conducted (e.g., Michel et al. 2007, Wilson et al. 2007, DOE 2009, Kramer et al. 2010), but these assessments are not based on in situ monitoring of environmental impacts and only are able to describe potential impacts. Furthermore, uncertainties associated with scaling up observed effects from pilot- to commercial-scale are undocumented.

2.1 Conceptual Approach: Stressors and Receptors

For the purpose of this document, environmental effects are described in terms of stressor/receptor interactions. *Stressors* are those factors that may occur as hydrokinetic tidal energy systems are installed, operated, or decommissioned. *Receptors* are those elements of the marine environment that may be affected by stressors. With a few exceptions, the approach is very similar to the framework proposed by Boehlert and Gill (2010) and, in that language, evaluates *environmental effects* to identify *potential environmental impacts*. Stressors and receptors discussed at the scientific workshop in March 2010 are summarized in Table 5 – Environmental stressors and receptors associated with tidal energy development.Table 5.

Table 5 – Environmental stressors and receptors associated with tidal energy development.

Stressors	Receptors
Presence of devices: static effects	Physical environment: near-field
Presence of devices: dynamic effects	Physical environment: far-field
Chemical effects	Habitat and invertebrates
Acoustic effects	Fish: migratory
Electromagnetic effects	Fish: resident
Energy removal	Marine mammals and seabirds
Cumulative effects	Ecosystem interactions

2.2 Environmental Effects

Environmental effects of tidal power generation are similar in many ways to those of wave power and offshore wind power generation. Assessments have identified a number of potential environmental impacts from tidal energy development. Gill (2005) describes a number of indirect ecological effects that would result from extensive installation of offshore renewable energy developments. These include:

- Alteration of currents and waves;
- Alteration of substrates, sediment transport and deposition;
- Alteration of habitats for benthic organisms;
- Noise during construction and operation;
- Emission of electromagnetic fields;
- Toxicity of paints, lubricants, and antifouling coatings;
- Interference with animal movements and migrations; and
- Strike by rotor blades or other moving parts.

Effects on biological resources could include alteration of the behavior of animals, damage and mortality to individual plants and animals, and potentially larger, longer-term changes to plant and animal populations and communities (Gill 2005, DOE 2009).

Development of tidal energy involves technology testing, site characterization, device installation, operation and maintenance, and decommissioning. Many installation and decommissioning effects have close analogues to existing industries (e.g., offshore wind) and are short-term. Consequently, this report places an emphasis on operational effects experienced over the long term and installation/decommissioning effects unique to tidal energy.

2.3 Installation Effects

Installation of tidal power generation devices may cause significant disturbance to the local environment. However, other than the actual placement of persistent structures (i.e., the device and power cables), most installation effects are likely to be temporary (weeks to months, with some effects lasting longer). Stressors present during deployment are similar to those from other construction activities in the marine environment (DOE 2009) and include construction noise (i.e., air compressors), increased vessel activity, and habitat disturbance associated with installation of anchors and power cables. The area of disturbed habitat depends on the number of devices to be installed and type of foundation. If project installation involves pile driving, nearby noise levels are likely to exceed damage threshold values for fish and marine mammals (MMS 2007), potentially causing temporary or lasting harm to affected individuals or populations. Deployment timing may help to mitigate the effects of these stressors on marine organisms, especially migratory fish, marine mammals, and seabirds (Gill 2005).

2.4 Operational Effects

Operation of a tidal power generation installation includes movement of turbine blades in the tidal current and the conversion of mechanical energy into electricity for transmission to shore. Most tidal energy generation devices will be controlled and monitored remotely. Post-installation monitoring will address device performance, structural integrity, and environmental indicators (e.g., noise, currents, marine mammal activity).

Rotating machinery, underwater noise, chemicals, and electromagnetic fields (EMFs) are frequently cited as stressors associated with device operation, although the potential for interaction with receptors is not well understood. Other important stressors, even less well understood, are those associated with energy removal and cumulative effects from interaction of multiple stressors or multiple devices.

Operational stressors vary temporally with the stage of the tide and status of the device. For example, when the device is not operating (i.e., currents are below cut-in speed), acoustic, electromagnetic, energy removal, and dynamic device (i.e., blade rotation) stressors are reduced. Depending on the tidal regime and device specifics, a turbine can operate nearly continuously or for less than half the time.

Receptors in the marine environment may vary temporally (e.g., seasonal trends, migratory behavior) and may be exposed to other anthropogenic stressors. As a consequence, the interaction between operational stressors and receptors may have higher temporal variability than either the underlying stressor or receptor. Similar considerations apply to the spatial variability of stressors (e.g., received acoustic levels will vary with proximity to an operating device), receptors (e.g., species are not uniformly distributed within a project area), and their interactions.

Normal operations also involve maintenance activities, which may involve the recovery of the device or device components to the surface. Some of the environmental stressors associated with maintenance are similar to installation (e.g., increased vessel traffic).

2.5 Decommissioning Effects

At the end of its operational life, a device will be decommissioned. Environmental stressors will be very similar to device installation (e.g., increased noise, surface traffic, disruption of habitat). If the entire project has reached the end of its operational life, all anchors and subsea cables may also be removed.

2.6 Accidents

During installation, operation, maintenance, or decommissioning, accidents may occur. Accidents involving tidal energy devices are to be expected at the pilot stage since many device deployments will involve relatively untested designs. An example of an acute accident is blade damage. Blade failures (also common in the early days of wind energy) have occurred during several device tests for a variety of reasons (e.g., Marine Current Turbines' SeaGen experienced blade failure due to a software error that incorrectly adjusted the blade pitch angle during peak current; loads on first-generation Verdant Power turbine rotors exceeded design specifications). However, the ecological significance of a blade failure is uncertain. The most ecologically significant accident would be the release of petrochemicals, which could be caused by a vessel collision. The significance of such an event could be mitigated by scheduling vessel operations during conditions (tidal stage, weather) when there is less likelihood of oil spills occurring and spill response procedures are known to be most effective. While most devices currently under development do not include ecologically significant quantities of lubricants, similar concerns exist for devices with hydraulic drive trains.

2.7 Scale of Development

The significance and uncertainty associated with a particular stressor/receptor interaction may vary with the scale of development. For example, the acoustic effects of a single pilot turbine may be insignificant in the context of existing ambient noise sources but could be significant for a commercial array consisting of a hundred turbines. To account for this, breakout group discussions during the workshop differentiated between pilot-scale deployments (to indicate high-priority areas in the near-term) and commercial-scale deployments (to indicate high-priority areas in the long-term).

Pilot projects were considered to have the following characteristics:

- Single devices or small device arrays;
- Deployment durations of less than a decade;
- Provisions for project shutdown and early removal if unacceptably large environmental impacts are observed;
- Power extracted by a pilot project is much less than natural tidal dissipation in the project area;
- The rotor swept area (sum of the cross-sectional area swept by all turbines) for a pilot project is much less than the cross-sectional area of the channel in which it is deployed; and
- The primary goal of pilot projects is research and development (i.e., revenues generated by electricity sales are relatively incidental compared to the implementation cost).

This working definition is qualitatively similar to that adopted by the Federal Energy Regulatory Commission (FERC) for pilot licensing (FERC 2008), but does not adhere to the same quantitative standards (e.g., FERC defines pilot projects as having a rated capacity of less than 5 MW).

For the purposes of breakout group discussions, commercial projects were considered to have the following characteristics:

- Large device arrays (e.g., > 100 devices);
- Service lives of 20-30 years and licensing periods of up to 50 years;
- Power extracted by a commercial project *may* be on the same order as natural tidal dissipation in the project area;
- The rotor-swept area for a commercial project *may* be on the same order as the cross-sectional area of the channel in which it is deployed; and
- The primary goal of commercial projects is utility-scale power generation that is cost-competitive with other forms of electricity.

As the tidal energy industry evolves worldwide, the scale of pilot projects will likely increase, and the line between late-stage pilot projects and early-stage commercial projects may be blurred.

2.8 References

Boehlert, G. and Gill, A. 2010. Environmental and ecological effects of ocean renewable energy development: A current synthesis. *Oceanography*, 23(2): 68-81.

Carstensen, J., Henrikson, O.D. and Teimann, J. 2006. Impacts of offshore wind farm construction on harbor porpoises: acoustic monitoring of echolocation activity using propose detectors (T-PODs). *Marine Ecology Progress Series*, 321: 295-308.

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

FERC (Federal Energy Regulatory Commission). 2008. Licensing hydrokinetic pilot projects. Available from: *http://www.ferc.gov/industries/hydropower/indus-act/hydrokinetics/pdf/white_paper.pdf.*

Gill, A. 2005. Offshore renewable energy: Ecological implications of generating electricity in the coastal zone. *Journal of Applied Ecology*, 42: 605-615.

Kramer, S., Previsic, M., Nelson, P. and Woo, S. 2010. *Deployment Effects of Marine Renewable Energy Technologies - Framework for Identifying Key Environmental Concerns in Marine Renewable Energy Projects*. Prepared for the U.S. Department of Energy by RE Vision Consulting, LLC, Sacramento, CA. DE-003.

Michel, J., Dunagan, H., Boring, C., Healy, E., Evans, W., Dean, J.M., McGillis, A. and Hain, J. 2007. *Worldwide Synthesis and Analysis of Existing Information Regarding Environmental Effects of Alternative Energy Uses on the Outer Continental Shelf*. Minerals Management Service, U.S. Department of the Interior, MMS OCS Report 2007-038.

MMS (Minerals Management Service). 2007. *Programmatic Environmental Impact Statement for Alternative Energy Development and Production and Alternate Use of Facilities on the Outer Continental Shelf*. U.S. Department of the Interior. OCS EIS/EA MMS 2007-046. October 2007.

Nunneri, C., Lenhart, H.J., Burkhard, B. and Windhorst, W. 2008. Ecological risk as a tool for evaluating the effects of offshore wind farm construction in the North Sea. *Regional Environmental Change*, 8(1): 31-43.

Shields, M.A., Dillon, L.J., Wolff, D.K. and Ford, A.T. 2009. Strategic priorities for assessing ecological impacts of marine renewable energy devices in the Pentland Firth (Scotland, UK). *Marine Policy*. 33(4)L: 635-642.

Wilson, B., Batty, R.S., Daunt, F. and Carter, C. 2007. *Collision risks between marine renewable energy devices and mammals, fish and diving birds*. Report to the Scottish Executive. Scottish Association for Marine Science. Oban, Scotland, PA37 1QA.

3. Environmental Stressors

In this section, seven environmental stressors are discussed:

- *Presence of devices: static effects* – stressors caused by the presence of the device and foundation, including new structures in the water column and disturbances during installation or removal or both.
- *Presence of devices: dynamic effects* – stressors caused by the operation of the device, including blade strike, entrainment, impingement, and the device wake.
- *Chemical effects* –stressors due to contaminants from lubricants, paints, or coatings.
- *Acoustic effects* – stressors from noise due to device operation or installation or both.
- *Electromagnetic effects* – stressors from EMFs associated with the generator and power electronics on a device or power cable or both.
- *Energy removal* – stressors, primarily on the far-field environment, which are a consequence of energy removal from tidal systems.
- *Cumulative effects* – stressors arising from a combination of other stressors or multiple sites (or both) developed in the same geographically connected body of water.

Each stressor is discussed using a common framework. First, the significance of each stressor element on receptors in the natural environment (Table 5) is assessed qualitatively as high, medium, low, not applicable, or unknown. Second, the uncertainty around this assessment is qualified as high, medium, low, or unknown. These results are presented as a matrix of stressor/receptor interactions. A key describing these matrices is shown in Figure 10. The color of the cell denotes the significance of the interaction. The number and color of triangles denotes the uncertainty of this significance. This evaluation is conducted separately for pilot and commercial scale deployments, as broadly described in Section 2.7.

High-priority stressor/receptor interactions (e.g., of high significance or high uncertainty or both) are then discussed in further detail. Each high-priority interaction is described, gaps in understanding are identified, approaches for monitoring this interaction are identified (with emphasis on the stressor), and mitigation measures are recommended.

Each breakout group also identified key literature references for their stressor.

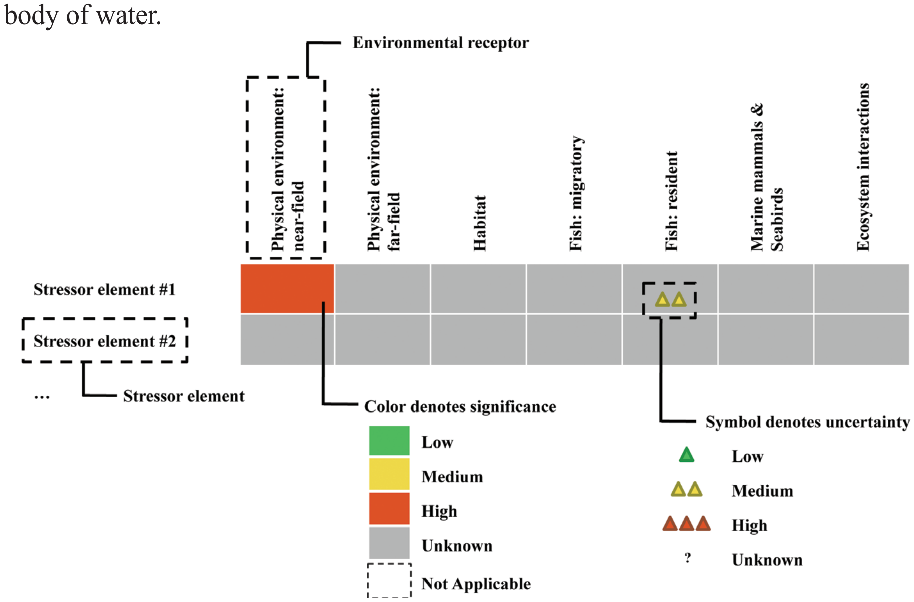


Figure 10 – Sample stressor matrix components

3.1 Presence of Devices: Static Effects

Name	Affiliation
Sharon Kramer (Chair)	H.T. Harvey & Associates
Anna Kagley	NOAA Fisheries Northwest Fisheries Science Center
Craig Collar	Snohomish County Public Utility District
Ginny Eckert	University of Alaska - Fairbanks
Jim McCleave	University of Maine
Julia Parrish	University of Washington
Melanie Spring Harris	NOAA Fisheries, Office of Habitat Conservation
Sam Johnston	Hydroacoustic Technology, Inc.
Simon Courtenay	Dept. Fisheries and Oceans Canada
Wayne Palsson	Washington Dept. Fish and Wildlife
Ilon Logan (Note Taker)	University of Washington

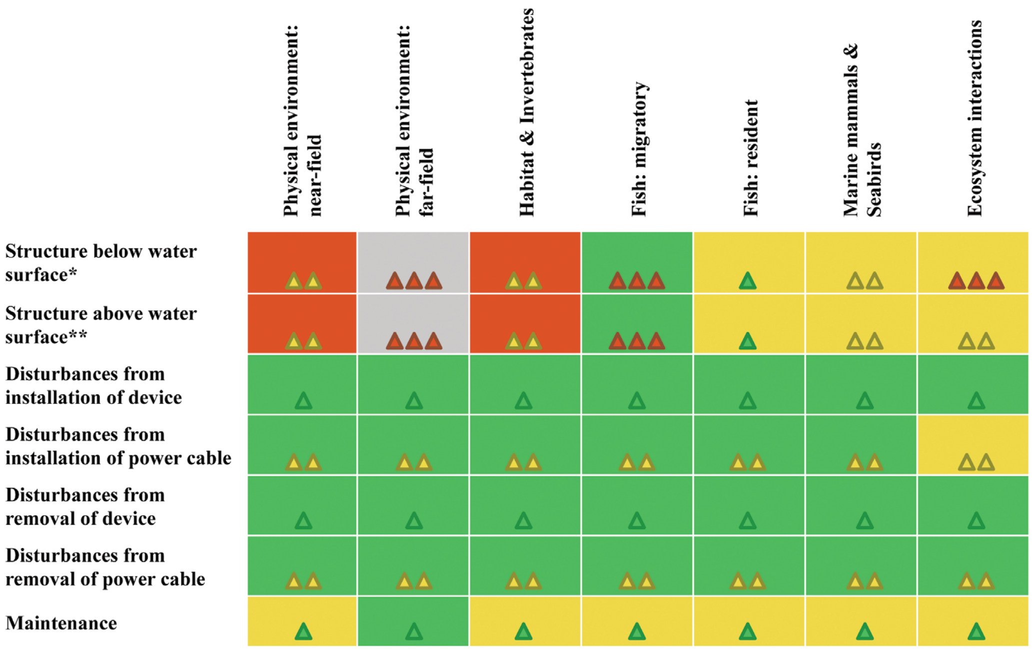
3.1.1 Introduction

Static stressors are primarily the result of immobile, hard structures including tidal energy power trains (rotor and generator), foundations, cables, and anchors. Tidal energy devices are secured to the seabed using monopile or gravity foundations. The power train is connected to the foundation by a support structure (rigid or compliant mooring). In some circumstances, the support structure may pierce the water's surface (e.g., MCT SeaGen). Although all tidal energy devices are secured to the seabed, this distinction (foundations and other near-bottom structure versus devices that have a greater water column profile or are surface-piercing) was used to evaluate environmental effects on benthic receptors and pelagic/surface receptors.

The main effects of static structure are on near-field physical environments and are associated with changes in hydrodynamics (turbulence, wake, etc.), sediment dynamics (scour, deposition, etc.), habitat, and ecosystem interactions. For example, foundations and support structures can act as artificial reefs, affecting scour and deposition in the near-field, and providing habitat for reef-associated species. In turn, attraction of reef species is likely to attract predators, including marine mammals and seabirds. Devices that are surface-piercing can affect water column hydrodynamics, provide structure for seabird roosting, or pose a collision hazard (Boehlert et al. 2008).

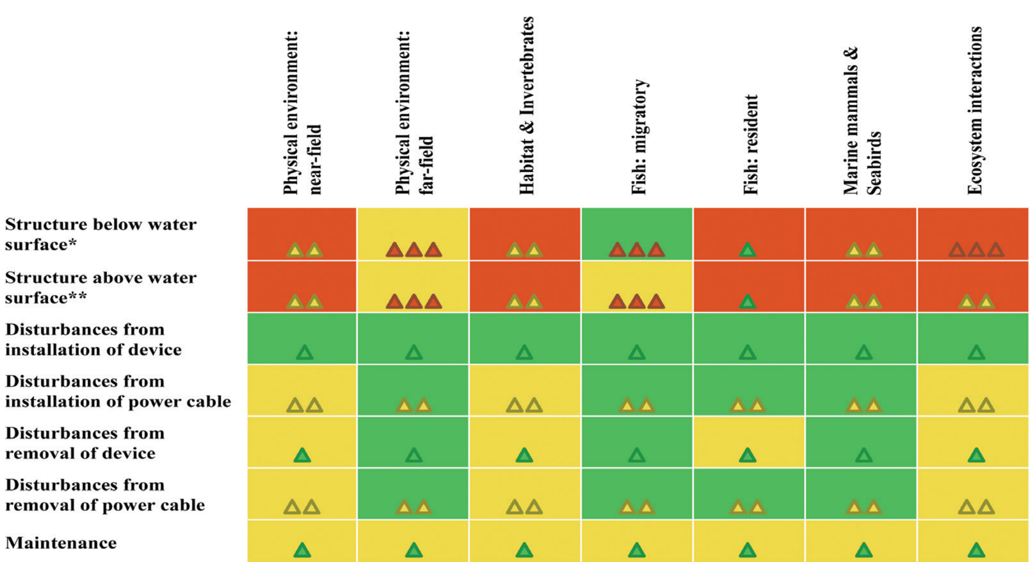
A matrix of stressor/receptor interactions, their significance, and uncertainty is given in Figure 11 for pilot-scale deployments and in Figure 12 for commercial-scale deployments. The colors denote significance and triangles denote uncertainty, as defined in Figure 10.

3.1.2 Stressor Matrix



* – foundations, shrouds, ducts, mooring cables, and power cables (seafloor) in scoured, energetic environments
** – haul out/roosting surfaces, lighting (surface)

Figure 11 – Stressor matrix: Presence of devices: Static effects – pilot-scale deployment



* – foundations, shrouds, ducts, mooring cables, and power cables (seafloor) in scoured, energetic environments
** – haul out/roosting surfaces, lighting (surface)

Figure 12– Stressor matrix: Presence of devices: Static effects – commercial-scale deployment

3.1.3 Discussion

Interactions between static structure and receptors were evaluated generically. As such, the results could be generally applicable, although many effects will be device- and site-specific. Therefore, structure types were considered together rather than addressed separately, even though some of the interactions could be distinctive; for example, slack mooring lines could increase the risk of marine mammal entanglement.

Interactions between receptors and static structure that are considered to have a high probability of occurrence include effects on near field physical environment (hydrodynamics, sediment dynamics) and on habitat. Both pilot- and commercial-scale developments are considered. With commercial developments, interactions among resident fish, marine mammals, seabirds, and ecosystems with static tidal devices are considered to have a high probability of occurrence. Uncertainty was greatest for effects on several receptors including the far-field physical environment, migratory fish, and ecosystem interactions, at both the pilot and commercial scales.

Installations of tidal energy devices and transmission cables are considered to have relatively low effects on receptors because of the dynamic nature of the habitats likely to be affected and the short duration of disturbance. Decommissioning the devices and cables is considered to have greater effects because decommissioning would involve removal of structure that could be used by resident fishes as habitat.

In general, commercial-scale projects would have greater effects than pilot-scale projects.

3.1.4 Priority Area: *Effects of static structure on benthic ecosystems*

Description

New static structures placed on the sea bottom will likely affect hydrodynamic processes and sediment movement and will change benthic habitat, thus affecting community structure. Numerous studies have demonstrated that reef-associated fish are likely to be attracted to novel structures (Wilding and Sayer 2002, Bortone 2006, Wilhelmsson et al. 2006, Hunter and Sayer 2009). However, how that attraction affects overall community structure, especially marine mammals and seabirds, is less well understood. It is uncertain whether fish species will be attracted to the devices (a phenomenon known as an artificial reef effect) and whether the devices will increase resident fish populations or be population "sinks," drawing fish away from natural habitat.

Gaps in Understanding

Effects on the magnitude and scale of hydrodynamic and sediment dynamic changes on fish interaction with structure and on changes to community structure are not well understood, especially for marine mammals and seabirds, in such dynamic and difficult-to-study tidal environments. Some understanding of these effects can be gained by evaluating analogues such as pier or bridge pilings and offshore wind turbines. Development of modeling approaches to evaluate effects of static structure on hydrodynamics and sediment dynamics is encouraged.

Approaches to Monitoring

Methods and equipment useful for evaluating the hydrodynamic disturbance of static structures include use of drifters or drogues (Muller et al. 2009), Acoustic Doppler Current Profilers (ADCPs) (Teledyne RDI, 2006), numerical models, and scale models in flumes. These techniques and instrumentation are well-developed.

Effects on sediment dynamics and habitat could be evaluated using video and still cameras. Depending on ambient conditions, video cameras could be deployed to monitor changes to benthic habitat in the nearfield. However, the effective range for video is relatively short, particularly below the photic zone (i.e. 7 m or less with full-spectrum lighting) or if natural turbidity is high. Therefore, cameras deployed directly on a tidal energy device will be limited to near-field observations. Cameras mounted to remotely operated vehicles (ROVs) may be able to survey broad areas, although the strength of the currents presents a challenging operating environment, even around slack water. Before-and-after comparisons of benthic habitat in the immediate vicinity of a tidal energy device installation would help to evaluate disruptions during installation and recovery. Similar comparisons would help to evaluate the rate of colonization on foundations, moorings, and support structures.

For monitoring fish communities, drift nets and acoustic approaches should be considered. Acoustic approaches could include active acoustics (sonar), acoustic cameras, and acoustic telemetry (both with stationary receivers and mobile hydrophone tracking) of tagged fish. However, detection probability for small fish using active acoustics may be low at some locations because of high sediment loads, turbulent mixing of fresh and salt water, and air-bubble entrainment (see also Sections 0, Fish: migratory, and 4.5, Fish: resident).

For evaluating effects on marine mammals, passive acoustic hydrophones, visual observations, and telemetry are the primary monitoring methods (see also Section 0, Marine mammals and seabirds).

Monitoring pilot deployments will provide information on near-field effects, but a phased approach to commercial buildouts using adaptive management is recommended, because effects may not be linear and it will be necessary to "learn as you go."

Mitigation Measures

Hydrodynamic effects may be decreased by minimizing anchor sizes, decreasing the number of moorings and slack lines, and streamlining support structures.

Multidisciplinary design teams (e.g., biologists working with engineers) could develop best management practices and improve structural designs to minimize biological impacts.

Mitigation measures to reduce the effects of installation on benthic communities should include minimizing extraneous lighting and defining "work windows" to avoid timing of sensitive species' migratory or reproductive activities.

3.1.5 Priority Area: *Effects of static structure on the water column and/or surface*

Description

New static structures placed in the water column will affect hydrodynamic processes, including changing pelagic habitat, which may affect community structure. There is reasonable certainty that pelagic fish will use devices as refuges from strong currents; however, effects on community structure, especially on marine mammals and seabirds, are less well understood. Whether migratory fish species will be attracted to the devices (the Fish Aggregating Device or FAD effect) is uncertain in temperate ecosystems (Wilhelmsson et al. 2006). Surface-piercing structures may attract seabirds that roost and marine mammals that haul out. There is reasonable certainty that seabirds will use surface-piercing structures to roost and that many bird species are sensitive to lighting. Surface structures will require lighting for safety and navigation, which will affect seabirds and other species.

Gaps in Understanding

Effects on the magnitude and scale of hydrodynamic changes, on fish interaction with structure, and on changes to community structure, are not well understood, especially for marine mammals and seabirds. These interactions are difficult to study in dynamic tidal environments. For example, hydrodynamic changes may affect fish behavior and distribution and could improve feeding success for pinnipeds. Birds are known to be affected by lighting, but specific effects on seabirds remain unknown. Knowledge about these effects could be extrapolated from analogues. Development of modeling approaches to evaluate effects of static structure on hydrodynamics is encouraged.

Approaches to Monitoring

Monitoring approaches will vary with receptor and species.

To evaluate effects on fish, acoustic methods generally do not work well near the surface because of turbulence and wave action; however, acoustic tags are an exception and can be used to tag fish and their predators. For example, if a predator consumes a tagged individual fish, then the two tags will remain together. However, the tagging intensity and receiver density required for these types of studies may not be cost-effective, particularly at the pilot scale.

To evaluate effects on seabird behavior, monitoring approaches include radar (depending on distance from shore) and visual observations from boats, ferries, and air taxis.

To evaluate pinniped behavior and feeding success, animal-borne video cameras (Moll et al. 2007) can be used to study predation and interaction with devices. Scat samples can be evaluated for coded wire tags, PIT tags, or acoustic tags from tagged fish. Remote webcams or cameras on devices could also be valuable monitoring tools.

Mitigation Measures

Minimizing or shrouding lights, using strobes instead of constant lighting, and careful selection of lighting color should be considered on surface-piercing structures. Structures can be designed to be less desirable for pinniped haul-out or seabird roosting behaviors. Tidal energy device profiles can be streamlined to reduce hydrodynamic effects and minimize the area that fish and pinnipeds can use to hold or rest against tidal currents.

3.1.6 Priority Area: *Frequency and duration of tidal energy device maintenance*

Description

Maintenance of tidal energy devices will entail removing structure (either the power train or entire device) and thereby disrupting habitats and species attracted to the devices. Reef-associated fish are likely to be attracted to novel structures on the bottom (Hunter and Sayer 2009); however, removal, cleaning and maintenance, and replacement will temporarily displace species. Frequency and duration of maintenance activities will be device- and site-specific, with devices deployed in shallower water likely requiring more maintenance and cleaning.

Gaps in Understanding

The primary gap in understanding is the range of maintenance options, especially for addressing biofouling. The extent of biofouling on devices is unknown and will be very site-specific. Preliminary indications are that biofouling may be significant and rapid for devices deployed within the photic zone (e.g., Clean Current deployment at Race Rocks and more gradual for deeper deployments (Polagye and Thomson 2010). The frequency of device removal for maintenance and cleaning, and whether portions of the structure (for example, the foundations) will remain in place are device- and site-specific. The effects of removal on resident fish attracted to structures are not known.

Approaches to Monitoring

Acoustic methods (acoustic surveys, cameras, acoustic cameras, telemetry) are recommended for monitoring fish and other species, as described above, but with an emphasis on evaluating behavior associated with maintenance events. Biofouling organisms should be evaluated in pilot deployments, by periodically recovering and examining devices, evaluating *in-situ* with ROVs, or using settlement plates. Information gained from pilot-scale deployments will be useful for evaluating the effects associated with scaling up to commercial build outs.

Mitigation Measures

Cleaning of biofouling should be done in a manner that contains any biocides present in marine coatings, and biofouling organisms should be tested for contaminant load. If rapid biofouling is an issue, projects should be placed below the photic zone or treated with anti-fouling coatings. Maintenance should be conducted using work windows to minimize effects on resident fish species, especially during mating or spawning and, for migratory fish, during peak migration periods.

3.1.7 Recommended References

Borton, S.A. 2006. A perspective of artificial reef research: the past, present and future. *Bulletin of Marine Science*, 78(1): 1-8.

Hunter, W.R. and Sayer, M.D.J. 2009. The comparative effects of habitat complexity on faunal assemblages of northern temperate artificial and natural reefs. ICES Journal of Marine Science, 66: 691-698.

Moll, R.J., Millspaugh, J.J., Beringe,r J., Sartwell, J. and He, Z. 2007. A new ‘view’ of ecology and conservation through animal-borne video systems. *Trends in Ecology and Evolution*, 22(12): 660-668.

Muller, H., Blank, B., Dumas, F., Lekien, F. and Mariette, V. 2009. Estimating the Lagrangian residual circulation in the Iroise Sea. *Journal of Marine Systems*, 78 Supplement 1: S17-S36.

Polagye, B. and Thomson, J. 2010. Screening for biofouling and corrosion of tidal energy device materials: *In-situ* results for Admiralty Inlet, Puget Sound, Washington. Northwest National Marine Renewable Energy Center Technical Memorandum. Northwest National Marine Renewable Energy Center. Seattle, WA. Available from *http://hdl.handle.net/1957/16203*.

Teledyne RDI. 2006. *Acoustic Doppler current profiler principles of operation: A practical primer*. Poway, CA: Teledyne. RDI P/N 951-6069-00.

Wildling, T.A. and Sayer, M.D.J. 2002. Evaluating artificial reef performance: approaches to pre- and post-deployment research. *ICES Journal of Marine Science*, 59: 222-230.

Wilhelmsson D., Malm, T. and Ohman, M.C. 2006. The influence of offshore windpower on demersal fish. *ICES Journal of Marine Science*, 63: 775-784.

3.2 Presence of Devices: Dynamic Effects

Name	Affiliation
Sue Barr (Chair)	OpenHydro Group Ltd.
Alison Agness	NOAA Fisheries – Northwest Region, Protected Resources
Bob Thresher	National Renewable Energy Laboratory
Brad Hanson	NOAA Fisheries Northwest Fisheries Science Center
David Ainsworth	Marine Current Turbines Ltd.
Fred Goetz	U.S. Army Corps of Engineers
Glenn Cada	Oak Ridge National Laboratory
Greg Ruggerone	Natural Resource Consultants
Gayle Zydlewski	University of Maine
Joanna Smith	The Nature Conservancy
Mary Ann Adonizio	Verdant Power
Kurt Fresh	NOAA Fisheries Northwest Fisheries Science Center
Teymour Javaherchi (Note Taker)	University of Washington

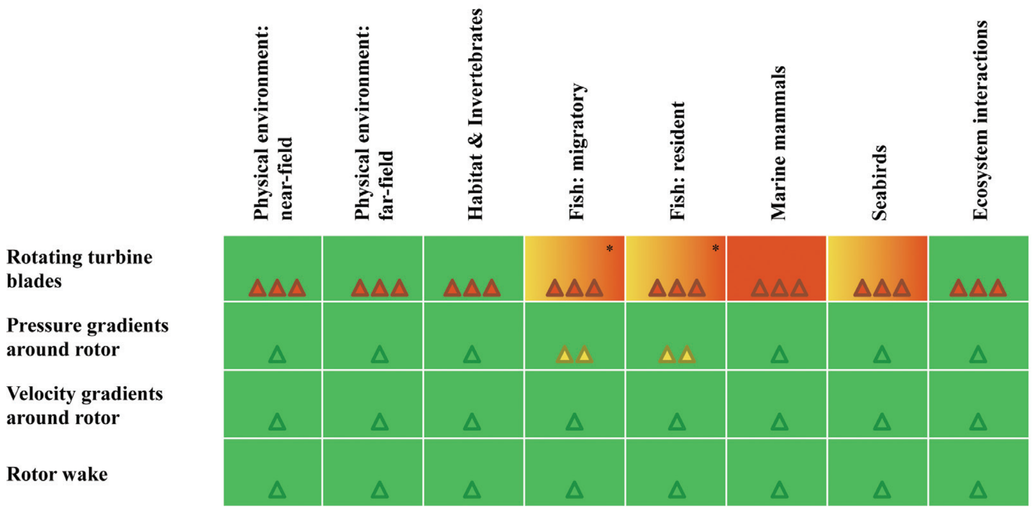
3.2.1 Introduction

Dynamic effects of device presence include strike, entrainment or impingement against moving turbine blades, and pressure and velocity gradients around an operating device. The presence of rigid, moving structures and possible cavitation near blades (from the sudden water pressure change from front to back of the blade) could result in animal strikes or mortality. Although collisions with any of the hard surfaces or cables associated with the device are possible, collision with the turbine rotors is the most intuitive risk to marine vertebrates (Wilson et al. 2007). Strike mortality is a product of the strike probability and force. Force is proportional to turbine velocity. Different turbine designs offer different potentials for strike mortality. For example, the speed of a vertical axis turbine rotor is equal along the blade, while the speed of a horizontal axis turbine rotor is faster towards the blade tip (DOE 2009). Although there is no direct evidence of marine animals' ability to avoid spinning tidal turbine rotors, Wilson et al. (2007) suggest that marine mammals and fish may see or hear the device and either avoid the area or take evasive action at close range.

When compared with rates of fish strike in conventional hydro dams, it is expected that the likelihood of strike is far less for un-ducted tidal turbines than for conventional hydropower turbines, because animals have little opportunity to avoid conventional hydro turbines and the rotational speed is much greater than that of tidal turbines. Exposure to conventional hydro turbines is a single, high-probability event, while exposure to turbines in a tidal energy array has a low likelihood but could be repeated for different devices within the array (DOE 2009). Turbine strike may be compared to collision with the bow of a ship (Wilson et al. 2007). However, unlike tidal turbines, large ship hulls generate a suction that can pull animals towards the ship and increase the likelihood of a strike (Fraenkel 2006).

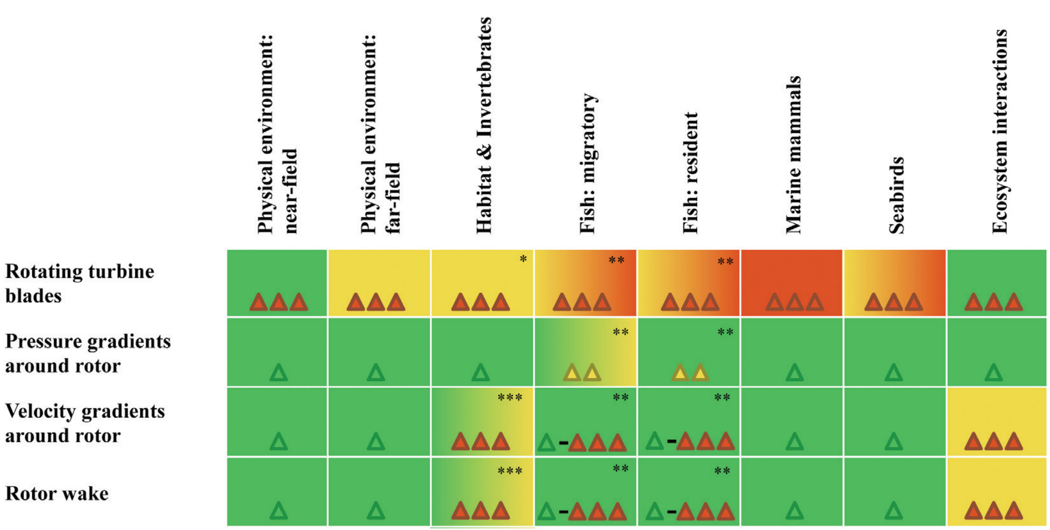
A matrix of stressor/receptor interactions, their significance, and uncertainty is given in Figure 13 for pilot-scale deployments and in Figure 14 for commercial-scale deployments. The colors denote significance and triangles denote uncertainty, as defined in Figure 10.

3.2.2 Stressor Matrix



* – high end of range if endangered species present, low end if no listed species

Figure 13 – Stressor matrix: Presence of devices: dynamic effects – pilot-scale deployments



* – site dependent
** – high end of range if endangered species present, low end if no listed species
*** – low end of range for benthic communities, high end for pelagic communities

Figure 14 – Stressor matrix: Presence of devices: dynamic effects – commercial-scale deployments

3.2.3 Discussion

The presence of singular or multiple tidal turbines in the marine environment will create the potential for a number of physical interactions with the water, seabed, and species or habitats in the surrounding area. In order to determine the likely effects arising from a moving turbine in the marine environment, the group discussed the following stressor elements:

- Direct interactions – blade strike, impingement, entrainment;
- Increase/decrease in water velocity;
- Increase/decrease in pressure; and
- Effects of the rotor wake.

The significance and likely occurrence of an effect on receptors for each of the stressor elements in Figures 13 and 14 was discussed at length. The group consisted of device developers, marine mammal and fish experts, and those with experience of marine mammal interactions with offshore wind turbines. It was concluded that changes in velocity, pressure, and effects from the wake of rotors were likely to be highly localized and, therefore, unlikely to produce measurable events, even in the near-field environment for smaller-scale projects. Examples of in-situ measurements were given from Verdant Power (Colby and Adonizio 2009), OpenHydro, and MCT in relation to the actual changes in pressure, wake effects, and physical effects such as cavitation. A number of these data, however, are not yet in the public domain, therefore data-led evidence on the physical effects is yet to be quantified. The conclusion is that velocity changes and pressure changes are highly localized to the blades themselves, and there is little potential for these changes to affect receptors.

The effects of wake from the turbines was determined to be aligned to energy extraction and the ability to optimally lay out turbines arrays and would, therefore, be unlikely to affect the receiving environment because of the dynamic nature of tidal energy sites. The high density of water, coupled with the rapid in-stream changes in hydrodynamics, as understood in a tidal stream environment, was thought to be so variable as to mask any measurable effect at a receptor level.

The key stressor of concern was the ability to predict, monitor, and mitigate the likely potential for direct interactions between marine receptors and the tidal technology devices themselves. This group of effects includes direct contact with moving blades or rotors, impingement within devices (where possible), and entrainment.

3.2.4 Priority Area: *Potential for direct interactions of marine species*

Description

The key priority identified within the group was the potential for direct interactions of marine species, including migratory fish, marine mammals, and resident fish (at their various life stages) with the rotating blades of a tidal turbine. This issue is of high priority where there are endangered or threatened species.

Gaps in Understanding

In general, there is insufficient knowledge to accurately assess the risk posed to fish, marine mammals, and seabirds.

Migratory Fish—Migratory fish, such as salmonids, are often endangered or protected under various legislative controls. Salmonids and other anadromous and marine fishes are known to use tidal currents to navigate through areas of interest (Moser and Ross 1994, Levy and Cadenhead 1995, Barbin 1998, Lacoste et al. 2001, Metcalfe and Hunter 2003). However, it was agreed that knowledge of fish behavioral ecology in relation to device interactions was limited and not at the level necessary to adequately understand potential effects.

Marine Mammals—It was agreed that little is known on the behavior of marine mammals in a tidal energy context, particularly their activity level or usage of tidal flows. The group determined that physical interactions between marine mammals and devices are likely to depend on site characteristics and the species or population of mammals found in that region. Therefore, any interactions would be specific to a project and would require adequate monitoring and associated mitigation in order to further understand the interactions. Details of the marine mammal monitoring and mitigation effort undertaken by Marine Current Turbines Ltd. are described in Section 1.6.3 of this report.

Levels of uncertainty were thought to be high for both the pilot-scale and commercial-scale projects.

For the case of a Puget Sound, Washington, project, it was agreed that there were some studies suggesting that Southern Resident Killer Whales utilize tidal currents to move in and out of Puget Sound, therefore increasing the likelihood of possible interactions. The movement of marine mammals throughout Puget Sound is not understood at a temporal or spatial resolution required to establish the potential for "take" under the federal Endangered Species Act; the levels of uncertainty and risk remain high.

Seabirds —The possibility of the interaction between tidal devices and seabirds was agreed to be highly unlikely in depths greater than that of the maximum diving depth of any resident birds. Because the potential effect of tidal devices on the aggregation of target prey species is poorly understood, it was agreed that diving birds were not a priority at this stage of development but that the levels of uncertainty were high. Should projects progress to a commercial scale, further studies would be required in order to understand interactions.

Approaches to Monitoring and Mitigation

In general, it was agreed that the ability to monitor for and mitigate against potential direct interactions of marine mammals, fish species, and seabirds with tidal turbines would be extremely complex. However, a mechanism for early establishment of what types of interaction and at what frequency interactions occur would be required to further understand interactions and potential mitigation.

Migratory Fish—The use of active acoustics was discussed to understand near-field interactions and activity of fish species around the turbines. Active acoustics have been used to study interaction with some success at Verdant Power's RITE project, although at high cost and with inconclusive outcomes. It was agreed that a further workshop was required to review the existing models for analysis of fish and modes of measurement such as acoustic telemetry and tagging protocols.

The existing models for behavioral ecology of fish species were thought to be too large-scale to be applied to species-specific interactions (e.g., protected or endangered species). However, existing models and understanding could be reviewed and possibly adapted to meet the survey and monitoring requirements associated with tidal energy projects.

Marine Mammals—Acoustic monitoring (both split- and multi-beam) is one approach to detect large cetaceans and pinnipeds in the region of a turbine. However, the resolution and range of such instrumentation is limited and this class of problem is analogous to the yet-unsolved military concern of reliable "swimmer detection." Any monitoring approach should allow for the immediate shutdown of a turbine in order to reduce the possibility of direct marine mammal interaction, particularly for at-risk or protected species. Further workshops are recommended to scope:

- Maximum swimming velocities of marine mammals;
- Safe stopping distance and risk "envelope";
- Available instrumentation for marine mammal detection; and
- System integration and data analysis.

Mitigation measures could include: using direct and low-cost options to increase the visibility of rotors to fish; using acoustic avoidance measures; and using shock absorbers on the leading edges of the blades (Wilson et al. 2007). Because devices require a minimum speed to operate, this stressor/receptor interaction is present only over a portion of the tidal cycle. Depending on the cut-in speed and site characteristics, a turbine may rotate between 40% and 80% of the time.

It was agreed that impacts should be monitored at the pilot scale to evaluate potential effects from larger-scale development. Adaptive management of the monitoring plan should be adopted to ensure all effects are correctly mitigated for over the project lifetime. In general, a "deploy and monitor" strategy should be adopted to reduce uncertainty in this area.

3.2.5 Recommended References

Barbin, G.P. 1998. The role of olfaction in homing and estuarine migratory behavior of yellow-phase American eels. *Canadian Journal of Fisheries and Aquatic Sciences*, 55(3): 564-575.

Colby, J. and Adonizio, M. 2009. Hydrodynamic analysis of kinetic hydropower arrays. Waterpower XVI, Spokane, WA. July 27-30, 2009.

Fraenkel, P. 2006. Tidal current energy technologies. Ibis, 148: 145-151.

Lacoste, K.N., Munro, J., Castonguay, M., Saucier, F.J. and Gagne, J.A. 2001. The influence of tidal streams on the pre-spawning movements of Atlantic herring, Clupea harengus L., in the St Lawrence Estuary. *ICES Journal of Marine Science*, 58(6): 1286-1298.

Metcalfe, J. and Hunter, E. 2003. Being there and getting there: Balancing the costs of migration against the benefits of changing habitat for North Sea plaice. *Journal of Fish Biology*, 63 Supplement 1: 237-238.

Moser, M.L. and Ross, S.W. 1994. Effects of changing current regime and river discharge on the estuarine phase of anadromous fish migration. In Dyer, K.R. and Orth, R.J. (Eds.). *Changes in Fluxes in Estuaries*. Fredensborg, Denmark: Olsen & Olsen. 343-347.

Verdant Power. Roosevelt Island Tidal Energy Pilot License Application, FERC No. 12611. Filed December 2010. Volumes 1-4 available at *http://www.theriteproject.com/Documents.html.*

Wilson, B., Batty, R.S., Daunt, F. and Carter, C. 2007. *Collision risks between marine renewable energy devices and mammals, fish and diving birds.* Report to the Scottish Executive. Scottish Association for Marine Science. Oban, Scotland, PA37 1QA.

3.3 Chemical Effects

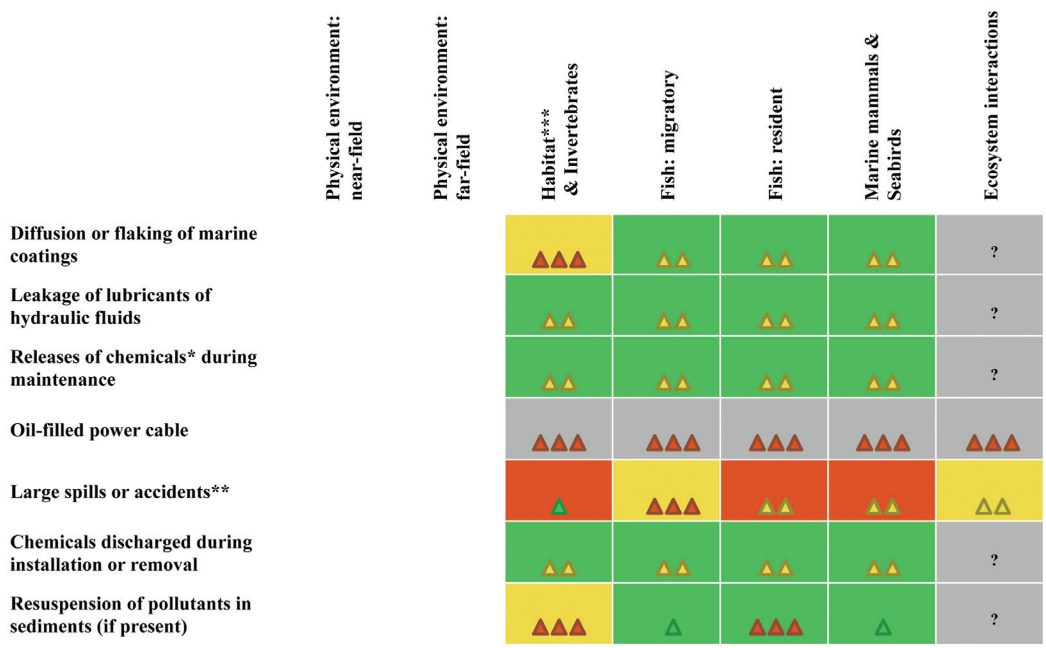
Name	Affiliation
Gary Gill (Chair)	Pacific Northwest National Laboratory
David Baldwin	NOAA Fisheries Northwest Fisheries Science Center
David Young	U.S. Environmental Protection Agency
Heather Trim	People for Puget Sound
Layna Goodman	U.S. Navy
Paul Jacobson	Electric Power Research Institute
Richard Anderson	Pacific Northwest National Laboratory
Scott Redman	Puget Sound Partnership
Erin Black (Note Taker)	University of Washington

3.3.1 Introduction

Depending on the tidal energy technology, several types of hazardous chemicals could be present in the marine environment during installation, operation, and removal. The chemical effects stressor section identified two major stressors of equal potential concern: (1) acute release (i.e., a spill) of large amounts of lubricants, hydraulic fluids, vessel fuel, or other petroleum based products associated with installation, operation, maintenance, or removal of tidal energy devices; (2) chronic release of toxic contaminants from antifouling coatings used on tidal devices that can potentially affect water and sediment quality. Further complications could result if the contaminants bioaccumulate in the food chain, potentially affecting public health if the aquatic organisms are consumed by humans. Spills have a higher certainty of impact if the spills are large. Impacts from chemicals in coatings are more uncertain due to lack of information about their composition and expediency of their release mechanisms. Other stressors identified and discussed but deemed to be of lesser concern were: slow leakage of lubricants associated with the operation of the tidal devices; release of cleaning solvents or lubricants associated with maintenance activities; release of oil from power conveyance cables (power cables may be filled with an organic-based fluid); and unintentional release of chemicals that may be utilized during installation, maintenance, or device removal operations.

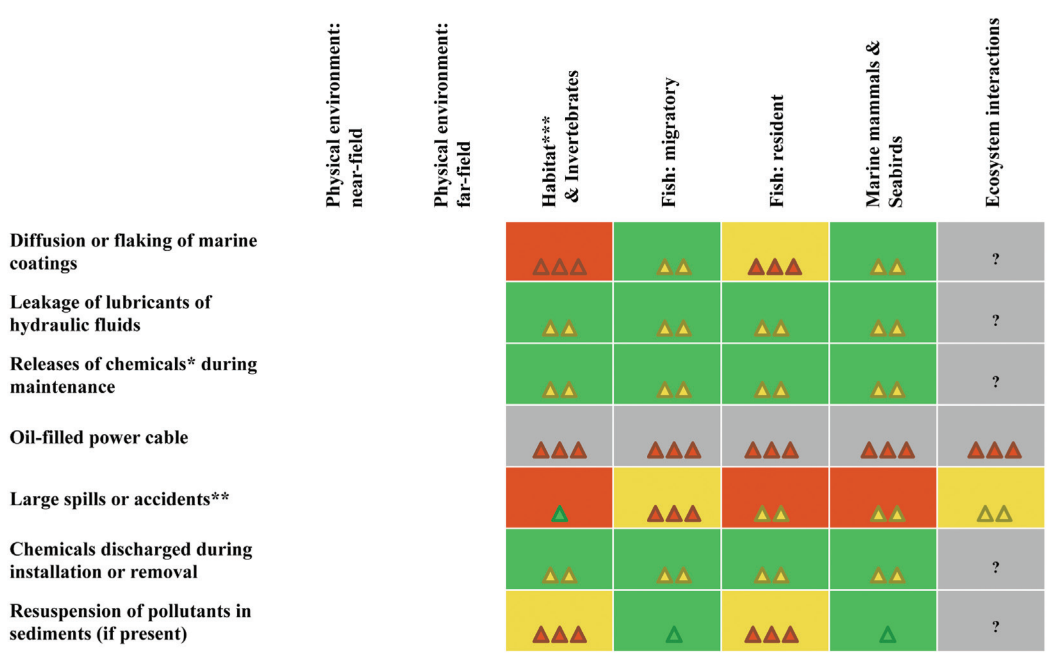
A matrix of stressor/receptor interactions, their significance, and uncertainty is given in Figure 15 for pilot-scale deployments and in Figure 16 for commercial-scale deployments. The colors denote significance and triangles denote uncertainty, as defined in Figure 10.

3.3.2 Stressor Matrix



* – cleaning solvents or lubricants/hydraulic fluids
** – supply vessel fluids, hydraulics, etc.
*** – habitat defined to include: sediment quality, water quality, benthic habitat and bio-accumulation of contaminants

Figure 15 – Stressor matrix: Chemical effects – pilot-scale deployment



* – cleaning solvents or lubricants/hydraulic fluids
** – supply vessel fluids, hydraulics, etc.
*** – habitat defined to include: sediment quality, water quality, benthic habitat and bio-accumulation of contaminants

Figure 16 – Stressor matrix: Chemical effects – commercial-scale deployment

3.3.3 Discussion

The chemical effects group identified the following stressor elements that may have potential impacts during the installation, operation, maintenance, or removal of a tidal power device:

- Diffusion of chemicals from or flaking of the marine coating(s) used to prevent corrosion or biofouling on the tidal device;
- Large spills of petroleum-based products (e.g., vessel fuel) during installation, operation, maintenance, or removal of tidal power devices;
- Leakage of lubricants, cleaning fluids, solvents, hydraulic fluids, and vessel fuel during installation or removal of the tidal device, normal operation, and maintenance activities;
- Release of contaminants from power conveyance cables (cables may be oil-filled or oil impregnated) during installation, operation, or removal; and
- Resuspension of historical contaminants buried in sediments during installation of power conveyance lines to shore.

In identifying stressor elements, the group felt that it was important to distinguish between the volume of fluids that might be released during installation, operation, maintenance, or device removal and the much larger release that might occur during an accident (e.g., sinking of a vessel or barge containing fuel or fluids). Chemical stressors, when viewed as potential contaminants, were not assumed to have any impact on the physical environment (either near- or far-field), but rather on the habitat, fish, marine mammals, and seabird and ecosystem receptors.

3.3.4 Priority Area: *Anti-fouling coatings*

Description

Most of the tidal energy structures will be submerged in saltwater where biofouling (growth of marine organisms) could occur. Severe biofouling of a turbine rotor will degrade device performance (Orme et al. 2000). Severe biofouling on the turbine foundation will increase drag, leading to increased stresses on foundation for individual devices and, for very large arrays, the far-field effects from their deployment (Garrett and Cummins 2007). To protect against long-term biofouling and corrosion, most components would be treated with antifouling or foul release coatings. The outer surfaces of antifouling coatings are designed to slowly erode, exposing a fresh layer of the biocide. This process releases the biocide into the aquatic environment through dissolution or flaking. Historically, major environmental impacts resulted from use of tributyltin as an anti-fouling biocide. Currently, copper is a common anti-fouling biocide. Anti-fouling coatings on marine tidal devices can have harmful impacts on marine organisms if concentrations reach threshold toxicity levels in water or sediments.

Gaps in Understanding

A major gap in understanding of this stressor is that it is unclear what anti-fouling biocides will be used by the tidal power industry. From the limited data available, biofouling rates in shallow water (e.g., within 15 m of the surface) are generally faster than at greater depths (e.g., 50 m below the surface; Polagye and Thomson 2010). Since it is unknown what coating(s) will be on a tidal device, it is also unclear what toxicological impacts the coating(s) may have or what behavior, fate, or bioaccumulative effects the biocide might have.

Approaches to Monitoring

Prior to any environmental monitoring, an initial assessment of the potential impact of the anti-fouling biocide on the environment should be conducted to assess whether sophisticated environmental fate and effect modeling or monitoring is warranted. One assessment approach would be to determine the mass of biocide released (from leaching studies) and then use this information to predict what the concentration level of the biocide would be in a specific sediment area or water volume. A range of receptor area sizes/volumes should be used for assessment purposes. If the predicted concentration of the biocide in a "target" receptor area or water volume exceeds toxicity screening criteria, then a risk management assessment may be warranted that involves more detailed modeling, monitoring, or mitigation measures. There are a variety of monitoring approaches that could be used to assess the impact of the anti-fouling biocide on the ecosystem, including caged fish or shellfish studies, biogeochemical behavior and fate studies, surface sediment monitoring, and water column monitoring.

Mitigation Measures

Use of anti-fouling biocides should be avoided, if possible. If it is deemed necessary, minimal amounts should be used. Where use of anti-fouling biocides is necessary, toxicity screening of materials should be conducted to inform selection and design. It is important to note that anti-fouling biocides are likely to be continually released into the environment, possibly at toxic levels of chronic exposure for some organisms, precluding or making highly problematic any mitigation measures. Because of this continual release and inability to mitigate, the impact on habitat is potentially high and also highly uncertain because of the paucity of information on toxicity and biogeochemical behavior of newly developed biocides. Foul release coatings, which create an inert, low-adhesion surface, may be an effective alternative. However, the feasibility of applying these coatings to tidal energy devices has not yet been demonstrated. Physical removal of surface fouling may be accomplished by high-pressure water jets once a device is recovered to the surface or transported to shore. Most device developers have proposed service intervals of no greater than every four years.

3.3.5 Priority Area: *Resuspension of pollutant chemicals from sediment*

Description

Installation of tidal power devices has the potential to disturb fine sediments and introduce historically deposited contaminants to the water column. The most likely place sediment disturbance could occur is where power conveyance cables pass through fine-grained sediments near shore. Nearshore areas are also more likely to be contaminated than offshore sediments. Water velocities at most tidal energy deployment sites are anticipated to be high enough that fine grained sediments containing contaminants will not be present in most cases.

Gaps in Understanding

The major unknowns with respect to resuspension of contaminated sediments are the lack of knowledge of how the power cable will be laid and the strongly site-specific nature of contamination.

Approaches to Monitoring and Mitigation

Use of directional drilling techniques to install the cable would prevent or significantly reduce sediment disturbance. Horizontal directional drilling bores beneath the nearshore area. Depending on soil composition and shoreline conditions, bores up to 500 m in length are feasible. If a technique that disturbs sediments is used to lay the cable (e.g., trenching through the nearshore environment), monitoring of the sediments in the area for contaminant levels should be conducted prior to installation, to avoid areas of concern.

3.3.6 Priority Area: *Large oil spills*

Description

A variety of petroleum-based products (lubricants, hydraulic fluids, vessel fuel, etc.) will be utilized or present during the installation, operation, maintenance, and removal of tidal energy devices. Although catastrophic release of these materials to the aquatic environment is likely to be of low probability with safe and effective operational practices, accidents should be anticipated. Mitigation options should be considered prior to deployment, and rapid and effective spill response procedures need to be developed prior to device installation. Unsuccessful containment or response to a large spill can have significant environmental impacts, especially if the spill reaches a highly sensitive ecosystem habitat (e.g., a wetland area utilized for breeding or spawning). One particular challenge is that tidal energy devices will be operated in high-energy environments and normal oil spill response procedures may not be effective. For example, placing a boom around the spill will not be effective in a high-velocity turbulent environment.

Gaps in Understanding

Based on the history of large accidents and chemical spills in the marine environment, it is clear that such an incident will have high impact. Research documenting the impacts of large spills is sufficient enough to rate the uncertainty associated with the nature and severity of the impact as low to moderate. Any uncertainty in impact would likely be associated with spills involving unusual materials, biotic species presence, or specifics of the ecosystem. A large spill incident will be equally harmful, whether it occurs during installation, operation, maintenance, or device removal. Two major gaps exist in the understanding of the impact of large spills on the environment: (1) the ability to predict where and when the spill will impact the shoreline, and (2) for some chemicals, information on the behavior, fate, (e.g., volatility, solubility, etc.) and bioaccumulation/biomagnification in the marine environment.

Approaches to Monitoring

Many of the sites proposed for tidal energy development in the United States already accommodate large-scale vessel traffic or, in the particular case of Cook Inlet, Alaska, oil and gas exploration. For these sites, the effectiveness of existing spill response procedures should be assessed in the context of tidal energy development. If existing procedures are not sufficient, additional studies and inputs to regional oil spill plans may be needed. Specific elements of these inputs could include:

1. *Develop both predictive and real-time trajectory modeling capability*. The goal would be to provide spill trajectory information in real time, using input from tidal current prediction, wind speed and direction, and other sensors, so that measures can be taken to minimize impact on the environment. Spill response teams can be directed to predicted target areas.
2. *Identify trajectory conditions that might lead to transport of spills to sensitive areas*. The specific hydrodynamic and atmospheric conditions that must exist in order for a spill to reach a particularly sensitive ecosystem area could be identified.
3. *Conduct baseline studies of sensitive environments vulnerable to spills*. This effort should be done in coordination with the previous item in order to prioritize and focus on the most sensitive areas that are likely targets of a spill. The focus should be to obtain that necessary pre-spill characterization information in order to assess the impact on the receptor environment.
4. *Avoid or minimize the use of toxic materials.* Choice of lubricants and fluids should be made based on environmental toxicity information.
5. *Identify remote sensing tools.* Determine whether remote sensing tools can be used to assist in the detection and tracking of spills.

Mitigation Measures

Installation, maintenance, and decommissioning activities should be scheduled during periods when hydrodynamic and atmospheric conditions would not allow a spill to reach a particularly sensitive ecosystem. Most of these activities would, by necessity, occur during less energetic periods when traditional spill response measures would be more timely and effective than during periods of strong tidal currents.

Designs that minimize the volume of lubricants and hydraulic fluids are preferred. A number of tidal energy devices require either no lubricants (water lubricated bearings) or only small quantities of biodegradable lubricants. The highest lubricant volumes are associated with hydraulic drive trains on devices. Although relatively common for the wave energy devices, this power take-off option is proposed for relatively few tidal device concepts.

3.3.7 Recommended References

Almeida, E., Diamantino, C. and de Sousa, O. 2007. Marine paints: The particular case of antifouling paints. *Progress in Organic Coatings*, 59: 2–20.

Brooks, S.J. and Waldock, M. 2009. Section 9, Chapter 24: Copper Biocides in the Marine Environment. In T. Arai et al. (eds.), *Ecotoxicology of Antifouling Biocides*. New York, NY: Springer. 413-428.

Karlsson, J., Ytreberg, E. and Eklund. B. 2010. Toxicity of anti-fouling paints for use on ships and leisure boats to non-target organisms representing three trophic levels. *Environmental Pollution*, 158: 681-687.

Konstantinou, I.K. and Albanis, T.A. 2004. Worldwide occurrence and effects of antifouling paint booster biocides in the aquatic environment: A review. *Environment International*, 30: 235– 248.

NOAA (National Oceanic and Atmospheric Administration). 2010. *Office of Response and Restoration.* Available at *http://response.restoration.noaa.gov/.*

Orme, J., Masters, I. and Griffiths, R. 2001. *Investigation of the effect of biofouling on the efficiency of marine current turbines.* In C. French (ed.) Proceedings of MAREC 2001 (Institution of Marine Engineers, 2001). 91-99.

Polagye, B. and Thomson, J. 2010. Screening for biofouling and corrosion of tidal energy device materials: *In-situ* results for Admiralty Inlet, Puget Sound, Washington. Northwest National Marine Renewable Energy Center Technical Memorandum. Northwest National Marine Renewable Energy Center. Seattle, WA.

Schiff, K., Diehl, D. and Valkirs, A. 2004. Copper emissions from antifouling paint on recreational vessels. *Marine Pollution Bulletin*, 48: 371-377.

3.4 Acoustic Effects

Name	Affiliation
Peter Dahl (Chair)	University of Washington
Bob McClure	BioSonics. Inc.
Bruce Mate	Oregon State University
Dominic Tollit	Sea Mammal Research Unit, Ltd.
Jim Thomson	University of Washington
Kit Rawson	Tulalip Tribes
Peter Browne	HDR, Inc.
Simon Geerlofs	U.S. Department of Energy
Tina Wyllie-Echeverria	Wyllie-Echeverria Associates
Chris Bassett (Note Taker)	University of Washington

3.4.1 Introduction

In this section, the risks of underwater sound to the marine environment and marine organisms associated with tidal energy devices, including both their construction and operation phases, are discussed and evaluated. Sound can be produced underwater by numerous mechanisms all involving some kind of vibration or impact feature (such as a bubble collapse). Observed effects of underwater sound include changes in responsiveness to other stimuli, masking, temporary threshold suppression, and injury, as well as the general effects on communication, echolocation, spawning, and shoaling behavior (Michel et al. 2007). Various activities and processes, both natural and anthropogenic, combine to form the sound profile within the ocean, generally referred to as ambient ocean noise. Except for sounds generated by some marine animals using active acoustics for echolocation, most ambient noise is broadband (composed of a spectrum of numerous frequencies without a differentiating pitch) representing virtually the entire frequency spectrum. Distant shipping is the primary source of ambient noise in the 20- to 500-Hz range (OMP 2006). Spray and bubbles associated with breaking waves are the major contributors to ambient noise in the 500- to 100,000-Hz range. Noise from wave and tidal action can cause coastal environments to have particularly high ambient noise levels. Anthropogenic activities that contribute to ambient ocean noise include ship traffic (commercial and recreational boating, as well as military training exercises), aircraft flying over water, dredging, nearshore construction activities, mineral/oil/gas exploration and extractions, geographical surveys, and seismic surveys.

It should be noted that because tidal devices necessarily operate in high-flow environments, it is essential that the phenomenon of pseudo-noise, defined as the signal recorded by an underwater sound measurement device (hydrophone) produced by turbulence being advected over the face of the hydrophone be distinguished from a truly propagating sound field associated with noise generation from tidal energy production. Non-propagating pseudo-sound (Strasberg 1988) should not be viewed as a genuine environmental stressor. Nonetheless, measurements of sound at proposed tidal energy sites can be easily contaminated by this effect. Strategies to reduce this effect are discussed in a subsequent section of this document.

It should also be noted that, as a practical matter, the frequency range of underwater noise associated with tidal energy devices is limited, and these limits need to be understood to properly bound the problem and more efficiently allocate measurement and analysis resources (e.g., Richard et al. 2007). To best understand this frequency range, the noise frequency spectrum can be partitioned into the following decades: 1-10 Hz, 10-100 Hz, 100-1,000 Hz, 1,000-10,000 Hz, and greater than 10,000 Hz (10 kHz).

In regards to the first decade (1-10 Hz), because tidal power generation will necessarily occur in shallow water (i.e., within depths on the order of 100 m or less) features of shallow water acoustic waveguide propagation must be considered (Frisk 1994). Specifically, sound does not propagate well for frequencies below the mode-1 cutoff frequency and, for a depth of 100 m and seabed properties representing hard, rocky substrate (expected in high-flow areas), the mode-1 cutoff frequency is ~10 Hz, increases with decreasing depth. Thus sound pressure in the 1- to 10-Hz range is expected to be of little significance in terms of risks and impacts. It is noted, however, that sound particle acceleration in this infrasonic range may be an issue and, thus, the 1-10 Hz frequency remains important. The fourth decade, 1,000-10,000 Hz (1-10 kHz), is expected to have less importance because the characteristic frequencies for power extraction by the rotor are limited to the 100- to 1,000-Hz frequency range or less. However, gearboxes and generators spin at higher rates, and noise from these may be appreciable in the fourth decade (Richards et al. 2007). Little noise is expected from turbine operation in the fifth decade.

In summary, the key frequency range of interest for investigations relating risks of underwater noise associated with tidal energy production should emphasize the first (1-10 Hz), second (10-100 Hz), and third (100-1,000 Hz) decades. The fourth decade may also be of importance when the turbine drivetrain incorporates a speed increasing gearbox. As a corollary, questions that might arise concerning sound frequencies far outside this frequency range, such as the observed phenomenon of fish avoidance of certain sound frequencies in the 100-kHz range, are not relevant to this problem unless those frequencies are less than 10,000 Hz (10 kHz).

A matrix of stressor/receptor interactions, their significance, and uncertainty is given in Figure 17 for pilot-and commercial-scale deployments. The colors denote significance and triangles denote uncertainty, as defined in Figure 17. For the purposes of this matrix, impacts on living organisms have been split into two levels, nominally consistent with usage by NOAA Fisheries:

- Level A – Immediate risk of mortality or physical injury (e.g., permanent hearing threshold shifts) – 180 dB broadband for marine mammals exposed to a continuous noise.
- Level B – Disruptions of behavior, including temporary shifts in hearing threshold (e.g., often resulting in change of swimming path as part of avoidance) – 120 dB broadband for marine mammals exposed to a continuous noise.

The elements of the stressor matrix differ for pilot-scale projects versus full-scale build-outs. In general, a pilot-scale project is expected to be of less risk than a full-scale build-out. As an approximate rule of thumb, a larger array of N devices would result in a total noise increase of $10\log_{10}(N)$ in dB. For example, two devices would result in an increase in noise level of 3 dB, compared to a single device, and an array of 10 devices would result in a 10-dB increase.

3.4.2 Stressor Matrix

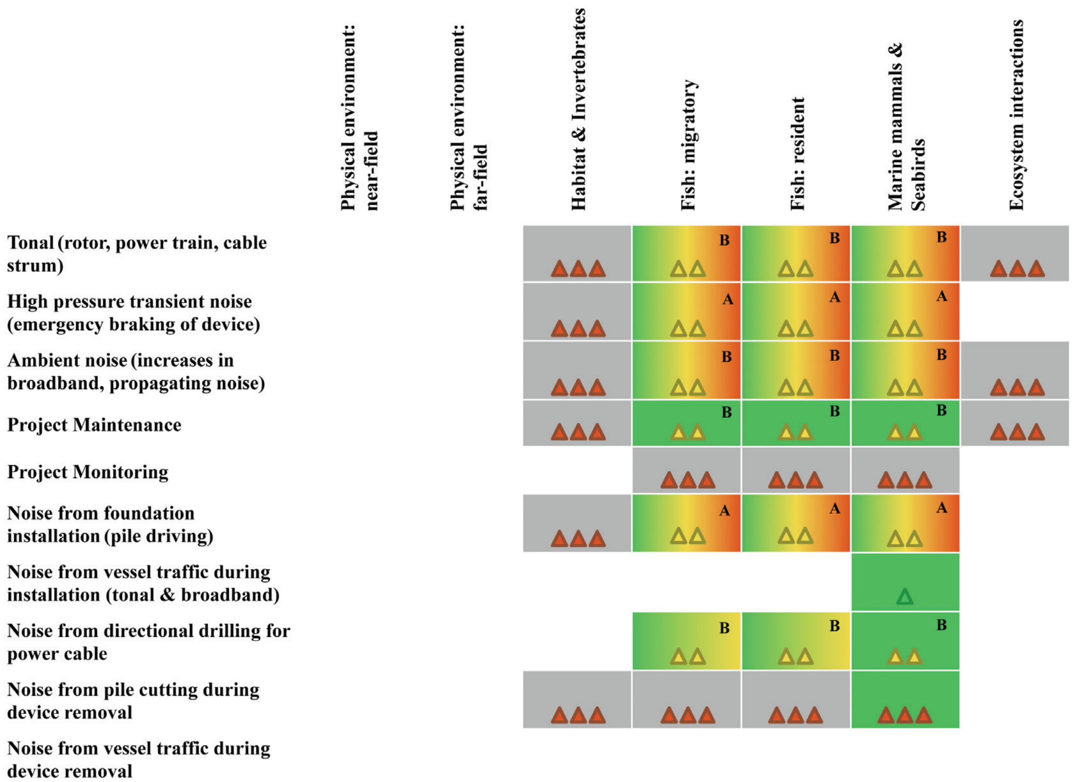


Figure 17 – Stressor matrix: Acoustic effects – pilot and commercial-scale deployments

3.4.3 Discussion

Several points relating the risks of underwater sound to the marine environment and marine organisms associated with tidal energy devices were discussed. The three deemed most relevant are summarized here.

Tonal components associated with tidal energy installations

Operation of tidal energy devices may generate tonal sounds. For the purposes of the workshop, tones have been defined as increases above ambient in the sound pressure level (SPL) in a 1/3-octave band. The 1/3-octave band center frequencies have standard definitions. For example, the typical lowest center frequency for underwater environmental sound measurements is 12.5 Hz, followed by 16 Hz, 20 Hz, 25 Hz, etc., with increasing separation between center frequencies, such that the center frequency of 2,000 Hz is followed by 2,500 Hz. It should be noted that SPL is defined in the underwater sound convention as decibels referenced to 1 micro Pascal (abbreviated dB re 1µPa). Rather than provide a precise definition of what constitutes a significant increase in SPL, it is noted that SPL can readily vary by 30 dB in the natural environment (Tougaard et al. 2009, Bassett et al. 2010).

For this element of the acoustic stressor, there is uncertainty around the low-frequency tonal components of the spectrum produced by tidal turbines. This is driven by both the workgroup participants' unfamiliarity with relevant literature, as well as the proprietary nature of turbine noise measurements. As a result, there is uncertainty over what effects these tonal components might have on different species of fish (resident, migratory) or marine mammals and at what frequencies these effects would be most significant for a particular species. What constitutes significance for a tonal-based stressor is to be decided by the appropriate agencies. It is noted that auditory thresholds for particular marine species may be used as a starting reference (Southall et al. 2007).

Increases in broadband ambient noise

Ambient noise should be either measured directly in, or converted to, 1/3-octave bands. This approach is nominally consistent with approaches to assess impacts from offshore wind turbines (Tougaard et al. 2009). The 1/3-octave bands can also be more readily compared to known underwater audiograms for selected species of fish and marine mammals, from which potential impacts described by "zone of audibility" or "zone of masking" can be estimated, if need be (Richardson et al. 1995). To the extent that tidal energy turbines produce continuous noise for long periods, the National Oceanic and Atmospheric Administration guideline for level B impacts of 120 rms dB needs to be assessed (the 120 value being the linear, or non-decibel, sum of all the octave bands.)

Ambient noise must not be confused with non-propagating noise (pseudo-noise) associated with advection of turbulence over the face of a hydrophone (Bassett et al. 2010). To avoid this effect, the measurement of ambient environmental background noise (in absence of a tidal energy device) cannot be measured exclusively during periods of slack water, because of the presence of ambient noise sources, primarily during high currents (e.g., moving cobbles). A technical challenge arises as to how ambient *operational* noise is measured, because, by definition, the tidal energy device operates during periods of high flow. Some promising approaches could involve placing flow shields over hydrophones or using drifting hydrophones. It is beyond the scope of this report to further articulate solutions, other than to note that pseudo-noise can be a serious confounding factor.

Baseline ambient noise measurements prior to project development need to be established to provide insight into the potential risks at a site. For example, are noise levels from an installed turbine so loud relative to ambient noise that they may interfere with social and predatory acoustic communication or migration patterns? Following construction, ambient noise in the vicinity must be studied within some standardized framework. This should describe received levels at various distances from the installed turbine, with attention paid to depth-dependence and directionality. Following this characterization, measurements at a standardized distance (e.g., 10 m from the source) may be sufficient to monitor for relative changes without resorting to extrapolation to a hypothetical 1 m from the source. Noise from flow around structures and from the wake of the turbines is not important, because the noise source is weak in strength or represents pseudo-sound and, therefore, should be discounted as a noise stressor.

Transient sources of high pressure noise such as with pile driving

Pile driving during the construction phase represents the most probable source of high acoustic pressure (in excess of ~1,000 Pa). Mitigation techniques, such as optimized construction timing to avoid species seasonally occurring in the area and the potential impacts on many marine species are both reasonably well understood. Best practices to avoid significantly affecting species should be established. It should be noted, however, that most device concepts do not propose pile driving as a part of device installation.

Recommendations

The following recommendations should be addressed to reduce the uncertainty with this stressor.

In the short-term, there is a need to investigate technologies to shield transducers from flow/turbulence-induced noise in order to make accurate measurements over the full range of tidal currents. Workshop participants recommend applying and, perhaps, modifying technologies currently used in towed-arrays for naval applications. There is also a need to investigate the nature of tonal components with respect to shallow acoustic modal propagation. This would help to bound investigations by establishing which components are below the waveguide cutoff frequency and thus of less importance. A final need is to establish standards for reporting noise fields associated with tidal energy devices, with specific emphasis on determining the appropriate range from the device at which measurements should be made.

Over the long-term, there is a need to improve on techniques to measure acoustic propagating noise fields within highly turbulent environments. Also, there is a need to expand the knowledge base on marine species concerning their sensitivities to anthropogenic noise (e.g., Mueller-Blenkle et al. 2010). This workshop group cautions, however, that this should not be an open-ended endeavor. That is, a comprehensive study that includes multiple species is not likely to be productive. Also, additional pressure density spectra and waveform data on a variety of tidal energy devices and operation phases should be collected to better bound the potential increase from ambient levels.

3.4.4 Priority Area: *Injury or mortality due to excessive transient pressure*

Description

Excessive transient pressure is defined as transient acoustic pressures exceeding 1,000 Pa. This may result in injury or mortality.

Gaps in Understanding

A large body of literature exists relating mortality associated with barotrauma, permanent auditory threshold shift (PPT), and temporary threshold shift (TTS). This is reviewed in Southall et al. However, there are still taxonomic gaps in understanding (e.g., baleen whales).

Approaches to Monitoring

If pile driving is part of the construction process (and, in many cases, it may not be) then monitoring should follow current best practices used in the marine construction industry, with ability to temporarily halt operations if significant issues are revealed. To quantify high transient pressure the standard sound energy level (SEL) definition as proposed by Southall et al. is recommended. In practice, a high transient pressure would be on the order of 1,000 Pa and 0.1-second duration.

Mitigation Measures

As this is expected to be largely associated with a short-term construction phase, mitigation should include construction timing. Mitigation might also include slow ramp-up for operations with intense noise (e.g., pile driving), bubble curtains, and the use of acoustic deterrents.

3.4.5 Priority Area: *Behavioral responses to prominent narrow band or tonal components*

Description

Behavioral responses to prominent narrow band or tonal components include a range of responses from relatively benign pauses in activity to potentially injurious flight from an area.

Gaps in Understanding

Recent conference proceedings (Noise on Aquatic Life 2008) provide some information on tonal disturbance. However, in reference to the comment made in the introduction, more information is needed on tonal disturbances within the 10- to 100-Hz, 100- to 1,000-Hz, and 1,000- to 10,000-Hz frequency ranges for tidal energy devices.

This workshop group also notes recent work on ship avoidance by fish, particularly in the context of fishery research vessels conducting surveys of fish populations. Quoting from Sund et al. (2008a), "it is emphasized that the otolith organs in fish are linear acceleration detectors with extreme sensitivity to infrasonic particle acceleration." What does this mean? Audiograms for fish typically show a decreased sound-pressure hearing sensitivity with frequency for frequencies < 100 Hz (Sund et al. 2008b). For particle acceleration, however, this would translate to a rather flat sensitivity (i.e., not decreasing), as discussed in Sund et al. (2008b). This issue needs to be understood in the context of the possibly very low, or infrasonic, emissions that could originate from tidal energy devices.

Approaches to Monitoring

Statistically reliable baseline estimates of 1/3-octave band SPL are needed. This workshop group proposes that operation-based measurements should be made at a distance 10 m from center of the rotor at the hub height of the tidal energy device. The reasoning behind this is that the device is large in spatial extent (rotor diameters generally greater than 5 m) and extrapolations to "1 m," based on spherical spreading or some hybrid spreading law, are likely to be suspect.

Mitigation Measures

To the degree they exist, tonal disturbances would occur during operation, and there are few mitigation measures beyond basic device design (rotational speed, number of rotors, etc.).

3.4.6 Priority Area: *Behavioral responses to increases in broad band noise*

Description

A significant increase in broad band noise associated with device operation is a concern. Referring to the introductory comments on the key frequency range of underwater noise associated with tidal energy production, the term broad band, therefore, necessarily implies the frequency range of 10-1,000 Hz. This increase may or may not be uniform, but it would not be concentrated within a particular 1/3-octave band (in which case, the noise would necessarily be viewed as narrow band). Because ordinary variation can result in 30-dB changes in broad band SPL (Tougaard et al. 2009), a significant increase needs to be at 30 dB, if not more.

Gaps in Understanding

The most significant gaps in understanding relate to how long the noise should be averaged and what constitutes a significant increase in broad band SPL as it relates to effects on animals, which may also differ between taxonomic groups. Unlike specific tones or very high transient pressure spikes, the impacts of an overall increase in broad band noise are less well known. To the extent they exist, it is this group's opinion that the impacts will be limited to the Level B kind. A major gap in understanding is to what extent behavioral modifications due to increased broadband noise from tidal energy devices might affect population viability.

Approaches to Monitoring

Statistically reliable baseline estimates of 1/3-octave band SPL are needed. To address the issue of time averaging, it is recommended that the time scale over which an average is made is 2 weeks, during which continuous averages are made at intervals 1 to 10 min.

Mitigation Measures

To the degree they exist, disturbances associated with broad band increases in noise would occur during operation, and there are few known mitigation measures beyond basic device design.

3.4.7 Recommended References

Bassett, C. Thomson, J. and Polagye, B. 2010. *Characteristics of Underwater Ambient Noise at a Proposed Tidal Energy Site*. MTS/IEEE Oceans 2010. September 20-23, 2010.

Dahl, P.H., Miller, J.H., Cato, D.H. and Andrew, R.K. 2007. Underwater Ambient Noise, *Acoustics Today*. 3(1): 23-33.

Frisk, G.V. 1994. *Ocean and Seabed Acoustics: A Theory of Wave Propagation*. Englewood Cliffs, NJ: Prentice Hall.

Mueller-Blenkle, C., McGregor, P.K., Gill, A.B., Andersson, M.H., Metcalfe, J., Bendall, V., Sigray, P., Wood, D.T. and Thomsen F. 2010. *Effects of Pile-driving Noise on the Behaviour of Marine Fish*. Technical Report, COWRIE Ref: Fish 06-08. March 31 2010.

Richards, S.D., Hardland, E.J. and Jones, S.A.S. 2007. *Underwater Noise Study Supporting Scottish Executive Strategic Environmental Assessment for Marine Renewables*. Technical report prepared for the Scottish Executive by QinetiQ Ltd., Farnborough, Hampshire. QINETIQ/06/02215/2.

Hawkins, A. 2008. Effects of Noise on Aquatic Life: the Key Issues. *Bioacoustics*. 17(1-3): 7-10.

Richardson, W.J., Greene, C.R., Malme, C.I. and Thomson, D.H. 1995. *Marine Mammals and Noise*. San Diego, CA: Academic Press.

Southall, B.L., Bowles, A.E, Ellison, W.T., Finneran, J.J., Gentry, R.L., Greene, C.R., Kastak, D., Ketten, D.R., Miller, J.H., Nachtigall, P.E., Richardson, W.J., Thomas, A. and Tyack, P.L. 2007. Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. *Aquatic Mammals*, 33(4): 411-521.

Sund, O., Karlson, H.E. and Knudsen. F.R. 2008. Comment on "Silent research vessels are not quiet" [2007. *J. Acoust. Soc. Am.* 121(4): EL145-EL150]. *J. Acoust. Soc. Am.* 123(4): 1831-1833.

Sund, O., Enger, P.S., Karlson, H.E. and Knudsen, F.R. 2001. Detection of Infrasound in Fish and Behavioral Responses to Intense Infrasound in Juvenile Salmonids and European Silver Eels: A Minireview. *In Behavioral Technologies for Fish Guidance*, Coutant, C. (Ed.). American Fisheries Society Symposium 26: 183-193.

Strasberg, M. 1988. Dimensional analysis of windscreen noise. *J. Acoust. Soc. Am.* 83: 544-548.

Tougaard, T., Henriksen, O.D. and Miller, L.A. 2009. Underwater noise from three types of offshore wind turbines: Estimation of impact zones for harbor porpoises and harbor seals. *J. Acoust. Soc. Am.*, 125: 3766-3773.

3.5 Electromagnetic Effects

Name	Affiliation
Gouri Bhuyan (Chair)	Powertech Labs
Andrew Gill	Cranfield University
Alicia Bishop	NOAA Fisheries, Northwest Regional Office, Hydropower Division
Greg McMurray	Pacific Energy Ventures
Jerry Johnson	University of Alaska - Fairbanks
Kate Savage	NOAA Fisheries - Alaska Regional Office, Protected Resources Division
Markus Horning	Oregon State University
Mirko Previsic	re vision consulting, LLC
Stephen Kajiura	Florida Atlantic University
Ryan Tyler (Note Taker)	University of Washington

3.5.1 Introduction

Tidal current turbines convert the kinetic energy associated with the current into rotary motion in order to drive a generator. The electricity that is generated may be conditioned at sea but, in all cases, will be transmitted to shore-based facilities via power cables. There are various options for connecting tidal current generators to an onshore electrical grid. For example, a pilot plant could involve an alternating current (AC) generator connected to an AC/DC/AC power electronic converter and a step-up transformer to the grid voltage, with power transmission via an AC cable. For a tidal farm, multiple AC generators could be connected to a step-up transformer through one or more AC/DC/AC power convertor(s) using AC cables and then to the grid at shore using AC cable again. There is also a possibility of connecting multiple AC turbines to an on-shore step-up transformer via alternating current/direct current (AC/DC — with the rectifier placed near turbine) and direct current/alternating current (DC/AC — with the inverter placed near the on-shore substation) power converters. In this scenario, a direct current (DC) cable between the power converters would need to be used. Most potential sites for pilot and commercial tidal current installations are expected to be located relatively close to the shore, implying that high-voltage AC power transmission (from a step-up transformer to a grid on shore) is the most likely scenario. However, some device developers have proposed rectification at the turbine to DC, transmission by DC cable, and inversion on-shore back to AC for grid connection. Tidal installation layout and the size of the power plant will vary according to the potential harvestable resource; it will be highly site specific.

A conductor carrying AC will produce simultaneous electric and magnetic fields with a frequency identical to the source current. However, the field induced by DC contains a static magnetic field only. The electrical fields are highly attenuated by the metal shielding around the cables. Although the magnetic fields penetrate most materials, their strength decreases with the square of distance from the cable. Potential sources of electromagnetic fields (EMFs) from the operation of either pilot or commercial operation of tidal current power plants are assumed to be from the generator and ancillary sub-systems, such as converters (power electronics), transformers, and power cables. Some generators, consisting of permanent magnets, are also thought to be potential sources of a magnetic field even when idle. Physical damage to the submarine cable of a tidal system, such as damage to shielding, could potentially cause leakage of an electrical field and this in turn could be a potential source for a magnetic field.

The above-mentioned potential EMF contributions from the operation of tidal current power systems will add to the earth's naturally occurring static geomagnetic magnetic field (that varies from 20 to 75 micro Tesla, depending upon the location) and low magnitude and frequency (alternating) magnetic field generated by tidal motion (for example, on the seafloor offshore of Vancouver Island, British Columbia, CA, has a natural magnetic field of about 0.02 micro Tesla with a 50 minute period). The marine environment already has many electrical cables used for power transmission, communications and other uses. Adding EMF signals from tidal devices and associated cabling must be compared against the existing fields.

Electro-reception and magneto-reception have been documented in scientific literature for some species of fish and other aquatic animals (see recommended references at the end of this section). Almost all of these investigations have used fields that simulate those found in nature. A limited number of studies have been conducted in the offshore wind energy sector to identify the impacts of EMF on marine organisms, particularly focusing on the submarine power cables (Gill et al. 2005). In most cases, the studies focused on animal behavior in mesocosms (experimental enclosures designed to approximate natural conditions) near conductors. Even though various species were found to be sensitive to EMF, their specific behavioral and physiological responses could not be established. Also, there is lack of sensitivity threshold data for the relevant marine species where some of the tidal projects are being planned.

Certain marine species are electro-sensitive while others are magneto-sensitive. For example, finfish, eels, sharks, and sea turtles use the earth's DC magnetic field for orientation, navigation, and migration (Kirschvink et al. 2001), while weak electric fields can be exploited by certain fishes (rays, sharks) for orientation and prey location. Physiological impacts, such as mortality or reproductive success, may be dominant for some of these organisms, whereas behavioral responsiveness, like migration or colony formation, may appear more critical for others. The duration (short to long-term) and type of exposure (e.g., DC/AC, steady-state/transients, etc.) may form another layer of complexity.

A matrix of stressor/receptor interactions, their significance, and uncertainty is given in Figure 18 for pilot-scale deployments and in Figure 19 for commercial-scale deployments. The colors denote significance and triangles denote uncertainty, as defined in Figure 10.

3.5.2 Stressor Matrix

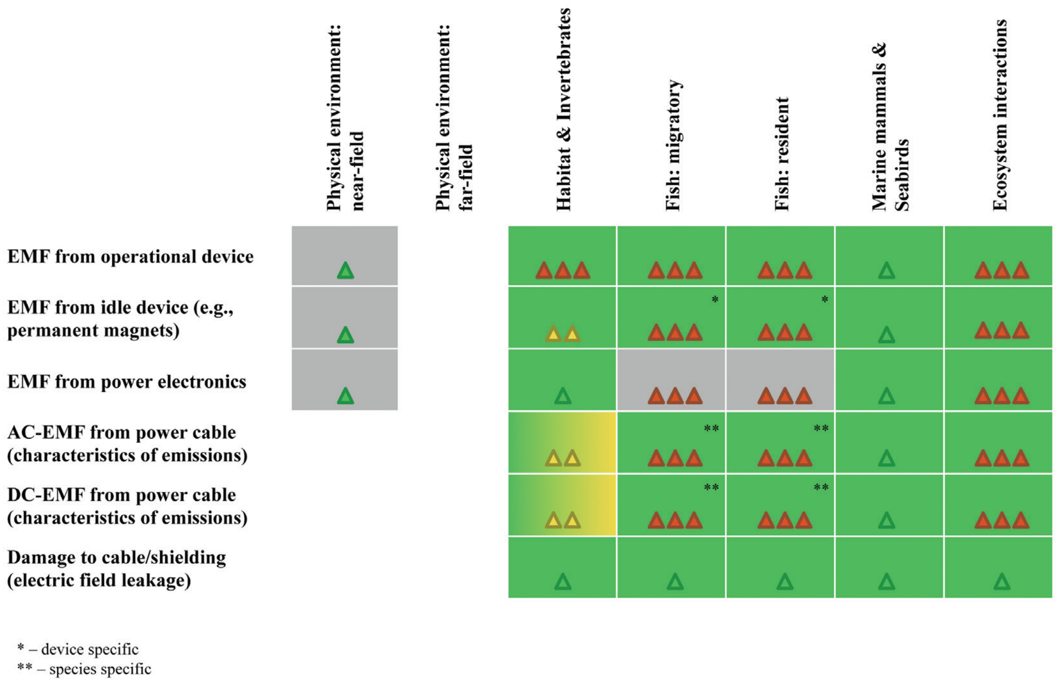


Figure 18 – Stressor matrix: Electromagnetic effects – pilot-scale deployments

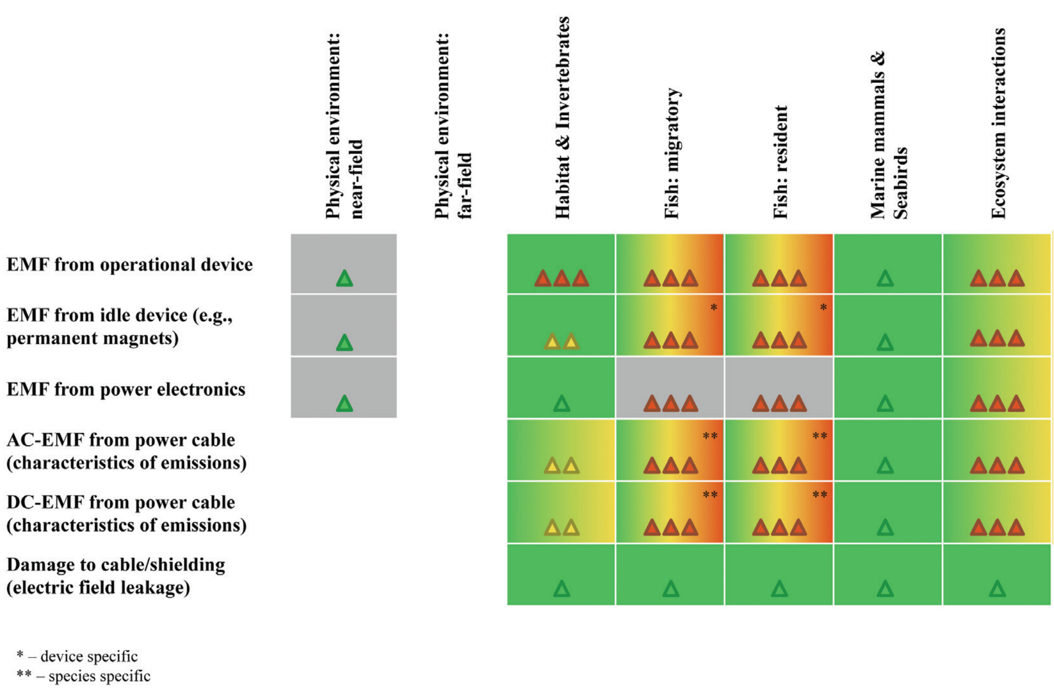


Figure 19 – Stressor matrix: Electromagnetic effects – commercial-scale deployments

3.5.3 Discussion

The group discussed the likelihood of effects of the above stressor elements on the following receptors: near-field and far field physical environment, habitat, migratory fish, resident fish, marine mammals and seabirds, and ecosystem/food chain interactions. In terms of the likelihood of effects of the EMF from the devices and power electronics on the near field physical environment, these are unknown. It is thought that the stressor elements are likely to have no effect on the far-field physical environment. The EMFs from the device and power electronics are likely to have low effect on habitats; however, EMF from AC and DC power cables are likely to have low to medium effect with high degree of uncertainty. Electric field leakage due to cable shield damage is thought to have a low effect. Depending upon the spatial layout of the devices and the cables, the EMF stressor elements could have low (for pilot-scale) to high (for commercial-scale) effects on migratory species. The EMF effects on resident fishes are thought to be similar to that of the migratory fish. The stressor elements are likely to have a low effect on marine mammals and seabirds. The likelihood of effect of the EMF from the tidal plant operation on the ecosystem interactions is thought to be low for pilot plants and low to medium with high uncertainty for commercial array operation.

3.5.4 Priority Area: *Quantifying EMF from devices (operating and idle)*

Description

Knowledge of expected level of EMF from pilot and commercial tidal plants will be essential in developing any necessary monitoring and mitigation strategy.

Gaps in Understanding

From the group discussion, as well as from the literature, it is very clear that state of knowledge on the EMF contributions from any tidal current power generation systems (generator, power electronics) is nonexistent in the public literature. There is some information in the public domain on EMF contributions for power cables to shore from offshore wind energy analogues (e.g., Gill et al. 2005).

Approaches to Monitoring

In a laboratory environment, it is possible to measure both magnetic and electric fields. Laboratory studies of magnetic and electric fields around cables may be effective at bounding the field strengths for different array sizes and configurations. These could be correlated against sensitivity thresholds for various species to provide a coarse estimate of the potential for significant interaction.

Given the high degree of uncertainty for this stressor, magnetic fields around some existing tidal current demonstration projects should be measured in cooperation with technology and project developers. Initially, measurements around the power take-off cables are likely to be most tractable. At-sea measurements of the electric and magnetic fields are possible but they do require appropriately constructed and calibrated instruments. For electric fields, the components need to be low noise and the electronic circuit has to have an appropriate 0 V reference, which has been calibrated and recorded both before deployment and after recovery from the field. The longer the instruments are deployed the more likely the electric field measurements will be relative rather than a true reflection of the emitted fields. Furthermore, the changing tidal water movement and organism movement will induce localized electric fields around the tidal device and in relation to the geomagnetic field, hence the measurements should be related to the tidal regime and the geometry of the measurements should be closely considered. Measurements of the magnetic field will also be challenging. The magnetic field will vary with the power generated by the device and, therefore, would need to be profiled over the tidal cycle. Given the strength of tidal currents at utility-scale sites, profiling with an ROV is not likely to be feasible. Multiple magnetometers would need to be deployed on a static frame, or a single magnetometer could be actuated along a track by a motor (which would require calibration in a magnetically quiet laboratory environment to account for the motor's magnetic field). Clearly, this presents a number of non-trivial engineering problems, which are compounded by a lack of protocols for EMF measurements of device components.

Modeling studies to determine the expected level of EMF in the vicinity of tidal current pilot/commercial project developments must be carried out, with necessary inputs from technology and project developers familiar with the design and cable layouts. Results from modeling and measurements could be compared for validation.

Mitigation Measures

Mitigation strategies that reduce the level of EMF contributions from the operation of tidal plants to the marine environment as well as strategies that reduce or avoid exposure of aquatic animals to EMF from tidal developments were briefly discussed among the group. For an example, peak flux of magnetic fields from submarine cables can effectively be reduced by burying them. However, burying cables, rather than laying them on the seabed, would result in greater environment disturbance during installation and may be technically challenging for hard substrates (bedrock, cobbles). Some studies have shown that core twisting or laying separate AC cables in close proximity to each other would decrease the induced magnetic fields (Pettersson and Schönborg 1997). This may also be accomplished by laying two DC cables of opposing polarity in close proximity (Öhman et al. 2007).

The mitigation strategies must first use modeling to assess various design options at the pre-installation stage. This would provide an estimate of the potential EMF that a device/system (including cabling) would produce. The strategies would also require having a knowledge of assessing risk and potential of severity of EMF effect (to the extent they are known) on relevant aquatic animal for a particular site.

3.5.5 Priority Area: *Characterizing the types of electric and magnetic thresholds for different sensitive organisms relevant to sites*

Description

In order to understand how the relevant marine life might be affected from the expected EMF levels and attributes, it is essential to establish relevant threshold values as well as behavioral responses to relevant EMF doses.

Gaps in Understanding

From the group discussion, it was very clear that the state of knowledge on the detection threshold of EMFs by some relevant fish species is very limited, including their behavioral responses to relevant EMF exposures that tidal development could generate. Due to the uncertainty in the significance of the effect, studies to monitor behavioral changes in response to EMF are not often carried out in the field.

Approaches to Monitoring

Controlled experimental investigations (Underwood 1992, Westerberg and Langenfelt 2008, Gill et al. 2009) should be carried out to establish relevant knowledge. These could involve catch and release or tagging studies (passive and active) for large, mobile species and caged organism studies for younger life stages or sessile organisms.

3.5.6 Recommended References

Bhuyan, G. 2010. World-wide status for harnessing ocean renewable resources. *IEEE Power and Energy Society ES General Meeting*. Minneapolis, MN, July 25-29, 2010.

Bullock, T.H, Hopkins, C.D., Popper, A.N. and Fay, R.R. (Eds.). 2005. *Electroreception*. New York, NY: Springer.

Charlier, R. and Justus, J. 1993. *Ocean Energies: Environmental, Economic, and Technological Aspects of Alternative Power Sources*. New York, NY: Elsevier.

Collin, S. and Marshall, N.J. (Eds.). 2003. *Sensory Processing in Aquatic Environments*. New York, NY: Springer.

European Wind Energy Association. 2009. Chapter 5: Environmental Impacts. In *Wind Energy - The Facts*. London, UK: Earthscan.

Gill, A., Gloyne-Phillips, I., Neal, K. and Kimber, J. 2005. *The potential effects of electromagnetic fields generated by sub-sea power cables associated with offshore wind farm developments on electrically and magnetically sensitive marine organisms – A review.* Final report prepared for Collaborative Offshore Wind Energy Research into the Environment (COWRIE) group. COWRIE-EM FIELD 2-06-2004.

Hara, T. and Zielinski, B. 2007. *Sensory Systems Neuroscience*. New York, NY: Elsevier.

Kajiura, S. and Fitzgerald, T. 2009. Response of juvenile scalloped hammerhead sharks to electric stimuli. *Zoology*, 112: 241-250.

Kajiura, S. 2003. Electroreception in neonatal bonnethead sharks, Sphyrna tiburo. *Marine Biology*, 143: 603-611.

Kajiura, S. and Holland, K.N. 2002. Electroreception in juvenile scalloped hammerhead and sandbar sharks. *Journal of Experimental Biology*, 205(23): 3609-3621.

Kajiura, S. 2001. Head morphology and electrosensory pore distribution of carcharhinid and sphyrnid sharks. *Environmental Biology of Fishes*, 61(2): 125-133.

Kalmijn, A.J. 1971. The electric sense of sharks and rays. *Journal of Experimental Biology*, 55: 371-383.

Kalmijn, A.J. 1984. Theory of electromagnetic orientation: A further analysis. *Comparative Physiology of Sensory Systems*, 525-560.

Kay, J. 1997. Equipment development for the measurement of underwater multi influence fields. *IPENZ Transactions*, 24(1/GEN): 48-63.

Khan, M.J. and Bhuyan, G. 2009. *Ocean Energy: Global Technology Developmental Status*. Technical Report for the International Energy Agency - Ocean Energy Systems prepared by PowerTech Labs Inc., IEA-OES T0104.

Khan, M.J, .G. Bhuyan, Iqbal, M.T. and Quaicoe, J.E. 2009. Hydro kinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review. *Applied Energy*, 86(10): 1823-1835.

Kirschvink, J.L. 1997. Magnetoreception: homing in on vertebrates. *Nature*, 390: 339-340.

Kobayashi, A. and Kirschvink, J.L. 1995. Magnetoreception and electromagnetic field effects: Sensory perception of the geomagnetic field in animals and humans. *Electromagnetic Fields*, 250: 367-394.

Koeller, J., Koeppel, J. and Peters, W. (Eds.). 2006. Chapter 14: Effect of Electromagnetic Fields on Marine Organisms. *In Offshore Wind Energy: Research on Environmental Impacts*. New York, NY: Springer. 223-234.

McGowan, D.W. and Kajiura, S.M. 2009. Electroreception in the euryhaline stingray, Dasyatis sabina. *Journal of Experimental Biology*, 212: 1544-1552.

Meyer, C.G., Holland, K.N. and Papastamatiou, Y.P. 2004. Sharks can detect changes in the geomagnetic field. J.R. Soc. *Interface*, 2005(2): 129-130.

Öhman, M.C., Sigray, P. and Westerberg, H. 2007. Offshore Windmills and the Effects of Electromagnetic Fields on Fish. *Ambio* 36(8): 630-633.

Paulin, M.G. 1995. Electroreception and the compass sense of sharks. *Journal of Theoretical Biology*, 174: 325-339

Petersen, J.K. and Malm, T. 2006. Offshore Windmill Farms: Threats to or Possibilities for the Marine Environment. *Ambio* 35(2): 75-80.

Pettersson, P. and Schönborg, N. 1997. Reduction of Power System Magnetic Field by Configuration Twist. *IEEE Transactions on Power Delivery*, 12(4): 1678–1683.

Tesch, F.W., Wendt, T. and Karlsson, L. 1992. Influence of geomagnetism on the activity and orientation of eel, Anguilla anguilla, as evident from laboratory experiment. *Ecology of Freshwater Fish*, 1: 52-60.

Walker, M.M., Dennis, T.E. and Kirschvink, J.L. 2002. The magnetic sense and its use in long-distance navigation by animals. *Current Opinion in Neurobiology*, 12: 735-744.

Walker, M.M., Diebel, C.E., Haugh, C.V., Pankhurst, P.M., Montgomery, J.C. and Green, C.R. 1997. Structure and function of the vertebrate magnetic sense. *Nature*, 390: 371-376.

Westerberg, H. & Langenfelt, I. 2008. Sub-sea power cables and the migration behaviour of the European eel. *Fisheries Management and Ecology*, 15: 369-375.

3.6 Energy Removal

Name	Affiliation
Scott Couch (Chair)	University of Edinburgh
Andrea Balla-Holden	U.S. Navy
Brian Polagye	University of Washington
Charles (Si) Simenstad	University of Washington
Graham Savidge	University of Queens
Harper Simmons	University of Alaska - Fairbanks
Mitsuhiro Kawase	University of Washington
Monty Worthington	Ocean Renewable Power Company, LLC
Neil McMahon	Alaska Energy Authority
Scott James	Sandia National Laboratories
Jeff Epler (Note Taker)	University of Washington

3.6.1 Introduction

Energy removal by hydrokinetic turbines may cause regional changes in the tidal regime because the existing regime and environment are, in large part, established by the natural removal of energy by friction and turbulence. Consequently, energy removal at a particular location will affect (augment or reduce) tides, currents, and mixing throughout a waterbody. These changes are strongly site-specific and depend on where power is extracted within a particular system. For example, removing the same amount of average power from two different sites in the same body of water may lead to very different effects on the far-field physical environment (Polagye et al. 2009). This stressor is common for all hydrokinetic devices, although aspects of the device (e.g., foundation and support structure) can alter the fraction of energy removed that is converted to useful electrical power.

Although energy removal effects are not readily generalized, changes to currents are sometimes related to the work done by the tide. Blanchfield et al. (2008) give an equation for the maximum power extractable (P_{max}) from a narrow channel linking an enclosed bay to the open ocean as

$$P_{max} = \gamma \rho g a Q$$

where ρ is the density of seawater (nominally 1,024 kg/m^3), g is the acceleration due to gravity (9.81 m/s^2), *a* is the tidal amplitude seaward of the narrow channel, and *Q* is the flow rate in the channel without extraction. The term γ is a constant that depends on the properties of the narrow channel and may be estimated by methods described in Blanchfield et al. (2008) or Karsten et al. (2008). For the simple case described above, the value of γ varies between 0.19 and 0.26. However, extending this relation to more complicated channel networks has been shown to be non-trivial (Polagye and Malte, 2010).

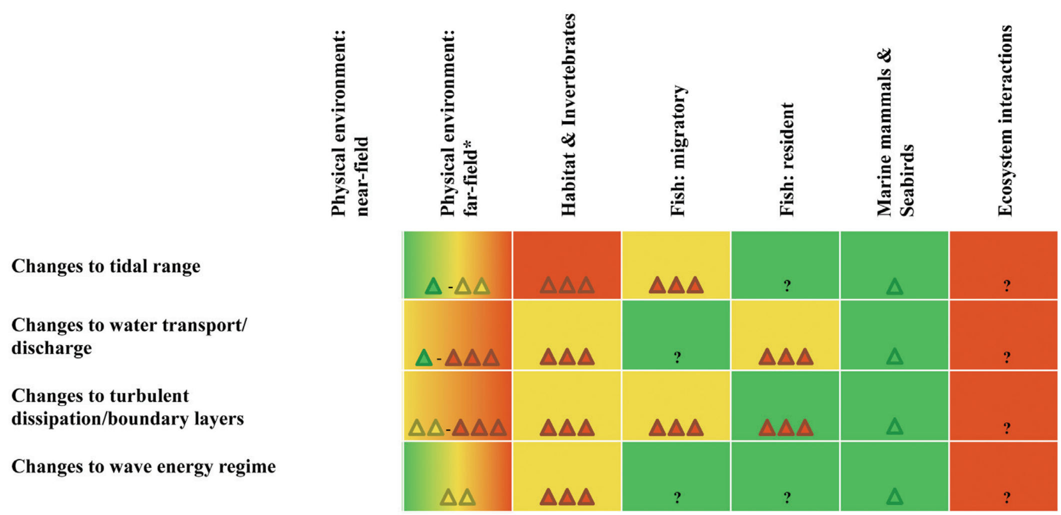
A number of national resource assessments attempt to relate far-field effects from energy removal to the naturally occurring kinetic power on a channel cross section. One assumption, made prior to detailed investigation (e.g., Bedard et al. 2006), was that extracting 15% of the kinetic power on a cross section represented an "environmentally acceptable" level of extraction. It has since been rigorously demonstrated (Garrett and Cummins, 2008), that the theoretical resource and, by extension, environmental effects of extracting kinetic power are unrelated to cross-sectional kinetic power. However, this misconception persists.

Analytical models (e.g., Garrett and Cummins 2007) and numerical models (e.g., Karsten et al. 2008) have been applied to study energy removal. There have been no attempts at physical modeling to date, although such studies are planned under DOE-sponsored research programs at the national Labs.

At a large scale, the effects of energy removal can be significant. For example, Karsten et al. (2008) estimate that extracting the theoretical limit of 7 GW of power would result in greater than 30% changes to tidal range in the Minas Basin in the Bay of Fundy. However, extracting 4 GW of power would change the tidal range by less than 10% and 2.5 GW could be extracted with less than a 5% change. Changes to tides and currents could affect water temperature, the behavior of some migratory fish, water quality, and sediment transport (DOE 2009). At the pilot scale, effects are expected to be immeasurably small. For example, a numerical model of a pilot project in northern Admiralty Inlet, Puget Sound (Polagye et al. 2009) suggests a maximum range reduction of 0.2 mm (the thickness of two human hairs) in South Sound. This is well within the range of modeling uncertainty, inconsequential in comparison to natural variability, and immeasurably small.

3.6.2 Stressor Matrix

No significant effects from energy removal are expected at the pilot scale (Karsten et al. 2008, Polagye et al. 2009). Because the energy removal stressor applies, by definition, to regional scales, it is not applicable to discuss the effect of this stressor on the near-field physical environment. The significance and uncertainty associated with stressor/receptor interactions at commercial scale are summarized in Figure 20. The colors denote significance and triangles denote uncertainty, as defined in Figure 10.



* – Range of significance and uncertainty for different aspects of the far-field physical environment – see discussion for details

Figure 20 – Stressor matrix: Energy removal –commercial-scale deployments

3.6.3 Discussion

Because energy removal is unlikely to result in any detectable changes at the pilot scale, this discussion focuses on commercial-scale deployments. Further, there is an emphasis on estuarine sites (e.g., Puget Sound) rather than open-ocean sites (e.g., Aleutian Islands, Alaska).

There is high uncertainty regarding the significance of energy removal, because the effects depend strongly on the particular stressor element, the natural tidal regime, and the estuarine environment. The specific elements of the energy removal stressor are changes to:

- Tidal range;
- Transport/discharge (residence time or flushing rate);
- Turbulent dissipation and boundary layer structure; and
- Wave energy regime – depending on the specific wave-current interaction.

The *far-field physical environment* is expected to be most significantly affected by energy removal. For the purposes of discussion, the far-field physical environment is separated into five areas:

- Sediment transport – significance depends on the sediment loading in the natural system;
- Exchange circulation – significance depends on the degree of stratification in the natural system;
- Water quality – significance depends on nutrient inputs to the natural system and residence time;
- Biological productivity – significance depends on nutrient inputs and oxygen availability in the natural system; and
- Intertidal area – significance depends on the intertidal area slopes in the natural system.

The significance and uncertainty for stressor/receptor combinations amongst these elements varies, as shown in Figure 21.

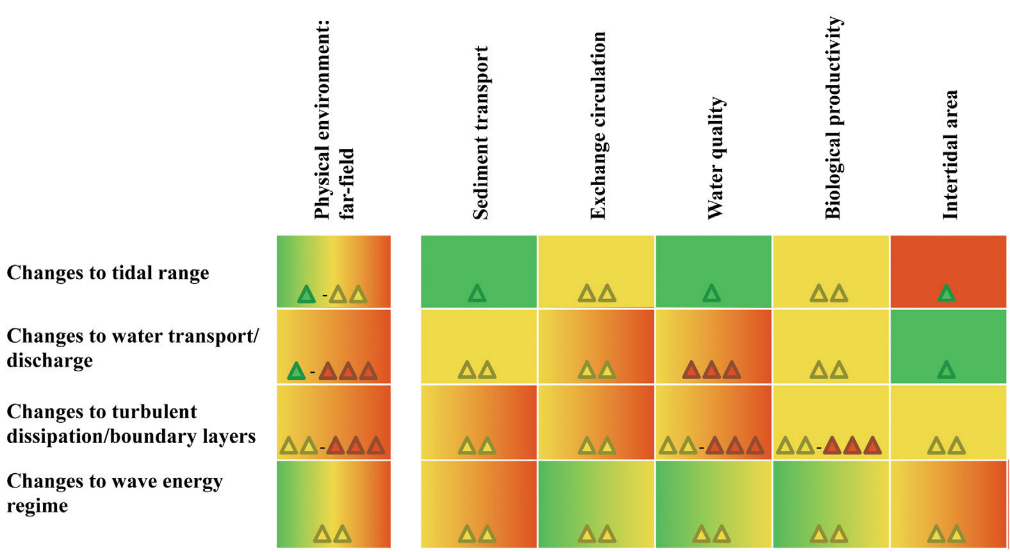


Figure 21 – Far-field environment detail for energy removal stressor

Habitat may be affected through changes to intertidal areas, changes in nutrient availability for kelp and eelgrass, disruption of upwelling, or dispersion of sediment. There is a high degree of uncertainty, because these conditions are site-specific. For example, vegetation in intertidal areas can be sensitive to small changes in the tidal range, but organisms that live on rocky walls are more adaptive to changes.

Direct effects on migratory fish are limited to relatively extreme cases in which a reduction in tidal range would make a river inaccessible (i.e., by creating a waterfall) or if the vertical structure of the water column were to change substantially (confounding the ability of migratory fish to navigate). The direct effects on resident fish are limited to larval dispersion, due to changes in transport. Energy removal would not be expected to have significant direct effects on marine mammals and seabirds.

Because of the potential changes to the far-field physical environment and habitat, ecosystem interactions could be significant but are largely unstudied.

Better engagement between tidal energy practitioners and physical oceanographers is needed. For example, some physical oceanographers are now investigating estuarine dynamics from the standpoint of energy input to the system (e.g., Warner and MacCready 2009). There may be analogues to energy removal by tidal turbines.

3.6.4 Priority Area: *Changes to the far-field physical environment and habitat*

Description

The hydrodynamic regime in an estuary is established, in large part, by the dissipation of tidal energy. Other environmental parameters (temperature, salinity, dissolved oxygen, and nutrients) are a function of the hydrodynamic regime and inputs to the system. Habitat follows from the hydrodynamic regime and environmental parameters. Hydrokinetic tidal energy conversion involves local removal of energy, thereby altering the hydrodynamic regime throughout the system. At the pilot scale, these effects will be immeasurable. However, at larger scales of development, changes may be environmentally significant. Environmental effects, such as changes to intertidal areas, are not likely to scale smoothly with extraction. "Tipping points" are to be expected, whereby a small increase in extraction will result in a disproportionately large change to the far-field physical environment or habitat. Two examples are given here, although others could likely be identified. First, incremental reductions in the tidal range that may initially have little effect could, beyond a certain point, isolate intertidal habitat by permanently inundating or drying out surrounding areas (e.g., reduction in range leading to a landlocked tide pool). Second, while low levels of extraction would not be expected to alter deep saline intrusions into fjord estuaries, there may be a point where the resistance posed by tidal turbines could prevent these intrusions from crossing the sill, with significant consequences for dissolved oxygen and water quality in parts of these ecosystems.

Gaps in Understanding

There is a growing body of knowledge pertaining to the hydrodynamic effects of energy removal (e.g., Blanchfield et al. 2008, Karsten et al. 2008, Polagye et al. 2009). Results are site-specific, and connecting changes in hydrodynamic conditions to other aspects of the physical environment is nascent. Neill et al. (2009) contains an example pertaining to sediment transport. To date, no attempts have been made to assess the implications for water quality or biological productivity. These are nonlinear processes that are difficult to model, even in natural systems.

Approaches to Monitoring and Closing Gaps

A principal challenge is that an understanding of the environmental effects of energy removal does not scale up from observations at the pilot scale (i.e., putting a device in the water will not reduce uncertainties). The available tools to close these gaps are also imperfect. Numerical models are an obvious choice but, at the estuary scale, tuning for calibration, boundary conditions, and an inability to validate a predicted change are all problematic. Physical models might be used for focused, qualitative investigations, but scale distortions (e.g., vertical exaggeration, Reynolds number) will complicate quantitative studies. A third approach is the use of basic physical arguments to describe how changes to the natural system might scale with extraction. However, relating these conclusions to real systems may be challenging, particularly when scaling is subject to large uncertainties. Fourth, an experiment could be conducted in a small bay linked to the ocean by a narrow channel, where the effects of energy removal might be observed from the operation of a small array. However, the cost to carry out such an experiment would be very high.

Initial research for a particular site should focus on establishing order or magnitude hydrodynamic changes at different levels of extraction, with the effect on particular receptors addressed by smaller, focused studies. Not all potential tidal energy sites in the United States have well-calibrated models for this type of study. Puget Sound, the nation's East Coast, and San Francisco Bay are reasonably well described, but Cook Inlet is poorly characterized and is in a constant state of flux because of its extremely high sediment loads and ice scour of the seabed.

Monitoring for changes to the far-field physical environment may be problematic, even for commercial installations. For example, measurements of tidal range (easier to obtain than for dissolved oxygen or turbulent dissipation) are confounded by long-term natural changes such as isostatic release and climatic variability. Range changes of less than 10 cm may not be statistically significant, compared to natural variations.

Mitigation Measures

A number of mitigation measures may be possible with respect to design and operation of tidal turbines.

Changes to the far-field environment depend on the power dissipated by hydrokinetic turbines. This includes the power extracted for electrical generation, power lost when the device's wake mixes with the free stream, and power loss due to drag on the device support structure. Wake mixing losses are unavoidable, but scale with device efficiency (i.e., the higher the efficiency, the slower the wake, and the greater the shear between wake and free stream). While arrays with high blockage ratios are most efficient/economic (Garrett and Cummins 2007), they also lead to the greatest wake mixing losses. Losses due to drag on device support structures can be minimized by streamlined designs (Polagye 2009), which should be considered a best practice.

The highly variable nature of estuaries means these environments may be more sensitive to stressors under certain conditions or during certain times of the year or both. While specific recommendations cannot be made at this point, device operators may consider adapting patterns of device operation according to the season and prevailing conditions to minimize impact on the far-field marine environment (e.g., shutting down an array during annual deep saline intrusions over sills in fjord estuaries).

Once the development is in place, it may be difficult to mitigate negative effects of tidal energy. For example, hypoxic conditions in a terminal estuary, resulting from diminished flushing due to energy extraction, may be ameliorated by bubbling oxygen directly through the water (as is sometimes done in stagnant ponds); however, such an operation would require significant installation costs, additional materials, and increased energy expenditure. This energy expenditure could potentially be more than offset by reducing the energy removal (e.g., by increasing the cut-in speed of the array), if this action alone could restore the system's oxygen balance. Thus, quantifying the effects of energy removal should be thought of as an aspect of development feasibility and should be taken into consideration early in the process if the size of a proposed project is expected to be large enough in scale to have environmentally significant far-field effects.

3.6.5 Priority Area: *Potential for ecosystem interactions*

Description

At large scales of development, energy removal may alter the hydrodynamic regime and change the far-field physical environment and habitat. In turn, migratory and resident fish could be affected. Consequently, there are opportunities for significant ecosystem interactions.

Gaps in Understanding

The linkages between receptors and aspects of their environment are poorly understood. For example, although changes to water transport (residence time and flushing rate) might lead to algal blooms and anoxic conditions, the factors contributing to algal blooms in natural systems are not well-understood. Even when a linkage is clear, effects will be site-specific and subject to uncertainty and variability.

Approaches to Monitoring

This is an active area of research in the coastal and estuarine community. Monitoring a myriad set of parameters to identify interactions is not expected to be a productive or economically feasible approach. A sensible approach may be to identify key environmental tipping points in advance of array build-out and focus a targeted monitoring program on these aspects of the marine environment. As an example of a tipping point, in San Francisco Bay, California, algal blooms are sensitive to small changes to circulation and water quality. This could be exacerbated by relatively low levels of energy removal by tidal turbines.

Along these lines, it would be helpful to quantify existing, natural variability in the hydrodynamic regime and the ecosystem response to this variability. If the changes anticipated from energy removal are much smaller, then they are unlikely to have a significant effect.

Mitigation Measures

Mitigation measures are identical to those previously discussed for changes to the physical environment and habitat.

3.6.6 Recommended References

Atwater J.F. and Lawrence, G.A. 2010. Power potential of a split tidal channel. *Renewable Energy,* 35: 329-332.

Bedard, R., Previsic, M., Polagye, B., Hagerman G. and Casavant A. 2006. *North America Tidal In-Stream Energy Conversion Technology Feasibility Study*. Palo Alto, CA: Electric Power Research Institute. EPRI TP-008-NA.

Blanchfield, J., Garrett, C., Wild, P. and Rowe, A. 2008. The extractable power from a channel linking a bay to the open ocean. *Proc. IMechE, Part A: J. Power and Energy* 222(3): 289-297.

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

Garrett, C. and Cummins, P. 2007. The efficiency of a turbine in a tidal channel. J. *Fluid Mechanic*s, 588: 243-251.

Garrett, C. and Cummins, P. 2008. Limits to tidal current power. *Renewable Energy,* 33(11): 2485-2490.

Karsten, R.H., McMillian, J.M., Lickley, M.J. and Haynes, R.D. 2008. Assessment of tidal current energy in Minas Passage, Bay of Fundy. *Proc. IMechE, Part A: J. Power and Energy* 222(5): 493-507.

Neill, S.P., Litt, E.J., Couch, S.J. and Davies, A.G. 2009. The impact of tidal stream turbines on large-scale sediment dynamics. *Renewable Energy*, 34(12): 2803-2812.

Polagye, B.L. 2009. Hydrodynamic effects of kinetic power extraction by in-stream tidal turbines. PhD thesis, University of Washington, Seattle, WA.

Polagye, B.L., Kawase, M. and Malte, P.C. 2009 In-stream tidal energy potential of Puget Sound, Washington. *Proc. IMechE, Part A: J. Power and Energy,* 223(5): 571-587.

Polagye, B.L. and Malte, P.C. 2010. Far-field dynamics of tidal energy extraction in channel networks. *Renewable Energy,* 36(1): 222-234.

Warner, S.J. and MacCready, P. 2009. Dissecting the pressure field in tidal flow past a headland: When is form drag “real”?. *J. Phys. Ocean.* 33(11): 2971-2984.

3.7 Cumulative Effects

Name	**Affiliation**
Jenny Norris (Chair)	European Marine Energy Center
Graham Daborn	Acadia University
Ian Boyd	Sea Mammal Research Unit, University of St. Andrews
Jim Brennan	Washington Sea Grant
Joe Breen	Northern Ireland Environment Agency (NIEA)
Keith Kirkendall	NOAA Fisheries
Pat Livingston	NOAA Fisheries - Alaska Fisheries Science Center
Skip Albertson	Washington Dept. of Ecology
Sue Saupe	Cook Inlet Regional Citizens Advisory Committee
Tom Mumford	Washington Dept. of Natural Resources
Ellie Humphries (Note Taker)	University of Washington

3.7.1 Introduction

Methods for assessing the potential cumulative impacts of tidal devices on elements of the receiving environment is nebulous, given the current lack of knowledge about the real effects of individual stressors on receptors. Assessing cumulative impacts is challenging, even for more mature power generation technologies (e.g., terrestrial wind power, conventional hydropower). Data that indicate the effects of individual stressor elements on receptors are needed in order to inform the assessment of cumulative impact. Until such data are available, any models or hypothetical assessments will be limited in usefulness.

There are many uncertainties associated with the notion of "cumulative impact" and the boundaries that may, in practice, be used to define the extent of the receiving environment. Political boundaries are rarely relevant from an ecological perspective, and a meaningful cumulative impact analysis may sometimes need to cross state or national boundaries — and even oceans. Adopting a typical project-based approach to a cumulative impact analysis is likely to limit the usefulness of its findings, but this will depend on the level of existing and planned development within the affected area. A high-level, large-scale Strategic Environmental Assessment may be the best way to ensure that cumulative effects associated with oceanographic processes that operate over much larger systems than the development site and with externalities such as interactions with other resource uses and users are identified. In-depth ecosystem modeling is needed, but models need to be informed by realistic data on patterns of interactions.

It is recognized that the term *cumulative impacts* may refer to:

- Scaled-up effects of individual (tidal device installation, operation, and decommissioning) stressors on receptors. This would occur in scale-up from pilot to commercial installations or from multiple devices installed within a geographically identifiable subunit (i.e., an estuary).
- Synergies among different combinations of stressors (tidal device installation, operation, and decommissioning) and receptors; and
- Synergies among the two previously cited definitions, together with other anthropogenic influences and other externalities.

For the purposes of this discussion, cumulative impact should be viewed as the potential impact on a receptor, caused by synergistic effects of individual stressors (i.e., the second definition). Viewed in this way, three main areas of concern can be identified. The significance and uncertainty associated with stressor/receptor interactions are summarized in Figure 22 for pilot-scale deployments and in Figure 23 for commercial-scale deployments. The colors denote significance and triangles denote uncertainty, as defined in Figure 10.

3.7.2 Stressor Matrix

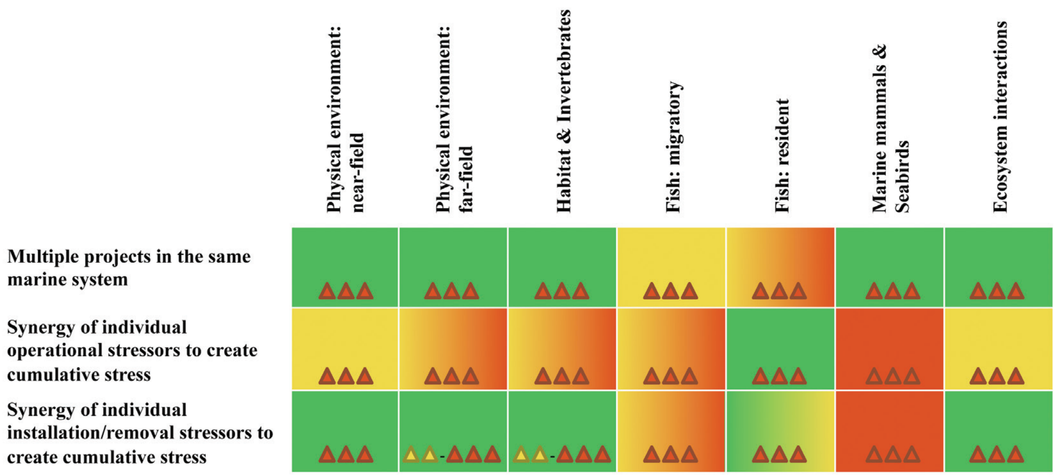


Figure 22 – Stressor matrix: Cumulative effects – pilot-scale deployment

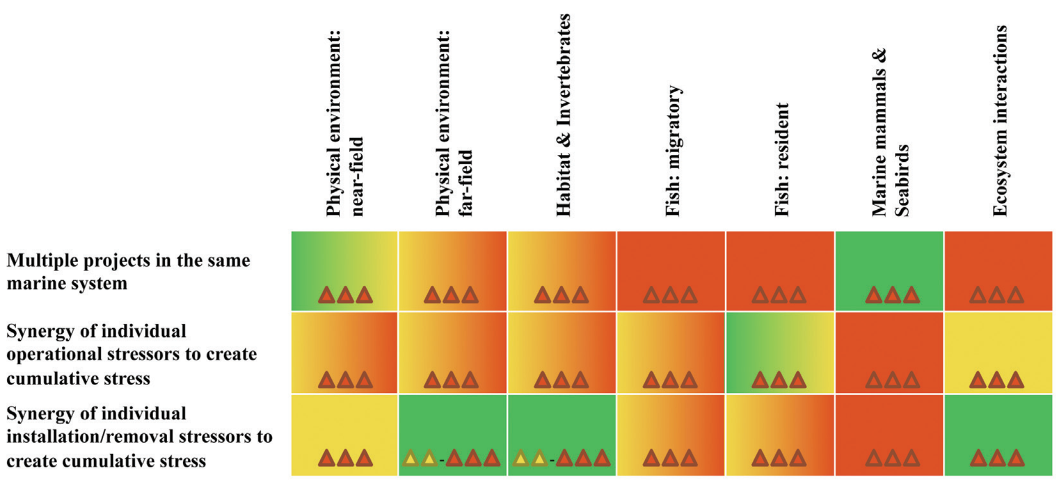


Figure 23 – Stressor matrix: Cumulative effects – commercial-scale deployment

The near field is defined as being within the same geographically identifiable subunit, while far-field is defined as being outside the subunit.

3.7.3 Discussion

Three top-priority issues have been identified:

- Effects on large mobile species;
- Effects caused by energy change in the receiving environment; and
- The difficulty of predicting, detecting and attributing effects and changes to receptors.

3.7.4 Priority Area: *Effects on large mobile species*

Description

Perhaps the primary concern with respect to cumulative impacts is the potential for damage to large and migratory fish, marine mammals, and seabirds. Damage includes collision with underwater moving parts and indirect harm, such as deleterious behavioral change (e.g., displacement), that may be caused by the physical presence of a device or array of devices and any outputs from such devices. Such potentially harmful outputs may include sound and vibrations, electromagnetic field induced along cables, or chemical leaching (although this third output seems relatively low-risk).

Although the effects on large mobile species is seen as a key concern amongst regulators and some expert stakeholders, real data are urgently needed in order to assess the extent of these effects.

The potential for collision between large mobile species and rotating blades or other moving parts is unknown. Until early test devices are monitored, speculation will continue on whether or not there is a significant risk of direct or indirect damage to these species. Large and migratory fish, marine mammals, and seabirds are sensitive species that often occur in locations where tidal energy development can be expected and these species are protected in many such areas. Their sensitivity derives partly from the areas over which they range (i.e., they have a high probability of encountering a device), their body size (i.e., that they have a high probability of colliding with such a device if encountered), and their slow rates of population recovery to compensate for losses that could occur as a result of collision. An important feature of many of these species is that even very low rates of attrition caused by these devices (which may be beyond our capacity to measure with current methods) may lead to long-term declines in these species. Consequently, declines may be difficult to correlate with direct or indirect effects of these devices. This means that considerable precaution is needed in the form of the design and placement of devices that are aimed at total avoidance of effects.

In order to begin to predict, let alone understand, the potential for damage at a cumulative level, the tidal energy industry needs to be informed of the actual effects of the individual stressor elements on these species. For example:

- Do different species actually collide with moving underwater blades?
- Are these species attracted by devices?
- Is there damage caused to hearing organs attributed to acoustic output from installation (e.g., any pile-driving required) or decommissioning?
- Do devices produce any discernible acoustic output that might cause displacement and possible secondary (i.e., consequential) harm to these species?
- What is the potential for large arrays of devices to produce a barrier effect with consequent harm to key species?

Gaps in Understanding

Although little data exist from tidal device operation, those available provide no evidence of harm caused to large mobile species. More data need to be collected from different types of devices and in varying locations in order to establish confidence levels. However, testing is still at a very early stage and at small scales of construction. There is a high level of certainty that low levels of attrition, which may not be measureable, will cause population declines.

Further, it is unclear whether any effects would be non-linear (i.e., not strictly additive) and whether there are thresholds (e.g., the threshold between laminar and turbulent flow) beyond which the system behaves differently.

Adopting a "deploy and monitor" strategy with respect to early test developments will allow devices to be placed in the water, installed, operated, and monitored. Funding will be required to enable these deployments to progress and to monitor for stressors (e.g., acoustic output, collision events, strandings). This will ensure that mitigation methodologies are developed alongside device development.

Approaches to Monitoring

Wherever possible, monitoring should be conducted according to agreed methodologies, ensuring that the purpose of the data gathering is: clearly defined and consistent with other deploy-and-monitor schemes. It is also important that monitoring protocols not be changed during the program, so that variables being monitored can be validly compared over time. If new monitoring technologies or protocols become available after the start of monitoring, it will be important to assess critically whether the original protocols should be continued in parallel with the new ones in order to ensure continuity of record.

There are early stage monitoring programs in place in some locations (e.g., European Marine Energy Center (EMEC), Strangford Lough, Minas Basin) that use protocols and standardized protocols under development (e.g., Equimar or Scottish Natural Heritage Web sites). Care should be exercised to ensure that all relevant work elsewhere with respect to monitoring protocols is taken into account. This will ensure consistency of approaches, where possible.

Radiotelemetry and sonar or acoustic imaging may be useful. There should be careful collection of baseline data before installation takes place, in order to be able to determine the change in the effects monitored.

Mitigation Measures

The adoption of a "deploy and monitor" strategy is the main way to gather data on actual device-biota interactions and to design future mitigation techniques. However, the high levels of uncertainty make it necessary to develop mitigation on the assumption that it is required.

Such deploy-and-monitor strategies should begin at a small scale and increase incrementally from pilot to commercial scale, monitoring carefully at each step. Any required design changes would then be implemented (e.g., blade design, shrouding, grating to avoid or minimize strikes and noise).

Other methods of mitigation include careful site selection or limiting the number of devices in a given location until the effect of their operation is sufficiently understood. This limit will be site- and device-specific.

3.7.5 Priority Area: *Effects of energy removal*

Description

Long-term, large-scale extraction of energy from tidal currents may cause changes to water quality, including both physical and biological parameters. Any such changes may affect sensitive or susceptible habitats, with significant scope for potential secondary effects driven by habitat change. These effects are likely to have non-linear characteristics and contain critical thresholds (also described in 3.6 – Energy Removal).

It is thought to be unlikely that cumulative energy removal from tidal flow at specific locations will cause any detectable change in overall global flow strengths and rates; however, local habitat change and any cumulative consequences may have significant ecological effects.

Gaps in Understanding

Without any data on which to base discussions, it is impossible to progress any further than conjecture on this issue. The effects of energy removal are site-specific. This is an issue that could potentially benefit from more detailed modeling, but such models do require actual data as input for validation.

Comparison of energy levels upstream and downstream of arrays of tidal devices and analysis of energy content of the tidal stream flowing through the devices in an array may be useful to establish the amount of energy removed from the flow (power extraction, wake mixing, drag on support structures, etc.). Industry needs to ground truth models that predict energy-extraction levels, for which data gathering from real deployments will be required. Initiating or supporting large-scale data collection upstream and downstream of arrays of tidal devices, as the industry progresses into testing arrays, would be a potential means of making progress in this area.

Approaches to Monitoring

Wherever possible, monitoring should be according to agreed general methodologies, ensuring that the purpose of the data gathering is clearly defined and consistent with other data-collection schemes.

There are early stage protocols and standards for using Doppler profiler data to assess resource intensity. However, resource intensity is not directly related to the recoverable resource, and there is not yet consensus on how national-scale resource assessments should be conducted. Care needs to be exercised to ensure that all relevant work elsewhere with respect to early-stage standards or protocols is taken into account. This will ensure consistency of approaches, where possible. If far-field effects are anticipated, a careful baseline monitoring program will be needed to attribute or detect effects from natural variation.

Mitigation Measures

The adoption of a "deploy and monitor" strategy is the only real way to gather informative data on actual interactions. However, it is difficult to see what kind of mitigation strategy could be put in place to minimize the unknown effects of energy extraction, when the critical levels of such extraction remain unknown.

Projects should begin at the small scale and increase incrementally from pilot- to large-scale, monitoring carefully at each step.

3.7.6 Priority Area: *Difficulty of predicting, detecting and attributing changes to the presence/ operation of tidal energy devices*

Description

There is, at present, insufficient understanding of the normal behaviors and responses of the different receptors to the various stressor synergies in a non-steady state. Without such understanding, it will be difficult to conduct a meaningful cumulative impact analysis. If the industry cannot accurately predict the extent and severity of cumulative effects, then it becomes impossible to perform a complete environmental impact assessment. If methods of detecting such effects are not developed, it is impossible to predict any such harm with any degree of accuracy.

If there are methods available or developed that enable the type and extent of change from cumulative impacts to be detected and measured, then determining the extent to which such changes can truly be ascribed to the presence of tidal energy devices still remains a problem. Although traditional before-after-control-impact (BACI) studies may be able to detect changes, selection of valid 'control' sites is challenging because inter-site differences create large numbers of variables. Multiple control sites are required (Underwood 1991, Underwood 1994) to distinguish between temporal variations at control and impact sites and natural temporal-spatial variability. Within an already dynamic system, it is difficult to see how changes due to cumulative effects might be truly ascribed to the presence of any particular development.

Gaps in Understanding

There are high levels of uncertainty about all potential environmental impacts of tidal energy devices on the range of possible receptors. Until adequate monitoring methods to determine the extent of such effects have been developed and tested, more is known about the effects of individual stressors on receptors, and there is a greater understanding of how to attribute change within a dynamic environment, it is difficult to see how these uncertainties can be reduced.

In order to progress, there is a need to support the development of the following:

- Adequate monitoring methods to determine the extent of the effects of individual stressor elements on receptors;
- Data collection and analysis according to agreed-upon "best practices," to increase knowledge about the effects of individual stressors on receptors; and
- Robust methods for ascribing change seen within dynamic environments to a particular stressor.

It may also be helpful to instigate robust Strategic Environmental Assessments (SEAs) for key potential tidal energy development areas to assess all receptors, highlighting receptors of particularly sensitivity, and identify potential cumulative effects that should be addressed through monitoring. This may require additional data collection at key SEA areas, to ensure sufficient baseline datasets. The SEA should incorporate multidisciplinary risk assessment and clear decision-making criteria.

Approaches to Monitoring

Once there is some knowledge of the effects of individual stressors on receptors, this information should be used to inform the development of existing ecological models to predict and, possibly, attribute change to cumulative effects of tidal devices.

One potentially useful area to develop protocols for would be the identification and monitoring of specific indicator species. While indicator species would be likely to be site-dependent, there may be a degree of site-independence in the monitoring methodology (data collection and interpretation). Support should be given to studies into the potential for a range of indicator species to identify changes from cumulative effects of tidal devices.

Mitigation Measures

It is difficult to envisage what types of mitigation, other than "deploy-and-monitor" at the test stages, might be possible in respect of these concerns. High-quality, robust, adequate baseline and monitoring data need to be acquired.

Projects should begin at the small-scale and increase incrementally from pilot- to large-scale, monitoring carefully at each step.

There may need to be some discussion among policy makers, regulators, and developers over the financial consequences of a particular development needing to be removed because of unacceptable environmental impacts.

3.7.7 Recommended References

Gordon, D.C. Jr., Keizer, P.D., Daborn, G.R., Schwinghamer, P. and Silvert, W. 1986. Adventures in holistic ecosystem modelling: The Cumberland Basin Ecosystem Model. *Netherlands Journal of Sea Research*, 20(2-3): 325-335.

King, S., Maclean, I.M.D., Norman, T. and Prior, A. 2009. *Developing Guidance on Ornithological Cumulative Impact Assessment for Offshore Wind Farm Developers.* London, UK: COWRIE Ltd. Available at *http://www.offshorewindfarms.co.uk/Pages/Publications/Latest_Reports/Birds/Developing_Guidance_onc4f9897d/*.

Miller, D., Wherrett, J., Law, A., Birnie, D., Malcolm, A., McKeen, M., Hock Tan, B., Baxter, S., Fisher, P. *Cumulative Impact of Wind Turbines*. Report prepared for Countryside Commission for Wales. Available at *http://www.macaulay.ac.uk/ccw/*.

Offshore Energy Environmental Research Association. 2008. *Fundy Tidal Energy Strategic Environmental Assessment Final Report.* Prepared by the OEER Association for the Nova Scotia Department of Energy. April 2008. Available at *http://www.offshoreenergyresearch.ca/OEER/StrategicEnvironmentalAssessment/FinalSEAReport/tabid/312/Default.aspx*.

Thomas, G. 1996. An Environmental Assessment of Visual and Cumulative Impacts arising from Wind farm Developments: A Welsh Planning Policy Perspective. MS thesis, University of Wales, Aberystwyth. Available at *http://users.aber.ac.uk/zwk/distlearn/virtlib/theses/thomas/thomas.html.*

Whitford, J. 2008. *Background Report for the Fundy Tidal Energy Strategic Environmental Assessment.* Prepared by Jacques Whitford for the Offshore Energy Environmental Research Association. Available at *http://www.offshoreenergyresearch.ca/OEER/StrategicEnvironmentalAssessment/BackgroundreportfortheFundyTidalEnergySEA/tabid/280/Default.aspx.*

Underwood, A.J. 1991. Beyond BACI: Experimental designs for detecting human environmental impacts on temporal variations in natural populations. *Aust. J. Mar. Freshwater Res.*, 42(5): 586-587.

Underwood, A.J. 1994. On beyond BACI: Sampling designs that might reliably detect environmental disturbances. *Ecological Applications*, 4(1): 3-15.

4. Environmental Receptors

In this section, seven environmental receptors are discussed:

- *Physical environment: near-field* – aspects of the physical environment in the region in which the specific stressors from tidal energy devices are directly observable (e.g., within the device wake)
- *Physical environment: far-field* – aspects of the physical environment beyond the near-field region, where specific stressors from tidal energy devices may affect the environment
- *Habitat and invertebrates* – habitat (including benthic and nearshore) and invertebrate species
- *Migratory fish* – fish that follow predictable movements through the environment during their lifecycle
- *Resident fish* – fish that maintain a home range or that stay in a relatively stable geographic area through most of their lifecycle
- *Marine mammals and seabirds*
- *Ecosystem interactions* – interrelations among different receptors within an ecosystem

While not ideal, “habitat” is combined with “invertebrates” and “marine mammals” is combined with “seabirds” for logistical reasons (i.e., maintaining and equal number of stressors and receptors). Sea turtles, which are of significant concern for some other types of marine renewable energy, were not discussed, because they are not present in the marine systems currently being considered for tidal energy development.

A framework similar to the one applied to stressors is used to discuss each receptor. First, the significance of each receptor element is assessed relative to the environmental stressors associated with tidal energy, (Table 5) using “high,” “medium,” “low,” “not applicable,” or “unknown ranking.” Second, the uncertainty around this assessment is qualified as “high,” “medium,” “low,” or “unknown.” These results are presented as a matrix of stressor/receptor interactions. A key describing these matrices is shown in Figure 24. The color of the cell denotes the significance of the interaction. The number and color of triangles denotes the uncertainty of this significance. This evaluation is conducted separately for pilot- and commercial-scale deployments, as described in Section 2.7.

High-priority stressor/receptor interactions (e.g., high significance or high uncertainty) are discussed in further detail. Each high-priority interaction is described, gaps in understanding identified, and approaches for monitoring this interaction identified (with emphasis on the stressor).

Each workshop breakout group also identified key literature references for their receptor.

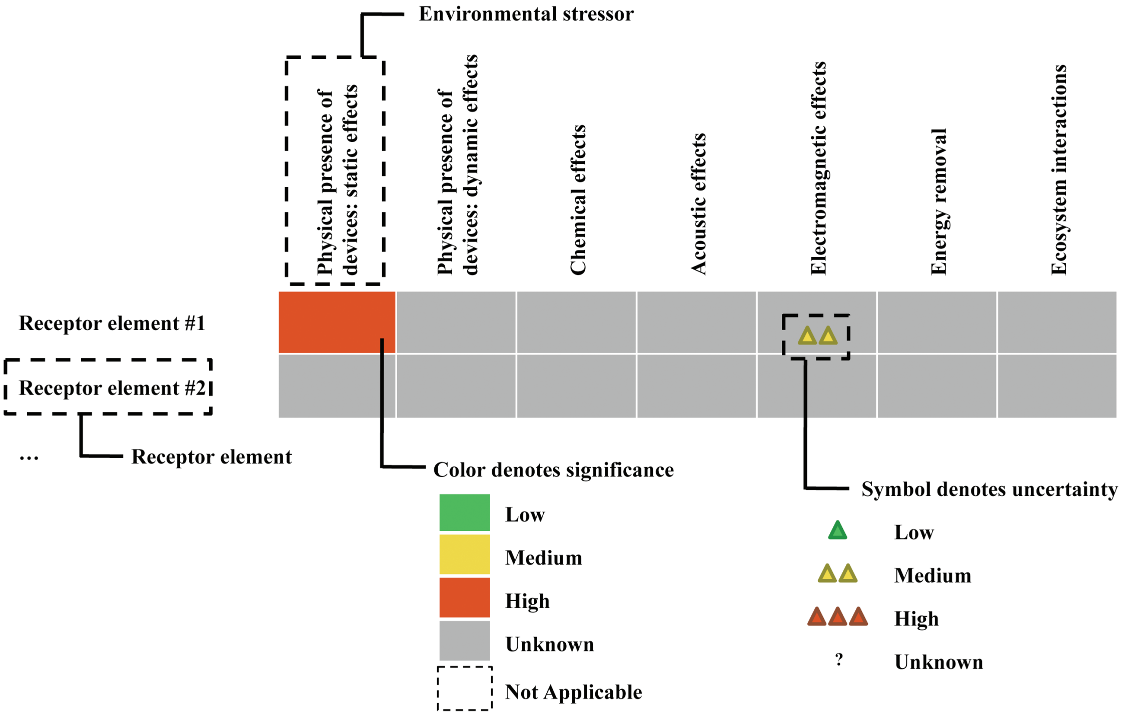


Figure 24 – Sample receptor matrix components

4.1 Physical Environment: Near-field

Name	Affiliation
Jim Thomson (Chair)	University of Washington
Adrianus Kalmijn	Scripps Institution of Oceanography (University of California San Diego)
Bob Thresher	National Renewable Energy Laboratory
Gary Gill	Pacific Northwest National Laboratory
Gouri Bhuyan	Powertech Labs
Graham Savidge	Queens University, Belfast
Jerry Johnson	University of Alaska - Fairbanks
Layna Goodman	U.S. Navy
Neil McMahon	Alaska Energy Authority
Peter Dahl	University of Washington
Chris Bassett (Note Taker)	University of Washington

4.1.1 Introduction

Workshop participants defined the physical near-field environment to be comprised of elements in the immediate region of a tidal turbine, where direct/specific effects of a turbine can be detected. These elements are water motion, water quality, acoustic noise, EMFs, and bottom/sediment properties. These basic elements combine to form the biologic suitability/productivity in the near-field region — identified as a key parameter in establishing priority issues.

Participants also identified, as broad priorities, those changes in water motion, such as wakes and acceleration of flow, that may lead to changes in pressure, mixing (i.e., water quality, stratification) and settlement of particulates (e.g., sediment, larvae). As a cumulative effect, these changes may then lead to changes in biological activity/suitability (e.g., habitat). In the extreme case, pressure gradients across turbine blades may be fatal to small organisms drifting with the flow.

Specific/actionable priorities were also identified, for which more information is needed regarding the flow around turbines and regarding the baseline hydrodynamics common to tidal energy sites. A combination of in situ measurements and computational models was suggested, as was the need for more information regarding the acoustic signatures of tidal devices during operation.

For many of the elements identified, the significance of effects will be specific to the environment and the scale of tidal energy development. For example, changes in mixing may only be important if there is strong stratification present (and this is unlikely at most high-energy sites). Across the various examples postulated, workshop participants found it unlikely that pilot-scale projects would have significant effects. In addition, it was agreed that pilot projects would provide important information to estimate the potential for commercial effects.

The significance and uncertainty associated with stressor/receptor interactions are summarized in Figure 25 for pilot-scale deployments and in Figure 26 for commercial-scale deployments. The colors denote significance and triangles denote uncertainty, as defined in Figure 24.

4.1.2 Receptor Matrix

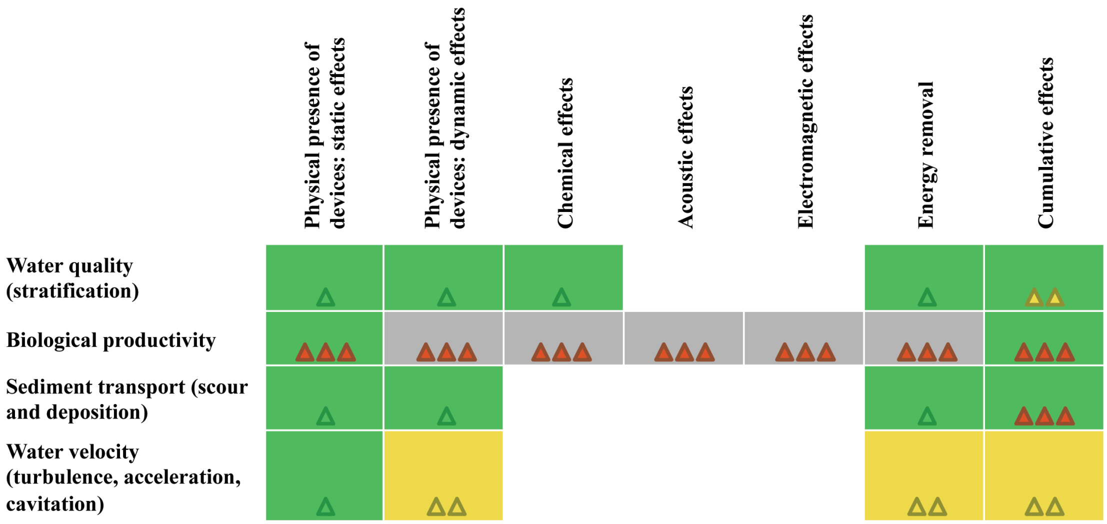


Figure 25 – Receptor matrix: Physical environment: Near-field – pilot-scale deployment

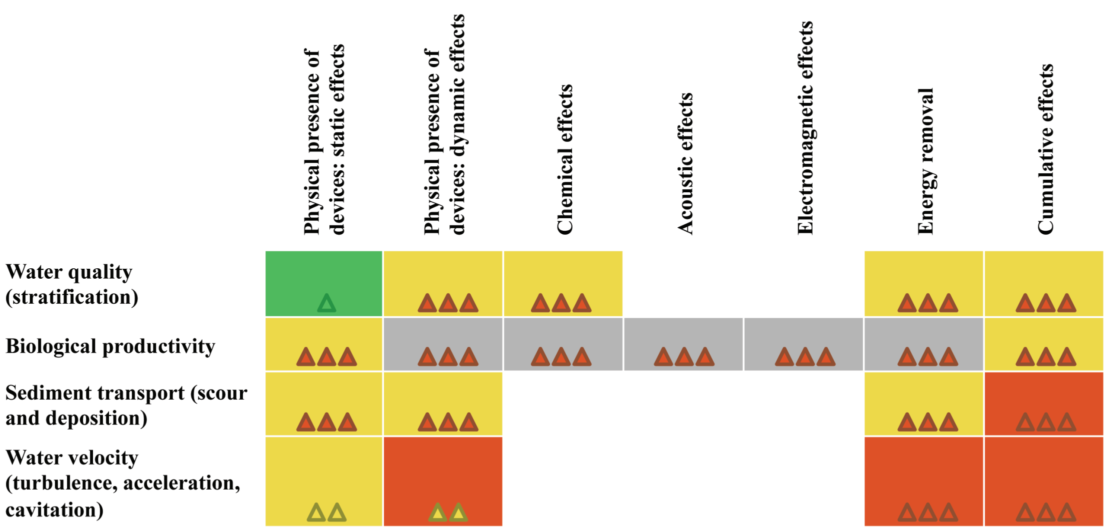


Figure 26 – Receptor matrix: Physical environment: Near-field – commercial-scale deployment

4.1.3 Discussion

In identifying water motion as the key element of the near-field physical environment, along with water quality, the important topics of acoustics and electromagnetic fields (EMFs) have been set aside. Both are key elements necessary to describe the local physical environment with potential for effects, but these are treated elsewhere, as stressors, within the workshop proceedings. In a similar manner, habitat/biologic condition is used as the cumulative element by which factors of the near-field physical environment are prioritized; however it is not listed explicitly, because it is treated elsewhere in this document as another receptor.

4.1.4 Priority Area: *Local hydrodynamics*

Description

Turbines will alter the flow of water in the form of drag and wake features. In addition, large pressure gradients are likely in the immediate vicinity of turbine blades. In extreme cases, cavitation may occur. The deceleration of flow may enhance settlement of particles, such as sediment and plankton, and the turbine wake may increase mixing. These impacts are dependent on device design and the baseline conditions of a given site.

Gaps in Understanding

There are no measurements of fluid velocity around tidal turbines in the public domain. Thus, it is difficult to estimate the potential significance of changes in fluid flow. In addition, there is limited understanding of the baseline flow conditions at tidal energy sites, because these are often oceanographically unique and poorly characterized. Numerical modeling is a promising tool to fill these gaps in understanding, but models must be properly calibrated with data for valid interpretation of results. In addition, implementing high-fidelity turbine models within existing oceanographic models is challenging (and unproven).

Approaches to Monitoring

Monitoring for hydrodynamic changes requires thorough quantification of baseline conditions, which may have many sub-tidal influences (e.g., seasonal stratification, wind forcing). The basic oceanographic tools use active acoustics (Doppler current profilers, and velocimeters), which may not be compatible with active acoustics measurements for detection/tracking of fish and marine mammals. Acoustic Doppler instruments are quite mature and common in oceanographic research, however many limitations remain. Profilers are necessarily lower accuracy because of volume averaging but are able to make remote measurements over long ranges (order 100 m). Velocimeters, in contrast, achieve high accuracy by confining measurement to a near-field point. Stable mounting is not trivial when using either instrument, and the resulting data are sparse compared with the scales of tidal energy sites. Monitoring should, at a minimum, include upstream and downstream velocity profiles, and data analysis should include turbulence statistics, boundary layer structure, and sub-tidal exchange flow at a project site.

4.1.5 Priority Area: *Water quality and sedimentation*

Description

Changes in mixing and settlement of particles (a result of changes in water flow) may change the water quality and sedimentation in the proximity of a turbine. In addition, the presence of antifouling coatings on the turbine may degrade the local water quality.

Gaps in Understanding

There are no measurements of water quality or sedimentation around tidal turbines in the public domain. In addition, there is limited understanding of the baseline conditions at tidal energy sites; many sites are well-mixed and lack settled sediments, but there are notable exceptions (e.g., Cook Inlet). Numerical modeling is a promising tool to fill these gaps in understanding, but models must be properly calibrated with data for valid interpretation of results.

Approaches to Monitoring

Monitoring for water quality and sedimentation changes requires thorough quantification of baseline conditions, which may be the result of sub-tidal processes (e.g., seasonal river discharge, coastal upwelling). Common oceanographic measurements of temperature, salinity, dissolved oxygen, dissolved nutrients, chlorophyll, and turbidity can be used to quantify a region, but data tend to be sparse in space and time, compared with natural variability. Thus, before-and-after comparisons are particularly challenging.

4.1.6 Recommended References

Brumley, B.H., Cabrera, R.G., Deines, K.L. and Terray, E.A. 1991. Performance of a broad-band acoustic Doppler current profiler. *IEEE Journal of Oceanic Engineering*, 16(4): 402-407.

Chapman, D. 1996. *Water Quality Assessments-A Guide to Use of Biota, Sediments and Water in Environmental Monitoring*. (2nd ed). Prepared for UNESCO/WHO/UNEP. London, UK: F and FN Spon.

Garrett, C.J.R., Keeley, J.R. and Greenberg, D.A. 1978. Tidal mixing versus thermal stratification in the Bay of Fundy and Gulf of Maine. *Atmosphere-Ocean*, 16(4): 403-423.

Gooch, S. Thomson, J., Polagye, B. and Meggitt, D. Site characterization for tidal power. MTS/IEEE *Oceans* 2009. Biloxi, MI, October 26-29, 2009.

Thomson, J., Polagye, B., Richmond, M. and Durgesh, V. 2010. Quantification of turbulence for tidal power applications. MTS/IEEE *Oceans* 2010. Seattle, WA, September 20-23, 2010.

Wiles, P.J., Rippeth, T.P, Simpson, J.H. and Hendricks, P.J. 2006. A novel technique for measuring the rate of turbulent dissipation in the marine environment. *Geophysical Research Letters*, 33(21): 1-5.

4.2 Physical Environment: Far-field

Name	Affiliation
Mitsuhiro Kawase (Chair)	University of Washington
Andrea Balla-Holden	U.S. Navy
Brian Polagye	University of Washington
David Baldwin	NOAA Fisheries - Northwest Fisheries Science Center
Harper Simmons	University of Alaska – Fairbanks
Mirko Previsic	re vision consulting
Scott Couch	University of Edinburgh
Scott James	Sandia National Laboratories
Skip Albertson	Washington Department of Ecology
Ryan Tyler (Note Taker)	University of Washington

4.2.1 Introduction

Tidal energy extraction may affect water quality, primary productivity, sediment transport, and the nature of the inter-tidal areas within the far-field marine environment surrounding a tidal energy extraction array. Energy removal and resultant changes in tidal range, transport, and mixing would be the primary stressor impacting these aspects of the marine environment; a secondary stressor would be chemical releases from the materials coating tidal energy extraction devices or from accidental chemical spills during device installation, operation, or servicing. A scientific understanding of sensitivities of these parameters is needed to determine the impact of a given level of energy extraction, but there is a large degree of uncertainty due to the nonlinear nature of the processes involved, highly site-specific factors, and cumulative effects (not to mention significant variability from existing natural and anthropogenic factors). To reduce uncertainty, it is recommended that tidal energy researchers and developers collaborate with the marine science community in order to leverage existing knowledge and ongoing research. Modeling capabilities should be developed, especially representations of energy extraction and its effects on an estuarine-scale hydrodynamic model with boundary conditions that can propagate energy dissipation throughout the model domain. Before modeling can begin in earnest, scientists must consolidate existing information to establish baseline conditions. Developers should phase the deployment of commercial-scale tidal energy arrays up to the full capacity. Far-field effects should be negligible for pilot-scale installations; for commercial-scale arrays, they should be thought of as an aspect of resource assessment and must be taken into consideration in planning for tidal energy generation.

4.2.2 Receptor Matrix

No significant effect on the far-field physical environment is expected for pilot scale deployments. The significance and uncertainty associated with stressor/receptor interactions are summarized in Figure 27 for commercial-scale deployments. The colors denote significance and triangles denote uncertainty, as defined in Figure 24.

* – in comparison to other elements
** – blank cells indicate no effect expected

Figure 27 – Receptor matrix: Physical environment: Far-field – commercial-scale deployment

4.2.3 Discussion

These considerations primarily apply to far-field impacts of energy extraction in a coastal embayment or an estuary, rather than, for example, areas of fast tidal currents in the straits between regional seas. The largest tidal energy prospects in the United States are of the former types. The far-field is defined as the marine area surrounding a tidal array beyond the scale over which the specific character of the tidal energy device or array is directly discernable. Seen from the far-field, the array may be indistinguishable from a natural energy-dissipating feature, such as form drag over varied topography. While the main concern of the scientific workshop was environmental impacts, conflicts with other marine uses as potential issues in the far-field environment were also discussed. Different sets of stressors (from those relevant to environmental impacts) may lead to use conflicts.

Aspects of the far-field marine environment that may be affected by tidal energy extraction include water quality (such as dissolved oxygen and nutrient concentration), primary productivity, sediment transport, and the nature of the inter-tidal areas. Each is a significant element of the regional marine environment and, in a heavily used region, is impacted in various ways by human activities. A tidal energy developer will be asked by permitting agencies, other marine resource users, and the regional community to demonstrate that development will not significantly and adversely affect the marine environment. For pilot-scale installations, such far-field effects should be negligible. However, commercial-scale development must anticipate the magnitude of far-field effects and how they would scale with the magnitude of energy extraction. The eventual scale of a tidal energy project will likely be constrained by the magnitude of the region-wide impact before the theoretical resource limit is reached.

It is anticipated that energy removal and resultant changes in tidal range, transport, and mixing will be the primary stressor from tidal hydrokinetic energy installations impacting the far-field marine environment. Changes in tidal range will reduce (or, in some cases, increase) the extent of the intertidal area that may form significant habitats. Reduction in tidal transport could result in reduced flushing of embayments, changes in water quality and pollutant dispersal (including algal blooms), and altered migration of organisms that use tidal currents. Reduction in the kinetic energy of the tidal current could reduce turbulence and mixing, which could, in turn, affect bottom sediment transport, supply of marine nutrients to the photic layer for primary production, and the exchange circulation and flushing of estuaries.

Chemical stressors may have far-field impacts as well; these include spills during installation, servicing, or operation and flaking of coating material containing toxic compounds. Tidal energy arrays will be located in areas of strong currents, and this could make it challenging to respond to spill incidents associated with tidal energy arrays. Uncertainties regarding impact of chemical stressors from tidal energy devices on the far-field marine environment are large at this point. These uncertainties include the identity of the chemical(s), their toxicity to biological organisms, and their exposure concentrations.

Static and dynamic effects of the presence of a device will be considered in the near-field analysis of the devices and are not of far-field concern. Impacts of electromagnetic and acoustic stresses are also likely confined to the near-field of the device/array or, in the case of the electromagnetic field, are primarily associated with the underwater transmission cables (although these may run over long distances). Although it is possible that, for example, fish aggregation around a tidal energy array could have an effect on the overall distribution of fish species and species assemblage in the surrounding marine areas (and, hence, on the overall marine ecosystem of the region), such higher-order, cumulative and ecological interaction effects will have correspondingly greater uncertainties and cannot be adequately addressed at this point.

4.2.4 Priority Area: Effects of energy removal

Description

The primary stressor of concern for the far-field physical environment is energy removal by tidal turbines. Although not likely appreciable for pilot scale developments, this stressor may be significant at the commercial scale. Energy removal may result in measurable changes to tides, currents, and mixing throughout a region, with attendant effects on water quality, habitat, and biological productivity.

4.2.4.1 Gaps in Understanding

It is agreed that energy removal could have an impact on each of the receptor elements, but this consensus is tempered by a high degree of uncertainty surrounding the important question: How can we determine how much energy can actually be removed without a significant impact? Different sites would be impacted to greater or lesser extents, even within the same far-field region surrounding a single tidal energy array.

There is a high level of uncertainty surrounding the impacts energy removal on the far-field physical environment because of the:

- Moderately to highly nonlinear nature of the processes involved, which makes it challenging to establish scaling relationships between levels of energy removal and the quantitative impacts on receptor elements. For instance, sedimentary processes are highly nonlinear and changes are event-dominated; impacts of energy removal may occur suddenly once a “tipping point” value of extraction is exceeded.
- Highly site-specific factors and combinations of factors affecting the degree of impact.
- Significant variability due to natural causes and anthropogenic factors other than tidal energy extraction (e.g., changes to nutrient concentrations from runoff).

Nevertheless, the general relationship between energy dissipation by tidal turbines and changes in tidal range/transport, at least for simple estuaries, is now established (Garrett and Cummins 2004, Garrett and Cummins 2007, Polagye et al. 2009) as shown in Figure 28. Energy dissipated by tidal turbines includes energy extracted for conversion to electricity, energy lost when the turbine wake mixes with the free stream, and energy lost due to drag on the device support structure. The initial scaling between energy dissipation by arrays (P) and reduction in tidal transport (Q) is linear (upper left-hand portion of Figure 28a). As one moves down the curve from left ("no extraction") to right, additional power extraction results in a progressively greater transport reduction, until the maximum level of dissipation (Pmax) is reached where the transport would be 40 ~ 50% of the original value. Beyond this point, adding more capacity to the array results in decreased energy harvesting, although the environment impact continues to grow. Comparable relations exist for changes to tidal range and average current magnitude as a function of dissipation (Figure 28b,c). Such large changes to the natural tidal regime would certainly be considered an unacceptable environmental impact (even setting aside economic limitations from the decreasing cost-effectiveness of an array approaching Pmax); hence the relevant portion of the range/extraction curve is the linear regime (up to P/Pmax ≈ 0.5). Establishing the slope of the curve in this regime, either from theoretical considerations or simple models, will help quantify changes in the water levels in the nearshore environment and in the extent of tidal flats. Other environmental processes, such as mixing, may depend on the energy density (~Q2) or power density (~Q3). Their sensitivity to energy extraction would be correspondingly greater (as shown for power density in Figure 28d).

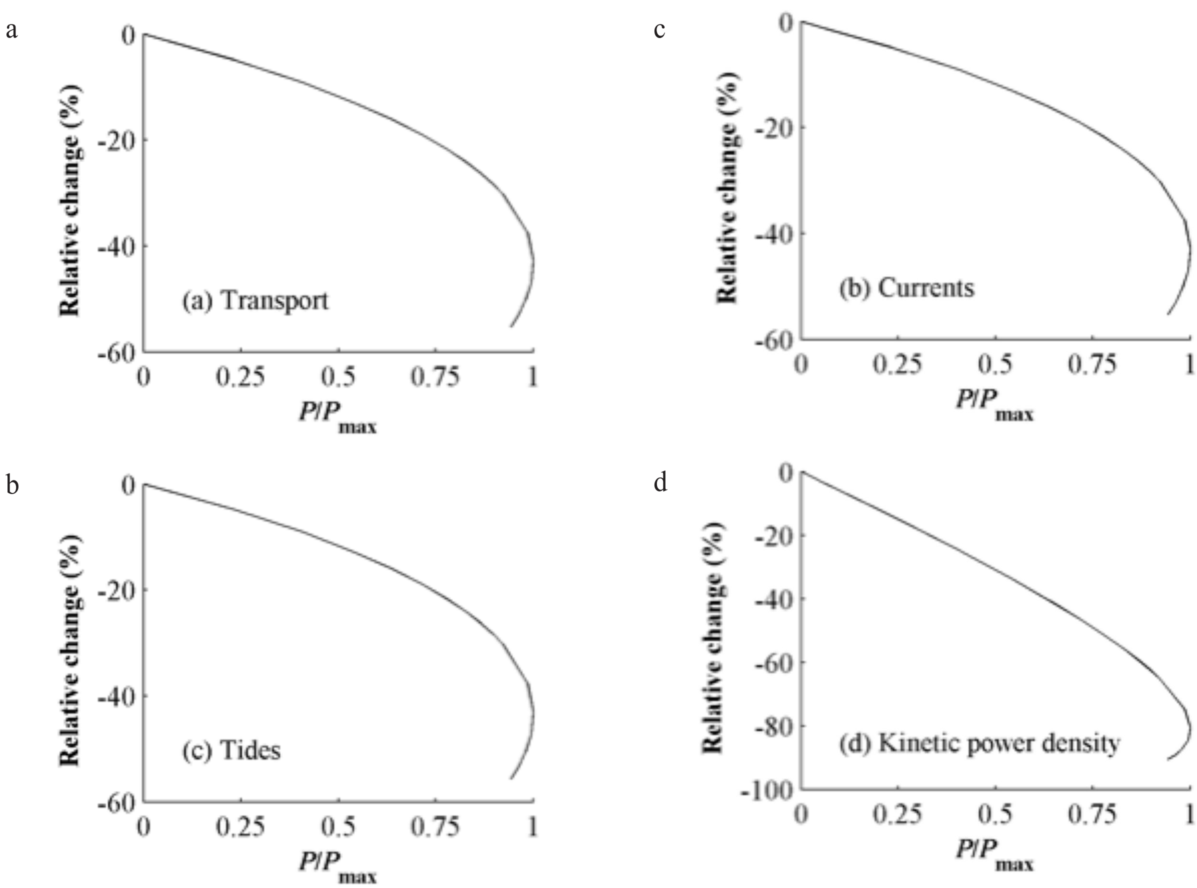


Figure 28 a, b, c, d – Relative changes to far-field flow quantities in an embayment as a consequence of kinetic power extraction for an embayment connected to the ocean by a narrow channel (after Polagye and Malte 2010).

Uncertainties also stem from the lack of data needed to characterize the baseline estuarine environment, including variability in the absence of tidal energy extraction. Certainly, there are existing data useful for such characterization for any given body of water, and necessary measurements may have already been made. Such studies may not be well-publicized and may only be documented in “gray literature”; locating these data sources and obtaining access should be a priority. In other cases, there is a paucity of available resource data; filling those basic gaps may require significant efforts.

Predictive tools (numerical models) for studying environmental effects of energy removal are available but require significant development. The level of accuracy needed to address questions of impacts of tidal energy extraction is uncertain, and whether available models meet this as-yet-to-be-determined level is also unclear. Some potential tidal energy development sites have existing models that could be used to investigate far-field impacts, given sufficient resources to convert them to this application. However, implementing and validating a specific model for a specific site is a difficult and time-consuming exercise. Moreover, model parameters may be highly “tuned” to reproduce existing conditions as a result of calibration and validation; they may not be appropriate to study conditions far from the current regime, including cases with tidal energy extraction.

This tempered view of the usefulness of models in addressing questions of far-field impact may be countered by the possibility that “imperfect” models could still be useful in determining a given estuarine system’s sensitivities to change. It is not anticipated that the model will exactly replicate the marine environment; rather interest is directed toward relative responses to perturbations and investigating whether the changes from energy extraction could reach some “tipping point” for environmental impact. Such a model must still be properly calibrated and used with full understanding of the dynamics underlying its behavior, its limitations, and the reasonableness of the outcomes. The degree of calibration error must be translated into a measure of uncertainty surrounding the conclusions drawn from any model. If one uses a model without basis for evaluating what is a reasonable result, then the model results can easily lead one to a wrong conclusion.

Approaches to Closing Information Gaps

Leverage existing knowledge and ongoing research and operations — Questions raised by tidal energy development are, in many ways, analogous to those raised by management of other marine resource uses and are active areas of research in coastal and estuarine oceanography. Monitoring and modeling programs to enable stewardship of the marine environment are in place or being developed for many coastal bodies of water, and data on parameters relevant to the question of far-field impacts due to energy removal are being collected. Baseline conditions, including the degree of natural variability, might be established from available data. Modeling capabilities developed to address general questions of variability and sensitivity could be used to test energy extraction scenarios and their impacts on the far-field environment. Tidal energy researchers and developers should actively engage the marine science community and seek collaborations.

Improve model confidence — Confidence in dynamical models of circulation, biogeochemistry, and sediment dynamics in coastal and estuarine environments must be gained through model development, rigorous verification, validation, and calibration. Such models could be used to evaluate scenarios for commercial-scale development with regard to their effects on the far-field physical environment. Two specific technical areas that must see development are:

- Representation of energy removal and its near-field effects in an estuarine-scale hydrodynamic model; and
- Boundary conditions that can adjust to additional energy dissipation throughout the model domain (i.e., not clamp energy fluxes at the open boundary).

Laboratory models — Workshop participants considered the possibility of laboratory experiments to simulate tides and energy extraction and using these to verify the performance of numerical models. Scaling will be a significant issue because relating system parameters at the laboratory scale to those at the estuarine scale is not be straightforward. Existing laboratory-scale models of marine environments, such as the University of Washington's model of Puget Sound, provide intriguing study opportunities; however, it is not clear if energy removal experiments can be usefully interpreted, beyond qualitative comparisons (e.g., direction of a change, such as tidal range).

Approaches to Monitoring

Consolidate existing information to establish baseline conditions — It is difficult to imagine a commercial tidal energy development in a region without a well-understood baseline physical environment. Physical characteristics of a given region can have significant seasonal (and possibly interannual) variability and one needs to monitor the system under consideration for at least a year in order to understand the baseline conditions, and how conditions change through the seasons. In many cases, important measurements have already been made, but finding the study sponsor and obtaining the data set can be difficult. Often, it is not that the data do not exist, but that nobody knows where the data are. Better efforts are required to integrate and archive disparate local knowledge. This would be of benefit not only to tidal energy developers but to the broader oceanographic community. It could also help developers identify critical baseline data gaps, and develop strategies for gathering needed baseline data and ongoing monitoring. As mentioned previously, these considerations are restricted to commercial-scale deployments and are not expected to be relevant at the pilot scale.

Take a phased approach to the development of commercial-scale tidal energy arrays — Because pilot-scale installations should not have measurable impacts on the far-field, monitoring at the pilot-scale will not yield useful information regarding commercial-scale development. At some point, a commercial-scale array that is likely to result in measurable far-field effects would have to be installed to validate a priori sensitivity studies. Subsequent development would then need to be managed adaptively as the nature and the magnitude of impacts are revealed. It will be a learn-by-doing exercise, but the project could be adaptively managed through continuing education and refining models through experience.

4.2.5 Recommended References

Atwater, J.F. and Lawrence, G.A. 2010. Power potential of a split tidal channel. *Renewable Energy*, 35: 329-332.

Barltrop, N., Varyani, K.S., Grant, A., Clelland, D. and Pham, X.P. 2007. Investigation into wave–current interactions in marine current turbines. *Journal of Power and Energy,* 221: 233-242.

Blunden, L.S. and Bahaj, A.S. 2007. Tidal energy resource assessment for tidal stream generators. *Journal of Power and Energy*, 221: 137-146.

Boehlert, G.W., McMurray, G.R. and Tortorici, C.E. (Eds.). 2008. *Ecological Effects of Wave Energy Development in the Pacific Northwest. U.S. Department of Commerce*, NOAA Technical Memorandum NMFS-F/SPO-92.

Bryden, I.G., Couch, S.J., Owen, A. and Melville, G. 2007. Tidal current resource assessment. *Journal of Power and Energy*, 221: 125-135.

Bryden, I.G., Grinstead, T. and Melville, G.T. 2004. Assessing the potential of a simple tidal channel to deliver useful energy. *Applied Ocean Research,* 26: 198-204.

Cada, G., Ahlgrimm, J., Bahleda, M., Bigford, T., Stavrakas, S., Hall, D., Moursund, R. and Sale, M. 2007. Potential impacts of hydrokinetic and wave energy conversion technologies on aquatic environments. *Fisheries*, 32(4): 174-180.

Centre for Marine and Coastal Studies. 2003. A baseline assessment of electromagnetic fields generated by offshore windfarm cables. Report prepared for Collaborative Offshore Wind Energy Research into the Environment, COWRIE-EMF – 01-2002 66. July 2003.

Clarke, J.A., Connor, G., Grant, A.D. and Johnstone, C.M. 2007. Design and testing of a contra-rotating tidal current turbine. *Journal of Power and Energy*, 221: 171-179.

Dolman, S.J., Green, M. and Simmonds, M.P. 2007. Marine Renewable Energy and Cetaceans. SC/59/E10. *Submitted to the Scientific Committee of the International Whaling Commission.*

Driscoll, F.R., Skemp, S.H., Alsenas, G.M., Coley, C.J. and Leland, A. 2010. Florida's Center for Ocean *Energy Technology.* Available from *http://www.mitenergyclub.org/assets/2009/3/4/Florida_s_Center_for_Ocean_Energy_Technology.pdf.*

Fraenkel, P.L. 2007. Marine current turbines: Pioneering the development of marine kinetic energy converters. *Journal of Power and Energy*, 221: 159-169.

Garrett, C. and Cummins, P. 2004. Generating power from tidal currents. *Journal of Waterway, Port, Coastal and Ocean Engineering*, 130(3): 114-118.

Garrett, C. and Cummins, P. 2007. The efficiency of a turbine in a tidal channel. *J. Fluid Mechanics*, 588: 243-251.

Gill, A.B. 2005. Offshore renewable energy: Ecological implications of generating electricity in the coastal zone. *Journal of Applied Ecology*, 42: 605-615.

Myers, L.E. and Bahaj, A.S. 2010. Experimental analysis of the flow field around horizontal axis tidal turbines by use of scale mesh disk rotor simulators. *Ocean Engineering*, 37: 218-227.

Neill, S.P., Litt, E.J., Couch, S.J. and Davies, A.G. 2009. The impact of tidal stream turbines on large-scale sediment dynamics. *Renewable Energy*, 34(12): 2803-2812.

Polagye, B., Kawase, M. and Malte, P. 2009. In-stream tidal energy potential of Puget Sound, Washington. *Journal of Power and Energy*, 223: 571-587.

Polagye, B.L. and Malte, P.C. 2010. Far-field dynamics of tidal energy extraction in channel networks. Renewable Energy, 36(1): 222-234.

Schiff, K., Diehl, D. and Valkirs, A. 2004. Copper emissions from antifouling paint on recreational vessels. *Marine Pollution Bulletin*, 48: 371-377.

Spurlock, D.S. 2008. Modeling flows for assessing tidal energy generation potential. MS thesis, Virginia Polytechnic Institute, Blacksburg, VA. Available at *http://scholar.lib.vt.edu/theses/available/etd-09212008-134411/unrestricted/D_Spurlock_Thesis.pdf*

4.3 Habitat and Invertebrates

Name	Affiliation
Tom Mumford (Chair)	Washington Department of Natural Resources
Charles (Si) Simenstad	University of Washington
Craig Collar	Snohomish County Public Utility District
David Young	U.S. Environmental Protection Agency
Glenn Cada	Oak Ridge National Laboratory
Graham Daborn	Acadia University
Heather Trim	People for Puget Sound
Peter Browne	HDR, Inc.
Simon Geerlofs	U.S. Department of Energy
Brie Van Cleve	Pacific Northwest National Laboratory
Erin Black (Note Taker)	University of Washington

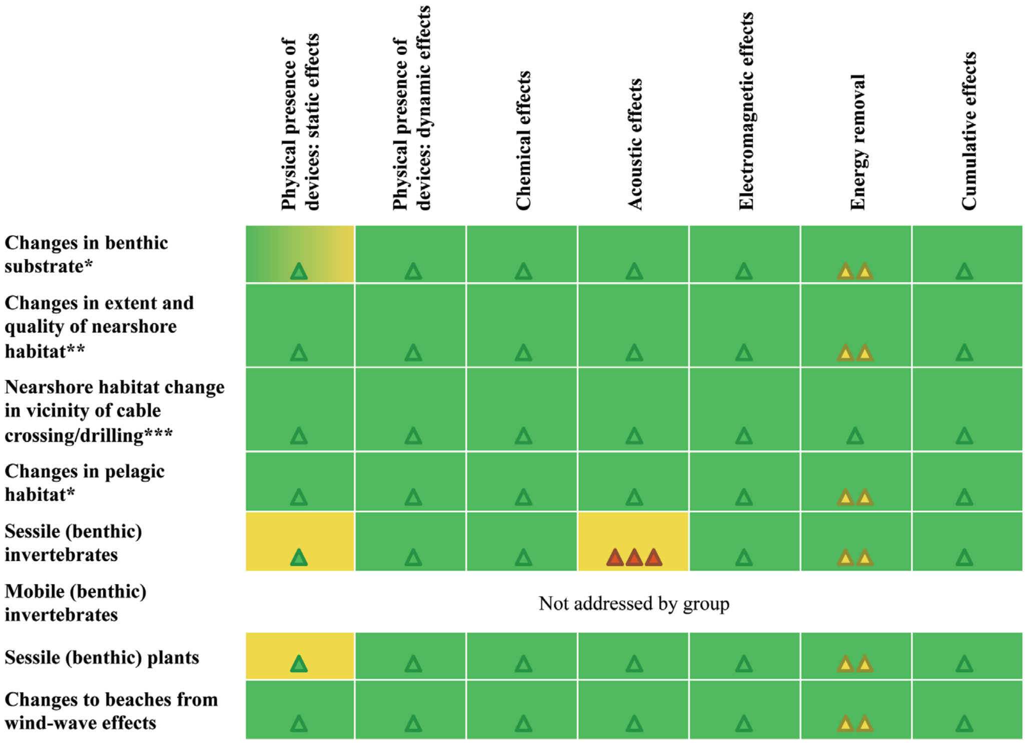
4.3.1 Introduction

This breakout group discussed the effects of tidal energy development on habit and invertebrates. These were separated into several categories of potential stressor/receptor interactions:

- *Benthic substrate:* habitat on the seabed;
- *Benthic (sessile) invertebrates:* invertebrates on the seabed unable to move in response to a disturbance (e.g., barnacles and sponges);
- *Benthic plants:* plants on the seabed, also unable to move in response to a disturbance;
- *Pelagic habitat:* the water column characteristics that provide physical, chemical, migratory, and feeding functions;
- *Nearshore habitat:* nearshore areas that could experience changes as a consequence of increased/decreased tidal rage with energy removal;
- *Nearshore habitat change in vicinity of cable crossing/drilling:* nearshore areas that could be disturbed by cables or drilling (may be different than the benthic habitat disturbed by device installation/operation); and
- *Beaches:* shoreline areas that could experience accretion or erosion as a consequence of energy removal.

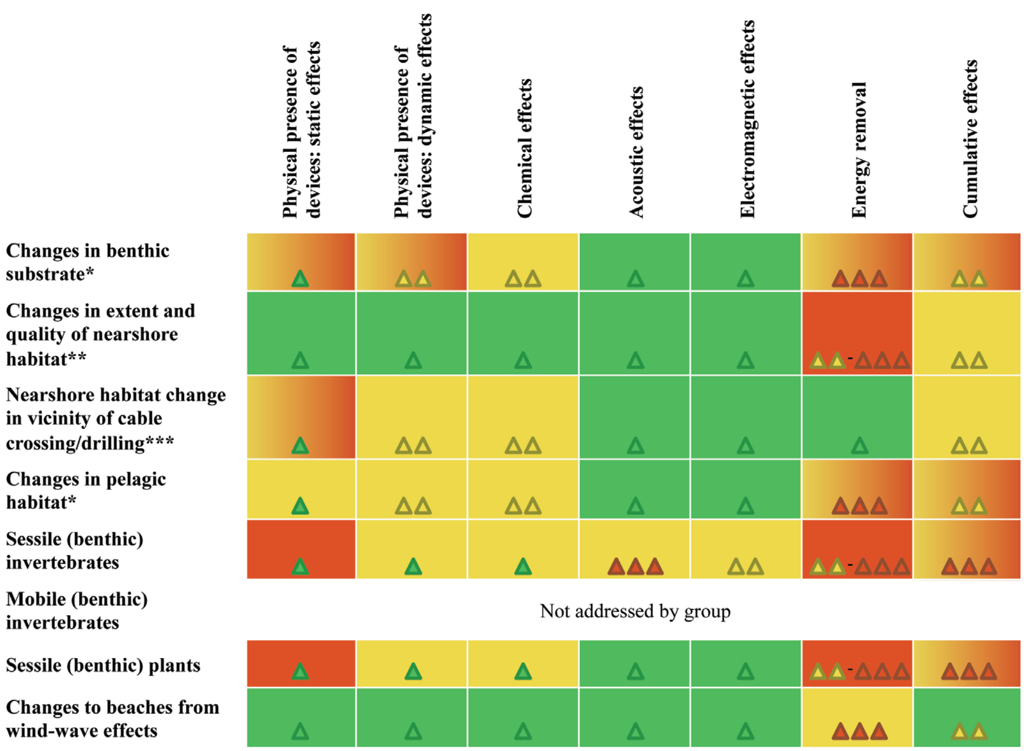
Mobile benthic invertebrates, such as crustaceans, were not explicitly discussed. The significance and uncertainty associated with stressor/receptor interactions are summarized in Figure 29 for pilot-scale deployments and in Figure 30 for commercial-scale deployments. The colors denote significance and triangles denote uncertainty, as defined in Figure 24.

4.3.2 Receptor Matrix



* – near and far field

Figure 29 – Receptor matrix: Habitat and Invertebrates – pilot-scale deployment



* – near and far field
** – due to changes in far-field tidal range
*** – technique dependent

Figure 30 – Receptor matrix: Habitat and Invertebrates – commercial-scale deployment

4.3.3 Discussion

Priority issue areas identified by participants in this breakout session included effects on sessile (benthic) invertebrates and plants, near- and far-field pelagic habitats, and near- and far-field benthic substrate. Outside of those priority issue areas, three broad issues were identified. These include:

- The critical need for modeling far-field effects of energy removal (mixing and tidal amplitude and height),
- Cumulative effects of multiple or commercial-scale projects, and
- Availability of data from existing projects.

This breakout discussion does not resolve conflicts between generalities and specificity. For example, there is a broad range of species within each receptor element, with a broad range of potential responses to stressors and impacts. The matrices presented in Figure 29 and 30 may reflect the worst-case scenario, best-case scenarios, or the average of the two cases; this should be made explicit in subsequent discussion. Species listed under the Endangered Species Act (ESA) specifically need close attention. In the case of ESA-listed species, loss of individuals should be considered as well as population-level effects. Also, population-level ESA thresholds are much higher than those for community-level effects. Although workshop participants spoke of the need to establish generalized monitoring protocols, many exceptions or unique approaches may have to be developed for particular situations. There is also a need to examine changes in benthic and pelagic food webs.

The general level of knowledge around each of the receptor elements is:

- *Benthic substrate:* moderate in the near-field (site-specific) and low in the far-field.
- *Sessile species and plants:* moderate to high
- *Nearshore habitat:* high
- *Pelagic habitat:* moderate to high

Some aspects of acoustic effects, electromagnetic effects, and energy removal might be addressed by pre-installation experiments. The presence of devices can only be rigorously assessed by pilot projects, and such projects would also provide further information on acoustic and electromagnetic effects.

4.3.4 Priority Area: *Sessile (benthic) species - invertebrates and plants*

Description

The impacts of development of multiple arrays or multiple sites could potentially have far-reaching effects, both spatially and in terms of "ripple effects" throughout the ecosystem, from a bottom up perspective. The impacts of energy removal and cumulative effects of multiple arrays or multiple sites could be significant, resulting in changes in abundance, distribution, and population or community structure of marine invertebrates and plants.

This is a top priority because marine invertebrates and marine plants are two groups of organisms not specifically considered in the other sections (marine mammals, birds, fish), yet form an important part of the marine ecosystem. They respond to many stressors, and because at least part of their life history is benthic, cannot move away from stressors. Hence they integrate the stressors at a particular location. They are particularly sensitive to changes in substrate grain size, energy regimes (currents/waves), and tidal regimes (amplitude and height). Changes in abundance, distribution, population, or community structure of marine invertebrates (over 3,000 species) and plants (over 650 species) have major effects on the upper trophic levels. Marine plants (seaweeds, including kelp species, and seagrasses, including eelgrass) also serve as biogenic habitats, providing habitat functions such as refuge, migratory paths, substrate for reproduction and production of prey items.

Gaps in Understanding

There is a high level of uncertainty about how much energy a tidal energy unit, units, or arrays of units would remove, and what would be the associated effects of energy removal, in particular the effects of changes in tidal and energy regimes. However, energy removal is unlikely to cause environmental changes at the pilot scale.

Uncertainty about the effects of acoustic regimes on invertebrates was thought to be high. There was concern expressed about whether there is information available or not, whether it may be considered proprietary, and whether it has been analyzed.

Approaches to Monitoring

Methods for measuring the types, abundance, and distribution of intertidal and subtidal benthic invertebrates and nearshore marine plants are well established (Murray et al. 2002). Accurate identification is difficult and expensive because there are few experts and the process is time consuming.

4.3.5 Priority Area: *Changes in pelagic habitat near-field and far-field*

Description

These impacts can be very widespread, potentially affecting large proportions of distinct ecosystems that are areas of interest for tidal energy development (e.g., Puget Sound and Cook Inlet).

Pelagic habitat is defined here as the water column characteristics that provide physical, chemical, migratory, and feeding functions. Although many of the workshop discussions focused on large charismatic megafauna, such as marine mammals, adult fish and seabirds, the pelagic ecosystem contains phytoplankton and zooplankton and is the means by which the spores, eggs, and larval forms of invertebrates and many fish are dispersed. Changes in currents, pressure gradients, estuarine stratification and mixing, and shear zones alter physical, chemical, and energy characteristics of this habitat. Changes could affect oxygen levels (hypoxia), nutrient levels, salinity, and vertical movement of plankton. These, in turn, affect a wide variety of organisms.

Gaps in Understanding

Although modeling indicates negligible far-field effects and minimal near-field effects at the pilot scale, there is concern about the effects of energy removal resulting from commercial-scale tidal energy projects. Specifically, effects of energy removal on a closed estuarine system are poorly understood, and the effect of changes on pelagic organisms is also poorly understood.

The best approach to closing this information gap may be modeling, because monitoring of pilot-scale deployments is unlikely to provide insight into commercial-scale concerns (see Section 4.2, Physical Environment: Far-field for a discussion on modeling challenges).

Approaches to Monitoring

Fundamental procedures exist, but, in general, studies to collect data about pelagic habitat changes as a consequence of energy removal would be very difficult and expensive to implement.

4.3.6 Priority Area: *Changes in benthic substrate both near and far-field*

Description

At issue are substrate grain size changes. Grain size distribution is affected by the energy regime, as well as the movement of sediments and erosion rates. The distribution and abundance of benthic organisms is almost entirely determined by the type, size distribution, and movement of the substrate. For example, because of the glacial origin of Puget Sound, most benthic habitats consist of a complex of unconsolidated sediments. Some areas, particularly in the San Juan Archipelago of Washington and the Strait of Juan De Fuca in Washington and Georgia Strait in British Columbia are consolidated but often in a complex with unconsolidated sediments. Tidal energy would be located in high-energy environments where there are several types of substrates. The substrate of Admiralty Inlet is a cobble/boulder bottom with few fine-grained materials. These comparatively large-sized substrates move or roll, resulting in few sessile organisms or ones that are resistant to abrasion. Conversely, the substrate in Cook Inlet consists of fine-grained sediments deposited by glacial outflow. Other substrates include exposed areas of hardpan (Tacoma Narrows, Washington) or bedrock (Deception Pass, Washington), scoured of unconsolidated materials and having a very different biota compared to sand or gravel.

This is a top priority because scour, resuspension, deposition, and sediment movement may cause changes in biota. These effects can be in the near-field (scour and deposition around devices), or far-field (large changes in currents, movement of substrate, or grain size).

Gaps in Understanding

Substrates in high-energy current areas are poorly mapped, and the dynamics are not well understood. This is, in part, driven by the difficulties inherent to operating in high-current areas and characterizing hard substrates.

Approaches to Monitoring

Grain size characterization is possible for finer-grained sediment. For example, optical backscatter sensors are capable of monitoring turbidity levels and laser in-situ scattering and transmissometry can assess grain size up to characteristic dimensions of 500 microns. However, in scoured environments, direct sampling of the seabed is challenging. For example, a Washington State Department of Ecology sediment monitoring program excluded all high-energy areas because of an inability to collect samples with conventional bottom grabs (Long et al. 2003). Monitoring sediment movement in deepwater, high-energy environments is not well developed.

4.3.7 Recommended References

Long, E., Dutch, M., Aasen, S., Welch, K. and Hameedi, M.J. 2003. *Chemical contamination, acute toxicity in laboratory tests and benthic impacts in sediments of Puget Sound: A summary of results of the joint 1997-1999 Ecology/NOAA survey*. Washington Department of Ecology, Report 03-03-049.

Murray, S.N., Ambrose, R.F. and Dethier, M. 2002. *Methods for Performing Monitoring, Impact, and Ecological Studies on Rocky Shores: Final Technical Summary*. MMS OCS Study 2001-070. Coastal Research Center, Marine Science Institute, University of California, Santa Barbara, CA. MMS Cooperative Agreement Number 14-35-0001-3076.

4.4 Fish: Migratory

Name	Affiliation
Kurt Fresh (Chair)	NOAA Fisheries - Northwest Fisheries Science Center
Andrew Gill	Cranfield University
Anna Kagley	NOAA Fisheries - Northwest Fisheries Science Center
Fred Goetz	U.S. Army Corps of Engineers
Greg Ruggerone	Natural Resource Consultants
Jim Brennan	Washington Sea Grant
Jim McCleave	University of Maine
Kit Rawson	Tulalip Tribes
Richard Anderson	Pacific Northwest National Laboratory
Sam Johnston	Hydroacoustic Technology, Inc.
Jeff Epler (Note Taker)	University of Washington

4.4.1 Introduction

Migratory fishes are formally defined as diadromous species. However, some fish species (e.g., Atlantic cod) that do not fully enter fresh water follow consistent and predictable patterns. Similar concerns are likely to exist for the species and, consequently, this work group adopted a broader definition of migratory fish as "fish that follow predictable movements through the environment during their lifecycle." Ultimately, for most species, assessing and evaluating population-level effects are of primary importance. Species that are at low population levels will be most at-risk to effects of the devices (e.g., fish that are listed as "endangered" under ESA). The risk posed by stressor effects on migratory fish depend on:

- Affected species;
- Life stage;
- Population level of affected species;
- Geomorphology of the area;
- Large scale site conditions;
- Local conditions;
- Type and number of turbines; and
- Other equipment involved (e.g., power cables).

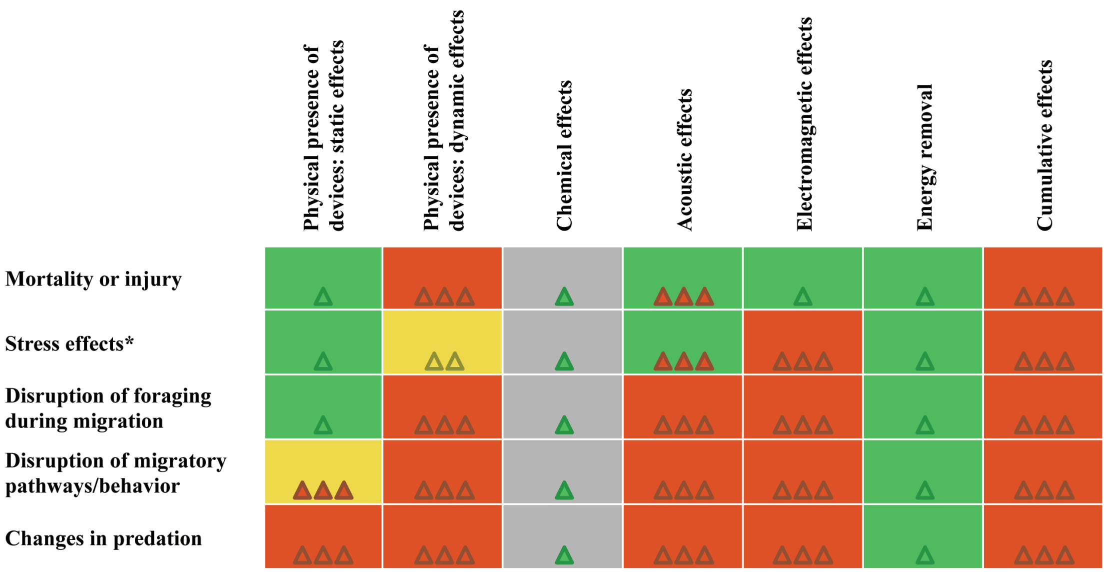
For all environmental issues related to migratory fish, workshop participants felt there was a lack of information on the physical effects of tidal energy devices that hampered the participants' abilities to evaluate stressor/receptor relationships. For some issues, information may be available, but it is not clear how it can be obtained. A thorough review of the physical effects of turbines on the environment is needed, and relevant data needs to be made publically accessible.

The most important "actionable" (can be studied over the near term) issues pertaining to migratory fish are understanding the dynamic effects (spinning movement of the blade) of tidal energy devices on migratory fish, assessing the acoustic signatures of different devices at varying distances from the devices during operation, and evaluating electromagnetic fields associated with energy generation. At large scales (assumed to be commercial-scale operations), evaluating cumulative effects of turbines and assessing effects of energy removal on migratory pathways were considered especially important. It is clear, however, that as more is learned about tidal energy effects, the prioritization of issues will need to be revisited. Some issues may become less of a priority for study and research, and others may increase in priority.

In order to assess baseline conditions and monitor potential turbine effects on migratory fish, a full evaluation of available tools and approaches is needed. Gaps or deficiencies in approaches to baseline assessments and project effects monitoring and evaluation must be identified and actions undertaken to address these gaps.

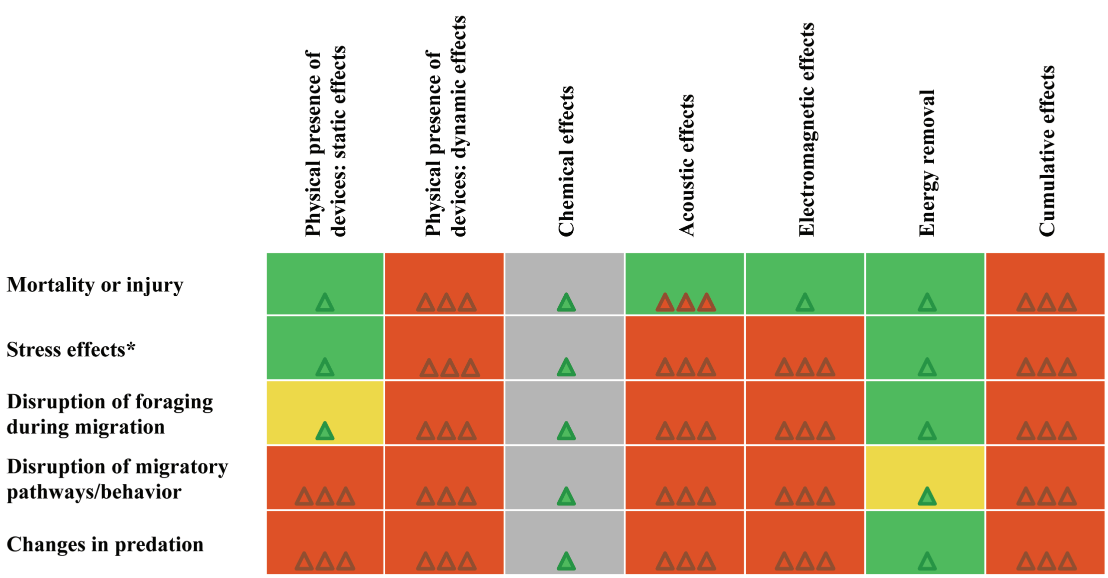
The significance and uncertainty associated with stressor/receptor interactions are summarized in Figure 31 for pilot-scale deployments and in Figure 32 for commercial-scale deployments. The colors denote significance and triangles denote uncertainty, as defined in Figure 24.

4.4.2 Receptor Matrix



* – reproduction alteration, growth, endocrine disruption

Figure 31 – Receptor matrix: Fish: Migratory – pilot-scale deployment



* – reproduction alteration, growth, endocrine disruption

Figure 32 – Receptor matrix: Fish: Migratory – commercial-scale deployment

4.4.3 Discussion

For all environmental issues related to migratory fishes, there is a perceived lack of information on the physical effects of tidal energy devices that hampered the workshop breakout group's ability to evaluate stressor/receptor relationships. For some issues, it is likely that more information was available than the group was aware of, but how to find and access this information was unclear. For example, little data is available on the magnitude of electromagnetic fields from tidal energy deployments, and there may be significant species-specific differences in sensitivity to the stressor. A thorough review of physical effects of turbines on the environment is needed, and data need to be made publically accessible at some point. Additional knowledge concerning physical changes associated with tidal energy generation may alter what are presently considered to be the major knowledge gaps.

Ultimately, it is likely that population-level effects will be the most important to evaluate. Organisms that have low population levels and that interact with the devices are most at risk (e.g., fish that are listed as "endangered" under ESA). Different approaches to monitoring and evaluation may be required, depending on the size or level of the population. For example, for endangered species (low population levels), "zero impact" may be required, such that the presence of these fish in the area during turbine operation may necessitate shutting down of the equipment. For other species, some level of injury, mortality, or behavioral change may be acceptable.

The effects of tidal energy devices on migratory fishes are site-specific and depend on species and life stage involved, population level of affected species, geomorphology of the area, large-scale site conditions, local conditions, and the specific turbines encountered. For most stressors, there are some species and life stages that will be at a greater level of risk to that stressor. An example of a life stage-specific effect is that some migratory fish make use of strong tidal currents to reduce their energy expenditure (Gibson 2003). Therefore, the timing of migratory movement would coincide with operational periods for tidal turbines. These species also avoid currents running in opposition to their migratory path by moving toward the bottom of the water column or into refuge areas where currents are weaker until the tide turns. It is possible that the wake in the lee of a tidal device support structure could provide this type of refuge. An example of a species-specific effect is the higher sensitivity of clupeids (e.g., shad) to noise at certain frequencies than salmonids. The greatest uncertainty with all stressor effects on migratory fish is with commercial-scale development.

To evaluate a number of these effects, devices need to be placed in the water and operated. Although some assessment and evaluation can come from models and baseline data collections, at some point, devices must be operated in the water to fully evaluate their environmental effects.

Ultimately, the cumulative effects of tidal energy stressors on migratory fish at large scales (e.g., multiple turbines) must be understood. Migratory fish do not necessarily respond to single stressors; rather, they respond to the overall environment they are experiencing, which includes tidal energy extraction, among other issues associated with an area. Understanding cumulative effects is especially complicated by a number of factors. One issue is that an effect can be produced by a single stressor or by multiple stressors associated with turbines. In addition to the turbine field, other elements of the environment, such as the ambient currents, species present in the area, and water quality, can determine how the fish respond. Effects on fish will be a product of their experiences passing through turbine fields, prior to encountering turbine fields, and after encountering turbine fields. For example, if fish are already stressed because of conditions experienced adjacent to the tidal energy devices or because of their life stage (e.g., spawning migration for some salmonids), the effects of the turbines may be greater. Furthermore, some fish may experience disturbances from multiple turbines in passing through an array.

To help address uncertainties around effects on migratory fish, it is clear that a greater understanding of the effects of specific stressor components on the fish (e.g., s and sound) is needed. Understanding whether these elements have linear (i.e., additive) or synergistic (i.e., non-linear or non-additive) effects, assessing whether there are effect thresholds, and considering the conditions in the surrounding environment and how these affect the fish without turbines are additional needs.

A greater understanding of the large scale effects (commercial scale operations) of energy removal on migratory pathways and behavior of migratory fishes is needed. It is recognized that the dominant large-scale effect of energy removal will be on habitat (e.g., shoreline conditions that are distant from the turbine fields). However, it is clear that removal of a sufficient amount of tidal energy could change currents in an area that can affect how fish migrate through the area. Furthermore, changes to tidal currents could also affect how fish are distributed or move through an area (Gibson 2003, Lacoste et al. 2001, Levy and Cadenhead 1995, Moser and Ross 1994, Metcalfe and Hunter 2003).

4.4.4 Priority Area: *Dynamic effects of device operation*

Description

The dynamic effects of devices (e.g., spinning movement of the blade) are fundamental to device operation and, arguably, the most direct effect that turbines could have on migratory fishes. Specific issues include blade strike and pressure changes that can cause injury, mortality, and affect behavior of migratory fish (DOE 2009). Although lethal affects are most dramatic, sub-lethal effects on behavior, including alterations in migration routes, changes to predator prey interactions, and changes in stress levels, are of particular concern. While these types of effects are most significant at large commercial scales, they still may be observable at pilot scales.

Gaps in Understanding

Information from tests involving single turbines can be used to help develop predictions for the effect on migratory fish at larger scales. To address or evaluate this issue, assessments will need to be location-specific and consider types of fish (e.g., clupeids, sturgeons, juveniles and adult salmonids) and type of device. For commercial-scale facilities, baseline studies (perhaps integrated into models) should be developed that quantify spatial and depth trends for migration and enable a pre-operation prediction of effects. The level of risk or impact can then be assessed, evaluated, and tested. For fish at low population levels, monitoring and operational mitigation (e.g., shutdown) may be needed. For other species, predicted impacts should be assessed with monitoring during operations, as appropriate.

Approaches to Monitoring

Only limited discussion of monitoring and baseline data collection was conducted. Additional workshops are needed to thoroughly evaluate monitoring and evaluation approaches. An objective of these workshops should be to conduct a full evaluation of the tools and approaches that will be needed to answer specific questions. Gaps or deficiencies in approaches to monitoring and evaluation must be identified and actions undertaken to address these gaps.

A diversity of baseline data and monitoring approaches will be needed that vary according to species of concern, location, device type, methods of installation and operation, and project scale. All monitoring and baseline work should be driven or guided by explicit questions or hypotheses. It is recommended that predictions of impacts be first developed using the best available information (e.g., baseline data, modeling) and the predictions tested with monitoring. For example, life history or behavior models may provide the best opportunities to develop pre-project predictions. Such predictions can then be tested using monitoring protocols that may involve either active or passive sampling methods.

The first step in determining if a tidal energy device affects migrating fishes is to determine whether migrating fish are present in the area where the device is to be installed, prior to device installation. Unfortunately, migratory fish abundance is seasonal in nature, and one species or another may be in the area at any time of year. At least one year of baseline data collection would be required to determine if migrating fish use the area where the device is to be installed. This monitoring would likely involve routine hydroacoustic surveys (density and fish size estimates) in combination with net sampling (species composition, if endangered species are not of concern) and acoustic telemetry. If this information can be captured at temporal and spatial scales relevant to tidal energy project size, the results of this monitoring could then be used to influence the selection of specific sites for devices (i.e., siting them outside identified migratory pathways). The importance of appropriate array siting with respect to migratory pathways is clear from the development of terrestrial wind power. One of the earliest commercial wind projects developed in the United States is located in Altamont Pass, California, and, due to poor site selection, causes the death of several thousand birds each year, including species protected by the federal Migratory Bird Treaty Act. This early mistake contributes to a perception that wind turbines are inherently hazardous to birds, despite evidence to the contrary. Tidal energy development would be well-served by avoiding such costly mistakes.

The second step in determining if tidal energy devices affect migratory fish species is to monitor operating devices. Even if it were determined (or presumed) that no migrating fish use the area, monitoring should be performed, because migrating fish might be attracted to the device. This type of monitoring would help to determine new design features or operational configurations that have less impact on migrating fish species. Depending on the environment, monitoring in the near field of the operating device could include active acoustics (split-beam, multi-beam, acoustic cameras), optical cameras, and, possibly, specialized netting. These would be primarily suitable for observation of blade strike or near strikes. Acoustic tags would enable detecting wider field responses, such as avoidance or attraction, or even changes in predation rate. However, it may be challenging to determine the root cause of avoidance or aggregation in the presence of multiple stressors. Fine-scale positioning acoustic tag systems could help measure behavioral responses of individuals to specific devices. However, obtaining useful knowledge may require a cost-prohibitive tagging intensity and receiver density.

Although modeling work prior to installation can help in predicting effects of various stressors, a key question is whether migratory fishes can (and do) avoid the tidal energy device. This avoidance in itself may cause other problems (i.e., increased susceptibility to predation, increased stress).

4.4.5 Priority Area: *Acoustic effects*

Description

Whether the sounds generated by the turbines affect migratory fish behavior or condition must be understood. Although high-intensity sound may be generated during installation and maintenance of turbines (e.g., from pile driving), operational effects are more of a concern. Depending on sound intensity, frequency, and distance from the turbine, a variety of lethal and sub-lethal effects are possible, particularly with respect to changes in behavior and condition of the fish. Tests could be used (e.g., in laboratory settings or field-based cage studies) to develop relationships between received sound levels and fish response. These results could provide noise specifications for developers to bring into their design processes. Depending on the specific circumstances, fishes could be attracted or repelled by noise from operating devices. Migratory species vary in their sensitivity to different sound levels, with some species and life stages more susceptible to different sounds than others.

Gaps in Understanding

It is not clear that acoustic changes caused by the devices can be detected by the fish because of ambient noise levels. As a first step to understand the nature of this issue, received noise levels from operating devices need to be characterized. Clearly, this requires that devices be placed in the water and appropriate sound measurements made. As discussed under Section 3.4, Acoustic Effects, obtaining these measurements is challenging in high-current environments because of pseudo-noise.

Approaches to Monitoring

Measured sound levels from tidal energy installations need to be related to what is known about effects of sound/noises on behavior and stress levels (e.g., on reproduction and immune systems) of the fish. This information can be used to develop predictions of effects on different species/life stages. There is some literature on sound effects on fish (e.g., Hastings and Popper 2005), but further study on specific species or life stages may be needed. Although some in situ work may be necessary and feasible, lab studies or field cage experiments may help elucidate possible effects on selected species. Where appropriate, in situ studies could use similar techniques to those previously described in the first priority area.

4.4.6 Priority Area: *Electromagnetic effects*

Description

A greater understanding of the effects of electromagnetic fields (EMFs) generated by the turbines is needed. Some species of fish, such as sturgeon and eels, appear to be particularly sensitive to EMF, and others, such as salmon, do not appear to be as sensitive.

Gaps in Understanding

Although turbine generators and power cables are expected to create EMFs, the intensity levels of the EMFs they generate are not, generally, known. Clearly, this gap in understanding of the stressor must be addressed before the overall importance of this issue can be assessed. This issue is a particular concern at full-scale commercial operations when large distances of cabling and large numbers of turbines are present in relatively small areas. Of particular concern are potential behavioral effects on species that use EMFs for orientation, navigation, foraging, and finding conspecifics.

This question should first be addressed through a thorough review of what is known about fish responses to EMFs generated by underwater power cables. This type of review could help guide an assessment of what species might be at risk and under what conditions. However, the present state of knowledge may be insufficient to conduct a meaningful risk assessment. More information that is publically available on physical changes resulting from different devices (e.g., variance in EMFs) is needed. Such knowledge may change the questions asked in the future about effects of EMFs on different receptor elements.

Approaches to Monitoring

As for acoustic effects, measured EMFs from tidal energy installations need to be related to what we know about effects of these fields on behavior and stress levels of fish. This information can then be used to develop predictions of effects on different species/life stages. Lab or field cage experiments may help to elucidate the effects on particular species. Where appropriate, in situ studies could use similar techniques to those described under dynamic effects. However, as noted in Section 3.5, Electromagnetic Effects, in situ studies of EMF effects are challenging to conduct and, often, inconclusive.

4.4.7 Recommended References

Boehlert, G. and Gill, A. 2010. Environmental and ecological effects of ocean renewable energy development: A current synthesis. *Oceanography*, 23(2): 68-81.

Gibson, R.N. 2003. Go with the flow: Tidal migration in marine animals. *Hydrobiologia*, 503: 153-161.

Gill, A., Gloyne-Phillips, I., Neal, K. and Kimber, J. 2005. *The potential effects of electromagnetic fields generated by sub-sea power cables associated with offshore wind farm developments on electrically and magnetically sensitive marine organisms – A review.* Final report prepared for Collaborative Offshore Wind Energy Research into the Environment (COWRIE) group. COWRIE-EM FIELD 2-06-2004.

Hastings, M.C. and Popper, A.N. 2005. *Effects of Sound on Fish*. Report prepared for California Department of Transportation, Contract No. 43A0139. Available from *http://www.dot.ca.gov/hq/env/bio/files/Effects_of _Sound_on_Fish23Aug05.pdf.*

Levy, D.A. and Cadenhead, A.D. 1995. Selective tidal stream transport of adult sockeye salmon (Oncorhynchus nerka) in the Fraser River estuary. *Canadian Journal of Fisheries and Aquatic Sciences*, 52(1): 1-12.

Lacoste, K.N., Munro, J., Castonguay, M., Saucier, F.J. and Gagne, J.A. 2001. The influence of tidal streams on the pre-spawning movements of Atlantic herring, Clupea harengus L., in the St Lawrence Estuary. ICES *Journal of Marine Science*, 58(6): 1286-1298.

Metcalfe, J. and Hunter, E. 2003. Being there and getting there: balancing the costs of migration against the benefits of changing habitat for North Sea plaice. *Journal of Fish Biology*, 63 Supplement 1: 237-238.

Moser, M.L. and Ross, S.W. 1994. Effects of changing current regime and river discharge on the estuarine phase of anadromous fish migration. In Dyer, K.R. and Orth, R.J. (Eds.). *Changes in Fluxes in Estuaries. Fredensborg*, Denmark: Olsen & Olsen. 343-347.

Ohman, M.C., Sigray, P. and Westerberg, H. 2007. *Offshore windmills and the effects of electromagnetic fields on fish*. Ambio., 36: 630-633.

Westerberg, H. and I. Lagenfelt. 2008. Sub-sea power cables and the migration behaviour of the European eel. *Fisheries Management and Ecology*, 15: 369–375

4.5 Fish: Resident

Name	Affiliation
Wayne Palsson (Chair)	Washington Department of Fish And Wildlife
Bob McClure	BioSonics, Inc.
Mary Ann Adonizio	Verdant Power
Melanie Spring Harris	NOAA Fisheries, Office of Habitat Conservation
Pat Livingston	NOAA Fisheries, Alaska Fisheries Science Center
Sharon Kramer	H.T. Harvey & Associates
Simon Courtenay	Fisheries and Oceans, Canada
Stephen Kajiura	Florida Atlantic University
Tina Wyllie-Echeverria	Wyllie-Echeverria Associates
Teymour Javaherchi (Note Taker)	University of Washington

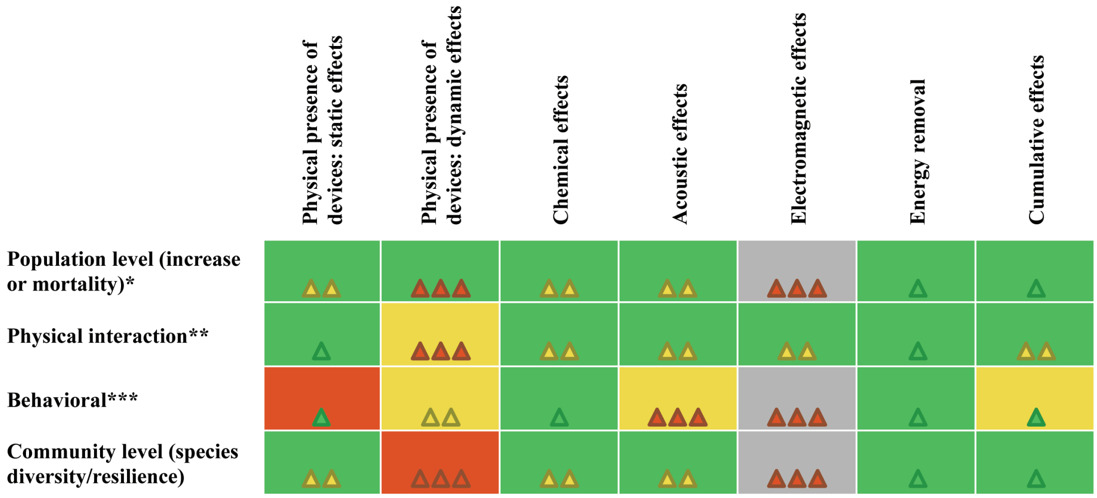
4.5.1 Introduction

This work group organized the elements of the resident fish receptor in terms of behavioral-, individual-, population-, and community-level effects. Resident marine fishes are defined as those saltwater fish that do not undergo diadromous migrations. Resident fish do undergo daily, tidal, and seasonal movements related to foraging, spawning, and energy conservation. Because this definition overlaps with the broad definition of migratory fish adopted in Section 4.4, Migratory Fish, some species are included in both groups' discussions. Depending on the locality, resident fishes form a broad taxonomic suite including but not limited to elasmobranchs (sharks, skates and rays) and their relatives, forage fishes (e.g., osmerids, clupeids), scorpaeniform fishes (e.g., rockfishes, greenlings, sculpins, ling cod), scombrids (e.g., tunas, mackerels) and flatfishes. These species can be oriented to the bottom or occur as pelagic fishes in the water column. The resident fish work group examined and prioritized the potential stressor effects that might result from pilot- and commercial-scale tidal energy installations. It is presumed that these devices would be installed in high-current areas with coarse seafloor substrates of cobble, boulders, and bedrock. Such environments are typical of many potential tidal energy sites in the United States, although there are notable exceptions (e.g., fine sediments in Cook Inlet).

Because the work group considered biological effects, its members identified the levels of biological organization as the receptor elements — namely behavior, individual, population, and community. In terms of behavior, the attraction or avoidance of resident fishes to or from the tidal devices were the main factors considered against the stressor effects. Stressor effects on individuals consisted of a much more diverse suite of factors including sub-lethal effects due to stress, disease, reproductive impairment, changes in growth, injury, or death. The physical effects of blade strike, impingement, or entrainment of eggs, larvae, juveniles, and adults were considered to be the most overt effects of device deployment. Stressor effects have the greatest potential to affect the environment when sublethal effects culminate in reducing population fitness or directly cause enough mortality to limit population growth and stability or compete with other ecosystem services provided by the population. Stressors from tidal energy devices also have the potential to affect resident fish at the community level, bringing about changes in species composition, food-web dynamics, and intraspecific interactions. The level of concern for effects is at the individual level for protected species, however, the group decided that population-level effects were the most important element to consider, followed by individual-level effects, behavioral effects, and community level effects.

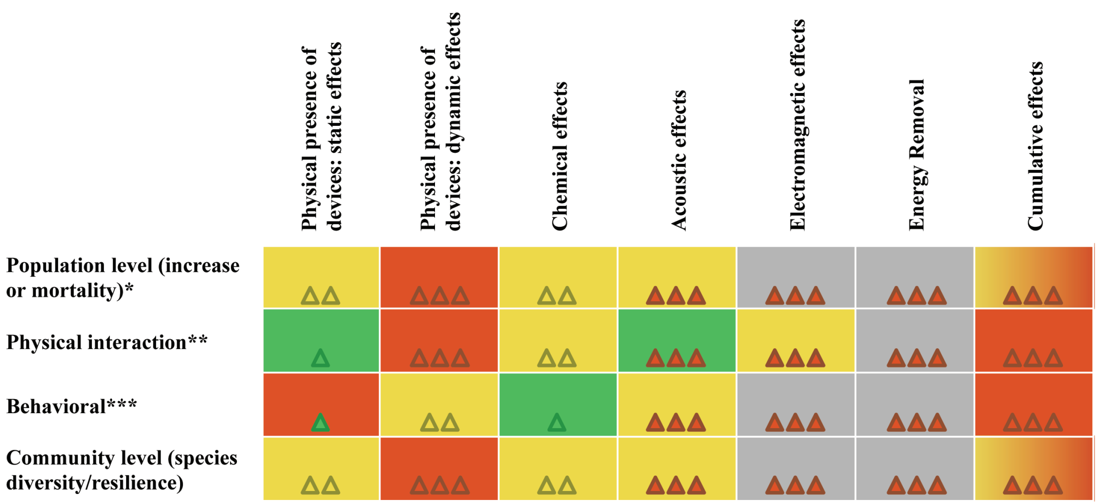
The significance and uncertainty associated with stressor/receptor interactions are summarized in Figure 33 for pilot-scale deployments and in Figure 34 for commercial-scale deployments. The colors denote significance and triangles denote uncertainty, as defined in Figure 24.

4.5.2 Receptor Matrix



* – Endangered species thresholds much higher
** – Sublethal to lethal effects, including stress, toxic impairment, reproductive failure, growth change due to strike, impingement, impairment, pressure wave
*** – Avoidance and/or attraction to device

Figure 33 – Receptor matrix: Fish: resident – pilot-scale deployment



* – Endangered species thresholds much higher
** – Sublethal to lethal effects, including stress, toxic impairment, reproductive failure, growth change due to strike, impingement, impairment, pressure wave
*** – Avoidance and/or attraction to device

Figure 34 – Receptor matrix: Fish: resident – commercial-scale deployment

The group considered each stressor effect on populations and individuals of resident fishes and discussed how to rate the potential effects and uncertainty. A "high" (red) impact stressor had the potential to greatly affect behavior, an individual, a population, or fish community. Effects may be either detrimental or beneficial. A "medium" (yellow) stressor effect was relatively less pervasive but, still was detectable at the different levels of biological organization. A "low" (green)" stressor effect was either not expected or detectable. A "low" level of uncertainty was defined as scientists having good understanding about the problem; a "medium" level of uncertainty meant that scientists have only basic knowledge about the problem; and a "high" level of uncertainty indicated that scientists barely know about the problem. The group also used the term "unknown" to emphasize stressor effects and uncertainties that were completely not understood.

4.5.3 Discussion

Energy removal and the cumulative effects of stressors had high or medium-high potentials to impact individuals and fish populations. Although pilot installations were thought to be of low effect for many stressors, the occurrence of protected species such as federally endangered or threatened fish species or fish that are the primary food stock of endangered marine mammals may increase the potential stressor effects of both pilot and commercial installations. The discussion of whether and to what extent stressors affected resident fish behavior, individuals, populations, or communities progressed from the reductionist to holistic scales of biological organization. Although the group prioritized population- and individual-level elements as the most important to consider, this approach provided a logical basis to address the level of knowledge and uncertainty about the stressors resulting from pilot- and commercial-scale installations.

Dynamic effects of commercial installations are likely to have the highest potential to change resident fish populations. However, this finding was also derived with a high level of uncertainty regarding the individual- and population-level effects from rotor strikes, impingement, and entrainment of fish.

Chemical effects were identified as a low stressor effect, both on the pilot- and commercial-scales. Chemical effects were primarily thought to be most important during the installation, maintenance, and removal of tidal devices because of the enhanced chance of oil spills due to collisions at sea. Knowledge exists from studies of chemical contamination from industrial and nonpoint sources and oil spills to provide the basis to predict chemical effects from tidal energy generation.

Acoustic effects include: sound generation during energy extraction when a device is rotating; installation process (although this would be just a short period of time); noise generation due to the turbulence wake of the turbine; and noise generated by supporting cables vibrating in the current. How or if these acoustic stressors affect resident fish are of high uncertainty, but were rated as medium effect in both pilot and commercial installations.

Electromagnetic fields (EMFs) can be potentially sensed by fish and evoke avoidance or attraction behaviors (Ohman et al. 2007). Sharks, skates, rays, ratfishes, and other elasmobranchs can detect faint electric fields (Kalmjin 1982, Kajiura and Holland 2002, McGowan and Kajiura 2009), and some fish have the capacity to sense the Earth's magnetic field for orientation behavior (Lohmann and Johnsen 2000, Montgomery and Walker 2001, Hellinger and Hoffmann 2009). How or if tidal devices or cables that transmit power to shore affect fish behavior is both unknown in terms of effects and uncertainty.

Energy removal by tidal device operation was deemed of low effect and low uncertainty for pilot installations but of unknown effect and high uncertainty for commercial installations.

Cumulative effects on behavior were evaluated on the presumed long-term and long-lasting effects of all stressors, as well as any interactive compounding or cancelling among stressor effects. The cumulative effects on behavior were deemed as medium for pilot-scale installations and high for commercial-scale installations, and there was low uncertainty for pilot-scale installations but high uncertainty for commercial-scale installations.

Behavior

Although the behavioral considerations were ranked at the third most important element, both pilot- and commercial-scale tidal generation installations had high potential for affecting resident fish behavior. Tidal energy devices would either cause fish to avoid or be displaced by the static effect of device deployment or attract benthic and pelagic resident fish to the device, in what was termed the "artificial reef effect." Avoidance or displacement could be caused if installation or operation of a tidal energy device alters habitat to a less favorable type. In many areas, artificial habitats consisting of quarried rock, concrete rubble, oil rigs, and sunken ships can attract marine fishes (Buckley and Hueckel 1985, Love et al. 2005, Bortone 2006, Whilhemsson et al. 2006). These artificial structures placed over fine or coarse sediments mimic natural rocky habitats for thigmotatic species, thus changing one fish community to another. Other fishes may be attracted to artificial habitats if food resources become newly concentrated near or on the structure. Although the artificial reef effect may seem beneficial, artificial reefs may serve to increase mortality on fish populations, because fishers and predators may kill more concentrated individuals on artificial structures than under natural conditions, or because the physical structure may disrupt the habitat for protected or other important resident fishes. This effect was rated as a low uncertainty, but the fish species and life stages that are attracted to tidal energy devices will need to be investigated for specific installations and areas. The artificial reef effect was also noted by Wilson et al. (2007) as Fish Aggregating Devices (FADs) in their evaluation of collision risks to fishes by tidal energy devices. Wilson et al. (2007) noted that demersal fishes may not be as affected by the static effects of the device as pelagic fishes might, but both demersal and pelagic fishes may encounter and collide with rotating turbines during feeding or other excursions into the water column. Rockfishes in the Pacific Northwest and Alaska are good examples of species that are attracted to artificial structures, with three species currently listed as threatened or endangered in Puget Sound. Given their behavior and sensitivity to overfishing, they may serve as good models to investigate behavioral effects by tidal devices.

Because of the anticipated attraction or avoidance behavioral effects, the dynamic effects of tidal devices were anticipated to have medium effects on resident fishes in both pilot- and commercial-scale installations. Open and shrouded blades may have different effects and responses by resident fish.

Video observations of fish schools taken at the OpenHydro tidal energy device deployed at the European Marine Energy Centre (EMEC) found that benthopelagic fish such as pollock moved in close to the downstream side of the turbine during slow currents (<1.2 m/s) when the turbine was rotating slowly or was stationary but were not near the turbine during faster currents when the turbine was rotating at higher speeds (e.g., 20 rpm). However, because these higher rotational speeds are accompanied by stronger currents, it was not known whether the change in behavior was caused by blade movement or if it was a natural response to the tidal currents.

The body of information developed under the Roosevelt Island Tidal Energy (RITE) demonstration project showed similar results (FERC Draft License application Project 12611, November 2008). Images obtained with a concurrent DIDSON camera and split-beam transducer showed resident and migrating fish present during slack water, when the devices were not operating. The images also showed that fish were not generally present when the velocity of the water increased to greater than 0.8 m/s and the machines were operating. On one occasion, images showed fish passing by the rotating machine blades along hydrodynamic streamlines. These observations, coupled with long-term stationary split-beam transducer arrays around the six demonstration units, suggest two types of fish behavior in reaction to stationary and rotating blades and that fish are not abundant when blades are rotating, due to a combination of accelerated currents, detection, and passage around machine flow lines.

These results highlight the behavior of fish using tidal currents to make directed movements to and from basins during flooding or ebbing tides. How commercial-scale deployment of tidal generators would affect these behavior is still unknown, but Wilson et al. (2007) suggest that avoidance behavior is one of the most important variables in predicting collisions and may be influenced by body size, time of day, current speeds, season, and turbidity. A medium level of uncertainty surrounds this dynamic stressor effect.

Physical Effects on Individuals

The potential effects of tidal power generation on individual fish were considered separately from behavior. The physical effects to individuals could impair fitness and survival in terms of growth, disease, reproductive failure, injuries, and death. Although static effects on individuals were considered low in effect and uncertainty for pilot- and commercial-scale installations, dynamic effects had high potential to affect individuals for commercial-scale installations and have medium effect for pilot-scale plants. However, blade strikes, entrainment, or impingement of resident fish had medium and high uncertainty. Wilson et al. (2007) conclude that rotor speeds will be at least as powerful as the tail stuns with which killer whales stun and kill fish and that contact with rotating blades can be fatal. Wilson et al. further suggest that demersal fishes may be more resistant to blade contact but that dynamic effects could include sublethal wounds, direct mortality, stress caused by experiencing pressure waves or unusual currents, decreased growth, and reproductive failure. The scaling up of these effects to the population level has the highest priority in understanding the effect of tidal energy development to resident fish. As noted in the previous section, post-installation monitoring at EMEC (shrouded rotor, OpenHydro turbine) and at RITE (open rotor, Verdant Power turbine) have not recorded any incidences of blade strike.

The chemical effects are likely important in the case of accidental spills during the installation, removal, or, especially, the maintenance of tidal generators. Because of the low amounts of lubricants used in tidal generators, these were not anticipated to have significant impacts. However, the chemicals used to abate settlement of invertebrates (e.g., anti-fouling paints) had an unknown level of effect. The installation of a pilot plant was not anticipated to have great risk to oil spills or chronic leaching of toxic substances, but these potential effects increased with commercial installations to a medium effect with medium uncertainty. Oil spills due to accidents or collisions in high-traffic areas have been documented to directly kill fish or contaminate them. Petroleum products have been shown to cause higher risk of cancers and reproductive impairment in resident fishes (U.S. EPA 1999).

The other stressor effects on individuals, including acoustic, EMFs, and energy removal, were considered to be of low effect and mostly low uncertainty for pilot installations. Acoustic production by tidal energy devices was not considered to have a significant physical effect on individual fish in either pilot- or commercial-scale installations. EMFs had potentially a medium effect in commercial-scale installations but, as with behavioral effects, the uncertainty was high because EMFs could have an important role on suitability of the surrounding habitat for resident fishes. The potential for energy removal to physically affect individuals was unknown, with high uncertainty at the commercial scale. This is anticipated to be a far-field effect where waters downstream of the facility may suffer from poor water quality due to decreased tidal energy flushing the basin. Fish can suffer less growth, reproductive failure, and death from hypoxia and high water temperatures (Diaz 2001, Palsson et al. 2008). Because of the potential for synergistic interactions, the cumulative stressor effects had high potential to affect individual resident fish, but the nature of these interactions had high uncertainty.

Population

Behavioral and physical impacts to individuals may accumulate and interact among stressors to affect populations. Although diffuse behavioral effects or physical impacts on a few individuals may not impact populations, if populations are small, any loss or behavioral shift may greatly affect population stability. If populations are large, greater effects may still impact population health or compete with ecosystem services provided by the population to predators and humans who harvest or depend upon species in other manners. Because of this, stressor effects on the populations were considered the most important element among behavioral, individual, and community elements for resident fish.

Almost all population-level effects were considered to be low for pilot-scale installations of tidal energy devices. However, the uncertainty was variable, ranging from low for energy removal and cumulative effects to medium for acoustic, chemical, and static stressors and high for dynamic and EMF effects. For EMFs, the potential effects were unknown both for pilot- and commercial-scale installations. Of all potential tidal energy effects, the dynamic stressor effects from tidal generators had the highest potential to affect populations. Amplifying the effects and uncertainties involving physical effects on individuals, the cumulative impacts of strikes, entrainment, and impingement may negatively affect resident fish populations. Whether and to what extent dynamic effects can cause reproductive failure or mortality on a population basis has high uncertainty. Static, chemical, and acoustic stressors have a medium potential to impact resident fish populations as a result of commercial installations, but the uncertainty ranges from medium to high, based on the lack of knowledge from behavioral and physical effects on individuals. Energy removal has an unknown effect on populations with high uncertainty. Using Admiralty Inlet, as an example, a large field of tidal energy devices could remove enough tidal energy to reduce the flushing of Hood Canal and other Puget Sound basins. During the past 10 years, fish kills, behavioral shifts, and other sub-lethal impacts to hypoxia have been documented in Hood Canal (Palsson et al. 2008). Decreasing flushing of this basin could increase the frequency of fish kills that already have removed 1/4 to 1/3 of the rockfish and lingcod populations at one prominent Hood Canal locality (Palsson et al. 2008). The cumulative stressor effects of commercial installations were rated as medium-high, in part because of the energy removal effects but also on the potential for stressor interactions acting to suppress fish populations. The "artificial reef effect" from the static stressor described previously could cause resident fish to be continually attracted to tidal generators but continually removed from the population by mortality or injury from rotating turbine blades. This cumulative stressor has a high level of uncertainty.

Community

Community-level impacts were not fully considered but, at a minimum, were rated the same as population-level impacts. The same issues for population-level impacts were anticipated to affect communities in terms of altering species composition, including measures of species richness, diversity, and evenness. Of note, however: static effects were likely to greatly alter the community structure from fishes that would normally occupy coarse sediments found in dynamic tidal habitats to fishes that occupy rocky habitats with greater structural relief. Community-level effects could also be anticipated from tidal energy removal. Using the same model of potential far-field effects in Hood Canal, increased hypoxic events resulting from less flushing due to tidal energy removal could have community-level impacts affecting the species composition of rocky and unconsolidated habitats, as described by Palsson et al. (2008).

Gaps in Understanding

The greatest information gaps for dynamic and energy removal stressors are discussed in more detail in the following sections. Other significant data gaps are how to understand the cumulative and interactive impacts of the stressors to populations and biological communities and how acoustic and EMF stressors may affect fish behavior and fitness. A combination of laboratory experiments, modeling, and field experiments is the suggested approach to reducing the identified levels of uncertainty. Laboratory experiments examining behavior of fish to acoustic and EMF stressors could provide the basic inputs to a model that predicts fish responses to these stressors at a given site. Field experiments would then be used to monitor and test model hypotheses. In the case of EMF, acoustic telemetry could be used to examine if shark behaviors are affected by existing underwater transmission lines, and measurement of magnetic and electrical fields at existing transmission cables could determine whether EMFs are produced that are detectable (from ambient conditions). Stress and sub-lethal effects may occur but are poorly understood; therefore, biomarkers (such as stress hormones taken from blood samples) could be used to assess the effects of barotrauma, acoustic stimulation, and EMFs. Laboratory studies would first be needed to determine the dose-response curve. One other data gap is scaling up experimental findings from pilot-scale observations to commercial installations, because when turbines are grouped, the probability of physical interaction between the device and fishes increases, but the increases may not be linear.

Approaches to Monitoring

The installation of pilot- and commercial-scale tidal generators would require a significant monitoring effort to assure that experimental and modeling results are valid in pilot- and commercial-scale installations and that unforeseen responses or conditions are identified for subsequent adaptive management. The BACI approach was identified as a desired approach (Smith 2002). Monitoring data at the different scales before generator deployment would be preferred. Subsequent to deployment, long-term monitoring may be required to determine population-level impacts. Locating a suitable control site is often difficult in high-current areas because fine-scale differences in habitats or current patterns may not match the sites where tidal energy devices are deployed. For example, the BACI approach was ineffective at detecting changes at the RITE demonstration project. Although pre- and post-installation monitoring was attempted at RITE from 2005-2009, the dynamic nature of site did not allow for appropriate before-and-after observations, as in a river/dam environment (Verdant Power 2008, Colby and Adonizio 2009). However, control sites do have the potential to provide the basis to observe large-scale changes that may not be due to tidal device deployment. Cooperative monitoring among different management authorities may provide synergies to offset some of the monitoring effort. For example, fishery agencies may be conducting population surveys of fishes and provide the perspective to evaluate population impacts.

A host of monitoring tools is available, but some may have limited effectiveness due to the high currents in the area or the operation of the blades and turbines. These tools include Acoustic Doppler Current Profilers (ADCPs), water quality meters, remotely-operated vehicles (ROVs), scientific echosounders, mid-water and plankton nets, advanced acoustic or visual plankton samplers, three-dimensional acoustic arrays, and acoustic telemetry systems. These devices could be deployed at the sites to measure avoidance and attraction, direct injuries or mortalities, alteration in current patterns, and abundance, or these devices may need to be placed or used outside the tidal operation areas to detect far-field effects. A key challenge will be deploying these tools during periods of turbine operation, when currents exceed 2 m/s.

4.5.4 Priority Area: *Population and individual level effects due to the dynamic stressor*

Description

Dynamic effects of device operation, especially rotor strikes, impingement, and entrainment of commercial installations have the highest potential to negatively affect individuals and enough individuals to impair population stability.

Gaps in Understanding

The effects of physical strikes are poorly understood but have the highest population impacts in a commercial build-out. Although there was consensus among workgroup participants on the uncertainty, there was no agreement on the extent of knowledge or potential effects. Impacts to protected species could occur in both pilot- and commercial-scale installations. The greatest data gap is the frequency and extent of individual strikes, entrainment, and impingement on species expected in a project area. Technology does exist to evaluate species vulnerability first by quantifying expected startle thresholds, reaction distances, avoidance behavior, and swimming speeds from literature studies or laboratory studies. These data can be used to develop models of fish behavior, as suggested by Wilson et al. (2007), to predict collision rate as a function of encounter, avoidance, and evasion rates. These models need to be validated in the field using acoustic tags and acoustic receiver arrays to track three-dimensional fish movement, behavior, and collisions during pilot operations. However, the tagging intensity and receiver density required to carry out such studies may entail a high cost for the relevant spatial scales. Field data should be used to validate models of effects to individuals that can be subsequently used in demographic and viability models to evaluate population level effects. A data gap still exists on how tidal energy devices may affect eggs, larvae, and juveniles. These early life stages will need to be investigated in the laboratory or, potentially, with conventional plankton nets, high frequency sonar, or other technologies, although conducting these evaluations in the field will be extremely difficult.

Approaches to Monitoring

As stated above, acoustic telemetry and acoustic arrays provide several methods to monitor individual specimens. However, population-level surveys using ROVs and conventional fish surveys, such as trawl surveys or demographic population models, may be required to evaluate population-level effects. Cooperative monitoring efforts will likely produce more comprehensive results.

4.5.5 Priority Area:
Far-field effects of energy removal at the population level

Description

Commercial installations may remove enough tidal energy to further decrease circulation in poorly flushed basins. Less tidal energy may increase the extent and frequency of poor water quality events such as hypoxia, high temperatures, and excessive nutrients.

Gaps in Understanding

The uncertainty level is high, with most scientists agreeing that energy removal may diminish flushing in receiving water bodies. For example, population impacts due to hypoxia have been well documented in Hood Canal, so operation of a commercial array of tidal generators in Admiralty Inlet could influence the frequency of fish kills. A comprehensive oceanographic model that predicts the circulation patterns, flushing rates, and water quality could be used to predict the influence of removing tidal energy in project areas. However, the effectiveness of such models to accurately predict the effect of perturbations may be limited (see Physical Environment: Far-field, Section 4.2). Pilot plants could be used to verify some model inputs and model results. However, some of the predictions may not be validated until a full-scale commercial project is installed.

Approaches to Monitoring

A comprehensive system of remote oceanographic sensors would be needed to monitor for changes in current profiles, flushing rates, and other oceanographic properties. If changes are found, then further ecological monitoring would be required to detect population-level impacts. This would be a very costly stand-alone effort and would need to leverage existing monitoring activities to be viable (Additional discussion of this topic is presented in Section 3.6, Energy Removal.

4.5.6 Recommended References

Bortone, S.A. 2006. A perspective of artificial reef research: the past, present and future. *Bulletin of Marine Science*, 78(1): 1-8.

Buckley, R.M. and G.J. Hueckel. 1985. Biological processes and ecological development on an artificial reef in Puget Sound, Washington. *Bulletin of Marine Science*, 37: 50-69.

Colby, J. and Adonizio, M. 2009. Hydrodynamic analysis of kinetic hydropower arrays. *Waterpower XVI*, Spokane, WA. July 27-30, 2009.

Diaz, J. 2001. Overview of hypoxia around the world. *Journal of Environmental Quality*, 30: 275-281.

EPA (U.S. Environmental Protection Agency). 1999. Wildlife and Oil Spills. *In Understanding Oil Spills and Spill Response*. Office of Emergency and Remedial Response. EPA 540-K-99-007: 21-26. Available at *http://www.epa.gov/oem/content/learning/pdfbook.htm.*

Hellinger, J. and Hoffmann, K.P. 2009. Magnetic field perception in the Rainbow Trout, (Oncorhynchus mykiss). *Journal of Comparative Physiology A-Neuroethology Sensory Neural and Behavioral Physiology*, 195(9): 873-879.

Kajiura S.M. and K.N. Holland. 2002. Electroreception in juvenile scalloped hammerhead and sandbar sharks. *Journal of Experimental Biology*, 205(23): 3609-3621.

Kalmijn, A.J. 1982. Electric and magnetic-field detection in elasmobranch fishes. *Science*, 218(4575): 916-918.

Lohmann, K.J. and Johnsen, S. 2000. The neurobiology of magnetoreception in vertebrate animals. *Trends in Neurosciences,* 23(4): 153-159.

Love, M.S., Schroeder, D.M. and Lenarz, W.H. 2005. Distribution of bocaccio (Sebastes paucispinis) and cow cod (Sebastes levis) around oil platforms and natural outcrops off California with implications for larval production. *Bulletin of Marine Science*, 77: 397-408.

McGowan, D.W. and Kajiura, S.M. 2009. Electroreception in the euryhaline stingray, (Dasyatis Sabina). *Journal of Experimental Biology*, 212(10): 1544-1552.

Montgomery, J.C. and Walker, M.M. 2001. Orientation and navigation in elasmobranchs: Which way forward? *Environmental Biology of Fishes*, 60(1-3): 109-116.

Öhman, M.C., Sigray, P. and Westerberg, H. 2007. *Offshore Windmills and the Effects of Electromagnetic Fields on Fish. Ambio* 36(8): 630-633.

Palsson, W.A., Pacunski, R.E., Parra, T.R. and Beam, J. 2008. The effects of hypoxia on marine fish populations in southern Hood Canal, Washington. *In Mitigating Impacts of Natural Hazards on Fishery Ecosystems*. McLaughlin, K. (Ed.). American Fisheries Society Symposium Series 64: 255-280.

Smith, E.P. 2002. BACI design. *In Encyclopedia of Environmetrics*, Volume 1 (Shaarawi, A. and Piegorsch, W. (Eds.). Chichester, UK: John Wiley and Sons, Ltd. 141-148.

Verdant Power. Roosevelt Island Tidal Energy Pilot License Application, FERC No. 12611. Filed December 2010. Volumes 1-4 available at *http://www.theriteproject.com/Documents.html*.

Wilhelmsson D., Malm, T. and Ohman, M.C. 2006. The influence of offshore windpower on demersal fish. ICES *Journal of Marine Science*, 63: 775-784.

Wilson, B., Batty, R.S., Daunt, F. and Carter, C. 2007. *Collision risks between marine renewable energy devices and mammals, fish and diving birds.* Report to the Scottish Executive. Scottish Association for Marine Science. Oban, Scotland, PA37 1QA.

4.6 Marine Mammals and Seabirds

Name	Affiliation
Markus Horning (Chair)	Oregon State University
Alison Agness	NOAA Fisheries – Northwest Regional Office, Protected Resources Division
Brad Hanson	NOAA Fisheries – Northwest Fisheries Science Center
Bruce Mate	Oregon State University
David Ainsworth	Marine Current Turbines Ltd.
Dominic Tollit	Sea Mammal Research Unit, Ltd.
Gayle Zydlewski	University of Maine
Joanna Smith	The Nature Conservancy
Joe Breen	Northern Ireland Environment Agency
Julia Parrish	University of Washington
Kate Savage	NOAA Fisheries - Alaska Regional Office, Protected Resources Division
Monty Worthington	Ocean Renewable Power Company
Ilon Logan (Note Taker)	University of Washington

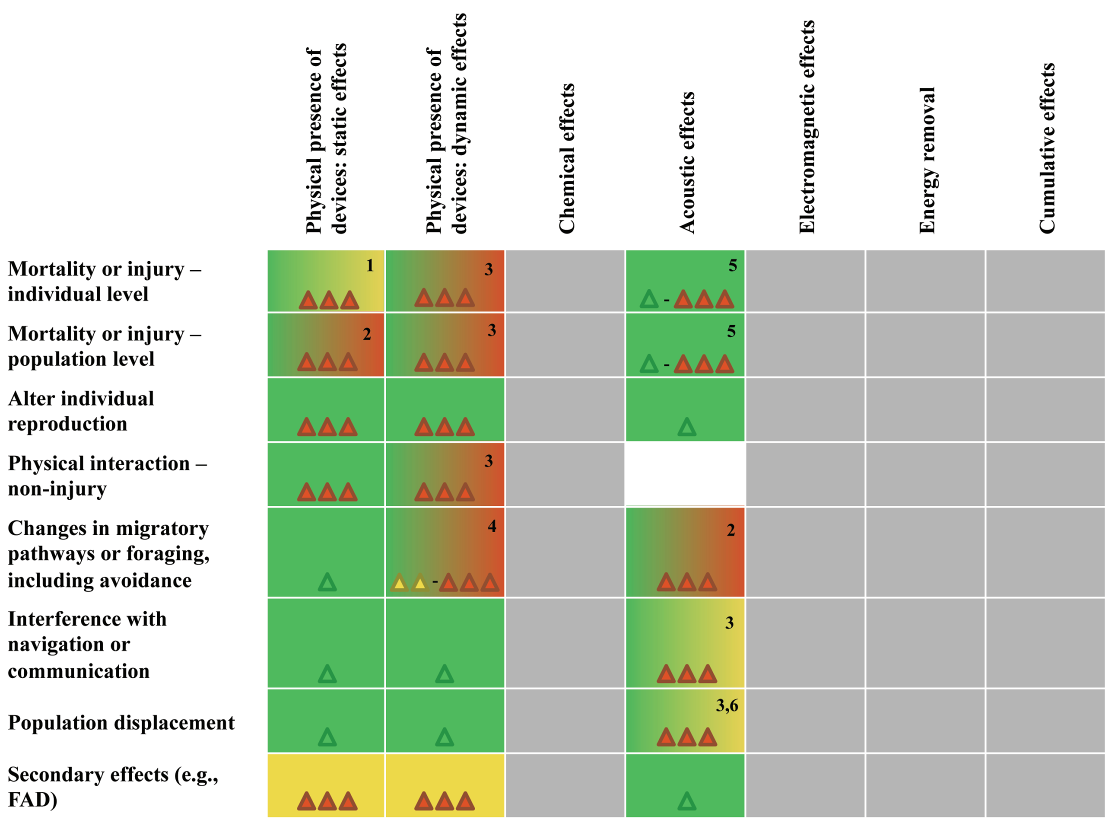
4.6.1 Introduction

There is minimal information presently available on the potential impact of tidal energy systems on marine mammals and seabirds. Substantial knowledge gaps remain on baseline natural history and habitat use for most of the potentially affected species, for specific sites, and at relevant spatial and temporal resolution. Such data are critical to predicting risk and type of interaction with tidal energy devices. Critical knowledge gaps extend to behavioral ecology and on how most species sense, perceive, and react to the environment and elements therein, potentially including tidal energy devices. Such information is also essential for the characterization of possible behavioral responses to operating devices. Acoustic effects are of particular concern within the context of behavioral ecology (how animals sense and respond to elements in their environment), and knowledge gaps extend to the lack of data on acoustic signatures of operating devices (at least, in terms of information available within the public domain) as well as the characterization of background/ambient noise levels at specific sites. These knowledge gaps are exacerbated by a lack of standards for assessing ambient sound levels and the acoustic signatures of operating devices during periods of high current velocities (an explanation of this is contained in Bassett 2010).

Of the range of potential stressors considered, physical strike (in relation to both static and dynamic presence of tidal energy devices) and acoustic effects were considered of highest concern (noise from device installation was identified as a specific issue of concern). Both stressors are associated with high levels of risk and effect uncertainty. On the whole, risk levels were deemed low in terms of likely population-level impacts. However, the group recognized that critically small and/or sensitive populations exist in some areas where real or publicly perceived impacts on single individuals may result in drastic regulatory consequences. Impacts for commercial-level installations are likely larger than for pilot installations and related to the extent and spatial arrangement of the installation. However, scaling of impacts is not necessarily directly linked to the scope of installations. Regarding individual animals, the most likely affected receptor elements associated with nonoperational physical presence (i.e., collision) includes possible consequences ranging from minor injury to mortality. The most likely affected receptor elements for dynamic operation of devices include all levels of physical injury already associated with static presence, as well as possible impacts on foraging and migratory behaviors or population displacement. Most likely affected receptor elements associated with acoustic effects include local habitat use and foraging behavior, as well as migratory pathways. Insufficient time was available to evaluate other stressors.

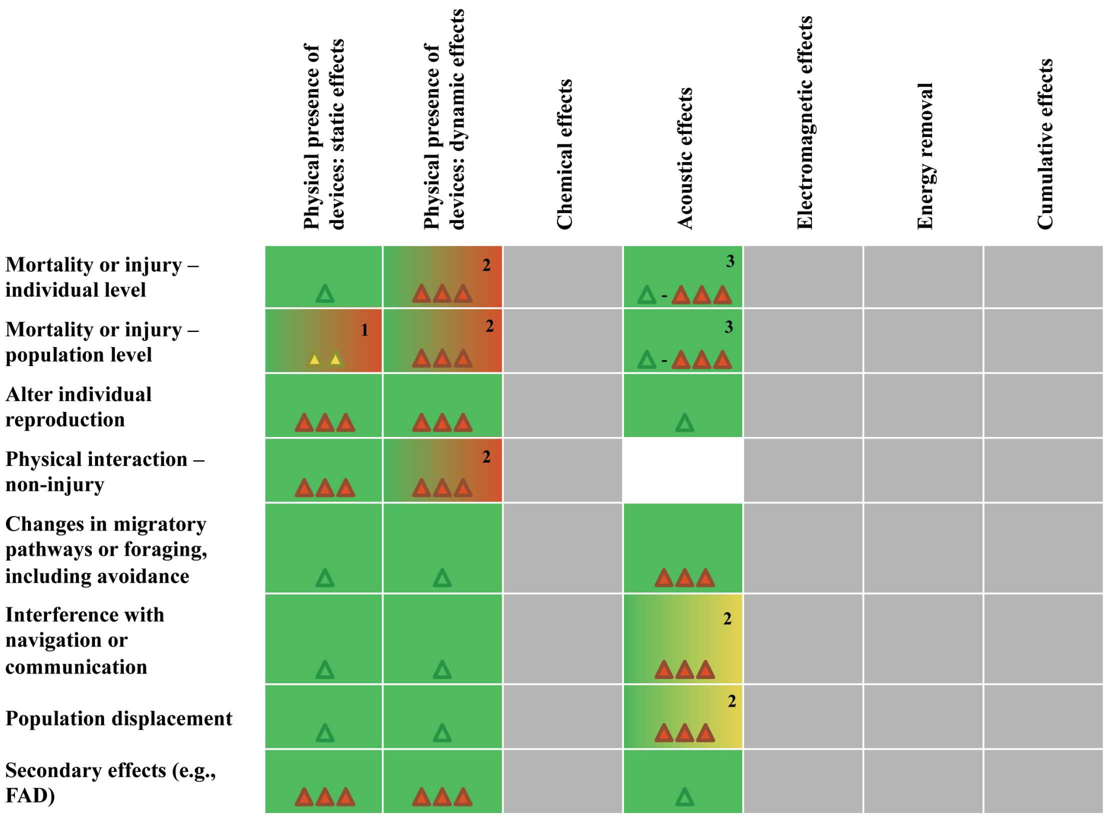
The significance and uncertainty associated with stressor/receptor interactions are summarized in Figure 35 for pilot-scale deployments and in Figure 36 for commercial-scale deployments. The colors denote significance and triangles denote uncertainty, as defined in Figure 24.

4.6.2 Receptor Matrix



1 – Specific to large whales and cables and derelict gear, and population consequences specific to specific status
2 – High significance and medium uncertainty applies to small and sensitive populations only
3 – Species, device, location, and population consequence specific to species status
4 – Species, device, location, and tide specific for foraging effects
5 – Depends on device and if acoustic data has been collected
6 – High concern for harbor porpoise

Figure 35 – Receptor matrix: Marine mammals and seabirds – pilot-scale deployment



1 – High significance and medium uncertainty applies to small and sensitive populations only
2 – Species, device, location, and population consequence specific to species status
3 – Depends on device and if acoustic data has been collected

Figure 36 – Receptor matrix: Marine mammals and seabirds – commercial-scale deployment

4.6.3 Discussion

Many of the considerations raised and discussed in this group are specific to tidal energy device installation sites, technology, and the natural history of the resident or migratory species potentially affected by installation, presence, or operation of tidal energy devices. It was noted that, while impacts or effects may exist, these are not always negative. For example, migratory routes may be affected by tidal energy devices resulting in altered pathways without any detectable or implicit effect on individual animal energetics, survival, or reproductive success. Generally, commercial-scale impacts and concerns are likely larger and higher than for pilot-scale installations and may be related to installation scope (extent and spatial arrangement), although impacts cannot necessarily be directly scaled to project size (e.g., installed generating capacity).

Physical presence (static and dynamic) and, specifically, physical strike, and acoustic effects were identified as environmental issues of top priority. Physical presence, excluding strike, may result in altered migratory pathways or in population displacement, including blocking effects at locations of constricted topography that may occur outside of migratory pathways. These effects could alter the use of an area or the use of resources within an area.

The species in this receptor group are very heterogeneous in natural history and habitat use. Not all technologies/designs have the potential to affect seabirds, with designs protruding above water level more likely to result in effects on seabird. Subsurface devices are commonly located at depths where interactions with birds are unlikely. All technologies may potentially affect marine mammals.

4.6.4 Priority Area: Physical presence

Description

The primary consideration for the physical presence of tidal energy devices is strike, through either static presence or dynamics of operating devices. The consequences of strike range from non-injury contact to minor or even fatal injuries. Indirect effects are possible, including mortality resulting from entrapment/entanglement and drowning. Secondary effects of physical presence were discussed, including potential function of tidal energy devices as prey aggregation or debris aggregation devices. Prey aggregation was deemed less likely due to high currents at installation locations (although fish aggregations have been observed in the wake of a test turbine at the EMEC during currents less than 1.2 m/s). Debris aggregation could occur (in part, due to high currents) and may have impacts on marine mammals and seabirds. Dynamic presence may also affect local habitat use and foraging behavior (i.e., through altered currents/upwellings and prey fields) and may result in area avoidance with possible impacts on migratory behavior and pathways, as well as increased energy demands associated with behavioral changes.

Gaps in Understanding

Workgroup participants agreed that likelihood and potential impacts of effects from static or dynamic presence are associated with high levels of uncertainty in general and also in relation to different technologies (i.e., shrouded versus open turbine designs). This uncertainty is directly related to the paucity of information on how most of the potential target organisms perceive the environment at relevant scales, how they might detect and respond to a tidal energy device, and what options animals might have to avoid a tidal energy device. Data scarcity specifically includes variation in behavioral ecology and habitat use with respect to locations, seasons, and age and sex of potentially affected organisms.

Participants also noted and discussed the difference between likely or actual impact versus perceived impact of tidal energy devices, especially in terms of public opinion. Even the perception of lethal impact on marine mammals, in particular, may result in extreme regulatory constraints on device operation.

Key knowledge gaps identified by the group include sufficiently detailed information on the basic natural history and habitat use for most of the potentially affected species, at the relevant temporal and spatial scales. For example, in some areas, local population sizes, vital rates, and demographics are not sufficiently well described to populate a risk matrix. Although migratory pathways are known for some species, this information is often available at larger temporal and spatial scales than required for assessments of the risk of adverse modifications in relation to tidal energy devices, particular at the pilot scale. Other examples include lack of information on area-specific habitat use, including area-specific prey selection, again at relevant spatial and temporal scales. This (required) information is likely specific to species, sites, and seasons. Such information is essential for the development of risk models and also as baseline data for the monitoring of potential impacts.

Key knowledge gaps also exist on how animals perceive elements of their environment, including how they might sense an operating tidal energy device. Sensory capabilities and sensory pathways are not well described for many species. Consequently, predictions of behavioral responses, energetic consequences, and risk assessments are impossible to provide.

Approaches to Monitoring

Rather than presenting specific monitoring techniques or specific experimental designs, the group decided to highlight conceptual approaches and elements. In addition, the group recognized the importance of developing a comprehensive research and monitoring plan that should be based on a broad consensus amongst technology companies, researchers, agencies, non-government organizations, and other involved parties, and should involve local stakeholders as much and as early as possible and practical.

The group briefly discussed the possibility of an adaptive research approach based on first monitoring for and identifying ultimate effects (i.e., population-level impacts, changes in vital rates) and progressively moving towards more proximate assessments of effects and, possibly, mechanisms for any species potentially affected. However, this approach was deemed impractical due to empirical difficulties and also due to the low likelihood of finding (or modeling) population level effects exceeding natural variability, in particular for pilot-scale deployments.

An alternate approach was proposed, based on assessments that move from possible proximate effects and mechanisms (i.e., individual animal behavioral responses or energetics effects) to more ultimate effects. In order to effectively allocate limited resources, this approach might be more fruitful if possibly affected species are ranked in order of concern or likelihood of impact.

The group recognized that physical strikes as one of the highlighted areas of concern may represent rare events, which may require a significant amount of resources for detection/quantification. This potential tradeoff between cost and knowledge gained needs to be considered within the comprehensive, consensus-based plan, and while weighing potential population-level impacts — particularly for critically small or sensitive populations. Within this context, the empirical distinction between hypothetical strike-related mortalities (proximate cause) and population displacement (a hypothetical ultimate effect, dependent on monitoring approaches utilized) may be very important. Research and monitoring approaches can build on existing and well-proven technologies and experimental designs, while considering or expanding the use of novel techniques, where appropriate. Details of the marine mammal monitoring and mitigation effort undertaken by Marine Current Turbines Ltd. are described in Section 1.6.3 of this report.

Either type of approach should be tailored to the needs (including resolution) of the issue at hand, with comprehensive project and research plans updated as results are obtained. All data and results should be made available in the public domain.

Although potential effects of tidal energy devices on marine mammals and seabirds are likely specific to sites and seasons, monitoring should not be restricted to locations and seasons of operation but should extend to larger spatial and temporal scales for the purpose of comparability and for the integration of effects that may transcend more directly affected areas. For example, ultimate effects of the proximally created impacts of tidal energy devices may only become apparent at distant sites of reproduction. Furthermore, any assumed alterations of population trajectories have to be viewed within the context of non-anthropogenic variance, cycles, and trends. There are, however, two challenges to such studies for marine mammals and seabirds whose life stages involve large spatial scales. First, study methodology would need to discriminate between ultimate effects from tidal energy devices and other proximate anthropogenic stressors in order to test specific hypotheses (Further discussion is contained in Section 3.7.6, Cumulative Effects). Second, the cost of life-cycle monitoring could be very high and, as with the question of blade strike, the tradeoff between the knowledge likely to be gained and study cost must be considered. However, without studies to establish the linkage between proximate stressors and ultimate effects, regulatory agencies may be required to take the precautionary approach of limiting exposure of some populations to proximate stressors.

4.6.5 Priority Area: Acoustic effects

Description

Acoustic effects may result in altered area use and foraging behavior, potential impact on migratory pathways, and population displacement, as well as interference with navigation and communication. Population displacement was considered as a distinct issue from migratory behavior, in part because of the possibility of distinct mitigation measures (i.e., in relation to timing of migration). In both (hypothetical) instances, individuals may avoid areas with operating tidal energy devices, but impacts may affect distinct life-history stages or portions of annual life cycle, and may or may not include critical habitat for protected species. Noise related to device installation is of particular concern, because higher sound pressure levels and impulse-type sound are more likely, and the potential for injurious sound pressure levels are much higher, than during continued operations. Thus, the potential impact during installation may be high, although this would be of shorter duration than for the continued operation of a tidal energy device. However, more mitigation opportunities with respect to installation noise effects may exist (as discussed in Section 3.4.4).

Gaps in Understanding

The group noted a nearly complete lack of information/data on noise signatures of tidal energy devices in the public domain (see Section 3.4, Acoustic Effects). This contributes to the high levels of uncertainty associated with assessment of risks and potential impacts of acoustic effects. Marine mammals are much more likely to be affected by noise from tidal energy devices than are seabirds. Noise is not considered a problem for seabirds — even if they can perceive it, they are known to habituate to noise. Conversely, the receptor elements considered problematic for marine mammals are driven by issues that may not be resolved through habituation (i.e., masking of acoustic communication and navigation functions). Species relying on sonar for orientation, navigation and feeding, or underwater acoustic communication were considered by the group to be more likely to be affected by tidal energy devices.

Virtually no information exists on the behavioral response of species of concern to acoustic signals, in relation to intensity, type, frequency, etc. This is, in part, due to regulations on marine mammal research. When coupled with the absence of data (in public domain) on noise types and levels generated by tidal energy devices and on ambient and background noise levels, predictions of behavioral responses, energetic consequences and risk assessments are impossible to provide.

Approaches to Monitoring

In addition to the general monitoring discussion in the previous section, a few select specific approaches, experimental designs, or techniques were mentioned or briefly discussed. Acoustic controlled exposure experiments were specifically recommended to establish biologically relevant exposure levels, as well as behavioral response parameters and thresholds. It was noted that the National Marine Fisheries Service exposure thresholds for behavioral disturbance from continuous noise (120 dB RMS) are based solely on studies of large whales and limited observations. Thus, these thresholds are not very robust. There is a need to standardize exposure criteria and thresholds (Southall et al. 2007). The use of both moored active sonar for near-field monitoring, and passive acoustic listening were techniques mentioned as having potential, as was high resolution behavioral telemetry. However, the primary bands or side bands for active sonars used to make these observations may be audible to marine mammals and result in confounding avoidance behavior, and the engineering required to design moorings for high current environments is non-trivial.

4.6.6 Recommended References

Southall, B.L., Bowles, A.E, Ellison, W.T., Finneran, J.J., Gentry, R.L., Greene, C.R., Kastak, D., Ketten, D.R., Miller, J.H., Nachtigall, P.E., Richardson, W.J., Thomas, A. and Tyack, P.L. 2007. Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. *Aquatic Mammals*, 33(4): 411-521.

Wilson, B., Batty, R.S., Daunt, F. and Carter, C. 2007. *Collision risks between marine renewable energy devices and mammals, fish and diving birds.* Report to the Scottish Executive. Scottish Association for Marine Science. Oban, Scotland, PA37 1QA.

4.7 Ecosystem Interactions

Name	Affiliation
Greg McMurray (Chair)	Pacific Energy Ventures
Alicia Bishop	NOAA Fisheries, Northwest Regional Office, Hydropower Division
Ginny Eckert	University of Alaska - Fairbanks
Ian Boyd	Sea Mammal Research Unit, University of St. Andrews
Jenny Norris	European Marine Energy Center
Paul Jacobson	Electric Power Research Institute
Scott Redman	Puget Sound Partnership
Sue Saupe	Cook Inlet Regional Citizens Advisory Committee
Sue Barr	OpenHydro
Ellie Humphries (Note Taker)	University of Washington

4.7.1 Introduction

For this work group session, participants attempted to integrate the possible environmental effects of tidal energy development across the receptor groupings, whereas, the cumulative effects session was intended to integrate across the stressor groupings. Accordingly, the discussion in this session largely addressed processes amongst the receptors, focusing largely, but not solely, on food web interactions and trophic dynamics. The breakout group was geographically diverse, with experience in or knowledge about high-energy tidal systems in Puget Sound, Alaska and the United Kingdom. All of the session participants were active in the wide-ranging discussions.

The significance and uncertainty associated with stressor/receptor interactions are summarized in Figure 37 for pilot-scale deployments and in Figure 38 for commercial-scale deployments. The colors denote significance and triangles denote uncertainty, as defined in Figure 24.

4.7.2 Receptor Matrix

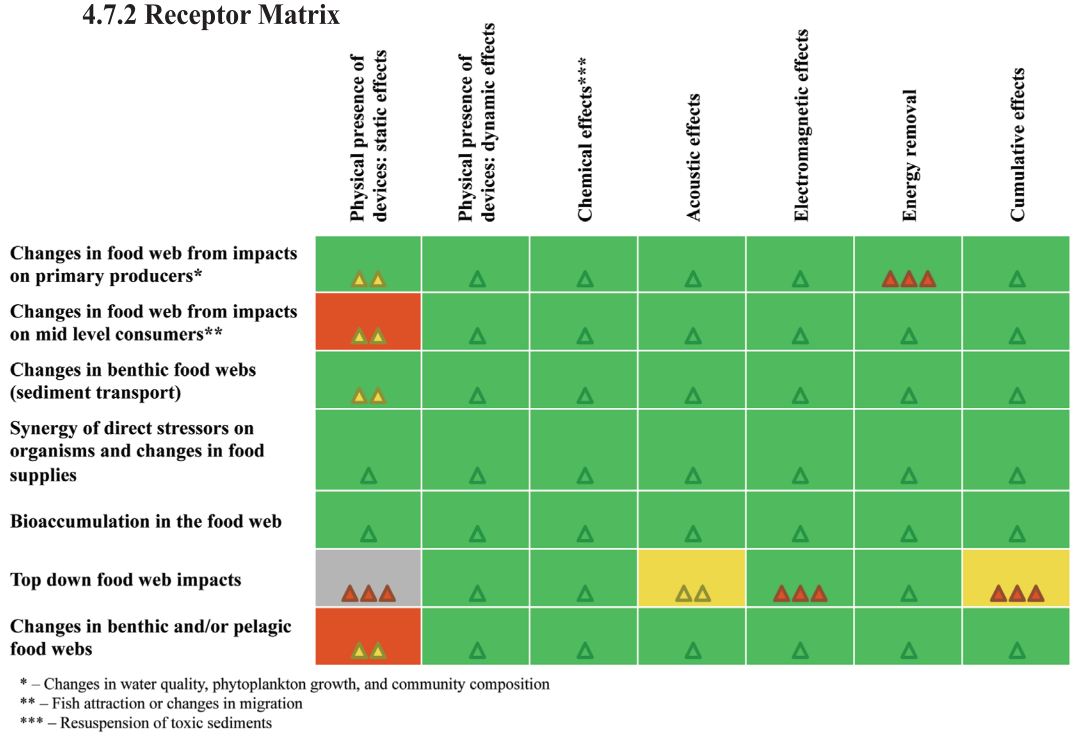


Figure 37 – Receptor matrix: Ecosystem interactions – pilot-scale deployments

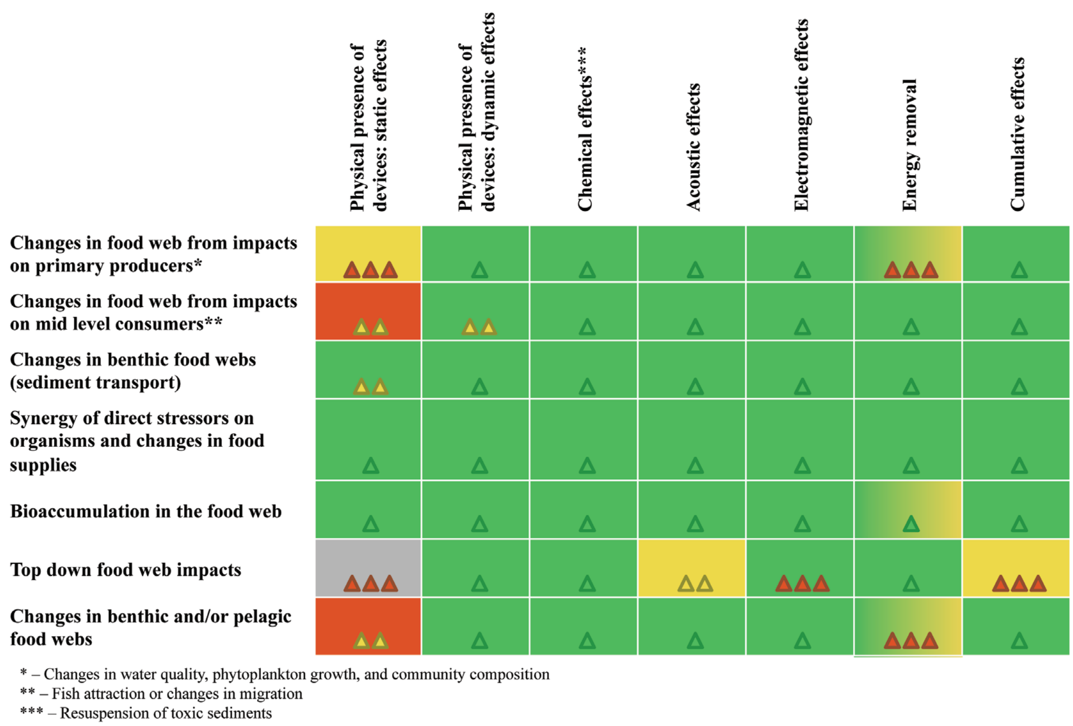


Figure 38 – Receptor matrix: Ecosystem interactions – commercial-scale deployment

4.7.3 Discussion

Because of the complexity of these systems, generalizations have limited value, and site-specific measurements are essential to understanding the possible or probable effects in any given system with a given technology and magnitude of development. In this context, pilot-scale projects and site-specific baseline and monitoring programs are considered very important. These systems are so turbulent that the conceptual approaches of water column stratification and stability, critical depth, and pelagic-benthic decoupling seem largely inapplicable at potential project sites, although these conceptual approaches may be key to understanding any far-field ecosystem interactions related to energy removal.

It is important to consider that there can be positive effects as well as negative ones. With changes brought about in ecosystem interactions, there are likely to be "winners" and "losers" in the species affected. These changes will be appropriately judged in the context of the overall integrity of the ecosystem, the specific management goals established for the ecosystem, and consideration of species or populations known to be at risk.

The relative spatial scales of tidal energy conversion operations (local) versus the spatial scales of the ecosystem (e.g., regional scale) were judged by the participants as likely to prevent significant system scale effects (i.e., environmental impacts) through ecosystem interactions, per se. There was no readily apparent nexus or pathway (at the level of a fatal flaw) between the envisioned stressors and the food web and trophic dynamics, as understood at a general level. However, given projects of sufficiently large size or number, ecologically significant effects would likely occur.

Uncertainty was generally moderate to high for effects seen as highly likely to have a substantial impact and generally low for effects seen as unlikely to have a substantial impact. That is, the group had much more confidence in its ability to rate effects as unlikely or low significance, as opposed to measurable and ecologically significant effects.

Trophic-dynamic ecosystem effects were viewed as being highly likely at local scales (even with a pilot project) and, perhaps, regional scales (with a commercial build-out), driven by attraction of predators and, possibly, by changes in the distribution and abundance of prey (especially forage fish) in both the pelagic and benthic habitats. This does not, however, mean that these effects will necessarily constitute significant deleterious impacts (see prior discussion of spatial scales). Although there was only moderate uncertainty about the high likelihood of trophic changes overall, there was high uncertainty about the likelihood of true top-down trophic changes (i.e., driven by changes in predation at the higher trophic levels). These latter effects were seen as equally likely for pilot- versus commercial-scale build-outs, but with expression at much broader spatial scales with a single or multiple commercial build-outs.

Energy removal was seen as having a low to moderate likelihood of mediating effects at the ecosystem scale with very large commercial build-outs, although the proportional amount of energy withdrawn from the system is probably quite low as predicted by initial efforts at modeling. These effects would be expressed in hydrology/hydrography and water chemistry in dead-ended systems (i.e., in estuaries and fjords but not in open-ended straits or passes between islands in archipelagos), where mixing at the landward end is largely dependent of the amount of tidal energy supplied. For example, deep-water replacement in inner basins, which is often density driven and episodic, could be reduced and exacerbate or result in hypoxic or anoxic conditions.

There was agreement that bioaccumulation could be of concern. However, it was viewed as highly unlikely that any project activity (e.g., transmission cable trenching and burying) would be allowed to take place in highly polluted sediments without strict mitigation measures. The group did not consider the accumulation of metals (e.g., copper or zinc) in the sediment from antifouling coatings because the highly energetic environment would largely prevent its sedimentation in the near field. There is a sense that antifouling coatings will not be maintainable in the near-benthic portion of the water column, as saltating particles will effectively "sandblast" the structures (discussed in Section 3.3, Chemical Effects,). However, this process would likely remove settling or newly settled propagules from the near-bottom-fouling community as well.

Pilot projects were generally viewed as not likely to have significant effects on ecosystem interactions. However, as shown in the Receptor Matrix, food web changes may be measureable at the pilot scale and, hence, important to measure and document before continuing to the commercial scale. Environmental studies need to focus on very explicit questions about the potential effects and support addressing management issues within the adaptive management realm.

Project construction and decommissioning will likely cause local and transient effects but were not judged likely to have a measureable effect on ecosystem interactions. Accidents — for example spills during servicing — were, likewise, seen as local and temporary. Thus, the group focused its attention on the longer-term operational effects.

4.7.4 Priority Area: *Top-down ecosystem effects*

Description

Top-down effects are a high priority, because a combination of stressors may cause significant changes in trophic structure and energy flow (in a food web context) by altering the relative abundance and distribution of predators and the availability of appropriate prey, especially forage fishes. It is plausible that the additive effect of small to moderate changes in each of the species involved could add up to a significant integrated effect, as expressed in trophic dynamics. The specific stressors would likely include fish attraction and artificial reef effects and, possibly, changes in benthic sediment in the far field, and strike effects on certain groups of organisms such as forage fish.

The level of uncertainty is moderate to high, and agreement among the group was relatively high.

Gaps in Understanding

The basic information gap in this area is the lack of detailed information on food web structure and energy flow for tidal systems suitable for hydrokinetic generation. Participants with field experience in these high-energy systems pointed out the difficulty in simply determining presence and absence of most species with traditional sampling methods. Even "slack" tides may be characterized by significant shear in the water column.

Approaches to Monitoring

Participants in this breakout group agreed that techniques and protocols appropriate for monitoring ecosystem interactions in high-energy tidal environments are generally not available. Practical metrics for these types of interactions have not been identified. However, new active acoustic techniques show promise in documenting the behavior of diving birds, marine mammals, and large and migratory fish, as well as their distribution and abundance in high-energy environments. This documentation is particularly important in the very nearfield (i.e., the immediate vicinity of the tidal energy device). The United Kingdom has several active programs to develop this type of information.

4.7.5 Priority Area: *Energy removal*

Description

Energy removal is a top priority because, even with a low to moderate likelihood of measureable expression, the consequences could be systemic, especially in a fjord environment or any other system limited by flushing. Changes in mixing rates at the terminus of the system could cause changes in hydrology/hydrography, water chemistry and deep-water replacement. Group members concurred that projects that take ecologically significant amounts of energy out of tidal systems are unlikely to be permitted (or consented). The obvious corollary to this observation is that the scientific community (or risk assessors) needs to provide adequate technical information about the relationship between energy removal and ecological effects to support environmental risk management.

The level of uncertainty is low to high, depending on the relative physical and hydraulic complexity and the spatial scale of the system. Agreement among the group was relatively high.

Gaps in Understanding

Hydrodynamic models validated and calibrated for specific locations where development may occur are needed to address information gaps related to this topic. These models will need to be informed by appropriate field measurements (as discussed in Section 4.2, Physical Environment: Far-field).

Approaches to Monitoring

Required protocols for monitoring the effects of energy removal comprise measurements of the stressor itself, as well as conservative and non-conservative measures of mixing. However, changes in primary production rates and the dominant species of phytoplankton would be appropriate indicators of bottom-up ecosystem effects. Protocols for sampling and measuring plankton species and primary and secondary production rates are well documented in the research literature.

5. Workshop Outcomes: Challenges

The premise of the tidal energy workshop is that ocean energy can provide clean, reliable power, and emerging turbine designs will make production of electricity from ocean energy technologically and economically feasible. Tidal energy projects could be a viable renewable energy source, displacing fossil fuel-based energy resources, providing benefits to the marine environment through the mitigation of carbon dioxide production (which can lead to ocean acidification, climate change) and a reduction in the risk of catastrophic spills associated with fossil fuel extraction and transportation. However, the risk to the marine environment and marine organisms from tidal energy generation is not well known. In order to appropriately site and operate tidal power installations, a better understanding of the risks of the technology is needed, in order to explore the potential contribution tidal power can make to a renewable energy portfolio.

Throughout the workshop, participants returned to the theme of data and information gaps as they considered the likely stressors associated with tidal energy development and environmental receptors. These gaps are compounded by the difficulty of working in the marine environment at locations with strong tidal currents. Operational challenges include the durability of in situ monitoring instruments, anchoring instrumentation in high current speeds, and the high cost of marine operations. Four major challenges are discussed below, encapsulating recurring themes from throughout the workshop.

1. Critical knowledge gaps hinder evaluation of environmental impacts.

Despite modest government investment in tidal power research and development, permitting of tidal device deployment remains a considerable barrier to advancement. The tidal power industry and regulators have identified uncertainty regarding environmental effects as one of the top barriers to getting tidal devices in the water (Bedard 2008).

Workshop participants identified numerous areas of uncertainty regarding stressor/receptor interactions, including the following priority challenges:

Existing data used to evaluate environmental effects are often from poor analogues, or data from tidal device operation are proprietary and not available.

Relatively little data about environmental effects have been collected from operating tidal energy projects, and any data that are available relate to a particular device design. Because these data have been collected by device developers at considerable expense, most are proprietary and, in many cases, not publically available.

Industrial analogues to tidal energy include oil and gas development, military sonar use, offshore wind development in European countries, shipping, and general marine construction. These activities have generated considerable information about baseline environmental conditions and species- and population-level effects. However, these are of limited utility in assessing a number of potentially significant stressor/receptor combinations, such as blade strike.

Environmental effects are difficult to generalize among different projects, and the significance of an effect may differ between species and individuals of the same species. Depending on the context for tidal energy development, environmental concerns vary greatly for the same stressor/receptor combinations. For example, when endangered species could be negatively affected, the significance of an interaction may increase acutely. Because of this variability, general conclusions about the significance of stressor/receptor interactions remain elusive.

Understanding marine mammal-device interaction is a critical challenge because few impact data exist, many marine mammal populations are at risk, and marine mammal regulatory protections are stringent.

Common to many locations in the United States where ocean energy devices may be sited, uncertainty regarding possible interactions between devices and marine mammals is the most likely “show-stopper”. This area of uncertainty has dramatic potential to impact development of the industry, because many populations of marine mammals are at risk and regulatory protections are robust, especially those for endangered or threatened stocks. Lack of understanding, combined with very low risk tolerance (as required by law), means that this concern could prohibit development if not addressed with improved effects data and mitigation techniques.

The factors that make this an issue of major concern will also apply, to a lesser extent, to other protected species, such as turtles, some sea birds, and some fish, depending on the location and turbine technology.

Potential energy removal effects for commercial arrays cannot be determined by scaling up measurements from pilot-scale installations.

Potential commercial-scale energy removal effects are not well understood and could result in significant negative impacts to marine ecosystems. Pilot projects are not effective ways to improve this understanding, because these effects are not likely to be measurable at the pilot-scale. Indirect study through numerical, physical, or analytical modeling is also problematic, because implementation, validation, and calibration are resource-intensive activities. Other challenges include the potential for ecosystem “tipping points” (where a small increase in extraction would result in a disproportionally large change to the regional physical environment or habitat), the existing, natural variability in the hydrodynamic regime, and understanding the ecosystem response to natural variability. In order to organize information/data gaps into actionable areas of focus, the workshop steering committee categorized information needs into four types that correspond to stages of tidal project development:

- Information that can be gained prior to deploying a small number of devices at the pilot scale;
- Information that can be gained by monitoring pilot deployments that will inform deployments at both pilot and commercial scales;
- Information needed to responsibly deploy a large number of devices at the commercial scale; and
- Information required to understand environmental effects that will only be obtainable (i.e., measureable) at commercial scale through post-installation studies.

The purpose of Table 6 and Table 7 is to relate information needs to the stage of project development where the information is required or can most beneficially be gained. Table 6 summarizes priority areas identified by stressor groups and Table 7 summarizes priority areas for receptor groups. A precautionary approach is taken in assembling these tables, emphasizing information needs highlighted by either stressor or receptor groups on each side of priority areas. For some of the cases summarized in these tables, the stressor and receptor are both reasonably understood and emphasis is on improving understanding of the stressor/receptor interaction (e.g., blade strike to an individual). In others, information gaps related to a specific stressor or receptor must first be addressed before stressor/receptor interactions can be evaluated (e.g., noise and electromagnetic fields created by device operation; species sensitivity to particular stressors).

In many cases, information needs at the commercial scale (both pre-deployment and baseline post-installation monitoring) will be determined by the results of pilot-scale activities.

Table 6 – Information needs to close critical gaps in understanding (stressor groups).

Stressor	Priority area	Before pilot	During pilot	Before commercial	During commercial
Presence of devices: static effects	Effects of static structure on benthic ecosystems.	Characteristics of benthic habitat. Characteristics of species presence/absence and behavior.	Disruptions to benthic habitat from installation/recovery. Rate at which structures are colonized. Fish and marine mammal interactions with modified benthic ecosystems.	Modeling to evaluate effect of support structure on hydrodynamics and sediment transport. *Other needs pending results of pilot studies.*	Effects of support structure on hydrodynamics and sediment transport. *Other needs pending results of pilot and pre-commercial studies.*
	Effects of static structure on the water column and/or surface.	Characterize species presence/absence and behavior.	Changes to behavior of birds. Changes to behavior of pinnipeds (haul out). Potential for aggregation of fish in the wake of the support structure, leading to changes in predator-prey interactions.	*Pending results of pilot studies.*	*Pending results of pilot and pre-commercial studies.*
	Disruption of habitat and mobile species during device maintenance.	Characteristics of species presence/absence and behavior.	Effects of maintenance events on aquatic species given frequency of device removal and maintenance procedures.	*Pending results of pilot studies.*	*Pending results of pilot and pre-commercial studies.*
Presence of devices: dynamic effects	Potential for direct interactions of marine species with turbine rotor.	Movements of marine mammals, fish, and seabirds at temporal and spatial scales required to assess potential for direct interactions.	Types and frequency of interactions.	*Pending results of pilot studies.*	*Pending results of pilot and pre-commercial studies.*
Chemical effects	Biofouling prevention needs are poorly defined.	Characteristics of anti-fouling biocides likely to be utilized.	Fate of chronically released biocides.	*Pending results of pilot studies.*	*Pending results of pilot and pre-commercial studies.*
	Resuspension of pollutants from disturbed sediments.	Characteristics of sediments which may be disturbed by project.	Magnitude of sediment disturbance during installation and maintenance activities.	*Pending results of pilot studies.*	*Pending results of pilot and pre-commercial studies.*
	Potential for large oil spills.	Effectiveness of spill response procedures in energetic tidal environments.	*Pending results of pre-pilot studies.*	Effectiveness of spill response procedures in energetic tidal environments.	*Pending results of pilot and pre-commercial studies.*
Acoustic effects	Excessive transient pressure from pile driving.	Thresholds for permanent and temporary hearing shifts for potentially affected species.	Sound pressure levels in 1/3-octave bands from pile driving.	*Pending results of pilot studies.*	*Pending results of pilot and pre-commercial studies.*
	Behavioral responses to prominent narrow band or tonal components from device operation.	Extent of behavioral response for potentially affected species to narrow band or tonal components.	Sound pressure levels in 1/3-octave bands from device operation.	*Pending results of pilot studies.*	*Pending results of pilot and pre-commercial studies.*
	Behavioral responses to increases in broad band noise from device operation.	Extent of behavioral response for potential affected species to broad band noise.	Sound pressure levels in 1/3-octave bands from device operation.	*Pending results of pilot studies.*	*Pending results of pilot and pre-commercial studies.*
Electromagnetic effects	Electromagnetic fields from operating and idle devices.	Laboratory studies and models of electric and magnetic fields from proposed devices.	Measurements of magnetic fields from energized cables and operating devices.	*Pending results of pilot studies.*	*Pending results of pilot and pre-commercial studies.*
	Behavioral responses by sensitive species to electromagnetic fields.	Extent of behavioral response for potentially affected species.	Changes to behavior of species with electric or magnetic sensitivity.	*Pending results of pilot studies.*	*Pending results of pilot and pre-commercial studies.*

Table 6 – *continued on following page*

Table 6 – *continued from previous page*

Stressor	Priority area	Before pilot	During pilot	Before commercial	During commercial
Energy removal	Changes to far-field physical environment and habitat.			Characteristics of far-field physical environment.	Changes to far-field physical environment.
	Potential for ecosystem interactions.			Quantification of existing, natural variability in hydrodynamic regime and ecosystem response to this variability.	*Pending results of pre-commercial studies.*
Cumulative effects	Cumulative effects on large, mobile species.		"Deploy and monitor" strategy to monitor for effects and develop mitigation strategies.	*Pending results of pilot studies.*	*Pending results of pilot and pre-commercial studies.*
	Cumulative effects of energy removal.				"Deploy and monitor" strategy to monitor for effects and develop mitigation strategies.
	Difficulty of predicting, detecting, and attributing changes to the presence/operation of tidal energy devices.		Adequate monitoring methods to determine extent of effects.	Processes similar to Strategic Environmental Assessments for key tidal energy development areas.	

Table 7 – Information needs to close critical gaps in understanding (receptor groups).

Receptor	Priority area	Before pilot	During pilot	Before commercial	During commercial
Physical environment: near-field	Effects on local hydrodynamics.	Characteristics of flow conditions.	Upstream and downstream hydrodynamic profiles.	*Pending results of pilot studies.*	*Pending results of pilot studies.*
	Effects on water quality and sedimentation.	Characteristics of water quality and sedimentation.	Upstream and downstream water quality and sedimentation profiles.	*Pending results of pilot studies.*	Changes as a consequence of energy removal.
Physical environment: far-field	Effects of energy removal on far-field environment.			Potential for critical "tipping points" in regional ecosystems. Development of robust numerical models to assess energy removal effects.	*Pending results of pre-commercial studies.*
Habitat and invertebrates	Effects on sessile benthic species – invertebrates and plants.	Characteristics of benthic species presence/absence.	Received levels of noise in vicinity of project.	Characteristics of sessile benthic species population.	Changes as a consequence of energy removal.
	Changes in pelagic habitat near and far-field.			Characteristics of pelagic habitat.	Changes as a consequence of energy removal.
	Changes in benthic substrate both near and far-field.	Characteristics of substrates in high current areas.	Changes as a consequence of device presence.	Characteristics of substrates.	Changes as a consequence of energy removal.
Fish: migratory	Dynamic effects of device operation for populations and individuals.	Characteristics of species presence/absence and behavior.	Types and frequency of interactions.	Models to predict fish behavior. *Other needs pending results of pilot studies.*	*Pending results of pilot and pre-commercial studies.*
	Acoustic effects for populations and individuals.	Lab or field cage experiments to evaluate noise sensitivity of particular species.	Received levels of noise in vicinity of project.	*Pending results of pilot studies.*	*Pending results of pilot and pre-commercial studies.*
	Electromagnetic effects for populations and individuals.	Laboratory experiments to determine EMF sensitivity of key species.	Measurements of magnetic fields from energized cables and operating devices.	*Pending results of pilot studies.*	*Pending results of pilot and pre-commercial studies.*
Fish: resident	Dynamic effects of device operation for populations and individuals.	Characteristics of species presence/absence and behavior.	Types and frequency of interactions.	Models to predict fish behavior. *Other needs pending results of pilot studies.*	*Pending results of pilot and pre-commercial studies.*
	Effect of energy removal at the population level.			Characteristics of species population levels.	Changes as a consequence of energy removal.
Marine mammals and seabirds	Physical presence of devices, both static and dynamic for populations and individuals.	Natural history and habitat use for potentially affected species, at temporal and spatial scales relevant to project size.	Types and frequency of interactions.	*Pending results of pilot studies.*	*Pending results of pilot and pre-commercial studies.*
	Acoustic effects on marine mammals for populations and individuals.	Extent of behavioral response for potentially affected species to tonal and broad band noise.	Received levels of noise in vicinity of project.	*Pending results of pilot studies.*	*Pending results of pilot and pre-commercial studies.*
Ecosystem interactions	Top-down ecosystem effects.	Characteristics of food web structure and energy flow in energetic tidal environments.	Changes to the food web.	*Pending results of pilot studies.*	*Pending results of pilot and pre-commercial studies.*
	Effects of energy removal at the ecosystem level.			Calibrated hydrodynamic models to assess effects of energy removal.	

2. A lack of clearly identified research priorities leaves researchers and developers with little guidance about the most pressing stressor/receptor interactions.

Not all possible stressor/receptor interactions (i.e., environmental effects) are likely to rise to the level of deleterious ecological significance (i.e., environmental impacts), particularly for pilot-scale developments. In light of the sheer number of possible interactions, an approach to prioritizing high-risk interactions is needed to guide research dollars and mitigation strategies. Through the process of developing matrices for each stressor and receptor session, workshop participants identified those effects of greatest potential significance and highest uncertainty. However, in a number of cases, the assessment of similar stressor/receptor interactions varied among workshop breakout groups because of the underlying uncertainties and group-specific assumptions. Such factors may complicate high-level prioritizations. Two examples include:

- Effects on fish — Both migratory and resident fish work groups adopted similar receptor elements, but the migratory fish group expected generally higher significance from tidal energy stressors than the resident fish group at both pilot and commercial scales of development.
- Ecosystem interactions — When considering their stressor's effect on ecosystem interactions, most stressor groups expected moderately to highly significant ecosystem interactions at the commercial scale with high uncertainty, but the "Ecosystem Interactions" receptor group expected generally low to moderate significance for these stressors with low uncertainty.

Some uncertainties are compounded by knowledge gaps about how receptors respond to existing, analogous anthropogenic stresses. Evaluating the effects of tidal energy development requires a better understanding of stressor/receptor interactions in the natural environment. Tidal energy project and/or device developers acknowledge the spectrum of data needed to support environmental impact analysis and decision making but are not able to bear the cost of addressing all uncertainties, even for the high-priority areas summarized in Table 6 and Table 7. Workshop participants agreed that tidal energy project developers cannot be expected to support basic oceanographic research and stock assessments that are disproportionally large compared to their project scopes. Workshop participants further noted that the United States currently lacks a mechanism to evaluate and prioritize critical information needs for tidal energy projects and to fund information collection. This would require an appropriate division of public and private/industry resources reflecting national energy policy priorities and energy developer responsibilities.

3. Technologies required to monitor high-priority stressor/receptor interactions are underdeveloped and costly.

The instrumentation required to monitor several high priority stressor/receptor interactions is either not at a sufficient technical maturity to deploy at tidal energy projects or its deployment is prohibitively expensive for project developers. In addition, the available instrumentation may produce vast streams of data that are not suitable for decision making without extensive post-processing. Workshop participants agreed that it is not enough to simply collect environmental data; these data must be in a form suitable for decision making, some of it in real time.

Participants identified a number of common reasons for these technology gaps including:

- Some interactions may be rare, requiring a high level of effort to capture;
- Tools that are effective for stock assessments are not well suited to detect effects below the population level.
- Existing methods for data collection and monitoring may be ineffective at tidal energy sites, due to high current velocities; and
- Mutual interference between instruments may limit the capability to simultaneously monitor a range of interactions.

4. Appropriate mitigation strategies for unavoidable environmental impacts are not well-developed.

Some environmental impacts that cannot be avoided may be sufficiently mitigated by installation/decommissioning procedures, operational adjustments, or design improvements. Development of mitigation strategies, which will be critical for moving the industry forward, requires an understanding of stressor/receptor interactions and clear guidance from environmental statutes and regulatory agencies on permissible levels of impact. Because of the newness of tidal technology in the United States, regulatory agencies struggle with the same information gaps as others and are working with industry to develop guidance.

6. Workshop Outcomes: Recommendations

Breakout group discussions generated a number of recommendations that fall into three broad categories:

1. Approaches to reducing uncertainties around potential impacts (i.e., those effects which may be ecologically significant for one or more receptors);
2. Approaches to mitigating environmental stressors; and
3. Development of strategic and coordinated technologies and capabilities.

Recommendation details, organized by general category, are presented below.

6.1 Approaches to Reducing Critical Uncertainties

Avoiding or mitigating impacts requires sufficient information to assess the magnitude of the impact and the effectiveness of mitigation strategies. This includes life-history data for animals of concern and device operational parameters. In general, stressor groups emphasized the need to quantify the magnitude of the stressor, while receptor groups emphasized the need for information to place the stressors from tidal energy development in the context of existing stressors from other activities.

Priority research areas should be established for stressor/receptor interactions.

As discussed in Section 5, research efforts must be prioritized in order to make best use of limited funding and address the most pressing issues in a timely manner. As tidal technologies and environmental understanding evolve, *risk assessment* may provide a mechanism to evaluate and compare risks associated with specific stressor/receptor interactions in order to support research, permitting, and siting decisions.

As an initial attempt at this type of prioritization, the workshop organizing committee created high-level stressor/receptor matrices of significance and uncertainty. This synthesis is based on a review of session matrices, session narratives, and priority area information gaps identified in Table 6 and Table 7. Results are shown in Figure 39 for pilot-scale deployments and Figure 40 for commercial-scale deployments.

Although no stressor/receptor interactions with high potential significance and low uncertainty are identified at the pilot-scale, a number of high uncertainty interactions with high potential significance are apparent. These should be prioritized for investigation at the pilot scale.

- *Marine mammal-device interactions*: Because many marine mammal populations are already at risk from existing stressors, accurate information about device or array impacts to populations, especially endangered or threatened species, is essential for the industry to move forward. Interactions include stressors associated with the presence of the device (static and dynamic) and behavioral changes due to noise.
- *Fish-device interactions*: These concerns are analogous to those discussed for marine mammals and are most acute for endangered species. For fish-device interactions, the priority should be on decreasing the uncertainty around potential impacts caused by presence of the device (static and dynamic) and behavioral changes due to electromagnetic fields.
- *Cumulative effects:* Uncertainty around cumulative effects is high. Pilot projects present an opportunity to better understand the extent of stressors on individuals of a species. A better understanding of particular stressors is the first step in identifying potential synergies between/among stressors.
- *Chemical spills:* Although the risk for large chemical spills at the pilot scale is low, the impact of such spills on multiple receptors is relatively certain. Effective spill response procedures for tidal energy environments are required and should be developed if not already in place.

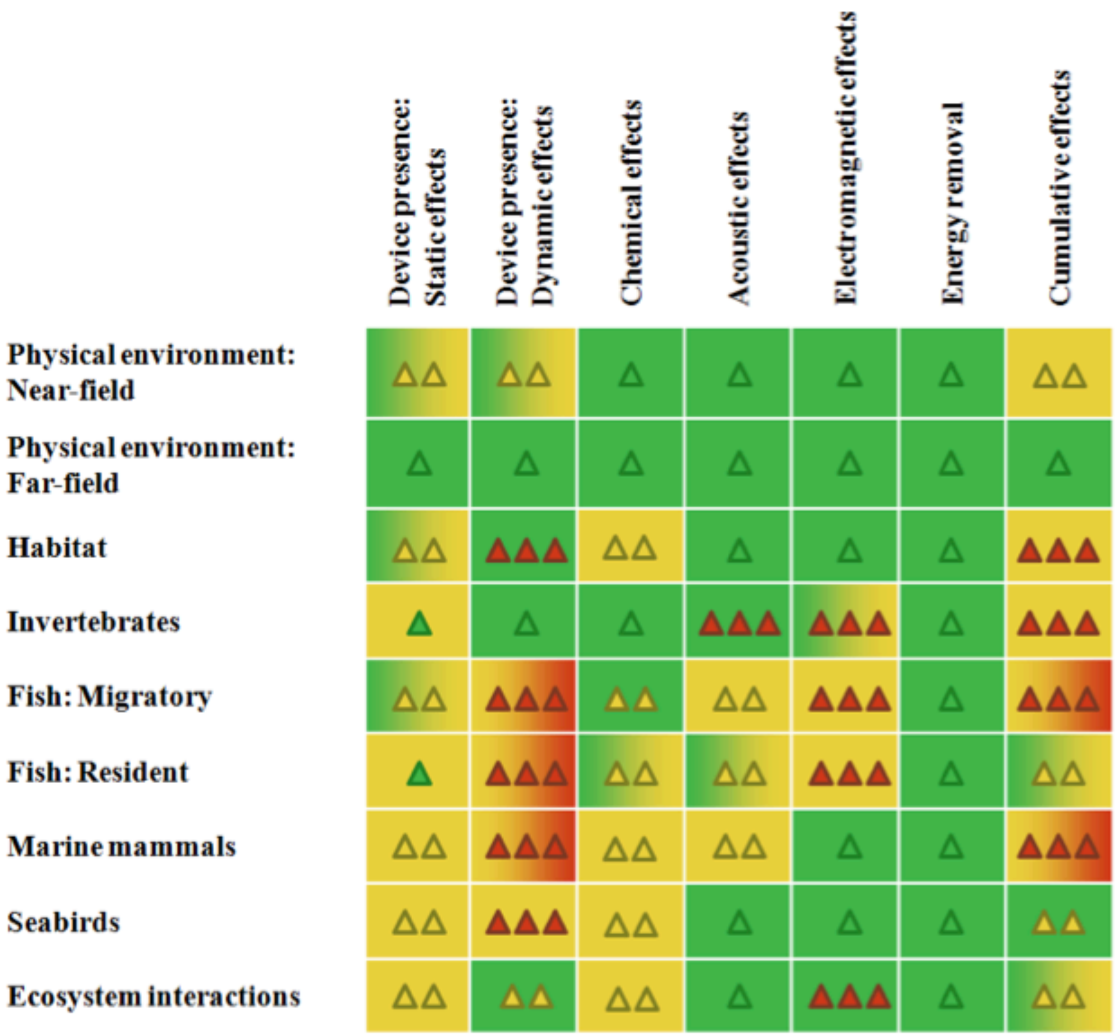


Figure 39 – Pilot-scale deployment generalized stressor/receptor significance (on a gradient green = low, red = high) and uncertainty (one green triangle = low uncertainty, two yellow triangles = moderate uncertainty, three red triangles = high uncertainty).

At the commercial scale, the potential significance of a particular environmental effect generally increases relative to the pilot scale. Energy removal, which is not a high priority issue at the pilot scale, emerges as a priority area of concern at the commercial scale. Because measurements from pilot projects cannot be scaled up to address this effect, research should be initiated to identify environmental "tipping points" (e.g., large environmental changes in response to incremental energy removal). This is a matter of particular concern for sites with the potential for multiple commercial-scale deployments. Information about environment "tipping points" would also inform market acceleration activities about the appropriate scales of development at specific sites.

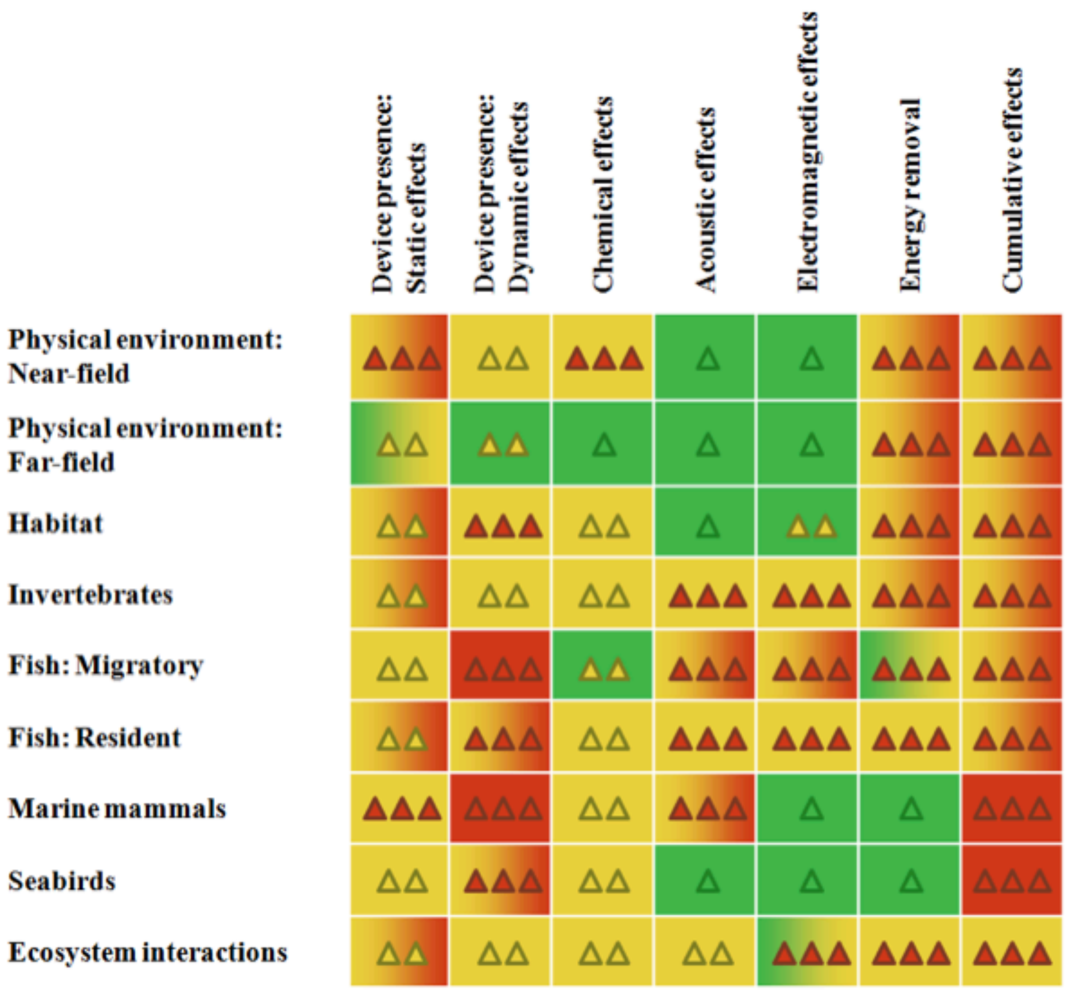


Figure 40 – Commercial-scale deployment generalized stressor/receptor significance (on a gradient green = low, red = high) and uncertainty (one green triangle = low uncertainty, two yellow triangles = moderate uncertainty, three red triangles = high uncertainty).

A first step to understanding many environmental impacts can be achieved only through monitoring of pilot-scale deployments.

Monitoring of pilot-scale projects is a critical step for closing information gaps for a number of high priority stressor/receptor combinations. Table 6 and Table 7 indicate that carefully monitored pilot-scale deployments are the first step in understanding the vast majority of critical uncertainties and are likely to provide more information than additional pre-device installation studies. For many, but not all, high-priority research areas, the emphasis at the pilot scale will be on monitoring effects on individual organisms in order to evaluate the potential for population effects at a commercial scale, and to inform baseline monitoring requirements for other pilot and commercial projects. As part of the permitting process for pilot projects, regulatory agencies should provide active, specific guidance as to what data and analysis products are required of tidal energy site developers. Efficiently closing knowledge gaps will require broad cooperation between site developers and regulatory agencies.

A phased approach to installation and operation may be required to mitigate potentially significant environment risks with high uncertainty, and long-term pilot projects may be required. For example, disturbance to the marine environment from project maintenance activities such as the removal of hard substrate from the tidal environment, cannot be fully assessed until device developers have verified that their maintenance intervals are technically achievable over the design life of a device.

It may be desirable to conduct pilot projects at dedicated test sites, where the physical and biological environment are well-characterized. Although there are no such test sites in the U.S. at this time, such facilities could be patterned after the European Marine Energy Center (EMEC) or Fundy Ocean Research Centre (FORCE). The U.S. Department of Energy is currently undertaking a strategic review of testing needs for marine renewable energy, including tidal energy.

The public sector must play a role in funding the study of high-priority stressor/receptor interactions, particularly for baseline assessments.

The public good that can be derived from the development of a clean renewable energy source requires that responsibility for environmental data collection and its costs be shared appropriately by industry and public interests. In the near-term, public funding should be used to enhance pilot-scale monitoring being undertaken by industry. This could occur at either dedicated test sites or individual technology demonstrations. As previously discussed, the technologies required to monitor some high-priority stressor/receptor interactions are underdeveloped and costly to deploy. Public funding for monitoring would reduce the burden on site developers and guarantee that the knowledge gained would enter the public domain in a timely manner.

National policy priorities should also guide investment of public dollars in environmental monitoring of regional or national importance. The Strategic Environmental Assessment (SEA) process commonly applied in Europe and Canada is one model for this type of strategic, regional, cost-sharing approach to data collection. SEA provides a mechanism to plan for pilot- or commercial-scale tidal energy development, identify research needs, and address cumulative impacts at a regional scale. The SEA approach, or a framework with similar goals, should be considered for the U.S., in order to guide data collection and to support permitting and siting decisions.

The effort to share relevant marine energy information through the International Energy Agency's Ocean Energy System Implementing Agreement (IEA-OES-IA) Annex IV should be continued, and other strategies to share data while protecting intellectual property should be developed.

The U.S. Department of Energy is leading an effort by IEA-OES-IA countries to compile existing information from marine energy projects and relevant technology analogues as part of the International Energy Agency's (IEA) Annex IV. In doing so, the annex will identify crucial information gaps and case studies from around the world, providing best practices for the marine energy industry. IEA-OES-IA activities under Annex IV began in 2009 and will continue through 2013.

Information from existing projects is needed to prioritize monitoring strategies. Intellectual property and competitive considerations for device developers decrease the likelihood that data collected from pilot projects will be freely placed in the public domain, especially when the collection of such data has come at high cost to the developer. One alternative to public disclosure would be the creation of a metadata archive describing, in detail, the types of data collected by ongoing projects and key lessons learned. Researchers and regulatory agencies would be required to negotiate access to these data on a case-by-case basis but would be aware of the data's existence.

In addition to these international efforts, provisions to ensure timely delivery of research and development results are needed.

Analogous and existing data should be compiled and reviewed to avoid duplication of data collection and monitoring efforts, particularly for baseline monitoring.

Assessing priority stressor/receptor interactions may be facilitated by the use of analogous, and better-understood, interactions. Analogues may include models of fish behavior, stock assessments, and the effects of noise on marine mammals. Although stressor analogues may be imperfect when applied to tidal energy devices, in some cases (e.g., artificial reef effects), these may provide useful insight for assessing environmental effects. Because analogies may be poor in some cases, a careful evaluation of applicability should precede their use. IEA-OES-IA Annex IV will investigate analogues to marine and hydrokinetic devices, including tidal devices.

Project and device developers should work with oceanographers and other researchers to share monitoring data collection, modeling methodologies, and study results.

High-priority concerns for tidal energy are also active areas of physical and biological oceanographic research. Summaries of the existing physical oceanographic data at potential development sites and biological oceanographic data on affected species could help to avoid duplication of effort in collecting baseline data for tidal energy development. Conversely, although tidal energy project developers cannot be expected to carry out large-scale physical or biological oceanographic research, the data collected during baseline or project monitoring may be of interest to oceanographic researchers. Efforts should be made to integrate baseline and monitoring data collection with broader efforts in relevant fields (e.g., in partnership with regional ocean observing initiatives).

6.2 Approaches to Mitigating Environmental Stressors

For environmental effects that have the potential to significantly impact one or more environmental receptors, mitigation strategies may be able to reduce that impact to an acceptable level. Table 8 summarizes proposed mitigation strategies made by stressor breakout groups. In a few cases, these recommendations address multiple stressors. For example, streamlining support structures would help to reduce the static effects of device presence and the effect of energy removal.

Table 8 – Potential mitigation strategies for environmental stressors.

Stressor	Priority area	General recommendations for mitigation
Presence of devices: static effects	Effects of static structure on benthic ecosystems.	Minimize anchor sizes. Minimize number of moorings and slack lines. Streamline support structures.
	Effects of static structure on the water column and/or surface.	Minimize lights, shroud lights, or use strobes instead of constant lighting. Design structure to be less desirable for pinniped haul out. Streamline support structures.
	Disruption of habitat and motive species during device maintenance.	Work windows should be scheduled to minimize impacts to fish (resident and migratory), migratory birds, and marine mammals. Follow best practices for containing anti-fouling coatings during biofouling removal.
Presence of devices: dynamic effects	Potential for direct interactions of marine species with turbine rotor.	Increase visibility of rotors to fish. Acoustic avoidance measures. Shock absorbers on leading edges of blades. Temporary device shutdown.
Chemical effects	Biofouling prevention needs are poorly defined.	Avoid use of anti-fouling biocides when possible.
	Resuspension of pollutants from disturbed sediments.	Use directional drilling to minimize disturbance to nearshore areas.
	Potential for large oil spills.	Turbine design should minimize volume of lubricants and hydraulic fluid.
Acoustic effects	Excessive transient pressure from pile driving. Behavioral responses to increases in noise (broad band or tonal) from device operation.	Schedule construction timing to minimize adverse effects. ”Soft start” pile driving. Bubble curtains. Design devices to minimize acoustic output.
Electromagnetic effects	Behavioral disruption from electric and magnetic fields.	Bury power cables. Twist cores for AC cables. Run DC cables of opposing polarity in close proximity.
Energy removal	Changes to far-field physical environment and habitat.	Minimize power dissipated by mixing of turbine wakes with free stream. Streamline support structures. Adapt patterns of device operation to avoid interfering with seasonally important events.
Cumulative effects	Effects on large, mobile species.	Limit number of devices at a given location until effects of operation are sufficiently understood.
	Effects of energy removal.	Projects should begin at small scale and increase incrementally to commercial scale.
	Difficulty of predicting, detecting, and attributing changes to the presence/operation of tidal energy devices.	Projects should begin at small scale and increase incrementally to commercial scale.

6.3 Development of Strategic and Coordinated Technologies and Capabilities

Workshop participants discussed several technical capabilities and tools that require development, but will be essential for addressing uncertainties and evaluating environmental impacts. These are discussed below and include generally accepted monitoring protocols, monitoring instrumentation, and hydrodynamic modeling capabilities.

Consistent, clear monitoring protocols should be developed and used by those conducting environmental research.

General protocols for pilot project monitoring (baseline and post-installation) should be drafted that specify the type of data to be collected, mechanisms for collection, and how these data will be used to address environmental uncertainties. Such protocols must retain some flexibility for site-specific considerations. To maximize the benefit of pilot projects, the lessons learned from these activities should enter the public domain in ways that benefit researchers and regulators, while protecting the intellectual property of device developers.

Meaningful monitoring protocols require an understanding of natural variability in order to establish thresholds for detecting measurable effects. Protocols must place the potential effects of tidal energy development within the context of natural mortality to aquatic species, changes to the physical environment (e.g., isostatic release on sea level), and changes to habitat from extreme weather events (e.g., shoreline erosion, seabed scour by debris).

Innovative approaches to monitoring instrumentation should be developed by partnerships between research institutions, industry, and funding agencies.

Monitoring instrumentation must be cost effective and should be adaptable between project sites. Although techniques to monitor aspects of the physical environment are relatively mature (e.g., measurements of water currents by Doppler profilers), approaches to monitoring the biological environment are less developed. Because advancing biological monitoring technologies would be of benefit to the broader oceanographic community, site developers should not be expected to bear the full cost of this instrumentation development.

A high-priority area of concern is mortality to fish and marine mammals from the rotating turbine blade (strike or impingement). Cost-effective instrumentation is required to detect, classify, and identify species moving in close proximity to an operating tidal energy device and make automated decisions based on the risk profile (e.g., temporary device shutdown if strike is imminent). This could involve integrating multiple types of instrumentation — acoustic telemetry (tags and receiver arrays), passive acoustics (hydrophones), and multi-scale sonar arrays — and pairing the output with a detection and classification algorithm to assess species-specific responses to device operation. Integrated monitoring systems will require significant hardware and software development.

Validated and calibrated hydrodynamic and ecosystem models can effectively address some critical uncertainties.

Not all concerns can be addressed by monitoring pilot projects. Because measurements are always sparse, modeling must play an important role. Two types of models are required:

- *Turbine-scale:* Models of the near-field hydrodynamic environment should be verified against measurements from pilot projects. In the longer term, the output of turbine-scale models could be used to investigate fish interactions and the fate of chemical contaminants (coatings and lubricants).

- *Estuary-scale:* Models of the far-field hydrodynamic environment, including provisions for power extraction by tidal turbines, will eventually be needed for project planning and permitting. It will be desirable to incorporate hydrodynamic, chemical, habitat, and biological linkages (e.g., larval transport). Because pilot projects are unlikely to measurably change aspects of the far-field physical environment, a fundamental challenge for such models is the validation of predictive cases with kinetic power extraction. Novel approaches are required to address this limitation.

Development of models at both scales will require rigorous validation and calibration. Once validated hydrodynamic models are in place, additional dynamics can be incorporated to model other aspects of the biogeochemical environment (e.g., sedimentation, dissolved oxygen, nutrients, productivity). It may be desirable to compile a list of validated hydrodynamic models covering potential development sites and to fund the development of hydrodynamic models at sites where no suitable model exists. An effective way to leverage modest investments in this area may be to contribute to the support or improvement of an existing model with the understanding that results will be made available for tidal energy project goals. In the near-term, models could be leveraged to provide preliminary assessments that guide high-priority monitoring activities. Model development will be an iterative process.

Expanded opportunities for interdisciplinary collaboration will promote improved experimental design and data collection.

Better coordination and synchronization among practitioners is required, with respect to experimental design and data collection; this could be achieved by expanding the forums for information sharing among disciplines (e.g., oceanography and engineering) and affiliation (e.g., universities and industry). For example, technical expertise is often compartmentalized between stressors and receptors (e.g., most marine mammal researchers are not trained in acoustics or chemistry and vice versa). An annual scholarly forum for exchanging information among practitioners would be helpful.

Future workshops on specific stressor or receptor topics were suggested by workshop participants as the industry moves forward and the need to understand and mitigate for environmental impacts becomes more acute. Examples include workshops on strategies to monitor for and mitigate against potential impacts to fish and marine mammals.

7. Concluding Remarks

The scientific workshop in March 2010 provided a unique forum to identify and prioritize critical knowledge gaps about the potential impacts of tidal energy generation devices on the environment. The diversity of invited participants and the workshop format resulted in lively evaluation and brainstorming discussions.

Two overarching conclusions can be drawn from the long list of specific knowledge gaps presented in Table 6 and Table 7:

- The next step to reducing critical uncertainties is careful monitoring of pilot-scale device deployments; and
- Research efforts must be prioritized and leveraged in order to effectively direct limited research dollars and resolve key uncertainties in a timely manner.

Some important uncertainties and potential concerns, however, can only be addressed by rigorous post-installation monitoring of commercial-scale arrays. When conducting research or directing funds to close high-priority uncertainties, the appropriateness of hypothesis testing at a particular scale of development should be critically assessed (i.e., in some cases, the significance of an effect and the ability to detect it will be dependent on project scale).

Participants found the structure of the workshop useful for eliciting and organizing environmental effects of tidal energy development and associated uncertainties. Future workshops on specific stressor or receptor topics were suggested, as the industry moves forward and the need to understand and mitigate for environmental impacts becomes more immediate. Participants also suggested that additional workshops focused on policy and management issues associated with tidal energy development may be useful, especially in light of federal- and state-level coastal and marine spatial planning efforts.[1] A secondary benefit of the workshop is that it provided a productive learning opportunity for tidal energy experts and novices alike. Nearly 80% of participants agreed to a moderate or great degree that the workshop increased their understanding of the potential environmental impacts of tidal energy development.

[1] More information on this process and efforts in the United States can be found at *http://www.msp.noaa.gov/*.

Appendix A — Glossary

Adaptive management	an approach to natural resource management that involves evaluating the results of management actions and modifying subsequent actions
Ambient	signals or stressors of nonhuman origin; background
Anadromous	species of fish that primarily live in the ocean and breed in fresh water
Anthropogenic	of human origin
Antifouling paint	a paint containing a biocide that is used to inhibit growth of fouling communities on manmade surfaces
Array	a gridwork; in this context, one comprised of tidal energy devices
BACI	before-after/control-impact study to identify environmental changes
Baseline	environmental conditions prior to device installation
Benthic	living on or in the substrate at the bottom of the water column
Biofouling	the buildup of fouling community organisms (e.g., algae, barnacles) on manmade structures
Biological productivity	in this context, primary productivity; the mechanism by which nutrients and carbon dioxide are converted to organic matter
Capacity	the maximum electrical power output from a tidal energy device
Cetaceans	the group of marine mammals that includes both the baleen (mysticetes) and toothed whales (ondontocetes)
Clupeids	herring, shad, sardines, and other forage fish
Commercial	of or related to large arrays of devices installed for a period of many years for the purpose of generating utility-scale power at a cost competitive with other forms of electricity
Conspecifics	two or more individual organisms, populations, or taxa
dB	decibels; in this context, a measure of sound pressure relative to 1 μPa
Diadromous	species of fish that migrate between salt water and fresh water at different life stages

DOE .... the United States Department of Energy; specifically the Advanced Waterpower Program under Energy Efficiency and Renewable Energy

Ecological .... in this context, pertaining to the interaction among organisms in the marine environment.

EIS .... environmental impact statement

Elasmobranchs .... cartilagionous fishes, including sharks, skates, and rays

EMF .... electromagnetic field

Environmental .... in this context, pertaining to water, nutrients, habitat, and organisms.

Environmental effects .... the broad range of potential measurable interactions between tidal energy devices and the marine environment; for potential effects, there is uncertainty around the fundamental nature of the interactions

Environmental impacts .... environmental effects that, with high certainty, rise to the level of deleterious ecological significance;for potential impacts, there is uncertainty around the details of the interaction (e.g., frequency, species-specific response) that would elevate the effect to the level of ecological significance

ESA .... federal Endangered Species Act of 1973

FAD .... fish attraction device

Far-field .... the region over which perturbations from tidal device operation are no longer distinguishable from other natural or anthropogenic perturbations, as distinguished from the near-field; depending on the tidal energy stressor, the distance from the turbine at which stimuli merge into the far-field might be on the order of few meters (for underwater visual stimuli), greater than tens of meters (for hydrodynamic disturbances from rotor or support structure), or greater than hundreds of meters (for acoustic stimuli)

Flatfishes .... a family of fish evolved as side-swimmers, including flounder, sole, and halibut

Forage fishes .... smaller fishes that are important sources of food for larger fish, birds, and marine mammals including osmerids and clupeids

Foul-release paint .... an inert coating that is used to inhibit growth of fouling communities on manmade surfaces

Foundation .... the anchoring system securing a tidal energy device to the seabed

Hydrodynamic .... of or related to the motion of water

Hydrokinetic .... of or related to renewable energy involving the extraction of energy from moving fresh or oceanic water

Intertidal zone .... an area exposed to air during low tides and submerged during high tides

Invasive species .... undesirable species that tend to dominate habitats at the expense of more desirable species; most are non-indigenous

Invertebrates.......................... animals without backbones; in this context, including crustaceans (e.g., crabs, lobsters, shrimp), barnacles, and sponges

Isobath................................... a contour of equal bottom depth

Kinetic power density .... kinetic energy flux per unit area; proportional to the cube of current velocity

kW... kilowatt

MHK .... marine and hydrokinetic

Migratory fish .... fish that follow predictable movements through the environment during their life cycles

Mitigation.............................. an action taken to prevent or avoid an ecological effect

Mooring .... the mechanical linkage by which the rotor and drive train on a tidal energy device are connected to the foundation

MW .... megawatt

Near-field .... the region over which perturbations from tidal device operation may be readily differentiated from other natural or anthropogenic perturbations, as distinguished from the far-field; depending on the tidal energy stressor, the distance from the turbine that would be considered near-field ranges from a few meters (for underwater visual stimuli), to within tens of meters (for hydrodynamic disturbances from rotor or support structure), or to within hundreds of meters (for acoustic stimuli)

Nearshore .... close to shoreline; in this context referring to shallow, biologically productive areas

NMFS.................................... NOAA National Marine Fisheries Service

NOAA................................... National Oceanic and Atmospheric Administration; a branch of the Department of Commerce

Pelagic................................... Pertaining to an organism living in the water column or the water-column habitat

Photic zone............................the depth of water over which solar energy plays a significant biological role; in a tidal energy context, depending on turbidity, this distance can vary from a few meters to tens of meters

Pilot......................................of or related to single devices or small arrays installed for short durations for the purpose of research and development

Pinnipeds...............................a group of marine mammals comprised of walruses, seals, and sea lions

Plankton ....plants or animals that drift in water without sufficient swimming capability to counter currents

Power train............................the mechanism by which rotational, mechanical energy from a tidal turbine rotor is converted to electrical energy; parts of the power train include a generator and may include a gearbox

Propagules.............................biological units capable of propagating new individuals or colonies; may be vegetative or reproductive

Receptor ....those elements of the marine environment that may be affected by stressors

Recruitment...........................the process by which young are added to a population

Resident fish..........................fish that maintain home ranges or that stay in a relatively stable geographic area throughout most of their life cycles

Risk assessment ....an evaluation of the potential adverse effects of an action

Rotor ....the component of a tidal energy device that extracts the energy in tidal currents and converts it to rotating mechanical energy.

ROV ....remotely operated vehicle; in this context an unmanned, submersible vehicle with propulsion, tethered to the surface by a power and data cable

Sacrificial anode....................aAn expendable piece of metal, generally zinc, that protects iron and steel from electrolysis in seawater

Salmonids ....a family of fish that includes salmon, trout, whitefish, and greylings

Saltating ....the process of particle transport by fluid

Scombrids ....a family of fish that includes tunas and mackerels

Scorpaeniforms.....................a family of fish that includes rockfish, greenlings, sculpins, and ling cod

SEA.......................................Strategic Environmental Assessment

Spatial ....in space

Stressor.................................those factors that may occur as hydrokinetic tidal energy systems are installed, operated, or decommissioned

Substrate...............................tn this context, referring to the seabed or its physical composition

Take......................................tn this context, anthropogenic actions leading to the harassment, injury, or death of a fish or marine mammal; generally discussed in the context of project permitting.

Temporal ....in time

Tidal energy device..............a device that extracts kinetic power from fast-moving tidal currents and converts that power to electricity; components include the rotor, power train, mooring, and foundation.

Tipping points ....critical thresholds, beyond which incremental changes caused by tidal energy devices result in disproportionately large changes in the marine environment

Trophic level ....the position an organism occupies in the food chain

Turbine.................................in this context, shorthand for either the entire tidal energy device or only the device rotor

Wake ....a lower-velocity region downstream of a blockage in a fluid flow, characterized by relatively more intense shear and mixing; in this context, the blockage is the tidal energy device rotor, power train, mooring, or foundation

Water quality.........................a measure of the physical, biological, and chemical properties of water, including turbidity, dissolved oxygen, chlorophyll, and nutrients

Appendix B — Plenary Session Extended Abstracts

For the March 2010 workshop, five plenary speakers were invited to introduce various aspects of environmental effects of tidal energy. The first two speakers provided an overview of the tidal energy industry in the United States and shared lessons learned from the Bay of Fundy in Nova Scotia, Canada. The next three speakers described the physical habitats and natural resources of the three selected sites: Coastal Maine, Puget Sound, Washington, and Cook Inlet, Alaska. These talks are summarized as extended abstracts in the following sections.

B.1 Tidal Technologies, Industry Overview, and the U.S. Department of Energy Water Power Team

Alejandro Moreno and Simon Geerlofs
U.S. Department of Energy

Introduction

This abstract provides an overview of tidal power, including the potential size and nature of tidal power resources, the technologies and devices used to capture tidal energy, the state of the tidal power industry, and the U.S. Department of Energy's efforts to support the responsible deployment of tidal power and other marine and hydrokinetic energy technologies.

Tidal power holds promise as a significant source of carbon-free, renewable, and predictable electrical energy located close to coastal load centers with high electricity demands. However, the tidal power industry is still in an early developmental phase worldwide and faces a number of technical and non-technical challenges to deploying devices, whether pilot-scale demonstration projects or commercial-scale device arrays. Although tidal power technology is developing rapidly, overcoming these challenges will require: continued research; development, and demonstration of devices; consistent testing and validation of device performance; and a focused, collaborative approach to understanding and addressing potential environmental risks. Environmentally responsible pilot projects and openwater testing opportunities, utilizing adaptive management principals and conducted in coordination with industry, regulators, national laboratories, universities, and other stakeholders, will be critical to realizing the potential for generating clean energy from the tides.

Tidal Power Potential

Ocean tides are driven by the combined gravitational forces exerted by the earth, moon, and sun, and by the rotation of the earth. Strong tidal currents result when rising and falling tides flow through constricting coastal and bathymetric features. Tidal currents contain an enormous amount of predictable, renewable energy in close proximity to coastal population centers with high demands for electricity. Estimates of the extractable tidal power potential in the United States vary widely: a preliminary study of seven sites in North America by the Electrical Power Research Institute found a potential extractable resource of 19.6 terawatt-hours per year (TWh/yr) (Bedard et al. 2007), and a 2009 study found that between 47 and 95 TWh/yr could be technically generated from tidal power across the country, based on an upscaled estimate of the resource available in Puget Sound (Polagye 2009)[1]. The large discrepancy between these two estimates results from the methodologies and assumptions used in the studies, which can lead to both over- and under-reporting the available resource. The U.S. Department of Energy continues to refine tidal energy assessments and is funding Georgia Institute of Technology to conduct a comprehensive assessment of both tidal and in-stream hydrokinetic resources in the United States; this assessment will be completed in 2010.

[1] The study's author notes that this is an order of magnitude estimate, assuming that Puget Sound accounts for 5-10% of the national resource and that device capacity factors range from 30% to 40%. The author cautions that, although technically feasible, dissipation of tidal energy of this magnitude could result in reduction of tidal transport and ecological changes within basins where tidal power is extracted. Refining future resource estimates will require a substantial modeling effort, a clear discussion of the cumulative effects of extraction, and an accounting of potential ecological and social limits to development.

Significant tidal power resource sites in North America include the Bay of Fundy, Cook Inlet in Alaska,Puget Sound, Western Passage in Maine, and Nantucket Sound in Massachusetts. Tidal power is being explored in other coastal states as well, and additional tidal resources may become available as the technology develops.

Tidal Power Technologies

Early tidal power projects utilized dam-like barrages to impound tidal flows within an estuary or bay, creating hydraulic head. Impounded water was then released through turbines, similar to how a conventional river-based hydropower system functions[2]. Tidal barrages have high capital costs and significantly alter coastal and estuarine ecology. By contrast, tidal power development in the United States today uses tidal in-stream energy conversion devicesto capture energy from freely flowing tidal currents. These devices function without use of impoundments or barrages, similar to how a wind turbine draws energy from moving air.

Generally, tidal in-stream energy conversiontechnologies can be divided into three categories: axial-flow turbines, cross-flow turbines, and reciprocating devices.

- **Axialflow or horizontal-axis turbines** typically consist of three or more blades that form a rotor. The flow of water is parallel to the rotor's axis. The kinetic flow ofthe water current over the blades creates lift,which causes the rotor to turn and drive an electrical generator. Axial flow turbines sometimes utilize a shroud to protect the turbine and accelerate the flow of water past the blades.
- **Cross-flow turbines** typically have two or three blades mounted along a shaft to form a rotor. The flow of water is perpendicular to the turbine's axis. The kinetic flow ofthe water current over the blades creates lift,which causes the rotor to turn and drive an electrical generator.These devices can extract energy from multidirectional flows without the need to orient to the direction of the flow.
- **Reciprocating devices** generate electricity through an oscillating motion, similar to the tail motion of a fish or whale, caused by the lift and drag forces of the water stream. Mechanical energy from this oscillation feeds into a power conversion system.

All tidal in-stream energy conversiontechnologies share some common characteristics, which include moorings, foundations, rotors or oscillating structures, a power conversion system, and transmission cables.

Tidal Power Industry

Technology developers based in the United Kingdom were quick to develop and deploy tidal power devices during the late 1990s and early 2000s to take advantage of the strong tidal flows located in U.K. waters. The first grid-connected axial flow turbine, known as Seaflow, was installed in May 2003 off the North Devon Coast of the U.K. Marine Current Turbine's 1.2 megawatt (MW) SeaGen project in Strangford Lough, Northern Ireland, has been connected to the electric grid since 2003. The European Marine Energy Centre in Scotland's Orkney Islands serves as an industry testing site for both tidal power and wave energy technologies. Compared to the United States, industry in the European Union has experienced greater access to capital and more extensive testing and pilot project resources. Aside from the United Kingdom, international development of tidal power is taking place in New Zealand and South Korea.

Exploration of tidal power technology in the North America is taking place in Nova Scotia, Maine, Washington, British Columbia, and Alaska. Verdant Power was the first company to deploy tidal power technology in the United States, installing six prototype units on monopoles in New York's tidally-influenced East River. Verdant Power is currently working with the U.S. Navy on a pilot deployment in Admiralty Inlet in Puget Sound. Clean Current tested a single turbine offshore of Race Rocks in the Strait of Juan de Fuca from 2006-2008, and has installed a device in Minas Passage in the Bay of Fundy. Marine Current Turbine is also planning to deploy in Minas Passage, and OpenHydro deployed a 1 MW turbine in Minas Passage in November 2009. OpenHydro has also been selected by Snohomish County Public

[2] The most well known tidal barrage currently in operation is La Rance tidal power plant in Brittany, France, which was completed in 1966. La Rance has a peak capacity of 240 MW.

Utility District for a pilot project in Admiralty Inlet. In March 2010, Ocean Renewable Power Company deployed a 60-kilowatt (kW) unit on a mobile testing barge off Eastport, Maine, to collect data in preparation for a pilot project license application. Ocean Renewable Power Companyis also working through the Federal Energy Regulatory Commission licensing process for a project in Cook Inlet.

A complete description of the global tidal power industry is contained in the International Energy Agency annual report for 2009.

Key Industry Challenges

The tidal power industry is still in a relatively early stage of development, although technology development is progressing rapidly, informed by lessons learned from wind power and advancements in ocean engineering. Device deployment is necessary in order to test and validate technologies and to gain better understanding of the potential environmental effects of tidal power. However, a complex regulatory and permitting situation, in addition to the technical challenges posed by the harsh marine environment, can complicate the deployment of tidal power devices.

Major industry challenges to the deployment of ocean energy devices include: technical risk and uncertainty regarding device cost, performance, and survivability prohibiting financing of development and demonstration projects; a lack of design tools, standards, and validation of data; the lack of reliable policy incentives to encourage the deployment and subsequent cost-reduction of new and innovative energy technologies; lengthy and complex permitting processes at both federal and state levels; a dearth of environmental and competing-use impacts data; and a need to integrate national energy priorities within coastal and marine spatial planning processes.

Overcoming Challenges—
DOE Water Power Activities

The mission of the U.S. Department of Energy's Water Power Team is to develop and employ novel technologies, improved operational procedures, and rigorous analysis to:

- Assess the potential extractable energy from domestic rivers, estuaries, and marine waters; and
- Support industry to harness this renewable, emissions-free resource through environmentally sustainable and cost-effective electric generation.

Although research and development in the marine and hydrokinetic energy industry has increased in recent years, no single design or technology has emerged as a clear leader. Until full-scale or near full-scale demonstration projects are deployed in realistic open-water conditions, such a determination will be very difficult to make. The U.S. Department of Energy is currently working to support the design, development, and testing of a variety of marine and hydrokinetic systems and identifying key cost drivers, performance characteristics, and technology improvement opportunities.

The U.S. Department of Energy leverages its extensive expertise in technology development to identify and fund research in areas where industry currently lacks either the capabilities or financial resources. It conducts research in six key areas that have been identified as critical to the success of the marine and hydrokinetic industry:

- System development, deployment, and verification to improve device functionality, to generate cost, performance and reliability data, and to test systems in relevant openwater settings;
- Research tools to develop design codes and models necessary for supporting system development and testing;
- Adequate test centers and facilities to generate and collect system data;
- Technology characterization to analyze and evaluate test data;

- Resource assessments to quantify energy availability and location; and
- Studies and projects to evaluate and minimize key environmental risks to permitting and deployment of demonstration projects.

The U.S. Department of Energy's Water Power Team collaborates with federal and state agencies, industry, national laboratories, national marine renewable energy centers, universities, and other stakeholders to carry out its activities.

Summary

Tidal power represents a regionally significant clean, renewable, and predictable energy resource. Modern tidal power technologies are designed to capture energy from the tides, convert that energy to electricity, and transmit the electricity to shore, all without use of dams or impoundments and with minimal environmental effect. Development of these technologies is still at a relatively early stage, but technology advancement is happening swiftly, with a number of devices tested worldwide. Nevertheless, the tidal power industry faces technical, regulatory, and environmental challenges and needs to test, deploy, and monitor devices in operational environments. No commercial-scale tidal power device arrays currently exist, and pilot project permitting is expensive and time-consuming. The Water Power Team is leveraging funding through industry and public partnerships to address key challenges and overcome information barriers that impede the responsible deployment of tidal power projects.

B.2 Ecological Effects of Tidal Energy: Experience from the Bay of Fundy

Graham R. Daborn
Acadia Centre for Estuarine Research, Acadia University

Introduction

Tidal power is an old technology. Mechanical mills driven by tidal movements in estuaries have been widespread in Europe for at least a thousand years, used variously for grinding grain or pumping water. Production of electricity from tidal waters has been a dream for a little over 100 years but, in that time, only three plants of commercial size have been completed: at Khislaya Guba (Russia), La Rance (France), and Annapolis Royal (Canada). All three are barrage-based systems, designed to convert the potential energy stored behind the barrage into electricity. Numerous other similar developments have been and are being considered in many countries, but many have not been pursued for economic or (occasionally) environmental reasons. The substantial environmental effects of barriers constructed in tidal estuaries — whether for power production, water storage, flood control, or transportation —have greatly diminished enthusiasm for such tidal barrage-based systems, although tidal lagoons and shore-fast reservoirs are still under active consideration.

The present focus on arrays of tidal in-stream energy converter (TISEC) devices arises, in part, because of the adverse effects expected from barrages, but also because arrays of TISEC devices offer the benefits of an incremental approach both to the investment required and for the assessment of long-term environmental effects

Tidal Power and the Bay of Fundy

Within the next two years is the centennial of Turnbull's original proposals (1910, 1912) for generating electrical energy from the tides in the Bay of Fundy. In those past 100 years, there have been four major and numerous minor proposals for large-scale tidal power development in the Bay. Most of these involved the creation of one or more barrages, but at least one (the Clarkson proposal of 1915) was for a kinetic energy conversion. Apart from the earliest studies of fisheries in the Outer Bay (1898-1911), tidal power proposals were responsible for surges in research activity in the Bay in every decade of the 20th century. Arguably, most of what isknown about the Bay ecosystem has resulted from the dreams of harnessing its energy (Daborn 2007).

In the 1970s, rising oil prices triggered an extensive examination of the potential for barrage-based tidal power development in the Upper Bay of Fundy. A review of existing knowledge (Daborn 1977) established that environmental and ecological information was too sparse to enable assessment of the environmental implications of any tidal power barrage in the Upper Bay, although hydrodynamic modeling did indicate that extraction of energy from the tides could have significant effects on the whole of the Fundy ecosystem and might even extend through the Gulf of Maine for the largest proposed development. It was recognized that the Upper Bay was biologically productive, but, because of the high levels of suspended sediment and the consequent lack of light, it was not clear on what this productivity was based.

In order to address the numerous questions presented by the proposed tidal power development, a major collaborative research network called the Fundy Environmental Studies Committee (FESC) brought together researchers from government agencies, local universities, and engineering companies, in a multidisciplinary, multi-institutional, collaborative effort that lasted from 1977 to 1984. The highly integrated program addressed all of the major research issues, from modeling of tides and currents to the dynamic properties of sediments, marshes, and mudflats and the migratory movements of fish, birds, and mammals. The final FESC report (Gordon and Dadswell 1984) represented a major increase in the understanding of the Bay of Fundy and its unique properties. In spite of seven years of integrated, collaborative efforts of more than 50 scientists, many questions remained unanswered when the FESC was terminated in 1984. In order to continue the integrated, collaborative, multi-institutional programinitiated by FESC, the Acadia Centre for Estuarine Research (ACER) was established at Acadia University in 1985. Since that time, ACER associates from several universities and government agencies in Canada, the United States, Argentina, and the United Kingdom have carried out numerous investigations into the Bay of Fundy ecosystem, from sediments to marshes to fish. Advantage was taken of the Annapolis Tidal Generating Station, which was opened at Annapolis Royal, Nova Scotia, in 1985, to examine the questions of fish passage through a tidal power barrage. As in previous decades, collaborative research investigations added enormously to the scientific knowledge and understanding of the Bay of Fundy system.

Tidal in-stream technology and the Bay of Fundy

The present considerations for tidal power conversion in the Bay of Fundy are primarily based upon new designs for TISEC devices, although there are also proposals for tidal lagoons or shore-fast impoundments. Most of the more mature TISEC technologies are either horizontal- or vertical-axis designs, and the ones closest to commercial development for grid-connected application, tend to be horizontal-axis. Locations with strong tidal currents suitable for TISEC devices occur at a number of sites in the Bay of Fundy, especially at the entrances to Passamaquoddy Bay and Minas Basin.

In 2007, the government of Nova Scotia decided, once again, to explore the prospects for generating electricity from the tides of the Bay of Fundy and, to that end, decided to have a test facility built in the Minas Passage that would accommodate commercial-scale TISEC devices. The Fundy Tidal Test Facility is designed to accommodate three separate devices at a time, with grid connections and a supportive research facility on shore. These facilities are currently under construction, but one device, a 1.2-MW Open-Centre Turbine sponsored by Nova Scotia Power, Inc., was installed onsite without connections to the grid in November 2009. The remaining berths will house a 20-m diameter Clean Current turbine and a gravity-based version of the two-propeller SeaGen produced by Marine Current Turbines.

In 2008, university and government scientists in the region met to consider the research needs presented by proposals for TISEC development in the Bay of Fundy. The research questions identified are probably similar to most other potential locations. They can be summarized as follows:

- **How much energy is available?** Current assessments of the amount of energy available at sites in the Bay of Fundy are based upon several alternative numerical models that can give widely divergent results. Although not really required for demonstration scale installations, effective, validated hydrodynamic models are essential foundations for economic and environmental assessments of commercial-scale developments.
- **How much energy can be extracted?** There are two aspects of this. One, relating to the efficiency of a device's energy conversion, is of primary interest to the designer and proponents. The more difficult and important aspect, however, is at what point does the extraction of energy begin to cause unacceptable changes to the ecology or to other resources of the system? Resolution of this question also depends upon validated hydrodynamic models.
- **What are the effects of energy removal on sediment dynamics?** This is a critical environmental question for many of the sites proposed for tidal-stream energy extraction, primarily because of the profound and complex ecological significance of sediments in macrotidal systems. The fundamental research involved here generally falls outside the scope of environmental assessments for demonstration projects but is essential for assessments of commercial scale arrays.
- **What environmental signals (e.g., vibrations or noise) are emitted by energy conversion devices, and how do these signals affect marine life?** Technology developers address concerns about vibrations that might affect the efficiency or durability of their devices, but there are great uncertainties about the potential effect of such signals on marine life, particularly mammals, birds, and fish. Presently-available technologies for monitoring movements of fish or birds in the vicinity of turbines have so far proved to be not only very expensive but also often less effective than expected under naturally occurring conditions.

- **What (if any) are the effects of electromagnetic fields generated by submarine electrical transmission lines?** Research into electromagnetic field effects is not new, but many questions remain unanswered about the ecological effects of electromagnetic fields and species-specific responses.

- **What are the implications of submersed ice or other debris?** Ice is an issue that applies in many but not all northern latitude sites where marine energy may be developed. The research questions have to do with the effects of ice on energy conversion devices (e.g., the potential for non-buoyant ice to be a threat to the devices in the Upper Bay of Fundy) but also the effects of energy extraction on the formation, persistence, and movements of ice (e.g., as a result of reduced mixing between fresh water and salt water in estuaries). In many estuaries, the presence of logs and other debris derived from shoreline erosion, resource harvesting,or other sources may represent significant threats to the integrity and efficiency of energy conversion devices.

- **What is the potential for energy extracting devices to affect the presence, mobilization, and effects of contaminants —both those associated with the devices and those occurring as a result of other activities?** Although the potential contaminant hazard of the devices themselves tends to be small, commercial-scale development will require consideration of larger cumulative effects. In turbid systems such as the Bay of Fundy, contaminants become closely associated with sediments, particularly those of finer grain sizes, so that contaminant fate becomes tied up with sediment dynamics.

- **What are the indirect effects of marine energy developments on marine biota?** In addition to direct ecological effects associated with changes in flows, sediment dynamics, noise, and strike effects on fish and mammals, alluded to previously, there may be other ecological effects that are, at present, unknown. These include: mortality effects on non-commercial species; indirect effects associated with changes in predators or prey; and ecosystem effects of habitat alterations. Answers to these questions require new investigations of behavior, application of new and improved models, and field-based monitoring and experimental studies. They are complex, time- and resource-consuming, and difficult to conduct. It seems that only a collaborative approach involving developers and university and government scientists is likely to lead to a progressive and well-founded marine energy industry.

These questions relate primarily to the perceived environmental effects of tidal (or wave) energy developments. However, the coastal marine ecosystem is already a well filled environment, with numerous other industries vying for access. Interference with those activities may trigger other social and environmental consequences. Public attitudes toward alternate energies are important, potentially mutable, and poorly known; these will play a major role in determining the public support for marine energy developments.

The past three decades of research on the Bay of Fundy have demonstrated unequivocally that macrotidal systems such as the Bay do not exist in isolation. Through the motions of the tides and the movements of fish, birds, and mammals, the Bayis physically and biologically connected to the Canadian Arctic, the eastern seaboard of the United States, Central and South America, and Europe. Some of the species involved are rare or endangered. The implications of energy extraction from the Bay of Fundy system must, therefore, be assessed carefully in the full context of these international biophysical linkages, and this may well apply to most other sites in the world that exhibit high potential for TISEC development.

Stressors, Receptors, and Risk.

As indicated, the major environmental questions raised by TISEC developments are familiar enough. The primary stressors include: changes to hydrodynamic characteristics; changes to sediments and substrates; noise during construction and noise and vibrations during operation; pressure changes; ice and debris; and contaminants. The receptors of most concern in the Bay of Fundy are marine mammals, fish (especially endangered and migratory species),benthic communities, plankton, and a few marine diving birds. However, in spite of all of the past work on the ecology of the Bay, it remains difficult to assess the true risk of TISEC development to these receptors. The difficulty arises in several ways:

- Many of the potential effects are indirect, resulting from changes to ecosystem processes. For example, the footprint of a TISEC array and the immediate changes to the substrate are easy to assess, but the secondary effects of changes in energy levels and, therefore, sediment distributions and dynamics may have greater effects on far-field benthic habitat.
- Monitoring for and detecting these secondary effects in a highly dynamic system that is continually undergoing changes from other forces, natural and anthropogenic, is extremely difficult. Far-field ecological changes attributable to energy development may be difficult to distinguish from natural perturbations.
- Many standard monitoring technologies do not work as well under the extreme flow conditions of some of these sites. For example, some acoustic devices used for monitoring fish and their movements appear less effective if levels of turbulence, turbidity, and entrained air are very high.
- Too little is known about the behavior of many species, especially during their migration and in the vicinity of TISEC devices.

A preliminary assessment of risk, recognizing differences in the near-field and far-field and the potentially different scales of demonstration/pilot projects and commercialarrays, has been conducted for the Bay of Fundy. The greatest uncertainties are associated with the behavior of fish and mammals in the vicinity of turbines. Previous monitoring conducted at the Roosevelt Island site by Verdant Power showed that very few fish were present in the experimental array; however, it was unclear whether this was because of active avoidance or simplybecausefish were scarce in that portion of the river. It was anticipated that the deployment of commercial-scale devices in the Bay would enable a first-order evaluation of the reactive behavior of fish and mammals as they approached a working turbine; however, the apparent inadequacy of existing technologies and the difficulties of maintaining monitoring equipment in place has shown that this is a much more challenging task than previously thought.

Adaptive management

In recognition of these uncertainties, federal and provincial governments and the developers of the Minas Passage (Bay of Fundy) project have instigated an adaptive management process to address the environmental implications of tidal energy conversion in the Bay. Following preparation of an Environmental Effects Monitoring Plan (EEMP), an independent Environmental Monitoring Advisory Committee that is responsible for examining the outcomes of monitoring activities and advising on the technologies and methodology on a continuing basiswas convened. The objective is to ensure that the EEMP delivers, over time, the answers needed by regulators, the scientific community, developers, and the public.

Reducing the uncertainties requires research that goes beyond the usual scope of environmental impact assessments. In recognition that successful demonstration of these commercial-scale devices will lead quickly to proposals for arrays, collaborative research projects involving regional universities, government agencies, and the consortium of developers (represented by the Fundy Ocean Research Centre for Energy or FORCE have been initiated in the following areas:

- Active and passive tracking of fish, lobsters, and mammals in the vicinity of the test site;
- Development of hydrodynamic and sediment models that can address the near- and far-field effects of energy extraction;
- Monitoring of sediment distributions and benthic populations;
- Monitoring of mammal and marine bird activities in the passage; and
- Investigation of the formation and fate of ice and the movements of large debris.

It is also anticipated that additional research into the development of new, robust monitoring technologies will be initiated in recognition of the exceptional needs for monitoring in these dynamic environments.

After 100 years, it seems that the dream of Fundy tidal power will continue to be a stimulus for innovation and a generator of new knowledge for decades to come.

References

Daborn, G.R. (Ed.). 1977. *Fundy Tidal Power and the Environment: Proceedings of a workshop on Environmental Implications of Fundy Tidal Power at Wolfville, N.S., Nov. 4-5, 1976*. Publication No. 28. Nova Scotia, Canada: Acadia University Institute.

Daborn, G.R. 2007. Homage to Penelope: Unraveling the ecology of the Bay of Fundy system. In *Challenges in Environmental Management in the Bay of Fundy—Gulf of Maine*. *Proceedings of the 7th Bay of Fundy Workshop, St. Andrews, NB, October 24-27, 2006*. Poehle, G.W., P.G. Wells and Rolston, S.J. (Eds.). BoFEP Technical Report No.3. 12-22.

DFO (Fisheries and Oceans Canada). 2008. Potential Impacts of, and mitigation strategies for, small-scale tidal generation projects on coastal marine ecosystems in the Bay of Fundy. *Canadian Science Advisory Secretariat Science Response, 2008/013*.

Gordon, D.C. and Dadswell, M.J. 1984. Update on the marine environmental consequences of tidal power development in the upper reaches of the Bay of Fundy. *Canadian Technical Report of Fisheries and Aquatic Sciences*, 1256.

B.3 Physical Habitat and Natural Resources: Maine

James McCleave, Gayle Zydlewski,
Huijie Xue and Michael Peterson
University of Maine

Interest in tidal power development in Maine coastal waters comes from the high tidal currents and energy densities. These features are caused by the Gulf of Maine-Bay of Fundy basin being in near resonance with the principal lunar semidiurnal (M-2) tidal constituent of the North Atlantic Ocean. The Electric Power Research Institute (Hagerman and Bedard 2006) listed 36 potential tidal plant sites in Maine, with eight optimistically listed as having 10 MW or greater electricity generating potential. The Maine Department of Environmental Protection (DEP 2010) added five sites and listed nine sites with active preliminary permits. The reason so many potential sites exist is that the last glaciations resulted in a series of parallel narrow estuaries and bays with numerous constrictions where high tidal flows occur.

This presentation considers four environmental aspects important during consideration of tidal power generation in Maine. It describes the physical settings of potential tidal energy sites, describes the biological and ecological settings, identifies ecologically significant features and sensitive areas, and mentions some species of particular concern.

The emphasis is on "Downeast" Maine, where potential sites could be termed bay sites, but also considers other parts of Maine briefly, where some sites are better termed estuarine sites. Four sites illustrate the latter. The Sasanoa "River" connects Sheepscot Bay and the Kennebec River, with Lower Hell Gate as the prospective site. Through here, the tide floods saline water into southern Hockomock Bay and the Kennebec River. The tide ebbs from both, receiving low-salinity water from the Kennebec River. Mean monthly discharge of the Kennebec ranges about 240-1100 $m^3 s^{-1}$. Cowseagan Narrows connects between the Sheepscot River and northern Hockomock Bay; the narrows are about 3 km long.

The primary site in the Penobscot River is about 5 km along the Verona Island narrows, immediately above the widening into Penobscot Bay. Tidal currents are strong, and the large freshwater discharge enhances currents, especially during the spring freshet (mean April discharge is >1,000 $m^3 s^{-1}$). The Bagaduce River narrows and Castine Harbor are listed by the Electric Power Research Institute as having a combined 10 MW potential, but that is doubtful. The practical importance of these sites is as a tidal energy demonstration and evaluation site for Maine Maritime Academy, in collaboration with the University of Maine.

In Maine, current development activity is focused on Cobscook Bay and the Western Passage of Passamaquoddy Bay, which differ in some ways and are similar in others. Both, especially Cobscook Bay, have complex geomorphology because of glacial action (Kelley and Kelley 2004). Glaciated estuaries, typical of the northeastern United States, do not fit the traditional conceptual models of increasingly fine sediment material found farther up the estuary. Instead, bedrock structures and glacial deposits control the shape and tidal flow and, hence, sedimentation. Subtidal areas are dominated by gravel, cobble, boulders, and bedrock. Intertidal areas are about half mudflat. Both bays, especially Cobscook, have limited freshwater input, so riverine sediment is lacking. The Dennys River, largest in Cobscook, has a maximum discharge of ~8 $m^3 s^{-1}$. The St. Croix River, largest in Passamaquoddy, discharges 45-150 $m^3 s^{-1}$ seasonally. In contrast, 0.5 km^3 of water goes in and out of Cobscook each tide — approximately equal to the Mississippi River discharge in the same time. There is even greater flow through Western Passage into Passamaquoddy. Mean tides in Western Passage are ~5.7 m. Extreme spring tides are ~7.6 m. Most of the flow into both bays comes through Head Harbor Passage on the Canadian side of the border.

Modeled flow and energy density during tidal cycles shows where tidal energy potential is greatest. However, the model does not capture the extreme turbulence to the flow, especially in Western Passage, where the flow through Head Harbor Passage makes a 90° turn. This results in a famous whirlpool, "Old

Table 9 – Differences and similarities of Cobscook and Passamaquoddy Bays

Attribute	Cobscook Bay	Passamaquoddy Bay
Size	Smaller	Larger
Geomorphology	Complex	Simpler
Average depth	Shallow (10 m)	Deep (25 m)
Shoreline:area ratio	Large (3:1)	Small
Intertidal area:total area ratio	Large (1:3)	Small
Tidal prism	Large	Small
Freshwater input	Very low	Low
Salinity	About 30 ppt	About 30 ppt
Temperature, annual range	~0-12 C	~0-12 C
Nitrate	High	High

Source: Mostly from Larsen (2004)

Sow," on flood tides, along with smaller whirlpools and general turbulence.

Flow into Cobscook and Passamaquoddy originates from the mouth of the Bay of Fundy, where the upwelling and mixing from the decreasing depth of water contributes three important characteristics to the water entering the bays: marine salinity of ~30 ppt in most areas; boreal, moderated temperatures with seasonal range ~0-12 C; and high nitrate concentration year-round.

These bays have long been noted for high productivity and biological richness, without much assessment of why, until a concerted effort was published in 2004. Nitrate and ammonium, necessary for plant growth, are part of the ecosystem flow of energy and production. Nitrate is high in Passamaquoddy and Outer and Central Cobscook (Garside and Garside 2004). Because of limited freshwater discharge, the only source of nitrate sufficient to support the observed primary productivity is the sea. Primary productivity of six different groups of taxa provides the organic material available to higher trophic levels.

Conventional wisdom is that increased tidal mixing results in increased nutrient availability, which results in increased phytoplankton production. But annual net primary productivity of phytoplankton in Cobscook is similar to non-macro-tidal estuaries (Phinney et al. 2004). Overall phytoplankton production is high, but biomass is very low because of high flushing and high turnover. Benthic micro-algal production is about 100 times the integrated water column phytoplankton value in Cobscook because light can penetrate to the bottom; the situation in Passamaquoddy is probably about reversed.

Rockweeds, primarily *Ascophyllum nodosum* and *Fucus vesiculosus*, dominate northeastern U.S. coasts in the intertidal and sublittoral fringe zones in both high- and low-flow areas (Vadas et al. 2004a). Ascophyllum productivity in Cobscook Bay is near the high end of other studies in the northeast. The high areal coverage in Cobscook, coupled with high productivity and two-year turnover time, means that rockweed contributes a huge amount of organic carbon to the marine ecosystem.

Canopy-forming kelps (e.g., *Laminaria longicruris*) are abundant along boreal, subarctic shores as narrow subtidal fringes (Vadas et al. 2004b). Highest biomass occurs in summer and is greater at low-flow than high-flow sites. Kelp growth continues through the summer, when growth of most other algae slows, because kelp can store nitrogen for use when water-column nitrogen is low. Kelp turns over three to four times per year, becoming detritus or being consumed directly by herbivores. Kelp contributes substantially to the organic carbon pool in Cobscook and less so in Passamaquoddy.

Several species of foliose and filamentous red and green algae are common on Maine's shores (Vadas et al. 2004c). *Palmeriaare* common red algae; *Ulva* and *Enteromorpha* are common green algae. Because of the extensive intertidal and shallow subtidal areas, these algae contribute a surprising amount of organic carbon to the ecosystem.

Seagrasses, especially *Zostera marina*, are abundant in protected intertidal and sublittoral fringe habitats (Beal et al. 2004). Production is greater in the sublittoral fringe than in the intertidal. Again, because of the extensive eelgrass beds in Cobscook (490 hectares) and two-month turnover time, seagrass contributes large amount of organic carbon to the ecosystem.

Phytoplankton, benthic microalgae, and rockweeds make the greatest contribution of fixed carbon to the ecosystem of Cobscook Bay. Productivity per unit area or per unit volume would be similar in Passamaquoddy Bay, but the proportions of the total contributed by the six groups would be very different, because the percentage of the area of Passamaquoddy Bay that is intertidal is much lower than in Cobscook Bay. Phytoplankton plays the dominant role in Passamaquoddy Bay. Recognizing that the values in Table 10 are based on different methods by different authors and mostly represent net production, not gross production, they should be viewed as estimates.

The macroinvertebrate fauna of Cobscook Bay and Passamaquoddy Bay is exceedingly diverse. Trott's (2004a) historical checklist of the benthic macroinvertebrates spanning 162 years lists 775 species in 17 phyla. The list is a thorough inventory and includes species not present today. Mollusca (187 species), Annelida (183), Arthropoda (149), and Cnidaria (95) dominate the list. A survey limited to 11 shallow subtidal stations in the eastern part of outer Cobscook Bay in 1975 yielded 172 species in 12 phyla (Larsen and Gilfillan 2004). Only 200.1 m^2 grab samples were taken. Annelida (59 species), Arthropoda (47), and Mollusca (44) dominated those samples.

There have been two published bottom-trawl surveys of fishes in Passamaquoddy Bay, neither of which is current, and there have been downward trends in many species in the meantime. Tyler (1971) caught 39 species in bottom tows over a 16-month period in 1965-1966 at a station north of Western Passage, 45 years ago. He categorized the fishes as summer periodic (four species), winter periodic (four), regular (13), and occasional (18). Regular species included commercially harvested fish, such as Atlantic herring (*Clupea harengus*), haddock (Melanogrammus aeglefinus), Atlantic cod (*Gadus morhua*), and winter flounder (*Pseudopleuronectes americanus*), and non-commerciallysought fish such as longhorn sculpin (*Mtoxocephalus octodecemspinosus*) and ocean pout (*Macrozoarces americanus*). Important summer periodics were silver hake (*Merluccius bilinearis*), white hake (*Urophycis tenuis*), and the anadromous alewife (*Alosa pseudoharengus*). Winter periodics included the little skate (*Raja erinacea*) and pollock (*Pollachius virens*).

MacDonald et al. (1983) trawled at Tyler's station, at a station farther up Passamaquoddy Bay, and at a station in Head Harbor Passage about monthly from 1976-198130 years ago. They categorized 62 species as Tyler did, including 49 species caught at Tyler's station. There were some qualitative differences, mainly because MacDonald et al. (1983) categorized greater percent-

Table 10 – Primary producers and production on Cobscook Bay

Taxonomic group	Representative	Habitat	Annual production rate, g C m^{-2} y^{-1}	Total annual production, g C y^{-1}
Phytoplankton		Water column	75-100	10^9-10^{10}
Benthic microalgae		Substrate to ~12 m	<750	(guestimate)
Rockweed	*Ascophyllum* *Fucus*	Intertidal to shallow sublittoral	490-700	6.3 x 10^9
Kelp	*Laminaria*	Sublittoral fringe	330	3.3 x 10^7
Red and green filamentous, foliose	(red) *Palmeria* (green) *Ulva, Enteromorpha*	Mid-low intertidal to shallow sublittoral	170 80	3.6 x 10^8 9.0 x 10^8
Seagrass	*Zostera*	Intertidal to sublittoral fringe	35	4.3 x 10^8

ages of the species as either summer or winter periodics and they considered separately adults and juveniles of haddock, Atlantic cod, pollock, and winter flounder.

There are no published studies of pelagic fishes in Passamaquoddy or Cobscook Bays. Personal observations suggest that juvenile Atlantic herring are very abundant in summer, despite MacDonald et al.'s (1983) claim that they are a winter periodic. Tremendous schools of herring were identified during acoustic surveys in Western Passage and Outer Cobscook Bay in August and September 2009. Atlantic mackerel (*Scomber scombrus*) were also abundant then, feeding on herring.

Migratory species are not well represented in the bottom surveys. Alewife, blueback herring (*Alosa aestivalis*), rainbow smelt (*Osmerus mordax*) and American eels (*Anguilla rostrata*) migrate through as juveniles and as adults. Atlantic salmon (*Salmo salar*) are rare in the Dennys River in Cobscook Bay, but juveniles and adults migrate through Passamaquoddy Bay to rivers in New Brunswick, Canada.

Marine mammals were especially abundant in Western Passage and Head Harbor Passage in 2009. Several species are present, commonly minke whales (*Balaenoptera acutorostrata*), fin whales (*B. physalus*), harbor seals (*Phoca vitulina*) and harbor porpoises (*Phocoena phocoena*), and, occasionally, endangered northern right whales *(Balaena glacialis*) and humpback whales (*Megaptera novaeangliae*).

Astounding numbers of seabirds are present as residents, migrants, and overwinterers. Many congregate along tidal fronts, either passively or actively. At some times as many as 25,000 Bonaparte's gulls (*Larus philadelphia*), 15,000 herring gulls (*L. argentatus*), 3,000 black-backed gulls (*L. marinus*),and 3,000 black-legged kittiwakes (*Rissa tridactyla*) may be present in the area. Red-necked phalaropes (*Phalaropus lobatus*) once were far and away the most common (as many as 2,000,000 at a time in 1977), but are rare now for unknown reasons. Similarly, the kittiwakes have declined from a high in 1996 of 65,000. A variety of ducks and common terns (*Sterna hirundo*) and Arctic terns (*S. paradisaea*)are also present.

One could argue that all of Cobscook Bay is an ecologically important and sensitive feature for several reasons. There is high species diversity. The extensive stands of rockweed, kelp, and seagrass provide nursery areas and habitat for numerous sessile and mobile organisms as well as foraging habitat for many species, including seabirds. The detritial food web is important because of the extensive areas of plants and their high turnover rates. As many as a hundred species of invertebrates that, elsewhere, are only found subtidally are found intertidally in Cobscook, for two reasons. Extreme spring low tides occur in early mornings and late afternoons, so low intertidal areas are not exposed to noonday sun. Because of the cool water in summer, heavy fog develops, insulating intertidal organisms from the summer sun. Gigantism occurs in several invertebrate species (e.g., sea stars, brittle stars, tunicates, sea urchins, and periwinkles) in Cobscook and Passamaquoddy.

However, Cobscook Bay and Passamaquoddy Bay are not pristine. Rockweeds are species of concern. There is a controversy over how much can be safely harvested without damaging the multiple roles that rockweeds play in the ecosystem. Species diversity in Cobscook and, probably, in Passamaquoddy has declined substantially in the last 30-35 years. Accumulated mud sediment has occluded normal interstices in gravel and boulder habitats, especially in inner Cobscook. Extensive stands of kelp have disappeared there, making kelp a species of concern.

Mussel beds have become dominant in many areas where they were rare before 1980. Invasive European green crabs(*Carcinus maenas*) have contributed to the decline of periwinklesnails (family Littorinidae), as has commercial harvesting. Mussel beds trap sediment, but where does the sediment come from, given the lack of riverine input? Trawling for scallops and sea urchins produces plumes of sediment, and the sediment spreads on the tidal flow and re-deposits everywhere. Sea urchin trawling didn't start much before 1987. Blue mussels (*Mytilus edulis*), soft-shell clams (*Mya arenaria*), sea scallops (*Placopecten magellanicus*),urchins, and periwinkles are all species of concern.

In Passamaquoddy and Cobscook, an ecologically significant feature is the predator-prey food web, based on Atlantic herring as the forage base. The summer abundance of juvenile herring schools attracts periodic fishes, such as Atlantic mackerel, resident fishes, such as haddock, many species of seabirds, and several species of marine mammals. Adult herring provide food for marine mammals. In all areas of Maine, the decline of Atlantic herring is of concern from the food web aspect to the lobster bait and human food aspect.

In other areas of Maine, estuaries and bays are important corridors for migratory fishes. The Penobscot, Sheepscot, Sasanoa, and Kennebec rivers are corridors for Atlantic sturgeon (*Acipenser oxyrhynchus*) and endangered shortnose sturgeon (*A. brevirostrum*) and overwintering areas for shortnose sturgeon. The Atlantic sturgeon is under consideration for listing as threatened. Thus, the sturgeons are species of concern. Maine is making significant efforts to restore anadromous alewife, blueback herring, American shad (*Alosa sapidissima*) and Atlantic salmon (*Salmo salar*) to rivers, so these are also species of concern.

A plan is in place for turbine removal and improved fish passage facilities in the Penobscot River and other rivers where anadromous fishes are or were present. A question worthy of thought would be whether people are simply proposing to replace river turbines with tidal turbines?

References

Beal, B.F., Vadas, R.L., Wright, W.A. and Nickl, S. 2004. Annual aboveground biomass and productivity estimates for intertidal eelgrass (*Zostera marina*) in Cobscook Bay, Maine. *Northeastern Naturalist*, 11(Special Issue 2): 197-224.

Department of Environmental Protection. 2010. *Status of tidal power project proposals in Maine as of January 1, 2010*. Maine Department of Environmental Protection. Unpublished document. Available at *http://www.maine.gov/dep/blwq/docstand/dams/hydro_FERC_process/index.htm*.

Garside, C. and Garside, J.C. 2004. Nutrient sources and distributions in Cobscook Bay. *Northeastern Naturalist*, 11(Special Issue 2): 75-86.

Hagerman, G. and Bedard, R. 2006. Maine Tidal In-Stream Energy Conversion (TISEC): *Survey and Characterization of Potential Project Sites.* Palo Alto, CA: Electric Power Research Institute, EPRI-TP- 003 ME Rev 1.

Kelley, J.T. and Kelley A.R. 2004. Controls on surficial materials distribution on a rock-framed, glaciated, tidally dominated estuary: Cobscook Bay, Maine. *Northeastern Naturalist*, 11(Special Issue 2): 51-74.

Larsen, P.F. 2004. Introduction to ecosystem modeling in Cobscook Bay, Maine: A boreal, macrotidal estuary. *Northeastern Naturalist*, 11(Special Issue 2): 1-12.

Larsen, P.F. and Gilfillan, E.S. 2004. A preliminary survey of the subtidal macrobenthic invertebrates of Cobscook Bay, Maine. *Northeastern Naturalist*, 11(Special Issue 2): 243-260.

Macdonald, J.S., Dadswell, M.J., Appy, R.G., Melvin, G.D. and Methven, D.A.. 1983. Fishes, fish assemblages, and their seasonal movements in the lower Bay of Fundy and Passamaquoddy Bay, Canada. *Fishery Bulletin*, 82: 121-139.

Phinney, D.A., Yentsch, C.S and Phinney, D.I. 2004. Primary productivity of phytoplankton and subtidal microphytobenthos in Cobscook Bay, Maine. *Northeastern Naturalist*, 11(Special Issue 2): 101-122.

Trott, T.J. 2004. Cobscook Bay inventory: A historical checklist of marine invertebrates spanning 162 years. *Northeastern Naturalist*, 11(Special Issue 2): 261-324.

Tyler, A V. 1971. Periodic and resident components of communities of Atlantic fishes. *Journal of the Fisheries Research Board of Canada*, 28: 935-946.

Vadas, R.L., Beal, B.F., Wright, W.A., Emerson, S. and Nickl, S. 2004. Biomass and productivity of red and green algae in Cobscook Bay, Maine. *Northeastern Naturalist*, 11(Special Issue 2): 163-196.

Vadas, R.L., Beal, B.F., Wright, W.A., Nickl, S. and Emerson, S. 2004. Growth and productivity of sublittoral fringe kelps (Laminaria longicruris) in Cobscook Bay, Maine. *Northeastern Naturalist*, 11(Special Issue 2): 143-162.

Vadas, R.L., Wright, W.A. and Beal, B.F. 2004. Biomass and productivity of intertidal rockweeds (Ascophyllum nodosum) in Cobscook Bay. *Northeastern Naturalist*, 11(Special Issue 2): 123-142.

B.4 Physical Habitat and Natural Resources: Puget Sound, Washington

Andrea Copping, Ph.D. and Brie Van Cleve

Pacific Northwest National Laboratory,
Marine Sciences Laboratory

The Puget Sound system and how it was formed

Puget Sound is a large, fjord-like estuary encompassing the second largest watershed area in the United States. It is the southern portion of the greater Puget Sound-Georgia Basin that is shared with British Columbia in Canada (Figure 41).

From the Canadian border south to Olympia and west to the Pacific Ocean, the Puget Sound basin comprises 7,252 square kilometer of inland marine waters and 4,023 km of shoreline. Puget Sound is connected to the Pacific Ocean through the Strait of Juan de Fuca to the west and the Strait of Georgia and Johnstone Strait in British Columbia. Together these water bodies are known as the Salish Sea, in recognition of Native American inhabitants of the area.

Puget Sound is approximately 160 km long with average depths of 62 m and maximum depths of 280 m. Meltwater flowing southward beneath the ice is believed to have scoured the major troughs that define Puget Sound today (Burns 1985). Glacial moraines created shallow sills at the mouths of several of the basins in Puget Sound, creating constrictions with strong reflux and tidal currents. The two major sills responsible for circulation in Puget Sound are located at Admiralty Inlet (near Port Townsend, Washington) and the Tacoma Narrows. The majority of the Sound's marine water enters through Admiralty Inlet. This inlet is constricted by topography (Point Wilson and Admiralty Head) and vertically constricted by a shallow sill making it an area of swift tidal currents (>3 m/s).

An estuarine system with lots of people

A number of major river systems bring freshwater into Puget Sound, making it one of the most productive estuaries in the county, which, in turn, has supported the development of one of the largest shipping ports in the country, a robust tourism and recreation industry, a substantial fishing industry, and major military installations. Nearly 4.5 million people live in the Puget Sound region and another 1.3 million are expected by 2025. The majority of inhabitants live in major cities on the eastern shore between Bellingham and Olympia, with Seattle and Tacoma boasting the largest populations.

The Puget Sound region is an important economic, security, and environmental asset. Total maritime trade in Washington averages $12 billion in exports and $60 billion in imports.[1] The Ports of Seattle and Tacoma are together the third largest container port in the United States. Over 80 percent of waterborne cargo moving from the lower 48 states to Alaska passes through Puget Sound ports.[2] Other maritime industries include shipyards, boat and shipbuilding and repair, naval facilities, cruise ships, and a large oil refinery.

Puget Sound is home to the majority of the Alaska fishing fleet — the largest fishing fleet in the United States — and is the point of entry of 50% of the seafood entering the country.[3] Approximately 10,000 jobs in the Puget Sound region and $3.5 billion in gross sales are attributed to the fishing industry.[4] Washington produces the largest amount of farmed shellfish in the United States, the majority from Puget Sound.[5] Aquaculture alone is worth $110 million in the region and supports thousands of jobs.[6]Recreational boating is a major activity in Puget Sound, accounting for $489 million in spending annually.[7] Puget Sound wildlife provide a basis for an ecotourism industry 80 boats strong, and visitors come from across the country to view the region's iconic killer whales.

---

[1] FAST Corridor: The Fast Partnership helps move our Economy. April, 2006. *www.psrc.org/fastcorridor/*

[2] Commit to Compete: Maritime transportation is critical to the future of the Pacific Northwest Economy. 2003

[3] Ibid and International Center of Maritime Industries fact sheet by the Trade Development Alliance of Greater Seattle.

[4] International Center of Maritime Industries fact sheet by the Trade Development Alliance of Greater Seattle.

[5] Focus on Puget Sound: Economic Facts by Washington State Department of Ecology, October 2008.

[6] *http://www.pcsga.org/pub/farming/farm_benefits.shtm*

[7] Focus on Puget Sound: Economic Facts by Washington State Department of Ecology, October 2008.

Who lives here and who is at risk

The shape of Puget Sound results in a narrow fringe of vegetated habitat types. These habitats (e.g., kelp forests, eelgrass beds, mudflats, coastal marshes and embayments, rocky reefs, and open water) host rich plant and animal diversity including over 230 species of marine and anadromous fish, 13 species of marine mammals, 165 marine dependant birds, and 3,000 species of marine invertebrates. Puget Sound is also home to five species of Pacific salmon, many populations of which are listed as threatened or endangered under the federal Endangered Species Act, as well as a population of endangered Southern Resident killer whales.

Table 11 – Examples of Puget Sound plant and animal life

Puget Sound supports abundant natural resources, making timber harvest, fishing, and shellfish harvest important regional industries. Indicators of stress to the ecosystem resulting from industrial and residential development include a loss of 25% of forest lands in the past 15 years, nearshore habitats such as eelgrass under stress, declines in commercial fish harvest, water quality issues such as beach closures and hypoxic zones, less than half of the Puget Sound herring stocks considered "healthy," and economically and culturally important species threatened by extinction. Three endangered species especially susceptible to potential negative impacts from tidal energy development are Southern Resident killer whales (currently 85 individuals in the population), Chinook salmon runs, and the marbled murrelet seabird.

How exactly tidal energy development will affect the Puget Sound ecosystem and especially these key species is poorly understood, making securing environmental permission under regulatory statutes challenging, time-consuming, and costly. Initial modeling estimates indicate that there is unlikely to be a measurable change in tidal prism from removal of energy from pilot-scale deployments at Admiralty Inlet or other locations in Puget Sound (Polagye 2009). Possibly additive or synergistic effects of tidal energy development with existing environmental issues, such as water quality, habitat impacts, and species population declines, further add to the uncertainty associated with development. In spite of technical and environmental challenges of tidal power

Table 11 – Examples of Puget Sound plant and animal life

Marine and anadromous fish	**Marine mammals**	**Seabirds**	**Marine invertebrates**	**Marine plants**
Pacific salmon (*Oncorhynchus spp.*)	Killer whale (*Orcinus orca*)	Rhinoceros Aucklet (*Cerorhinca monocerata*)	Olympia oyster (*Ostrea lurida*)	Eelgrass(*Zostera marina*)
Pacific Herring (*Clupea pallasi*)	Pacific harbor seal (*Phoca vitulina*)	Common Murre (*Uria aalge*)	Dungeness crab (*Cancer magister*)	Surf grass (*Phyllospadix spp.*)
Rockfish (*Sebastes spp.*)	Pacific harbor porpoise (*Phocoena phocoena*)	Brandt's cormorant *(Phalacrocorax penicillatus*)	Giant Pacific octopus (*Enteroctopus dofleini*)	Kelp (*Desmerestia spp.*)
Pacific Cod (*Gadus macrocephalus*)	Stellar sea lion (*Eumetopias jubatus*)	Tufted Puffin *(Fratercula cirrhata*)	Sea star (*Pisaster spp.*)	Bull kelp (*Nereocystis spp.*)
Walleye Pollock (*Theragra chalcogramma*)	California sea lion (*Zalophus californianus*)	Marbled Murrelet (*Brachyramphus marmoratus*)	Shrimp spp. (*Pandalidae*)	Giant kelp (*Macrocystis spp.*)
Lingcod (*Ophiodon elongates*)	Minke Whale (*Balaenoptera acutorostrata*)	Harlequin Duck (*Histrionicus histrionicus*)	Geoduck (*Panopea generosa*)	Non-floating kelp (*Laminaria, Costaria spp.*)
Sixgill shark(*Hexanchus griseus*)	Dall's porpoise (*Phocoenoides dalli*)	Pigeon Gillemot (*Cepphus columba*)	Cockle (*Clinocardium nuttallii*)	Pickleweed (*Salicornia spp.*)

generation in Puget Sound, there is strong interest in renewable energy generation among public and private entities, and Puget Sound offers sites with abundant power densities in close proximity to load centers.

Proposed tidal projects

At locations in Admiralty Inlet, there are two distinct efforts to test and develop tidal energy. One project is proposed by the Snohomish County Public Utility District (SnoPUD), using OpenHydro devices. A second project is lead by U.S. Navy Region Northwest, using Verdant Power devices. There are several other potential tidal energy sites in Puget Sound (e.g., Tacoma Narrows) that are not under active development.

In early 2007 SnoPUD received preliminary permits from the Federal Energy Regulatory Commission (FERC) to study seven locations in and around Puget Sound for tidal energy development. The seven sites combined could provide as much as 100 MW of energy —or enough power for about 70,000 residences. Following a screening process, SnoPUD narrowed its focus to two sites: Deception Pass and Admiralty Inlet. Only Admiralty Inlet is under active development.

In April 2009, SnoPUD selected OpenHydro, an Irish tidal turbine developer, to design, build, and install up to two hydrokinetic turbines at a project site in northern Admiralty Inlet, west of Whidbey Island (Figure 42). InDecember 2009, SnoPUD submitted a draft license application to the FERC to install one or two tidal power generation turbines off Admiralty Head. A 10-meter diameter OpenHydro design is proposed for deployment in >60 meters of water on the cobble seabed in late 2011 or early 2012. This water depth will avoid interactions with shipping traffic and mayhelp to limit environmental impacts. At peak performance, each unit is expected to produce about 600 kilowatts (kW)of electricity, enough to power about 500 homes. Washington State law now requires the utility to meet 15% of its load with renewable resources (not including additional traditional hydropower) by 2020.

Since 2007, SnoPUD and its contractors have carried out a number of studies to characterize the physical and biological environment in the project area. Owing to the intense tidal currents in the area, preexisting data are limited. Characterization studies have included:

- Tidal currents (Acoustic Doppler Current Profilers)
- Ambient noise (recording hydrophones)
- Aquatic species abundance (vessel-based hydroacoustic surveys, both mobile for broad area assessment and moored for assessment of "fish flux" through a fixed site)
- Marine mammal sighting and passive acoustic surveys (focusing on the endangered Southern Resident killer whales, but also including seal, sea lion, and porpoise populations)
- High resolution bathymetric survey (including ROV surveys of the seabed); and
- Water quality measurements

These studies suggest significant spatial and temporal variations in the physical and biological environment at the proposed development site.

U.S. Navy Region Northwest was directed by Congress to carry out research and development activities in tidal power in Puget Sound. A one-year demonstration project is planned at a site further south in Admiralty Inlet off Marrowstone Island (Figure 2) using Verdant Power turbines. As with the SnoPUD project, deployment of three to six turbines could take place in late 2011 or early 2012. Each turbine would generate 40 kW of electricity at rated capacity and supply power to one building and the lights in a parking lot at the U.S. Navy's magazine on nearby Indian Island. Although the Navy is not required to obtain a pilot demonstration license from FERC, the U.S. Navy's environmental planning process follows internal guidelines and the National Environmental Policy Act, which requires compliance with applicable federal and state statutes. Consequently, the permitting process and time lines are very similar to those for the SnoPUD project.

Figure 41 – The Puget Sound-Georgia Basin is bisected by the U.S.-Canadian border.

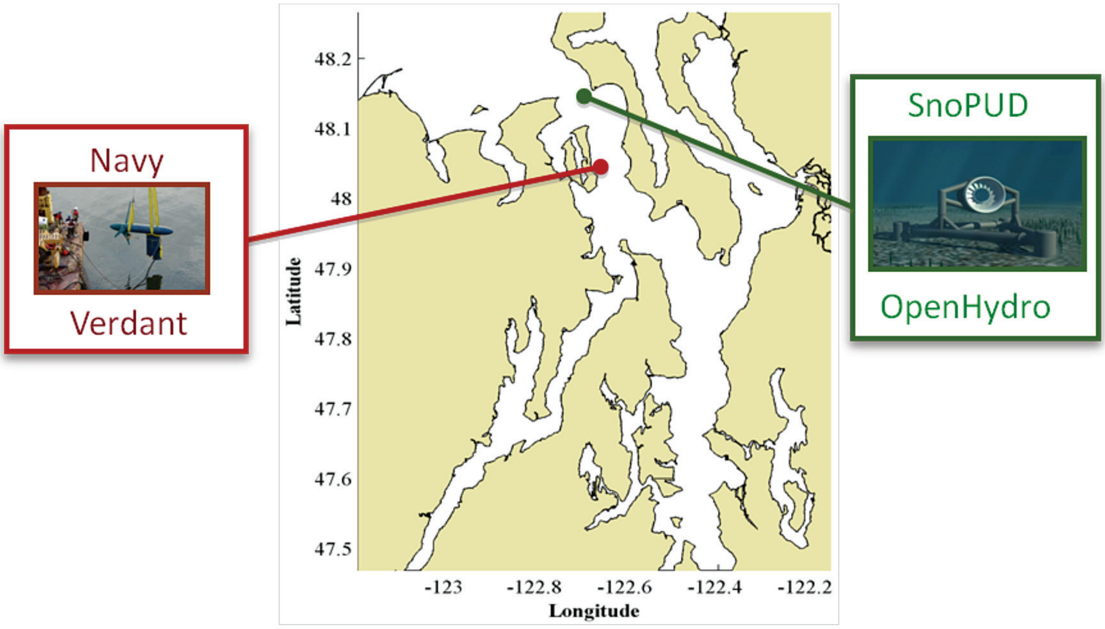


Figure 42 – Sites of Puget Sound pilot tidal projects.

Reference

Polagye, B. 2009. *United States National Tidal In-stream Resource Estimate*. Technical Report to US Department of Energy by Northwest National Marine Renewable Energy Center, University of Washington, Seattle, WA.

B.5 Physical Habitat and Natural Resources: Alaska, with a Focus on Cook Inlet

Sue Saupe
Cook Inlet Citizens Regional Advisory Committee

Background – Alaska Tidal Resources

Alaska has more than 70,000 km of coastline; more than double that of the rest of the U.S. coastal states combined. This extensive coastline and the unique regional tidal ranges and currents create enormous tidal energy potential, primarily in areas of the Gulf of Alaska. Most of the Gulf of Alaska has mixed semi-diurnal tides, and the Aleutian Islands and western and northern Alaska have predominantly diurnal tides and have much lower tidal ranges. The location of the Gulf of Alaska basin relative to the North Pacific amphidromic point and the complex interaction of the M_2 (lunar semi-diurnal) tidal wave with the Gulf of Alaska's coastline and its bays and estuaries results in tidal ranges and currents that vary significantly throughout the Gulf. For example, the tide is focused into the narrow ends at the head of Cook Inlet, an extension of the northwestern Gulf of Alaska, and the natural period of oscillation in this long, narrow inlet is similar to that of the tides, amplifying the tides even further.

In 2003, the Alaska State Legislature commissioned an Alaska Energy Policy Task Force[1] to develop a long-term energy policy for Alaska to: promote research, development, and demonstration of clean and renewable energy; promote conservation and energy efficiency across all of Alaska; increase the proportion of renewables in long-term fuel sources. An Alaska Renewable Energy Atlas was published and most recently updated in 2009 to include the most current information on the potential for developing geothermal, wind, solar, hydroelectric, tidal, and wave energy resources (AEA 2009). Since 2006, the Alaska Energy Authority has partnered with the Electric Power Research Institute (EPRI) to study tidal energy potential in Alaska and has identified three main areas of interest that were highlighted in the Renewable Energy Atlas of Alaska — Cook Inlet, specific areas of southeast Alaska, and several Aleutian Island passes (Figure 43). Also shown in Figure 43 are other areas where there has been interest in tidal energy development, as evidenced by current, proposed, or expired FERC permits[2]. In 2008 the Alaska Legislature established a Renewable Energy Grant Fund,[3] authorizing the Alaska Energy Authority to distribute renewable energy grants based on an annual funding of $50 million (with an additional $50 million added in FY09).

Despite the massive tidal energy potential in Alaska, the lack of extensive infrastructure for much of coastal Alaska (roads, transmission lines, and docks) presents major challenges to developing tidal energy resources. However, there are several areas where tidal energy potential is high and can be linked to existing power grids or can be delivered to specific locales. Specifically, upper Cook Inlet is of high interest, given its proximity to energy demands and electrical infrastructure. More specifically, an area west of Fire Island in upper Cook Inlet is under intense evaluation for the planned in-water installation and testing of a group of TideGen turbines by Ocean Renewable Power Company, LLC (ORPC) by 2011 or 2012. Several other areas of Cook Inlet have also been identified as having potential (Figure 43), including Turnagain Arm, the Forelands, Kalgin Island, and Harriet Point. In Cook Inlet, pending preliminary permits to FERC have been submitted by ORPC to explore the resources at the East Foreland and by Turnagain Arm Tidal Energy for a tidal fence near the mouth of Turnagain Arm (Table 12). Several other FERC permits for Cook Inlet were either expired or were withdrawn or dismissed for various reasons – including areas near Kalgin Island and in Kachemak Bay.

Southeast Alaska is another area of Alaska with potential for tidal energy development (Figure 43). Cross Sound and Icy Strait show substantial energy potential (Polagye and Bedard 2006) that could meet energy needs for local communities as well as supply energy via inter-tie to Canada and the Pacific Northwest. Other very local but high quality sites have been identified, mainly in areas that funnel southeast Alas-

[1] Established by HCR 21; sunset in April 2004.

[2] *http://www.ferc.gov/industries/hydropower/indus-act/hydrokinetics.asp*

[3] Established by HB 152

ka's tidal energy through very narrow passes. Natural Currents Tidal Development, LLC has obtained preliminary permits from the FERC for Icy Strait and Port Clarence and has permits pending for Kootznahoo Inlet and Gastineau Channel[4].

The Renewable Energy Atlas (AEA 2009) also identifies several eastern Aleutian Island passes as having exploitable tidal power resources (Figure 43). Although the tidal ranges are low compared to other areas of the Gulf of Alaska, significant currents are produced by tidal flushing between the north Pacific and the Bering Sea through the numerous deep and narrow passes between the various Aleutian Islands as well as atmospheric-induced barotrophic flow and the baroclinic flow of the Alaska Coastal Current. Except for a few specific locations, there is low potential for tidal energy development further east and north in the Bering Sea and Arctic regions due to their significantly lower tides and heavy winter ice.

The focus in the next section is on upper Cook Inlet, due to the current interest in the area and because a pilot project is currently permitted with plans for in-water turbine deployment in 2011 or 2012. The physical habitat and natural resources of this area will be the presented, as well as briefer descriptions for other areas of interest in Cook Inlet, Southeast Alaska, and the Aleutians.

Cook Inlet Physical Environment

Cook Inlet has attracted the most recent attention for tidal energy development in Alaska for several reasons – strong semi-diurnal tides and associated currents, proximity to infrastructure for deploying equipment and personnel during research and development, and the ability to distribute energy to the adjacent city of Anchorage or other areas of the Alaska Railroad railbelt. The electric grid of the railbelt is along the Alaska Railroad that extends from Fairbanks to Anchorage and south to Whittier in Prince William Sound and Seward on the Kenai Peninsula and provides electrical power to more than two-thirds of the entire population of the state. Despite the proximity of Cook Inlet's tidal energy resources to this infrastructure, extreme tidal ranges, suspended sediment loads, and seasonal broken sea ice in the upper Inlet create an unusual environment of extreme tidal currents, ice scouring and transport, and sediment erosion and deposition, creating challenges to any marine development or operation in the area.

The main body of Cook Inlet is a roughly 290 km-long tidal estuary along a southwest to northeast axis extending from the western Gulf of Alaska in the North Pacific Ocean (Figure 44a). At its mouth, the inlet is more than 120 km wide and narrows northward. Upper Cook Inlet also includes Turnagain and Knik arms, extending about 60 km to the east and north, respectively. Upper Cook Inlet is the area north of a constriction point called the Forelands, where the Inlet narrows to less than 20 km. Everything south of the Forelands is considered Lower Cook Inlet, although some documents further divide it into the central (or middle) and lower portions of the Inlet. Kachemak and Kamishak Bays are two additional major areas of the Inlet, inside the mouth on the east and west sides, respectively.

Cook Inlet is generally less than 70 m deep, although depths are much greater at the entrance and in several deep channels (Figure 44a). Wide shallow areas ring much of the upper and western Inlet, often revealing kilometers-wide mudflats during low tides.

The standing wave around the North Pacific amphidromic point pushes into the mouth of Cook Inlet and the shape of the Inlet basin promotes resonance of the Gulf of Alaska M_2 tide and focuses its energy at its narrow and shallow head. This amplifies the tide height compared to the rest of the Gulf of Alaska, creating a significant difference in tidal range from an average of 2-3 m at the mouth and 8 m at the head, with extreme tidal ranges approaching 12 m in the upper Inlet. These large tides produce strong currents, with some places in the Inlet averaging 2 kts and exceeding 8 kts during maximum tides in areas of extreme constriction such as between McKenzie and Cairn Points and between the West and East Forelands (Figure 44a).

The Cook Inlet watershed drains over 100,000 km^2 (Glass et al. 2004) and is bordered by the Chigmat and Alaska Ranges to the west and northwest, by the

[4] *http://www.ferc.gov/industries/hydropower/indus-act/hydrokinetics.asp*

Chugach Range and smaller Talkeetna Range to the north and northeast, and by the Kenai Mountains to the east. These ranges have ice fields and glaciers as well as significant snowfall that all contribute to seasonal inundations of freshwater to the Inlet. The interaction of Cook Inlet's unique bathymetry and geography (channels, shallow flats, constrictions, embayments, and changes in the direction of its main axis) with tidal, geostrophic, and baroclinic currents creates a complex hydrographic regime throughout the Inlet. The significant freshwater inputs into the upper Inlet create a density-driven western boundary current from north to south along the west side of upper Cook Inlet, resulting in ebb-tidal currents that are greater than flood-tidal currents. In the lower Inlet, the Alaska Coastal Current flows west and north into Cook Inlet and upwelling of colder, nutrient-rich water occurs near the entrance onto the shallow shelf. As these sources of water are transported north and west in the Inlet, they mix with the fresher water flowing south along the west side. The combination of barcolinic circulation, bathymetry, tidal forces, and geography results in especially complex circulation patterns throughout Cook Inlet, with strong vertical mixing, gyres, and shear zones that occur where southward-flowing lower salinity water meets seawater intruding westward from the entrance.

The low-salinity waters of upper Cook Inlet allow ice formation when air and water temperatures drop in late fall. Typically, by mid-November (November 24th, on average), sea ice has formed in the upper Inlet and, on average, the termination of significant ice is April 8 (Nelson and Whitney 1996). Much of the ice forms initially as shore-fast ice that is subsequently floated by high tides and remains broken and mobile. The ice can become entrained in surface currents and transported into shipping lanes, temporarily re-grounded elsewhere, converge at frontal zones, or become concentrated due to prevailing winds temporarily concentrating and packing the ice. Multiple grounding and refloating of ice pans can create multi-layered ice that can be up to 10 m thick and pose significant risk to ships or infrastructure.

The rivers that discharge into upper Cook Inlet also introduce considerable loads of suspended sediments, mainly as glacial flour. The strong tidal currents maintain these clay particles in suspension and transport them to the very shallow nearshore areas or areas of lower energy downstream. In the upper Inlet, suspended sediment loads exceeding 10,000 mg/l have been measured, concentrations greater than 2,000 mg/l are common, and average values are about 200 mg/l (Feely and Massoth 1981). In contrast, significantly lower suspended sediment concentrations are found in lower Cook Inlet, reflecting the intrusion of seawater into the lower Inlet. The enormous plumes of sediment in upper Cook Inlet are visible in satellite imagery (Figure 44b) and provide a visual "proxy" for the transport of freshwater from the upper to the lower Inlet along the west side. The interaction of suspended sediments, currents, and bluff erosion plays a major role in structuring nearshore and benthic habitats throughout Cook Inlet.

Cook Inlet Biological Habitats and Resources

The marine habitat and resources of upper Cook Inlet are influenced by extreme tides and currents, the reworking of sediments by currents and seasonal ice, high suspended sediment loads and subsequent low light transmission through the water column, low in situ primary production, and extreme salinity gradients. In Cook Inlet, these factors create a general trend of decreased marine species diversity in upper Cook Inlet, compared to the middle and lower Inlet. Despite these differences, the upper Inlet has recently been described as more productive than previously believed, with the transport of terrigenous and salt marsh carbon described as the likely carbon source to the nearshore food web (Houghton et al. 2005a).

Habitat

Overall, Cook Inlet is represented by a diverse array of intertidal and subtidal benthic habitats. Substrate sediment grain size is a significant factor defining the infaunal and epifaunal communities that dominate in the different habitats. The sediment grain size is, in turn, influenced by currents and wave energy. For example, the strong currents of the upper and central Inlet prevent subtidal deposition of most of the glacial flour that is introduced into the upper Inlet, and a significant portion is swept out of the Inlet. For much of the upper and central Inlet, especially in the channels, the strong currents ensure that the benthic habitat is swept clear of sand and mud so that gravel (from cobbles to boulders) habitat dominates. Other subtidal habitats include areas dominated by sand waves (lower Cook Inlet near the entrance) and silt/clay sediments (deepest Kachemak Bay).

Deposition of fine-grained sediments occurs in the lower energy environments of the shallow near-shore, quiet embayments, and in the eddies that form behind land projections, such as the Forelands and Point Possession. This allows mud and sandy mud to dominate in the mid- and lower intertidal and very shallow subtidal zones of upper and western Cook Inlet, especially in Knik and Turnagain arms, the Susitna and Beluga River deltas, Trading and Redoubt bays, and the backs of most of the bays on the west side of the Inlet.

Invertebrates

The extensive mud flats of Cook Inlet are an important stopover for a variety of migrating shore-birds and seabirds, including sandpipers, plovers, and dunlin (Gill and Tibbits 1999). They also provide ideal habitat for the deposit-feeding clam, Macoma balthica, which is especially abundant in muddy areas near river sources and in the lee of promontories (Lees et al. 2001) and is a major prey item of the migratory birds. This bivalve is one of the few intertidal invertebrates that occurs in upper Cook Inlet. They are the only food source for over-wintering Pribilof rock sandpipers (*Calidris ptilocnemis ptilocnmeis*) in Cook Inlet (Gill et. al. 1999), which hostsa large proportion of this rock sandpiper subspecies' entire population. Tidal currents create icescouring that scrapes the mud flats and provides ice-free areas for the birds to forage, despite the severe Cook Inlet winter conditions. M. balthic-aisalso an important prey for other shorebirds, diving birds, crabs, isopods, and fish.

Subtidal invertebrates that have been documented in upper Cook Inlet include isopods (*Aregia pugettensis*, Onisicidea), Alaska bay shrimp (*Crangon alaskensis*), California bay shrimp (*C. franciscorum*), blacktail shrimp (*C. nigricauda*), sand shrimp (Crangon spp.), brine shrimp (Lagunogrammarus setosus), mysids (*Mysis litoralis, Neomysis sp., N.kadiakensis, N. rayii, N. mercedis*), nereid polychates (Neanthes limnicola), stink bug (Pentatomidae), and aquatic sow bug (*Saduria entamom*) (Houghton et. al. 2005a and 2005b).

Fish

In Cook Inlet, salmon are important subsistence, recreational, personal-use, and commercial fish. Five salmon species occur in Cook Inlet, and all five of these species spawn in the main rivers of upper Cook Inlet. These include chinook or king salmon (*Oncorhynchus tshawytscha*), red or sockeye salmon (*O. nerka*), silver or coho salmon (*O. kisutch*), dog or chum salmon (*O. keta*), and pink or humpback salmon (*O. gorbuscha*). Adult salmon return between May and October to their natal rivers and streams to spawn, and the timing of their return within that window is species-dependent. Pink salmon can also spawn intertidally. Salmon smolts out-migrate from freshwater to the oceans from mid-April through mid-July, although they have shown up in beach seine surveys throughout the year.

Other fish species that occur in upper Cook Inlet include the demersal starry flounder (*Platichthys stellatus*), yellowfin sole (*Limanda aspera*), rock sole (*Lepidopsetta bilineata*), Pacific cod (*Gadus macro-cephalus*), and Pacific staghorn sculpin (*Leptocottus armatus*). Dominant seasonally-abundant forage fish include threespine stickleback (*Gasterosteus aculeatus*), Pacific herring (*Clupea pallasi*), walleye pollock (*Theragra chalcogramma*), capelin (*Mallotus villosus*), Pacific sandlance (*Ammodytes hexapterus*), eulachon (*Thaleichthys pacificus*), longfin smelt (*Spirinchus thaleichthys*), saffron cod (*Eleginus gracilis*), pacific sandfish (*Trichodon trichodon*), and ninespine stick-leback (*Pungitius pungitius*) (Houghton et al. 2005a, 2005b, Moulton 1997).

Birds

In addition to the migrating birds previously described as associated with foraging on tidal mud flats, there are numerous other birds that use Cook Inlet, including 30 waterfowl species, 29 shorebird species, 16 jaeger, gull, or tern species, 5 loons or grebes, 3 merganser species, 2 heron and crane species, 2 auk or puffin species, 1 shearwater species, 1 rail, and 1 cormorant. In upper Cook Inlet, the shorebirds and waterfowl are the most common.

Marine Mammals

There are few resident marine mammals in upper Cook Inlet. Beluga whales (Delphinapterus leucas) are the most abundant marine mammal species in Upper Cook Inlet, despite the fact that the population of this genetically isolated stock has declined to the point that it has recently been listed as endangered. In addition, their summer feeding range has contracted and is focused in upper Cook Inlet, critical habitat area for these whales. Harbor seals (*Phoca vitulina*) have occasionally been sighted in upper Cook Inlet, using the mud and sand flats to haul out (Rodrigues et. al. 2006). Other occasionals include gray Stellar sea lion (*Euretopias jubatus*), sea otter (*Enhydra lutris*), Dall's porpoise (*Phocoenoides dalli*), harbor porpoise (*Phoecena phoecena*), minke whale (*Balaenoptera acutorostrata*), fin whale (*Balaenoptera physalus*), and killer whale (*Orcinus orca*).

Biological Habitat and Resource Differences in Lower Cook Inlet

In general, lower and eastern Cook Inlet havewider ranges of intertidal habitats than does upper Cook Inlet and include much more rocky habitat and its associated epifauna. For example, Kamishak Bay has extensive unprotected rocky wave-cut platforms and rocky reefs. The combination of upwelled nutrients, circulation, and other environmental factors led Hood and Zimmerman (1986) to describe areas of lower Cook Inlet as being some of the most biologically productive ecosystems in the Gulf of Alaska.

Unlike the mud flats of upper Cook Inlet —where the infaunal Macoma balthica clam dominates and where few epifaunal organisms can find appropriate attachment sites or can survive the scouring sediments and seasonal ice—epifaunal algae and invertebrates dominate in the rocky intertidal habitats. Depending on wave exposure and substrate, common algae in the lower and eastern Inlet include the rockweed (*Fucus distichus =gardneri*),red algae such as *Palmaria mollis*, *P. hecatensis*, *P. callophylloides*, *Odonthalia flocossa*, *Neorhodomela aculeata*, and *Develeria ramentacea* (which dominates some exposed tidal flats in Kamishak Bay),green algae such as *Ulva* spp., *Monostroma* sp., *Chladophora sericea*, and *Acrosiphonia arcta*, kelps such as *Alaria* spp., *Laminaria spp., Agarum* spp., *Saccharina latissima*, and *S. groenlandica*, and the canopy kelps: bull kelp (*Nereocystis leutkeana*) and bull kelp (*Eularia fistulosa*).

Dominant rocky intertidal epifaunal invertebrates include blue mussels (*Mytilus trossulus*) and barnacles (*Balanus glandula, Semibalanus balanoides, S. cariosus,* and *Chthamalus dalli*). Grazers include limpets (*Lottia persona, L. pelta, L. scutum*), the perriwinkle snails *Littorina sitkana* and *L. scululata*, and numerous chitons. Numerous bryozoans, sea stars, whelks, sea cucumbers, urchins, nudibranchs, and other invertebrates occur in the low intertidal and shallow rocky nearshore environments. Lower and eastern Cook Inlet infaunal invertebrates are adapted to coarser-grained sediments, including the commercially and recreationally harvested razor clams (*Siliqua patula*), littleneck clams (*Leucoma staminea*), and butter clams (*Saxidomas gigantea*), as well as the soft-shell clam (*Mya arenaria*), numerous polychate worms, and other burrowing invertebrates.

In the 1970s and early 1980s, tanner crab (*Chionocetes bairdi*), red king crab (*Paralithodes camtschaticus), Dungeness crab (Metacarcinus magister*), northern shrimp (*Pandalus borealis*), coonstripe shrimp (*P. danae*), humpy shrimp (*P. goniurus*), sidestripe shrimp (*Pandalopsis dispar*), and scallop *(Patinopecten caurinus*) were all commercially harvested from lower Cook Inlet. These populations rapidly declined in the mid-1980s and have not returned to commercially harvestable levels, although several species have recently been open to personal-use harvests, and scallops have been commercially harvested in Kamishak Bay.

All of the birds that were reported for upper Cook Inlet also use habitat throughout the rest of Cook Inlet. The threatened Steller's eider (*Polysticta stelleri*) is also found in Cook Inlet, south of the Forelands. The marbled murrelet (*Brachyramphus marmoratus*) has been observed nesting in Cook Inlet and is considered a Bird of Conservation Concern in Alaska by the U.S. Fish and Wildlife Service. As well, most of the fish species reported in upper Cook Inlet also occur in lower Cook Inlet. However, many of them occur in much higher numbers and in commercially or recreationally harvestable sizes. Other species,such as arrowtooth flounder (*Atheresthes stomias*), butter sole(*Pleironectes isolepis*), and black cod or sablefish (*Anoplopoma fimbria*), occur in lower Cook inlet that have not been reported for upper Cook Inlet. Gray whales (*Eschrichtius robustus*) and humpack whales (*Megaptera novaeangliae*) are also commonly seen seasonally in lower Cook Inlet.

Cook Inlet – Potential Stressors of Tidal Energy Development

As previously described, there is significant interest in tidal energy development projects in upper Cook Inlet, as well as in other areas throughout the Inlet. Currently, the area west of Fire Island in upper Cook Inlet is under intense evaluation for the planned in-water installation and testing of a group of TideGen turbines by Ocean Renewable Power Company, LLC, (ORPC) by 2011 or 2012. Environmental and site characterization studies have been ongoing, as has consultations with federal and state agencies. Many of the required studies have been completed, and concerns raised by most agencies have already been addressed. The main concerns for this project have included:

- Conflict with existing uses, such as shipping and commercial fishing (nearby salmon set-net sites)
- Difficulty in maintaining turbines in high suspended sediment and seasonal sea ice environment
- Turbine strikes on fish and marine mammals, especially to endangered beluga whales.
- Changes to hydrodynamics and sediment transport that might impact sediment deposition for important prey species such as Macoma clams that rely on a specific habitat for deposit-feeding.
- Alterations to marine habitat and benthos (vegetation and invertebrates) due to dredging or infrastructure placement
- Avoidance of habitat by mobile organisms such as forage fish —prey of beluga whales
- Collisions/entanglements
- Underwater noise/vibration; and
- Electromagnetic radiation fields.

Field surveys and studies, literature reviews, modeling, and negotiated mitigation measure development are on-going by ORPC and its contractors. These data will be used to determine detailed monitoring that will be required during in-water deployments of the turbines.

Biological Habitats and Resources of Other Potential Tidal Energy Sites in Alaska

The currents in Cross Sound and Icy Strait areas of northern Southeast Alaska (Figure 43) have the potential to produce enough energy to meet regional needs and for export (Polagye and Bedard 2006). These areas are the main routes of tidal exchange for water moving from the northern part of the southeast Alaska panhandle to the Gulf of Alaska. However, before placing in-water turbines in the area, there are concerns particular to these areas that must be considered. The strait is an important shipping route for vessels that use the inside passage (inland water of southeast Alaska panhandle) before entering the Gulf of Alaska and is a scheduled route for Alaska Marine Highway ferries. Thus any infrastructure would have to allow for safe shipping navigation.

The area is a significant feeding and refuge area for many marine species that thrive in these extremely productive waters, including many important commercial, subsistence, personal-use, and sport harvests. For example, all five species of Pacific salmon, as well as Dungeness, tanner, and king crabs, scallops, shrimp, black cod, and herring are supported by these waters. The strong currents and tidal mixing in the area provide nutrients for primary production and secondary production that is transported throughout the area and concentrated by local flow patterns and frontal systems. These concentrations attract small schooling fishes such as herring and the nearshore areas are important habitat for other forage fish such as juvenile walleye pollock, juvenile salmonids, sandlance, and capelin. These concentrations of pelagic food attract feeding marine mammals, and there is significant use by humpback whales.

Concentrations of zooplankton and herring attract feeding marine mammals. Humpback whales heavily use some concentration areas of Icy Strait. Sea otters have recently been re-colonizing the waters of Icy Strait and Cross Sound and rely on nearshore areas for foraging. Any development of tidal energy projects in these waters must progress with careful attention to protecting sensitive environments and species through close consultation with state, federal, and local laws and regulations.

In addition to the major tidal energy potential described for Icy Strait and Cross Sound, numerous high quality (strong power density) but small (in terms of cross-sectional area) sites have been identified that can provide local power (Polagye and Bedard 2006). These areas tend to be in narrow passes or inlets and have the potential to interfere with safe navigation. They are often important passages for marine fish, feeding birds, and marine mammals. The abundance of rocky nearshore habitat and high currents in these areas are prime conditions for canopy kelps. Three canopy kelps occur in nearshore waters of southeast Alaska, including bull kelp, dragon kelp, and giant kelp (*Macrocystis porifera = integrifolia*). All of these provide important habitat for many invertebrates and fish, including early life stages of many commercially important species.

Discussions on tidal energy development in Alaska have also included the potential in numerous eastern Aleutian Island Passes (Figure 43). The Unimak Pass is a major transportation route for ships transiting a great circle route from the west coast of the United States and Asia. The major flow through Unimak Pass is from the Gulf of Alaska into the Bering Sea. This flow periodically reverses itself, given the right atmospheric storm conditions. The pass is approximately 18 km wide at its narrowest point and, generally, is less than 100 m deep —relatively shallow in comparison with major passes farther west in the Aleutian chain.

Areas within about 10 km of land in these narrow straits between islands are generally less than 60 m deep, and several shallow banks occur in the area. These can be important feeding areas for marine mammals and, together, the passes comprise a major migration corridor for mammal populations entering and leaving the Bering Sea, especially for gray and humpback whales. There are two records of another endangered whale, the right whale (Eubalaena glacialist) reported from Unimak Pass. Steller sea lions are year-round residents and have numerous haul-outs in the Aleutian Islands. Sea lion populations have followed a downward trend in the eastern Aleutian Islands since the late 1970s.

Again, any development of tidal energy projects in these waters must progress with careful attention to protecting these area-specific, sensitive environments and species through close consultation with state, federal, and local laws and regulations.

Table 12 – Pending and Issued FERC permits for hydrokinetic energy projects in Alaska.

Status	Docket No.	Project Name	Licensee	Waterway	Authorized MW	Issue Date	Expiration Date
Issued	P-13298	Port Clarence	Alaska Village Elec. Coop Inc.	Port Clarence	0.3	05/08/09	04/30/12
Issued	P-13509	Turnagain Arm Tidal	Turnagain Arm Tidal Energy	Cook Inlet	2.2	02/05/10	01/31/13
Issued	P-13605	Icy Passage Tidal	Natural Currents Energy Services, LLC	Pacific Ocean	0.3	04/30/10	03/31/13
Issued	P-13606	Gastineau Channel Tidal	Natural Currents Energy Services, LLC	Gastineau Channel	400	04/30/10	03/31/13
Pending	P-12679	Cook Inlet Tidal Energy	ORPC Alaska, LLC	Cook Inlet	5.0	4/1/2010	---
Pending	P-13821	East Foreland Tidal Energy	ORPC Alaska 2, LLC	Cook Inlet	5.0	8/2/2010	---
Pending	P-13823	Killisnoo Tidal Energy	Natural Currents Energy Services LLC	Kootznahoo Inlet	0.25	8/5/2010	---

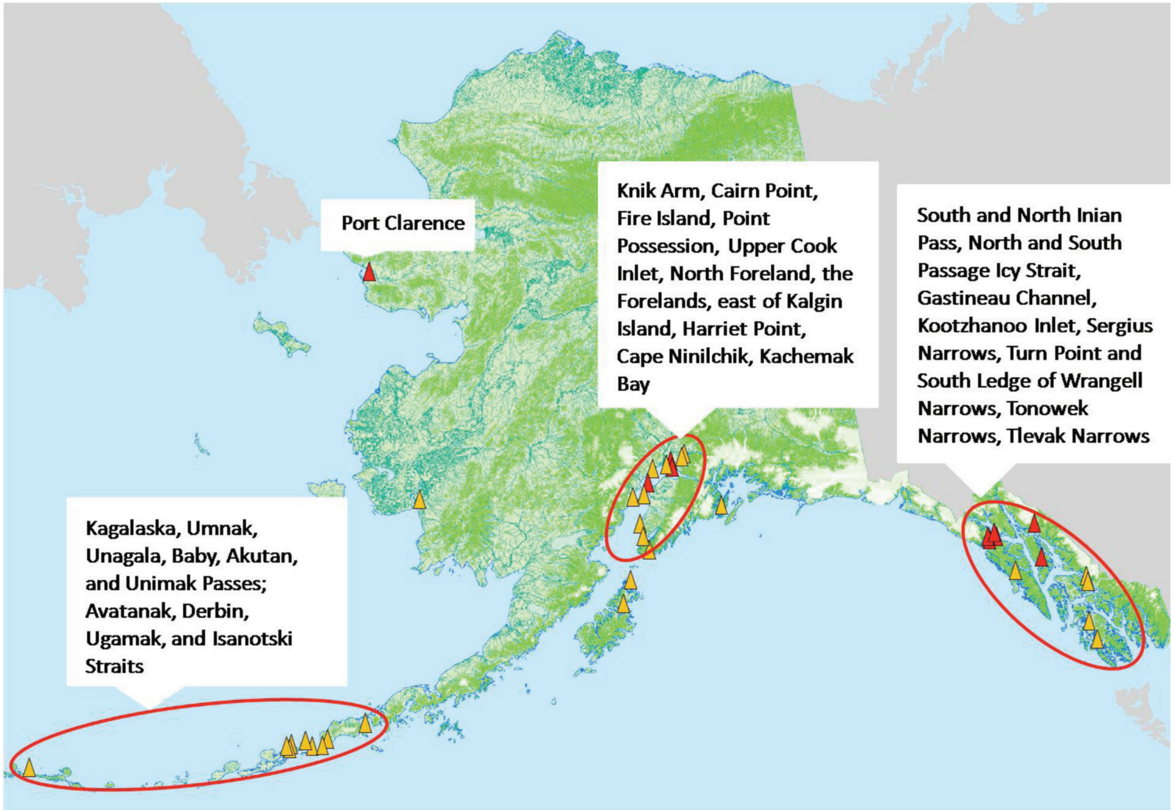


Figure 43 – Areas of significant hydrokinetic energy potential in Alaska (yellow triangles) and areas with pending or issued FERC permits (red triangles, Table 12).

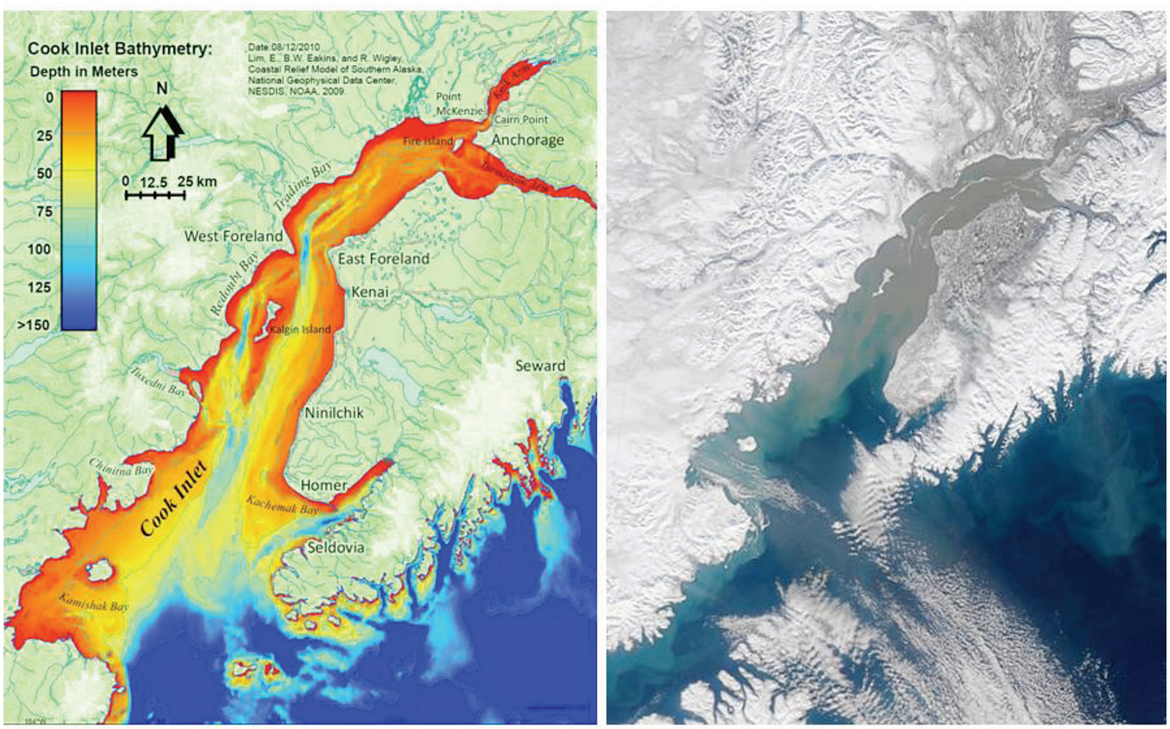


Figure 44 – Cook Inlet bathymetry (left) and satellite image showing suspended sediment plumes (right, ORBIMAGE)

References

Alaska Energy Authority. 2009. *Renewable Energy Atlas of Alaska: A Guide to Alaska's Clean, Local, and Inexhaustible Energy Resources.* Report by Alaska Energy Authority and Renewable Energy Alaska Project.

Bartsch-Winkler, S. and Ovenshine, A.T. 2004. Macrotidal subarctic environment of Turnagain and Knik arms, upper Cook Inlet, Alaska; sedimentology of the intertidal zone. *Journal of Sedimentary Research*, 54(4): 1221-1238.

Feely, R.A. and Massoth, G.J. 1982. *Sources, composition, and transport of suspended particulate matter in Lower Cook Inlet and northwestern Shelikof Strait, Alaska.* NOAA Technical Report ERL-415 PMEL-34.

Gill, R.E., Jr. and Tibbitts, T.L. 1999. *Seasonal shorebird use of intertidal habitats in Cook Inlet, Alaska*. Final Report. U.S. Department of Interior, U.S. Geological Survey, Biological Resource Division and OCS Studies, MMS 99-0012.

Glass, R.L., Brabets, T.P., Frenzel, S.A., Whitman, M.S. and Ourso, R.T. 2004. *Water quality in the Cook Inlet basin Alaska*, 1998– 2001. U.S. Department of Interior, U.S. Geological Survey, Circular 1240.

Haley, B., Tomlins, G., Smith, O., Wilson, W. and Link, M. 2000. *Mapping Cook Inlet rip tides using local knowledge and remote sensing.* Report prepared by LGL Alaska Research Associates, Inc., Anchorage, AK, Pacific Geomatics, Ltd., Surrey B.C, Canada, and the University of Alaska, Anchorage, AK., for the U.S. Department of Interior, Minerals Management Service.

Hood, D.W. and Zimmerman, S. (Eds.). 1986. *The Gulf of Alaska: Physical Environment and Biological Resources.* U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Houghton, J., Starkes, J., Chambers, M. and Ormerod, D. 2005a. *Marine fish and benthos studies in Knik Arm, Anchorage, Alaska.* Report prepared for the Knik Arm Bridge and Toll Authority, and HDR Alaska, Inc., Anchorage, AK, by Pentec Environmental, Edmonds, WA.

Houghton, J., Starkes, M. Chambers, and D. Ormerod. 2005b. *2004-2005 marine fish and benthos studies-Port of Anchorage, Anchorage, Alaska.* Report prepared by Pentec Environmental, Edmonds, WA, for Integrated Concepts and Research Corporation.

Lees, D.C., Driskell, W.B., Payne, J.R. and Hayes, M.O. 2001. *Final report of CIRCAC intertidal reconnaissance survey in Upper Cook Inlet.* Prepared for Cook Inlet Regional Citizens Advisory Council, Kenai, AK.

Naidu, A.S., Feder, H.M., Foster, N., Geist, C. and Rivera, P.M. 1992. *Macoma balthica monitoring study at Dayville Flats, Port Valdez*. Draft final report. Submitted to Alyeska Pipeline Service Company, Anchorage, AK.

Nelson, W.G. and Whitney, J.W. 1996. A description of summer and winter environmental conditions within Cook Inlet, Alaska. *Society of Petroleum Engineers paper #SPE 35688* presented at the Western Regional Meeting, Anchorage, AK, May 22-24, 1996.

Polagye, B. and Bedard, R. 2006. *Tidal in-stream energy resource assessment for southeast Alaska.* Report to Alaska Energy Authority, Electric Power Research Institute Tidal In Stream Energy Conversion Reports, TP-003.

Polagye, B. and Previsic, M. 2006. *System level design, performance, cost and economic assessment – Knik Arm Alaska tidal in-stream power plant.* Electric Power Research Institute Tidal In Stream Energy Conversion Reports, TP-006.

Rodrigues, R., M. Nemeth, T. Markowitz, and D. Funk. 2006. *Review of literature on fish species and beluga whales in Cook Inlet, Alaska.* Final report prepared by LGL Alaska Research Associates, Inc., Anchorage, AK, for DRven Corporation, Anchorage, AK.

Whitney, J. 2002. Cook Inlet, Alaska: *Oceanographic and Ice Conditions and NOAA's 18-year Oil Spill Response History 1984-2001.* NOAA HAZAMAT Report 2003-01.

Appendix C — Workshop Participant List

Session chairs and their sessions are presented in boldface type.

Name	Affiliation	Receptor Group	Stressor Group
Adonizio, Mary Ann	Verdant Power	Fish: resident	Devices: dynamic effects
Agness, Alison	NOAA Fisheries, Northwest Region, Protected Resources Division	Marine mammals and seabirds	Devices: dynamic effects
Ainsworth, David	Marine Current Turbines, Ltd.	Marine mammals and seabirds	Devices: dynamic effects Chemical effects
Albertson, Skip	Washington Dept. of Ecology	Physical environment: far-field	Cumulative effects
Anderson, Richard	Pacific Northwest National Laboratory	Fish: migratory	Chemical effects
Baldwin, David	NOAA Fisheries - Northwest Fisheries Science Center	Physical environment: far-field	Chemical effects
Balla-Holden, Andrea	U.S. Navy	Physical environment: far-field	Energy removal
Barr, Sue	OpenHydro Group, Ltd.	Ecosystem interactions	**Devices: dynamic effects**
Bhuyan, Gouri	Powertech Labs	Physical environment: near-field	**Electromagnetic effects**
Bishop, Alicia	NOAA Fisheries, Northwest Region, Hydropower Division	Ecosystem interactions	Electromagnetic effects
Boyd, Ian	Sea Mammal Research Unit, University of St. Andrews	Ecosystem interactions	Cumulative effects
Breen, Joe	Northern Ireland Environment Agency	Marine mammals and seabirds	Cumulative effects
Brennan, Jim	Washington Sea Grant	Fish: migratory	Cumulative effects
Browne, Peter	HDR, Inc.	Habitat and invertebrates	Acoustic effects
Boehlert, George	Oregon State University	Steering Committee	Steering Committee
Cada, Glenn	Oak Ridge National Laboratory	Habitat and invertebrates	Devices: dynamic effects
Collar, Craig	Snohomish County Public Utility District	Habitat and invertebrates	Devices: static effects
Copping, Andrea	Pacific Northwest National Laboratory	Steering Committee	Steering Committee
Couch, Scott	University of Edinburgh	Physical environment: far-field	**Energy removal**
Courtenay, Simon	Fisheries and Oceans Canada	Fish: resident	Devices: static effects
Daborn, Graham	Acadia University	Habitat and invertebrates	Cumulative effects
Dahl, Peter	University of Washington	Physical environment: near-field	**Acoustic effects**

Session chairs and their sessions are presented in boldface type.

Name	Affiliation	Receptor Group	Stressor Group
Eckert, Ginny	University of Alaska - Fairbanks	Ecosystem interactions	Devices: static effects
Fresh, Kurt	NOAA Fisheries - Northwest Fisheries Science Center	**Fish: migratory**	Devices: dynamic effects
Geerlofs, Simon	U.S. Department of Energy	Habitat and invertebrates	Acoustic effects
Gill, Andrew	Cranfield University	Fish: migratory	Electromagnetic effects
Gill, Gary	Pacific Northwest National Laboratory	Physical environment: near-field	**Chemical effects**
Goetz, Fred	U.S. Army Corp of Engineers	Fish: migratory	Devices: dynamic effects
Goodman, Layna	U.S. Navy	Physical environment: near-field	chemical effects
Hanson, Brad	NOAA Fisheries - Northwest Fisheries Science Center	Marine mammals and seabirds	Devices: dynamic effects
Horning, Markus	Oregon State University	**Marine mammals and seabirds**	Electromagnetic effects
Jacobson, Paul	Electric Power Research Institute	Ecosystem interactions	Chemical effects
Johnston, Sam	Hydroacoustic Technology, Inc.	Fish: migratory	Devices: static effects
Johnson, Jerry	University of Alaska - Fairbanks	Physical environment: near-field	Electromagnetic effects
James, Scott	Sandia National Laboratories	Physical environment: far-field	Energy removal
Kajiura, Stephen	Florida Atlantic University	Fish: resident	Electromagnetic effects
Kagley, Anna	NOAA Fisheries - Northwest Region, Science Center	Fish: migratory	Devices: static effects
Kawase, Mitsuhiro	University of Washington	**Physical environment: far-field**	Energy removal
Kirkendall, Keith	NOAA Fisheries, Northwest Region, Hydropower Division	Steering Committee	Steering Committee
Kramer, Sharon	H.T. Harvey & Associates	Fish: resident	**Devices: static effects**
Livingston, Pat	NOAA Fisheries - Alaska Fisheries Science Center	Fish: resident	Cumulative effects
Mate, Bruce	Oregon State University	Marine mammals and seabirds	Acoustic effects
McCleave, Jim	University of Maine	Fish: migratory	Devices: static effects
McClure, Bob	BioSonics, Inc.	Fish: resident	Acoustic effects
McMahon, Neil	Alaska Energy Authority	Physical environment: near-field	Energy removal
McMurray, Greg	Pacific Energy Ventures	**Ecosystem interactions**	Electromagnetic effects
Mumford, Tom	Washington Department of Natural Resources	**Habitat and invertebrates**	Cumulative effects
Norris, Jenny	European Marine Energy Center	Ecosystem interactions	**Cumulative effects**
Palsson, Wayne	Washington Department of Fish and Wildlife	**Fish: resident**	Devices: static effects

Session chairs and their sessions are presented in boldface type.

Name	Affiliation	Receptor Group	Stressor Group
Parrish, Julia	University of Washington	Marine mammals and seabirds	Devices: static effects
Polagye, Julia	University of Washington	Steering Committee	Steering Committee
Previsic, Mirko	re vision consulting, LLC.	Physical environment: far-field	Electromagnetic effects
Rawson, Kit	Tulalip Tribes	Fish: migratory	Acoustic effects
Redman, Scott	Puget Sound Partnership	Ecosystem interactions	Chemical effects
Ruggerone, Greg	Natural Resource Consultants	Fish: migratory	Devices: dynamic effects
Saupe, Sue	Cook Inlet Regional Citizens Advisory Committee	Ecosystem interactions	Cumulative effects
Savage, Kate	NOAA Fisheries - Alaska Regional Office, Protected Resources Division	Marine mammals and seabirds	Electromagnetic effects
Savidge, Graham	University of Queens	Physical environment: near-field	Energy removal
Simenstad, Charles (Si)	University of Washington	Habitat and invertebrates	Energy removal
Simmons, Harper	University of Alaska - Fairbanks	Physical environment: far-field	Energy removal
Smith, Joanna	The Nature Conservancy	Marine mammals and seabirds	
Spring Harris, Melanie	NOAA Fisheries, Office of Habitat Conservation	Fish: resident	Devices: static effects
Thomson, Jim	University of Washington	**Physical environment: near-field**	Acoustic effects
Thresher, Bob	National Renewable Energy Laboratory	Physical environment: near-field	Devices: dynamic effects
Tollit, Dominic	Sea Mammal Research Unit, Ltd.	Marine mammals and seabirds	Acoustic effects
Trim, Heather	People for Puget Sound	Habitat and invertebrates	Chemical effects
Van Cleve, Brie	Pacific Northwest National Laboratory	Steering Committee	Steering Committee
Wainstein, Michelle	Washington Sea Grant	Steering Committee	Steering Committee
Walker, Sue	NOAA Fisheries - Alaska Region, Habitat Conservation	Steering Committee	Steering Committee
Worthington, Monty	Ocean Renewable Power Company	Marine mammals and seabirds	Energy removal
Wyllie-Echeverria, Tina	Wyllie-Echeverria Associates	Fish: resident	Acoustic effects
Young, Tina	U.S. Environmental Protection Agency	Habitat and invertebrates	Chemical effects
Zydlewski, Gayle	University of Maine	Marine mammals and seabirds	Devices: dynamic effects

Appendix D — Workshop Agenda

Monday, March 22

Opening Lecture: Changing Tides – Developing Best Practices for the Tidal Energy Industry

Sue Barr, Open Hydro .... 1900-2030: 110 Kane Hall

Tuesday, March 23

Plenary Sessions... 0830-1230: Mary Gates Hall Auditorium

- Simon Geerlofs, U.S. Department of Energy
- Graham Daborn, Acadia University
- Jim McCleave, University of Maine
- Andrea Copping, Pacific Northwest National Laboratory
- Sue Saupe, Cook Inlet Regional Citizens Advisory Committee

Stressor Breakout Groups .... 1400-1630: Mary Gates Hall breakout rooms

Stressor Group Recap .... 1630-1730: Mary Gates Hall Auditorium

Evening Reception .... 1800-2000: Burke Museum

Wednesday, March 24

Regroup.. 0830-0900: Mary Gates Hall Auditorium

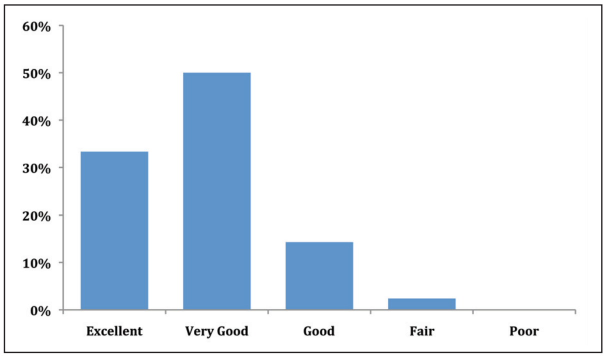
Receptor Breakout Groups... 0900-1130: Mary Gates Hall breakout rooms

Stressor Breakout Groups .... 1400-1530: Mary Gates Hall breakout rooms

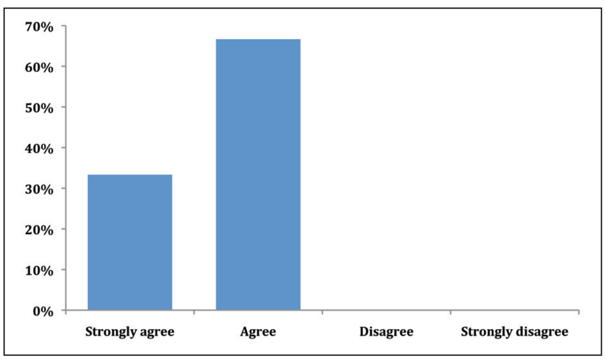
Wrap Up .... 1530-1600: Mary Gates Hall Auditorium

Appendix E — Workshop Evaluation Results

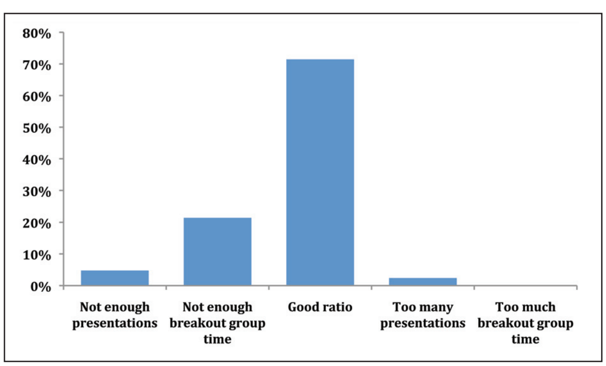
1. Rate the overall quality of the workshop (42 responses)



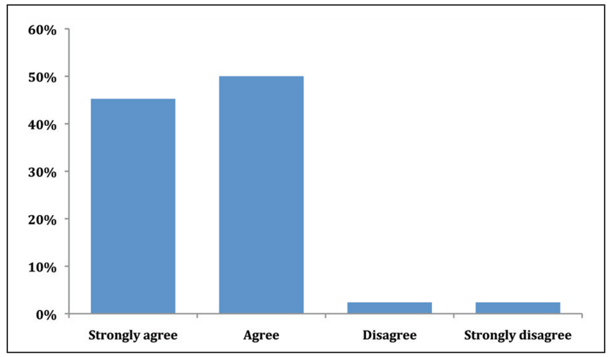
2. The goals of the workshop were clear (42 responses)



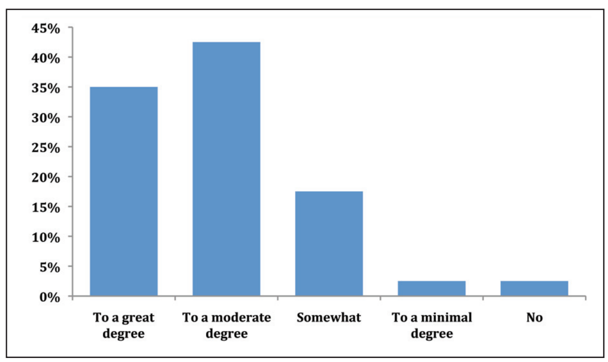
3. Select all that apply to the balance between presentations (plenary) and breakout groups (42 responses)



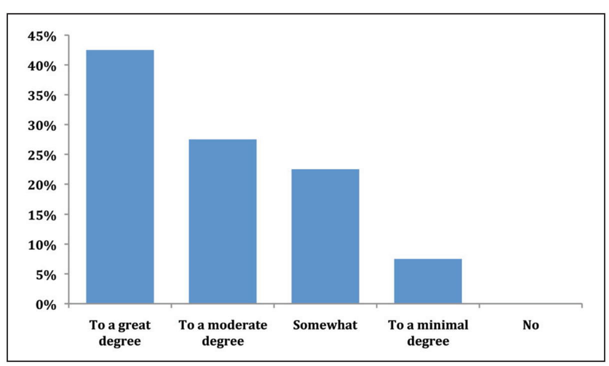
4. The design of the workshop facilitated exchange of expertise among participants (42 responses)



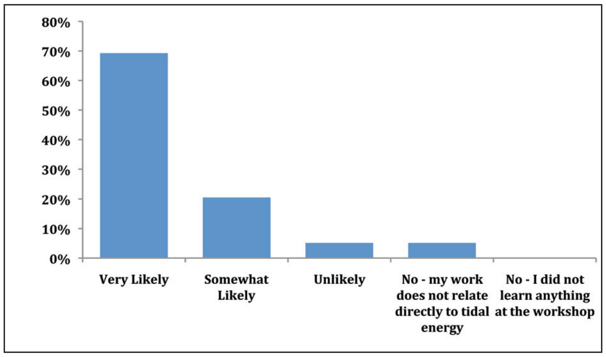
5. Did this workshop increase your understanding of potential impacts of tidal energy development on the ocean environment? (40 responses)



6. Has this workshop provided you new viewpoints and insights? (40 responses)



7. Will you apply information learned at this work shop to tidal energy-related projects? (39 responses)



8. What was most valuable about this workshop?
    - Diversity of expertise assembled to address questions.
    - Stressor/receptor breakout group discussions.
    - Interaction and networking opportunities.

9. What was least valuable about this workshop?
    - Time spent populating stressor/receptor matrices.
    - Time limitations for breakout groups.
    - Frustrations with having to generalize stressor/receptor interactions when concerns were specific to sites, species, and devices.

10. How would you improve similar workshops?
    - Additional time within each breakout group (+1 day).
    - Focus on specific scenarios, rather than general cases.
    - Presentations by device developers on what monitoring and mitigation approaches have been employed as part of their projects.

NOAA Technical Memorandum NMFS F/SPO-116