U.S. DEPARTMENT OF ENERGY

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under Contract DE-AC05-76RL01830

Identification and Prioritization of Analysis Cases for Marine and Hydrokinetic Energy Risk Screening

Environmental Effects of Marine and Hydrokinetic Energy – Fiscal Year 2010

RM Anderson
SD Unwin
FB Van Cleve

June 2010

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Summary

In this report we present an introduction to the Environmental Risk Evaluation System (ERES), a risk-informed analytical process for estimating the environmental risks associated with the construction and operation of marine and hydrokinetic energy generation projects. The process consists of two main phases of analysis. In the first phase, preliminary risk analyses will take the form of screening studies in which key environmental impacts and the uncertainties that create risk are identified, leading to a better-focused characterization of the relevant environmental effects. Existence of critical data gaps will suggest areas in which specific modeling and/or data collection activities should take place. In the second phase, more detailed quantitative risk analyses will be conducted, with residual uncertainties providing the basis for recommending risk mitigation and monitoring activities.

We also describe in detail the process used for selecting three cases for fiscal year 2010 risk screening analysis using the ERES. A case is defined as a specific technology deployed in a particular location involving certain environmental receptors specific to that location. The three cases selected satisfy a number of desirable criteria: 1) they correspond to real projects whose deployment is likely to take place in the foreseeable future; 2) the technology developers are willing to share technology and project-related data; 3) the projects represent a diversity of technology-site-receptor characteristics; 4) the projects are of national interest, and 5) environmental effects data may be available for the projects.

Project Overview

Energy generated from the world's oceans and rivers offers the potential to make substantial contributions to the domestic and global renewable energy supply. The U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) Wind and Water Power Program supports the emerging marine and hydrokinetic (MHK) energy industry. As an emerging industry, MHK project developers face challenges with siting, permitting, construction, and operation of pilot- and commercial-scale facilities, as well as the need to develop robust technologies, secure financing, and gain public acceptance.

In many cases, little is known about the potential effects of MHK energy generation on the aquatic environment from a small number of devices or a large-scale commercial array. Nor do we understand potential effects that may occur after years or decades of operation. This lack of knowledge affects the solvency of the industry, the actions of regulatory agencies, the opinions and concerns of stakeholder groups, and the commitment of energy project developers and investors.

To unravel and address the complexity of environmental issues associated with MHK, Pacific Northwest National Laboratory (PNNL) is developing a program of research and development that draws on the knowledge of the industry, regulators, and stakeholders and builds on investments made by the EERE Wind and Water Power Program. The PNNL program of research and development—together with complementary efforts of other national laboratories, national marine renewable energy centers, universities, and industry—supports DOE's market acceleration activities through focused research and development on environmental effects and siting issues. Research areas addressed include

- **categorizing and evaluating effects of stressors** – Information on the environmental risks from MHK devices, including data obtained from in situ testing and laboratory experiments (see other tasks below) will be compiled in a knowledge management system known as *Tethys*, after the mythical Greek titaness of the sea, to facilitate the creation, annotation, and exchange of information on environmental effects of MHK technologies. Tethys will support the Environmental Risk Evaluation System (ERES) that can be used by developers, regulators, and other stakeholders to assess relative risks associated with MHK technologies, site characteristics, waterbody characteristics, and receptors (i.e., habitat, marine mammals, and fish). Development of Tethys and the ERES will require focused input from various stakeholders to ensure accuracy and alignment with other needs.
- **effects on physical systems** – Computational numerical modeling will be used to understand the effects of energy removal on water bodies from the short- and long-term operation of MHK devices and arrays. Initially, PNNL's three-dimensional coastal circulation and transport model of Puget Sound will be adapted to test and optimize simulated tidal technologies that resemble those currently in proposal, laboratory trial, or pilot study test stages. This task includes assessing changes to the physical environment (currents, waves, sediments, and water quality) and the potential effects of these changes on the aquatic food webs) resulting from operation of MHK devices at both pilot- and commercial-scale in river and ocean settings.
- **effects on aquatic organisms** – Testing protocols and laboratory exposure experiments will be developed and implemented to evaluate the potential for adverse effects from operation of MHK devices in the aquatic environment. Initial studies will focus on electromagnetic field effects, noise associated with construction and operation of MHK devices, and assessment of the potential risk of

physical interaction of aquatic organisms with devices. A variety of fish species and invertebrates will be used as test animals, chosen due to their proximity to and potential susceptibility to MHK devices.

- **permitting and planning** – Structured stakeholder communication and outreach activities will provide critical information to the project team to support execution of other project tasks. Input from MHK technology and project developers, regulators and natural resource management agencies, environmental groups, and other stakeholder groups will be used to develop the user interface of Tethys, populate the database, define the risk attributes of the ERES, and communicate results of numerical modeling and laboratory studies of exposure of test animals to MHK stressors. This task will also include activities to promote consideration of renewable ocean energy in national and local Coastal and Marine Spatial Planning activities.

The team for the Environmental Effects of MHK Development project is made up of staff, faculty, and students from

- Pacific Northwest National Laboratory
  - Marine Sciences Laboratory (Sequim and Seattle, Washington)
  - Risk and Decision Sciences (Richland, Washington)
  - Knowledge Systems (Richland, Washington)
- Oak Ridge National Laboratory (Oak Ridge, Tennessee)
- Sandia National Laboratories (Albuquerque, New Mexico; Carlsbad, California)
- Oregon State University, Northwest National Marine Renewable Energy Center (Newport, Oregon)
- University of Washington, Northwest National Marine Renewable Energy Center (Seattle, Washington)
- Pacific Energy Ventures (Portland, Oregon).

Acronyms and Abbreviations

DOE	U.S. Department of Energy
EERE	DOE Office of Energy Efficiency and Renewable Energy
EMF	electromagnetic field
ERES	Environmental Risk Evaluation System
FERC	Federal Energy Regulatory Commission
FY	fiscal year
MHK	marine and hydrokinetic
PNNL	Pacific Northwest National Laboratory

Contents

Figures

Table

1.0 Introduction

The concept of risk is basic to human experience in that we all evaluate decisions and situations in terms of their potential to lead to outcomes that are either favorable or unfavorable. A great variety of issues (e.g., societal, economic, and political priorities) influence attitudes and decision making associated with the development and commercialization of marine and hydrokinetic (MHK) technologies. In addition to these issues, stakeholders and decision makers also need to be risk-informed. That is, they need to have access to information and processes that allow identified risk and resulting uncertainties to be systematically and consistently taken into account in decision making related to investment, regulation, design, and operation of MHK technologies. The risk-informed approach described in this report will help the stakeholder and decision makers to assess their tolerance toward risk, determine how to prioritize research activities and issues, and compare the costs and benefits of different options. Figure 1 depicts a general framework for management of risks as it is often applied in engineered and natural systems management contexts. In particular, the boxes on the right-hand side illustrate the view that managing environmental risk—the focus of this study—will facilitate management of regulatory and, ultimately, investment risk.

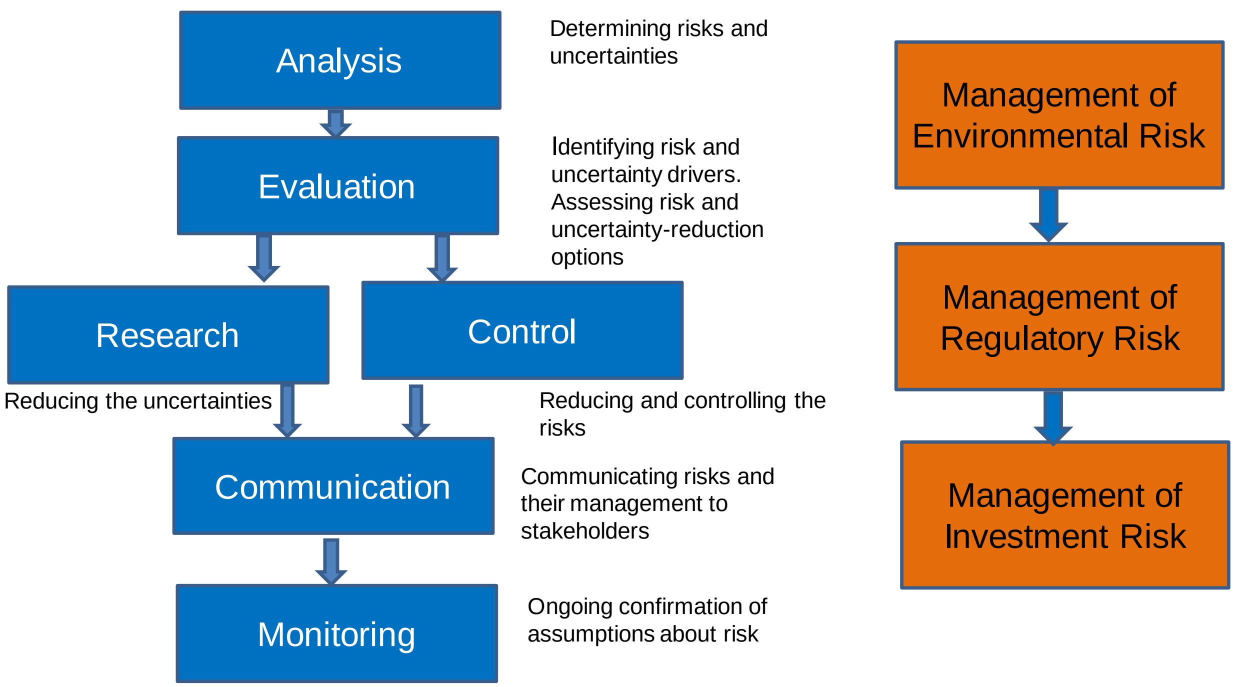

Figure 1. Elements of Risk Management

The risk assessment process begins with the identification and description of scenarios, resulting from sequences of events that lead to adverse impacts (Figure 2). It is useful to distinguish between scenarios that are episodic and, at the other end of the spectrum, those that are chronic. Episodic scenarios involve events that may or may not take place and are thus characterized by their likelihood or rate of occurrence. They are also characterized by the degree of impact or severity of their consequences. An example of an episodic scenario would be collision of a vessel with an MHK device or array of devices. The likelihood of occurrence would be related to factors such as vessel traffic volume and the proximity of shipping lanes to the devices. Consequences could include environmental damage due to spills and financial loss due to damaged property or loss of generation of power. In contrast, chronic risk scenarios involve events or circumstances that are always in effect so that risk characterization involves assessing only the severity of the consequences. An example of a chronic risk scenario would be low-level chemical releases from anti-biofouling coatings used on device structures. Between these two extremes, we may also identify an intermediate category of intermittent events. These are really episodic but are of high enough frequency that they are anticipated. Here, an example would be adverse impacts to animals associated with turbine rotation such as blade strike. A key feature of understanding risk is describing the uncertainty associate with the occurrence of an episodic, intermittent, or chronic event, as well as the uncertainty of the resulting consequences. This analysis will limit its focus to environmental effects.

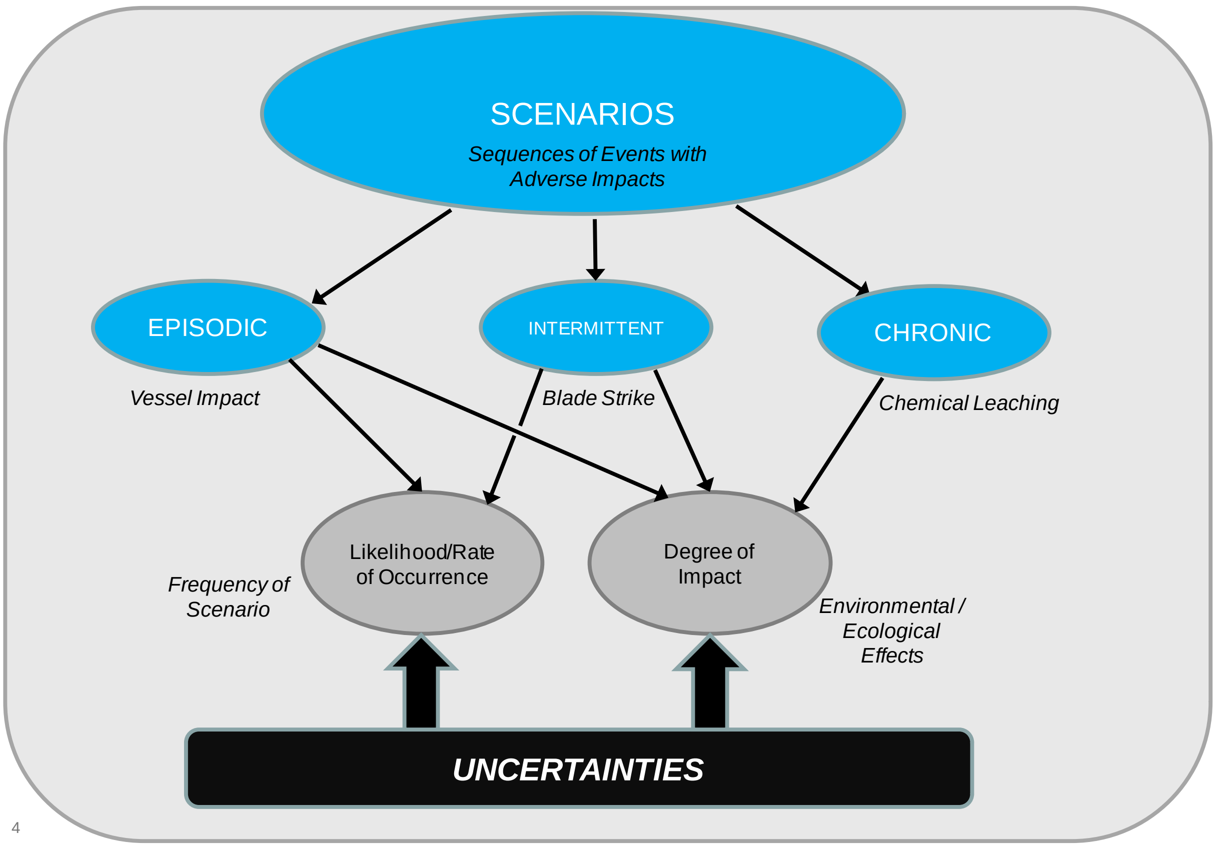

Figure 2. Description of Risk

2.0 Development of Marine and Hydrokinetic Risk-Informed Decision Framework

As part of the EERE MHK program, we will develop and implement a multi-phase risk methodology that can be applied to, and used to select among, a wide range of technologies and siting options, and to prioritize research directed towards uncertainty reduction. The overall process is depicted in Figure 3.

One challenge for a risk-informed approach to the analysis and management of MHK technologies is the diversity of existing and prospective device designs and environments in which they might operate. This report will describe a process of identifying and prioritizing specific case studies (devices deployed in specific locations) for analysis. The process will be guided by stakeholder review and is represented in the first three boxes (blue) in Figure 3.

As shown in the next five boxes (green) in Figure 3, preliminary-phase (phase 1) risk analyses will take the form of screening studies in which key environmental impacts and risks are identified and key uncertainties are characterized relative to the cases selected. Key uncertainties are those to which our assessments of scenario likelihoods or impacts, and thus of risk, are highly sensitive. There will be multiple rounds of screening studies as new cases are selected for analysis. This initial phase of analysis will lead to more finely resolved definitions of ecological impact scenarios (stressors, receptors, impact mechanisms) and suggest specific data collection efforts or model improvements in an attempt to resolve identified risk-critical uncertainties.

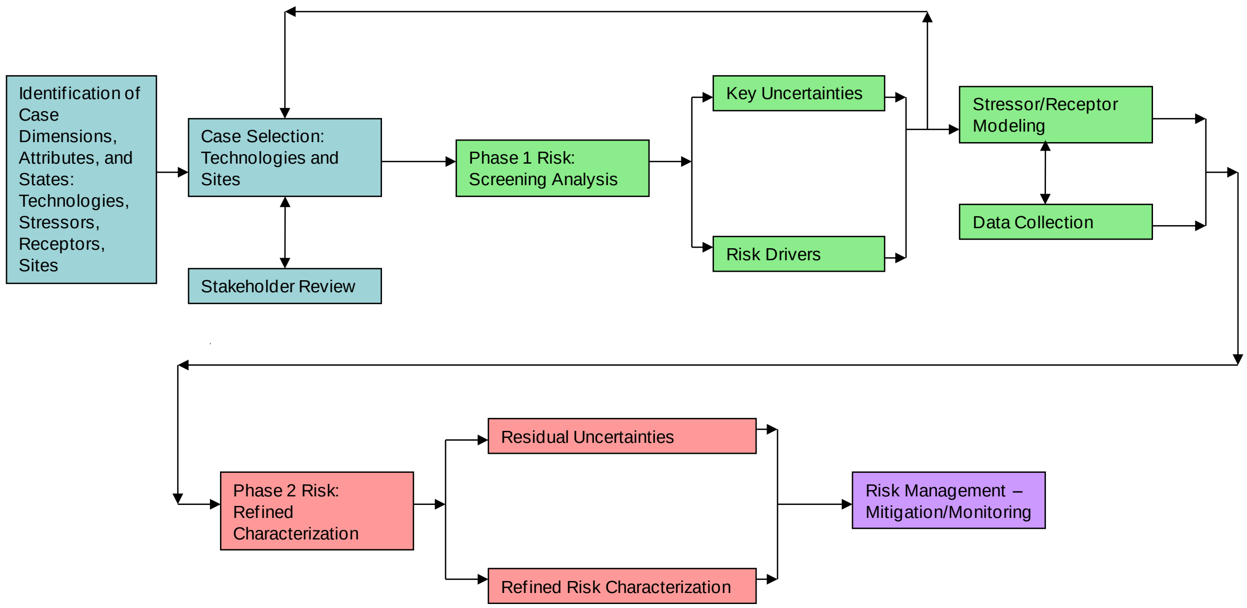

Figure 3. Risk-Informed Analytical Process

The next three boxes (red) refer to a more detailed and more quantitative phase (phase 2) of risk analysis that will be based on improved scenario characterization and augmented data generated in the previous steps. The more refined characterization of risk and residual uncertainties that remain after this stage forms the basis for choosing appropriate actions for managing risk, as indicated in the final box (purple). Unacceptable risks and large uncertainties may be addressed through additional modeling and data collection efforts, while sensitivity and importance analyses will be used to identify effective risk mitigation strategies and monitoring approaches.

3.0 Case Development

Given the impracticality of capturing all technologies and siting features in a single round of analysis, the concept of an analysis *case* is introduced. Case studies will allow the sequencing of analyses within each phase of this environmental effects project. A case is defined as a combination of an MHK technology (such as a specific tidal, wave, or instream device) and a deployment site, where the latter is defined by waterbody and site features and the specific set of environmental receptors potentially at risk. The cases selected will provide the vehicle for the development of risk and decision methodology, and for this reason it is important that they capture a broad range of device, siting, stressor, receptor, and uncertainty issues. In this way, the cases initially considered will help set methodological precedents for application to a wide range of subsequent risk analyses for other devices and site/receptor characteristics. It is crucial that the cases initially selected for analysis represent a broad range of risk issues.

Identifying cases relies to some extent on our current understanding of which technology and siting features are likely to drive the risk. For example, the design and technology features selected to distinguish between cases are chosen to reflect the distinguishing risk characteristics anticipated. In this way, a case is intended to represent a class of devices that possess *risk-relevant* features (to be defined below as *attributes*). We expect that our understanding of which features are and are not risk relevant will evolve as the analysis proceeds.

A systematic approach to the selection and prioritization of cases is being developed, in which the goal is to produce an objective, transparent, and easily reviewable process. This report outlines the current version of that approach and identifies the analysis cases that have been selected as a result of its application. We begin by describing how an analysis case is defined. Next, the basis for case selection is outlined. Finally, the case selections are identified.

The key *dimensions* of an analysis case define the power-generating technology, the siting of its deployment at the site and waterbody scale, and the potential environmental receptors. Each dimension can be defined more specifically by the *state* of different *attributes* associated with that dimension: for example, for an axial flow turbine, *axial flow* would be a state, *orientation with respect to flow* would be an attribute, and *MHK Technology* would be the dimension. That is, a case is defined as a specific combination of states associated with each attribute across the four dimensions. Figure 4 summarizes the relationships between cases, dimensions, attributes, and states.

In the following sections, we will discuss the key dimensions, the types of attributes, and the states associated with each attribute. Following that, we outline our approach to case identification and prioritization. These discussions are intended to convey a sense of the bases for identifying attributes and corresponding states. The taxonomy of dimensional attributes and states resulting from this approach is shown in Appendix A.

Four key dimensions are identified: MHK technology, waterbody features, site characteristics, and receptors. As already described, the intent in defining the attributes and states of each dimension is to identify features that are likely to display contrasting risk characteristics.

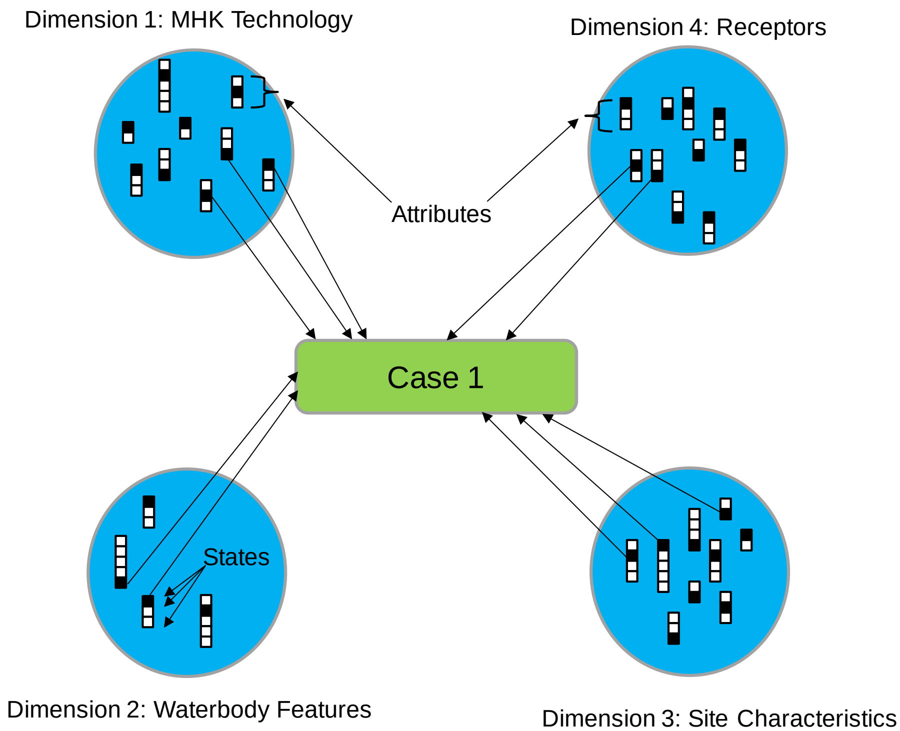

Figure 4. Dimensions, Attributes, States, and Cases

Dimension 1: MHK Technology –The types of stressors distinguish the risk impacts of various MHK power generation technologies as does the degree of impact each might cause. The major MHK technologies we will address are tidal, wave, and riverine. Although there may be some commonality of relevant environmental stressors between these categories, they also have distinguishing stressor attributes. Less clear is the extent to which attributes within each of these categories affect stressors and so we have adopted a conservative approach to distinguishing attributes. For example, with respect to blade strike, one potentially relevant attribute is whether the rotor blades are ducted. Therefore, a case associated with unducted blades will provide some insight into the class of all horizontal turbine systems but will not address effects associated specifically with ducting. If the importance of this effect is significant, or both significant and uncertain, turbine ducting is a legitimate, risk-relevant attribute. Additional risk-relevant attributes within this category for blade strike may be device size, rotational speeds, and power rating; these attributes might also be risk-relevant attributes for noise and electromagnetic field (EMF) stressors.

Dimension 2: Waterbody Features – Waterbody features are differentiated by attributes that reflect the variety of waterbody types, including estuarine, coastal, open ocean, or riverine, in either tropical, temperate, or subarctic climatic zones. This dimension also includes water quality attributes (e.g., salinity, temperature, turbidity) and physical attributes at the waterbody scale (e.g., prevailing wind, frequency of storm events, tidal regime).

Dimension 3: Site Characteristics – This dimension is made up of site-specific physical features, including current speed and flow, wave height, and water depth. Because most MHK devices are gravity mounted or moored to the seabed, an important set of attributes describes the nature of the benthic environment and habitats present at the site. Physical attributes include typical sediment grain sizes and whether the substrates are hard and stable or soft and easily mobilized. Biological attributes categorize benthic vegetation type.

Dimension 4: Receptors – This dimension includes biological attributes of ecological, cultural, or economic importance that may be present at the MHK project site and have the potential to be directly or indirectly impacted by MHK development or operation. Attributes characterize seasonality of presence of important species groups (e.g., whales, reef fishes, diving birds), behavior at the project site, and special status or regulatory protections in place. The receptor dimension also includes attributes to characterize presence and special status of high-value habitats, including coral and rocky reefs, kelp forests, seagrass beds, and deep water corals or sponges. Water quality and sediment transport patterns are also included as receptors that may be affected by MHK energy development.

4.0 Approach to Case Selection and Prioritization

As previously outlined, the greater the degree to which the set of cases chosen for analysis spans the analytical space of attributes and states, the greater the likely value of those analyses as methodological precedents (Figure 5). Therefore, one objective of the selection methodology is to choose cases for near-term analysis that, in combination, capture the greatest diversity of attributes and states.

At the same time, we wish to avoid an abstract approach is which we address purely hypothetical state combinations. Rather, we wish to connect the studied cases to existing or pending technologies and projects. The EERE MHK Technology Database[1] and the Federal Energy Regulatory Commission (FERC) MHK project permit database[2] were used to determine whether cases represented mature projects likely to be developed.

Developer willingness to participate in this process is an important criterion for selection of cases. Cases will not be selected if the attention on that case will have real or perceived negative impact on the project. Willingness to participate is crucial because risk evaluation will require access to project plans, studies, and data.

The approach to case selection entailed a three-step, iterative process:

1. *Compilation of Attributes and States* – In this first step, the initial lists of attributes and states associated with each of the dimensions were compiled. These are shown in Appendix A.
2. *Stakeholder Feedback* – In this second step we met with three important stakeholder groups to discuss the dimensions/attributes/case approach to case selection and elicit feedback. On April 13, 2010, representatives of the ocean energy industry met in Seattle, Washington. On April 13 and May 27, 2010 federal and state regulatory agency representatives met in Seattle, and on June 17, 2010 we met with representatives from environmental organizations through a webex-supported teleconference. Participants were presented with the case selection process, including three preliminary cases, and invited to provide feedback. The discussions that took place contributed to the development of the set of criteria currently being implemented in choosing cases (Figure 6). Three cases were identified based on these discussions.

[1] Accessible at http://www1.eere.energy.gov/windandhydro/hydrokinetic/about.aspx (June 2010).
[2] Accessible at http://www.ferc.gov/industries/hydropower/indus-act/hydrokinetics.asp (June 2010).

3. *Coverage of Analytical Space* - For FY 10, the attributes and states of the three cased identified through discussion stakeholders were compared to the table of attributes and states (Appendix A) to ensure broad coverage of the analytical space. For the MHK Technology Dimension, the states that will be used in FY 10 analysis are highlighted in Figure 5. Figure 5 (and the equivalent for other dimensions) thus provides a confirming visualization that the analytical space is being captured. The cases identified at this step represent hypothetical but credible attribute–state combinations (for example, large marine mammals as receptors would not be an element selected in combination with riverine devices).

DIMENSION	ATTRIBUTE	STATE 1	STATE 2	STATE 3	STATE 4	STATE 5
Operational (includes installation, operation, maintenance, decommissioning)						
MHK Technology	Max rotational speed of device (RPM)	10-15	15-20	20-30	>30	None
MHK Technology	Tip speed of device (m/s)	0-5	5-10	>10	None	
MHK Technology	Direction of generation	One way	Two-way	N/A		
MHK Technology	Adjustable turbine speed	Yes	No	N/A		
MHK Technology	Time to shut down	0-6sec	6-15sec	>15sec	N/A	
MHK Technology	Removable rotor for maintenance	Yes	No			
MHK Technology	Average hours of power generation per day	<12	12--18	>18		
MHK Technology	Emergency removal time (hrs)	<12	12--24	>24		
MHK Technology	Time to decommission	12--24 hours	1 day - 1 week	>1 week		
	Geometry and orientation					
MHK Technology	Project status	pilot	commercial			
MHK Technology	Number of devices	0-3	3--10	10--50	>50	
MHK Technology	Geometry	cross channel/paralle	along channel/perpe	other configuration		
MHK Technology	Vertical location in water column	Surface	Bottom	Water column	Mid	
MHK Technology	Orientation wrt wave direction	Parallel/overtopping	Perpendicular	Point	Overtopping	N/A
	Rotor Configuration					
MHK Technology	Size of turbine swept area (m^2)	20-60	60-100	100-200	200-500	None
MHK Technology	Orientation of axis wrt flow	Axial	Transverse	N/A		
MHK Technology	Orientation of blades wrt axis	Perpendicular	Parallel	N/A		
MHK Technology	Shape of leading edge of turbine blade	Rounded	Sharp	N/A		
MHK Technology	Pitched blades	Yes, fixed	Yes, adjustable	No	N/A	
MHK Technology	Rotor diameter (m)	5-7	7-10	10-15	None	
MHK Technology	Dynamic rotor seal	Yes	No	N/A		
MHK Technology	Gearbox	Yes	No			
	Device Configuration					
MHK Technology	Yaw mechanism	Yes	No			
MHK Technology	Ducted/venturi	No duct	Shallow duct	Shallow venturi	Deep venturi	
MHK Technology	External generator	Yes	No			
MHK Technology	Turbine/generator located onsite in water	Yes	No			
MHK Technology	Surface-Piercing	Yes	No			
MHK Technology	Power rating of device (kW)	10-50	50-100	100-1000	>1000	
MHK Technology	Approximate power output at 2.5 m/s (kW)	10-50	50-100	100-200	>200	
MHK Technology	Power cable location	Buried	Surface-laid			
MHK Technology	Cable landfall	Directional drilling	Through nearshore			
MHK Technology	Coupled with bidirectional airflow turbine	Yes	No			
MHK Technology	Impedance matching of waves	Yes	No			
MHK Technology	Adjustable natural resonance frequency	Yes	No	None		
	Fouling, Corrosion Protection					
MHK Technology	Anti-fouling coating/paint	Yes	No			
MHK Technology	Surface area covered by anti-fouling coating/paint (m	0 - 30	30-60	>60	None	
MHK Technology	Composition of anti-fouling coating/paint	Toxic	Non-toxic	None		
	Lubrication					
MHK Technology	Bearings	Yes	No			
	Mooring/Foundation					
MHK Technology	Footprint on bottom ()m^2	5-8	8-11	11-14	>14	
MHK Technology	Distance from edge of waterway	0-20m	20-60m	60-150m	>150m	
MHK Technology	Mooring method	Gravity-mounted	Driven piles	Anchored		
MHK Technology	Cables	Slack	Taut	N/A		

Figure 5. Representation of Space Coverage

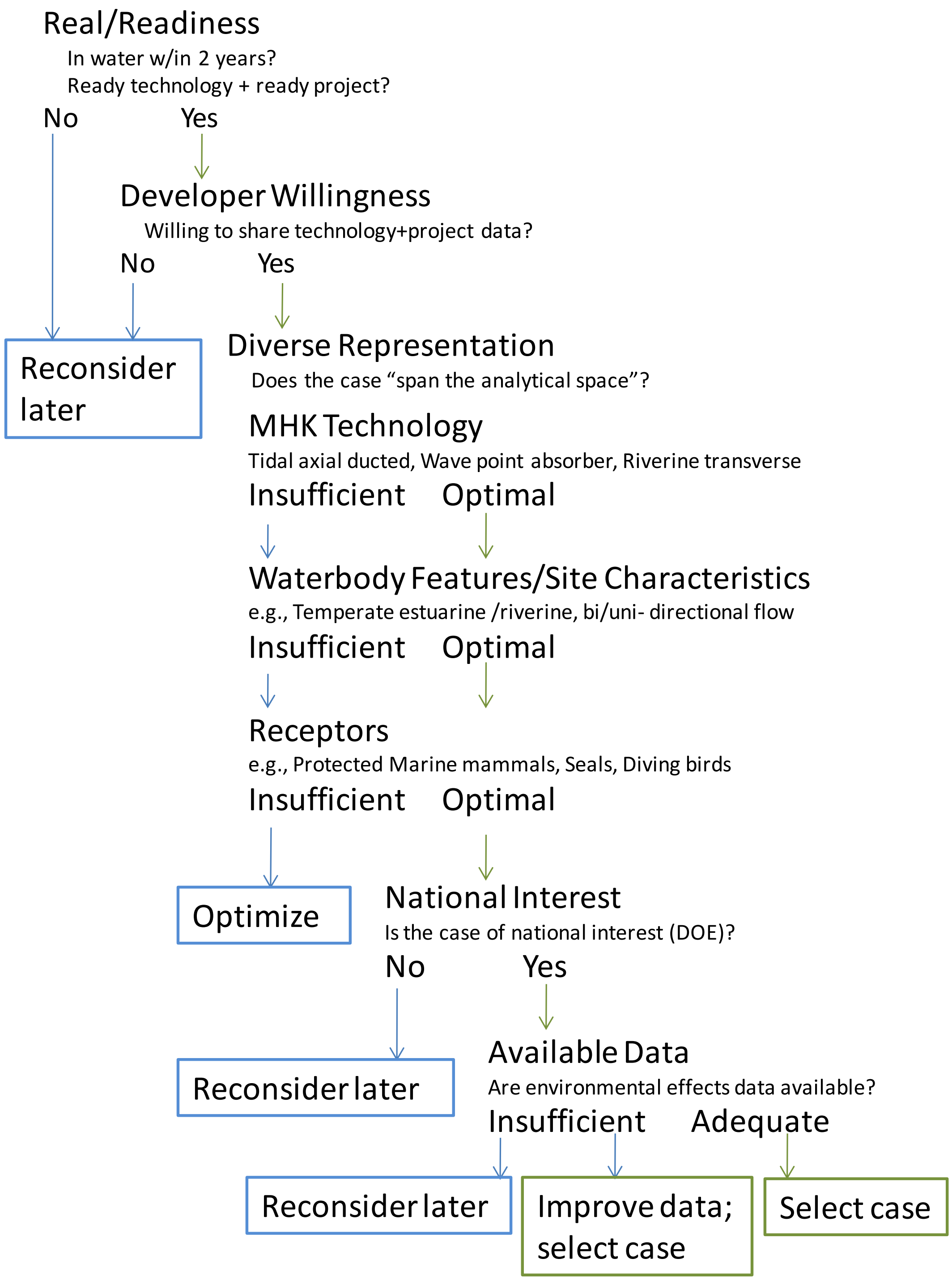

Figure 6. Case Selection Criteria and Decision Pathway

5.0 Cases Selected

The previous section describes the approach to analysis case selection. To reiterate, cases are chosen based on their collective ability to span the analytical space, project maturity and realness, and the willingness of the developer to participate in the risk analysis. An additional criterion is used to affirm case selection: the candidate case must be of national interest. In addition, the availability of environmental effects data is desirable.

The three cases are as follows, described in terms of key entries from each of the four dimensions:

- Open-Center Turbine (Open Hydro, www.openhydro.com) in Admiralty Inlet, Puget Sound, Washington – a ducted, axial flow technology in a temperate, estuarine waterbody; a site with bidirectional water flow, where protected whales, salmon, reef fish, and diving birds are key receptors of concern
- Free-Flow Power Turbine (Free Flow Power Corporation, www.free-flow-power.com) in Baton Rouge, Louisiana (Scotlandville Bend, Mississippi River) – a ducted, axial flow technology in a riverine system; unidirectional water flow, with migratory birds, waterfowl, and protected sturgeon as key receptors
- PowerBuoy Wave Device (Ocean Power Technologies, www.oceanpowertechnologies.com) off Reedsport, Oregon – a point absorber wave energy converter deployed on a surface buoy in a deepwater temperate ocean site; pinnipeds, seabirds, and protected, migratory whales are key receptors of concern.

Table 1 demonstrates how each of the chosen cases meets the criteria for selection.

Table 1. Case Satisfaction Criteria for FY10 Screening Analysis

	MHK Cases			
	Open-Center Turbine	Free Flow Power Turbine	Power Buoy Wave Device	Collectively
Selection criteria				
Project readiness and realness	Preliminary permit issued by FERC	Preliminary permit issued by FERC	Preliminary permit issued by FERC	
Developer willingness to participate in the risk analysis	Yes	Yes	Yes	
Collective ability to span the analytical space	—	—	—	Adequate. The three cases are described by a diversity of attributes and states
National interest	First utility-sponsored tidal energy project; DOE investment	First commercial-scale in-river project in the United States.	First commercial-scale project in the United States; DOE investment	
Availability of environmental data	Adequate baseline available	Adequate baseline available	Adequate baseline and some early effects data	

6.0 Next Steps in FY10 Risk Screening Analysis

Stakeholder review of ERES will continue throughout the summer of 2010, concurrently with the risk screening analysis. An important first step for screening analyses will be to identify a list of scenarios that are of greatest concern and the factors that influence the outcomes: likelihoods, impacts, and uncertainties. The attributes listed in Appendix A become the catalog of factors that potentially influence scenario outcomes. For example, the generation of EMF due to normal device operation is a potentially hazardous scenario, and influencing factors include those associated with the particular technology (e.g., its operational details, geometry and orientation, and device configuration; see Appendix A). Conceptual models will be identified that relate stressors to receptors for the selected scenarios as a function of the influencing factors. At the screening stage, these conceptual models will likely be based largely on expert judgment. Uncertainties associated with both lack of knowledge about processes and parameters as well as uncertainty due to natural variability of processes and parameters will influence outcome uncertainty and thus risk to receptors. From these analyses, key impacts, uncertainties, and risk drivers will be identified and ecological impact scenarios refined to focus on these risk-critical uncertainties for the next, more quantitative stage of risk analysis.

7.0 Appendix A

Dimensions, Attributes, and States

DIMENSION	ATTRIBUTE	STATE 1	STATE 2	STATE 3	STATE 4	STATE 5	STATE 6
	Operational						
MHK Technology	Max rotational speed of device (RPM)	10-15	15-20	20-30	>30	N/A	
MHK Technology	Tip speed of device (m/s)	0-5	5-10	>10	N/A		
MHK Technology	Direction of generation	One way	Two-way	N/A			
MHK Technology	Adjustable turbine speed	Yes	No	N/A			
MHK Technology	Time to shut down	0-6sec	6-15sec	>15sec			
MHK Technology	Removable rotor for maintenance	Yes	No	N/A			
MHK Technology	Average hours of power generation per day	<12	12--18	>18			
MHK Technology	Emergency removal time (hrs)	<12	12--24	>24			
MHK Technology	Time to decommission	12--24 hours	1 day - 1 week	>1 week			
MHK Technology	Project status	pilot	commercial	prototype			
	Geometry and orientation						
MHK Technology	Number of devices	0-3	3--10	10--50	>50		
MHK Technology	Geometry	cross channel	along channel	other configuration			
MHK Technology	Vertical location in water column	Surface	Bottom	Water column	Mid		
MHK Technology	Orientation wrt wave direction	Parallel	Perpendicular	Point	Overtopping	N/A	
	Rotor Configuration						
MHK Technology	Size of turbine swept area (m^2)	20-60	60-100	100-200	200-500	N/A	
MHK Technology	Orientation of axis wrt flow	Axial	Transverse	N/A			
MHK Technology	Orientation of blades wrt axis	Perpendicular	Parallel	N/A			
MHK Technology	Shape of leading edge of turbine blade	Rounded	Sharp	N/A			
MHK Technology	Pitched blades	Yes, fixed	Yes, adjustable	No	N/A		
MHK Technology	Rotor diameter (m)	3--5	5--7	7--10	10--15	N/A	
MHK Technology	Dynamic rotor seal	Yes	No	N/A			
MHK Technology	Gearbox	Yes	No				
	Device Configuration						
MHK Technology	Yaw mechanism	Yes	No				
MHK Technology	Ducted/venturi	No duct	Shallow duct	Shallow venturi	Deep venturi		
MHK Technology	Bearings	Yes	No				
MHK Technology	External generator	Yes	No				
MHK Technology	Turbine/generator located onsite in water	Yes	No				
MHK Technology	Surface-Piercing	Yes	No				
MHK Technology	Power cable location	Buried	Surface-laid				
MHK Technology	Power cable landfall	Directional drilling	Through nearshore				
MHK Technology	Coupled with bidirectional airflow turbine	Yes	No				
MHK Technology	Impedance matching of waves	Yes	No				
MHK Technology	Adjustable natural resonance frequency	Yes	No	N/A			
	Fouling, Corrosion Protection						
MHK Technology	Anti-fouling coating/paint	Yes	No				
MHK Technology	Surface area covered by anti-fouling coating/paint (m	0 - 30	30-60	>60	None		
MHK Technology	Composition of anti-fouling coating/paint	Toxic	Non-toxic	None			
	Mooring/Foundation						
MHK Technology	Footprint on bottom (m^2/device)	5-8	8-11	11-14	>14		
MHK Technology	Distance from edge of waterway	0-20m	20-60m	60-150m	>150m		
MHK Technology	Mooring method	Gravity-mounted	Driven piles	Anchored			
MHK Technology	Anchoring cables	Slack	Taut	N/A			
	Resource Characterization						
MHK Technology	Power density (kW/m^2)	0-3	3--10	10--15	>15		
MHK Technology	Power rating of device (kW)	10-50	50-100	100-1000	>1000		
MHK Technology	Approximate power output at 2.5 m/s (kW)	10-50	50-100	100-200	>200		
MHK Technology	Resonance wave period	Long	Short	N/A			
	Bottom						
Site Characteristics	Sediment grain size	Bedrock	Boulder (>256mm)	Cobble (>64mm)	Gravel (>4mm)	Sand (>.06mm)	Mud/clay (<.06mm)
Site Characteristics	Bottom roughness	Smooth	Rough				
Site Characteristics	Vegetation present	Rooted vegetation	Floating	None			
Site Characteristics	Vegetation type	SAV	Macroalgae	None			
Site Characteristics	Bottom slope (%)	0-1	1-2	2-4	>4		
	Flow and Wave						
Site Characteristics	Water depth (m)	<10	10-40	40-100	>100	N/A	
Site Characteristics	Avg flow/current speed (m/s)	0-2	2-4	4-6	6--8	>8	N/A
Site Characteristics	Peak flow/current speed (m/s)	0-2	2--4	4--6	N/A		
Site Characteristics	Tidal amplitude (m)	0-2	2--4	4--6	>6	None	
Site Characteristics	Flow directionality	one way	two way	N/A			
Site Characteristics	Avg Wave Height (m)	0-.5m	.5-1m	1-1.5m	1.5-2m	N/A	
Site Characteristics	Peak Wave Height (m)	0-2m	2-3m	3-4m	4-5m	N/A	
Site Characteristics	Avg Wave Period (sec)	1-5s	5-10s	10-15s	>15s	N/A	
Site Characteristics	Peak Wave Period (sec)	5-10s	10-15s	15-20s	20-25s	>25s	N/A
Site Characteristics	Avg Wave Length (m)	0-4m	4-6m	6-8m	8-10m	>10m	N/A
Site Characteristics	Peak Wave Length (m)	<6m	6-10m	10-15m	>15m	N/A	
Site Characteristics	Avg streamflow (cubic ft/sec)	<5,000	5,000-10,000	10,000-50,000	50,000-100,000	>100,000	N/A
Site Characteristics	Peak streamflow (cubic ft/sec)	10,000-20,000	20,000-50,000	50,000-200,000	200,000-300,000	>300,000	N/A

Dimensions, Attributes, and States (contd)

	Water Quality Parameters						
Waterbody	Phosphorus concentration > 0.1 mg/L	Yes	No				
Waterbody	Nitrogen concentration > 1 mg/L	Yes	No				
Waterbody	Chlorophyll a concentration > 10 ug-at/L	Yes	No				
Waterbody	Salinity (ppt)	<0.5	0.5-10	10--30	>30		
Waterbody	pH	<6	6.5-7.5	>7.5			
Waterbody	Oxygen concentration (mg/L)	0-2	2--5	>5			
Waterbody	Annual average temperature (deg C)	0-5	5--10	10--15	15-20		
Waterbody	Turbidity (NTU)	0-1	1--10	>10			
Waterbody	Silicate >20ug-at/l	Yes	No				
	Physical Characteristics						
Waterbody	Geographic zone	Tropical	Temperate	Subarctic			
Waterbody	Estuarine	Fjord	Well mixed	Partially mixed	Salt wedge	N/A	
Waterbody	Ocean	Coastal	Open ocean	N/A			
Waterbody	Nearshore	Intertidal	Subtidal	Dry land	N/A		
Waterbody	Riverine	Streams	Tributaries	Large Rivers	N/A		
Waterbody	Tidal prism (x10^6 m^2)	<0.5	0.5-3	>3	N/A		
Waterbody	Tidal regime	diurnal	semidirunal	N/A			
Waterbody	Range of river stage	<0.5 m	0.5-3m	>3m	N/A		
Waterbody	Avg flow/current speed (m/s)	0-2	2-4	4-6	6--8	>8	N/A
Waterbody	Avg streamflow (cubic ft/sec)	<5,000	5,000-10,000	10,000-50,000	50,000-100,000	>100,000	N/A
Waterbody	Seasonal flow variability	Yes	No	N/A			
Waterbody	Avg wave height	0-.5m	.5-1m	1-1.5m	1.5-2m	N/A	
Waterbody	Avg Wave Period (sec)	1-5s	5-10s	10-15s	>15s	N/A	
Waterbody	Avg wave length	0-4m	4-6m	6-8m	8-10m	>10m	N/A
Waterbody	Prevailing wave direction	NW-NE	NE-SE	SE-SW	SW-NW		
Waterbody	Prevailing wind speed (knots)	0-10	10--30	>30			
Waterbody	Prevailing wind direction	NW-NE	NE-SE	SE-SW	SW-NW		
Waterbody	Seasonality of prevailing wind/wave direction	Yes	Yes				
Waterbody	Frequency of major storm events	0-2 per year	3-5 per year	>5 per year			
Receptors	Water quality	0-2 mg/L Oxygen	2--5 mg/L Oxygen	>5 mg/L Oxygen			
Receptors	Sedimentation pattern	Scoured	Accretional	Erosional			
	Reptiles						
Receptors	Chelonians (sea turtles, terrapin)	Present	Absent				
Receptors	Chelonians seasonality of presence	Year round	Spring	Summer	Fall	Winter	N/A
Receptors	Chelonians endangered/special status	Yes	No	N/A			
Receptors	Chelonians behavior at site	Transiting	Foraging	Mating	Nesting	N/A	
Receptors	Chelonians commercially/recreationally/culturall	Yes	No	N/A			
Receptors	Other reptiles	Present	Absent				
Receptors	Other reptiles seasonality of presence	Year round	Spring	Summer	Fall	Winter	N/A
Receptors	Other reptiles endangered/special status	Yes	No	N/A			
Receptors	Other reptiles behavior at site	Transiting	Foraging	Mating	Nesting	N/A	
Receptors	Other reptiles commercially/recreationally/cultu	Yes	No	N/A			
	Aquatic and Marine Mammals						
Receptors	Cetaceans (whales, porpoise)	Present	Absent				
Receptors	Cetaceans seasonality of presence	Year round	Spring	Summer	Fall	Winter	N/A
Receptors	Cetaceans endangered/special status	Yes	No	N/A			
Receptors	Cetaceans behavior at site	Transiting	Foraging	Mating	Rearing	N/A	
Receptors	Pinnipeds (seals, sea lions)	Present	Absent				
Receptors	Pinnipeds seasonality of presence	Year round	Spring	Summer	Fall	Winter	N/A
Receptors	Pinnipeds endangered/special status	Yes	No	N/A			
Receptors	Pinnipeds behavior at site	Transiting	Foraging	Mating	Rearing	N/A	
Receptors	Lutrinae (sea otter, river otter)	Present	Absent				
Receptors	Lutrinae seasonality of presence	Year round	Spring	Summer	Fall	Winter	N/A
Receptors	Lutrinae endangered/special status	Yes	No	N/A			
Receptors	Lutrinae behavior at site	Transiting	Foraging	Mating	Rearing	N/A	
Receptors	Other aquatic/marine mammals	Present	Absent				
Receptors	Other aquatic/marine mammals seasonality of pr	Year round	Spring	Summer	Fall	Winter	N/A
Receptors	Other aquatic/marine mammals endangered/spe	Yes	No	N/A			
Receptors	Other aquatic/marine mammals behavior at site	Transiting	Foraging	Mating	Rearing	N/A	

Dimensions, Attributes, and States (contd)

	Fish						
Receptors	Elasmobranchs + Acipenseridae (sharks + sturgeon)	Present	Absent				
Receptors	Elasmobranchs + Acipenseridae seasonality of presen	Year round	Spring	Summer	Fall	Winter	N/A
Receptors	Elasmobranchs + Acipenseridae engendered/special st	Yes	No	N/A			
Receptors	Elasmobranchs + Acipenseridae behavior at site	Transiting	Foraging	Schooling	Resident	Mating	N/A
Receptors	Elasmobranchs + Acipenseridae commercially/recreat	Yes	No	N/A			
Receptors	Salmonids (salmon + trout)	Present	Absent				
Receptors	Salmonids seasonality of presence	Year round	Spring	Summer	Fall	Winter	N/A
Receptors	Salmonids endangered/special status	Yes	No	N/A			
Receptors	Salmonids behavior at site	Transiting	Foraging	Schooling	Mating	N/A	
Receptors	Salmonids migration	Out migrating juvenile	Out migrating sub-adu	in migrating adult	N/A		
Receptors	Salmonids migrating depth	Near surface	mid-water column	near bottom	N/A		
Receptors	Salmonids commercially/recreationally/culturally imp	Yes	No	N/A			
Receptors	Bottomfish (sole, flounder, halibut, shad)	Present	Absent				
Receptors	Bottomfish seasonality of presence	Year round	Spring	Summer	Fall	Winter	N/A
Receptors	Bottomfish endangered/special status	Yes	No	N/A			
Receptors	Bottomfish behavior at site	Transiting	Foraging	Schooling	Resident	Mating	N/A
Receptors	Bottomfish commercially/recreationally/culturally im	Yes	No	N/A			
Receptors	Reefish (rockfish, etc)	Present	Absent				
Receptors	Reefish seasonality of presence	Year round	Spring	Summer	Fall	Winter	N/A
Receptors	Reefish endangered/special status	Yes	No	N/A			
Receptors	Reefish behavior at site	Transiting	Foraging	Schooling	Resident	Mating	N/A
Receptors	Reefish commercially/recreationally/culturally import	Yes	No	N/A			
Receptors	Other fish	Present	Absent				
Receptors	Other fish seasonality of presence	Year round	Spring	Summer	Fall	Winter	N/A
Receptors	Other fish endangered/special status	Yes	No	N/A			
Receptors	Other fish behavior at site	Transiting	Foraging	Schooling	Resident	Mating	N/A
Receptors	Other fish commercially/recreationally/culturally imp	Yes	No	N/A			
	Aquatic and Marine Invertebrates						
Receptors	Crustaceans (crabs, lobsters, shrimp, barnacles)	Present	Absent				
Receptors	Crustaceans seasonality of presence	Year round	Spring	Summer	Fall	Winter	N/A
Receptors	Crustaceans endangered/special status	Yes	No	N/A			
Receptors	Crustaceans behavior at site	Transiting	Foraging	Resident	Mating	N/A	
Receptors	Crustaceans commercially/recreationally/culturally in	Yes	No				
Receptors	Benthic infauna (mollusks, worms)	Present	Absent				
Receptors	Benthic infauna seasonality of presence	Year round	Spring	Summer	Fall	Winter	N/A
Receptors	Benthic infauna endangered/special status	Yes	No	N/A			
Receptors	Benthic infauna behavior at site	Transiting	Foraging	Resident	Mating	N/A	
Receptors	Benthic infauna commercially/recreationally/culturall	Yes	No	N/A			
Receptors	Other invertebrates	Sessile	Motile	None			
Receptors	Other invertebrates seasonality of presence	Year round	Spring	Summer	Fall	Winter	N/A
Receptors	Other invertebrates endangered/special status	Yes	No	N/A			
Receptors	Other invertebrates behavior at site	Transiting	Foraging	Resident	Mating	N/A	
Receptors	Other invertebrates commercially/recreationally/cult	Yes	No	N/A			
	Diving birds						
Receptors	Diving birds	Present	Absent				
Receptors	Diving birds seasonality of presence	Year round	Spring	Summer	Fall	Winter	N/A
Receptors	Diving birds endangered/special status	Yes	No	N/A			
Receptors	Diving birds behavior at site	Transiting	Foraging	Resident	Mating	Rearing	N/A
Receptors	Other aquatic/marine-dependant birds	Present	Absent				
Receptors	Other aquatic/marine-dependant birds seasonality of	Year round	Spring	Summer	Fall	Winter	N/A
Receptors	Other aquatic/marine-dependant birds endangered/sp	Yes	No	N/A			
Receptors	Other aquatic/marine-dependant birds behavior at sit	Transiting	Foraging	Resident	Mating	Rearing	N/A
	Aquatic and Marine Plants + Alga						
Receptors	Macroalgae (e.g. Laminaria, Nereocystis, etc)	Present	Absent				
Receptors	Macroalgae seasonality of presence	Year round	Spring	Summer	Fall	Winter	N/A
Receptors	Macroalgae endangered/special status	Yes	No	N/A			
Receptors	Seagrass (e.g. Zostera, Phyllospadix, etc)	Present	Absent				
Receptors	Seagrass seasonality of presence	Year round	Spring	Summer	Fall	Winter	N/A
Receptors	Seagrass endangered/special status	Yes	No	N/A			
	Special Habitats						
Receptors	Coral reef	Present	Absent				
Receptors	Coral reef protected/special status	Yes	No	N/A			
Receptors	Rocky reef	Present	Absent				
Receptors	Rocky reef protected/special status	Yes	No				
Receptors	Kelp forest	Present	Absent				
Receptors	Kelp forest protected/special status	Yes	No	N/A			
Receptors	Deep water corals/sponges	Present	Absent				
Receptors	Deep water corals/sponges protected/special status	Yes	No	N/A			

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