ANL/EVS/R-11/12

Conceptual Models of Potential Marine and Hydrokinetic Technology Impacts on Biological Resources

FY2012 Final Report:
Subtask 2.1.1.2 Impacts of Individual and Multiple Stressors
Subtask 2.1.1.4 Impacts of MHK Arrays
Subtask 2.1.1.5 Cumulative Impacts of Anthropogenic Stressors

Environmental Science Division

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1 INTRODUCTION TO ECOLOGICAL RISK ASSESSMENT

The U.S. Environmental Protection Agency (EPA) defines ecological risk assessment as the process of evaluating "…the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more stressors" (EPA, 1998).

The EPA identified multiple steps in performing an ecological risk assessment (EPA, 1998). The first step is problem formulation, which consists of systematically identifying potential stressors, exposure routes, and ecological effects. The critical step in problem formulation is the development of a conceptual model that diagrammatically identifies how a stressor may affect ecosystem receptors, as well as the appropriate risk assessment endpoints (measurable ecological variables) needed to test risk hypotheses about stressor and receptor interactions (EPA, 1998).

The EPA has identified several practical benefits from developing conceptual models, shown in Table 1. Aside from the utility of such models for clearly and visually communicating risk, the formation of a conceptual model allows one to understand linkages between biotic and abiotic variables within an ecosystem; develop risk hypotheses about which receptors are most likely to be adversely affected; and identify the data needed to characterize risk probability. In the case of a marine and hydrokinetic technology (MHK) device, an example of a risk hypothesis could be that noise from device operations (the stressor) could exceed the tolerance thresholds of demersal fish species (receptors), resulting in avoidance of the MHK device and a subsequent decrease in the abundance of affected species (assessment endpoint) in the vicinity of the device.

TABLE 1. Benefits of Developing Conceptual Models

1. The process of creating a conceptual model is a powerful learning tool.
2. Conceptual models are easily modified as knowledge increases.
3. Conceptual models highlight what is known and not known and can be used to plan future work.
4. Conceptual models can be powerful communication tools. They provide an explicit expression of the assumptions and understanding of a system for others to evaluate.
5. Conceptual models provide a framework for prediction and are the template for generating more risk hypotheses.

Source: *Guidelines for Ecological Risk Assessment* (EPA, 1998).

In addition, conceptual models identify known and assumed linkages between receptors (both species and habitat), so that hypotheses concerning indirect stressor effects can be formulated. For example, an MHK device may not affect an organism directly (i.e., blade strikes, noise) but rather, indirectly — by disturbing habitat or reducing the abundance of a required food resource. Such higher-order interactions can be predicted by following the receptor linkages within the conceptual model.

The second phase of risk assessment is the analysis phase. In the analysis phase, the risk hypotheses identified in the conceptual models are evaluated. The evaluation includes characterizing the exposure of specific receptors to the stressor and characterizing the ecological effects of that exposure. We began the analysis phase in FY 2011. The analysis phase must be data informed and the lack of data collected at actual MHK deployments has been problematic. The analysis phase will continue in FY 2012 as more data become available on the ecological effects of MHK deployments and the biological effects thresholds of biota exposed to potential MHK stressors.

The third and final phase of the EPA risk assessment process is risk characterization in which the assumptions, scientific uncertainties, and strengths and limitations of the analyses are presented. Following risk characterization, the risks are communicated to managers. Although the overall workflow of the problem formulation phase, the analysis phase, and the risk characterization phase is sequential, there exists a strong feedback between the analysis phase and the problem formulation phase. For example, data collected during the analysis phase can generate new risk hypotheses or eliminate risk hypotheses identified in the problem formulation phase. For the DOE sponsored Market Acceleration Program, this feedback is exemplified by our use of monitoring or experimental data generated by industry and other labs to revise the linkages in the conceptual models. In turn, the conceptual models can be used to direct research by the other National Labs.

2 IMPACTS FROM A SINGLE MHK DEVICE'S OPERATIONS

There are numerous recent and comprehensive reviews summarizing the potential ecological impacts of MHK construction and operations (EPRI, 2004; Gill, 2005; Michel et al., 2007; Wilson et al., 2007; Boehlert et al., 2008; Nelson et al., 2008; U.S. Department of Energy, 2009; Boehlert and Gill, 2010; Polagye et al., 2010; Kramer et al., 2010; Frid et al., 2011). Therefore, the goal of Section 2 is not to provide another assessment of the ecological risks associated with MHK technology, but rather to synthesize these reports into a set of conceptual models and formulate risk hypotheses that identify the appropriate ecological endpoints to be evaluated under 2.1 Market Acceleration subtasks 2.1.2 and 2.1.3. The conceptual models described in this report summarize the recent reviews mentioned above and therefore show all of the potential risks associated with MHK technology as identified by experts. A draft of the report "Conceptual Models of Potential Marine and Hydrokinetic Technology Impacts on Marine Resources" was sent to 22 individuals representing the National Marine Fisheries Service, Bureau of Ocean and Energy Management, the U.S. Fish and Wildlife Service, the Federal Energy Regulatory Commission, and the U.S. Geological Survey. Three individuals provided reviews. The report was modified to reflect the concerns of the reviewer as appropriate. Comments are available upon request. **It should be understood that many of the stressor-receptor linkages identified in the conceptual models, though identified by subject matter experts, are speculative because there have been relatively few field deployments of MHK devices**. With new data specific to real MHK field deployments, many of these linkages may be revealed to be insignificant during the analysis phase of the risk assessment (Section 5.1). See Section 5 for a preliminary review of the existing ecological studies of actual MHK deployments.

2.1 Effects on Habitat

For a single MHK device and its associated infrastructure (e.g., transmission lines, anchors, mooring lines, and docking stations), the spatial extent of significant habitat alteration is likely to be relatively local, with changes occurring primarily in the MHK footprint and in the immediate vicinity. A major concern for commercial-scale MHK projects is that ecosystem-level impacts may result from the deployment of multiple MHK devices that create large-scale changes in habitat (Figure 1). These potential ecosystem-level impacts will be discussed in Section 3.2. Potential habitat impacts from a single MHK device and its associated infrastructure may include the following:

- Loss of natural bottom from device and infrastructure placement;
- Alteration of benthic hydrodynamics and change in local patterns of sediment scour and deposition during construction and operations (Shields et al., 2011);
- Sediment scouring from the movement of unsecured transmission cables and anchor chains (Shields et al., 2011). Additional episodic scour or habitat

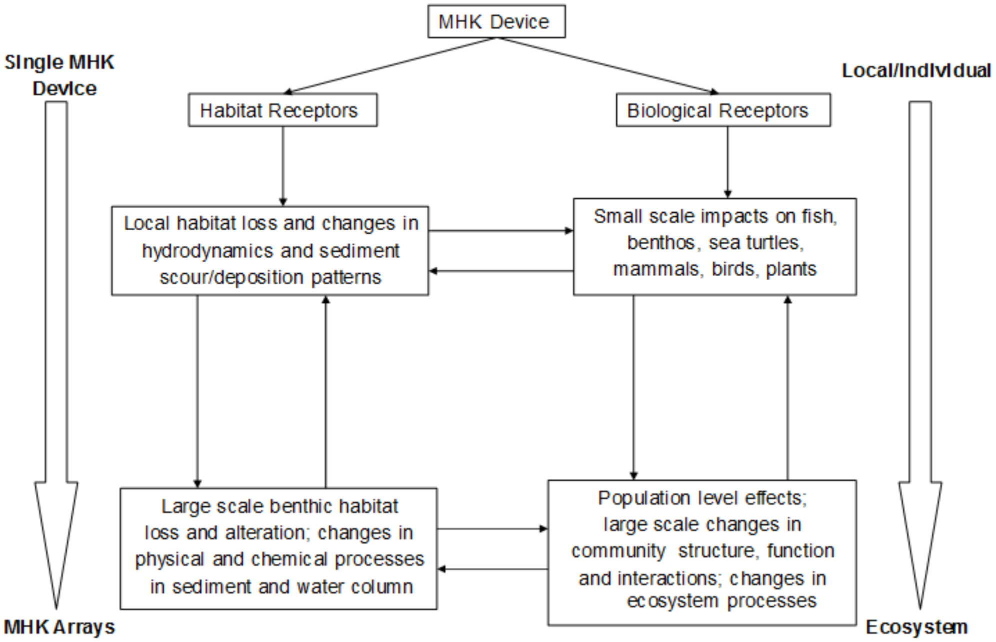

FIGURE 1. Hypothesized Effects of a Single MHK Device and MHK Device Arrays on Ecosystem Receptors

damage may occur if a wave energy converter (WEC) or associated infrastructure breaks free from its moorings;

- Alteration of local sediment characteristics by deposition of organic matter and shell material from biofouling communities that form on the device;

- Trapping of fine and large organic matter by the device structure, particularly in rivers;

- Change in the light field from platform lighting. Birds (Montevecchi, 2006) and fish (Keenan et al., 2007) are particularly likely to respond to changes in the light field; and

- Release of lubricants and the leaching of anti-fouling coatings that are applied as part of the regular device maintenance.

Bottom substrate types potentially affected by an MHK device include vegetated bottom; oyster and mussel beds; coral reefs; rock bottom; live hard bottom; and sediments composed of mud, sand, gravel, and cobble; often distributed in a patchy mosaic across the bottom. Loss of natural aquatic bottom as a result of MHK device and transmission line placement could affect all sediment types. However, device placement is not likely to be permitted in sensitive benthic habitats such as coral reefs; seagrass; shellfish beds; macroalgal beds; and in freshwater areas with a high density of mussels; therefore, direct effects on these critical habitats are unlikely.

The potential for MHK deployments to alter benthic habitat largely depends on sediment type. Impacts from scour could be greatest for live bottom and reef habitats because of the high density and sensitive nature of reef biota. However, siting requirements would likely avoid these habitats; thereby, minimizing the potential for impacts. Soft sediments, particularly mud and fine sands, are easily resuspended and therefore easily disturbed by physical and hydrodynamic alterations to the sediment. In soft sediments, altered hydrodynamics in the vicinity of the MHK device could potentially create scour on the lee side of the device, which could increase grain size or remove sediment entirely (Boehlert and Gill, 2010). This resuspended material could settle in depositional areas downstream of the MHK device where flow is reduced. Organic matter trapping (e.g., silt and plant material) and deposition of shell or organic matter from biofouling organisms could also alter grain size in the vicinity of the device as they do around oil platforms (Boehlert and Gill, 2010).

Contaminants from anti-biofouling coatings would accumulate less in bare rock substrate, while muddy, organic-rich sediments have the greatest chance of retaining such contaminants (Chapman, 1992). Similarly, the potential for the reintroduction of buried contaminants into the water column would be highest in muddy, organic-rich sediments that are often found in estuaries and river beds where resuspension could occur as a result of riverine flows and tides. However, contaminant issues will likely be minor for a single device deployment and will be discussed in greater detail in Section 3.2.

2.2 Effects on Biota

Direct impacts on biota from a single MHK device can result from the structure and placement of the device, device operation, device maintenance activity, and the construction and physical presence of transmission lines (Figure 2). As indicated in Figure 2, noise, electromagnetic fields (EMFs), strikes, and structure-induced behavioral changes have the potential to affect virtually all categories of aquatic organisms (U.S. Department of Energy, 2009).

Pressure changes, entrainment, cavitation, blade strike, and noise have all been cited in the existing literature as being potential concerns associated with MHK device operations (Figure 2). For current-based MHK technology, the potential for pressure changes to kill or injure organisms is considered very unlikely and cavitation is expected to only exist in a relatively small, localized area that is downstream of the turbine (EPRI, 2011). At this time, both the frequency and intensity of cavitation events associated with MHK devices is unknown, and it requires more study. WEC, tidal, and riverine MHK operations may entrain plankton (including the eggs and larvae of fish and invertebrates), potentially resulting in injury and mortality of the entrained biota. Overtopping and linear attenuating WEC devices also have the potential to trap or inhibit the offshore migration of hatchling sea turtles. For a single device, mortality from entrainment would likely be too low to affect population dynamics, assuming the device was sited to avoid important habitats.

Organisms have the potential to collide with structural components of WEC and current-based MHK technologies. Mammals, sea turtles, fish, diving birds, and large invertebrates (such

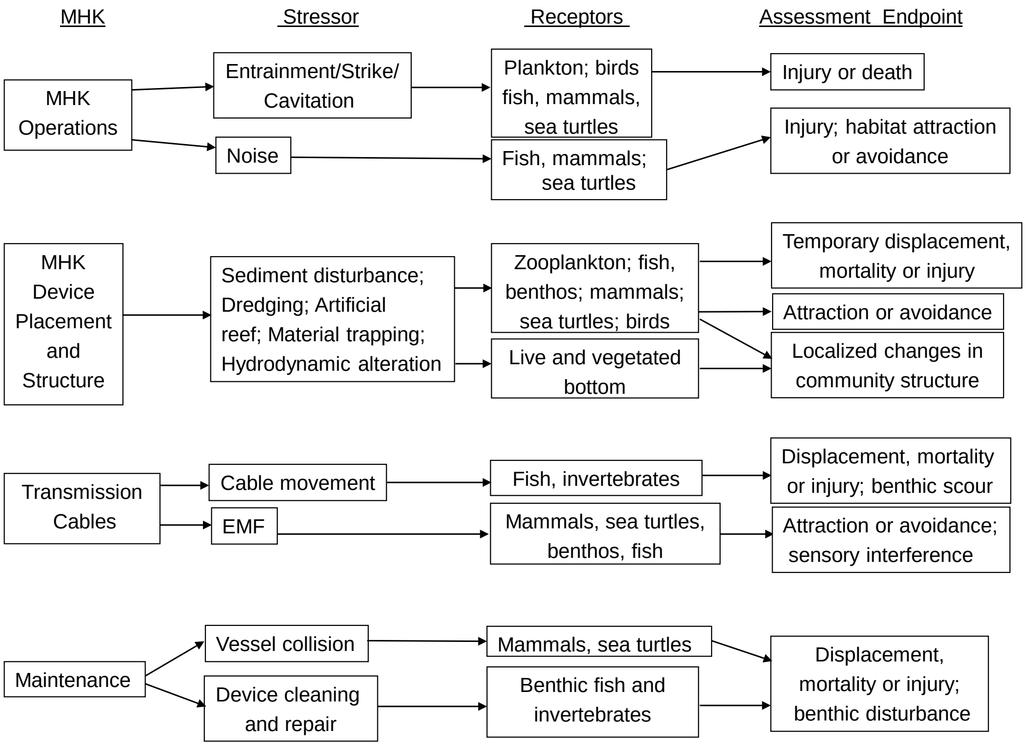

FIGURE 2. Hypothesized Effects on Aquatic Biota from a Single MHK Device

as jellyfish) all may potentially be affected (Wilson et al., 2007; Grecian et al., 2010; Langton et al., 2011; Furness et al., 2012). Collision risk may also be affected if the device acts as an attractant (e.g., an artificial reef), and by the degree to which flow changes; EMF and noise generated by a device will act to attract or repel biota. The risk of collision with an MHK device is largely unstudied for all animals but fish, but it is expected to vary with device design, current speed, and receptor characteristics. Although risk may differ by MHK device, the existing laboratory and field studies of adult fish and MHK turbine interactions do not suggest that there is a significant risk of collision (See Section 5). An analysis of the potential for collision risk with marine mammals is being conducted under subtask 2.1.3 *Effects on Aquatic Organism.*

Both WEC and current-based MHK technology will generate noise during construction and operation, which may result in attraction or avoidance behavior in mammals, sea turtles, fish, and invertebrates (Boehlert and Gill, 2010; Langton et al., 2011; Gill et al., 2012). Noise generated by MHK devices could adversely affect aquatic organisms if it alters their movement patterns in a way that increases energy expenditure or reduces food acquisition (Langton et al., 2011). In addition, noise generated by MHK devices has the potential to interfere with intraspecific communication; and thus, to affect normal behavior, including reproduction. The potential biological impact of the noise generated by the MHK device during operations is largely unknown, but it will be a function of the device design, receptor tolerance, and ambient noise levels. By necessity, MHK devices will be placed in areas of high flow, wave energy, and turbulence. Such areas have naturally high levels of ambient noise. In addition, shipping, boating, and fishing activities — if present in the project area — will add to the baseline ambient noise levels. See Section 5 for a discussion of the existing noise monitoring studies of actual MHK deployments. Studies thus far suggest that noise from vessel traffic, seismic surveys, and other existing anthropogenic noise will be more significant than noise generated by MHK devices (Section 5).

As shown in Figure 2, several potential direct impacts associated with the MHK structure have been identified. Impacts could occur during the initial placement of the MHK device (including WEC anchoring structures), which could result in the following:

- Mortality, injury, and displacement of biota during the construction phase, particularly of benthic organisms with low mobility; and

- Avoidance of the site by biota during construction. Alternatively, biota may be attracted by organic matter resuspended into the water column.

The construction related stressors would be temporary. Figure 2 also shows that in the operational phase, potential long-term impacts on biota mediated through the MHK device structure include the following:

- Change in benthic and pelagic communities in the vicinity of the device due to the presence of the structure and altered sediment-water interactions (Shields et al., 2011).

- Behavioral changes in which biota are attracted to manmade underwater structures such as oil rigs and piers (Wilson et al., 2003; Langton et al., 2011). This “reef effect” could be most widespread, and possibly ecologically significant, in the case of MHK device arrays (see Section 3.2).

- The MHK structure could also serve as an attachment site for invasive species (Witt et al., 2012).

- Shedding of organic matter (exudations, fecal pellets, dead biomass) and shell material from biofouling organisms may alter sediment characteristics in the immediate vicinity of the MHK structure. Because benthic community composition is strongly determined by sediment grain size (Lohse et al., 2008), the accumulation of organic matter and shell materials could, over time, affect the local benthic community. Such effects could be most widespread, and possibly ecologically significant, in the case of MHK device arrays (see Section 3.2).

Following placement of an MHK device, maintenance activities could affect aquatic biota in a variety of ways (Figure 2). The primary stressors associated with maintenance activities are increased boat traffic and the repeated raising and lowering of the MHK device for maintenance and for the removal of accumulated debris, as described below:

- Greater boat traffic in the form of device maintenance vessels may increase the probability of vessel collisions with vulnerable receptors such as sea turtles and marine mammals.

- Raising and lowering the MHK device represents a chronic short-term disturbance, particularly to benthic organisms. The raising of a device and the removal of accumulated debris may result in impacts to fish and aquatic invertebrates that have colonized the device. Maintenance and cleaning may also result in chronic hydrodynamic alterations and changes in sediment characteristics.

The primary potential impact modes of transmission lines (connecting MHK projects with electricity transmission and distribution systems) are (1) benthic habitat disturbance or elimination during initial line placement and (2) the EMFs emanating from the line (Figure 2). The initial transmission line placement would disturb or replace natural substrate and displace, injure, or kill benthic organisms within the placement footprint and adjacent areas affected by sedimentation. These activities would be temporary and the benthos would eventually recover. Because transmission lines would be secured to the substrate or buried in the sea floor, potential impacts would affect primarily benthic invertebrates and demersal fishes.

MHK devices and transmission lines will emit EMFs of variable intensity and these may interact with the sensory organs of nearby marine and riverine organisms that have the ability to sense these fields. EMFs from subsea cables have been shown to alter behavior in elasmobranchs (Gill et al., 2009; reviewed in Gill et al., 2012). The strength of the EMF is largely dependent on voltage capacity of the transmission line and whether the line uses alternating current (AC) or direct current (DC) (Gill, 2005). If the EMF signal is above a receptor’s tolerance threshold, avoidance may result, potentially impacting daily and seasonal movements, including migration patterns. This may be of particular concern for riverine and estuarine dependent fishes that migrate to specific spawning habitats and for coastal species that may have daily movements between offshore and nearshore waters for feeding. Although EMF is often cited as a concern in the literature, recent studies do not suggest significant impacts to biota. See Section 5 for a discussion of the existing EMF modeling and monitoring studies of actual MHK deployments.

2.3 Factors Influencing the Vulnerability of Biota to Direct MHK Device Effects

The vulnerability of individual species to specific MHK device stressors can be evaluated by considering the impact mode and receptor-specific traits. Ecological risk associated with direct physical action by an MHK device will be influenced by traits such as receptor size, mobility, and habitat preference (Table 2). For example, species of marine mammals or sea turtles that occupy nearshore surface waters have a greater risk of vessel or WEC collisions than do deepwater species. Similarly, for a tidal turbine, diadromous and estuarine-dependent fish species have a greater risk of encountering device blades than do species that prefer high-salinity waters. Consequently, in risk evaluation, particular emphasis should be given to species of marine mammals, sea turtles, fish, and invertebrates with habitat preferences that would coincide with the location of the MHK device; thereby, increasing the potential for those biota to

TABLE 2. Relevant Receptor Characteristics Influencing the Risk of Impacts from a Single MHK Device

Impact Mode	Potential Biological Impacts from Wave and Current MHK Devices	Relevant Receptor Characteristic
Physical action	Entrainment Entanglement (wave only) Cavitation (current only) Blade strikes (current only) Vessel collisions	Size, mobility, morphology Habitat and depth preference at all life stages
Sensory/ physiology	EMFs Noise	Physiological and sensory tolerance Sensory modes; habitat preferences
Behavior	Attraction or avoidance of MHK device	Flow and substrate preference Diving, swimming, and migratory patterns

encounter an operating device. Species size and life stage are also important, because the risk of blade strikes will likely be highest for organisms within a specific size range. For example, because of their small size, fish eggs and larvae are less likely to suffer blade strikes than are the same species during later, larger, life stages. Conversely, these smaller life stages are more vulnerable to entrainment because they lack strong swimming ability. For diving birds, the risks of collisions with surface components of WEC devices is relatively low given the devices' low profile in the water and lack of exposed moving parts (Furness et al., 2012). The risk of underwater collision with spinning turbines or stationary components may be highest for plunge divers and nocturnal species, especially if they use the above-water portions of the MHK device for perching and initiating feeding dives (Grecian et al., 2010; Furness et al., 2012). If the MHK device were to serve as a fish attractant, the number of birds diving near the device could increase and potentially the probability of bird collisions could also increase.

Species vulnerability can also be predicted for stressors whose actions are mediated through sensory physiology. For example, elasmobranchs, paddlefish, and catfishes have well-developed organs for detecting EMFs; and therefore, may be particularly vulnerable to MHK-generated EMFs (reviewed in Gill et al. [2009] and Gill et al. [2012]). Clupeids are known to be sensitive to noise, while elasmobranchs and flatfish are less vulnerable, because they lack a swim bladder (Popper and Hastings, 2009). Thus, knowing species-specific tolerance thresholds is critical in evaluating risk, and more research is needed to characterize MHK device emissions (EMF and noise) and receptor thresholds. Research conducted under Subtask 2.1.3 *Effects on Aquatic Organism* will address data gaps regarding the affects of EMF on fish and invertebrates.

Impacts from a single MHK device can occur from direct action of the device on biota or from changes in habitat. Habitat changes would likely be local and would be largely related to chronic disturbances from EMF and noise generation, turbine operation, and maintenance activities. Disruption of normal behaviors and, less likely, physical injury from collisions could be the principal potential impacts on biota resulting from MHK operations and support vessels. A single MHK device is unlikely to lead to population-level impacts.

3 POTENTIAL IMPACTS FROM MULTIPLE MHK DEVICE OPERATIONS

As with Section 2, the goal of Section 3 is not to provide another assessment of the ecological risks associated with MHK technology, but rather to synthesize the many existing evaluations of the potential ecological risks associated with MHK technology as identified by management and regulatory agencies and in the scientific literature. It should be understood that many of the stressor-receptor linkages identified in the conceptual models, though identified by subject matter experts, are speculative, because there have been relatively few field deployments of MHK devices. As new data specific to real MHK field deployments is collected, many of these linkages may be revealed to be insignificant during the analysis phase of the risk assessment. See Section 5 for a preliminary review of the existing ecological studies of actual MHK deployments.

3.1 Effects of MHK Arrays on Habitat

The physical and biological impacts of MHK technology are scale dependent (Figure 1). Therefore, impacts from multiple MHK devices may differ qualitatively and quantitatively compared to a single device. For example, if a field of MHK devices is added to a system, the stressors described in Section 2 for single MHK technology, such as loss of benthic habitat, hydrodynamic alterations, and a change in sediment characteristics, will accumulate and potentially result in large-scale habitat alteration (Figures 1). In addition, the proximity of the MHK units to one another in the arrays may create unique hydrodynamic interactions, with as-yet-unknown effects on hydrology and sediments (Figure 3). Figure 3 identifies the primary concerns identified in the literature for MHK arrays. Habitat changes from the deployment of multiple MHK devices could potentially result from high-contaminant loads, the creation of an artificial reef, organic matter trapping, and hydrodynamic alterations that could subsequently affect geomorphology, water chemistry, and sediments (U.S. Department of Energy, 2009; Boehlert and Gill, 2010; Shields et al., 2011). These habitat changes could in turn affect the biological components of the ecosystem.

Anti-fouling paints are necessary to limit or prevent the attachment and growth of sessile organisms that reduce operational efficiency by increasing drag or interfering with mechanical movements. Many anti-fouling paints contain toxic compounds to prevent biofouling communities from developing. These toxicants can leach into the sediment and water column and potentially reach levels that are lethal or sub-lethal to non-target organisms (U.S. Department of Energy, 2009). Compared to a single MHK device, MHK arrays could result in higher contaminant concentrations in the sediment and water column as a result of accidental releases of operating fluids (e.g., lubricants) and leaching from anti-fouling coatings (Figure 3). Because of the potential for contamination, many developers use non-petroleum based lubricants. Similarly, the use of non-toxic antifouling coatings by developers will also greatly reduce the potential for contaminant effects. If toxic coatings and lubricants are used, the toxicant concentrations in the sediment and water column will be strongly site-dependent, with high-current areas likely requiring less anti-fouling maintenance because of the negative relationship that typically exists between current speed and larval invertebrate settlement

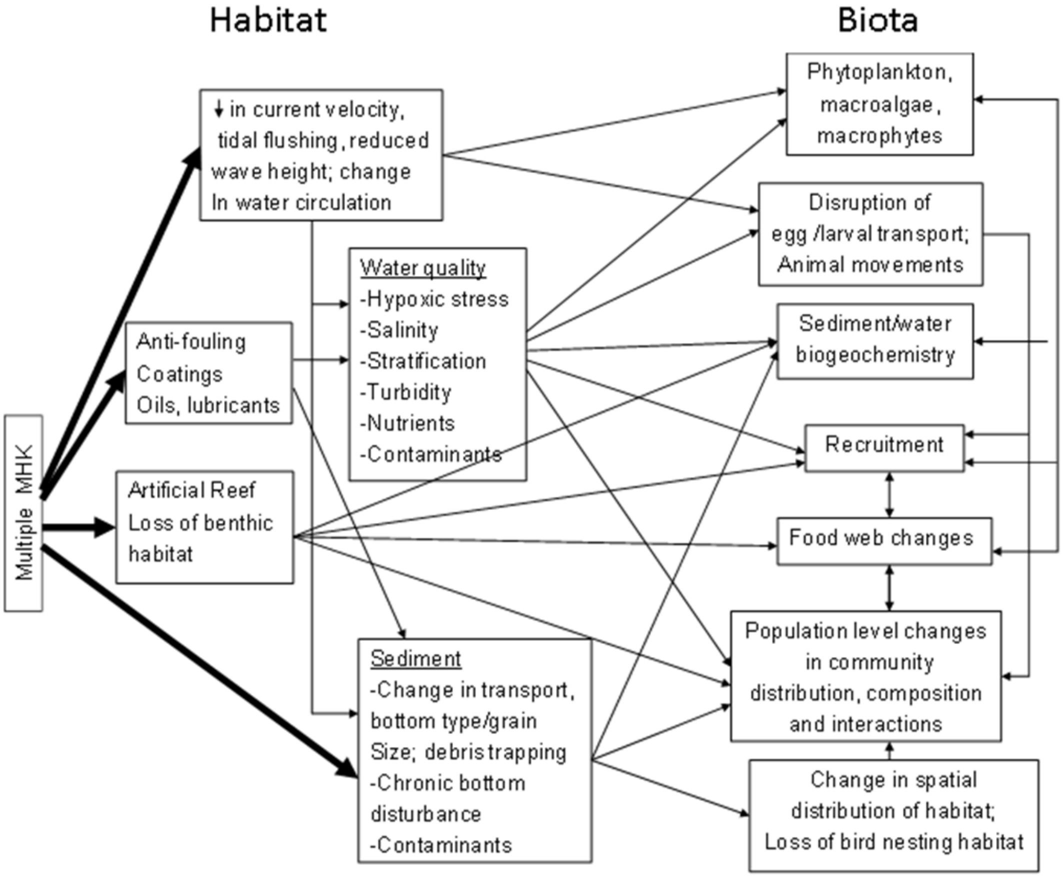

FIGURE 3. Hypothesized Ecosystem-Level Effects of MHK Device Arrays on Habitat and Biota

(Ableson and Denny, 1997; Larsson and Jonsson, 2006). Areas of high current velocity will also have a greater and more rapid dilution potential; and thus, may be expected to retain fewer contaminants locally as compared to areas with slower current. Contaminants may potentially accumulate in more distant low-flow, depositional areas that have high-sediment organic matter (Chapman, 1990). Such areas could include ecologically significant habitats such as saltmarshes, submerged aquatic vegetation, macroalgal beds, side channels, backwaters, and shellfish reefs. Contaminant loads associated with MHK arrays, as well as their effects on live bottom habitat and associated biota, require further study. Although contaminant concerns exist, a preliminary risk estimate for traditional anti-fouling biocides suggests low ecological risk even for compounds known to be toxic to biota (Andrea Copping, personal communication, 2012).

The existence of multiple surface-water or underwater MHK structures in a particular area represents the replacement of natural habitat with a new habitat similar to a large artificial reef (Figure 3). Such a change would be qualitatively less in areas with hard rock bottom habitat than in areas with soft-sediment or open water habitats. The biotic effects of an artificial reef are discussed in Section 3.2. See Section 5 for a discussion of this “reef effect” based on monitoring studies at actual MHK deployments.

MHK devices are designed to extract energy from the motion of waves or currents (tidal or river). Therefore, MHK arrays will likely have a greater capacity to reduce hydrodynamic energy and alter hydrodynamics over large spatial scales than would a single MHK device and these alterations could generate a number of habitat effects (Figure 3). Changes in tidal energy and water circulation resulting from the operation of a current-based MHK array have the potential to affect soft sediment estuaries by changing the patterns of shoreline erosion and deposition (Shields et al., 2011). For example, simulations of tidal MHK arrays indicated that single and multiple rows of arrays of the devices would decrease tidal flow speed in the shadow of the turbines and increase and increase tidal flow speed to either side of the array (Walkington and Burrows, 2009). Such changes could potentially affect sediment deposition downstream of the turbines, thereby changing bottom type over a large riverine or estuarine area (Boehlert and Gill, 2010). At the same time, the tidal array may increase flow to the sides of the array, resulting in bank erosion along the shoreline of the channel (Walkington and Burrows, 2009). Similarly, simulations by Neill et al. (2012) suggested that tidal energy extraction (300 MW) could affect the geomorphology of sandbanks, although this may be counterbalanced by natural seasonal erosion and accretion processes within the estuary.

In addition, by removing energy from tidal flow, tidal MHK arrays may potentially reduce the volume and effectiveness of tidal flushing, change water column gradients and circulation patterns, and reduce the penetration of seawater into an estuary (Shields et al., 2011; Kadiri et al., 2012). Yang and Wang (2011) used three-dimensional models that simulated the effects of tidal turbines on flood tide velocity, tidal amplitude, and tidal flushing in an estuarine system. They found that flood tide velocity and water volume flux across the channel decreased with increasing numbers of turbines. They also found the volume flux and tidal flushing were related such that tidal flushing time increased with the number of tidal turbines. However, realistic numbers of turbine (34-100 turbines; 48.5-55.9 MW extracted energy) reduced of volume flux by only <0.2%. The impacts of such a reduction on water quality and biota are uncertain. Vertical and horizontal water column gradients (salinity, nutrients, temperature, and dissolved oxygen) may be affected if there is a reduction in sediment resuspension or the volume of tidal exchange and an increase in turbulent flow. For example, in large bays with heavy freshwater inflow, decreased tidal flushing could result in hypoxia (Yang and Wang, 2011). Similarly, lower sediment resuspension could reduce the release of critical nutrients into the water column. Investigations conducted under Market Acceleration subtask 2.1.2 will help to determine whether the hydrodynamic alteration associated with MHK arrays poses a significant risk to aquatic ecosystems.

The effects of MHK arrays on water circulation, tidal exchange, and chemical and physical gradients will vary by site. For example, the potential for reduced nutrient upwelling and breakdown of water column stratification would be less problematic in vertically mixed estuaries with high marine inflow, compared to a salt-wedge estuary with strong vertical gradients in water chemistry. Similarly, tidal flushing would be less problematic if the MHK array was not located in an estuarine inlet.

Unlike the current-based MHK technology just discussed, WECs are designed to extract energy from waves (Figure 3), which potentially could reduce wave height and velocity (Michel et al., 2007; Largier et al., 2008; Shields et al., 2011). Other sources of wave energy reduction include the reflection of waves upon contact with the WEC structure and any associated platform as well as the complex wave refraction patterns created by wave contact with multiple proximate WECs.

The reduced wave energy could have the following results:

- Reduction in wave energy at the shoreline. One potential result at sandy beaches could be greater sand accretion in the swash zone at the expense of offshore sand bars (Largier et al., 2008), although others have suggested WECs could have the opposite effect (Shields et al., 2011).

- A decline in the energy of water moving within the surf zone (longshore currents) which could, ultimately, decrease longshore transport of sediment and change patterns of beach erosion and accretion as well as the distribution of bird nesting habitat (Largier et al., 2008; Shields et al., 2011).

Shields et al. (2011) pointed out that these processes of wave erosion and accretion are naturally variable, and that the relative effect magnitude of a WEC on coastal processes is uncertain. The effects of current and wave-based MHK arrays on sediment and water column habitat just described have been identified in the literature, but have not been demonstrated to occur. Field measurements and modeling under the MHK Market Acceleration Tasks 2.1.1 and 2.1.3 will be used to determine the effects of MHK technology on hydrology, water chemistry, and sediment transport.

3.2 Effects of MHK Arrays on Biota

If an MHK array is deployed, the potential direct impacts described in Section 2 for single devices (e.g., noise, blade strikes, and EMFs) have the potential to impact biota at a greater frequency, intensity, and spatial scale compared to a single MHK device. Thus, multiple MHK devices are more likely to have population- and ecosystem-level effects than would a single MHK device (Figure 1). In addition, multiple MHK devices could create unique stressors that are not possible with a single device. For example, WEC arrays that use mooring lines to anchor each WEC device to the seabed could entangle large marine mammals that swim into the wave park. Such a scenario may be less likely in the case of a single WEC device. In addition, MHK arrays may have a greater potential to disrupt animal movements and migrations than a single device. Similarly, EMFs generated by transmission cables associated with the MHK array could be additive or subtractive, depending on how the cables are oriented in relation to one another (Gill et al., 2012).

Several reviews have identified anti-biofouling coatings, lubricants, and oils associated with MHK array deployments as potentially contaminating the water column and sediments (Figure 3). Fish and invertebrates in their early life stages are usually most sensitive to toxicants and may be most vulnerable. The type of compound used will also determine the species affected. For example, anti-fouling coatings often contain copper, which is a potent crustacean toxicant (Moore and Ramamorthy, 1984). Contaminant loading associated with MHK devices and the associated effects on biota require further study. However, many MHK devices are free from oil-based lubricants; and therefore, there is minimal risk from hydrocarbon contamination associated with the devices. In addition, a preliminary risk estimate for traditional anti-fouling biocides suggests low ecological risk even for compounds known to be toxic to biota (Andrea Copping, personal communication, 2012). To minimize the potential for contamination, developers can use non-toxic anti-fouling coatings, which will further minimize contaminant risk. As discussed in Section 5, preliminary laboratory studies of such coatings indicate the compounds are indeed non-toxic to aquatic biota.

As depicted in Figure 3, both WEC and current energy MHK devices would be expected to attract structure-oriented biota, such as sessile invertebrates and reef fishes. Similarly, surface components of the MHK devices could provide haul-out sites for seals (Nelson et al., 2008) and roosting sites for birds (Grecian et al., 2010; Langton et al., 2011). Manmade underwater structures ranging from docks to oil rigs often act as artificial reefs and serve as powerful fish aggregators, greatly altering local food web dynamics (Powers et al., 2003). Such artificial reefs could also serve as new attachment sites for invasive species. An inherent risk with artificial reefs is that they simply attract fish without actually increasing secondary production, while at the same time, they increase fishing pressure by concentrating fish in one location (Powers et al., 2003). However, this is unlikely to be the case with MHK arrays, because fishing is not likely to occur in their vicinity; In effect, MHK array sites could act as marine reserves that could actually be beneficial to fish populations (Witt et al., 2012). If anti-fouling paint is effective, the ability of the MHK devices to act as new artificial reefs or replace the function of a natural reef or live hard bottom habitat will be greatly reduced, because attached invertebrates are key components of reef communities, which, in turn, attract larger species. There is also concern that artificial reefs can disrupt regional gene flow. Many of the questions related to artificial reefs are unresolved; consequently, the ecological implications of a MHK reef effect are uncertain (Witt et al., 2012). See Section 5 for a discussion of this “reef effect” based on monitoring studies at actual MHK deployments.

Physical and chemical conditions largely dictate species distribution and abundance. Thus, if large geographic-scale habitat changes were to occur as a result of an MHK array (discussed in Section 3.1), such changes could impact biotic ecosystem components at the population and community levels (Figure 3). Because of the loss of or changes to substrate characteristics, MHK arrays could potentially have the following effects:

- Alteration of the distribution, composition, and interactions of benthic communities (Shields et al., 2011), and
- Alteration of sediment biogeochemical processes such as nutrient cycling and organic matter breakdown.

As discussed in Section 3.1, tidal and riverine MHK arrays could alter sediment grain size and transport and affect water column processes by reducing current velocity and the volume of tidal exchange between the estuary and the ocean, disrupting chemical gradients in the water column (e.g., salinity and temperature) and changing coastal water circulation (Michel et al., 2007; Boehlert and Gill, 2010). As depicted in Figure 3, a number of indirect effects on biological communities could have the following results:

- A change in the distribution of fish, invertebrates, phytoplankton, zooplankton, and sediment-associated primary producers (e.g., macrophytes, macroalgae, and microalgae) that are sensitive to chemical gradients;

- Disruption of reproduction, larval transport, and settlement due to increased turbulence (Shields et al., 2011). Disruption of the transport of estuarine-dependent species that rely on both vertical and horizontal water column salinity gradients for tidal transport. Similarly, larvae of many riverine fish species drift in the main channel where MHK devices are proposed and these could also be affected by changes in local salinity gradients; and

- Changes in sediment upwelling and tidal mixing which could affect sediment and water column biogeochemistry and alter planktonic and microbial communities and ecosystem functions (Shields et al., 2011).

For WEC arrays deployed in wave parks, device operations have the potential to reduce wave height, weaken longshore currents, and reduce wave energy at the shoreline, potentially affecting coastal biota (Lohse et al., 2008; Largier et al., 2008; Section 3.1). These changes could result in the following:

- Disruption of the transport of larval fish and invertebrate species that rely on currents to transport eggs or larvae to nursery habitats (Shields et al., 2011). The potential for impacts may be highest for WECs placed near large coastal inlets where they could disrupt current-based transport of eggs and larvae.

- Alteration of the distribution and abundance of intertidal organisms, particularly on rocky shorelines, where species distributions and interactions are tightly linked to wave energy.

The vulnerability of individual species to large-scale habitat changes can be evaluated by considering receptor-specific traits, as summarized in Table 3.

In conclusion, many of the potential impacts from MHK arrays identified in the existing literature and discussed here must be considered speculative, because there have been few deployments from which to collect data. Compared to a single device deployment, impacts from an MHK array would occur at a potentially greater spatial scale and would have a greater potential to result in population-level impacts. Disturbances from the placement, operations, and maintenance activities associated with an MHK array could result in primarily behavioral impacts on biota. For most organisms, lethal impacts resulting from the MHK device are possible, but not likely, to generate population level effects. Avoiding locating commercial scale MHK developments in sensitive areas is one way of minimizing the potential for ecological impacts. Population and ecosystem level impacts from MHK device operations will be difficult to evaluate, given the complex feedback interactions between the various ecosystem components identified in Figure 3. Currently, the 2.1 Market Acceleration efforts are focused on investigating the direct impacts to habitat that could in turn lead to ecosystem level impacts for biota (Figure 3). If these habitat studies conclude that MHK operations result in only minor impacts to the habitat component of ecosystems, then there may be no need to monitor the biological effects shown in Figure 3.

TABLE 3. Relevant Receptor Characteristics Influencing the Potential Risk of Impacts from Potential Habitat Alteration by MHK Arrays

Impact Mode	Potential Impacts	Relevant Receptor Characteristic(s)
Contaminants	Primarily sub-lethal impacts	Physiological tolerance; use of contaminated habitat
Benthic habitat	Loss or alteration of benthic habitat	Sediment preference and benthic resource requirements at all life stages; Recolonization ability following disturbance
Hydrology	Change in water circulation, current and wave energy, tidal flux, and water column structure	Migratory behavior (seasonal, anadromous, catadromous); Spawning location (inshore, offshore); Transport routes and mechanisms during early life stages; Flow and water energy preference; Water quality requirements;
Artificial reef	Altered community composition and food webs interactions	Behavioral orientation toward structure

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4 CUMULATIVE IMPACTS

The commercial development of MHK technologies could incrementally add to existing environmental stresses in aquatic ecosystems. There are multiple existing anthropogenic stressors for aquatic habitat and biota that are unrelated to MHK developments but have analogs to potential MHK impacts (Table 4). Hydrokinetic energy developments have the potential to interact and/or interfere with other forms of offshore energy development (i.e., wind, oil, and gas), defense-related activities, habitat restoration, mining, construction, commercial shipping, recreational and commercial fishing, and recreational boating and beach use.

To fully understand the potential cumulative impacts of commercial scale hydrokinetic energy development, impacts must be evaluated by considering both (1) the current level of impacts to resources of concern from existing anthropogenic stressors and (2) the incremental increases in impacts from the deployment of one or more MHK devices at specific locations. In general, a generic cumulative impact analysis is not possible as MHK related impacts and the existing impacts from other anthropogenic activities will vary by project location and the nature of the MHK development. In a relatively pristine area with little human activity, the addition of one or more MHK devices would represent a large relative increase in some stressors, although the actual incremental magnitude of the impact on the ecosystem may be small and ecologically insignificant. Determining this incremental increase can be difficult at this time because some of the potential ecological impacts associated with MHK technology —both single and multiple deployments — are not well understood or vary in uncertain ways with location and technology. The results of field and laboratory studies that address potential impacts to habitat and biota related to MHK technology are reviewed in Section 5. Table 4 provides examples of possible MHK interactions with existing anthropogenic stressors and the additional potential increase in risk resulting from MHK devices based on the results of existing studies.

The cumulative impacts on habitat that are most certain to occur are bottom-disturbing activities resulting from the placement and operation of the MHK device. Bottom disturbance from MHK deployments would add to the existing impacts on benthic habitat from dredging, and trawling, as well as construction activities such as the placement offshore oil and gas infrastructure, docks, piers, and offshore wind farms (Table 4). The cumulative effect of construction activities and MHK projects is a function of existing and future construction activities and the location and the number MHK devices deployed. In addition to construction, dredging is another source of bottom disturbance that occurs extensively in rivers, harbors, and nearshore areas. Dredging is a significant and repeated localized disturbance that can alter plant and animal communities (Boyd et al., 2005). Similarly, depending on location, trawling occurs over a large portion estuarine and continental shelf habitat and is known to have long-term chronic impacts on benthic communities (Jones, 1992). Given the nature, spatial extent, and chronic nature of dredging and trawling, they are likely to be far more damaging to the benthos than WEC or turbine MHK deployments.

TABLE 4. Potential Cumulative Impacts Associated with MHK Device Arrays and Their Relationship to Existing and Proposed Anthropogenic Impacts

Potential MHK Impact	Analogous Anthropogenic Impacts	Additional Potential Impact from MHK Devices
Aquatic Habitat		
Habitat disturbance from altered hydrology and sediment transport dynamics	Alterations in hydrology and sediment dynamics from shoreline development, channel maintenance, and channelization	Could be locally high; impacts could increase with multiple MHK devices
Benthic habitat disturbance from MHK device placement and operations	Habitat disturbance and loss from construction of underwater structures, including offshore oil and gas infrastructure, docks, piers, and offshore wind farms	Could result in large scale change in benthic habitat depending on project footprint; change in benthic community may not be negative
Scour from transmission cables and anchoring lines	Dredging and destructive fishing methods like trawling; scour from mooring lines, pipelines, and cables	Relatively minor if lines are secured properly
Hypoxia from decreased tidal flushing	Eutrophication-based hypoxia from agricultural and urban runoff, sewage discharge, and industrial outfalls	Uncertain; impacts would be project specific and may be low if tidal flow impacts were minimal
Creation of an artificial reef	Existing artificial reefs	Could be positive if the array acts as a marine reserve
Contamination from fuels, lubricants, and anti-fouling coatings	Pollution from terrestrial inputs, ocean dumping, and offshore oil and gas	Likely minimal if non-toxic products are used
Fish and Invertebrates		
Potential injury or mortality during construction and operations from blade strikes, entrainment, and cavitation	Adult and juvenile mortality from commercial and recreational fishing, egg and larval mortality from entrainment at power plants and industrial water users; impacts from conventional hydropower	Potential minor additive effect particularly for early life stages; could be a significant additive effect in confined channels with few or no other anthropogenic activities, or for rare or endangered fishes
Interference with movements of early life stages in riverine and coastal systems	Disruption of riverine migration by dams and conventional hydropower	Potentially higher for early life stages

TABLE 4 (Cont.)

Potential MHK Impact	Analogous Anthropogenic Impacts	Additional Potential Impact from MHK Devices
Disturbance of normal behaviors due to noise, EMF, construction activities, and support vessel traffic	Noise from vessel traffic, offshore construction, naval testing, seismic surveys, underwater construction; EMF from multiple transmission cables	Relative noise impacts could be higher in areas with little other anthropogenic impact and for migratory species; EMF impacts likely localized and minor
Reduction in host fish for freshwater mussels	Existing loss of fish species diversity due to human activities	Could be higher for rare mussels and those with highly specific host requirements
Marine Mammals		
Collision with MHK components; Vessel strikes from MHK construction and service vessels	Vessel strikes from commercial and recreational boating	Negligible additional risk from collision with MHK components; increase in collision risk from maintenance vessels
Disturbance of normal behaviors from MHK device operation (noise and EMF)	Noise from vessel traffic, offshore construction, naval testing, seismic surveys, underwater construction; EMF from multiple transmission cables	More data needed to characterize noise impacts; EMF impacts likely localized and minor, but little data available
WEC entanglement	Fishing by-catch	Minor if mooring lines are managed properly
Sea Turtles		
Collision with MHK components; vessel strikes from MHK construction and service vessels	Vessel strikes from commercial and recreational boating	Likely a negligible additional risk from collision with MHK components; increase in collision risk from maintenance vessels
Disturbance of normal behaviors from MHK device operation (noise and EMF)	Noise from vessel traffic, offshore construction, naval testing, seismic surveys, underwater construction; EMF from multiple transmission cables	More data needed to characterize noise impacts; EMF impacts likely localized and minor, but little data available
WEC entanglement	Trawling by-catch, entanglement in fishing gear	Minor if mooring lines are managed properly
Birds		
Coastal and wetland disturbance or loss from construction of onshore MHK infrastructure	Coastal and wetland loss from human development	Very minor increase

Habitat alteration from changes in hydrodynamics and sediment transport	Wetland and shoreline habitat loss and modification from human development	Habitat impact magnitude is project dependent and not well characterized
Blade strike	Offshore wind turbines	Likely minor; only diving birds would be affected
Endangered Species		
Direct and indirect impacts to endangered fish, sea turtles and marine mammals	Injury or mortality from vessel strikes (commercial and recreational); historic overexploitation and habitat degradation	Some synergistic interaction if incremental MHK device effects push population to below self-sustaining numbers

An MHK array has the potential to alter sediment transport and shoreline geomorphology which could add to the existing habitat impacts from human modifications of riverine and coastal shorelines and channels (Table 4). MHK developments could also potentially affect the success of projects designed to restore and enhance these coastal and riverine habitats. Given the magnitude and spatial extent of natural and human modification of coastal habitat, MHK deployments may result in a comparatively minor incremental increase in habitat change. However, project specific studies are needed to quantify what level of energy extraction can be achieved without adversely affecting sediment transport.

MHK arrays also have the potential to increase the magnitude of common water quality problems that are related to human activities, such as hypoxia and water pollution (Table 4). For example, channel dredging in river mouths can alter water quality and plant and animal communities upstream of the actual dredging activity (Johnston, 1981; Quammen and Onuf, 1993; Lou et al., 2007). As described in Section 3.1, energy extraction by an MHK array also has the potential to affect water quality by reducing current velocity, tidal flow, and tidal flushing in aquatic habitats. One potential result is an increase in estuarine hypoxia (Section 3.1). As with sediment transport, project specific studies are needed to address the trade-off between the need for economically feasible energy extraction and avoiding environmentally detrimental hydrodynamic changes. Contamination from fuels, lubricants, and anti-fouling coatings from MHK arrays are not likely to contribute to existing pollutant loading in aquatic habitat, as the use of hydrocarbon based lubricants and non-toxic fouling coatings can reduce the potential for contamination (Table 4).

Conventional hydropower can kill or injure fish by blade strike, cavitation, or entrainment. However, as discussed Section 5, MHK related mortality from blade strikes and entrainment is likely to be minor in fish and invertebrates at the level of the individual and also at the population level considering other natural and anthropogenic sources of mortality. In freshwater systems, the disruption of fish spawning runs or the movement of early life stages by MHK arrays could additively or synergistically interact with ongoing and historical impacts from dams and conventional hydropower (Table 4). For sea turtles and marine mammals, vessel strikes and entanglement are currently significant sources of disturbance, injury or mortality (Table 4). Blade strike or hull collision impacts on marine biota are primarily associated with recreational boating. Such collisions are potentially lethal and are of much greater force than the force associated with blade strike from an MHK device. However, the increase in vessel traffic for MHK device maintenance could increase the risk of vessel collision (Table 4). For endangered cetaceans or sea turtle species, the death of relatively fewer individuals could have significant population effects.

Electric transmission cables producing EMFs have been present in aquatic environments for over a century. Communications cables and oil and gas pipelines are widespread but lesser sources of EMF in aquatic environments (Normandeau, et al., 2011). The number of EMF producing cables has increased over the years to accommodate coastal and offshore development. Today, transmission cables associated with offshore renewable energy including wind farms and MHK developments represent newer sources of EMF in the environment. Transmission cables from MHK arrays will likely produce EMF levels that are detectible by fish, invertebrates, sea turtles and marine mammals (Michel, et al., 2007; Normandeau, et al., 2011). However, studies of the effects of EMF on fish and invertebrates have been inconclusive or suggested no significant ecological effect (Section 5.4). The response of sea turtles and marine mammals to cable generated EMF fields has not been studied experimentally. Both are known to rely on the detection of magnetic fields for navigation (Normandeau, et al., 2011), but the ecological significance of the additional EMF generated by future commercial scale MHK developments is uncertain. Further complicating the cumulative analysis is the potential for EMF fields to cancel or augment on another depending on the spatial arrangement of the cables (Gill et al., 2012). Thus, a quantitative cumulative effects analysis of EMF will require site and project specific information.

A cumulative effects analysis of MHK derived noise must consider the multiple existing sources of anthropogenic noise in marine and freshwater environments and the noise levels generated by these activities compared to MHK deployments. Recreational and commercial vessels, dredging, construction, and seismic surveys can all be significant sources of noise in aquatic environments (Table 4). Noise from an MHK device could add to these existing acoustic stressors, to some degree. Although no mortality is expected, noise generated during placement of an MHK device and the construction of associated infrastructure may reach a nuisance level and drive marine animals from the area (Section 5.2). However, these noise levels would be temporary and construction could be scheduled for times of the year when there is a lower abundance of species of concern such as marine mammals, sea turtles, or migratory fish. Noise generated by the operating turbine represents a potential long-term stressor. Studies of MHK deployments suggest that the devices can increase noise levels above background levels within some distance of the device (Verdant Power, 2010; ORPC, 2011; Polagye et al., 2012). The proportional increase in noise above background from the MHK device is related to the specific MHK technology and the noise generated by existing natural processes or human activity within the area. As discussed in Section 5, both modeled and field recorded noise levels do not suggest noise generated by tidal turbine operations reach levels injurious to marine animals under natural conditions, although they may be sufficient to cause avoidance behavior within hundreds of meters of the turbine.

For most birds, the potential for direct injury or mortality from MHK deployments is likely minimal, although diving birds are potentially vulnerable to blade strike (Table 4). However, potential impacts on birds could be mediated through habitat changes. For example, if MHK arrays were to significantly modify local patterns of shoreline erosion and accretion, it could increase already significant anthropogenic losses in the nesting habitat of protected bird species. However, more studies are needed on the effects of MHK arrays on coastal geomorphology.

5 ANALYSIS PHASE

After conceptual model development, the second phase in the EPA Risk Assessment Framework is the analysis phase (EPA, 1998). The analysis phase consists of (1) identifying the temporal and spatial extent of the potential stressors identified in the conceptual model, (2) quantifying the degree of exposure the receptor has to the stressor, and (3) characterizing the biological/ecological effects of the exposure levels identified in (1) and (2). Overall, the analysis phase attempts to characterize the nature and magnitude of the potential ecological effects that can be expected based on a presumed the level of exposure of the resources (e.g., a habitat, a species) to one or more of the specific stressors identified in the conceptual model.

The nature of potential risk to biota from MHK deployments at the individual and population level were identified in Section 2 and Section 3. Populations are controlled by multiple biotic and abiotic factors with complex interactions that are often not well understood, particularly at the scale of an individual MHK site. Therefore, evaluating higher order, ecosystem-level impacts (Figure 3) is not possible at this time, given that impacts from even a single MHK device are not well understood. Eventually, such a risk assessment could theoretically be achieved using existing programs that are capable of modeling population and ecosystem responses to environmental change over multiple generations. For example, modeling programs such as ECOPATH (http://www.ecopath.org) and STELLA® (http://www.iseesystems.com/softwares/Education/StellaSoftware.aspx) can be used for this purpose and it may be possible to develop individual-based models (IBMs) to better understand and predict ecological responses to MHK development. The drawback to these models for MHK applications is the large number of assumptions and site- and species-specific data required to parameterize any such models. Information about ecosystem biomass, production, mortality, energy sources and sinks, and trophic efficiency are typically necessary. Such data is not likely to be available for most MHK development areas and would be prohibitive to collect because of the time and cost required. Some ecosystem energy studies may require years or tens of years to complete. For now, we will focus on the data available to analyze the direct stressor-receptor linkages related to the operation, structure, and transmission cables of a single MHK device (Figure 2).

Evaluating direct MHK impacts identified in a conceptual model will require field and laboratory data about the strength of interactions between stressors and receptors. In the case of MHK devices, the analysis step is made especially difficult by the fact that there is currently little information about the interaction between an actual MHK device and biological receptors. However, this is slowly changing as more controlled experimental studies are undertaken and new and existing monitoring data becomes more widely disseminated. Currently, our partner labs are working to quantify exposure levels and changes in key environmental processes (EMFs, acoustics, toxicity, hydrology, sediment dynamics), as well as effects thresholds for aquatic organisms. These studies will significantly enlarge our understanding of the potential for direct impacts to biota from MHK devices. What follows is a brief description of the current state of knowledge on MHK effects based on data collected during actual MHK deployments (Table 5) or controlled studies designed to mimic conditions generated by an MHK device. We examine

TABLE 5. Summary of Existing Current MHK Device Deployments for which Data is Available

Project	Location	Technology	Organisms Monitored	Method
Verdant Power	East River, New York, NY	Axial-flow turbine with a fixed pitch, three-blade rotor; 35 rpm	Fish	Fixed hydroacoustics and mobile hydroacoustics arrays and a DIDSON system
ORPC	Cobscook Bay, ME	Cross-flow turbine suspended below a barge	Fish	DIDSON acoustic camera and a single beam SIMRAD echo sounder
SeaGen	Strangford Lough, Ireland	Twin 16-m diameter rotors connected by a cross beam	Marine mammals	Telemetry; visual observation; passive acoustic monitoring
			Benthos	Underwater camera
			Seabirds	Visual observation
Hydro Green Energy	Mississippi River, Hastings, MN	A ducted hydrokinetic turbine with three blades, 12 ft in diameter	Fish	Telemetry; tagging
OpenHydro	Bay of Fundy, Nova Scotia, Canada	Open center turbine with no center axis	Marine Mammals Fish	Passive acoustic monitoring
OpenHydro	EMEC, Scotland	Open center turbine with no center axis	Fish and marine mammals	Video recordings
Lysekil Project	Sweden	Wave energy converter	Benthic fish and invertebrates	Visual surveys

organismal interactions with the MHK device (i.e., attraction, avoidance, strike, and entrainment), underwater noise, EMFs, and changes in benthic communities.

5.1 Animal-Device Interaction

5.1.1 Behavioral Changes

Verdant Power, East River, New York, NY. A fixed hydroacoustic system was used to evaluate the swimming direction and velocity of fish swimming near turbines, and the potential effect of larger turbine arrays on fish distribution in the study area (Verdant Power, 2010; Table 5). Also collected were 290 hours of diving bird observations over 3 years, including the time of day, number and species of birds, behavior, proximity to turbine field, and tidal direction. They also compared bird activity during migration periods while turbines were operational as well as stationary.

Observations were taken from shore with binoculars and cameras both before and after turbine deployment. From the monitoring effort Verdant concluded the following:

- Fish may not naturally use areas occupied by turbines since lower numbers of fish were observed in the mid channel habitat where the turbines were located compared to the slower velocity non-turbine zones inshore. This effect was observed even when the turbines were not operating;

- For fish recorded in the vicinity of the turbine, there was some evidence of avoidance behavior as fish approached the turbines;

- Comparatively low numbers of fish were found near the turbines when they were in operation compared to when they were not operating;

- The authors believe that fish movements are primarily influenced by natural tidal currents and only secondarily by the rotating turbines; and

- Diving birds did not appear to be attracted to the turbines.

Verdant concluded that the fact that fish generally occupied habitat outside of the vicinity of the turbine, combined with the apparent avoidance by fish of the turbine while in operation, minimized the potential for harm. Based on these findings, Verdant also concluded that the installation of an array of turbines in the strong current zones (consistent with energy production needs) would be unlikely to have large impacts on fish populations (Verdant Power 2010).

ORPC, Cobscook Bay, ME. ORPC installed a cross-flow turbine and monitored fish interactions using a DIDSON acoustic camera and a single beam SIMRAD echo sounder (Zydlewski et al., 2011). Of the thousands of fish observed with the DIDSON, most passed by the ORPC turbine. A small percentage of the fish passed through the turbine or actively avoided the turbine. Most fish that passed through the turbine did so at night, suggesting visual avoidance during the day. Of the fish that did pass through at night, most were small. Overall, abundance of fish was highest at slack tide when the turbine is not rotating (Zydlewski et al., 2011).

SeaGen, Strangford Lough, UK. The SeaGen consists of twin 16-m diameter rotors connected by a cross beam and mounted on a pile. The device was deployed in 2008 and has been operational ever since. The maximum rotational speed is 14 rotations per minute (rpm), and peak rotor tip speed is around 12 m/s. Pre- and post-deployment monitoring for marine mammals, birds, and benthos has been ongoing since 2005 (baseline) and continued through the 2008 deployment to the present. The results of the multi-year monitoring effort can be found in Royal Haskoning (2011) and Sparling (2011). The major conclusions were as follows:

- Aerial surveys indicated a decline in harbor seals at the study site since deployment, but this was also true of other local and national sites, signifying a larger population trend unrelated to SeaGen. Aerial surveys did not indicate a significant change in seal use of haul-out sites after SeaGen installation (Royal Haskoning, 2011).

- Shore-based surveys results indicated high temporal variability in harbor seal and grey seal abundance, but no significant decrease in abundance after the turbine was installed. The distribution of harbor seals in the study area appeared to be affected by turbine operations, although it is uncertain whether the shift was biologically significant (Royal Haskoning, 2011).

- For harbor seals, no statistically significant changes in transit rate in and out of Strangford Lough were detected before, during, or after turbine installation. However, while in operation, the SeaGen did appear to reduce the transit rate of harbor seals by an average of 20% compared to non-operational period, although data were available for only four seals. Harbor seals did appear to avoid coming within 250 m of the turbine, and the avoidance behavior was evident whether the turbine was on or off (Royal Haskoning, 2011).

- Acoustic monitoring of harbor porpoises indicates their activity level declined during turbine installation in some sections of the project area, but increased to pre-installation levels following the cessation of construction activities.

- Shore-based surveys indicated that bird sightings in the vicinity of the SeaGen were lower while the SeaGen was in operation compared to periods when the rotor was still (Royal Haskoning, 2011). Species specific analyses found a reduction of up to 50% for terns and ~25% for cormorants. The decrease was due in part to a redistribution of birds rather than an overall reduction in abundance within the study area (Royal Haskoning, 2011). However, there was no overall decrease in the number of birds in Strangford Narrows following the installation of the turbine.

The study did not monitor control areas along with the project area; therefore, post-deployment trends cannot necessarily be attributed to SeaGen operations. A common problem for statistical inference from SeaGen monitoring data was low statistical power. It is clear that large numbers of replicates and control areas are necessary to provide data adequate for statistical analysis.

OpenHydro, Bay of Fundy, Nova Scotia, Canada. The OpenHydro open center turbine was deployed in the Bay of Fundy in 2009 and passive acoustic monitoring was used to assess the effects of the turbine on marine mammals, fish, and birds (Tollit et al., 2011). The OpenHydro turbine is an open-center non-axial turbine with a rotational speed of 12 rpm and a rotor diameter of 10 m. During monitoring, the turbine appeared to be non-functional; therefore, the data can only be used to assess the effects of the turbine itself, not its operation. Environmental monitoring of the turbine was conducted by the Fundy Ocean Research Centre for Energy. The authors’ findings were as follows:

- No significant difference in porpoise presence between the turbine and control site and there was no evidence that harbor porpoises displayed avoidance or attraction to the turbine.

- Clicks generated for echolocation were lower at the turbine site compared to the control site, but the cause and biological significance was unclear.

Fish were also monitored using acoustic telemetry during the November 2009 to December 2010 deployment to assess the fish and turbine interactions. Three species were tagged: striped bass (*Morone saxatilis*), Atlantic sturgeon (*Acipenser oxyrinchus*), and American eel (*Anguilla rostrata*). Data analysis is ongoing (Redden et al., 2011).

OpenHydro, European Marine Energy Center (EMEC), Scotland. At the EMEC facility, an OpenHydro turbine has been monitored for environmental effects since 2009 (Barr, 2011). Only fragments of data are available at this time. A portion of the monitoring has involved video recording of the interaction of pollack (*Pollachius pollachius*) and marine mammals with the turbine. Results thus far indicate the following:

- Pollack have been observed to aggregate around the turbine, but pollack were present around the turbine less than 13% of the total hours of video footage.

- Tidal stage and water velocity appeared to be the primary determinant of fish presence or absence around the turbine.

- No fish collisions or entrainment were observed.

- No marine mammals were observed to interact with the turbine based on video data.

Based on these recent studies, there is only equivocal evidence that MHK devices affect animal behavior. There is some evidence that MHK devices have the potential to alter the behavior of individual fish, birds, and marine mammals that move within the vicinity of the device while it is in operation. However, most studies do not indicate significant numbers of animal-device interactions as the high velocity areas or time periods in which the turbines are typically operating are generally not suitable for aquatic organisms. In addition, the behavioral changes that are found appear to be minor and often consist of avoidance behavior that reduces the chance of the organism colliding with the device. Overall, there is no evidence that the behavioral changes have a significant fitness cost to individuals.

5.1.2 Blade Strike

For species that do interact with the MHK device, blade strike is among the potential impacting factors of concern to regulators. Comparisons of blade strike mortality from conventional hydropower turbines and MHK turbines suggest comparatively little mortality for adult fish from MHK turbines, as the water velocity, turbulence, pressure, and rotor speeds associated with conventional turbines far exceed those of MHK turbines (EPRI, 2011). Electric Power Research Institute (EPRI) found that mortality from blade strike for most size classes of fish is not likely to occur at blade speeds less than 15.7 ft/s (4.8 m/s), which is faster than MHK turbines are expected to rotate (typically less than 10 ft/s). Strike probability models for conventional hydropower have been applied to MHK technology. While strike models already exist, they typically are overly conservative because they fail to account for two critical variables: (1) the habitat preferences and movement patterns of the species of interest and (2) the ability of the organism to avoid the rotating blades when passing near or through the turbine. The habitat preferences of fish and marine mammals have been accounted for in some recent blade strike models (Wilson et al., 2007), but more refined methods are needed that are parameterized to account for more realistic probabilistic exposure (see Section 5.2). The second factor, the ability of the organism to avoid blades, has been investigated in several recent laboratory and field experiments on fish. A summary of these studies is provided below.

EPRI and Alden Flume Studies. Injury, survival rates, and behavior of two size classes of rainbow trout and largemouth bass passing through a Lucid Spherical Turbine (LST) (vertical cross-flow) and a Welka UPG turbine (ducted axial flow) were examined (Amaral et al., 2010; Jacobson, 2011). The LST has a rotational speed of 64 to 127 rpm and the Welka has a rotational speed of 3 to 16 rpm. Control and experimental groups were tested at Alden's large flume fish testing facility.

- For both the Welka turbine and the LST, the survival of small and large size classes of rainbow trout and largemouth bass was greater than 98% in the short (1 hour post study) and long-term (49 hours post study).

- Fish were generally able to avoid entrainment and swim around the LST. Between 83% and 94% of the rainbow trout avoided the operating LST by passing by the sides, top, or bottom. Similar results were found for the Welka turbine.

- Fish that were struck by the blades of the LST typically were hit in the caudal fin and fish were not stunned or severely injured. For the Welka turbine, no strikes were observed.

- There was no evidence of scale loss or injury for those fish that did pass through either turbine.

Both species seem to avoid the turbine. The authors believe that the avoidance behavior observed in these trials provides strong evidence as to how fish are likely to react when approaching a wide range of hydrokinetic turbine designs in the field.

USGS Conte Lab. Mechanical injury, avoidance behaviors, and migratory delay were studied in Atlantic salmon smolts and adult American shad interacting with an Encurrent model ENC-005-F4 vertical axis turbine (Jacobson et al., 2011; Castro-Santos and Haro, USGS, unpublished data). Low flow areas were created upstream and downstream of the turbine to allow fish to voluntarily pass through the turbine. Control tests were also run with the turbine removed. The passage of fish was monitored with passive integrated transponder (PIT) telemetry, video cameras, and an integrated hydrophone array and acoustic tracking system. A total of 173 salmon smolts and 208 adult American shad were introduced to the flume structure. The video portion of the study did not result in useable data.

- Salmon smolts did not show avoidance behavior toward the turbine and no injuries were recorded from passing through the turbine. Survival was 98.3% for treatment smolts and 96.4% for controls.

- Shad appeared to actively avoid the turbine either by swimming around it or, for those individuals that passed successfully, holding station just upstream of the unit. No injuries were observed on adult shad and mortality was not statistically different between control and treatment groups.

- The authors concluded that at the level of the individual turbine, effects are likely to be small, with conservative estimates of fish mortality at less than 5%.

However, the authors emphasize that larger scale studies must be conducted to determine the cumulative effect of multiple turbines distributed across a larger waterway. The avoidance behavior displayed by the shad suggests that a turbine array has the potential to alter upstream migrations.

Hydro Green Energy, Mississippi River, Hastings, MN. The Hydro Green turbine is a ducted turbine with three blades that are 12 ft in diameter (Normandeau Associates, Inc., 2009). The rotational speed is 21 rpm. Tagged fish were ejected through the rotating turbine to assess the probability of injury, mortality, and increased predation. A control group that passed around the turbine was used as well. Approximately 170 individuals of five species were tested: yellow perch (*Perca flavescens*), bluegill (*Lepomis macrochirus*), channel catfish (*Ictalurus punctatus*), smallmouth buffalo (*Ictiobus bubalus*), and bigmouth buffalo (*Ictiobus cyprinellus*). Survival was 98% or greater for all fish, which was similar to controls. No fish that passed through the turbine had evidence of injury or descaling and no post passage predation was observed.

SeaGen, Strangford Lough, UK. The carcasses of marine mammals have been examined for signs of blade strike since the deployment of the SeaGen turbine (Royal Haskoning, 2011). Although methods are not described in detail, the authors of the report state with high confidence that post-mortems do not suggest any evidence of blade strike.

Verdant Power, East River, New York, NY. A DIDSON camera was used in the Verdant study to provide an image of the turbine and any fish in the vicinity. Although the observational period was small, no blade strikes of fish were observed during operation of the Verdant turbine (Verdant Power, 2010).

Oak Ridge National Laboratory (ORNL) larval and juvenile fish studies. ORNL examined the risk of blade strikes on larval and juvenile freshwater fish (Schweizer et al., 2012). Four species were examined: striped bass (*Morone saxatilis*), walleye/sauger hybrids (*Stizostedion* spp.), crappie (*Pomoxis* spp.), and fathead minnows (*Pimephales promelas*). The incidence of blade strike and injury to fish was examined in a circular flume at water velocities of 0.5 m/sec, 0.85 m/sec, and 1.15 m/sec. Fish were exposed to cylindrical, hydrofoil, and two-edged blade shapes. They found:

- For the youngest fish tested (1 to 14 days post-hatch striped bass), mean survival was lowest among fish that had passed through the blade, although the survival rates were typically not significantly lower than control fish.

- The post-blade passage survival appeared to increase with age, as older fish were able to avoid the blade. Significant differences between blade exposed and control groups were not observed for walley/sauger, fathead minnows, or crappie, all of which were >20 days post-hatch.

- The observed mortalities among the youngest larvae may have resulted from contact with the blade or turbulence and shear stresses downstream of the blade (Schweizer et al., 2012). Shear stresses sufficient to injure fish may occur near HK turbine rotors and/or blades (U.S. Department of Energy, 2009).

Experimental tests of blade strike on birds, sea turtles, and marine mammals are not possible, and therefore, inferences about risk from blade strike for these animals will generally be based on monitoring data gathered at turbine deployments. Pacific Northwest National Laboratory (PNNL) and Sandia National Laboratory (SNL) modeled the force generated by collision with a rotating OpenHydro turbine and analyzed the potential injury to killer whales resulting from such a strike (Carlson et al. 2012). For a 4,000 kg adult whale moving at 1 to 3 m/s they estimated a maximum strike pressure of 2,350 to 2,365 kPa. Potential injury to the head of a killer whale from a strike of this magnitude was estimated based on the morphology and anatomy of killer whale skulls and information on the biomechanical properties of whale tissues and similar synthetic materials. No laceration of the skin or bone injury was indicated by the analysis (Carlson et al. 2012). They concluded that whale tissue would return to normal shape following blade strike and that there would be no permanent damage to the skin. In addition, the report emphasized that there was a very low probability of a collision between a killer whale and a turbine.

Overall, recent studies in laboratory and natural settings suggest a low potential for injury and mortality from blade strike, except in the case of very young larval stages of fish. However more data is needed particularly with different rotational speeds and blade designs. The significance of mortality to early life stages is likely low, because natural mortality is extremely high and the impacts of MHK devices will be highly localized. A significant determinant of risk is whether the MHK device will be located in the habitat preferred by the species of interest. Therefore, the question of device placement in relation to preferred habitat is key. Avoiding significant migratory routes and important juvenile, spawning, and feeding habitat will minimize the potential for blade strike. Endangered species are protected at the level of the individual, and consideration of their preferred habitat will be an important siting consideration. Some developers have taken additional protective measures to further minimize the potential for blade strike on protected species. For example, the SeaGen has a warning system that deactivates the rotor when marine mammals are detected in the vicinity of the device.

5.2 Noise

Noise generated by the initial construction and placement of the MHK device would be typical of common bottom disturbing activities such as pile-driving, dredging, and vessel traffic. The effects of such noises would be temporary and can be minimized by avoiding biologically sensitive time periods (e.g., major migrations and spawning runs) and locations (spawning grounds and juvenile habitat) and using existing technologies and methods known to minimize ecological impacts. Therefore, the focus of this section is noise generated by MHK devices. Unfortunately, monitoring data evaluating noise effects on biota are available for only a few MHK projects.

SeaGen, Strangford Lough, UK. There are no publically available data on the noise field produced by the SeaGen. Bedford and Fortune (2010) states that "The noise produced by SeaGen is comparable to a large vessel underway making it clearly audible to marine mammals." Modeling predicted that noise from SeaGen would be audible to seals and porpoises at distances up to approximately 1.4 km during periods of high ambient noise when tidal flow was strong, and greater than 1.4 km from the device when ambient noise is low. The authors also concluded that there was little potential for physiological damage to marine mammals from noise generated by the SeaGen, unless exposure to the noise was long-term and continuous. The potential ecological consequences were predicted to be a reduction in communication and foraging efficiency. However, the noise may also help marine mammals avoid the turbine. While in operation, the SeaGen did appear to reduce the transit rate of harbor seals by an average of 20% and detections of harbor porpoises decreased (Bedford and Fortune, 2010). However, the data set was small and the change in behavior could not be linked to noise generated by the turbine.

Verdant Power, East River, New York, NY. Underwater noise measurements were made surrounding the four operating turbines across an area of 180 m by 365 m (Verdant Power, 2010). Far field point measurements were also taken outside of the study area up to a distance of 1,850 m away. The authors found that turbine generated noise was 145 dB re 1µPa at 1 m from the turbines, which would be audible to most fish species. The noise level appeared to return to background levels (~125 dB re 1µPa) less than 200 m from the turbine. The turbine-generated increase in noise above background appeared to be small and did not rise above the threshold levels enough to cause damage, even in sensitive fish species, with the exception of tautog (*Tautoga onitis*; Verdant Power, 2010).

ORPC, Cobscook Bay, ME. ORPC measured noise generated by a test turbine to estimate the noise produced by their commercial-sized TidGen turbine unit (ORPC, 2011). They also measured ambient noise in Cobscook Bay for comparison. At 68 m from the ORPC turbine, an increase of up to 35 dB re $\mu Pa^2/Hz$ above the ambient background noise level was found, although the turbine-generated noise level was typically only around 10 dB re $\mu Pa^2/Hz$ above background. The increase in noise extended up to 500 m from the turbine. Sound pressure levels from the turbine were below 100 dB re $\mu Pa^2/Hz$, even at the maximum rotational speed. At the full five-turbine buildout, the sound pressure levels are modeled to be less than 122 dB re $\mu Pa^2/Hz$ at less than 100 m from the turbine, although the authors state this estimate is conservative and actual sound pressure levels are not likely to reach this level (ORPC, 2011). The report concludes with a communication from the National Marine Fisheries Service that the noise levels generated by the TidGen are not likely to exceed the harassment threshold (120 dB re μPa^2) for marine mammals.

ORNL and Pacific Northwest National Laboratory (PNNL) noise studies. PNNL has conducted laboratory experiments to assess potential noise impacts to fish from MHK devices (Halvorsen et al., 2011). Salmon smolts were exposed to a sound spectra sample from an OpenHydro turbine (155 to 163 dB re 1 µPa rms) for 24 hours after which they were examined for hearing impacts and external and internal tissue damage. Continuous exposure would not be realistic under natural conditions. Therefore, the results of the study give a conservative basis from which to assess impacts on fish. They found:

- There was no clear evidence that sound exposure reduced hearing ability relative to control fish.
- Low-level tissue damage was found after sound exposure, but the effect was not consistent. All injuries were considered to have low physiological cost to the smolts (Halvorsen et al., 2011).

PNNL plans additional noise effect studies using rockfish (*Sebastes* spp.).

ORNL will evaluate noise generated by MHK devices in freshwater systems. The main objectives of the study are to determine levels of acoustic output from MHK devices. There are plans to study noise impacts using penned fish held under field conditions and exposed to noise recordings of MHK devices (Bevelhimer et al., 2011). Sampling and data analysis protocols are still in development.

Northwest National Marine Renewable Energy Center (NNMREC). NNMREC is conducting a study of the potential noise impacts of the Public Utility District No. 1 (Snohomish County) tidal demonstration project in Admiralty Inlet, Puget Sound, Washington (USA). Several baseline acoustic studies have been undertaken (Polagye et al., 2011; Polagye et al., 2012). So far, it has been concluded that water moving across the seafloor produces a naturally high level of sound and that vessel traffic is the primary contributor to anthropogenic sources of noise (Polagye et al., 2012). Initial studies of porpoises in the area show little behavioral changes in response to vessel noise, potentially due to habituation (Polagye et al., 2011). Data gathered thus far suggest that southern resident killer whales (the primary marine mammal of concern in Admiralty Inlet) would generally detect turbine noise only within a few hundred meters of the device, and that the detection of sound will not necessarily produce behavioral responses (Polagye et al., 2012). The impacts of turbine sound on marine mammals will depend on ambient noise, current velocity, species tolerance thresholds, and the distance of the animal from the turbine.

In summary, noise has been very challenging to measure due to the difficulty of separating ambient noise from noise produced by the MHK device (Polagye et al. 2012). Therefore, it is difficult to evaluate with confidence the potential for noise effects based on species specific noise thresholds identified in the scientific literature. The few existing measurements of sound pressure generated by MHK devices are under the 180 dB re 1µPa and

190 dB re 1μPa threshold established to prevent injury to cetaceans and pinnipeds, respectively (Southall et al., 2007). However, near the turbine, the measured noise levels may be within the range expected to cause behavioral disruption to marine mammals (120 dB re 1μPa). Preliminary studies conducted under Market Acceleration 2.1 suggest noise from MHK devices can result in minor injuries to fish. However, laboratory sound exposures are typically several hours, and do not take into account the ability of fish to move away from the noise source. Therefore, based on studies thus far, it appears that noise from MHK operations is unlikely to cause significant physiological harm to biota, but behavioral alteration, especially near the device, may occur. However, generalizing about the effects of noise is difficult because it varies with the design of the MHK device. In addition, noise associated with wave energy devices has not been measured or the data is not publicly available. Clearly, more measurements of noise produced by wave and current MHK devices are needed.

5.3 Changes in Benthic Communities

MHK devices may affect benthic communities by altering local water-sediment interactions, the deposition of biological debris from biofouling organisms, and by attracting fish and invertebrates that prefer hard structures (Figures 2 and 3). The capacity of MHK devices to alter sediment type (a primary determinant of benthic ecology) is currently under investigation under Market Acceleration Subtask 2.1.2.2.

SeaGen, Strangford Lough, UK. Video surveys were conducted from a reference station and at stations located 20 m, 150 m, and 300 m from the SeaGen turbine. Post-deployment changes in benthic community structure have been completed, but no quantitative data were provided in the annual reports (Royal Haskoning, 2011). The report states that changes in benthic communities after installation are similar to changes observed at the reference station. Studies of invertebrate colonization of the SeaGen indicated that barnacles and mussels dominated the community (Royal Haskoning, 2011).

Lysekil Project, Sweden. The effects of the Lysekil wave park on benthic communities was assessed in Langhamer et al. (2009) and Langhamer (2010). The Lysekil project is a linear array of WECs consisting of five surface buoys connected to concrete foundations that will eventually house generators. Each foundation was 2.5 m in diameter and 1 m high. The disk-shaped power buoys were 3 m in diameter and 0.8 m thick. The generators were not operational during the monitoring; therefore, the results do not account for operational impacts. In the soft sandy sediment surrounding the foundations, macrofaunal abundance was higher than at the reference site before and after the WEC deployment (Langhamer, 2010). Overall abundance, diversity, and species richness were low at both reference and test sites, likely because of the strong natural current regime. On the foundations of the WEC, a biofouling community developed consisting of sea squirts, hydroids, algae, barnacles, and serpulid worms (Langhamer et al., 2009). Mussels were found to have developed on buoys. Species diversity and density of benthic fish was higher on the WEC foundation than in surrounding control areas, but lower than natural hard-bottom habitats in the area.

5.4 EMF

Based on the design characteristics of existing AC and DC subsea cables and their measured voltages, Normandeau et al. (2011) modeled EMFs produced by the two cable types in the marine environment. In the immediate vicinity of the cable, the magnetic field was modeled to range as high as ~18 µT for AC cables and up to ~160 µT for DC cables. Modeled magnetic fields decreased in magnitude rapidly with distance from the cable and within 20 m of the cable it diminished to 1 µT. Assuming a 5-knot current, the modeled induced electric fields from the DC cable was up to 0.194 mV/m and decreased almost an order of magnitude 10 m away from the cable. There have been several recent and extensive reviews of EMFs and their effects on biota, although few address MHK devices directly (CMACS, 2003; OWET, 2010; Normandeau et al., 2011). Based on these reviews, magnetic fields as low as 0.01 µT and electric fields as low as 1 nV/m can be detected by fish (OWET, 2010; Normandeau et al., 2011). However, the level at which behavioral disturbance occurs is much less clear. Field studies of the biological effects of EMFs are few and there are none for grid-connected MHK transmission cables.

Gill et al. (2009). Although the cable was not grid connected, the study by Gill et al. (2009) is one of the few field studies of EMFs. The behavioral effects of an EMF similar to one generated by an offshore wind farm AC cable were examined in mesocosm experiments, replicated in time on three occasions. Two sections of cable were buried 0.5 to 1 m in depth; when energized, they generated a magnetic field up to 12 µT and an induced electric field of approximately 2.2µV/m (Gill et al., 2009). A non-energized cable was buried in a separate mesocosm to be used as a control. Within each mesocosm, acoustic telemetry was used to record the individual movements of three species of electrosensitive elasmobranchs: thornback ray (*Raja clavata*), spurdog (*Squalus acanthias*), and small-spotted catshark (*Scyliorhinus canicula*). Trials lasted 3 hours, with no electricity flowing through the cable in hour 1, the cable energized in hour 2, and the cable de-energized in the third hour to examine delayed effects. The EMF extended up to 2 m on either side of the cable (defined as the EMF zone). The results indicated the following:

- For two of the three trials, catshark abundance within the EMF zone was significantly higher when the cable was energized compared to before and after. No significant EMF effect on abundance in the EMF zone was detected for the thornback ray or the spurdog.

- The rate of movement of thornback rays was greater when the cable was on. Catshark moved significantly more after the cable was switched off.

Based on these studies, EMFs generated by subsea cables affected the behavior of some elasmobranch species. However, the effects varied with species and even within species the effects were inconsistently found among the individuals.

ORNL ongoing EMF studies. The effects of EMFs on freshwater fish were evaluated in laboratory studies conducted by ORNL under Market Acceleration Subtask 2.1.3.1 (Čada et al., 2012). Magnets were used to simulate the magnetic fields generated by transmission cables. Spatial distribution and activity level of four species [fathead minnows (*Pimephales promelas*), juvenile sunfish (*Lepomis* spp.), juvenile channel catfish (*Ictalurus punctatus*), and juvenile striped bass (*Morone saxatilis*)] were then examined using video recordings of their locations in the tank. In addition, the behavioral responses of sunfish, paddlefish (*Polyodon spathula*), and lake sturgeon (*Acipenser fulvescens*) to AC fields was examined. Paddlefish and lake sturgeon are known to be electrosensitive species. Magnetic field strength within the experimental tanks ranged from background levels to ~36,000 and 124,000 µT for the DC and AC experimental trials, respectively. The following results were reported:

- For the DC trials, no effect on distribution or activity level was found for any species except the fathead minnow, which showed significantly greater activity when exposed to the experimental magnetic field compared to the control fish.
- For the AC trials, juvenile sturgeon displayed the most consistent behavioral response to the magnetic field. Pectoral fin flare, gliding, and body spasm were the most common behavioral alterations recorded and the reactions typically lasted for less than 2 seconds. The percentage of fish exhibiting a response increased with the power of the electromagnetic field. No long-term effects on lake sturgeon were noted.
- Paddlefish and sunfish showed no response to the magnetic field in most of the trials.

Only minor behavioral alterations were observed even though the maximum magnetic field strength in the experimental aquaria was much higher than modeled for existing or proposed subsea cables (Čada et al., 2011). Based on these results and earlier studies with freshwater snails (*Elimia clavaeformis*) and clams (*Corbicula fluminea*), the authors conclude that a single transmission cable associated with an MHK device would not result in significant changes in the behavior of freshwater fish or invertebrates.

PNNL ongoing EMF studies. Using controlled laboratory experiments, PNNL exposed fish and invertebrates to EMF fields of 0.13 and 3 mT, which were within or slightly higher than the range expected to be generated by transmission cables associated with MHK technology (Woodruff et al., 2012). The effect of EMFs on the following endpoints were assessed: physiological stress response (coho salmon [*Oncorhynchus kisutch*]), egg and larval development (rainbow trout [*Oncorhynchus mykiss*], Atlantic halibut [*Hippoglossus hippoglossus*], and California halibut [*Paralicthys californicus*]). A relatively uniform EMFfield strength of 3.2 mT was used for the salmon and halibut trials (Woodruff et al., 2012). The following results were reported:

- No statistically significant differences in the levels of the stress hormone cortisol were found between the control and EMF exposed coho salmon. Melatonin levels were significantly lower for EMF-exposed fish (for both 0.13 and 3 mT exposures).

- No statistically significant effects from a 17-d EMF exposure were found on the fertilization success or hatch success of rainbow trout eggs.

- Significantly lower development rates were detected in EMF-exposed rainbow trout larvae at 20 days post-fertilization.

- No effects were found on the metamorphosis, development rate, or survival of larval California halibut following a multi-week EMF exposure. Average growth of EMF-exposed larval Atlantic halibut was slower than that of control fish, but the differences were not statistically significant.

To examine EMF effects on invertebrates, Dungeness crab (*Metacarcinus magister*) were exposed to a non-uniform EMF field that mimicked transmission cables. For these trials, EMF was 1 mT near the source and decayed to background within 1 mile. The endpoints assessed were detection of EMF fields, odor detection, and avoidance or attraction to EMF (Woodruff et al., 2012). The following results were reported:

- No statistically significant differences in antenna flicking rate or any obvious changes in movement were detected after exposure to EMF.

- No statistically significant differences in food detection or feeding behaviors were found between EMF exposure and control crabs.

- EMF exposure may have increased general crab activity and behavioral variability, but the effect was not found consistently.

- The data did not suggest Dungeness crab displayed any avoidance or attraction behavior in relation to the EMF field.

- Control crabs spent significantly more time buried in the sand and showed fewer activity changes compared to EMF-exposed crabs.

PNNL will continue EMF experiments in 2012 using elasmobranchs and American lobster (*Homarus americanus*) (Woodruff et al., 2012).

Studies conducted thus far suggest that EMFs produced by subsea cables have the potential to cause behavioral alteration in electrosensitive species. However, the ecological significance of these behavioral alterations is unclear and is difficult to evaluate. For example, unlike laboratory EMF exposures, under natural conditions organisms will have the ability to move away from the EMF field, avoiding long-term exposure. Given the minor behavioral changes found in experimental tests and the ability of organisms to habituate to stimuli, the effects of EMFs are not likely to be significant for a single device. Avoiding siting the MHK deployment in sensitive habitats will also minimize the potential impacts.

5.5 Other Biological Studies

ORNL is in the process of identifying new and existing anti-fouling coatings and evaluating their toxicity using literature reviews, leaching experiments, and toxicity tests on biota (Glass-Mattie et al., 2011). Initial tests were conducted using two anti-fouling coatings: Intersleek® 757 and Intersleek® 970. No toxicity from either coating was found in preliminary toxicity tests with water fleas and fathead minnows (Glass-Mattie et al., 2011). Toxicity tests of other anti-fouling coatings are planned for 2012 including Smart Surfaces® coatings by Fujifilm, experimental coatings (pending development), and additional tests of the Intersleek® products. In addition, preliminary risk estimates for anti-fouling biocides were performed by PNNL and the analysis suggests low ecological risk, even for compounds known to be toxic to biota (Andrea Copping, personal communication, 2012).

5.6 Impacts on Habitat

This section will discuss studies of habitat related impacts from proposed or existing MHK deployments and the implications of these impacts for ecological risk. Because there are few MHK deployments, there is little habitat monitoring data and most existing analyses are based on simulations developed for actual or proposed WEC or tidal array projects. Modeling the hydrodynamic effects of WEC and tidal MHK devices is complex and highly site and array specific. In addition, few of the models have been validated, due to the lack of deployments. Therefore, the following studies should be considered preliminary.

ORPC, Cobscook Bay, ME. Under the DOE sponsored MHK Market Acceleration program, SNL developed a hydrodynamic model to assess the impacts of the proposed ORPC TidGen five-turbine array planned for deployment in Cobscook Bay, MA (Jesse Roberts, Sandia National Laboratory, unpublished data). One concern associated with tidal arrays is there potential to disrupt the transport of organisms such as eggs, larvae, and zooplankton that lack the ability to swim against the prevailing current (Section 3.2). Sea scallops and sea urchin are abundant in Cobscook Bay (Russell, 2001; Singer, 2011) and impacts to these important fishery species are of particular concern. Simulation of passive particle movement through Cobscook Bay with and without the TidGen array indicated that the array would not significantly alter particle movement trajectories (Jesse Roberts, Sandia National Laboratory, unpublished data). These results suggest that the proposed array would have no significant large-scale effect on the transport of permanent plankton or early life-stages of fish and invertebrates A more quantitative comparison of particle tracks with and without the turbine would be necessary to confirm this speculation. Also, more localized impacts to plankton in the vicinity of the turbine as well as their cumulative effects over time cannot be assessed at the resolution of this study. The model results also indicated that the flushing rate within Cobscook Bay was not significantly different between turbine and non-turbine conditions (Jesse Roberts, Sandia National Laboratory, unpublished data). The array resulted in a decrease in tidal range of less than 1 cm, which is within the uncertainty of the model. The negligible impact on tidal flushing and tidal range suggest the TidGen array will have little large-scale impact on water quality within Cobscook Bay. Consequently, large-scale impacts to biota from the array are also expected to be minor.

SeaGen, Strangford Lough, UK. The hydrodynamic effects of the SeaGen turbine in Strangford Lough, UK, was studied using an Acoustic Doppler Current Profiler (Royal Haskoning, 2011).

The results indicated that, after the installation of the SeaGen, there was no significant change in current direction. The comparative difference in pre and post-installation water velocity was greatest during the neep ebb tide (16.1%) and least during the neap flood tide (1.6%). The wake generated by the SeaGen appeared to extend no more than 300 m from the turbine (Royal Haskoning, 2011) and beyond this no changes in hydrodynamics were found 2.5 m below the surface or at the seafloor. Based on these results and additional monitoring data (Section 5.3) the study concluded that the operation of the SeaGen did not result in habitat changes significant enough to affect biological communities and ecosystem processes.

Verdant Power, East River, New York, NY. Verdant Power used modeling simulations partially validated by field collected Acoustic Doppler Current Profiler (ADCP) measurements to assess the hydrodynamic impacts from their KHPS turbine array (Colby and Adonizio, 2011). Flow velocities were reduced in the wake of the turbine and flow direction was altered in the near field. A simulation with 30, 35 kW turbines, showed a reduction in channel water velocity of 0.07 m/s (3.4%) and an increased water level by 1.2 cm (0.08% increase) between the inlet and the turbines. The authors state that these changes would not be detectible by instrumentation and would not result in ecologically significant impacts to biota.

WEC simulations. As discussed in Section 3, MHK arrays have the potential to indirectly affect biota through changes in physical conditions. There are few project specific modeling studies for WECs. Millar et al. (2007) modeled a 30-MW wave farm at the Wave Hub site (offshore of Cornwall, UK) and found a reduction in wave height of less than 4 cm near the shoreline, depending on wave direction. Using the proposed plan for the 203 MW, 320-km^2 Pelamis wave farm (São Pedro de Moel, Portugal), Palha et al. (2010) found a reduction in wave height near the shoreline of 9% to 23%, depending on the time of year. However, a review by Bell and Side (2011) suggests that given the complexity of wave and sediment dynamics, methodological improvements are needed to improve the forecasting of existing models. Although the results of these WEC studies were not focused on ecological impacts, they do suggest that further monitoring studies of physical habitat changes overtime, and potentially studies linking habitat and ecological change, will be required to fully assess ecological risk.

Based on these simulations, there appears to be potential for MHK devices to affect sediment transport and nearshore currents, especially in the littoral zone of tidal estuaries and hydrodynamically active beaches. Although there is the potential for these alterations in physical habitat to affect biota as described in Sections 3.1 and 3.2, the actual ecological impacts of such changes have not been investigated; until such investigations are undertaken, impacts on biota are speculative. The first step would be to modify existing site specific models to account for multiple spatial scales. Such models would include high resolution domains to address near-field turbine effects and larger domains to examine impacts to large scale circulation. In addition, modeling and montoring efforts need to account for cumulative impacts overtime that occur from the continuous presence of the device in the environment over multiple tidal cycles. However, realistic predictions may be difficult to achieve as aquatic systems are highly dynamic and natural process such as tropical storms and hurricanes can reshape aquatic habitats rapidly and more significantly than MHK arrays.

5.7 Conclusion

Many of the monitoring studies described in this report do not contain pre-deployment or control monitoring data, which complicates the interpretation of the results described in the reports. However, some preliminary inferences about MHK effects can be made based on the animal-MHK device interactions described in the monitoring studies. Of the direct MHK stressors identified in Figure 2, behavioral changes and benthic habitat alteration appear to be the primary measurable effects associated with exposure to MHK devices. Behavioral changes in fish, birds, and marine mammals during turbine operations were described in monitoring reports, but the changes were generally minor, localized, or inconsistently observed. More data is needed before generalizations can be made about how behavioral changes vary by MHK device type, major groups of organisms (e.g., fish, cetaceans, birds), and activity (e.g., feeding, migration, communication). Benthic habitat alteration resulting from the placement of hard structure is expected where the device is placed in soft sediments. Although MHK devices may increase the abundance and diversity of benthic communities compared to surrounding soft sediment, the ability of the MHK devices to mimic artificial reefs is uncertain (Langhamer, 2010). However, use of the MHK device by benthic species can be enhanced by design modifications. For example, Langhamer and Wilhelmsson (2009) increased the abundance of a crab species by drilling holes in the concrete foundations of a WEC.

Existing data does not suggest that there is a significant potential for injury or mortality from the device operations identified in Figure 2, with the exception of early life stages of fish and invertebrates. Operational impacts from EMFs and noise do not appear to reach thresholds that are high enough to result in injury to adults. Similarly, mortality or injury from blade strike, entrainment, and cavitation do not appear to be significant because of the low rotational velocity of most MHK devices (Kramer et al., 2011). However, impacts to larvae require more study. Impacts from blade strike are not likely to generate population-level effects and the probability of lethal strike appears to be low, but the presence of endangered species — particularly marine mammals and sea turtles — could make even one incident of injury a cause for regulatory concern. For endangered species, mitigation measures such as appropriate siting and early warning systems can further reduce the potential for blade strike.

In assessing existing studies, there are clear challenges to implementing an effective monitoring program. First, although some variation of a Before/After Control Impact (BACI) design is recommended for environmental effects studies (Underwood, 1994; Stewart-Oaten et al., 1992; Schroeter et al., 1993), their application to MHK monitoring can be costly because of the increased effort and cost required and logistical difficulties of collecting data at multiple control sites. In addition, BACI designs have not necessarily achieved the desired level of confidence in understanding impact magnitudes. One primary reason is the high natural variability in animal populations. Greater replication can increase statistical power, but depending on the spatial and temporal variability, the number of replicates required may not be realistic from a time, cost, or logistical perspective. Second, it is unclear whether the behavioral effects found during past monitoring studies are ecologically significant. For example, even if an organism is found to temporarily alter its movement and distribution in response to MHK operations, the consequences for individual fitness may be minimal. The difficulty of putting monitoring results in an ecological context is a significant challenge in the risk assessment of

MHK operations. Finally, while existing data suggest low, localized ecological risk for a single device, the risk may increase with additional devices. This will become more relevant as more commercial-scale MHK arrays come under consideration by regulators. The ecological risks associated with attraction/avoidance behaviors, barriers, noise, and EMFs at the commercial scale will ultimately have to be evaluated to fully understand the ecological impacts of MHK devices.

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