Arnold Schwarzenegger
Governor

DEVELOPING WAVE ENERGY IN COASTAL CALIFORNIA: POTENTIAL SOCIO-ECONOMIC AND ENVIRONMENTAL EFFECTS

PIER FINAL PROJECT REPORT

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Prepared By:

H. T. Harvey & Associates, Project Manager: Peter A. Nelson
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Prepared For

California Ocean Protection Council

Laura Engeman
Contract Manager

Christine Blackburn
Deputy Program Manager

Neal Fishman
Ocean Program Manager

Drew Bohan
Executive Policy Officer

Sam Schuchat
Executive Officer; Council Secretary

California Energy Commission

Melinda Dorin & Joe O'Hagan
Contract Manager

Linda Spiegel
Program Area Lead
Energy-Related Environmental Research

Mike Gravely
Office Manager
Energy Systems Research Office

Martha Krebs, Ph.D.
PIER Director

Thom Kelly, Ph.D.
Deputy Director
ENERGY RESEARCH & DEVELOPMENT DIVISION

Melissa Jones
Executive Director

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Author Affiliations

Dane Behrens
Bodega Marine Laboratory
University of California Davis
2099 Westside Road
Bodega Bay, California 94923

Jim Castle
Farallon Institute for Advanced
Ecosystem Research
P.O. Box 750756
Petaluma, California 94975

Greg Crawford
Department of Oceanography
Humboldt State University
1 Harpst Street
Arcata, California 95521

Rani N. Gaddam
Department of Ecology and
Evolutionary Biology
University of California Santa Cruz
1156 High Street
Santa Cruz, California 95064

Steven C. Hackett
Department of Economics
Humboldt State University
1 Harpst Street
Arcata, California 95521
Planwest Partners
1125 16th Street Suite 200
Arcata, California 95521

John Largier
Bodega Marine Laboratory
University of California Davis
2099 Westside Road
Bodega Bay, California 94923

David P. Lohse
Department of Ecology and Evolutionary Biology
University of California Santa Cruz
1156 High Street
Santa Cruz, California

Kyra L. Mills
Farallon Institute for Advanced Research
P.O. Box 750756
Petaluma, California 94975

Peter A. Nelson
H.T. Harvey & Associates
1125 16th Street, Suite 209
Arcata, California 95521

Pete T. Raimondi
Department of Ecology and Evolutionary Biology
University of California Santa Cruz
1156 High Street
Santa Cruz, California 95064

Matt Robart
Bodega Marine Laboratory
University of California Davis
2099 Westside Road
Bodega Bay, California 94923

William J. Sydeman
Farallon Institute for Advanced Ecosystem Research
P.O. Box 750756
Petaluma, California 94975

Sara Ann Thompson
Farallon Institute for Advanced Ecosystem Research
P.O. Box 750756
Petaluma, California 94975

Sheri Woo
H.T. Harvey & Associates
1125 16th Street, Suite 209
Arcata, California 95521

Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Developing Wave Energy in Coastal California: Potential Socio-Economic and Environmental Effects is the final report for the Ocean Energy Study (contract number 500-07-036), conducted by H. T. Harvey & Associates. The information from this project contributes to PIER's Energy-Related Environmental Research program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

The California Ocean Protection Council was established by the requirements of the California Ocean Protection Act[1] that was signed as law in 2004 by Governor Arnold Schwarzenegger. The council consists of the Secretary for Resources Mike Chrisman (Chair); State Lands Commission Chair, State Controller John Chiang; Secretary for Environmental Protection Linda Adams; two public members, Susan Golding, CEO and President of the Golding Group, and Geraldine Knatz, Executive Director of the Port of Los Angeles; and two non voting members, Senator Darrell Steinberg and Assembly member Pedro Nava. The council will help coordinate and improve the protection and management of California's ocean and coastal resources and implement the Governor's 'Ocean Action Plan'[2] released in October 2004.

The council is tasked with the following responsibilities:

- Coordinate activities of ocean-related state agencies to improve the effectiveness of state efforts to protect ocean resources within existing fiscal limitations.
- Establish policies to coordinate the collection and sharing of scientific data related to coast and ocean resources between agencies.
- Identify and recommend to the Legislature changes in law.
- Identify and recommend changes in federal law and policy to the Governor and Legislature.

1. http://resources.ca.gov/copc/docs/COPA_2008.pdf

2. http://resources.ca.gov/ocean/Cal_Ocean_Action_Strategy.pdf

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Abstract

Growing interest in converting the energy of California's ocean waves into electricity is matched by concerns regarding the potential effects of wave energy conversion technology on marine resources. This study finds ecological and socio-economic challenges associated with wave energy conversion are likely to depend fundamentally on project scale and location. Social and cultural impacts to fisheries, marine transportation, and some recreation are expected, and may have economic ramifications. Changes to the physical environment are predicted to result from a reduction in wave energy and alterations to nearshore wave-driven processes. Benthic communities may exhibit direct or indirect responses to these changes, with the potential for non-linear effects. Fish are expected to use wave energy conversion installations as artificial habitat, and environmental perturbations such as acoustic or electro-magnetic stimuli may affect behavior. Marine bird and mammals effects are expected to be minimal, but there is cause for caution regarding select species. Dramatic ecological, social, or economic effects are not clearly indicated by this study, but a strong case for caution is supported when developing wave energy conversion technology off the California coast. Impacts to human activities, wave exposure, benthic communities, fishes, birds and mammals are all virtually certain, but the impacts' magnitudes and the cumulative effects remain difficult to anticipate.

Keywords: wave energy; nearshore; fisheries; transportation; wave shadow; benthic; non-linear; artificial reef; Fish Aggregation Device; collision; migration; ocean observing; monitoring

Executive Summary

Introduction

Renewable energy companies are increasingly interested in converting the energy of California's ocean waters into electricity. Wave energy conversion technology is evolving and the need for renewable energy is clear, but the benefits from wave energy conversion technology must be balanced with its potential negative effects on marine resources. In an effort to guide regulatory and scientific discussions on the potential environmental effects of wave energy conversion development, the California Ocean Protection Council and the California Energy Commission provided funds to develop this study.

Purpose

This study reviewed the social, economic, and environmental issues associated with wave energy technologies in California, and identified specific research needed to further evaluate its potential effects. The study also identified the largest information gaps in these social and ecological disciplines: environmental economics, nearshore physical processes, nearshore intertidal (area that is exposed at low tide and submerged at high tide) and benthic (occurring on the bottom of the ocean and the associated sediments) habitats, and the ecology of marine and anadromous fishes (fish that breed in fresh water but live their adult life in the sea), marine birds and marine mammals.

Project Outcomes

Socio-economic Effects. Commercial or regional scale wave energy conversion, while improving the cost-competitiveness of the technology, will likely present economic, cultural, and social challenges (Hackett, Chapter 2). Commercial and recreational fisheries, marine transportation, and recreational boating will likely be affected, but the degree of impacts will likely depend on the scale and location of the project(s). Simultaneously, opportunities associated with construction, deployment, and operations and maintenance will contribute jobs and income to local communities.

Near-shore Physical Process Effects. Decreases in wave energy and changes in nearshore wave-driven processes are the basis for the majority of anticipated ecological impacts of wave energy conversion technology. Using numerical models and the existing literature, (Largier and co-authors, Chapter 3) found that wave energy conversion devices are expected to extract 3-15 percent of the incident wave energy, and will create triangle-shaped wave shadows in their lee (side towards shore). Incident waves are those waves that originate offshore. This energy reduction is likely to affect wave shoaling (wave heights changes due to shallower water depths), sediment transport, beach building and mixing.

Nearshore Intertidal and Benthic Habitats Effects. Elevational patterns in the littoral zone (essentially the area between just above the high tide line out into open water until where the continental shelf ends), species distributions, relative abundance and community structure are all likely to be affected by decreases of wave energy (Lohse and co-authors, Chapter 4). Wave energy conversion installations may alter patterns of disturbance, long believed to be a major factor in the structure of marine communities. Other indirect effects include the ecological effects of changes to sediment deposition, beach sand characteristics, and estuarine processes even a low magnitude, local reduction in wave energy may have disproportionate ecological effects. Predicting nonlinear (simple changes in one area that may create complex changes in another) responses will be challenging to anticipate and to manage, and some species or communities already near an ecological threshold may be "pushed" suddenly and unexpectedly into a dramatic response, one that is not necessarily a degraded, or even an unfamiliar, condition.

Fish and Fish Habitat Effects. Wave energy conversion installations are likely to act as artificial reefs that add vertical relief that are attractive to reef-associated fishes and provide hard substrate attractive to algae and invertebrates (Nelson, Chapter 5). Mid-water and floating surface components of wave energy conversion installations could form the nucleus for fish aggregations. The distinctions between the effects of an artificial reef and fish aggregation device depend partially on the location of the device (bottom versus mid-water versus surface) and partially on fish response. Fish responses to fish aggregation devices are principally due to spatial orientation and secondarily, one of habitat association. Habitat conversion is likely the primary effect of wave energy conversion installations on California fishes, but unintended behavioral effects could also occur.

Marine Bird and Mammal Effects. Given documented patterns of behavior and life history (Thompson and co-authors, Chapter 6), year-round residents of shallow waters outside the surf zone (Common Murres, Harbor Porpoises) will more likely encounter wave energy conversion devices than seasonal or infrequent visitors (Common Loon, Humpback Whale). However, individual species differ in their behavior and ecological physiology and these factors are also likely to impact the magnitude or degree of any marine bird or mammal impact. For example, the sea otter's dependence on clean fur for regulating body temperature makes them susceptible to oil spills associated with any hydraulic fluids leaking from the wave energy conversion device; the sea lion's natural tendency for "hauling out" on to floating platforms suggests that they would make no distinction between a wave energy conversion buoy and a navigational aid. Although few major impacts of wave energy conversion installations on marine birds and mammals are anticipated, baseline data collected before any installation will be critical for evaluating post-installation effects. Particular concerns include seabird collision (exacerbated by navigation lights for nocturnally active species), disturbance to local breeding colonies, and changes in distribution or availability of forage fishes. For marine mammals, collision, interference with migratory behavior, and the disruption of sensory mechanisms are also potential impacts.

Conclusions and Recommendations

There are no clear conclusions of dramatic ecological, social, or economic impacts—positive or negative—in this study, however caution must be taken when developing wave energy conversion technology off the California coast. Impacts to human activities, wave exposure, benthic (bottom dwelling) communities, fishes, birds and mammals are all certain, but the level of impact and the cumulative effects are currently difficult to anticipate and must be studied further.

These recommendations identify the most important impacts, however other useful recommendations are found within individual chapters (see also Nelson and Woo, Chapter 1).

For potential social and economic effects caused by WEC implementation, researchers must or should:

- Collect higher-resolution spatial data on marine uses, beach recreation, wildlife viewing, tourism, and non-use values (culturally significant areas and existence values), commercial fishing, and vegetation harvest; compile this data into a geographical information system (GIS) map format.
- Inventory marine cultural resources, in a GIS compatible format, to assess the cultural and historical connectivity of sites.
- Identify the minimum scale of commercial and recreational fishing and other activities that are needed to sustain small harbor facilities and local fishing industry complexes.
- Describe the public's level of acceptance regarding wave farm development in California, and identify the factors that have led to those levels.

For wave energy conversion-induced physical process changes and their potential effects in the nearshore environment, researchers must or should:

- Determine the efficiency and performance criteria of each device, as described by the device manufacturers or through "third party" studies.
- Select and evaluate a suitable refraction-diffraction (change in wave height and direction) model to run simulations of waves around wave energy conversion array-like objects, before permitting significant wave energy conversion arrays.
- Collect detailed monitoring of wave conditions inshore of pilot systems using combinations of different instruments, confirmed with existing agency data collection programs. If a significant shadow zone is indicated, monitoring should extend to benthic processes, including defining settlement and resuspension rates.
- Directly observe impacts on sediment transport, morphology, and nearshore water quality through before-and-after studies, in areas expected to exhibit an inordinate impact on

ecological communities (for example, estuary mouths such as at the Russian River, or areas receiving contaminated outflows such as the Noyo River plume at Fort Bragg).

For potential effects on biological communities in the nearshore environment, researchers must or should:

- Evaluate how biological communities vary along a wave energy gradient, particularly since the relationship could be non-linear rather than linear. Qualitative models are provided in this study (for example, the zonation model), but data to support these models are needed. Wave energy changes in the 0 to 15 percent range should be studied.
- Design studies that would determine how the frequency and size of disturbance events varies, when wave exposure also varies.
- Identify the relative importance of suspended sediment and light, versus the availability of nutrients, to plant growth in the nearshore environment.

For potential effects on fishes and fish habitats, researchers must or should:

- Assess artificial reef effects and fish aggregation device effects, determining the processes associated with wave energy conversion-related fish community formation, evaluating alterations in local predatory behavior (especially of salmonids), and assessing the evidence for a fish aggregation device effect.
- Characterize physical stimuli associated with wave energy conversion technology especially electromagnetic field (EMF), sound and vibration, and evaluate their potential impacts on selected species.
- Evaluate the potential impacts of wave energy conversion development on fisheries management. Because public access (including fishing access) to wave energy conversion sites is likely to be curtailed for safety reasons, wave energy conversion sites will probably function as de facto marine reserves, with fisheries management and conservation implications.

For potential effects on marine birds and mammals, researchers must or should:

- Support the development of a coast-wide program for tracking seabird mortality patterns comparable to the Coastal Observation and Seabird Survey Team (COASST).
- Monitor Gray Whale migration behavior, to evaluate responses to wave energy conversion installations, and to determine if there is a minimum installation size such that behavior appears to be unchanged.
- Conduct a literature review on light induced seabird mortality and perform additional studies if the literature cannot provide information sufficiently applicable to wave energy conversion installations.

- Perform direct field studies on species that are almost certainly affected by wave energy conversion installations, such as some marine birds (that is, gulls and cormorants) and mammals (that is, sea lions). Collision and entanglement with installations are effects of particular concern; researchers should provide wave energy conversion designers with criteria so that wave energy conversion systems can be designed to minimize negative effects.

To provide more complete baseline information, and to better monitor potential wave energy conversion-induced effects, researchers utilizing ocean observing systems must or should:

- Foster partnership agreements between ocean observing system organizations, ecological monitoring programs, and the wave energy conversion industry, so data can be freely shared.
- Design data collection using standardized instruments and quality assurance/quality control (QA/QC) protocols, particularly for water quality measurements.
- Widen existing observation networks to fill spatial "gaps' in coverage, such as observing estuaries.
- Evaluate the extent to which existing ocean observation systems can provide useful data for studying nearshore physical and ecological processes.

Benefits to California

In 2006, the California Legislature passed the California Global Warming Solutions Act (AB 32). Among other important requirements, this legislation requires the California Air Resources Board to adopt regulations such that greenhouse gases are reduced to 1990 levels by 2020. Wave energy could assist in reducing California's greenhouse gas emissions by providing a renewable and reliable energy source. Other benefits to California include job creation and other forms of economic opportunity. Wave energy could meet a significant proportion of the state's energy demand. While significant technological and economic issues remain, ecological issues, at this stage, appear manageable.

1.0 Developing Wave Energy in Coastal California: Potential Socio-Economic and Environmental Effects: Introduction

Peter A. Nelson and Sheri Woo
H. T. Harvey & Associates

Introduction

California's energy usage is growing at 1.25 percent annually, with peak demand increasing at 1.35 percent per year (California Energy Commission 2007). Currently, the State of California obtains less than 12% of its electricity from renewable sources (California Energy Commission 2008), yet the California Global Warming Solutions Act of 2006 requires that renewable energy will supply 20 percent of California's needs by 2010. Despite efforts to accelerate this supply[3], and even with the addition of nearly 400 MW from new renewable energy resources, increasing energy demand has matched renewable energy source growth, resulting in no net gain in the proportion of renewable energy capacity (California Energy Commission 2007). Because ocean wave energy is a renewable and rapidly evolving technology, interest in wave energy is growing; however, this interest is accompanied by concerns over its potential ecological impacts (Pelc and Fujita 2002).

Wave energy has the potential to meet a significant proportion of California's energy demands. In 2006, California used almost 281,200 gigawatt hours (GWh) of energy, requiring a power capacity of roughly 32 gigawatts (281,200 GWh divided by 8760 hours, as calculated from data obtained from the California Energy Consumption Database, accessed September 4, 2008 [http://www.ecdms.energy.ca.gov/]). According to a report by the California Energy Commission (PIER 2008), California wave energy resources indicate a *theoretical potential*[4] of 38 gigawatts with an estimated *technical potential*[5] of between seven and eight gigawatts, or about a quarter of 2006 demands. Although legal, social, economic and, indeed, environmental factors are likely to reduce this fraction further, wave energy has the potential to become a major contributor to California's energy needs.

In an effort to guide regulatory and scientific discussions of potential environmental effects of wave energy conversion (WEC) development, the California Ocean Protection Council and the California Energy Commission provided funds to develop this study. The intent of this study is

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3. For example, Senate Bill 1250, Perata, Chapter 512, Statutes of 2006

4. *Theoretical potential*: The total and unconstrained energy resource potential; legal, political or other non-economic factors are *not* considered (PIER (2008) Summary of PIER Funded Wave Energy Research. California Energy Commission, PIER Program, CEC-500-2007-083).

5. *Technical potential*: The theoretical energy resource potential, minus those unavailable for non-economic [that is, for environmental and social] reasons (Ibid.).

two-fold: 1) to review the potential environmental issues—including social, economic, and ecological—associated with WEC development in California, and 2) to identify information gaps and research needed to further evaluate the effects of this developing technology.

The basic approach to this study was to contact respected and acknowledged experts in the fields of California marine biology and ecology, environmental sociology and economics, and oceanography. Their charge was to review WEC technologies and to anticipate the technologies' possible effects; where information is too scarce to make such predictions, scientists were asked to identify what research would be needed to address the information gaps. This paper is a reflection of this process; in this first introduction and overview chapter, we provide a brief summary of information similar to that provided to the scientists. The following chapters are essentially "stand alone" chapters that are collected into this paper.

Scope of This Study

The task of reviewing the potential environmental effects of any emerging technology is monumental, and some assumptions were considered to limit the scope of this study. Below is a description of assumptions that each scientist used to provide a similar context for their analyses and discussions.

1.1.1 Geographic Scope

The geographic scope of this paper includes all California state waters, but emphasizes the region from Point Conception north to the Oregon Border (Figure 1.1), where wave energy projects are most likely to be sited; south of Point Conception, wave energy potential is significantly less (PIER 2008). Wave energy potential largely defined the geographic scope of this study. However, the predictability of wave energy should also be considered. Although wave energy potential is greater north of Point Conception, wave energy predictability appears to be significantly greater in Southern California (Figure 1.2; Nelson, unpublished data). This fact, and the fact that many more people live in Southern California than in northern parts of the state, suggest that our emphasis may be challenged in the future, especially when coupled with social and economic factors.

California state waters extend from the shoreline to three nautical miles offshore, and this nearshore area coincides with where WEC technology is likely to be installed and deployed, due to logistical and economic reasons. However, a few preliminary license applications have included waters beyond three nautical miles.

1.1.2 Habitat Scope

The habitat classifications used in this paper are based on the categories and definitions developed in the California Department of Fish and Game's Master Plan for Marine Protected Areas (2008). The habitat classifications are rocky reefs, intertidal zones, sandy or soft ocean bottoms, underwater pinnacles, seamounts, kelp forests, submarine canyons, and seagrass beds. An open water habitat ("pelagic") was added to include organisms more commonly found in the water column and less closely associated with specific bottom habitats. At this time, no habitats that have been clearly excluded from possible WEC installations, so we assume that the WEC industry will not avoid any specific habitat types.

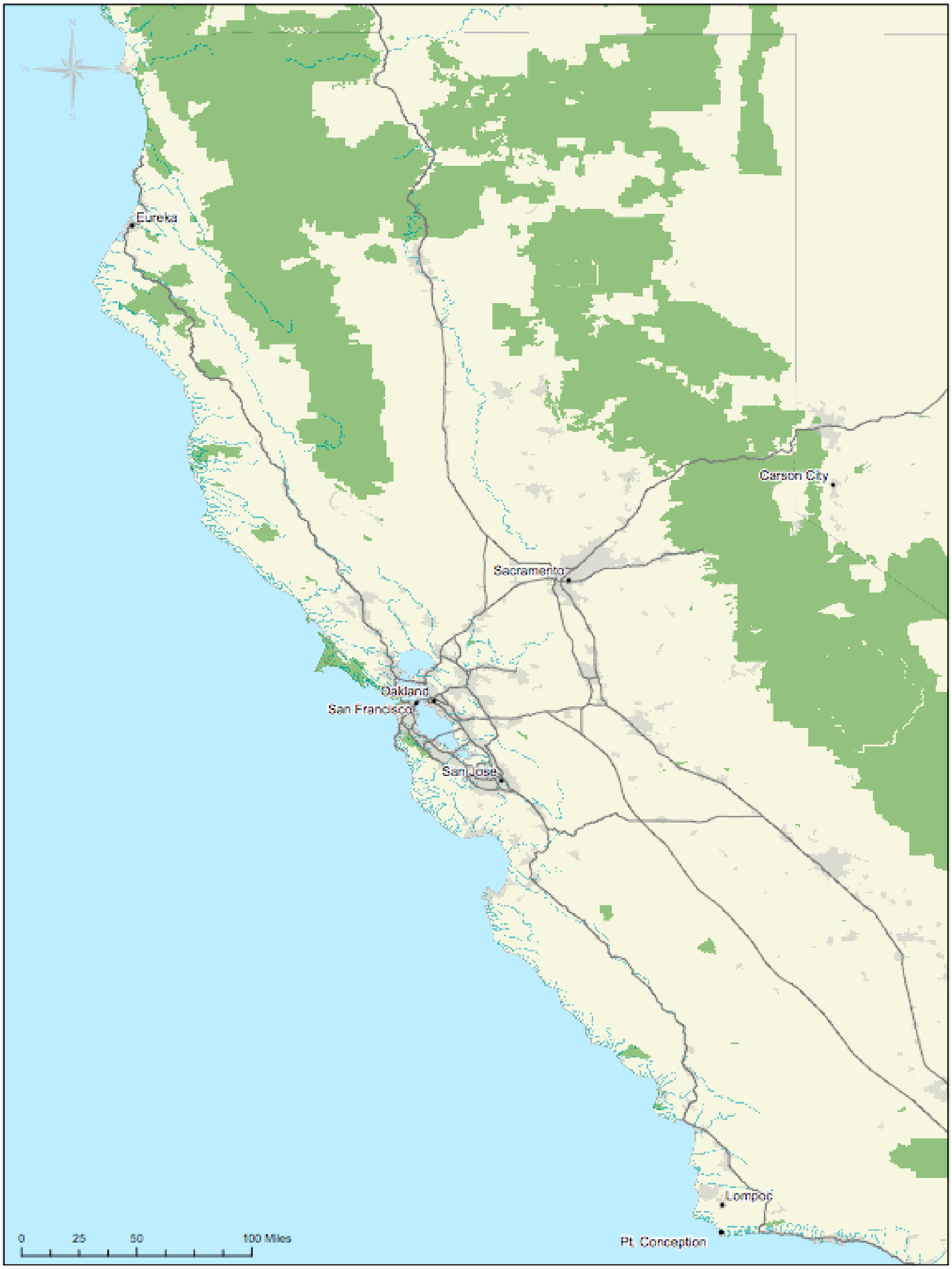


Figure 1.1: Northern and Central California, from Pt. Conception to the California and Oregon border.

Source: Nelson et. al.

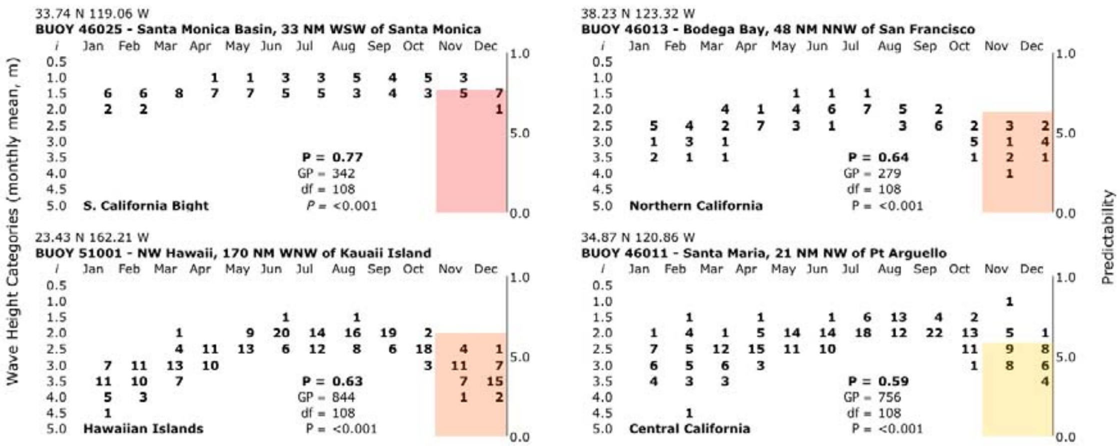


Figure 1.2: Predictability of wave height (as a proxy for wave energy) varies with location

Wave height in the Southern California Bight (upper left) is more predictable than in Central or Northern California (right), or in the Hawaiian Islands (lower left). Matrices show the frequencies of mean monthly wave heights when classified into one of ten size categories. Data sets cover eight to 25-year time periods, and all data are from the National Data Buoy Center. Predictability (P) was calculated following Colwell (1974), and is indicated by the height of the colored bars.

Source: Nelson et. al.

1.1.3 Scope of WEC Scale and Project Size

This study explores three spatial scales of WEC installations in California waters: pilot projects, commercial installations or arrays, and regional networks. These scales reflect the probable process for wave energy development, as well as the range of potential ecological and social effects (that is, local to regional effects). Each installation scale is described in terms of its size, power output, and total footprint area of the installation or network (PIER 2008) (Table 1.1). Estimated footprints do not include the area required by the cable conveying electricity from the WECs to shore.

Table 1.1: WEC installation scales

scale	output (MW)	footprint (km^2)	footprint (mi^2)
pilot	< 5	0.1 – 1.5	0.04 – 0.6
commercial	5 – 150	1 – 8	0.4 – 3.1
network	≥ 100	3 or more commercial scale installations; distance between multiple installations is the critical factor in determining footprint area.	

Source: Nelson et. al.

We consider social and ecological processes associated with WEC installations at each scale, but these size categories merely serve as guides for our evaluation and are not to be considered absolute or binding in any way.

Each scale's footprint area, defined as the area covered by the installation or networks including the space between them but not the transmission line, is affected by the selection of a specific WEC technology. The footprint area also depends on the WEC's available wave energy (in units of area per energy, km^2 MW^{-1}), which in turn depends on the energy density of the site. The "size" of an array must also consider possible mitigations needed; for example, if an effect limits navigation and vessels are prohibited from approaching within 500 meters of the array, the effective size is far greater than if one is considering the effect of availability of haul-out sites for California Sea Lions (*Zalophus californianus*).

1.1.4 Effects Not Considered

The goal of this paper is to review potential social and ecological effects of WEC technology on California's marine resources and identify critical research and data needs. However, this topic is broad and evolving technology and state and federal regulatory policies are apt to alter the scope of this discussion in the future. For this reason, the authors of these chapters focused their discussions on reviewing WEC effects that had the greatest uncertainty and/or potential for impact.

The following are topics not discussed in this paper, but are noted as important to the overall discussion of WEC effects.

- <u>Laws and Regulations</u>: Managing the impacts of WEC technology on California's natural resources will be within the context of applicable policies and regulations. An institutional analysis would certainly assist in evaluating social and economic effects, but such an analysis was outside the scope of this study. How State and Federal agencies and other institutions might be expected to promulgate and enforce regulations, and to set policies and guidelines, should be considered in a separate study.

- <u>Toxicology</u>: Toxicological effects are assumed to be covered by the existing literature on the antifouling compounds and oil spills; it is considered of minor importance compared to the toxicological effects within confined areas such as harbors and marinas.

- <u>Plankton ecology</u>: WEC impacts to plankton ecology are assumed to be negligible; plankton distribution and abundance processes occur over such large scales that even regional WEC networks would have negligible impact. Local predation effects and possibly local aggregation are possible, but significant effects are unlikely on the local plankton ecology, except to the possible benefit of planktivores associated with the installation or array. The increased availability of settlement sites is expected to have a similarly minor effect.

- <u>Fish impingement or entrainment</u>: Currently, only the overtopping WEC devices (see section 3 of this Introduction, below) could potentially entrain small fishes, or lead to fish impingement on screens or slots. Due to the nature of the overtopping design, the potential for fish mortality is low, compared to the screens and turbines employed in large hydropower systems. For these reasons, fish entrainment and impingement is not considered here, although future designs may necessitate revisiting this assumption.

- Construction-related factors: Construction-related activities such as anchor set-down, directional drilling, and ocean floor cable burial have been evaluated and discussed by others (PIER 2008), and their evaluations appear to agree that few and localized effects will occur. However, cumulative effects associated with commercial or regional scale installations may merit closer consideration.

Wave Energy Conversion Technologies

Wave energy conversion (WEC) is defined here as the process involved in producing usable electricity from the kinetic energy of ocean waves, and supplying it to the regional electricity transmission and storage systems. While WEC technology is evolving quickly, the most advanced devices can be classified into four categories (Table 1.2 and Figure 1.3; see also Minerals Management Service 2007; EPRI 2008; PIER 2008).

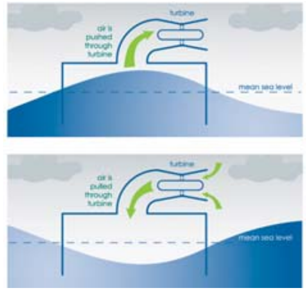
The structural components of point absorbers and attenuators are buoys (surface or subsurface), cables, and anchors. These vary in size and configuration, but do not require exposed turbines that could strike or impinge aquatic organisms. Overtopping and oscillating water column (OWC) devices must be fixed relative to the ocean floor or shoreline. OWC designs may be deployed, floating at the surface; others are submerged and fixed to the ocean bottom. Overtopping devices rely on a turbine driven by seawater, so there is the potential for organisms to be entrained, impinged, or struck by components of the device. All devices, except those built into the shoreline, require an underwater power cable that conveys electricity produced by the WECs to the storage and transmission “grid” onshore; most plans call for an armored and shielded cable, buried or protected within a metal pipe on the seafloor. These components are considered in the discussions of potential impacts.

Table 1.2: WEC technology design categories and power generation descriptions (adapted from Minerals Management Service 2007; PIER 2008).

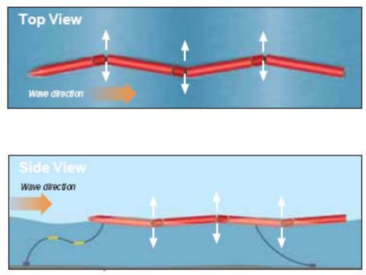
Design category	Example manufacturer	Placement	Principle of power generation
oscillating water column (OWC)*	Oceanlinx	Ocean surface (floating) or fixed to ocean bottom	Rise and fall of a water column forces air through a turbine that generates electricity
attenuators	Pelamis	Ocean surface (floating), anchored to prevent drifting	Elongated, multi-segment, floating device is oriented parallel to wave travel; flexing action of segments drives generators (similar to an hydraulic ram)
overtopping	Wave Dragon	Ocean surface but tethered offshore or built out from shoreline	Waves fill a basin creating a pressure head; water is released back into ocean, driving a turbine
point absorbers	AquaBuOY	Ocean surface (floating), anchored to prevent drifting	Floating structure; absorbs wave energy (e.g., hydraulic turbine, direct acting) from any direction as the device rises and falls

* Also referred to as a terminator.

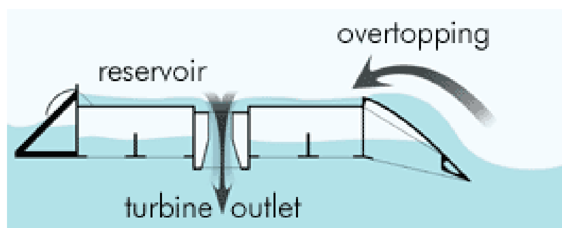
Source: Nelson et. al.



Oscillating water column device: Oceanlinx.



Attenuator: Pelamis



Overtopping device: Wave Dragon

Point absorber: AquaBuOY

Figure 1.3: Photographs and diagrams of WEC design types (supplied by their manufacturers and used by permission)

Source: Nelson et. al.

WEC technologies vary widely in design, size, and appearance (Figure 1.3), but fundamentally they will add submerged structures analogous to artificial reefs, offshore oil platforms, navigation buoys, or fish aggregation devices (FADs). Devices posing a navigational hazard (i.e., at or near the surface) must have lights to meet US Coast Guard requirements. A recent review by the California Energy Commission (PIER 2008) lists the characteristics of several advanced designs that range in size from the point absorber AWS Ocean Energy Archimedes Wave Swing of 7 x 9.5 meters with a 2-MW capacity (not shown), to the overtopping Wave Dragon of 53 x 33 meters with a 20-kW capacity (Figure 1.3). A commercial-scale design for the Wave Dragon is 390 x 220 meters with 4- to 11-MW capacity. A technical review of WEC technology by the Electric Power Research Institute (Previsic et al. 2004) includes additional details of these and other devices.

The chapters of this paper summarize existing information on the potential environmental impacts of wave energy technology, present analyses of applying this information to California's marine ecosystem, and provide recommendations that will fill data gaps or that allow additional evaluations. Chapter topics include:

- Human uses of the nearshore marine environment, including areas of high vessel traffic, and areas of recreational, cultural or economic importance.
- Wave-driven nearshore physical processes that provide the basis for subsequent discussion of ecological processes and effects on marine communities and benthic habitats, fishes, marine birds, and marine mammals.

Description of the ocean observing systems that are relevant to coastal processes. Several tools can assist in monitoring the effects of WEC technology; conversely, WEC installations can assist in observing the ocean.

Themes Common to All Chapters

Although the chapters are essentially "stand alone" sections of text, common themes in the analyses and recommendations were noted: 1) the need for field studies, 2) the recognition of climate change effects in conjunction with WEC effects, and 3) the need for research designed such that study results provide natural resource managers and the WEC industry with information that can be useful in siting new projects, and re-designing the devices or operation of the devices, to minimize if not completely avoid negative effects.

While numerical and computer modeling can indicate the probability and severity of possible effects, the results are inherently uncertain due to assumptions necessary whenever a model represents real conditions. Therefore, field data collection, pilot studies, and large scale "mesocosm" studies will be needed to obtain more certain and quantitative results. This theme was particularly stressed in the chapters on physical processes, biological communities in the nearshore environment, fishes, and marine birds and mammals. (However, in the socioeconomics evaluation, the author recognizes that WEC effects can become manifest before "actual physical alteration of the environment occurs … People and social systems" can and do respond to announcements of future projects, not only the project itself.)

As a contributing factor to effects caused by WEC installations, climate change was a factor that the scientists recognized but did not explicitly evaluate. Some considered that it could exacerbate effects due to WEC technology (for example, further affecting species that are already on the edge of their habitat), but separating or assigning fractions of "cause" to WECs or to climate change would be extremely difficult. Climate change could change the economic feasibility of WEC installations, if areas experiencing climate change begin using more energy to maintain comfortable indoor temperatures.

The need to understand and develop some basic ecological processes was discussed in the chapters. An example of "pure" research that has some practical application is the "abundance vs. redistribution" question, which is whether species abundance will increase, or whether species simply redistribute themselves when new, albeit artificial habitat becomes available. In each of the chapters, the scientists briefly discuss a few "pure" research studies, however, they also recognize that new studies should provide some information that could inform WEC designs. An example of research with immediate and directly applicable mitigating results is the recommended study on light susceptibility of seabirds; if certain light criteria are defined and found to be hazardous to seabirds, then engineers could possibly design lights in other wavelengths, intensity, orientation or concentration. Each proposed study should provide management with a plan such that study results can be directly applied to WEC mitigation.

The responsible development of WEC for California must begin by collecting solid baseline information on human, physical, and biological processes. Without this standard for comparison, impact analyses will inevitably be compromised. After installation, studies should employ a Before-After-Impact-Control design with multiple control sites (Kingsford 1999), or, better, multiple control sites and multiple impact sites (Keough and Quinn 2000). Continued nearshore monitoring will also be required, ideally incorporating some of the ocean observing systems already in place. Monitoring beyond the initial impact analysis will be necessary to detect long-term or subtle effects and well as interactions with cyclical oceanographic events (e.g., El Niño-Southern Oscillation) or global climate changes.

Recommendations

Recommendations were selected from the chapters that follow. This list attempts to identify the most important recommendations, but importance is a relative concept and other useful recommendations are found within individual chapters.

For potential social and economic effects caused by WEC implementation, research is needed to:

- Collect higher-resolution spatial data that connect coastal marine locations to the social and economic benefits that the marine environment provides to users, local communities, and others. The data needed include marine uses, beach recreation, wildlife viewing, tourism, and non-use values (e.g., culturally significant areas and existence values), commercial fishing, and vegetation harvest. After collection, this data should be compiled into a geographical information system (GIS) map format.
- Develop a research methodology to map the locations of valuable commercial fishing grounds, similar to the methods of Scholz et al. (2006).
- Develop IMPLAN economic impact models that consider the unique input-output relationships of the state's diverse commercial fisheries.
- Inventory marine cultural resources, in a GIS-compatible format, to assess the cultural and historical connectivity of sites.
- Identify the scale of commercial and recreational fishing and other activities that are needed to sustain small harbor facilities and local fishing industry complexes.
- Describe the public's degree of acceptance of wave farm development in California, and identify the factors that have led to increasing or decreasing that degree of acceptance.

For potential ecological effects due to WEC-induced physical process changes in the nearshore environment, research is needed to:

- Determine the efficiency and performance criteria of each device, as provided by the device manufacturers or as determined through "third party" studies. Efficiency will likely be a function of wave height and period, and may be further complicated by waves of diverse periods and directions.
- Select and evaluate a suitable refraction-diffraction model to run simulations of waves around WEC array-like objects. Modeling should occur prior to permitting significant WEC arrays. For such models to predict WEC effects, detailed information on the devices' dissipative and scattering characteristics is required.
- Detailed monitoring of wave conditions inshore of pilot systems is also recommended, using combinations of different instruments, in conjunction with existing agency data collection programs. A wave monitoring buoy should be deployed prior to WEC installation and should be maintained for several years in the nearshore region. If a significant shadow zone is indicated, monitoring should extend to benthic processes, including defining settlement and resuspension rates.
- Directly observe impacts on sediment transport, morphology, and nearshore water quality through before-and-after studies. Studies would be best located in areas expected to exhibit an inordinate impact on ecological communities (for example, estuary mouths such as at the

For potential effects on biological communities in the nearshore environment, research is needed to:

- Describe how biological communities vary along a wave energy gradient, particularly since the relationship could be non-linear rather than linear. Qualitative models are provided in this study (for example, the zonation model), but data to support these models are needed. Wave energy changes in the 0 to 15% range should be studied. To minimize any differences in other physical factors (e.g., wave exposure, sea surface temperature, upwelling regimes, substrate composition), the sites surveyed would ideally be located within a small region of coastline.
- Design studies that would determine how the frequency and size of disturbance events varies, when wave exposure also varies.
- Identify the relative importance of suspended sediment and light, versus the availability of nutrients, to plant growth in the nearshore environment.
- Identify the relative importance of fertilization rates in the nearshore environment. If wave energy increases rates of fertilization by decreasing wave energy, then the relative abundances of species with limited dispersal ability could increase, which could affect community structure.

For potential effects on fishes and fish habitats, research is needed to:

- Characterize the EMFs associated with WEC technology, and review the potential behavioral response of key species to those stimuli. Laboratory and mesocosm studies may be warranted, but should be designed based on *in situ* measurements of WEC-associated EMF and California species likely to encounter WEC arrays and to be sensitive to low levels of EMFs (e.g., Pacific Lamprey (*Lampetra tridentata*), White Sharks (*Carcharodon carcharius*), Green Sturgeon (*Acipenser medirostris*) and salmonids (*Onchorhynchus* spp)).
- Confirm new information specific to WEC-generated sound and vibration that suggests that underwater noise and sound pressure are not causes for concern. Without such information, there is potential for significant effects on fish physiology and behavior.
- Assess artificial reef effects and FAD effects, determining the processes associated with WEC-related fish community formation, evaluating alterations in local predation (especially of salmonids), and assessing the evidence for a FAD effect.
- Evaluate the potential impacts of WEC development on fisheries management. Because public access (including fishing access) to WEC sites is likely to be curtailed for safety

reasons, WEC sites will probably function as *de facto* marine reserves, with fisheries management and conservation implications.

For potential effects on marine birds and mammals, research is needed to:

- Support expansion of a standardized, coast-wide citizen science program to track seabird mortality patterns similar to the Coastal Observation And Seabird Survey Team (COASST). Pre-installation, data from such a program would provide or augment existing baseline information; after WEC installation, the program should continue monitoring to detect potential WEC effects and distinguish these from other environmental processes.
- Monitor Gray Whale and Harbor Porpoise behavior (e.g., visual surveys, theodolite measurements of movements, autonomous acoustic monitors), to evaluate responses to WEC installations, and to determine if there is a minimum installation size such that behavior appears to be unchanged.
- Review the literature on light induced seabird mortality, and perform additional studies if the literature cannot provide information sufficiently applicable to WEC installations. Once the degree of light induced seabird mortality is characterized, provide lighting criteria to WEC designers, so WEC lighting can be modified to minimize seabird mortality.
- Perform direct field studies on species that are almost certainly affected by WEC installations, such as some marine birds (e.g., gulls and cormorants) and mammals (e.g., sea lions). Collision and entanglement are effects of particular concern; similar to potential lighting effects on seabirds, researchers should provide WEC designers with criteria so that WEC systems can be designed to minimize negative effects.

To provide more complete baseline information, and to better monitor potential WEC-induced effects, researchers utilizing ocean observing systems need to:

- Foster partnership agreements between ocean observing system organizations, ecological monitoring programs, and the WEC industry, such that data can be freely shared among all.
- Design data collection using standardized instruments and QA/QC protocols, particularly for water quality measurements.
- Widen existing observation networks to fill spatial "gaps' in coverage, such as estuaries.
- Evaluate the extent to which existing ocean observation systems can provide useful data for studying nearshore physical and ecological processes.

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2.0 Economic and Social Considerations for Wave Energy Development in California

Steven C. Hackett
Humboldt State University / Planwest Partners

Abstract

The prospect of climate change due to anthropogenic greenhouse-gas emissions is stimulating regulatory policies, such as California's Global Warming Solutions Act, that will create enhanced market opportunities for electricity generated from renewable sources. Electricity from wave energy conversion has the potential to be cost-competitive with on-shore wind technology. Wave energy conversion facilities developed at commercial or regional scales will have a variety of economic and social impacts. This chapter begins by summarizing existing knowledge from various technical reports and published studies on the economic and social aspects of important marine uses in California. Usage information is summarized for high traffic areas, areas of importance for recreational, cultural, and economic reasons. The potential economic benefits of wave energy conversion are characterized, and summary information is provided on the economic contribution provided by commercial and recreational fisheries, coastal and marine recreation and tourism, and ports and harbors. A review of this information indicates significant gaps in our understanding of key economic and social tradeoffs involved with implementing wave energy conversion on a commercial or regional scale. Among the most important priority recommendations for future research is to produce higher-resolution spatial data that connects coastal marine locations to the economic and other benefits they provide for users, local communities, or others, and to compile this information in a GIS map format. This information (along with a better understanding of social impacts) can then be compared to the benefits provided by wave energy conversion so that policy makers and the public can make informed decisions regarding implementation of this new form of energy generation.

Introduction

Anthropogenic greenhouse gas emissions are widely understood to contribute to global climate change (Intergovernmental Panel on Climate Change 2007). Within that context, laws such as California's Global Warming Solutions Act (AB 32) are taking shape that will create enhanced market opportunities for electricity generated from renewable sources that produce fewer anthropogenic greenhouse gas emissions. The California Energy Commission (2008) estimates that wave power densities north of Point Conception are between 26 and 34 kW/m, and note that this represents a potentially attractive wave climate that is also found relatively close to shore. Previsic and Bedard (2007) predict that once wave energy conversion (WEC) devices reach a cumulative installed base of about 25,000 megawatts, they will produce a megawatthour of electric energy at or below the cost of electricity generated from on-shore wind technology.[6] WEC can thus potentially help California meet its renewable energy commitments under AB 32 and related legislation.[7] Development of wave farms will also have various positive and negative impacts on existing coastal marine uses, as well as on social and economic conditions in coastal communities.

Figure 2.1 lists some examples of potential impacts from developing WEC facilities.[8] These facilities utilize an area of the ocean in which other uses such as fishing and pleasure boating would be restricted. This area would comprise not only the plan area of the devices and their foundations and moorings, but also a safety exclusion zone around the devices as well as the facility's sub-sea electric transmission cables (Electric Power Research Institute 2004). These facilities would also impose potential obstacles or costly transit lane detours for coastal marine traffic.[9] Impairment of visual aesthetics or whale migration would adversely affect tourists and coastal residents. The relatively sheltered water on the landward side of wave farms could enhance some forms of recreation and impair others, and may induce changes in the pattern of coastal erosion, sediment transport, and beach nourishment over time that could impact the coastal zone and its use.

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6 The Electric Power Research Institute (2004) estimates a levelized cost of electricity (LCOE) in the range of 10-11 cents per kilowatt-hour for two commercial-scale wave energy conversion facilities off San Francisco, with uncertainties in the cost estimates between +35 to -25%. The California Energy Commission (2008) notes that at the higher end of the Northern California wave energy density range, LCOE may be as low as 7 cents per kilowatt-hour. The California Energy Commission (2008) also reports that initially the LCOE will likely be higher than the above values because the deployment of relatively unproven technologies entails greater risks for investors, which is typically reflected in a higher cost of capital. Moreover, initial deployments of the technology will likely involve much smaller wave energy conversion facilities.

7 In addition to AB 32, California also has a renewable portfolio standard (RPS) established in 2002 under Senate Bill 1078 and accelerated in 2006 under Senate Bill 107. California's RPS program requires electric corporations to increase procurement from eligible renewable energy resources by at least 1% of their retail sales annually, until they reach 20% by 2010.

8 Some potential impacts such as changes in air and water quality are not addressed here due to space considerations. See the California Energy Commission (2008) for more details.

9 Commercial fishers interviewed for this chapter also emphasize that wave farms could serve as a hazard to the practice of night drifting on multi-day fishing trips, and that Dungeness crab traps mobilized by strong winter storms could easily foul point absorbers or attenuators and their cables. Mariners also note that *tug and tow* barge traffic frequently transit either to the inside or outside of established shipping lanes to avoid large container ships and tankers, and this practice could be displaced by wave farm development.

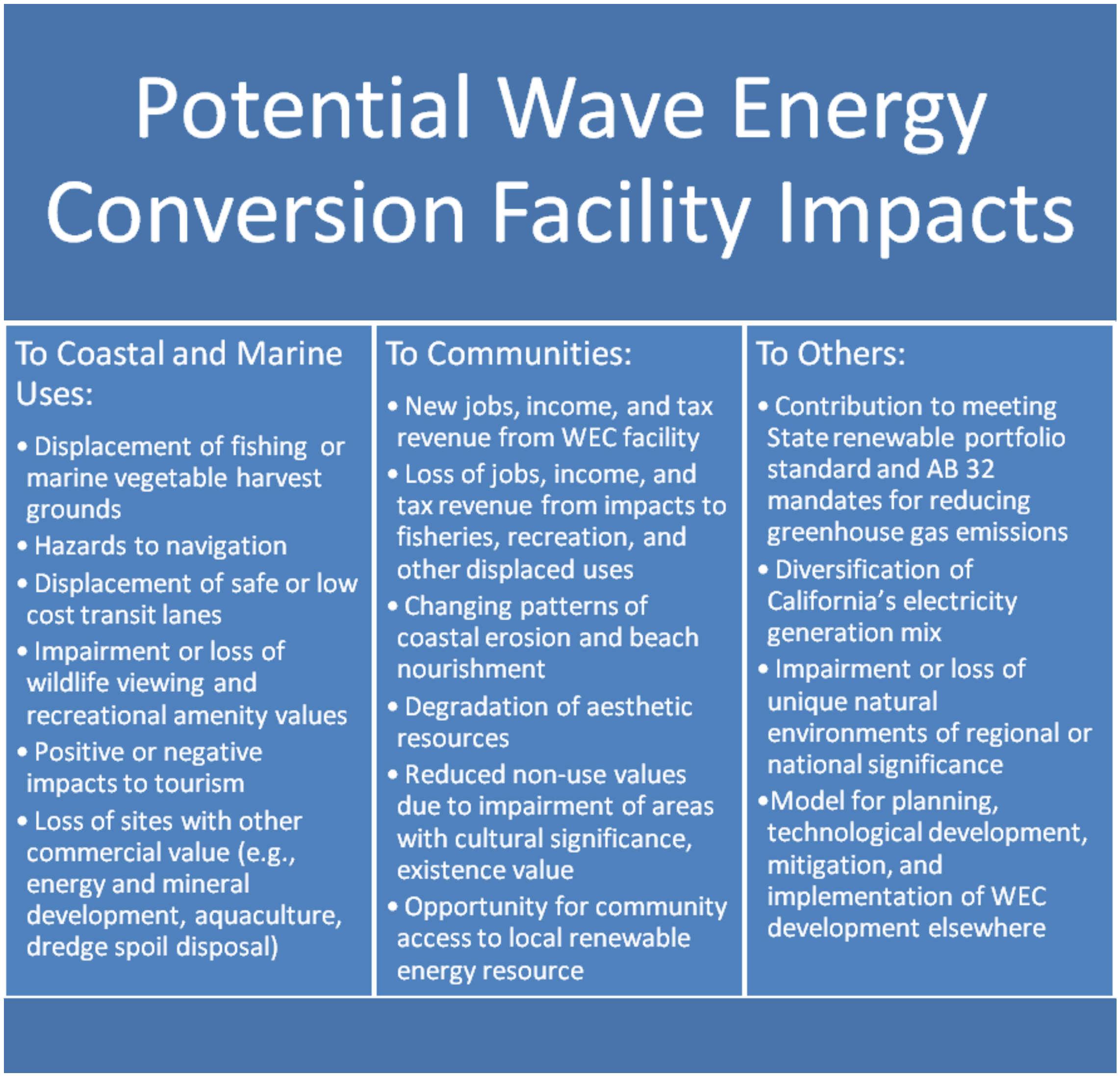

Figure 2.1: Potential Wave Energy Conversion Facility Impacts
Source: Hackett

A deterministic assessment of the ocean area required by commercial or network scale WEC facilities is not possible in this chapter, as it depends on specific technology, density, and capacity information that is not available. At the pilot scale, the Federal Energy Regulatory Commission (2007) reports that a 1 megawatt project in Washington State would utilize four WEC buoys in a 60 by 240 foot area about 1.9 nautical miles offshore, along with sub-sea transmission cables and on-shore facilities. In contrast, the California Energy Commission (2008) estimates that commercial WEC projects may have a generating capacity of 100 to 150 megawatts. A commercial project could involve one large overtopping or oscillating water column device, or a large number of point absorber or attenuator devices. Commercial or network scale wave farms could occupy up to several square miles of the marine environment. Desirable sites feature depths up to 100 meters, locations within 10 miles of the coast, and proximity to onshore electric transmission lines with sufficient feed-in capacity.[10] Such locations are likely to also be productive fishing grounds and high-traffic areas near port communities, and development at a commercial or network scale could generate significant impacts on diverse coastal marine stakeholder groups.[11]

This chapter has a broad mandate–to summarize economic and social information relating to coastal and marine uses and values that may be impacted by WEC facilities, to identify knowledge gaps, and to suggest priority research needs. Current knowledge is summarized on areas of importance in the marine environment, the economic contribution of marine uses and values to local communities in the region, and ongoing research on these topics. Some information is also provided on the beneficial local and regional economic impacts that might derive from wave farm development. In some cases sufficient data resolution allows for regional and local analysis within the focus area for this white paper – the California coast north of Point Conception. In other cases a statewide level of resolution is all that is available. The summary of current knowledge provides a context for a identifying the gaps that exist in our understanding of the potential economic and social implications of wave farm development in California, and for prioritizing areas for future research. Among the most important priority recommendations for future research are the production of higher-resolution spatial data that connects coastal marine locations to the economic and other benefits they provide for users, local communities, or others; and compilation of this information in a geographical information system (GIS) map format. This information (along with a better understanding of social impacts) can then be compared to the benefits provided by WEC so that policy makers and the public can make informed decisions regarding implementation of this new form of energy generation.

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10 Previsic and Bedard (2007) note that the grid infrastructure in California's coastal regions tends to be weak and are typically not set up to accommodate large generation capacities. Most coastal towns in Northern California are connected to the electric transmission system by 60 kV substations, and most of these substations offer a feed-in capacity of between 30 and 50 MVA.

11 Many current Northern California wave energy project permit areas are in fact located in high traffic areas. According to the Federal Energy Regulatory Commission (2008), on March 13, 2008, three-year preliminary study permit P-12779 was issued for PG&E's Humboldt WaveConnect wave energy project area, which encompasses all of the coastal waters for several miles on either side of the entrance to Humboldt Bay's ports and marinas. On that same day PG&E was also issued preliminary study permit P-12781 for its Mendocino WaveConnect wave energy project area, which likewise occupies the coastal waters immediately offshore of Noyo Harbor and Fort Bragg. In a move to protect local control, the Sonoma County Water Agency applied for a permit covering approximately 490 square miles and encompassing the county's entire coast, including the waters immediately offshore of Bodega Bay. Its FERC permit P-13076 is currently pending. Readers may wish to use the map in this white paper (Nelson PA, Woo S (Chapter 1) Introduction and overview: ecological impacts of wave energy conversion in California. California Ocean Protection Council to familiarize themselves with the location of these and other wave energy project areas along the California coast.

Current Knowledge

2.1.1 Areas of Importance

Coastal and marine locations that are important for economic and social reasons are described below. In some cases the spatial resolution is low, with information only available at regional or state-wide scales. Readers may wish to use the map in this white paper (Nelson and Woo Chapter 1) to familiarize themselves with specific locations discussed below.

2.1.1.1 *High Traffic Areas*

Ports and harbors are the locus of considerable marine activity, and could provide WEC facilities with ready access to the electric transmission grid. The ocean area adjacent to ports and harbors may feature relatively lower lifecycle costs for wave farms by reducing the amount of underwater transmission cable required to move electricity to the coastal grid, and by reducing transit time for vessels servicing the wave farm. These spatial benefits may come at the cost of adverse impacts on some current port and harbor users.

The most important high-traffic area in the marine environment north of Point Conception is the greater San Francisco Bay area and adjacent offshore waters. Among the vessels utilizing these waters are container ships heading to the Port of Oakland; tankers delivering crude oil to Bay Area refineries; and break-bulk freighters, passenger ferries, cruise ships, commercial and recreational fishing vessels, and pleasure boats calling at the Ports of San Francisco, Richmond, and other smaller area ports. Naval, Coast Guard, law enforcement, and research vessels, as well as vessels in transit, also utilize this area. Clearly wave farm development in the waters off the Golden Gate could adversely affect safe shipping and transit in this highly trafficked area, making this an unlikely site for wave farm development on a commercial scale.

Other moderately high-traffic areas in the region include Morro Bay, Monterey Bay, Half Moon Bay, Bodega Bay, Fort Bragg, Eureka, Crescent City, and several smaller harbors.[12] In contrast to the greater San Francisco Bay area, user impacts from wave farm development near these smaller ports would disproportionately affect commercial and recreational fishermen. In some cases wave farm development may bring welcome economic development opportunities to rural coastal communities. Some additional details on selected California ports and harbors north of Point Conception are given in Table 2.1.

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12 NOAA Community Profiles, available at http://www.nwfsc.noaa.gov/research/divisions/sd/communityprofiles/index.cfm, provide a good source of information for activity at smaller California ports and harbors. These community profiles provide detailed information on harbor infrastructure, numbers of commercial vessels, commercially licensed fishers, and fish processors, commercial landings by fishery, and sport fishing activity. Scholz and Steinback (2006), Pomeroy et al. (2002), and Pomeroy and Dalton (2003) offer additional information on harbor and port communities in the Central and/or North Central coast region of California.

Table 2.1. Summary Information for Selected Ports and Harbors North of Point Conception

2.1.1.1.1.1.1 Ports and Harbors	2.1.1.1.1.1.2 Highlights
Eureka/Humboldt Bay	Shipped just under 500,000 revenue tons of general cargo, lumber/logs, and dry bulk in 2001, down from a peak of more than 1.2 million revenue tons in 1991 (PB Ports & Marine, Inc. 2003).[13] 18.6 million pounds of fish were landed in Humboldt Bay in 2006, worth $12.3 million (CDFG 2008).[14]
San Francisco	Increasingly important for break-bulk cargo (e.g., steel, lumber, and newsprint). Hosts 60 to 80 cruise ship calls, and 200,000 passengers annually – up from 40,000 passengers per year in 1998 (Port of San Francisco 2008; Moyer et al.2005). About 6.1 million commuter and excursion tourist trips occurred at the Port of San Francisco in 2005 (Moyer et al.).
Richmond	California's third largest port in annual tonnage, handling more than 19 million short tons of general, liquid, and dry bulk commodities each year (Port of Richmond (2008)
Oakland	Fourth largest container port in the US and 20th in the world in annual container traffic (Martin Associates 2006). Handles nearly all container traffic in Northern California. Moved a record 2.4 million "twenty-foot equivalent units" in 2006 (Port of Oakland 2007).[15]
Monterey/Moss Landing	Busiest ports in the Monterey Bay National Marine Sanctuary area. Between 1981 and 2000 this area generated an annual average of 235,000 Commercial Passenger Fishing Vessel (CPFV) trips, 944,000 private/rental boat trips, and 1.3 million shore fishing trips (Starr et al. 2002).

Source: Hackett

2.1.1.2 *Areas of Importance for Recreational Reasons*

Recreational fishers and boaters could potentially experience displacement from safe transit routes and valuable recreation sites, alteration of physical and biological conditions, and fish aggregation on underwater wave energy structures that may benefit recreationalists in adjacent waters. Surfers could experience wave energy attenuation on the landward side of wave farms. WEC device layouts considered by Halcrow Group Limited (2006), for example, were estimated to result in up to a 13% localized reduction in the height of typical surfing waves in their study area on the southwestern coast of England. As noted in the introduction, the relatively sheltered water on the landward side of wave farms could enhance some forms of recreation and impair

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13 For cargo rated as weight or measure, the size of a shipment in revenue tons is the number of metric tons or the number of cubic meters in the shipment, depending on which measure produces the higher revenue.

14 CDFG (2008) note that Crescent City was by some measures an even more important commercial fishing port than Eureka, generating 17.8 million pounds of commercial landings in 2006 (primarily Dungeness crab), worth $22.7 million.

15 The US Corps of Engineers (2000b) and the Port of Oakland (2008) provide additional information on the infrastructure at the Ports of Oakland and Alameda.

others, and may induce changes in the pattern of beach sand nourishment over time that could impact beach recreational uses.

Recreational fishing is one of the better-documented activities in the marine environment that is potentially impacted by wave farm development. Figure 2.2 plots CDFG (2006) data on the number of 2005 California angler trips by district and fishing mode. One can see that the overwhelming share of total statewide angler trips occurs in the South District (Los Angeles, Orange, and San Diego counties). In contrast, the Wine and Redwood Districts (Sonoma through Del Norte counties) generated fewer than 10% of total statewide angler trips in 2005, and more than half of these trips occurred in private or rental boats.

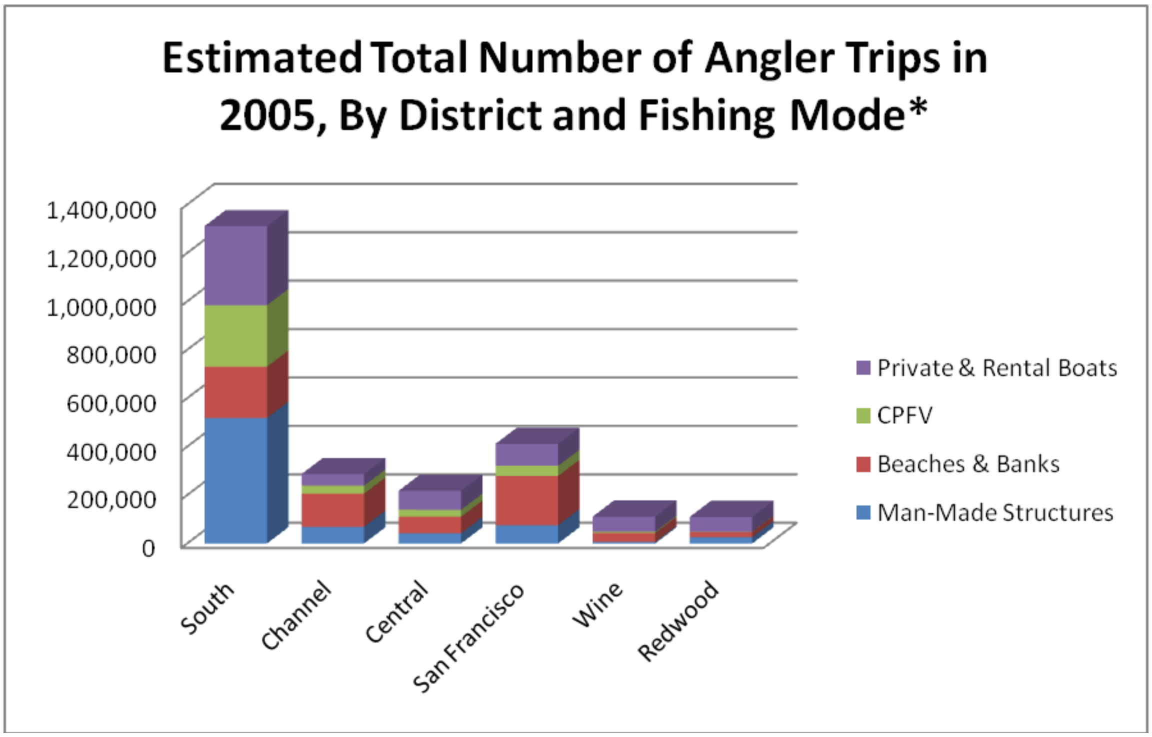

Figure 2.2. Estimated Total Number of Angler Trips in 2005, By District and Fishing Mode (CDFG 2006)

* South (Los Angeles County to San Diego County), Channel (Santa Barbara and Ventura Counties), Central (Santa Cruz County to San Luis Obispo County), San Francisco (Marin, San Francisco, and San Mateo counties on the coast, and the six counties surrounding San Francisco and San Pablo bays), Wine (Mendocino and Sonoma Counties), Redwood (Del Norte and Humboldt Counties).
Source: Hackett

Until the recent collapse, Chinook salmon (*Oncorhynchus tshawytscha*) were a mainstay of Central and Northern California recreational fisheries.[16] In their study of the Monterey Bay

16 On April 10 2008, Governor Schwarzenegger issued a state of emergency proclamation for the salmon fishing season in California (Schwarzenegger 2008). This proclamation came after the Pacific Fishery Management Council voted to cancel all commercial salmon fishing off the California and Oregon coasts due to collapse of the Sacramento River fall run of Chinook salmon. A federal disaster declaration was

National Marine Sanctuary, Starr et al. (2002) report that although rockfish (*Sebastes* spp.) catches have been declining from 1981 to 2000, they have been one of the most important recreational sport fishing resources in Northern and Central California, with catches averaging 2.4 million fishes annually. Likewise Scholz et al. (2006) report that rockfish and salmon are two of the most important Central Coast recreational fisheries.[17]

Other recreational data tend to be at a relatively coarse, statewide level of resolution. Coastal marine wildlife viewing, particularly whale watching, is potentially impacted by wave farm development. According to Pendleton (2006) and Leeworthy and Wiley (2001), for example, California ranks second in the nation in terms of number of coastal birdwatchers with more than 2.5 million people participating in some kind of coastal bird-watching during 1999 and 2000. Other types of wildlife viewing, including whale watching, are equally important in California. Leeworthy and Wiley (2001) report that 2.5 million people participated in wildlife viewing other than bird watching in California during 1999 and 2000.

Research conducted by Leeworthy and Wiley (2001) reveals that 12.6 million people frequented California beaches in 1999 and 2000, generating 151.4 million visitor days of activity. Ehler et al. (2003) note that when recreational activities are ranked by participation rates, photographing scenery and swimming were the second and third most popular marine activities, respectively, in California. Ehler et al. (2003) report that there were 4.18 million participants engaged in beach photography, for a total of nearly 108 million days, while 8.4 million people engaged in nearly 95 million days of swimming at the beach (Leeworthy and Wiley 2001; Ehler et al. 2003). Pendleton and Rooke (2006) report that at 17.6 million participants, California ranks second only to Florida in the total number of coastal recreationalists. While California also ranks second to Florida in the percentage of its population that participates in marine recreation (10.7% for Florida, 8.7% for California), its large population places California first in the nation in the number of residents that participate in marine recreation annually (12.2 million).

Drawing upon data from the National Survey of Recreation and the Environment, Kildow and Colgan (2005) report that 1.1 million surfers participated in a total of 22.6 million days of surfing in California in 2000.[18] As noted by Lazarow and Nelsen (2007), there has been little formal

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issued for the salmon fishing season in California and Oregon in 2006, though fishing was not completely curtailed.

17 In their beach angler survey for the Monterey Bay area, CDFG (2007) found that beach fishing effort was focused from Sand City in Monterey County north to Capitola in Santa Cruz County. Additional recreational fishing data for California are available at http://www.recfin.org.

18 According to the website wannasurf.com, while Southern California by far dominates the total number of surf spots in California, relatively high densities of surf spots also occur between Carmel and Santa Cruz, as well as between San Mateo and San Francisco. The three-county North Coast region accounts for about 3% of all user-defined surf spots in California. Note that surf spot data on this website are generated from contributions by website visitors, and do not necessarily meet rigorous social-science research standards.

research addressing the value of surfing at major surf destinations around the world, though they note that the socio-economic value of surfing to some communities is believed to be significant. Lazarow and Nelsen (2007) go on to say that any negative impact to the surfing amenity (such as from WEC facilities) may have serious consequences for the resident surfing population, visitors, the surf industry and local economies.

According to a California coastal recreation and aesthetics study by Miller (1981), beach recreational activities, including sunbathing and walking, were the predominant forms of activities, and were generally followed in decreasing order of popularity by open beach activities (outdoor sports, hang gliding) and water-related recreational activities (e.g., swimming, wading).[19] Miller (1981) also developed and assigned aesthetic value scores (using a visual management system methodology) to each coastline segment of California. The study indicated a preponderance of high, medium high, and medium scores for the entire California coast.

The California Department of Boating and Waterways (2007) provides data on combined freshwater and marine pleasure boat registrations by county. These data may provide a rough indication of regional pleasure boating activity, some of which could be adversely affected by wave farms.[20] Contra Costa had the largest number of registered pleasure boats among all California coastal counties north of Ventura, while Del Norte had the fewest. As shown in the pie chart on the left side of Figure 2.3, about 23% of California's 886,450 pleasure boats are registered in coastal counties north of Ventura. The pie chart to the right shows that the great majority of these regional pleasure boats are registered in the nine-county San Francisco Bay area. The three-county North Coast region accounts for only 2% of total state-wide pleasure boat registrations, and less than 7% of regional registrations.[21]

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19 Between Big Sur and Gaviota, water related activities were notably more popular than open beach activities, while water contact recreation was minimal in segments north of Pt. Reyes.

20 County of registration is not necessarily a good indicator of the spatial location of recreational activity, as people in inland counties may trailer them to the coast for recreational fishing opportunities.

21 By way of comparison, the four-county Southern California region accounts for about 30% of all pleasure boat registrations in California.

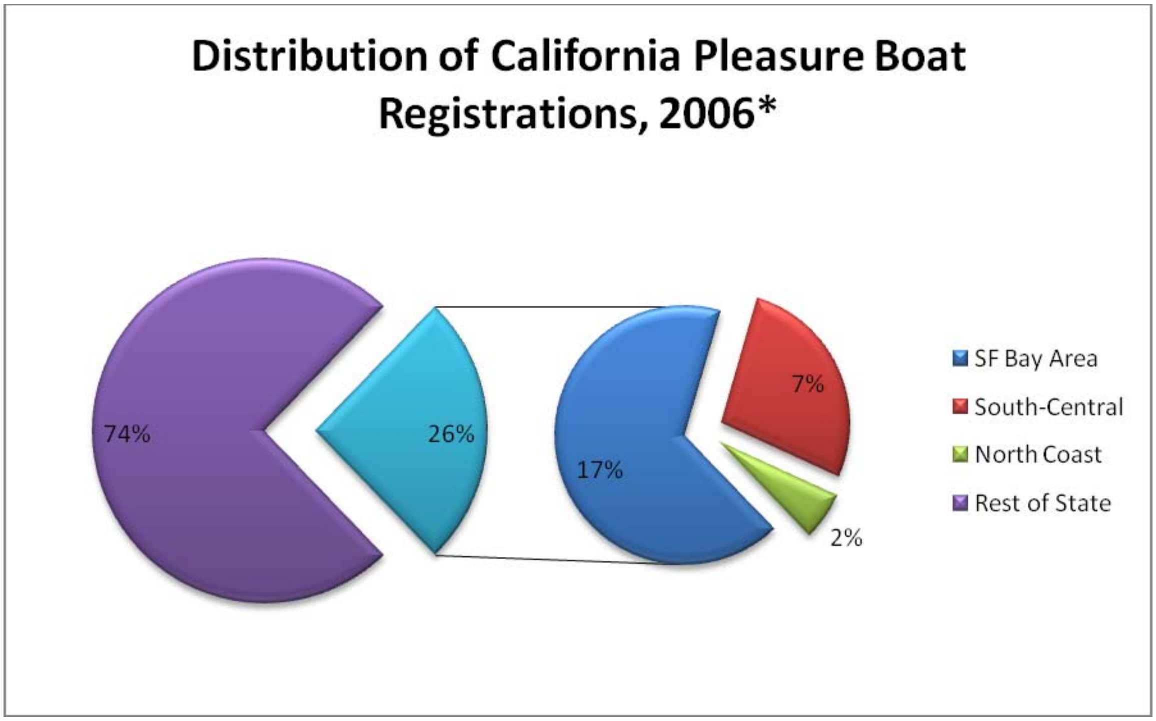

Figure 2.3. Distribution of California Pleasure Boat Registrations, 2006 (California Department of Boating and Waterways 2007)

*Note that data are for combined freshwater and salt water pleasure boat registrations.
Source: Hackett

2.1.1.3 Areas of Importance for Cultural Reasons

Cultural resources in the coastal marine environment include coastlines and natural resources with religious importance, such as Native American inhabitation sites (both prehistoric and post-European), natural elements with traditional cultural significance, resource-producing maritime activities, and submerged resources. Some locations are publicly identified, others are held in confidentiality, and many are yet to be discovered.[22] Wave farm development could potentially impact these cultural resources. For example, wave farm development near harbors may affect uses and values tied to culturally significant coastal marine locations, either through loss of access or alteration of physical or biological conditions, which could in turn affect coastal communities where these people live and work.

Coastal sites have been used for millennia for fishing, marine mammal and bird hunting, and other resource-gathering activities. Offshore rocks have been used for resource gathering, as meeting places for tribes, as docking and harboring areas for the first non-Indian explorers, as a means of stabilizing log flumes, and for lighthouses (Smith and Hunter 2003), among other things. Traditional harbors and shipping routes provide both historical and present cultural value.

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22 Personal communication, Jerry Rohde, 31 March 2008.

Submerged cultural resources, including inundated habitation sites, wharves, shipwrecks, and ship wreckage are all critical components of the offshore cultural heritage. In some locations, inventories have been made of sunken vessels and known losses drawing on a variety of existing information sources. Many sunken vessels contain hazardous materials that could harm natural resources (Smith and Hunter 2003).

2.1.1.4 Areas of Importance for Economic Reasons

Commercial fishing and marine vegetable harvesting represent some of the better-documented uses of the marine environment. Moreover, some areas being studied for wave farm development are currently utilized as fishing grounds for Dungeness crab (*Cancer magister)*, pink shrimp (*Penaeus duorarum*), and nearshore fisheries, among others.[23] Potential impacts include displacement from safe transit routes and valuable harvesting grounds, alteration of physical and biological conditions, and fish aggregation on underwater wave energy structures that could benefit fishers in adjacent waters.

As shown in Figure 2.4, commercial fishers in Monterey area ports produced the largest overall poundage of landings among all port areas north of Point Conception since 2000. Coastal pelagic species (CPS) such as northern anchovy (*Engraulis mordax*), market squid (*Loligo opalescens)*, and Pacific sardine (*Sardinops sagax*) dominate statewide landings quantities, particularly in port areas from Monterey south, though this total spans a broad diversity of species. By comparing Figure 2.4 and Figure 2.5, one can see that many (though not all) components of CPS tend to be relatively lower-value fisheries, though they account for a significant share of landed value. To provide a statewide context, between 2000 and 2006 the coastal region north of Point Conception generated between 23 and 45% of total statewide landings in pounds, and between 45 and 63% of the total statewide value of landings in constant 2000 dollars (CDFG 2008). CPS and squid seiners are among the fishers that may be impacted by wave farm development near Monterey area ports.

23 See Fishermen Interested in Safe Hydrokinetics (2008) for more details.

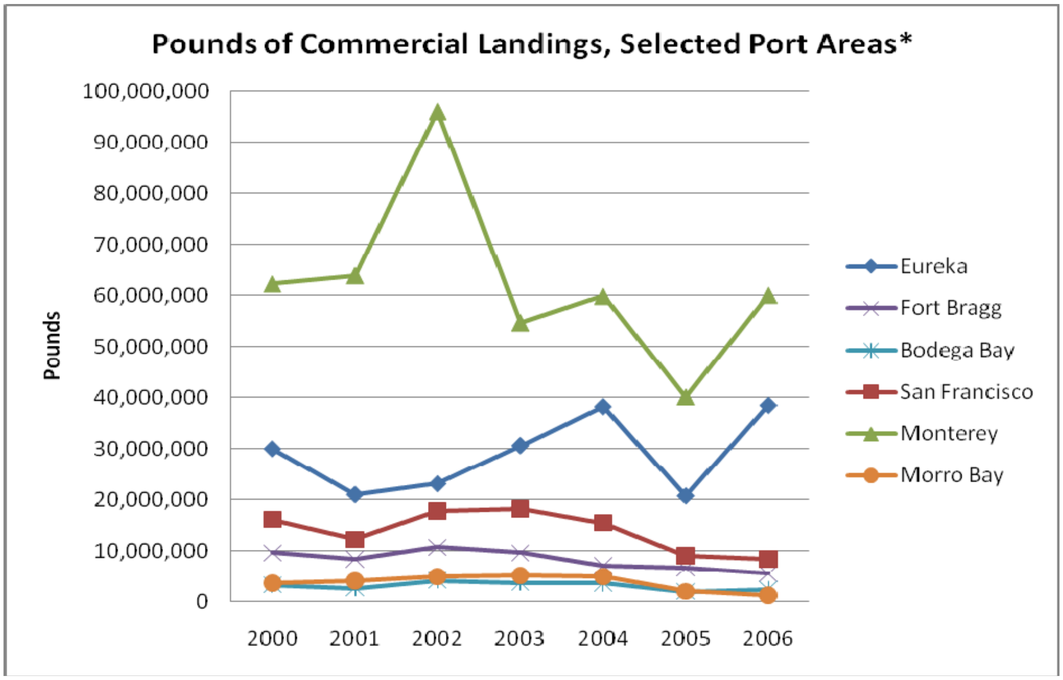

Figure 2.4. Poundage of Commercial Landings, Selected Port Areas (CDFG 2008)
***** California is divided into nine port areas for the purpose of reporting fisheries statistics. Each statistical area is named for a major port within its boundaries. Port areas south of Point Conception are Santa Barbara, Los Angeles, and San Diego.
Source: Hackett

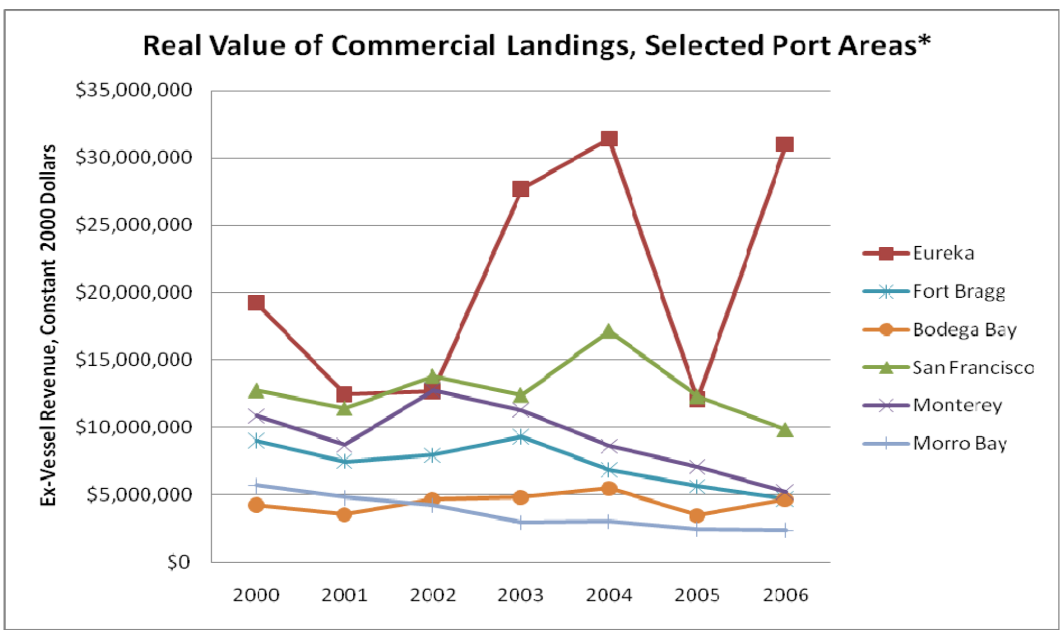

Figure 2.5. Real Value of Commercial Landings, Selected Port Areas (CDFG 2008; BLS 2008)

* Nominal values adjusted to constant 2000 dollars using the producer price index for intermediate feeds and foods. California is divided into nine port areas for the purpose of reporting fisheries statistics. Each statistical area is named for a major port within its boundaries. Port areas south of Point Conception are Santa Barbara, Los Angeles, and San Diego.
Source: Hackett

Eureka area ports were consistently the second largest producers in California waters north of Point Conception, though they generated the largest total real (ex-vessel) value of landings in this region. Dungeness crab, Pacific whiting (*Merluccius productus*), Dover sole (*Microstomus pacificus*), and sablefish (*Anoplopoma fimbria*) are some of the species that dominate commercial landings in Eureka area ports, though as with the Monterey area, overall landings span a broad diversity of species. Also important is the pink shrimp fishery, harvested using trawl gear in coastal waters along the North Coast. Key components of landings in San Francisco area ports include Chinook salmon and Dungeness crab, a variety of groundfish species, and Pacific herring (*Clupea palasi*) from area bays.[24] While most of the California sea urchin fishery occurs south of Point Conception, Hansen and Dewees (2007) note that there is also urchin harvest activity along the Sonoma and Mendocino coast.

With the exception of Eureka area ports, which benefited from cyclically abundant and valuable Dungeness crab landings, the real value of commercial landings (in constant 2000 dollars) has been relatively constant or moderately declining in California port areas north of Point Conception since 2000. In addition, Scholz and Steinback (2004) report a substantial decline in the number of commercial fishing vessels delivering fish at ports ranging from Bodega Bay to Monterey since 1981. For a variety of reasons the decline in fishing vessels was large relative to the decline in pounds of fish commercially landed at these ports.[25]

Working within the context of California's Marine Life Protection Act (MLPA) process, Scholz et al. (2006) have developed an innovative research methodology to map the location of valuable commercial fishing grounds. Some variant of this methodology may be adaptable for identifying impacts on commercial and recreational fishers from wave energy development. The focus area of their research was the Central Coast region (Point Conception north to Pigeon Point) of California. Building on a research methodology developed in earlier projects (Scholz et al. 2004; 2005), Scholz et al. (2006) developed and deployed a local knowledge interview instrument using an interactive computer interface, to collect geo-referenced information about the extent and relative importance of Central Coast commercial fisheries.

The GIS maps produced by Scholz et al. (2006) show that the largest concentration of fisheries occurs within a few miles of the coast – locations also attractive to wave farms. A number of other fisheries occur 10 or more miles offshore in some areas of the Central Coast region. While commercial fishers utilize the entire Central Coast region, there is considerable spatial heterogeneity in the location of various fisheries. Scholz et al. (2006) provide maps showing where fishers located the top 20% of all fishing grounds (ranked by number of fisheries).

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24 Chinook salmon and Dungeness crab tend to have a relatively high ex-vessel value per pound.

25 Important reasons for the disproportionately large decline in commercial fishing vessels in California include the development of limited-entry fisheries for salmon, groundfish, squid, sardines, and the nearshore fisheries. Also contributing to the decline was the buyback program in the Pacific groundfish trawl fishery, and the loss of California's major tuna processors.

Important areas include the Carmel and Monterey coast, and an area starting at Point Buchon and extending south for roughly 11 miles.

Recent work by Scholz et al. (2008) analyzes the impact of proposed MPA's in the North Central region of the California coast (Pigeon Point to just north of Point Arena). They document the importance of Dungeness crab and salmon to the region's commercial fisheries over the last seven years. They use the same spatial analysis methods as in Scholz et al. (2006), which allows them to document the impacts of proposed MPA's to commercial landings and revenue. Scholz et al. (2008) estimate annual losses due to proposed MPA's in the overall North Central region to range from about 2.5 to 8% of profits.

Reductions in wave energy may also affect marine vegetable productivity on rocky shore ecosystems to the landward of wave farms, which in turn could affect kelp harvesters and abalone divers, among others. There is a small artisanal edible marine vegetable harvesting industry that hand-gathers various species of plants along the rocky shorelines of Mendocino and Sonoma Counties. Wave farms being considered for nearby North Coast locations could impact this artisanal harvesting activity, but no publicly available data exist for this industry.[26] Bedford and O'Brien (2003) note that giant kelp (*Macrocystus pyrifera*) has been one of California's most valuable living marine resources, harvested from San Diego County north to Santa Cruz County. They note that historical fluctuations in landings were due to climate change and natural growth cycles, as well as market supply and demand. The overall declining harvest trend is shown in Figure 2.6.[27] Kalvass et al. (2003) note that much smaller tonnages of bull kelp (*Nereocystis leutkeana*) are harvested in California waters.

26 Some of these include sea palm (*Postelsia palmaeformis*), wakame (*Alaria marginata*), kombu (*Laminaria digitata*), nori (*Prophyra perforata*), and fucus (*Fucus vesiculosis*) (Fishermen Interested in Safe Hydrokinetics 2008). These edible sea vegetables grow in rocky cold-water shoreline habitats. Small-scale hand-harvesting occurs along the Mendocino coast from MacKerricher State Park north of Fort Bragg, south to the town of Elk. This area is one of the few places in the US where these edible sea vegetables are produced (personal communication, Larry Knowles, Rising Tide Sea Vegetables, 15 April 2008).

27 California's major commercial kelp harvester closed operations in 2005. Kelco (today a division of International Specialty Products) began operating in the late 1920s, harvesting kelp in order to extract algin, a product used in a variety of pharmaceutical, household and food products. Most commercial kelp harvest occurred in Southern California.

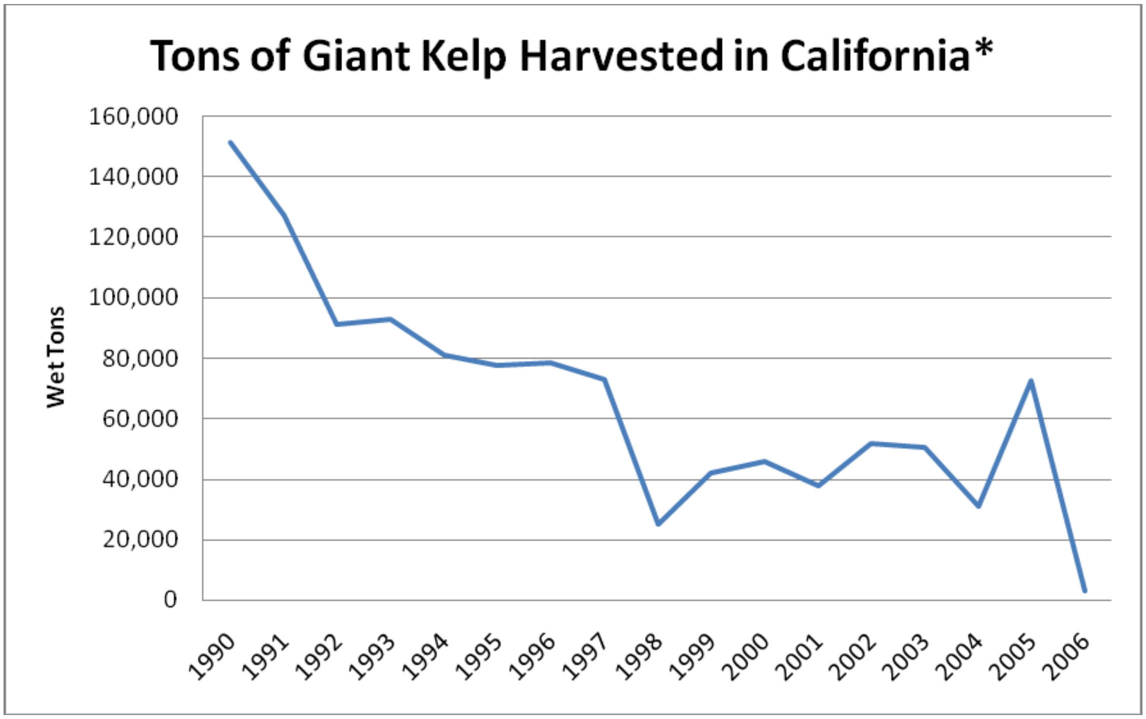

Figure 2.6. Tons of Giant Kelp Harvested in California (NMFS Southwest Regional Office 2008)
Source: Hackett

2.1.2 Economic Contribution of Marine Uses and Values

The development of commercial- or network-scale wave farms can be expected to generate jobs and income, while at the same time displacing existing marine uses and values that would otherwise provide economic benefits to coastal communities in the region. These current or potential economic contributions are summarized below. One category – marine minerals extraction – is omitted, as it is dominated by oil and gas development in Southern California waters largely outside of the focus area for this chapter. Another – commercial marine vegetable harvest – is led by a declining giant kelp industry south of Santa Cruz, but (as noted above) also features a small artisanal harvest industry in Mendocino and Sonoma Counties. Space considerations limit discussion of this marine use.[28]

2.1.2.1 Wave Farms

The construction, operation, maintenance, and ultimate decommissioning of wave farms can be expected to generate additional jobs and income to coastal communities and the surrounding region. These positive economic impacts are likely to be associated with stimulation of marine construction and related support industry sectors, as well as sectors associated with the

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28 Fishermen Interested in Safe Hydrokinetics (2008) report that there are four businesses in the Fort Bragg area that produce relatively small quantities of hand-harvested edible marine vegetables. The resulting sun-dried marine vegetables command a relatively high value per pound in the marketplace (personal communication, Larry Knowles, Rising Tide Sea Vegetables, 15 April 2008).

operation and maintenance of these facilities. For example, at the pilot scale, the 1 megawatt Makah Bay Offshore Wave Energy Pilot Project in Clallam County Washington consists of four wave energy conversion buoys, a submarine transmission line, and a shore station (Federal Energy Regulatory Commission 2007). This project would generate $874,088 in annual operations and maintenance expenditures, and electric energy worth approximately $60,000. At a commercial scale, the Electric Power Research Institute (2004) carried out a study to assess the economics and performance of a wave power facility with generation capacity of approximately 100 to 150 megawatts. That study estimated a total plant investment of $241 to $279 million, with annual operations and maintenance (O&M) costs ranging from $10.6 to $13 million. A portion of these construction and O&M expenditures would be injected into the local economy and generate additional economic impacts.

Looking beyond facility-related spending, additional tourism spending may be stimulated by the development of WEC facilities. For example, the Federal Energy Regulatory Commission (2007) argues that an interpretive and education plan for the Makah Bay offshore wave energy pilot project could contribute to the tourism industry by providing information to the public on the proposed project and the unique environment in which it would be located. According to this view, travel spending would likely be generated by the public to view the interpretive displays and surrounding area.

2.1.2.2 Commercial Fishing

While there is a highly diverse fishing industry along California's Central Coast north of Point Conception, the *wetfish* and other CPS fisheries are mainstays of Monterey Bay area ports (Pomeroy et al. 2002).[29] Hackett (2002) estimated that real value added by fishers in the wetfish industry complex (updated here to constant 2000 dollars) fluctuates due to both market and environmental conditions, and ranged from a low of $12 million in 1992 to a high of nearly $41 million in 2000. Two-thirds of real value added by fishers was generated from the market squid fishery. Real value added by wetfish fishers in 2000 represented 29% of the total for all fish landed in California.

For many years, Chinook salmon have provided one of the richest fishery resources in Northern California. Estimates of the negative economic impacts of recent salmon fishery declines and closures provide an indication of the contribution these fisheries could provide to the state economy. Following the federal disaster declaration for the salmon fishing season in California and Oregon in 2006, the California Department of Fish and Game (CDFG) estimated an economic impact of $61 million associated with a Klamath-area commercial (and recreational salmon) season closure in state waters (Schwarzenegger 2006). Disaster struck again in 2008, with negative statewide impacts estimated to be about $62 million, along with a loss of nearly

29 The wetfish species are northern anchovy, jack mackerel (*Trachurus symmetricus*), Pacific mackerel (*Scomber japonicus*), Pacific sardine, market squid, various tunas (bluefin (*Thunnus orientalis*), skipjack(*Katsuwonus pelamis*), and yellowfin (*Thunnus albacares*)) and Pacific bonito (*Sarda chiliensis*). The term *wetfish* has its origins in how the fish were processed in canneries.

700 jobs, from the complete statewide commercial salmon season closure in California in 2008 (Tillman 2008; Schwarzenegger 2008).

Dungeness crab landings fluctuate considerably from year to year, but the fishery serves as an increasingly important economic lifeline for Northern California fishers as the salmon and groundfish fisheries have declined (Dewees et al. 2004; Scholz et al. 2008). Dewees et al. (2004) documented the race for fish, or derby, which occurs annually at the start of the Dungeness crab fishing season, and that results in economically excessive levels of investment in vessel and gear by fishers. In fact, Dewees et al. (2004) estimate that 171,090 traps were deployed in California's crab fishery in December 2000, nearly six times the 29,115 traps that on average where deployed from 1971-72 through 1975-76 (Didier 2002). Dewees et al. (2004) find that crab fishers are divided on the merits of alternative management systems that might attenuate derby conditions and improve economic conditions in the fishery. Dungeness crab processing serves as an important source of employment in rural Northern California fishing communities (Hackett et al. 2003; 2004).

Hackett et al. (2003) analyzed the economic status of California's Dungeness crab processing industry, with an emphasis on the types of seafood products made from Dungeness crab and the value added by processors. Their results show that value added by processors in the 1999-2000 season was between $8.3 and $8.4 million, which represented between 47.5 and 50% of the value added by crab fishers (as measured by ex-vessel revenue). Between 485 and 552 people were estimated to be employed during times of peak crab processing activity in 2000-2001, with 88 to 142 employed during off-peak periods.

2.1.2.3 Recreational Fishing

Steinback et al. (2004) estimate that recreational fishing expenditures in California in 2000 supported over 22,000 jobs and produced $1.63 billion in total economic impact. These impacts are generated by expenditures on food, lodging, equipment, and trip-related expenditures. Of this total, Steinback et al. (2004) estimate that $510 million in economic impact and nearly 7,000 jobs were generated in Northern California. According to Star et al. (2002), anglers spent an estimated $176.5 million in Central and Northern California in 1998 and 1999.

Until recent declines, salmon has been one of the most important recreational fisheries in Northern California. CDFG estimated that the 2008 closure of the recreational salmon fishery resulted in $187 million in negative economic impact to the state economy, along with a loss of 1,566 jobs (Tillman 2008).

2.1.2.4 Coastal and Marine Recreation and Tourism

Coastal marine amenity values generate recreation, tourism, and wildlife viewing activity that provides thousands of jobs and billions of dollars in income to coastal communities. For the most part these data are only available at a statewide or limited regional level of resolution. Hanemann et al. (2002) estimated that average expenditures per person on beach related items and services in 2000 were $23.19 per trip for beach visitors. King (1999) updated an earlier analysis by King and Potepan (1997) and estimated that in 1998 California residents spent approximately $8.63 billion on beach visits, while out-of-state tourists were estimated to have spent nearly $3.5 billion. Major direct expenditure categories were gas and auto-related purchases, beach-related lodging, grocery purchases, and restaurant meals. King (1999) estimated that the total economic impact of these direct beach visitation expenditures totaled $63.4 billion in 1998, and generated nearly 900,000 jobs. More recently, Kildow and Colgan (2005) estimate the non-market consumer surplus value of beach visits in California to be approximately $2.25 billion dollars annually, while their estimate for the market value of beach visits is $3.75 billion.[30]

Leeworthy and Wiley (2001) estimated that 1.38 million recreational dives occurred in California in 2000. Using the dive activity estimates of Leeworthy and Wiley (2001), and an estimated range in diver-day expenditures of $100 to $200, Pendleton and Rooke (2006) estimate that total annual expenditures from SCUBA diving in California ranged from $138 to $276 million in 2000. Leeworthy and Wiley (2001) also estimate that there were 3.82 million snorkeling days in California in 2000. Using a range in snorkeler-day expenditures associated with snorkeling of $40 to $90, and the estimates of Leeworthy and Wiley (2001), Pendleton and Rooke (2006) estimate that total annual snorkeling expenditures in California ranged from $153 to $344 million in 2000. Applying the forecast methodology in Leeworthy et al. (2005), Pendleton and Rooke (2006) predict that by 2010 annual SCUBA diving expenditures in California could increase to $161 to $323 million, while annual snorkeling expenditures in California could increase to $170 to $382 million. Building on the work of Leeworthy and Wiley (2001), Pendleton and Rooke (2006) estimate annual non-market consumer surplus values in California in 2000 ranged from $20.7 to $69 million for SCUBA diving, and $19.1 to $114.6 million for snorkeling. These values are predicted to increase modestly through 2010.

Pendleton (2006) reports that as of 1999, more than 100 million participant days were spent on coastal bird watching and other wildlife viewing in California. Pendleton (2006) estimates that whale watching in California generates approximately $20 million in gross revenues annually, and net revenues of between $4 million and $9 million. Monterey, San Francisco, and several locations in Southern California offer boat-based whale watching tours, and Leeworthy and Wiley (2003) estimate that total expenditures per whale watcher per trip exceeded $195.

2.1.2.5 Port and Harbor Economic Impacts

Kildow and Colgan (2005) report that the economic impact of deep sea freight in the North Central region of California (centered on the San Francisco Bay area) in 2000 contributed over $650 million in gross state product, and generated over 5,000 jobs. Likewise they report that

30 In analyzing travel expenditures, employment, and revenues for the California coast north of Point Conception, Ehler et al (2003) report total destination spending estimates (which exclude air and travel arrangements) of nearly $16 billion in 2000, of which nearly 75% occurred in San Francisco, San Mateo, Monterey, and Alameda Counties. These counties were estimated to account for $1.95 billion of the $2.65 billion in recreation-related travel expenditures, and $5.3 billion of the $6.6 billion in total earnings generated by travel spending.

marine transportation services in this region contributed more than $860 million to gross state product and generated more than 10,000 jobs.[31]

Port of Oakland: According to Martin Associates (2006), nearly 450,000 jobs in the state of California are related, in some way, to the movement of cargo through the Port of Oakland's marine terminals. This cargo supported about $56.3 billion of economic activity, including $12.3 billion of personal income and consumption expenditures, and $1.3 billion of state and local tax revenue.[32]

Port of San Francisco: According to Moyer et al. (2005), activities at the Port of San Francisco generate 29,531 jobs, produce annual revenues totaling $1.6 billion, and contribute $120 million in local and state taxes annually. Port officials claim that each of the 60 to 80 cruise ship visits per year generates between $750,000 and $1 million for San Francisco businesses.

Monterey Bay Area Ports: Pomeroy et al. (2002) note that the permanent employment at wetfish processing businesses in the Monterey Bay area ranges from 6 to 80 full time employees, with up to an additional 80 to 500 people employed by these firms during the height of the season, primarily at their packing plants. Hackett (2002) estimated real value added by wetfish processors (many of whom also perform their own distribution and export functions) in 2000 (updated here to constant 2000 dollars) ranged between $42.8 and $102.9 million, with the median estimate being $71.3 million. Pomeroy and Dalton (2005) estimated that in 2003 (using constant 2000 dollars) the value added to fish landed at Monterey Bay ports (Santa Cruz, Moss Landings, and Monterey) by vendors reached $24 million, and value-added by processors exceeded $35 million.[33]

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31 Looking beyond individual ports and harbors, Rust and Potepan (1997) estimated the economic impact of the boating industry on the economy of California. Boating refers to both recreational and commercial uses of "small" vessels, omitting passenger ferries, crew boats, fire boats, and tug and barge operators that operate heavy, deep-draft vessels or support the ocean shipping industry. Rust and Potepan estimated that the boating industry contributed $11 billion to the California economy in 1995 (about 1.2% of gross state product), and stimulated demand for 183,000 jobs. Nearly two-thirds of this economic impact was generated by the boating industry itself, while the remainder derived by commercial and recreational boater spending on other goods and services, such as food, lodging, and fuel.

32 Martin Associates also estimate that cargo activity at the Port of Oakland generated 28,522 direct, induced and indirect jobs, $2.0 billion of total personal income and consumption expenditures, and $1.8 billion in direct operating revenue for businesses providing maritime services for cargo and vessels at the port. The firms involved in providing transportation and cargo handling services at the Port made $418 million in local purchases of goods and services in support of their port operations, and there were $208 million of state and local taxes generated through the business activity at the port.

33 For the twelve species in their study, Pomeroy and Dalton (2005) estimate over $60 million in ex-vendor revenues for the same year. For sardine alone the value-added was nearly $9 million, while for squid the value-added was $30 million. Regional commercial fish landings and related fishing activity have become increasingly concentrated at Moss Landing, and Pomeroy and Dalton (2003) estimate that the total direct annual economic value of the fishing industry at Moss Landing harbor ranges from $18 to

Other Ports and Harbors: A variety of North Central and North Coast ports and harbors generate economic impact by way of landing, receiving, and processing fish, providing services to commercial and recreational fishers and pleasure boaters, and servicing vessels. Other activities generating economic impact include servicing minor volumes of cargo (e.g., Port of Humboldt Bay), hosting Coast Guard stations, tourism visitation, and marine research. Little in the way of published information is currently available on the economic impact of these facilities.[34]

2.1.3 Ongoing Research on Marine Uses and Values

Most of the ongoing research on marine uses in California north of Point Conception is focused on commercial and recreational fisheries in the context of the Marine Life Protection Act (MLPA) process. As described earlier in the chapter, Dr. Astrid Scholz and colleagues at Ecotrust have developed a methodology for mapping valuable commercial fishing grounds that may be adaptable for assessing the impacts of WEC facilities. Ecotrust is engaged in several additional studies that utilize the same underlying research methodology. In one of these, Ecotrust is extending their research on commercial fishing use patterns to the North Central Coast study region. Composite datasets will be created for the fishing grounds of each fishery. In another ongoing study, Ecotrust is also identifying valuable recreational fishing use patterns in the North Central Coast study region. This research is focusing on CPFV's, private boat recreational anglers, kayak-based anglers, and pier and shore anglers. Fishers will be asked to identify all fishing areas that are of value over their cumulative fishing experience, and to rank these using a weighted percentage.

Research currently being carried out by Professor Steven Hackett and associates at Humboldt State University and the University of Maryland may prove to be useful in understanding the economic impact of reduced commercial fishing opportunities due to the development of wave farms in the marine environment. Hackett was contracted by CDFG to survey participants in each of California's marine fisheries to gather information on fishing and vessel-related costs, as well as other information on fishing activity. Professor Dennis King at the University of Maryland is working with Hackett, and will use the survey data to develop customized IMPLAN models capable of estimating the economic impact of events such as the development of wave farms that reduce commercial fishing activities in California.[35]

The development of wave farms in California may have adverse social and economic impacts on coastal communities that have traditionally been supported by commercial fishing. In order

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$25 million.

34 Some data components necessary for initiating an economic impact assessment of smaller harbors and ports are readily available, though a detailed analysis is beyond the scope of this chapter.

35 Resource managers and stakeholders have depended upon outdated economic impact information, including multipliers, from King and Flagg (1984), and at this time there are no IMPLAN economic impact models available that take into account the unique input-output relationships in the state's diverse commercial fisheries.

to understand these impacts, it is important to have comprehensive baseline socioeconomic information at the community level. Dr. Caroline Pomeroy (California Sea Grant Marine Advisor) and Cindy Thomson (Fisheries Economist, Southwest Fisheries Science Center, NOAA Fisheries Service) are currently engaged in a socioeconomic baseline study for the North Coast fishery ecosystem. The purpose of their study is to describe North Coast (Fort Bragg through Crescent City) fishing communities (people, activities, and infrastructure) and understand how they are affected by regulatory, economic, environmental, and other factors. In addition, Pomeroy and Thomson are creating an inventory of fishery-dependent businesses and harbor amenities at Central and Northern California (Avila to Crescent City) fishing ports. Within this same geographic region, Pomeroy and colleagues are also developing baseline socioeconomic information that can be used for ecosystem-based fishery management.

Research being conducted by Professor Linwood Pendleton at UCLA may be applicable to tracking the impacts of wave farms on a broad set of marine uses, including recreation. Pendleton and colleagues are modeling indicators of use over time (e.g., commercial fishing, CPFV, beach attendance, park attendance, harbor revenues, dredging, and so forth) as a function of environmental indicators, economic data, demographic information, as well as data on regulations, restoration, and other related areas. Pendleton is also working with Christopher LaFranchi on an internet survey of private coastal uses from Santa Cruz to the San Diego/Orange County line. This survey will cover all types of private coastal uses, as well as charter and party boat trips, and these data can be used to estimate expenditure profiles and the net economic benefits associated with beach visitation. Note that CDFG's California Recreational Fisheries Survey is also surveying recreational fisheries on an ongoing basis.[36]

WEC facilities may impact culturally significant sites, values, and traditional marine uses, and several ongoing studies are engaged in marine cultural research in California. The National Marine Protected Areas Center West Coast Pilot Marine Cultural Resources Project is developing, testing and applying analytical tools, and gathering scientific and ecological data for adaptive management of marine environments. The pilot project is developing an understanding of: human use patterns in a regional, ecosystem context; ecologically important areas; important submerged cultural resources; and improved governance structures for west coast marine protected areas. An inventory of marine cultural resources, in a GIS-compatible format, is being developed that will help researchers assess the cultural and historical connectivity of sites. Researchers can also integrate data layers to identify regionally based, priority ecological and submerged cultural resource areas in need of new or enhanced protection and management (Smith and Hunter 2003).[37] In Humboldt County, Planwest

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36 This program incorporates and updates the comprehensive sampling methodologies of the former Marine Recreational Fisheries Statistics Survey and the California Department of Fish and Game's Ocean Salmon Project.

37 Ongoing research by the Monterey Bay National Marine Sanctuary on shipwrecks also continues, involving exhaustive exploration of registry papers, line drawings, port entry and exit records, cargo manifests, captain's logs, passenger journals, photographs, charts, and mementos.

Partners and Humboldt State University's Center for Indian Community Development has contracted with NOAA Fisheries to produce a historic and cultural characterization of Humboldt Bay. The historic and cultural characterization of Humboldt Bay will document historic sites, traditional cultural practices and current cultural practices related to the bay.

Knowledge Gaps

The North Central and North Coast regions hold some of the highest wave power densities in California, and a number of potential wave farm developers were granted three-year preliminary permits to study WEC in this region (Nelson and Woo Chapter 1). These permit areas occupy many square miles of ocean area, including productive fishing grounds and high-traffic areas in the coastal waters off the entrance to Humboldt Bay, Noyo Harbor, and Bodega Bay.[38] As the Federal Energy Regulatory Commission (2008) notes, those holding preliminary permits have the first priority in applying for a license for the project that is being studied. If permit holders file a development application, then a notice of the application is published, and interested persons and agencies are given an opportunity to intervene and to present their views concerning a project and the effects of its construction and operation.

Currently there are significant gaps in the higher-resolution information necessary to assess the impact of specific WEC development projects. With the exception of commercial and recreational fishing, relatively little baseline information is available for the North Central and North Coast regions of California on the economic and other values associated with marine uses, beach recreation, wildlife viewing, tourism, and non-use values (e.g., culturally significant areas, existence values). Moreover, somewhat higher resolution spatial data (e.g., commercial fishing/vegetation harvest logbooks) that link economic, social, and cultural values to specific locations in the coastal marine environment are incomplete or non-existent. Thus there is no information currently available to gauge the extent to which the spatial displacement of commercial and recreational fishing, marine vegetable harvest, pleasure boating, shipping, tourism, beach recreation, wildlife viewing, and other coastal and marine uses will generate adverse socio-economic impacts on communities in California's North Coast region.[39] Yet as Richardson et al. (2006) note in the context of evaluating marine reserve sites, reliance on coarse-resolution economic information from official statistics is ineffectual in preventing displacement of fishers from valuable fishing grounds. This same problem may also plague the design and location of wave farms.

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38 Note that activities centered on Morro Bay in the South Central Coast region may also be impacted by WEC development.

39 Ehler et al. (2003) note that quantitative estimates of the socioeconomic impacts of marine-related recreation such as personal watercraft usage, snorkeling, pleasure boating, kayaking, wildlife watching, and beach visitation in California north of Point Conception are scarce, and that sport fishing has more data collected on it than other marine recreational activity.

While many effects from wave farm development will not be realized until an actual physical alteration to the environment occurs, this is not true of the human environment (CGER 1992). People and social systems respond – sometimes drastically – to announcements of possible future development projects, well in advance of any actual physical or biological alterations to the environment. It is not known how well the public is informed about potential wave farm development in California, what factors have helped shape the views they do have, and what conclusions they have drawn.

WEC may also impact non-use values linked to sites with cultural significance, existence value, and visual amenities, but no comprehensive baseline cultural inventory or non-market valuation data relating to the coastal and marine environment exists in Northern California. Information about cultural resources along the coastal environment tends to be more limited, fragmentary, and anecdotal than for terrestrial cultural resources (Rohde 2008).

Finally, the development of wave farms will generate positive local and regional economic and social impacts, but no such impact information currently exists for the North Coast region of California, which is currently a high-priority area for wave farm development.[40]

Priority Research Needs

A list of priority research needs is given below. While they are not necessarily in rank order, a thorough assessment of wave farm proposals will clearly require spatial information that is not currently available at a sufficient level of resolution.

1. Relatively high-resolution spatial data and analysis of use and non-use values generated by specific locations in the coastal marine environment, including high traffic areas near harbors and ports.[41] Use values should include economic and other measures of commercial and recreational fishing, marine vegetable harvest, pleasure boating, shipping, tourism, wildlife viewing, and beach recreation, among others. Non-use values should include estimates for areas possessing cultural significance, existence value, and visual amenities. These data should be compiled into a GIS map framework in a manner similar to Scholz et al. (2004; 2005; 2006; 2008).[42]

40 For a discussion of the costs and benefits of electricity generation using alternative energy resources on the outer continental shelf, see Weiss et al (2007).

41 The California Energy Commission (2008) also recommends that a GIS survey be conducted as part of a comprehensive assessment, in order to help policymakers screen out areas where development is not feasible, for example, for environmental reasons or usage conflicts. Note that some efforts appear to be underway in this regard. The National Marine Fisheries Service Southwest Region, in cooperation with the NOAA Coastal Services Center, is reported to be creating a web-based marine spatial planning tool to assist with hydrokinetic project tracking, identification of hydrokinetic project impacts, and siting issues (Pacific Fishery Management Council 2008).

42 Methods used by Dalton and Ralston (2006) may also be useful in modeling the linkage between

One significant barrier to estimating higher-resolution economic information for particular marine areas is the lack of existing spatial data. In some important commercial fisheries potentially displaced by wave farms, such as Dungeness crab and nearshore rockfish, fishers are not required to maintain logbooks that indicate the spatial location of their catch.[43] Commercial landing receipts also provide spatial data, but these records are usually completed by receiver/processors rather than the fishers themselves. Moreover, while CPFV operators must keep logbooks, there is only limited spatial data from the California Recreational Fisheries Survey to document use by recreational fishers, and none for pleasure boaters.[44] In this way, specific sites being considered for wave farms could be evaluated for the various use and non-use values that would be lost upon development.

Note that the MLPA process is moving northward in California, and the North Coast region will soon undergo the same intense research focus that has occurred in the Central Coast region. Assessment of the spatial impacts of MPA's (and other restricted areas) should be coordinated with that of WEC facilities so that cumulative impacts of these spatial displacements on commercial and recreational fisheries (along with other factors that affect use patterns) are taken into account. Table 2.2 lists the types of information that research should address.

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reductions in fishing grounds and changes in total fishing effort.

[43] There also appears to be limited/incomplete logbook data for the sablefish and hagfish trap fisheries. Marine vegetation harvesters keep logbooks, and CDFG is in the process of creating a database for these logs. Personal communication, Peter Kalvass, Rebecca Flores Miller, and Terry Tillman, California Department of Fish and Game, 01 and 03 April 2007.

[44] Interview methods in which fishers are asked to rate the relative importance of particular fishing grounds can be distorted by incentives to strategically misrepresent and/or to keep especially productive locations secret.

Table 2.2. Specific Spatial Information Needs

Research Should Address The Extent to Which Specific Locations in the Coastal Marine Environment
Are high-traffic areas (shipping lanes, areas near harbors and ports)
Are known to be productive areas for catching fish or harvesting marine vegetation (including temporal variation)
Support a number of different directed fisheries
Generate significant commercial landings revenue (including temporal variation)
Already restrict or exclude one or more marine uses
Play an important role in beach recreation
Are known to be safe locations to fish or recreate
Are utilized as safe or low-cost transit routes
Prevent crowding or gear entanglement at other locations
Provide emergency access routes to safe harbors
Are essential for sustaining commercial or recreational fishing activity and the local communities that depend upon them (perhaps due to other prior area closures)
Have significant nonuse value (e.g., unimpeded seascape, biodiversity, cultural significance)
May pose a hazard to navigation if wave energy conversion facilities were developed

Source: Hackett

2. Identification of the minimum scale of commercial and recreational fishing and other activities necessary to sustain small harbor facilities and local fishing industry complexes (e.g., processors, ice/bait/fuel suppliers, boatyards, chandlers), and (to the extent possible) the specific fishing grounds necessary to support this minimum scale of sustainable commercial fishing.

3. Identification of the scope of economic impacts that can generally be expected from the development of various scales of wave farms. This scoping process would identify data needs and requirements, and thus help guide specific environmental impact assessment on various proposed wave farm projects.

4. Identification of the scope of the social impacts of wave farm development and a process for enhancing local input into siting, scale, and possible mitigations, building on principles and guidelines established by the IGCP (1994). This scoping process would identify data needs and requirements, and thus help guide specific environmental impact assessment on various proposed wave farm projects. Cultural resource mapping methods developed by the West Coast Pilot Marine Cultural Resources Project are also likely to applicable here.

In terms of developing a process for enhancing local input, currently local jurisdictions, residents, and coastal marine stakeholders have little influence on the location of FERC wave energy permit areas. The Sonoma County Water Agency and the Tillamook Intergovernmental Development Entity, have each attempted to inject local control into this process by applying for preliminary FERC permits. Thus in addition to creating a process for assessing social impacts, an institutional analysis that addresses the potential benefits, costs, and barriers to local agencies and jurisdictions acquiring WEC facility permits and licenses should be undertaken.

5. An understanding of how members of the public view wave farm development in California, and the factors that have helped shape those views. This understanding could then be used to develop a balanced information campaign to better inform Californians about the relevant tradeoffs, and ultimately to help guide the decisions of regulators and policy makers.

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3.0 The Potential Impact of WEC Development on Nearshore and Shoreline Environments through a Reduction in Nearshore Wave Energy

John Largier, Dane Behrens, Matt Robart
Bodega Marine Laboratory, University of California Davis

Abstract

Nearshore wave energy and nearshore wave-driven processes will change inshore of WEC devices. Waves influence or control many aspects of the nearshore environment, including circulation, impact forces on plants and animals, erosion of shoreline sand and rock, fluxes of sediment and particulate organic matter, fluxes of pollutants and nutrients, turbulence and organism-scale fluxes, water aeration, turbidity and light availability, sealevel setup and flooding, intertidal splash, and more. In this preliminary review it is not possible to fully evaluate impacts, but rather the focus is on identifying any phenomena that may change significantly with WEC.

The distribution of wave energy in northern California averages about 30 kW/m and peaks to over 1 MW/m during storms. Wave energy is much less in southern California. WEC devices are expected to extract 3-15% of the incident energy, resulting in a wave shadow in the lee of the device, or array of devices. However, wave diffraction will allow wave energy to fill in behind the device, resulting in a triangular shaped wave shadow with a cross-shore extent that depends on wavelength and alongshore device length and an orientation that depends on the incident angle of the waves. While diffraction mitigates the intensity of the wave shadow effect, it results in a broader swath of wave reduction (the same total energy loss is spread over a greater alongshore distance). Where this swath of reduced wave energy contacts the coast depends on the angle of the incident waves.

The consequences of reduced wave energy on nearshore physical processes are reviewed, including a discussion of wave shoaling, cross-shore sediment transport and beach building, longshore sediment transport, and turbulence and mixing in the nearshore. Then, in turn, the consequences of these expected changes are considered for nearshore geomorphology, ecology, pollution and human activities. The aim of this review is to identify the specific ways that waves shape the nearshore environment and to identify how these specific processes and effects may change with development of offshore WEC. More in-depth study, including fieldwork and modeling, is required to obtain an authoritative opinion on the likelihood and severity of possible adverse impacts.

It is recommended that pre-implementation models of wave sheltering and diffraction be completed, followed by observations of changing wave conditions on implementation. Secondly, it is recommended that specific case studies be developed near sites of special interest (e.g., critical coastal area, estuary mouth, runoff zone of impact). Thirdly, it is recommended that the climatology of wave conditions is reviewed for marginal or critical sites with a view to identifying locations where the loss of nearshore wave energy has little effect.

Introduction

"The goal of the white paper is to discuss the state of knowledge regarding potential environmental issues associated with wave energy technologies in California that need to be taken into consideration during development of this industry." This chapter is concerned with how nearshore wave energy and nearshore wave-driven processes will change inshore of WEC devices, or arrays of devices.

Waves are a primary determinant of nearshore environments, influencing or controlling the circulation (e.g., longshore currents, rip currents, undertow), the impact forces on plants and animals, the erosion of shoreline sand and rock, the fluxes of sediment and particulate organic matter, the fluxes of pollutants and nutrients, the turbulence and organism-scale fluxes, the water aeration, the turbidity and light availability, the sealevel setup and flooding, and the intertidal splash. Specific ways that waves shape the nearshore environment are identified in this chapter, and discussion addresses how these processes and effects may change owing to reduced wave energy inshore of WEC devices. In other chapters the consequences of this nearshore environmental change will be addressed in terms of nearshore ecological communities (Lohse et al. Chapter 4), nearshore birds (Thompson et al. Chapter 6) and nearshore fishes (Nelson Chapter 5).

It should be noted that there are two sets of nearshore environmental impacts associated with WEC development: (i) direct impacts due to construction at or near the shoreline, either for cables or for installation of wave-overtopping devices; and (ii) indirect impacts due to reduction in wave energy reaching the shore and nearshore waters. This chapter addresses only the latter suite of issues, which are novel aspects of WEC development. Although the former set of issues is likely to have much greater localized impact at specific nearshore sites, there is significant prior experience with construction impacts and their assessment is best addressed by consulting engineers with experience in making assessment of the environmental impacts associated with installing cables and constructing breakwater structures.

The approach is to identify any phenomena that may be changed significantly by the development of WEC, without implying that there will be a significant impact. The biggest concern is with effects that amplify small changes in wave height, such as changes in the number of extreme events, or with cumulative effects (including, for example, possible interactions between WEC effects and climate change). It is not possible to reliably determine the likelihood or extent of impacts in this overview and many of these possible effects may prove to be occasional, negligible or non-existent. More in-depth study, including fieldwork and modeling, is required to obtain an authoritative opinion on the likelihood and severity of possible adverse impacts (see Section III on Priority Research Needs).

The geographic interest is from Pt Conception to the Oregon border, those parts of the California coast along which wave energy is greatest (see Section IIA, below). However, there is an emphasis on regions where WEC sites have been proposed north of San Francisco (e.g., Sonoma coast, near Fort Bragg, near Eureka, and near Trinidad).

Current Knowledge and Knowledge Gaps

3.1.1 Spatial and Temporal Patterns in Nearshore Waves

The amount of wave energy that arrives at the coast varies substantially among the regions of the world. The power of ocean waves is often expressed in kilowatts per meter wave crest (kW/m). Average values for this parameter range from 10 kW/m to 100 kW/m. Advances in wave measurement technology over the last half-century have facilitated large monitoring efforts along the world's coastlines, and have provided a wealth of information on the distribution of wave energy. The National Data Buoy Center (NDBC, http://www.ndbc.noaa.gov) of the National Oceanic and Atmospheric Administration and the Coastal Data Information Program (CDIP, http://cdip.ucsd.edu) of Scripps Institution of Oceanography provide the two largest inventories of long-term measured wave data for California. CDIP also provides model output for wave conditions nearshore (e.g., Figure 3.1), based on observations of incident swell on the outer shelf. Both programs provide databases accessible to the public.

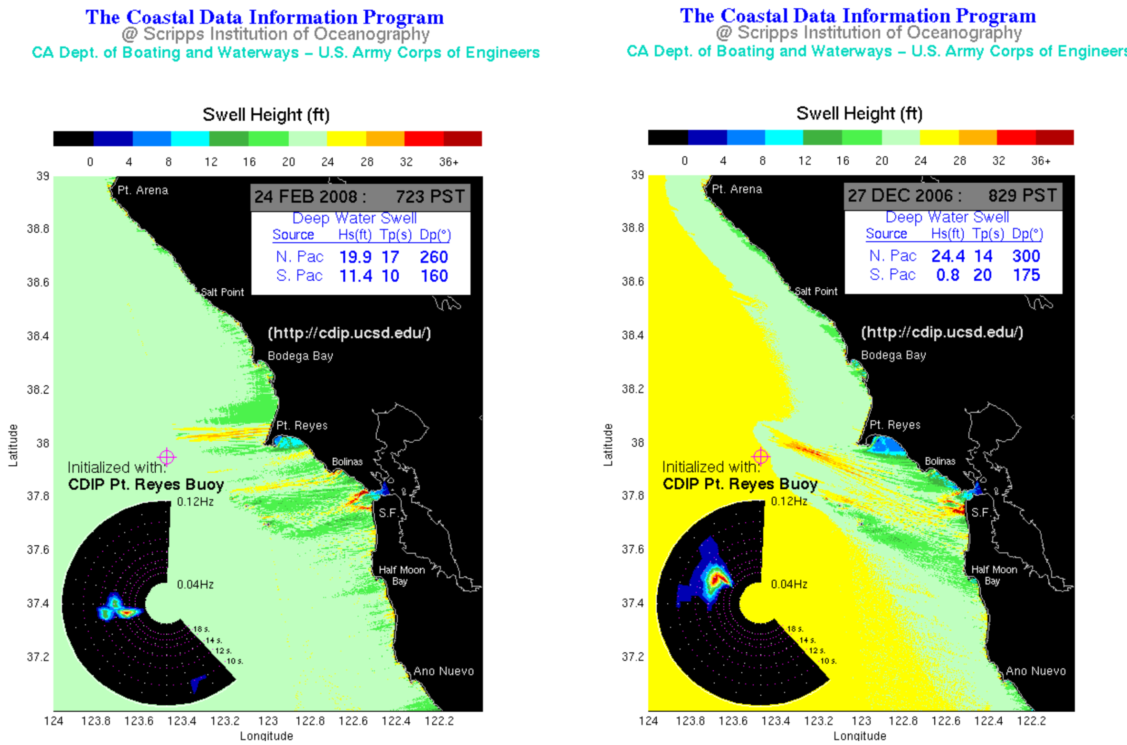

Figure 3.1. Model output for swell wave height over the shelf and along the shoreline of San Francisco and the north coast.

This demonstrates the importance of refraction and diffraction in creating nearshore locations subject to large waves, and others where waves are much weaker. Model input is the measured wave field at the CDIP Pt Reyes Buoy on the outer continental shelf. For more information and real-time output see http://cdip.ucsd.edu
Source: Largier et. al.

The distribution of wave energy in northern California averages about 30 kW/m and peaks to over 1000 kW/m during storms. A sharp decline in the wave energy along the coastline south of Point Conception results from the sudden change in orientation of the coastline, which shields southern California from the waves generated by storms in the northern Pacific Ocean (PIER, 2007). Table 3.1 shows NDBC measurements of the average wave energy flux for various locations along the California coast, from Point Conception to the Oregon border. If the wave energy over the 800 km between Point Conception and Oregon was completely captured, this average 30 kW/m would yield 24,000 MW, about two-thirds of California's 37,000 MW of energy demand; in reality, WEC is likely to harness only a fraction of this energy even if WEC is completely developed along the whole coast. Presevic & Bedard (2007) expect that no more than 20 percent of California's energy demand could be harvested by WEC.

Table 3.1. Average wave energy flux (wave power) from NDBC buoy measurements at Californian locations north of Point Conception

Note that these buoys are offshore, typically in depths of greater than 100m and out of wave shadow zones found nearer to the shore (e.g., northern Gulf of Farallones). Table modified from PIER (2007).

NDBC buoy	Latitude	Location	Wave Energy Flux (kW/m)
46011	34.88	Santa Maria	26
46028	35.74	Cape San Martin	30
46042	36.75	Monterey	30
46013	38.23	Bodega Bay	30
46014	39.22	Point Arena	32
46030	40.42	Blunts Reef	29
46022	40.72	Eel River	34
46027	41.85	St. Georges	27

Source: Largier et. al.

Wave height changes from day to day, and so too does wave energy density E and wave energy flux F, which is the same as power (the rate of shoreward delivery of energy): $E = \rho g H^2 / 8$ and $F = Ec_g$ where H is wave height in meters, g is gravity (9.8m/s^2), ρ is water density (kg/m^3), and c_g is the wave group speed (m/s). E is in units of J/m^2 and F is in units of W/m (although typically expressed as kW/km in WEC literature). In deep water $c_g = gT/4\pi$ and $F = \rho g^2 H^2 T / 32\pi \sim 979 H^2 T$ (for seawater density of 1025kg/m^3), and in shallow water $c_g = \sqrt{gh}$ where h is the water depth, so that $F = \rho g^{3/2} H^2 h^{1/2}$.

The largest waves are observed during winter, following intense high-latitude storms. Figure 3.2 shows data from the CDIP Point Reyes Buoy, both significant wave height H_s and associated wave power (or energy flux), which varies from less than 10 to more than 100 kW/m. Significant wave height is a long-standing convention derived from visual estimates of wave height and it is the average height of the highest one-third of all the waves occurring in a particular time period.

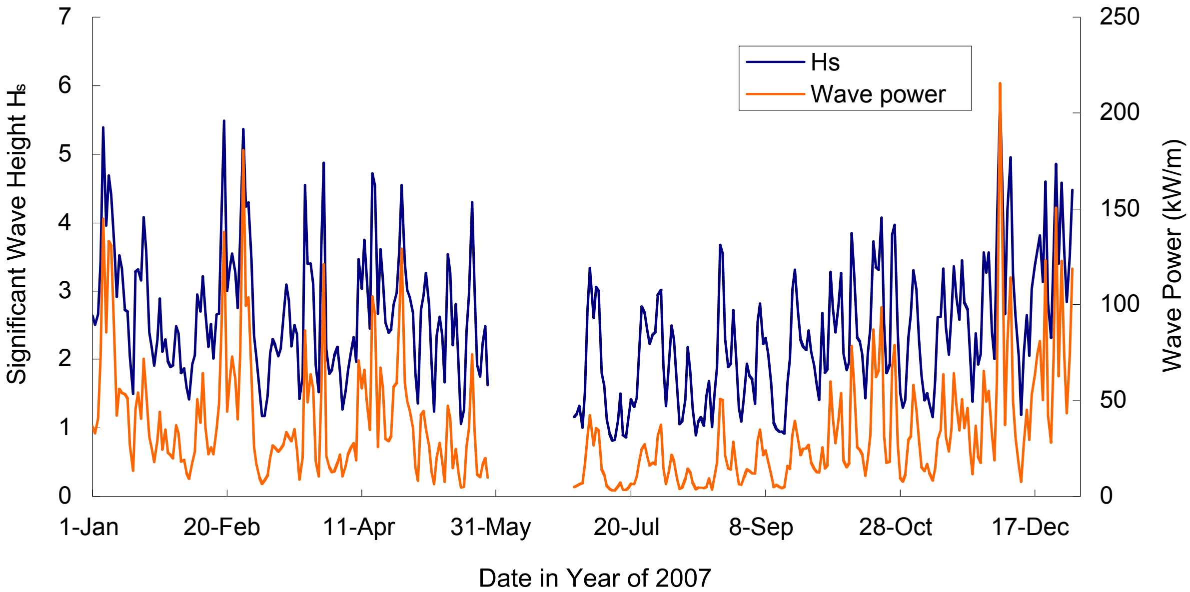

Figure 3.2. Daily average significant wave height Hs (m, blue line) and wave power (kW/m, orange line) observed at CDIP Pt Reyes Buoy in 2007

Note: Data missing for June
Source: Largier et. al.

Typically waves observed off Point Reyes have a significant wave height of about 2m, with waves bigger than 4m (and power greater than 100 kW/m) being uncommon and waves bigger than 6m being very rare. The distributions of wave heights for the years 2004-2007 are plotted in Figure 3.3 [for another example of wave height variability, see Figure 2, Nelson and Woo Chapter 2].

The full wave field (or wave spectrum) is comprised of both "swell," longer period waves generated long distances away (e.g., Gulf of Alaska) and "sea," shorter period waves generated by winds blowing nearby. Although one typically finds more energy in the swell, the strong winds off northern California blowing over long fetches are capable of generating energetic local sea that contains significant energy. These waves are not adequately represented by the outer-shelf data from the CDIP and NDBC buoys, but they are important nearshore and also may provide significant energy for WEC devices, depending on the design of the WEC devices. However, this may also be nuisance energy in that it is not effectively extracted by WEC designed to extract the more reliable long-period, long-wavelength swell incident on the northern California shelf.

In the deep waters far offshore, waves are considered deep-water waves as they don't interact with the sea bed and propagate at a speed proportional to the wave period

$c = gT/2\pi$. This is typically in depths greater than $L/2$ where L is the wavelength and given by $gT^2/2\pi$ (i.e., the longest period swell interacts with the bottom over the whole shelf, with depths of up to 200m). Grant et al (1984) found significant wave-driven bottom boundary layer effects in 90m depth off northern California. Inshore of depths of L/20, waves are treated as shallow-water waves, with propagation speed c being a function of water depth $c = \sqrt{gh}$ so that refraction of long-period swell may occur in water depths of 50m or more (refraction refers to the bending of waves as part of the crest slows down over a shallow region while other parts continue without slowing). Given that waves naturally dissipate their energy fastest through bottom drag, loss of wave energy occurs mostly inshore of the 50m isobath.

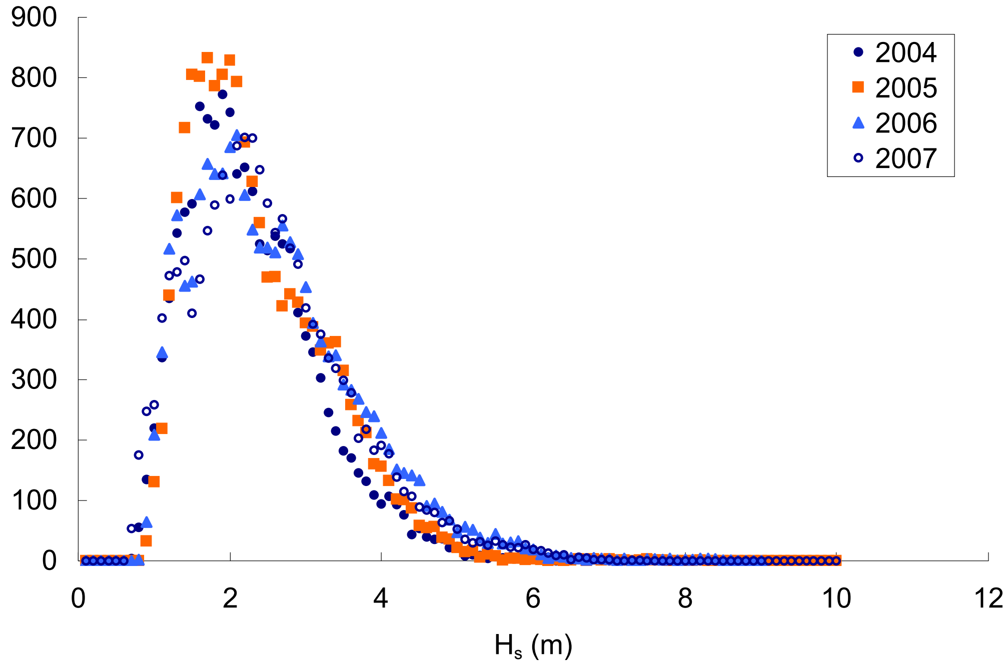

Figure 3.3. The distribution of significant wave height Hs for the years 2004 to 2007 at the CDIP Pt Reyes Buoy.

Wave heights between 1m and 4m are most common, corresponding to power of about 100 kW/m or less. The power of the largest waves may be several times 100 kW/m.
Source: Largier et. al.

3.1.2 Change in Nearshore Waves Due to Offshore WEC

Devices that harvest electrical power from waves extract potential or kinetic energy from waves as they pass. The amount of energy that devices extract from waves varies significantly. The Electric Power Research Institute (EPRI) has evaluated many devices to determine which models are most suitable for pilot studies and eventual commercial use (Bedard et al., 2005). EPRI identified a set of eight preferred devices, of which the Pelamis, built by Ocean Power Delivery, is the highest rated device. This tubular device has a diameter of 3.5 meters, a length of 150 meters in the direction of wave propagation, and a production capacity of 750 kW. It is designed for deployment in depths greater than 50 meters (Bedard et al., 2005). There are four distinct categories of WEC devices, with differences in form and principle of operation (PIER, 2007). See Table 3.2 below.

Table 3.2. Summary of types of WEC device (adapted from PIER 2007)

Device type	Principle of operation	Example device
Point absorbers	Isolated floating structure; absorbs wave energy regardless of direction as the device changes elevation	Aqua Energy
Attenuators	Elongate floating structure oriented parallel to wave direction; flex at segments drives a hydraulic pump	Pelamis (previously known as Ocean Power Delivery)
Overtopping devices	Floating structure facing waves; waves focused into a basin creating a head of water; head converted to energy by turbine	WaveDragon
Oscillating water column	Structure fixed to ocean floor or shoreline; Waves push enclosed column of water, displacing air through a turbine	Oceanlinx (previously Energetech)

Source: Largier et. al.

The amount of energy harvested by WEC devices and the number of devices determines the scale of energy production. A limited number of pilot studies conducted by device manufacturers have helped to provide initial estimates of power production capacities. However, the amount of power provided by a given device varies from this capacity as the incident wave power varies (e.g., differences between sites, Table 3.1, or between seasons, Figure 3.2). Available information on energy removal by WEC devices is limited and can be expected to be both device-specific and site-specific. Further, it can be expected that the performance of each device is a function of wave height and period (and perhaps complicated further by the presence of waves of diverse periods and directions). This information does not appear to be available, but it will be needed to make proper assessment of WEC implementation at specific sites with specific technology.

Information on the energy capture of four devices is presented in Table 3.3. This is converted to a percentage energy removal by assuming incident wave energy flux to be 21 kW/m, based on the conditions at the proposed commercial site near San Francisco (Presevic & Bedard, 2007), and because the expected power produced by each device is based on performance evaluations for the site of CDIP buoy station 0037 in Oregon, which has a wave energy flux of 21.2 kW/m (Bedard et al., 2005). The power productions are lower than the capacity power rating for each device, which is presumably achieved under more energetic wave conditions. The percent power extracted from waves is calculated as the ratio between power production per meter crest-length and the incident wave energy flux. Along its 150m length, the Pelamis extracts twice as much energy as is available in a 3.5m length of wave crest, clearly energy from a greater crest length is diffracted inward to replenish lower wave energy density alongside the device.

Table 3.3. Energy production during trials for WEC devices deployed off Oregon, with incident energy flux of 21.2 kW/m

Device	Device width (m)	Power out per device (kW)	Power out per length (kW/m)	Proportional power out
Aqua Energy	6	17	2.83	13%
Pelamis	3.5	153	43.7	206%
WaveDragon	260[1]	1369	5.27	25%
Energetech	35	259	7.40	35%

[1] Larger WaveDragon prototypes are proposed for future commercial use, corresponding to higher power productions. This prototype was chosen because its power production was already evaluated for a wave energy density of 21.2 kW/m (EPRI, 2006)

Source: Largier et. al.

In estimating the loss of wave energy incident on nearshore and shoreline, one will have to consider an array of devices and perhaps devices of larger scale. In addition, the efficiency of energy capture is a key factor. Available information is on the power produced (i.e., captured), with little information on the power lost from the wave, in other words, the efficiency of these WEC devices is unclear. It is likely that much more energy is lost from the wave than is captured by the device and associated infrastructure.

Energy extraction by and energy loss from a WEC device (or array of devices) will result in a wave shadow behind the device, where wave heights are reduced. However, with distance away from the device, wave energy on either side of the wave shadow will be diffracted into the shadow zone (Figure 3.4). Diffraction is a process in which energy of waves is transferred along a wave crest, perpendicular to the direction of wave propagation (as in the phenomenon of light diffraction). Thus diffraction acts to fill wave energy into the "shadow" regions behind the obstruction (Komar, 1998), and a pattern of constructive interference may occur. The closest analogy to wave diffraction through a field of WEC devices is diffraction through a shore-parallel breakwater structure with multiple gaps. Researchers have produced analytical solutions (Johnson, 1952; Penney & Price, 1952) and numerical solutions (Filianoti, 2000; McIver, 2005) for wave height distributions shoreward of the structures. These effects can be modeled deterministically by e.g. a coastal refraction-diffraction model such as RefDif (Kirby & Dalrymple, 1983) or a stochastic refraction-diffraction model (Janssen et al. 2008).

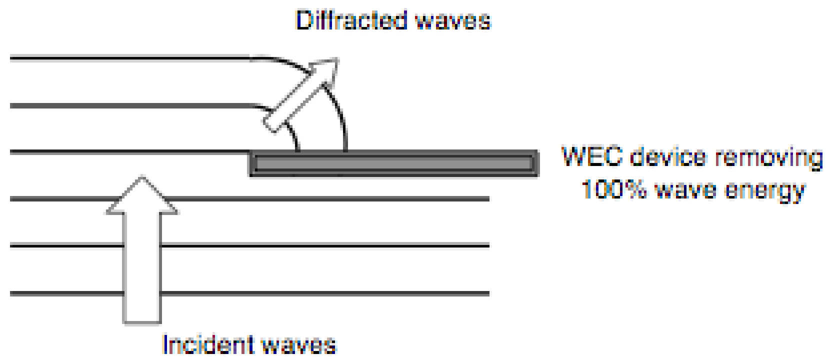

Figure 3.4. Schematic of diffraction of waves into the wave shadow behind a WEC device (or breakwater) that extracts 100% of the incident wave energy.

In reality some portion of the wave energy propagates through the device and the wave shadow is a combination of transmitted and diffracted waves. Note that water depth does not have a first-order role in diffraction (unlike for refraction), although depth does affect the wavelength and thus does have a second-order effect on diffraction.
Source: Largier et. al.

The factors that influence this process are the width of the gap, angle of wave approach, and wavelength. For large gaps, incident waves pass through almost unchanged, while wave heights are significantly decreased for narrow gaps on the order of one or two wavelengths (Penney & Price, 1952). Immediately behind a WEC device that extracts 10% of the wave energy flux, one can expect waves to be 10% less powerful (or wave height to be reduced by 5.1%) while the waves remain at full power away from the device. With distance down-wave from the device the shadow will be filled in until energy is again homogeneous along the crest. If 10%-extraction WEC devices cover 10% of the alongshore length, then one can expect that there is a general 1% loss in wave power at distances beyond the shadow zone (or 0.5% reduction in wave height). The wave period (wavelength) and device width will determine the length of this shadow zone in the direction of wave propagation, and this with the distance from shore will determine whether there is a localized wave energy minimum at the shoreline. If beyond the wave shadow zone, the homogeneous loss of energy at the shoreline will be a function of proportional energy loss at each device and the density (or alongshore spacing) of devices. Bedard et al. (2005) conducted a theoretical investigation of the energy loss due to one 2250m-long by 1110m-wide cluster of Pelamis devices in a commercial-scale plant design for Waimanalo Beach, Oahu, Hawaii. A 2m significant wave height (15.2 kW/m wave energy flux) was reduced to 1.7m down-wave of the plant (energy flux of 11.8 kW/m), corresponding to a 22% reduction in wave energy (and 12% reduction in wave height). With diffraction of wave energy into the wave shadow, Bedard et al. (2005) argue that a total loss of no more than 5-10 percent would be experienced at the shoreline (although this effect would be spread out over the entire 12-km shoreline). A more recent numerical modeling analysis by Halcrow (2006) investigated the potential impacts of two proposed WEC sites near the coast of Cornwall, UK. The first site included four WaveDragons, while the second included one WaveDragon, two

Fred Olsen FO[3], thirty Power Buoy PB150 and six Pelamis devices. Wave height reductions of 3 to 13% were predicted at the shoreline.

3.1.3 Wave-driven Physical Processes

Waves generate a number of processes that are essential to the maintenance and adjustment of shorelines and shoreline/nearshore ecosystems. Wave breaking provides by far the most important energy input in nearshore waters and is responsible for the generation of nearshore currents, high levels of turbulence, and the transport of sediments. These processes control the morphology of the beaches, as well as the sand barriers and spits at the mouths of estuaries and bays (Komar, 1998). Further, waves are a primary determinant of nearshore habitats. In this section, specific nearshore wave-driven processes are identified with a view to identifying how a reduction in available wave energy may impact nearshore and shoreline environments. Texts by Komar (1998) and Dean & Dalrymple (2002) provide a good background on wave processes in coastal waters.

3.1.3.1 Wave Shoaling and Breaking

The transport of wave energy to the coastline has been studied for many years, and also the evolution of waves as they propagate into shallow nearshore waters. The nearshore is of interest because wave properties change as waves interact with the bottom in shallower water. In particular, the propagation speed of waves decreases and becomes a function of water depth, as discussed above, and this provides the basis for a number of fundamental behaviors in the coastal zone. As waves slow down on approaching the shoreline their period does not change, so their wavelength must decrease while energy is conserved, resulting in an increase in wave height and steepness, a process referred to as shoaling. Additionally, the dependence of propagation speed on depth causes wave crests to bend, or refract, towards shallower water. This leads to wave focusing on headlands and bars and wave energy being less in embayments. The height of the waves near to the shore is a function of the deepwater wave height, as well as the degree of refraction and the degree of shoaling that the wave undergoes (Dean & Dalrymple, 2002). This is represented by the relation $H = H_0 K_s K_r$ where H_0 is the deep-water (incident) wave height, $K_s = \sqrt{c_{g0}/c_g}$ is the shoaling coefficient and $K_r = \sqrt{\cos\theta_0/\cos\theta}$ is the refraction coefficient. Given the deepwater wave height H_0, the group velocity c_{g0}, and the wave angle θ_0, the wave height at a shallower depth can be calculated.

As the waves approach the shore, their steepness generally increases up to the point where they become unstable and break. Theoretical studies of waves in constant-depth water showed that a wave breaks when its height exceeds approximately 80 percent of the water depth (Dean & Dalrymple, 2002). If few irregularities exist in the shore profile, waves will collapse in a characteristic "breaker line" at the point where they reach the critical height to depth ratio. After this point, breaking continues until the wave height decreases to a lower threshold characterized by a stable wave height (Dally et al, 1985). As a wave breaks and releases its energy, a number of factors influence the role and effects of this added energy in the coastal zone. For example, the slope of the beach face will determine whether the majority of the wave energy will reflect off the shoreline or dissipate in the beach. Reflection of incident waves can generate standing waves offshore which influence bar growth (Lau & Travis, 1973), and edge waves, which create beach features such as cusps and spits (Guza and Thornton, 1982).

On breaking, waves transfer their momentum to the water (imposing a force known as "radiation stress"), which drives nearshore circulation as well as creating a setup of sealevel on the beach. Alongshore gradients in setup result in alongshore currents and rip currents; in addition, gradients in radiation stress are important factors in driving nearshore circulation.

3.1.3.2 Forces Exerted by Breaking Waves

Organisms and other objects in the surfzone (where waves are breaking) are subject to four distinct hydrodynamic forces due to breaking waves: (i) drag, (ii) lift, (iii) acceleration, and (iv) impingement forces. Water velocity at the substrate depends directly on wave size and speed. Following Denny (2006), the maximum velocity at the substrate (in the surf zone) scales with the square root of the maximum wave height: $u_{sz} \cong 0.6\sqrt{gH_{max}}$ $u_{sz} \cong 0.6\sqrt{gH_{max}}$ where u_{sz} is the water velocity at the substrate in the surf zone, and H_{max} is the maximum wave height. Thus, a 15% reduction in wave height would result in 7.8% reduction in the wave-induced water velocity felt by a surf-zone organism. The forces scale with the square of velocity:

$$drag: \ F_D = \frac{1}{2}\rho u^2 A_f C_d ,$$

where F_D is the drag force, A_f is the frontal area of the organism, and C_d is the drag coefficient.

$$lift: \ F_L = \frac{1}{2}\rho u^2 A_p C_l ,$$

where F_L is the lift force (perpendicular to the flow direction), A_p is the platform area of the organism, and C_l is the lift coefficient.

$$impingement: \ F_I = \frac{1}{2}\rho u^2 A_f C_I ,$$

where F_I is the impingement force and C_I is the impingement coefficient.

$$acceleration: \ a_{max} = \frac{2\pi^2 HK}{T^2}, and \ F_A = \rho V C_M a ,$$

where a_{max} is the maximal acceleration, K is a depth-dependent constant, V is the volume of water displaced by the organism, and C_M is the inertia coefficient, determined by the shape of the organism.

From this set of equations, we can see that the hydrodynamic forces acting upon benthic organisms fluctuate linearly with wave height. Considering wave height reduction by wave capture devices, the force reduction would be linearly proportional to the change in wave height. In other words, the previously discussed 7.8% reduction in water velocity would correspond to a 15% reduction in each of the four forces, and a 15% total reduction in the forces acting upon an individual organism.

3.1.3.3 Turbulence

Waves create turbulence, a property of water motion that involves chaotic water movement on multiple scales, resulting in small-scale, non-linear, three-dimensional flow patterns. Turbulence can be increased by the presence of obstacles in the flow path of a fluid, by the roughness of the surface over which the water is flowing, by the water velocity, and also by waves. Turbulent flow serves many functions to benthic communities, and can be particularly important to the transport of small particles, including food, propagules, and sediment.

Turbulent flow is inherently three-dimensional, and can create vertical water movement that results in the mixing of water masses that may otherwise be separate. A reduction in wave height would result in less vertical mixing of the water column within the surf zone, which may in turn result in nearshore stratification and a rise in sea surface temperatures, lowered surface salinity, and/or increased retention of contaminants within the surface layer.

Turbulence also causes mixing on much smaller scale, closer to the vicinity of individual organisms. The three dimensional fluctuations in water velocities are individual eddies, each of which consist of discrete parcels of water moving around and amongst one another. This chaotic movement of water serves to deliver nutrients and food, and to remove waste substances from the vicinity of organisms. For example, reductions in overall wave height could decrease the delivery of nutrients to individual blades of a macrophyte by allowing the formation of a thicker viscous sublayer (in which fluxes are due only to molecular processes). Turbulent flow is also important to the suspension of sediment particles and will be discussed in further detail in the following section. Similarly, patterns of particulate organic matter transport may also be interrupted.

3.1.3.4 Wave Runup

When breaking waves make contact with a non-vertical shoreline, water rushes up the shore, well beyond the point of mean sea level. Wave runup R is the maximum vertical extent of wave uprush on a beach or shoreline above the still-water level (SWL, Figure 3.5). The runup height is dependent on wave energy, beach slope, and beach roughness and still-water modulations due to tides, winds and runoff to the ocean.

There are a variety of expressions for wave runup, from the simple $R \sim 3H$ for surging waves on a planar beach (Hunt 1959) to much more complex expressions. Most commonly used is the expression $R = \varepsilon H$ where H is again the wave height and the Iribarren number $\xi = \tan\alpha / (H/L)^{0.5}$ with deepwater wavelength $L = g.T^2/2\pi$ and α representing the shore slope. This suggests that wave runup depends on wave height and length (period), as well as beach slope (and permeability), except for special cases.

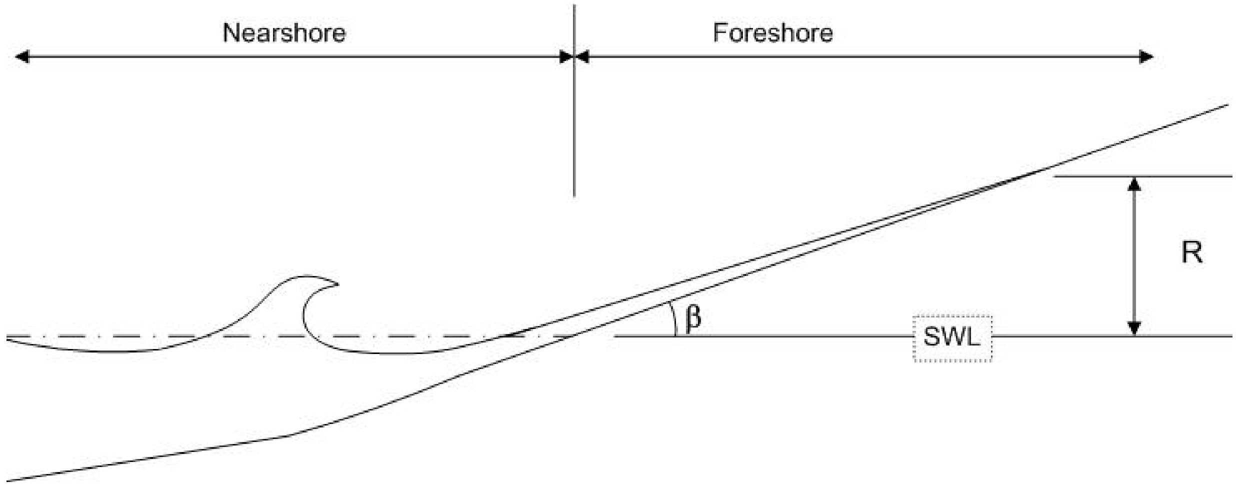

Figure 3.5. Schematic representation of the runup of waves on a beach
Source: Largier et. al.

3.1.3.5 Nearshore Currents

Nearshore currents are primarily due to wave radiation stresses, but also due to alongshore differences in wave setup. Waves drive cross-shore and longshore currents, which are independent of wind-driven, tidal and geostrophic flows. Rip currents and undertows provide water transport in the offshore direction to counteract mean water flow in the direction of the wave motion. Undertow is a flow in the offshore direction that occurs subsurface, allowing water to escape the shoreline underneath the wave-driven onshore flow. Rip currents are discrete areas of rapid offshore flow that are fed by longshore currents near the beach. Since waves often meet the coastline at an oblique angle, this causes some net flow in the longshore direction as well. Undertow and rip currents are important for the transport of larval organisms away from shore during the early stages of development, as well as for sediment transport.

Longshore currents are generated by a combination of obliquely breaking waves and longshore variations in wave set-up on the beach (O'Rourke and LeBlond, 1972). When waves break at an angle to the shore, there is an onshore-directed radiation stress that results in wave setup of the sealevel, and a longshore-directed radiation stress that drives the longshore current. These two components of radiation stress combine to yield

$$S_{xy} = En \sin\alpha \cos\alpha$$

where E is the wave-energy density, n is the ratio of the wave group and phase velocities, and α is the angle the wave crests make with the shoreline (Komar, 1998). With a wave train arriving from deep water, S_{xy} reaches the nearshore relatively unaltered and is expended when the waves break on the beach. This dissipation of S_{xy} within the nearshore was initially adopted as the direct cause for the generation of longshore currents in the studies of Bowen (1969b), Longuet-Higgins (1970), and Thornton (1970). While it is still considered the primary cause of these currents, although much remains to be investigated, in particular the generation of nearshore currents by multiple wave trains, and the effects of the beach topography on the currents (Komar, 1998).

3.1.3.6 Longshore Sediment Transport

Waves arriving at an angle oblique to the shoreline will generate currents that carry suspended sediment along the coast, while waves that arrive from a direction perpendicular to the coastline either deliver sediment directly to the beach, or capture and rework it in the form of offshore bars. Several relations address the transport of sediment in these longshore currents. Longshore sediment transport has been studied from several approaches. These are mostly based on wave power evaluations, process-based models, and laboratory studies, and they vary in how they address the sources of the longshore current. The first approach correlates the energy flux of waves in the direction parallel to the shore with sediment transport measured from sediment traps. In this case, the shore-parallel energy flux is $P_l = \rho g H^2 c_g \sin 2\theta$, which is a maximum for waves approaching the beach at 45°. Then, the alongshore sediment transport is given by the empirical relationship $Q = CP_1^n$ with n~1 and C~125 (Dean & Dalrymple, 2002), or from the analysis of Inman and Bagnold (1963):

$$Q_l = KP_l / (\rho_s - \rho) g (1 - p)$$

where *K* is a non-dimensional calibration coefficient, ρ_s is the sediment density, ρ is the density of seawater and *p* is the porosity of the sediment. Taking ρ_s to be 2650 kg/m³, ρ to be 1020 kg/m³, *p* to be 0.35, and K to be 0.70 (Komar, 1998), this can be simplified to the form: $Q_l = 0.46 \rho g^{3/2} H_{bs}^{5/2} \sin\theta \cos\theta$ where Q_l is the longshore flux of sediment and H_{bs} is the significant wave height at the breaker line. There are a number of more recent expressions for Q, and all confirm that the longshore sediment flux is strongly related to the breaker wave height and incident angle. The importance of the wave height is clear, considering that its exponent varies from 1.5 to 2.5. A decrease in wave height due to offshore WEC would lead to an amplified decrease in longshore sediment flux (Table 3.4).

Table 3.4. Reduction in longshore sediment flux corresponding to decrease in wave breaker height, calculated with different published relationships

Equation	Reduction in wave breaker height	Decrease in longshore sediment flux
Inman and Bagnold (1963)	5%	12.0%
	10%	23.1%
Inman and Bagnold (1963) Kraus	5%	9.7%
et al. (1982)	10%	19.0%
Kampuis (1990)	5%	7.4%
	10%	14.6%

Source: Largier et. al.

Although the dependence on H is clear, these analyses are only rough estimates as these expressions have been derived for straight beaches with regular offshore topography, and may not adequately represent the longshore flux that would occur adjacent to beaches with non-uniform shapes.

3.1.3.7 Cross-Shore Sediment Transport and Beach Shape

Waves have a large impact on the shape, or profile, of beaches both above and below the water level. The beach profile is important in that it can be viewed as a natural mechanism that causes waves to break and dissipate their energy. Faced with increased waves, the beach responds by reducing its overall slope and shifting the breaker zone farther offshore, thereby enhancing the dissipation of the waves before they reach the shore. The ability of a beach to adjust itself to the prevailing forces makes it an effective method of coastal defense (Komar, 1998). The effect of waves on beach profiles is sometimes analyzed in terms of two simplified cases, storm conditions and calm conditions. Dean and Dalrymple (2002) associate these periods with "destructive" and "constructive" forces, respectively. During storm events, "destructive" forces take sediment off the beach and tend to flatten its profile. The waves often deposit the sediment in a bar that accumulates just seaward of the breaker line, leading to a profile with two separate concave zones separated by the bar. The "constructive" forces are evident after the storm and slowly act to move the sand back onto the beach, actually steepening it against the gravitational forces. During this period, the profile often returns to a single, concave shape without a bar. This model is sometimes extended so that beach profiles are characterized by their winter (storm) and summer (calm) profiles.

Dean (1973) presented a model that explains the shift from a summer profile to a winter profile, based on a consideration of the trajectory of a suspended sand particle during its fall to the bottom after being re-suspended in the water column by wave action. If the grain fall requires a short time relative to the wave period, then the particle will be acted upon predominantly by onshore velocities. On the other hand, if the fall velocity is low, then the grains will tend to shift offshore. Using various laboratory data sets, Dean found a critical wave steepness H_∞/L_∞ such that when $\frac{H_\infty}{L_\infty} < \frac{1.7\pi w_s}{gT}$ sediment flux is toward the shore and when $\frac{H_\infty}{L_\infty} > \frac{1.7\pi w_s}{gT}$ sediment flux is away from the shore, where w_s is the settling velocity. This relationship provides a basis for determining whether the beach is acquiring or losing sediment – an outcome that depends directly on wave height H_∞ which will be altered by offshore WEC.

Variance of wave heights throughout the year typically causes a long-term balance in the amount of sediment supplied to and taken from a beach (Dean, 1988). If wave heights were permanently reduced, while sediment continues to be supplied from outside the littoral cell, the beach may experience long-term accretion as a consequence. According to Dean's relation a sufficient decrease in wave height would lead to continuous sediment deposition on the shore. This would also likely increase the steepness of the beach.

Wave action also plays a large role in the cross-shore transport of sediment in the form of bars. In many coastal systems, sediment stripped from the beach during periods of intense wave activity is stored in bars located seaward of the shoreline (Dean, 1973). Landward migration of sandbars is the primary mode of onshore sediment transport back to the beach face during the times of low waves following storms (Komar, 1998). This process has been documented by Hayes (1972) and Owens and Frobel (1977), indicating that wave action is the cause of bar movement towards the shore, but recognizing that it is difficult to ascertain the specific impact of a decrease in wave energy on bar movement.

3.1.4 Impact of Change in Wave Energy on Shoreline and Nearshore Geomorphology

Coastlines are dynamic systems that adjust to accommodate the amount of energy supplied to them from waves and other environmental forces. A decrease in the energy input from waves may have a number of potential impacts in the nearshore zone. The most likely impacts are changes in the profile of the beach and decreases in both the cross-shore and longshore transport of sediment. As a consequence of the reduced sediment transport, the most likely response of the estuarine and lagoonal inlets along the coast is a reduction in the number of closure events and a decrease in lateral movement.

Most sandy beaches follow a cycle of erosion and accretion that parallels the cycle in wave energy. Although waves are responsible for stripping the sediments from the beach during storms, they also generate the currents that carry sediment along the coastline and rebuild the beaches. The construction of coastal structures has clearly demonstrated this rebuilding process, as many beaches downdrift of major jetties have experienced substantial erosion (Dean and Dalrymple, 2002).

The lack of research in the fields of sediment transport and inlet morphology makes it difficult to assess the impacts of reducing wave energy in the nearshore zone. Despite this, the analysis in this section provides several basic conclusions. First, beaches may adjust to accommodate the lower wave energy by more frequently forming the typical summer shape consisting of a single concave decline in elevation. This is because waves of great height and steepness are required to strip sediment from the beach, form bars offshore and reduce the overall slope of the beach profile. A reduction in wave energy will correspond with lower wave heights and steepness. This would prevent the formation of an offshore bar, lead to a steeper beach face, and possibly upset the long-term balance of sediment erosion and accretion on beaches. Second, longshore currents would most likely weaken in response to reduced wave energy. This type of change would lead to a decrease in the sediment transported along the coast. This was shown by several theoretical and empirical equations, all of which showed a strong nonlinear relationship between total littoral flux and breaking wave height. Finally, reduced sediment transport from wave-driven currents will decrease the tendency of coastal inlets to move laterally, adjust their geometry, and close. This would result from an increased ability of inlet channel currents driven by waves and river flow to scour the smaller supply of sediment that arrives at the mouth of the inlet. This analysis also showed that the height and incident angle are the most important wave parameters in determining the effects of reducing the energy supply to the coast. Wave height is particularly important due to its large role in empirical and theoretical equations that quantify the current velocity parallel to the coast and the amount of sediment carried in its drift. It is unlikely that a reduction in wave energy of five percent or less would cause any of the changes discussed above. This analysis merely provides an outline of the possible outcomes of wave energy reduction in the nearshore zone, and conclusive evidence regarding long-term shifts in beach processes and characteristics would require much further investigation.

3.1.4.1 Estuary Mouth Morphology

Waves have a substantial impact on the morphology of estuary and lagoon inlets. In particular, the planform and cross-sectional geometry of these inlets are controlled in large part by the local sediment flux. It is important to consider the effect of the wave climate on inlets because they exert major influences on the processes of navigation, habitat restoration, shoreline protection, and mitigation. Additionally, the geometries of these inlets control the evolution and ecological health of their adjacent marsh, lagoon or estuarine systems (Goodwin, 1996).

Inlets are dynamic systems, much like beaches. They represent a balance between sedimentation from wave-driven currents and scouring from tidal and riverine flows in the inlet channel (Komar, 1996). The rate of delivery of sediment into the inlet from the ocean side is governed by the rate of longshore and cross-shore transport provided by waves (Goodwin, 1996). In many cases, tidal or riverine flow is sufficient to prevent permanent sedimentation in the inlet channel. However, in semi-arid or arid climates, this is not always the case. In California alone, more than 15 inlets experience closure every year (Goodwin and Cuffe, 1993). When inlet currents cannot adequately prevent the sedimentation caused by waves, inlets respond by migrating (Galvin, 1971), adjusting their cross-sectional geometry (Jarrett, 1976), or completely closing (Escoffier and Walton, 1979; O'Brien, 1971), effectively ending communication between ocean and lagoon waters.

Sedimentation occurs in inlets either as a response to deposition of suspended sediment from longshore currents or from onshore movement of sandbars (Ranasinghe and Pattiaratchi, 2003). As discussed above, both cases are primarily controlled by wave action. Many authors relate the processes of inlet migration, geometry adjustment, and closure to wave energy in a qualitative manner (e.g. Komar, 1996; FitzGerald, 1996). However, few studies have obtained adequate data to test theories of inlet adjustment in response to wave-driven sedimentation. This is due partly to the physical difficulty and costs associated with accurate measurement of key parameters such as longshore or cross-shore sediment transport; cross-sectional area; velocities and sediment flow in the inlet (Goodwin, 1996). Bruun and Gerritsen (1966) presented a non-dimensional index for determining the susceptibility of an inlet to close based on littoral transport rates and tidal influence. This index can be expressed as $B = \Omega / P$ where Ω is the annual volume of sediment transported in longshore currents in the vicinity of the inlet, P is the tidal prism, and B is a non-dimensional inlet stability index. They used empirical data to specify ranges of values for B that separate stable inlets (low B values) from inlets that are likely to close (high B values).

Based on this relationship, a decrease in wave energy increases the likelihood that an inlet will remain open to the ocean, assuming that the tidal prism remains constant. Apart from this, it is difficult to predict how a reduction in wave energy at the coast would influence inlet processes with any certainty. If a reduction in wave energy leads to a decrease in both the longshore and cross-shore transport of sediments, coastal inlets will likely experience less migration, channel adjustment, and closure, but it is unlikely that the extent of this will be significant unless the reduction in sediment transport is high.

3.1.5 Impact of Change on Offshore Habitats

Waves interact with the bottom when the water depth is comparable with the wavelength, which can happen far offshore for large long-period waves. While significant influences of waves on bottom boundary layers have been seen at depths of 90m of northern California (Grant et al 1984), typically waves have strong influences on bottom currents at depths of 50m and less. A reduction in near-bottom orbital velocities in the wave shadow due to WEC devices may allow increased sedimentation of fine sediments in regions where they may not have accumulated previously. Further, if wave-induced velocities dominate the near-bed boundary layer, then a reduction in waves may also reduce the flux of dissolved and particulate material to benthic organisms. While these effects need to be evaluated in more detail, it is the frequency of sub-critical wave days that may be an issue – one can imagine that a modest reduction in wave energy could easily result in a doubling of the number of sub-critical days. Just as these sub-critical days may stress organisms high in the intertidal owing to the absence of dessication-mitigating splash, sub-critical benthic flows may stress benthic organisms that rely on water-borne fluxes of food. While much of the wave shadow will move around with changes in the direction from which waves approach, there will be a smaller region immediately behind the device that would be sheltered from wave energy under all conditions. Given that wave devices are likely to be located far enough offshore that wave energy is not yet dissipated by interaction with the bottom, it is also unlikely that there will be significant wave-driven benthic processes at this depth or in this permanent wave shadow zone immediately behind the device. However, it is clear that further evaluation of possible offshore impacts is necessary and that these possible impacts depend on the detail of the device and the wave shadow, as well as on the location of the device relative to the depth at which waves have an influence on the bottom.

3.1.6 Impact of Change on Human Activities

Through influencing nearshore processes, changes in wave energy may have impacts on human activities, specifically in nearshore waters. If the reduction in wave height is significant, this may benefit the transit of vessels to/from harbor entrances (e.g., Humboldt Bay), allowing for safer passage. Further, the reduced impact on breakwaters may allow for longer survival of these structures and the reduced sediment transport may reduce the accretion of sand bars near the mouths of harbors like Humboldt Bay.

Secondly, a reduction in wave energy may reduce the likelihood of cliff and bluff erosion as well as reduce the risk of flooding of lowlands during the concurrence of big waves with wind setup and high tides. Whether these effects are likely to be significant is unclear. Part of the answer lies in specialist studies on these topics and part of the answer lies in how the WEC devices extract energy during storm periods – do they extract a constant amount of energy, a proportion of available energy, or nothing during storm conditions.

Thirdly, the recent focus on attempting to understand the pattern of nearshore pollution has pointed towards the importance of nearshore wave-driven flows in redistributing contaminated land runoff (e.g., Grant et al 2004). Even small changes in wave energy may make significant changes to the rip currents and longshore currents that transport and mix the contaminated waters into the big ocean. Present studies are working towards quantifying the relationship between wind, tide, wave and runoff forcing on the "zone of impact" of runoff – this would provide a clear idea of the potential for changes in the location and severity of non-point-source pollution in nearshore waters.

Priority Research Needs

While a wise implementation of WEC devices may be environmentally benign, the brief review of issues in this chapter includes several possible impacts and suggests that poorly planned WEC devices may have significant impact on nearshore environments. This report and the recommended actions are intended to provide a set of warnings on what to avoid in the design of wave-energy facilities along the Californian coast. For example, extensive wave farms close to the shore are likely to significantly change the dynamics of river/estuary mouths.

Knowledge gaps fall into three themes:

1. Propagation of wave energy and the pattern of WEC wave shadows;
2. Wave-driven nearshore processes that are primary determinants of ecological habitat, geomorphological structure, and risk for ocean users.
3. Anticipated changes in incident waves due to climate change.

The wave shadow: To study the sheltering effects of WEC on the nearshore wave climate, two complementary approaches are recommended. First, a suitable refraction-diffraction model needs to be selected and set up to run simulations of waves around WEC array-like objects. Depending on the details of the area and the various aspects to be studied this could be modeled e.g. with a linear deterministic model such as RefDif (Kirby & Dalrymple, 1983), a nonlinear deterministic wave model (e.g. Janssen et al. 2006) or a stochastic refraction-diffraction model (Janssen et al. 2008). For such models to predict the impact of WEC, detailed information is needed regarding the dissipative and scattering characteristics of these devices. In addition to modeling, we recommend detailed monitoring of wave conditions inshore of pilot systems, using a combination different instruments such as bottom-mounted velocity measuring devices, ADCP's, buoys and radar data in combination with CDIP and NDBC data. In the event of a significant shadow zone, the monitoring effort should extend to benthic processes, including settlement and resuspension rates.

Nearshore conditions: The above projections will allow for estimates of wave energy reduction nearshore. Studies would be best in addressing specific locations where there is already a marginal issue. For example, these would include studies of estuary mouth stability (e.g., Russian River mouth) and the transport of contaminated runoff in river plumes (e.g., Noyo River plume at Fort Bragg). Prior to design it would be wise to evaluate these processes, with the help of models, but it may only be possible to directly observe impacts on sediment transport, morphology and nearshore water quality through before-and-after studies. Further, it may be necessary to conduct studies of a specific wave process that is expected to have an inordinate impact on ecological communities (see next Lohse et al. Chapter 4). Standard techniques exist for studies of nearshore wave conditions, water circulation, and sediment transport (e.g., radar, drifters, Jetski, current meters, etc.).

Climatology: An analysis of existing wave data (and model output) would provide a reasonable idea of what conditions and extreme events can be expected at specific sites. These can be evaluated relative to potential problems at this site, evaluating risk under present conditions and assessing whether changes in wave conditions would increase or decrease risk.

It is recommended that a wave modeling study be conducted prior to permitting significant WEC arrays and that a wave monitoring buoy be deployed prior to WEC deployment and maintained there for several years in the nearshore region in which the largest changes are expected. In addition, it is recommended that a pre-permit survey of nearshore geomorphology and ecology be conducted in regions where reduced wave energy is projected to occur, and that this same region be surveyed annually to track any environmental change due to WEC affects on wave energy nearshore.

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4.0 Predicted Effects of Wave Energy Conversion on Communities in the Nearshore Environment

David P. Lohse, Rani N. Gaddam, Peter T. Raimondi

Department of Ecology and Evolutionary Biology, University of California Santa Cruz

Abstract

The California coastline includes a complex array of habitats ranging from sandy beaches to rocky reefs to estuaries. One factor that influences the structure of the communities in these habitats is wave exposure. Thus, the installation of Wave Energy Conversion (WEC) devices along the California coast is likely to have two kinds of ecological impacts; those associated with the construction and maintenance of the devices, and those caused by the device's attenuation of wave energy in the nearshore environment. The direct impacts of the devices themselves are relatively easy to predict. However, because the amount of wave energy lost depends on the size, type, and location of the WEC devices, the responses of nearshore communities to a reduction in wave energy are more difficult to predict. On rocky reefs a reduction in wave energy will likely influence zonation patterns (in both intertidal and subtidal communities) as well as species distributions and abundance along the shore. Further effects could be caused by changes in disturbance regimes, sediment deposition, and flow characteristics of sites. Impacts to sandy habitats are less easy to predict but not unimportant. Because both long shore and cross shore sediment transport are likely to be affected, species associated with finer grain size may be favored. This change in sediment transport will also likely affect estuarine communities by changing the dynamics of beach openings to smaller estuaries, and the quality of sediments entering estuaries.

Because relationships between physical processes and biological responses are typically non-linear, predicting the magnitude of ecological change is difficult yet critical. Species or ecological communities that exhibit threshold responses could be dramatically affected by small changes in wave energy, which could lead to vastly different species assemblages and communities. Because little is currently know about the quantitative relationship between wave energy and community attributes it is essential to investigate this relationship. The development of coupled empirical-hydrodynamic models that examine the relationship between wave energy and community structure could increase our ability to predict and mitigate impacts to ecological communities resulting from wave energy devices.

Introduction

Currently there is a great deal of interest in utilizing Wave Energy Conversion (WEC) devices along the California coastline to generate electricity. Because these devices require a certain amount of wave energy to make this a viable venture, the wave regime of the coastline north of

Point Conception makes this an ideal area for these devices (PIER 2007). This region of the California coast consists of a number of different nearshore habitats, including offshore reefs, subtidal kelp forests, soft sediment habitats such as sandy beaches and estuaries, and extensive intertidal rocky benches. The WEC devices will have several direct impacts on the areas surrounding them. In addition, wave energy inshore of the devices could be reduced by up to 15% (Faber Maunsell et al. 2007; Largier et al. 2008), depending upon the type, size, and configuration of the devices installed. It is therefore critical to understand the impact that reduced wave energy will have on these nearshore communities.

This chapter will review (1) the direct impacts of the WEC devices on the benthic community surrounding the structures, (2) the specific biological processes affected by wave energy in nearshore communities and how a reduction in wave energy is likely to affect them, and (3) recommended areas for research. The primary focus of this chapter is on rocky reef communities, but the potential impacts to sandy beach and estuarine communities are addressed as well.

Current Knowledge and Knowledge Gaps

4.1.1 Direct Impacts of WEC to the Benthic Community

During the construction, operation, maintenance, and decommissioning of WEC devices, there will be various impacts on the benthic communities surrounding their installation (Hagerman and Bedard 2004; Minerals Management Service 2007). The types of devices considered and the potential scales of the installations have been reviewed in previous chapters (Largier et al. 2008; Nelson 2008b). For all four types of WEC devices being considered (point absorbers, attenuators, overtopping devices, and oscillating water columns), the seabed will be disrupted due to drilling and/or anchoring, and the running of transmission cables to the shoreline. Some devices (e.g. overtopping devices) have an additional potential for entrainment of species. These disturbances will be worse in sensitive areas such as rocky bottom, kelp forest, or seagrass beds. In addition, as the footprint of the installation increases in size (from pilot, to commercial, to network) the impacts will be greater as more habitats are affected by the larger scale installations.

4.1.2 Direct Impacts – Construction

Below is a summary of anticipated impacts to benthic communities during construction of WEC devices (see Hagerman and Bedard 2004; Minerals Management Service 2007 for a detailed description).

1. *Placement of supports or anchors for wave energy units and placement of transmission lines on the seafloor:* This would crush benthic organisms, increase turbidity due to suspension of sediments, and alter the availability of various habitat types.

2. *Change in turbidity:* Construction activities could decrease photosynthesis by phytoplankton, which could reduce local primary productivity and hence the food chain.

3. *Modification of seafloor:* This could be particularly an issue if placement of the wave energy devices was on or near hard surfaces where associated organisms could be killed. In sandy bottom areas, changes to sediment deposition could have consequences on certain benthic organisms.

4. *Impacts due to installation of pilings:* Pile drivers (if required by a particular device) could cause impacts due to vibrations and noise; both behavioral avoidance and mortality could ensue.

The potential for impacts to populations of seafloor organisms from such losses of individuals is unclear, although it is unlikely that substantial proportions of populations would be affected as long as unique habitat areas are identified and avoided.

4.1.3 Direct Impacts - Operation and Maintenance

Once construction of an offshore WEC device had been completed and operation has commenced, seafloor habitats and seafloor biota could be affected by the presence of the structures themselves, traffic and noise from vessels used to maintain the structures, and noise associated with device operation. Below is a summary of anticipated impacts during operation and maintenance of WEC devices. Many of the impacts associated with construction (mentioned above) may also be problematic in the operation phase.

1. *Entrainment or impingement of fish and invertebrates*: Depending on the type of device, seawater could be withdrawn and entrainment and/or impingement could occur. Entrainment occurs when organisms are withdrawn along with seawater. Impingement occurs when organisms entrained are collected (typically on screens). Typically organisms die as a result of entrainment or impingement.

2. *Release of exotic substances*: Chemicals or effluent could be released near to the units or from vessels used to service the units.

3. *Electromagnetic fields*: The electromagnetic field associated with the units or transmission cables could affect all organisms in the vicinity of the units.

4. *Introduction of hard substrate*: Most wave energy arrays are likely to be constructed in areas of sandy bottom, hence structures, such as pilings, would create an artificial reef that would lead to the colonization of species associated with hard surfaces. In addition the array would introduce complexity into a typically simple habitat. This would almost certainly act as an attractor to many species and would lead to a biological community both different and much more diverse than the pre-existing, natural community. This could lead to impacts both during operation (interactions between the complex hard substrate community and the natural soft bottom community) and during decommissioning (destruction of a potentially highly diverse *artificial reef* community). The impacts associated with the provision of hard surfaces and complexity will be directly affected by the density of the units and the area over which they extend. As with any reef in the midst of sandy habitat there is also the possibility that the hard structures could provide habitat for invasive species. Most invasive

invertebrate or algal species along the west coast of the US are mainly associated with bays and estuaries; hence this latter effect is likely to be minor.

4.1.4 Unanticipated Impacts – Shell Mounds

One potential impact that was not fully appreciated until fairly recently is the accumulation of shell material under and near to artificial structures that are placed in nearshore waters. These *shell mounds* are a matrix of shell material, primarily from mussels of the genus *Mytilus*, and debris and sediments that accumulate in the interstices between the shells. Shell mounds accumulate below the installation, primarily due to the scraping of the artificial structures and transmission lines during maintenance activities. Most information about shell mounds come from studies of oil platforms, where the depth of the mounds can reach 8 meters (Phillips et al. 2006). Because the mounds tend to be stable, the interstices of the mounds can accumulate exotic substances (e.g. lubricants, chemicals) that have been released (Phillips et al. 2006) and can become anoxic. These toxins could be liberated when the mounds are disturbed or removed during maintenance and/or decommissioning.

4.1.5 Direct Impacts – Decommissioning

The decommissioning of a wave energy array could include the removal of all structures associated with the units. As a result there could be impacts due to the loss of the structures, the activities associated with the removal, and the vessels and machines used in the removal operations. Below is a summary of anticipated impacts during decommissioning of WEC devices.

1. *Removal of units*: The major source of impacts would be noise from the operation or from explosives if they were used. In addition, sediment is likely to be suspended, and there could be a short-term increase in turbidity. Exotic substances (e.g. lubricants, chemicals etc) could also be liberated during the removal of units.

2. *Loss of structure*: As noted above, the provision of hard and complex substrates into an area that is likely to be simple soft bottom habitat is likely to lead to a more diverse biological community. The loss of that habitat would lead to the destruction of the community. Depending on the species composition this might be considered an impact. For example if species of special interest (e.g. abalone, certain rockfish) became associated with the artificial habitat a case could be made that the removal of the structures could constitute a negative impact.

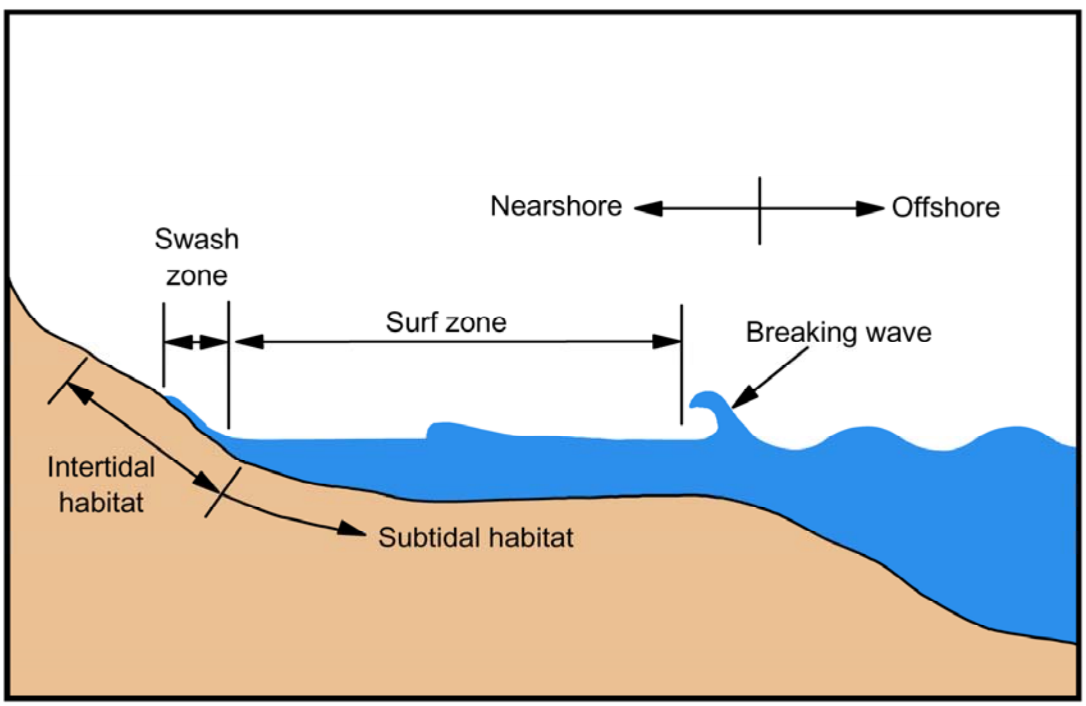
4.1.6 Wave Processes and the Nearshore Community

Although the installation and upkeep of WEC devices will affect the benthic communities under and near them, by reducing wave energy WEC can also affect the structure of coastal communities inshore of the devices.

When a wave travels through deep water, there is no net movement of water in the direction of its propagation. However, as it reaches shallow water the wave begins to interact with the ocean bottom. This alters its shape, thereby causing a net movement of water in the direction of the wave’s travel. Farther inshore the depth eventually becomes too shallow and the wave becomes unstable and *breaks*, creating an area of high turbulence known as the surf zone. When the wave finally reaches the shore, its forward momentum propels the water traveling with it up the shore, a process known as run-up. Gravity and friction act to stop the forward progress of this body of water, and it eventually reverses direction and flows back down the shore. Thus run-up creates a region of the shore, known as the *swash zone*, where water rushes in and out with each passing wave. The actual location of the swash zone moves up and down the shore with the rise and fall of the tides (Figure 4.1). The extent of this zone is affected by wave height and the slope of the shore (Largier et al. 2008).

To live in a wave-swept habitat (i.e., the surf and swash zones) can be challenging. For example, when a wave washes over an organism, it is exposed to hydrodynamic forces that may exceed its capacity to remain attached to the substrate. These forces can be quite large; measurements taken in the swash zone have found water velocities in excess of 10 m/sec, and accelerations approaching 500 m/sec^2 (Bell and Denny 1994; Gaylord 1999). In addition, when a wave strikes the shore it carries with it any objects suspended in the water column. Thus, an organism in a wave-swept habitat runs the risk of being abraded by sand particles, or struck by logs (or other water borne objects). Just how well an organism is adapted to meet these challenges can influence where along the shore it lives, how well it forages for food, and how it interacts with other species.

Figure 4.1: Diagram showing the different wave-impacted regions of the nearshore environment



Source: Lohse et. al.

4.1.7 Non-linearity and Wave Exposure in Biological Systems

The impacts of WEC on biological communities in the nearshore environment are likely to result from the direct effects due to the structures themselves and the reduction of wave energy inshore of the devices. The direct effects of the installation, operation, and upkeep of these devices (discussed above) are relatively straightforward to predict. However, determining how changes in wave energy will affect nearshore communities is more problematic. Although wave energy is a continuous variable, most studies dealing with the effects of 'exposure' (a phrase that has been used to grossly describe the wave energy climate of an area) on communities have treated it as a categorical variable (Lindegarth and Gamfeldt 2005). Thus, there is limited knowledge about how biological communities vary along a gradient in wave energy (see Denny et al. 2004). Such information is needed, particularly since the relationship could be non-linear rather than linear (Lindegarth and Gamfeldt 2005; Burrows et al. 2008).

Non-linear dynamics are rarely studied or incorporated into management and policy decisions (Burkett et al. 2005). Instead, managers are more likely to assume and plan for linear relationships (Canadell 2000). Thus, estimates of biological responses to physical changes will almost certainly be incorrect, as illustrated in Figure 5.2. If the relationship between wave energy and a biological parameter is linear, the response of the biological variable to a change in wave energy is linearly proportional regardless of the starting value of wave energy. However, in a non-linear relationship the response is not constant. If the change in wave energy occurs in the area of the curve with the greatest slope (the *threshold* region), the biological response for the non-linear curve is greater than for the linear relationship. In contrast, if the initial wave energy value occurs in the *asymptotic* region of the curve, the non-linear response is less than the linear response. Thus, depending upon the shape of the curve and the initial value of wave energy, assuming a linear relationship when it is truly non-linear could over or underestimate the true response. This could result in poor policy and management decisions.

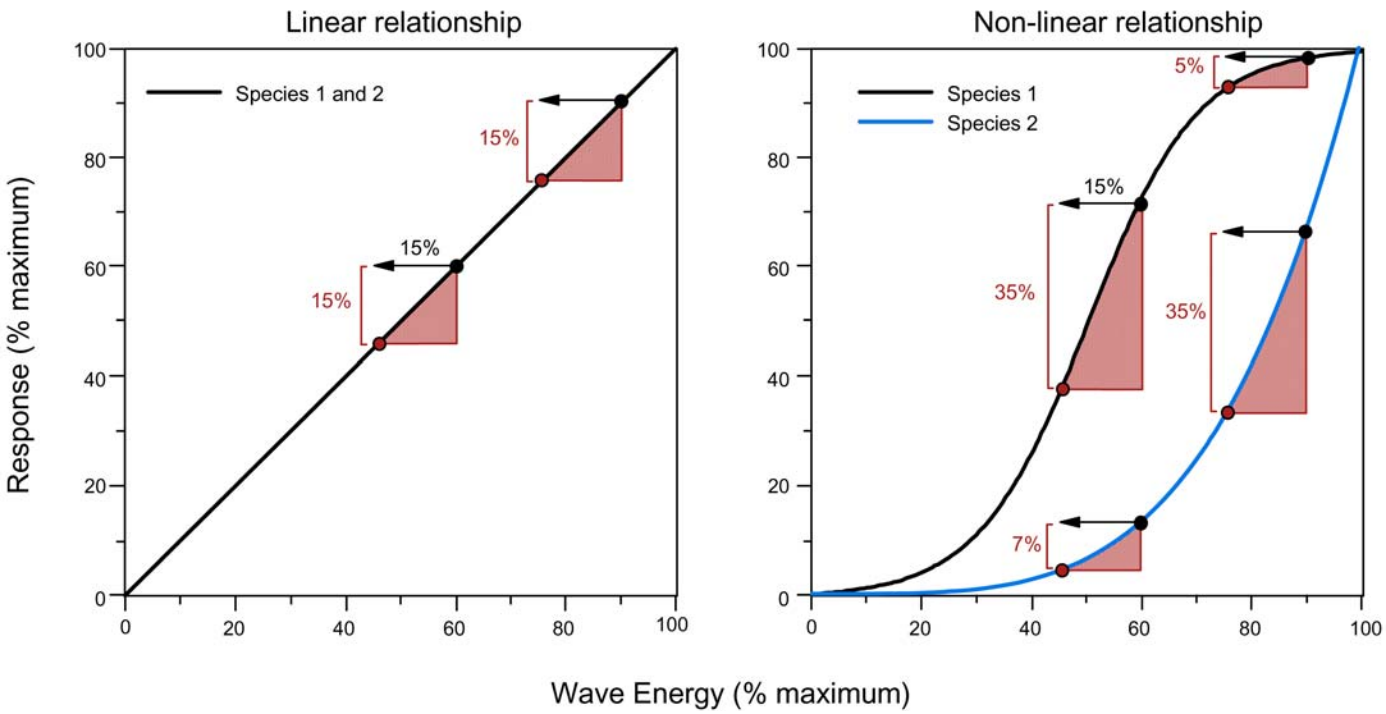


Figure 4.2: The difference between linear and non-linear responses to a reduction in wave energy

Shown are the biological responses to a 15% reduction in wave energy (the amount predicted by the use of some devices, see Faber Maunsell et al. 2007; Largier et al. 2008) for two initial values of wave energy: 90% or 60% of maximum. Values in red represent the change in the biological parameter from its initial (black dot) to its final (red dot) value. If wave energy is reduced from 90% to 75%, assuming the relationship is linear when it is really non-linear would overestimate the response of species 1, and underestimate the response of species 2. If wave energy is reduced from 60% to 45%, assuming a linear relationship would underestimate the response of species 1, and overestimate the response of species 2.
Source: Lohse et. al.

A good example of a non-linear relationship between wave energy and community structure comes from the kelp communities along the coast of central California. Kelps are important species not only because they contribute much to the primary production of nearshore communities, but because they provide structure to the water column that is fundamentally important to the diversity of kelp communities (Graham et al., in press). Along the California coastline the kelp species *Macrocystis pyrifera* tends to be found in lower wave energy environments, while *Nereocystis luetkeana* occupies more exposed habitats (Foster and Schiel 1985; Graham et al. in press). Observations suggest that the switch from one kelp species to the other appear to fit the non-linear threshold scenario described above (Figure 5.3). That is, a relatively small change in wave energy can have a pronounced effect on which species of kelp is present and, therefore, the composition of the resulting community (Hagarman and Bedard 2004). Therefore it is essential to anticipate non-linear effects or, at a minimum, implement monitoring that allows for their detection.

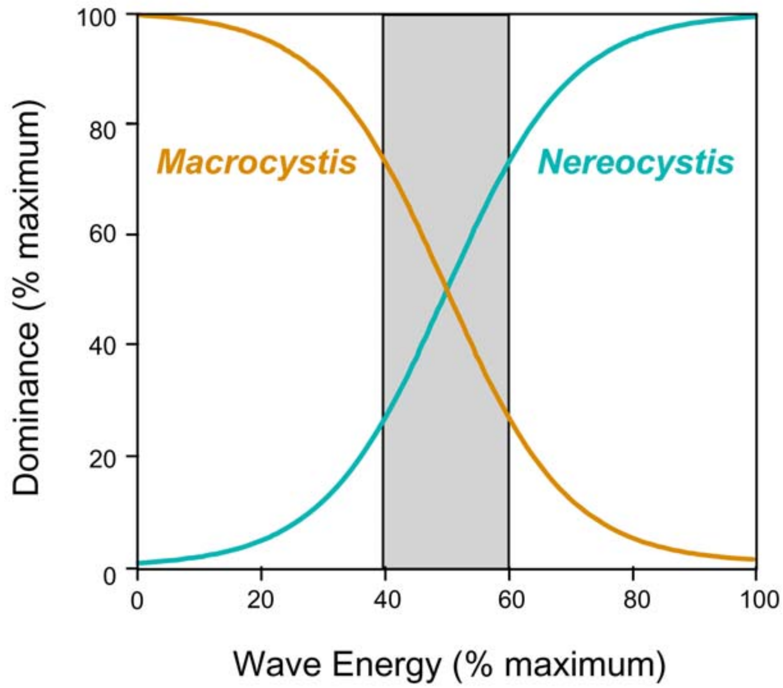


Figure 4.3: Hypothetical relationship between wave energy and the dominance of *Macrocystis* and *Nereocystis*

The shaded area indicates the threshold region - that is, the region where small changes in wave energy would create large changes in kelp dominance. Note that there are no quantitative data to illustrate the relationship between wave exposure and kelp species. Source: Lohse et . at.

4.1.8 Species Trends at Wave Exposed and Wave Protected Sites

Information on the effects of wave exposure gradients on specific species is limited. Available information suggests that while wave exposure can limit the distribution of some species along the shore, for other species it appears to affect their abundances (Table 5.1). Further study is clearly needed to determine how other species respond to changes in wave energy.

Table 4.1. Distributional trends of some nearshore species along the California coast with respect to wave exposure

This is not intended to be an exhaustive list, and further study is clearly needed to determine how species respond to changes in wave energy. In most cases, the distributional trends are based on qualitative, not quantitative, assessments of wave exposure.

Distributional trend	Scientific name	Common name	Data source
Distribution limited to wave exposed areas	*Postelsia palmaeformis*	Sea palm	Paine 1979
Relative abundance tends to increase with wave exposure	*Mytilus californianus*	California mussel	PISCO dataset [a*]
	Littorina keenae	Eroded periwinkle	
	Nereocystis luetkeana	Bull kelp	Graham et al. in press
Relative abundance tends to decrease with wave exposure	*Phragmatopoma californica*	California sandcastle worm	PISCO dataset [a*]
	Tegula funebralis	Black turban snail	
	Macrocystis pyrifera	Giant kelp	Graham et al. in press
	Sebastes mystinus	Blue rockfish[b]	PISCO dataset [a**]
	Sebastes atrovirens	Kelp rockfish[b]	
	Embiotoca lateralis	Striped surfperch[b]	
	Sebastes chrysomelas	Black & yellow rockfish[b]	
	Sebastes carnatus	Gopher rockfish[b]	

[a] Species were identified from PISCO surveys conducted between Point Conception and the California/Oregon border. Although it is likely that the abundance of other species varies with wave exposure, the PISCO dataset was the only comprehensive one available for the entire California region being considered for WEC. [*]For more information about intertidal PISCO surveys, see http://cbsurveys.ucsc.edu. [**]For more information about subtidal PISCO surveys, see http://www.piscoweb.org/research/community/subtidal.

[b] Decreases specifically with respect to NW swell

Source: Lohse et. al.

4.1.9 Species Distribution and Vertical Zonation

In nearshore environments species' distributions are, in part, determined by how well they can tolerate the physical conditions of a given location. For example, because of the tidal cycle, intertidal organisms spend part of their time exposed to the air and part immersed in the water. Typically, locations higher on the shore spend more time in air and less time submerged than those lower on the shore. Because species differ in their ability to tolerate this gradient, they are not distributed uniformly throughout the intertidal zone. Instead they are found in bands along the shore, a phenomenon known as vertical zonation.

Although intertidal zonation patterns are largely determined by the tidal cycle, wave exposure also plays an important role. Specifically, due to wave run-up and wave splash, incoming waves extend the upper boundary of the intertidal zone above that set by the tidal cycle. In general, the larger the wave, the greater the run-up, the higher the intertidal zone extends on the shore. Thus, the zone each species occupies tends to be both broader and located higher on the shore at wave exposed sites (Figure 4.4).

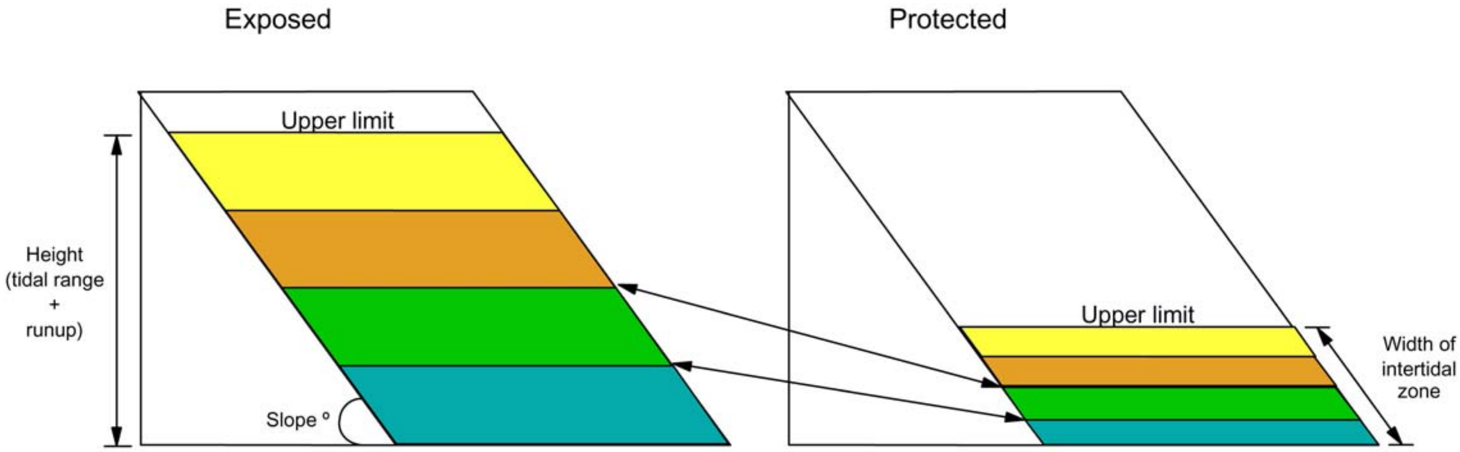


Figure 4.4: Comparison of zonation patterns at wave exposed and wave protected intertidal sites

Note that each zone is smaller in width and located lower on the shore at the protected site.
Source: Lohse et. al.

If the wave exposure of a given intertidal site were reduced, there would be less wave splash and shorter run-up. Consequently, species distributions would change to resemble that seen at more wave protected sites (see Harley and Helmuth 2003). That is, the zone occupied by each species would both shift downward and decrease in size (width). Just how much each zone would shrink would depend upon the amount of wave reduction, and the slope of the shore (Figure 4.5). Since each species occupies less total area, the number of individuals in the population would decrease. The extent of this loss can be calculated by multiplying the area lost by the average density of the species at that site.

Because water motion/turbulence and light penetration both decrease with depth (distance from the shore) species in subtidal habitats are also distributed in zones. Specifically, the more tolerant a species is to water motion, the shallower (closer to shore) it can live (e.g. Kastendiek 1982), while the more shade-tolerant a species is, the deeper it can live. If wave energy is reduced, waves should travel farther inshore before they break. Since this would shrink the size of the surf zone, this should allow species' distributions to expand shoreward towards shallow water. However, because a reduction in wave energy should reduce the amount of suspended sediments (discussed further below), algal species may be able to live deeper (e.g. Kautsky et al. 1986; Vogt and Schramm 1991; Korpenin et al. 2007). Thus, a reduction in wave energy could change the relative abundance of species in subtidal communities.

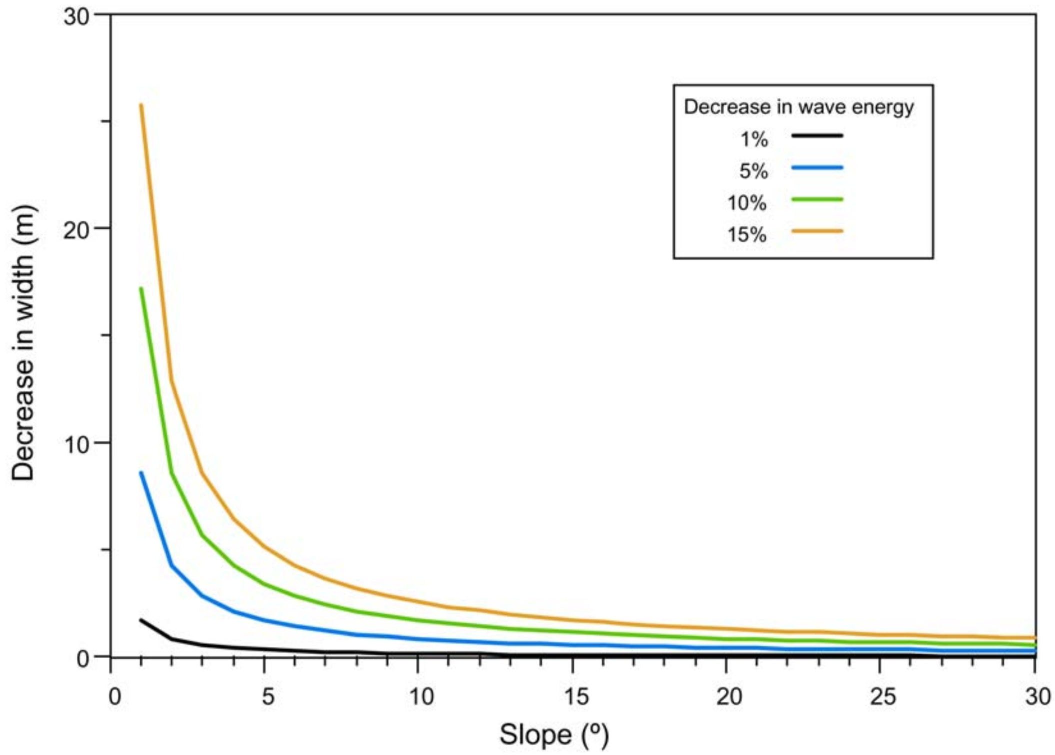


Figure 4.5: Predicted decrease in width (m) of an intertidal zone as a function of both slope of the shoreline and the amount wave energy is reduced

Calculations were made using an initial height (tidal range + run-up) of 3 meters, and assuming a 1:1 (linear) relationship between the % reduction of wave energy and the % decrease in vertical height.
Source: Lohse et. al.

4.1.10 Community Composition

Two physical factors that can influence where a species lives along the coast are temperature and wave exposure. In general, sea surface temperature (SST) decreases with increasing latitude. Thus, how well a species can tolerate warm/cold temperatures will strongly influence its biogeographic distribution along the coast. Changes in SST can cause species ranges to change, allowing species to "invade" areas where they were previously absent or causing resident species to disappear (e.g. Barry et al. 1995). Currently, there is evidence that the range of many species is slowly spreading northward due to a rise of SST attributed to global climate change (Helmuth et al. 2006).

An important factor that influences local SST is the depth of the mixed layer. Since the heat generated from insolation is shared throughout the mixed layer, the shallower the mixed layer, the less volume of water is being heated, the warmer the SST. Since the depth of the mixed layer is generally shallower in lower wave energy environments, a reduction in wave height may lead to a rise in SST (Largier et al. 2008). Although it is uncertain whether a WEC device could significantly reduce the depth of the mixed layer, if it did the degree to which this would alter the species composition of nearshore communities would depend not only upon how much SST increased, but possibly also how close the given community was to a biogeographic boundary, like Point Conception (Pielou 1979) and Point Reyes (see http://cbsurveys.ucsc.edu for more info). For similar reasons, since the depth of the mixed layer affects how much any substance released into the water will be diluted, reducing wave energy could also change the distribution of pollutants/contaminants in the nearshore environment (Largier et al. 2008). This could affect the abundance of species sensitive to these substances.

Although it operates at a much smaller spatial scale, another factor that can influence species distributions along the coast is wave exposure. Due to wave diffraction, the amount of energy an incoming wave imparts to the nearshore environment depends upon the geomorphology of the shore. Specifically, wave energy tends to be concentrated at points/headlands and dissipated in bays/inlets. Since species differ in their ability to live in fast moving water, the composition of the community can differ even between adjacent sites. For example, the area of the shore dominated by the alga *Saccharina* (= *Hedophyllum*) *sessile* in more wave protected sites is occupied by *Lessoniopsis littoralis* in higher wave energy areas (Dayton 1975). Similarly, the alga *Postelsia palmaeformis* is common in high wave energy areas, but absent from more protected locations (Paine 1979; Nielsen et al. 2006). As previously mentioned, in subtidal kelp forests *Macrocystis pyrifera* is found in wave protected areas, while *Nereocystis luetkeana* occurs in wave exposed locations. Since species like *M. pyrifera* and *S. sessile* are canopy species that provide structure or shelter to other species, their distributions affect the distribution of many other species in community. Thus, a reduction in wave exposure that alters their distribution could lead to dramatic changes in the composition of the community.

While reducing wave exposure might allow less *robust* species to occupy areas previously too energetic for them, the composition of the community could also change because wave exposure influences how ecological processes like predation, competition, and disturbances affect community structure (e.g. Menge and Sutherland 1976, 1987). For instance, because the ability of predators to search for and feed on prey is reduced in high wave energy environments (Menge 1978; Sebens 2002), rates of mortality tend to be higher in wave protected areas (e.g. Menge 1976; Boulding et al. 1999; Robles and Desharnais 2002). Thus, a reduction in wave energy could alter the relative abundances of species in the community. Similarly, differences both algal biomass and diversity between exposed and protected sites have been linked to differences in grazing pressure and nutrient availability (Nielsen 2001, 2003). Interestingly, since the intensity of competition depends upon population size, competition tends to be less important where rates of predation are high. Thus, reducing wave energy could also decrease the relative importance of competition. For example, because predation on the mussel *Mytilus californianus* by the seastar *Pisaster ochraceus* is more intense, *M. californianus* is less abundant and occupies less of the shore in wave protected areas (e.g. Robles and Desharnais 2002). Since *M. californianus* is the competitive dominant (Paine 1966, 1974), any changes in its abundance can have important consequences for the structure of the entire community.

4.1.11 Wave Induced Disturbance

A disturbance is an unpredictable event that can indiscriminately kill individuals. In the nearshore environment, disturbances are usually the result of large waves striking the shore. For instance, large, storm-generated waves can cause large boulders to flip or roll (e.g. Sousa

1979a, b; McGuiness 1987a, b), can rip organisms from the substrate (e.g. Dayton 1973; Paine 1979, 1988; Paine and Levin 1981), or cause water borne objects, like logs (Dayton 1971), to impact the shore. The net result of these events is the removal of individuals from an area of the substrate (= mortality), thereby creating a patch of open space. Since this exposes the surviving individuals to more hydrodynamic force (Denny 1987; Bell and Gosline 1997), once a patch is formed it is not uncommon for subsequent waves to enlarge it (e.g. Dayton 1971; Denny 1987; Guichard et al. 2003). In kelp forests this can happen when a *disturbed* kelp plant entangles itself around its still attached neighbors, causing them all to get ripped from the substrate (Rosenthal et al. 1974).

Interestingly, although many studies have examined the role of disturbance in communities, there is surprisingly little data on whether the frequency and size of disturbance events varies among sites that differ in wave exposure. What is available suggests that the size of disturbance events increases with increasing wave exposure (Paine 1979; Menge et al. 2005). This is supported by evidence that more wave-related disturbances appear to occur during the winter, when wave energy is high, than during summer (e.g. Paine and Levin 1981; Menge et al. 1993; Blanchette 1996).

However, there are data suggesting that because the agents of disturbance can also vary with exposure, the total area disturbed may not differ between exposed and protected sites. Specifically, Menge et al. (2005) found that while the patches created in exposed locations were larger, more patches were created in protected areas. Thus, it is possible that a reduction in wave exposure might not change the amount of mortality caused by disturbances. However, because patch size is important in terms of succession (see below), if a reduction in wave energy affects patch size it could affect the species composition of the community.

Succession is the process by which, following a disturbance, the species composition of a patch changes over time. This occurs because species differ in their ability to colonize (dispersal ability) and persist (competitive ability) in these patches. Often these traits are inversely related; that is, species that are good at dispersal are poor competitors, while good competitors are poor dispersers (e.g. Connell and Slatyer 1977). Thus, the species that initially colonize a patch (= good dispersers) are often replaced by species that arrive later but are better competitors. Both the frequency and size of disturbances can influence species composition. How often disturbances happen is important because it can determine whether a given area is dominated by early (frequent disturbances) or late (infrequent disturbances) successional species (Sousa 1979a; Connell 1978). It can also determine the overall diversity of the community (Connell 1978; Lubchenco 1978; Sousa 1979a). Patch size is important because it can affect a number of processes like grazing intensity, recruitment, and competition (e.g. Sousa 1984; Keough 1984; Farrell 1989). For example, Sousa (1984) found that small patches tended to be dominated by algae that are more resistant to grazing (e.g. *Analipus japonicus* and *Cladophora columbiana*), while large patches were dominated by species that are more susceptible to grazing (e.g. *Ulva californica*, *Fucus gardneri* and *Pelvetiopsis limitata*). Since, as discussed above, a reduction in wave energy could change both the frequency and size of patch creation, it could affect the structure of the community. However, additional information is needed to be able to predict exactly what these changes might be. For example, the diversity of the community could either increase or decrease with a reduction of wave energy depending upon the initial level of disturbance (see Connell 1978; Lubchenco 1978; Sousa 1979a).

An important agent of disturbance in the subtidal habitat is the rolling of boulders along the seafloor. The larger the boulder, the greater the hydrodynamic forces needed to move it. Since wave induced water movement decreases with depth, this type of disturbance is more likely to occur in shallower water. By reducing wave energy, the range of depths subject to this type of disturbance would potentially decrease.

Additional disturbances could occur if structures from the WEC devices become dislodged and impact the shore. The likelihood/frequency of these disturbances is unknown, but their consequences to the nearshore community are worth considering.

4.1.12 Sediment Transport and Deposition

As previously discussed (Largier et al. 2008), the movement and deposition of sediments in the nearshore environment are processes that are strongly affected by wave energy. In general, the amount and size of the sediment suspended in the water column is positively related to wave energy. Thus, if wave energy is reduced, the amount of sediment deposition in the nearshore environment should increase as smaller particles come out of suspension. Because this would affect the longshore transport of sediments, and change the size distribution of particles in the nearshore environment, this could have important impacts on nearshore communities.

At some rocky shore sites sand is an important agent of disturbance (e.g. Menge et al. 2005). Depending upon the velocity of the water, sand can either act like an abrasive that scours organisms with each passing wave, or settle out of the water column and bury the organisms on the surface of the rock (Littler et al. 1983; D'Antonio 1986; Menge et al. 1994). Since organisms differ in their ability to tolerate these processes, the distribution of species both within (e.g. D'Antonio 1986) and among sites (e.g. Schoch and Dethier 1996) can be influenced by sand. Thus, anything that affects the transport of sediment in the nearshore environment could affect the structure of rocky intertidal communities. However, to be sand influenced requires a nearby source of sand. Since there are many rocky shore sites along the coastline where this is not true, these effects will not be universal, and need to be considered on a site-by-site basis.

Unlike on rocky shores, where organisms live attached to the surface of the rocks, those in sandy beach communities live buried within the sediment. While this insulates them from the hydrodynamic forces rocky shore organisms must deal with, this lifestyle presents its own set of challenges. Specifically, because sediment deposition varies with wave energy, the shape and particle size of sandy beach habitats are dynamic and subject to change depending upon current conditions. In general, because there is little sediment deposition, beaches in high energy environments (dissipative beaches) have shallower slopes and are composed of finer sediments than those in low energy environments (reflective beaches). Since waves on high energy beaches break farther offshore, conditions on these beaches are actually more benign than those on reflective beaches. In fact, studies indicate that species richness and abundances/biomass tend to be higher on dissipative beaches than reflective beaches (Defeo and McLachlan 2005). Since a reduction in wave energy could increase sand deposition, this could affect the shape of the beaches and, therefore, the structure of the community. These changes could also be important for some beach spawning fish (Nelson 2008a). However, because our current understanding of what determines the structure of sandy beach communities is still limited (Defeo and McLachlan 2005), it is difficult to predict exactly what these changes would be.

Estuarine/wetland habitats could be also be affected by the attenuation of wave energy. Primarily, a reduction in wave energy could alter the dynamics of beach openings to smaller estuaries, by affecting the time the estuary is closed to the ocean. This could greatly impact benthic estuarine species, as well as birds and fish, especially those dependent on regular opening and closing events for food, nutrients, and a path to and from the ocean. In addition, the characteristics of sediments entering estuaries, primarily grain size, could be altered, causing additional impacts to estuarine communities. Unlike species along the rocky and sandy shores, many estuarine species would not have the opportunity to move to a more hospitable location, and would suffer if unable to adapt to these changes.

4.1.13 Growth Rate

To live in a wave swept environment, many nearshore organisms have adopted a sessile lifestyle. Because this precludes them from searching for food, they rely on water movement to supply them with needed nutrients (algae) or food (suspension feeders). Thus, the rate at which an individual grows will depend upon how much food/nutrients it can collect from the water as it flows over them. Since for many species reproductive output is often positively related to size (e.g. Hines 1978; Leslie 2005; Phillips 2007), anything that affects growth rates will also affect reproductive rates. Similarly, since the ability to remain attached to the substrate in moving water (Denny et al. 1985; Gaylord et al. 1994; Blanchette 1997) and, for some species, the risk of predation (e.g Paine 1976, 1979; Sommer et al. 1999; Smith and Jennings 2000) depends upon size, anything that affects growth rates can also affect mortality rates.

In general, for a given concentration of food/nutrients in the water column, the rate of delivery increases with the velocity of the water. Thus, growth rates of suspension feeders tend to be greater in high wave energy environments (Menge 1992; McQuaid and Lindsay 2000; Steffani and Branch 2003). Consequently, by reducing food availability, a reduction in wave energy could reduce growth rates. However, for some species the ability to successfully capture particles is reduced in faster moving water (Eckman and Duggins 1993; Trager et al. 1994; Okamura 1984, 1987). Thus, for these species the extent to which their growth is affected will depend on which factor, (food supply or feeding efficiency), is more important. Since particulate and dissolved matter from the senescence/degradation of kelp appears to be an important food source for suspension feeders (Duggins et al. 1989), growth rates could also be depend upon the extent to which algal growth is affected changes in wave energy (see below).

Algal growth can be limited by the availability of nutrients (Nielsen 2001, 2003) or light (e.g. Nielsen et al. 2003). As with suspension feeders, algae rely on water movement to supply them with nutrients. Thus, a reduction in wave energy could reduce the supply of nutrients. However, reducing wave energy could also decrease the amount of particulate matter suspended in the water column (see *Sediment transport and deposition above*). Since particles in the water column essentially block light, this would increase the amount of sunlight available for use in photosynthesis. Thus, whether a reduction in wave energy would affect growth rate could depend upon the extent to the individuals in the population are limited by nutrients or sunlight.

4.1.14 Dispersal and Fertilization Rate

Most nearshore species reproduce by releasing either gametes or larvae/propagules into the water column. Depending upon the species, the duration of this stage can last from minutes to months. Since, during this time, they are subject to the movements of the water column, these propagules can, depending upon larval duration, end up traveling from meters to hundreds of kilometers away from their parents (Shanks et al. 2003). Because a reduction in wave energy could affect nearshore circulation (Largier et al. 2008), this could decrease the distance the larvae/propagules produced by the local population disperse along the shore. For those species with longer larval durations, this could have important consequences for the genetic structure (e.g. Todd 1998) and possibly the dynamics of their populations (Underwood and Fairweather 1989, however see Eckert 2003). In comparison, species with shorter larval durations, which includes most species of algae, usually do not travel far. While their dispersal distances would also potentially decrease, it is unclear how this would affect the dynamics of their populations. However, it could affect their ability to find newly created patches of open space (e.g. Sousa 1985, 2001; Menge et al. 1993), which would affect the rate at which the community would recover following a disturbance.

For those nearshore species that release gametes into the water column, whether fertilization occurs will depend on not only whether sperm and egg encounter one another, but also on whether the hydrodynamic conditions permit them to merge. This makes it difficult to predict how a reduction in wave energy will affect rates of fertilization. If, as discussed above, reducing wave energy decreases dispersal distances, it is possible that the encounter rates would decrease if the sperm must travel to the egg. However, since the concentrations of gametes released into the water decreases dramatically with distance from the adult (Pennington 1985; Oliver and Babcock 1992), if eggs and sperm are released simultaneously it is possible that encounter rates would increase. Since fertilization success is inversely related to turbulence (Mead and Denny 1995), the rate of fertilization may be higher since reducing wave energy would reduce turbulence once contact is made. Thus, whether a reduction in wave energy will alter rates of fertilization could depend upon the relative importance of these processes. If the number of larvae/propagules produced were changed, this would likely only affect the settlement of those species with limited dispersal ability. For algae, this could change the relative abundance of the gametophyte and sporophyte stages (see Thorner and Gaines 2003), which, since these two stages can differ in their susceptibility to grazers (e.g. Lubchenco and Cubit 2000; Thornber et al. 2006), could affect the structure of the community.

4.1.15 Settlement

For many species the juveniles present in a population are not the offspring of the local adults. Instead, they are larvae/propagules produced by distant adults that have transported to the population via water movement (oceanographic processes). A successful larva/propagule is one that, at the end of the planktonic stage, returns to the shore and undergoes settlement to become a juvenile. Consequently, anything that affects the number of larvae delivered to a site can have important consequences for the dynamics of the population (Caley et al. 1996).

There are essentially two ways an offshore WEC device could affect onshore settlement. The first involves the physical presence of the device. Unless covered with some type of antifouling coating, the hard surfaces of the device would serve as suitable substrate for many nearshore organisms. Since any currents traveling shoreward would encounter the WEC device first, any larvae that settled onto the device would then not be available to settle on the shore (e.g. Gaines et al. 1985). Further, the presence of the WEC device in the water column would potentially attract a variety of fish species, including planktivorous species commonly associated with kelp beds. Since many of these planktivores feed on the larvae/propagules of intertidal species, their presence could further reduce the number of larvae reaching the shore (e.g. Gaines and Roughgarden 1987). Of course, if the larvae that settle on the device survive to reproductive age (which could depend on WEC maintenance schedule), their progeny will be added to the pool of larvae available for settlement onshore. How many of these larvae end up settling in the populations directly inshore of the WEC devices would depend, in large part, on the species' dispersal potential (e.g. Shanks et al 2003).

Onshore settlement could also be affected by any reductions in wave energy. Once a larva reaches the shore, to enter the local population it must not only come in contact with an appropriate place to settle, but also remain there long enough to metamorphose into a juvenile. Both of these processes are affected by the rate of water movement. Specifically, for a given concentration of larvae in the water column, the number of larvae that come in contact with a given settlement site is proportional to the rate of water movement. Thus, a reduction in wave energy could reduce the number of potential settlers delivered to a given settlement site. However, this reduction could also decrease the chances that those that do arrive are swept away (e.g. Todd 1998; Taylor and Schiel 2003; Jonsson et al. 2004). Therefore, whether or not a reduction in wave energy would affect settlement will depend upon the relative importance of these two processes. The fact that the recruitment of some species is greater in areas where water velocity is low enough for sand deposition to occur is suggestive (Pineda 1994).

However, it is important to note that any changes in the rate of settlement are only important if the amount of settlement is insufficient to utilize all of the available resources (e.g. Caley et al. 1996). On rocky shores such *recruitment limited* populations are ones where there are too few settlers to occupy all open space on the rock. Under these conditions, any changes in the amount of settlement would ultimately lead to variations in the number of adults. In contrast, in *recruitment unlimited* populations the number of settlers exceeds that supportable by the available resources. For these populations the number of adults is independent of the magnitude of settlement. Therefore, any changes in the amount of settlement would not affect the number of adults. Of course, it is possible that if settlement was reduced enough, a recruitment unlimited population could become recruitment limited. Thus, to determine whether a change in wave energy would lead to changes in adult abundance it is important to not only measure settlement, but to also determine whether the population is recruitment limited or unlimited. Current information suggests that some populations along the California coast are recruitment limited (Connelly and Roughgarden 1998).

Priority Research Needs

Although the amount of wave energy striking the shore is a continuous function, most information about the effects of wave energy on the structure of nearshore communities is based on studies that have compared 'protected' and 'exposed' sites. Thus, additional information about the biological response to small changes in wave energy in the 0-15% range (Faber Maunsell et al. 2007; Largier et al. 2008) is clearly needed. Although it is possible to estimate some of the types of changes that can occur (Table 5.2), until empirical information is available, it is difficult to predict the extent to which nearshore populations and communities will change. The following suggestions (below) could prove useful in making these predictions:

1. *Conduct quantitative surveys:* Since wave energy varies naturally along the shore, one way to potentially assess the effects of WEC devices on nearshore communities is to conduct biological surveys at sites that differ in wave exposure. To minimize any differences in other physical factors (e.g. sea surface temperature, upwelling regimes, composition of the substrate), the sites surveyed would ideally be located within a small region of coastline. If the wave regimes of the sites are also quantified, correlations between differences in community structure (e.g. species diversity, relative abundances, size distributions, variations in spatial patterns) and wave energy could be used as a predictive tool to estimate the potential effects the installation of WEC devices will have on nearshore communities. This information could also be useful in directing future research to determine the exact mechanism(s) (Table 5.2) by which small changes in wave energy affects populations/communities.

2. *Develop measurement tools:* Although there are currently devices in use to measure wave energy (e.g. Bell and Denny 1994; Gaylord 1999) these only measure the maximum wave force experienced over the period of deployment. Thus, the development of a device that gives a better temporal resolution to the variations in wave energy on the shoreline would be welcome.

3. *Develop predictive models:* The development of coupled empirical-hydrodynamic models that examine the relationship between wave energy and community structure could increase our ability to predict and mitigate impacts to ecological communities resulting from wave energy devices.

Table 4.2. Summary of predicted impacts to nearshore biological processes due to the reduction of wave energy

Nearshore biological process	Potential impacts due to a decrease in wave energy
Species distribution and vertical zonation	• Change in size and location of intertidal zones (would decrease in width and shift downward) • Change in size of subtidal surf zone (would decrease in width)
Community composition	• Shift in geographic range of some species if local SST rises, especially if near a biogeographic boundary • Change in species composition and relative abundance of local communities
Wave induced disturbance	• Change in species composition of the community if frequency and size of patch creation is reduced • Alteration of mortality rate of species
Sediment transport and deposition	• Increase in sediment deposition, causing changes in longshore transport and particle size distribution • Change in beach shape and structure of sandy beach community • Change in dynamics of estuary closure/opening events
Growth rate	• Decrease in the rate of food supply for suspension feeders, could increase feeding efficiency for suspension feeders; overall change will depend on the relative importance of these two processes • Decrease in the rate of nutrient supply for algae, increase in light availability; overall change will depend on the relative importance of these two processes
Dispersal and fertilization rate	• Decrease in dispersal distance/increase in larval retention, could affect the structure of the community • Increase or decrease in encounter rate of gametes depending on species; increases success of fertilization
Settlement	• Decrease in onshore larval delivery, increase in successful attachment; changes to settlement rate will depend on the relative importance of these two processes. These changes will only be important if the population is recruitment limited

Source: Lohse et. al.

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5.0 Ecological Effects of Wave Energy Conversion Technology on California's Marine and Anadromous Fishes

Peter A. Nelson

H. T. Harvey & Associates

Abstract

Wave energy conversion (WEC) development is likely to produce localized effects on the ecology and possibly the behavior of California fishes. Natural habitat will be altered by introducing hard substrate and vertical structure; thus, a clear implication is that WEC installations will function much like artificial reefs and possibly as FADs (Fish Aggregation Devices). The ecological effect of an artificial reef is principally a local change in fish distribution and diversity. WEC installations will likely act similarly, and site selection will be important in determining the localized effects. WEC devices and their operation may also generate stimuli such as acoustic or electrical signals with potential effects on fish behavior. Pilot projects offer the means to test for fish response to WEC technology, but how project spatial and temporal scales will moderate project effects is a major unknown, and collecting baseline information prior to project deployment is crucial.

Introduction

Wave energy conversion (WEC) installations will likely have both positive and negative effects on California fishes. The primary anticipated effect is that of habitat conversion, which occurs when one habitat is altered so it functions in a manner ecologically comparable to another habitat. WEC installations are likely to act as artificial reefs, particularly in soft bottom areas where anchoring and mooring gear will add vertical relief and provide hard substrate. Mid-water and surface elements of these structures may also aggregate fishes in a manner analogous to Fish Aggregation Devices (FADs, Hunter and Mitchell 1967). Potential direct, negative effects include behavioral changes due to electromagnetic fields (EMF), but indirect effects are also possible, and include decreased fish density at nearby natural reefs, and increased predation on special status species[45].

This chapter examines the impacts of WEC technology on fish behavior and ecology, evaluates spatial and temporal impacts across a range of scales, reviews the species or species-groups

45 Species petitioned for or officially granted threatened or endangered status; also species that enjoy unusual legal protection such as White Sharks, *Carcharodon carcharius.*

likely to be affected by WEC systems, and describes the range and variety of potential behavioral and ecological responses to these installations. The smallest projects are analogous to navigational buoys, but larger systems, particularly multiple arrays distributed along many kilometers of coastline, have no obvious anthropogenic analogue. This chapter concludes by identifying key knowledge gaps and research priorities.

Components of WEC Technology

Understanding the components of WEC technology is important to anticipating their possible effects on fish biology and ecology. Chapter 1 (this volume) offers a brief overview of WEC design options; further details are available from the EPRI website (oceanenergy.epri.com, EPRI 2008), in PIER (2008) and from the Minerals Management Service (2007). WEC technology is evolving and specific device descriptions quickly become dated; consulting a particular manufacturer's website or contacting them directly is the best way to get current information.

A generic, offshore WEC system would include these components:

- Wave energy conversion device(s), located at any depth from surface to bottom;
- associated buoys, cables, and anchors; and
- buried or anchored power transmission line(s) that connects the WEC system to the power grid.

The energy conversion device and the system of buoys and lines associated with its anchor system is discussed below given the assumptions that the energy conversion device and power-bearing lines have the potential to emit electromagnetic fields, and that all off-bottom buoys and lines fundamentally add vertical structure and hard substrate to the local environment. The impact of connecting WEC-derived power to transmission lines will be greatest during deployment and decommissioning. Onshore installations are constructed in natural surroundings (beaches, cliffs, bluffs) or on man-made features (piers, jetties). Onshore installations generally present fewer and shorter cables and anchors than WEC devices, but do require foundations if keyed into natural surroundings. Because WEC derived power must be connected to the onshore power grid, a buried transmission line, in the case of onshore installations, is unnecessary (PIER 2008).

Effects of Project Size

Project size is an obvious factor when considering WEC impacts on fish, but project size may not cause proportionally sized impacts (Lohse et al. Chapter 4). This section discusses the potential effects of three categories of project size: pilot projects, commercial projects, and regional projects.

5.1.1 Pilot Projects

Pilot projects are generally characterized by their small spatial scale and temporary nature (<5 years, Nelson and Woo Chapter 1), and are likely to cause local and direct effects on fish behavior and distribution. Their effects are expected to be manifest within ca. 500 m, and to be largely individually based with minimal or no effects on the fish community or demographics of nearby natural sites. Pilot projects allow the study of fish behavioral responses, for example monitoring temporal patterns of association through sampling or direct observation with remotely operated vehicles (ROVs) or divers. While localized artificial reef/FAD effects are likely, effects to fish production or distribution associated with nearby natural habitat are assumed to be negligible due to a pilot project's temporary nature and limited footprint. The fishes expected to recruit to these installations would number in the hundreds or low thousands, which are too few to have a discernable effect on local populations or on area reefs.

5.1.2 Commercial Projects

At greater sizes and operating over longer time periods, commercial-scale WEC installations may affect the distribution of fish populations on surrounding reefs. In locations where habitat availability limits local populations, commercial-sized WEC installations may increase total fish biomass (Figure 5.1). This increase may vary among species, locations and oceanic conditions, where, for instance, offshore productivity affects larval survival and subsequent recruitment. The appearance of a diverse fish assemblage around a WEC installation is not necessarily indicative of an increase in local fish biomass, however, as these fishes may have left nearby natural reefs with no net increase in total abundance. An increase in fouling community biomass on artificial substrates must represent increased local production, so some degree of biomass increase is associated with artificial reefs, and the short-term accumulation of post-settlement age fishes associated with a new artificial reef is necessarily the product of re-distribution rather than production.

For artificial reefs, the 'distribution versus production' debate is still unresolved (Brickhill et al. 2005; Bortone 2006), and some negative effects of artificial reefs and habitats have been posited (Grossman et al. 1997; Mason 2003). Other studies however, have suggested that artificial habitats have the potential to contribute to stock recovery (Love et al. 2006), and Love et al. (2007) suggest that oil platforms may serve as juvenile rockfish nurseries (as defined by Beck et al. 2003). The magnitude of an artificial reef effect is strongly correlated with project size (Bohnsack et al. 1991).

Commercial-scale projects are expected to remain in operation for greater lengths of time than pilot projects. For longer-lived species (e.g., rockfishes: *Sebastes* spp), operations spanning twenty-five years or more would be sufficiently long to impact local populations.

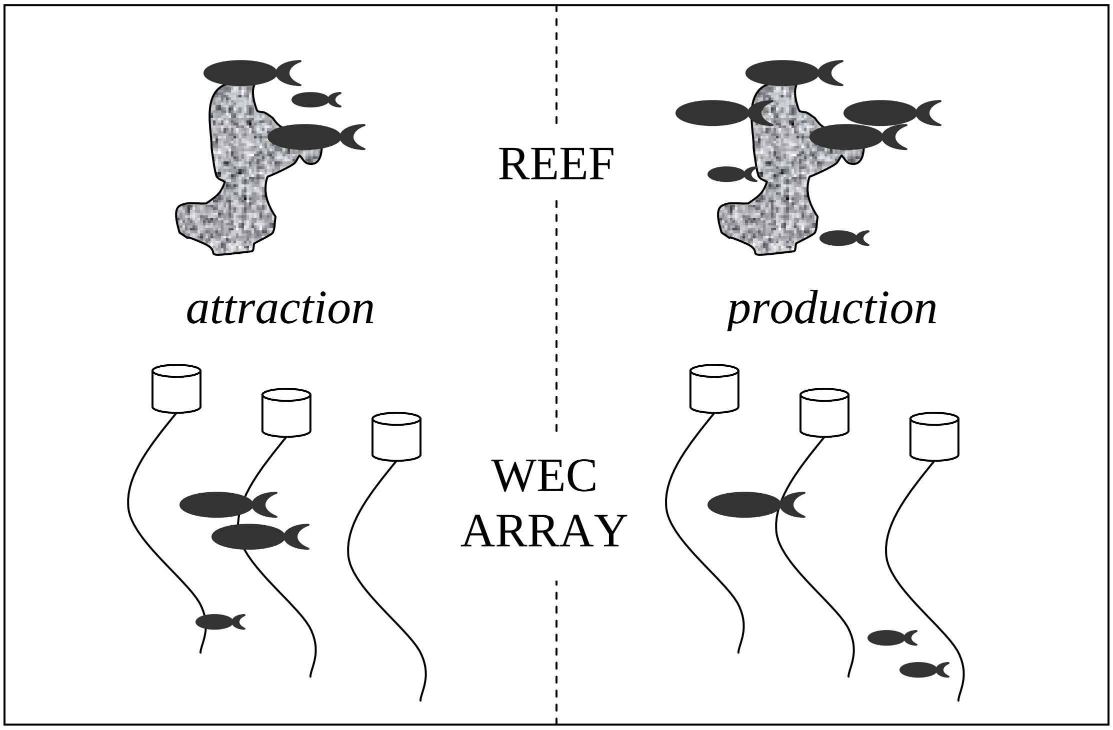

Figure 5.1 Ecological effects of attraction versus production at a WEC array

WEC arrays (bottom) are likely to function as artificial reefs, either attracting (left) migrating adults and juvenile recruits or enhancing (right) local biomass by increasing otherwise limiting natural habitat (top) for juvenile recruits or adults
Source: Nelson

5.1.3 Regional Projects

Would multiple commercial WEC installations result in cumulative and regional effects? Some regional impacts could be anticipated from studying pilot and isolated commercial projects, but effects at the population-level may be difficult to anticipate and could be region-specific. For example, a series of WEC arrays could provide “stepping stones” between subpopulations, increasing the rate of genetic exchange between these units, thus affecting the genetic structure of the population. For example, Hastings (2000) argues that the soft bottom habitat that separates stretches of rocky Mexican and Central American coastlines represents a significant barrier to dispersal and migration in chaenopsid fishes. While the barriers described by Hastings (2000) are substantial, genetic discontinuity over short coastline distances can be significant (Dawson et al. 2006). Genetic patterns may also be due to competitive interactions between sister species (Bernardi 2005) rather than vicariance, evolutionary divergence caused by physical barriers.

Multiple commercial WEC installations and a strong artificial reef effect could cause population-level effects on abundance if habitat availability is limiting. However, this would be difficult to distinguish from other factors (fishing, productivity, climate change). Controlled studies that address the relative importance of attraction versus production on multiple commercially sized WEC installations may inform ecological effects on a larger regional scale.

Site Selection and Habitat Change

5.1.4 Habitats and Habitat Value

The WEC installation location determines which habitat(s) will be affected, both directly and indirectly. In California, a variety of habitat types are found in areas maximally exposed to wave energy, including the following habitat types, as identified by California's Marine Life Protection Act (California Department of Fish & Game 2008): rocky reefs, intertidal zones, sandy or soft ocean bottoms, and kelp forests. Other habitats (e.g., underwater pinnacles, seamounts, submarine canyons and seagrass beds) are assumed to be incompatible with WEC due to depth, bathymetry or conservation issues. Largier et al. (Chapter 3) and Lohse et al. (Chapter 4) describe anticipated WEC effects on habitat.

Quantitative metrics for evaluating habitat (Bond et al. 1999) or species diversity (Magurran 1988) may be useful for selecting and comparing alternative WEC sites. Habitat valuation techniques are usually a measure of biodiversity applicable to sites with comparable habitat; ostensibly, such techniques permit two or more similar sites to be compared in terms of their relative importance or worth. These methods, whether quantitative or not, are inappropriate for examining WEC impacts: for example, soft bottom habitat altered by the addition of WEC concrete footings cannot be compared to soft bottom control sites because the impact site has been radically altered. The exercise would degenerate to comparing the 'values' of fundamentally different habitats. There would be value in comparing WEC sites to neighboring natural reef sites (Carr and Hixon 1997), and these studies could substantially contribute to understanding WEC effects on fish ecology, and to an improved knowledge of artificial habitats generally (Brickhill et al. 2005).

WEC components in mid-water or at the surface may have a 'FAD effect' (FAD: Fish Aggregation Device), serving as the spatial focal point for a fish assemblage not associated with the ocean bottom (Rountree 1990; Kingsford 1993; Hair et al. 1994). The distinction between artificial reef- and FAD-effects depends partially on the location of the device (ocean bottom versus mid-water or surface) but mostly on the manner of a fish's association. Artificial reefs are assumed to function primarily as habitat, but fish response to FADs appear to be one principally of orientation and secondarily one of habitat association, although this is likely to vary among species (Hunter and Mitchell 1967; Dooley 1972; Nelson 1999; Castro et al. 2002). Rocky reef species are typical recruits to artificial reefs (Reed et al. 2006). Juveniles of substrate-associated species and pelagic fishes are attracted to artificial structures (FADs) at the surface and mid-water (Mitchell and Hunter 1970; Parin and Fedoryako 1999; Dempster and Taquet 2004), but studies of FAD- or flotsam-associated fishes in temperate waters are few compared to tropical studies. The most relevant studies to WEC off California are a handful of studies on drift algae and associated fishes (Mitchell and Hunter 1970; Kingsford 1992; Kingsford 1995b), but these are all from the Southern California Bight, a distinct biogeographic province from the geographic focus of this white paper.

The siting of any WEC project determines which habitats are modified, and the modified habitats determine which fish assemblages are affected. Therefore determining which habitats may be impacted, how potential impacts may manifest themselves on biological communities, the potential for mitigation (if necessary), and identifying alternative WEC sites are important steps in selecting potential sites. Despite the complexities associated subjectivity, some measure of habitat valuation might also be considered. Areas of high fish biomass or diversity are typically granted greater conservation, commercial, or recreational importance, but areas of low fish biomass or diversity are not necessarily indicative of low habitat value (Hobbs and Hanley 1990). In many instances, the basic understanding of how habitat characteristics affect fish distribution is lacking, so anticipating the effects of change is difficult.

5.1.5 Fish Distribution and Habitat Alteration

Fish distribution is closely associated with habitat (Allen and Pondella II 2006). Diverse fish species inhabit the surf zones, rocky reefs, and coastal surface waters of California. These fish species are rarely unique to a particular habitat, but form an identifiable ecological assemblage (Allen et al. 2006a). When habitat is altered, change in the fish community often follows. Indeed, this is the principle behind constructing artificial reefs; the local fish community responds dramatically to this form of habitat alteration (Seaman and Sprague 1991).

The effects of habitat alteration are expected to vary among species. For example, vertical relief and hard substrate added to a flat, soft bottom area (as would occur when WEC footings, devices, and cables are installed) are likely to draw typically reef-associated fishes (Solonsky 1985; Pondella et al. 2006). Presumably this comes at the cost of habitat for some members of the soft bottom fish assemblage. A substantial reduction of onshore wave energy within the shadow of a WEC array may also alter habitat (Largier et al. Chapter 3); changes in beach characteristics may affect beach-spawning fishes. These fishes include Grunion (*Leuresthes tenuis*), Surf Smelt (*Hypomesus pretiosus*) and Night Smelt (*Spirinchus starksi*), all species that spawn on the beach slope and deposit their eggs on or beneath the surface of the sand or gravel (Martin and Swiderski 2001). Although they share wave slope location preferences, their preferences in substrate grain size and slope steepness differ (as do their latitudinal distributions). Grunion spawn on fine sand beaches (Walker 1952), but Surf Smelt and Night Smelt select steeper beaches with coarse sand or gravel (Mike Zamboni[46], personal communication, June 12, 2008) (Thompson et al. 1936). Beach slope and grain size are partially functions of wave energy (Bascom 1979; Largier et al. Chapter 3), and therefore WEC installations have the potential to affect local spawning habitat for these fishes. Alterations in wave energy are also likely to affect the availability or distribution of wrack, the detached macroalgae and marine plants that may accumulate in surf zones. Here, this material provides fishes, especially juveniles, shelter from predators and prey habitat in an otherwise exposed environment (e.g., Crawley et al. 2006).

Coastal marine habitats potentially affected by WEC can be categorized as intertidal, surf zone, pelagic, reef-associated, and soft bottom habitats. Due to shared ecological traits, species belonging to the fish assemblages associated with these habitats may be exposed to the same

46 Commercial beach fisherman, Trinidad, Humboldt County, California

potential project effects. Because of the predictable association between fish species and habitat type, these associations may be used to anticipate at a basic level the probability that WEC technology will affect particular species guilds and the type of potential effects to which these fish assemblages may be exposed (Table 5.1).

Table 5.1. Habitat types, potential for WEC effects, and candidate species

Species were selected to represent a diversity of ecological strategies, and to include special status species and several of commercial or recreational significance. Probability of effect was a subjective determination based on a species' natural history and the expected changes to habitat and ecological communities (Largier et al. 2008; Lohse et al. 2008).

Habitat	Impact type	Effect description	Common name	Scientific name
Probability of potential effect: High				
Reef-associated	Direct	Habitat expansion (artificial habitat)	Cabezon	Scorpaenichthys marmoratus
			Copper Rockfish	*Sebastes caurinus*
			Kelp Greenling	*Hexagrammos decagrammus*
			Rosylip Sculpin	*Ascelichthys rhodorus*
Probability of potential effect: Moderate				
Soft bottom	Direct	Habitat loss (WEC installation in soft bottom habitat)	Big Skate	*Raja binoculata*
			Spotted Cuskeel	*Chilara taylori*
			Sand Sole	*Psettichthys melanostictus*
			Green Sturgeon	*Acipenser rostris*
Pelagic	Direct	Habitat alteration (introduction of EMF)	White Shark	*Carcharodon carcharias*
Probability of potential effect: Low				
Intertidal	Indirect	Habitat alteration (reduction in local wave energy; alters magnitude and frequency of wave-generated disturbance; alters algal community)	Tidepool Sculpin	*Oligocottus maculosus*
			Monkeyface Prickleback	*Cebidichthys violaceus*
			Plainfin Midshipman	*Porichthys notatus*
			Penpoint Gunnel	*Apodicthys flavidus*
Surf zone	Indirect	Habitat alteration (reduction in local wave energy; alters beach and surf zone slope and bathymetry)	Redtail Surfperch	*Amphistichus rhodoterus*
			Calico Surfperch	*Amphistichus koelzi*
			Surf Smelt	*Hypomesus pretiosus*
			Speckled Sanddab	*Citharichthys stigmaeus*
Pelagic	Direct	Habitat alteration (introduces midwater and surface structure; FAD effects; local aggregation of predators or prey	Chinook Salmon	*Onchorhynchus tshawytscha*
			Eulachon	*Thaleichthys pacificus*
			Pacific Herring	*Sardinops sagax*
			White Shark	*Carcharodon carcharias*

Source: Nelson

Restrictions to public access in the vicinity of WEC installations may result in the creation of a *de facto* marine reserve, where fishes are protected from recreational or commercial fishing. At the commercial- or regional-scale, the effects on fish ecology could be substantial (Paddack and Estes 2000; Kaiser et al. 2007), and the interaction of California's Marine Life Protection Act[47] with wave energy development may have significant social and economic implications. There are numerous reviews of the science behind marine reserves (e.g., Carr 2000; National Academy of Sciences 2001; Pomeroy 2002; Sale et al. 2005; Blyth-Skyrme et al. 2006).

5.1.6 Coastline Features

Large-scale features of coastal geography include coastline orientation and shape, bathymetry, offshore rocks, islands, underwater pinnacles, and the proximity of coastal streams, rivers and estuaries. Each plays a role in fish biogeography by affecting, for example, larval dispersal or habitat characteristics. These are potentially important factors in anticipating the effects of WEC installations on fishes. These features are also relevant to WEC logistics, affecting wave exposure and local current patterns (Bascom 1979).

Habitat and biogeography together determine, to a considerable extent, which fish species will be exposed to WEC-associated impacts. Habitat types (e.g., kelp forests) are inhabited by a characteristic assemblage or guild of fishes (Stephens and Zerba 1981; Carr 1991; Lea et al. 1999; Allen and Pondella II 2006; Gunderson and Vetter 2006). Two reviews are particularly relevant to this discussion: Allen et al. (2006b) describe the fish fauna associated with the surf zone and sandy beaches, and Stephens et al. (2006) discuss the role of rocky reefs and kelp forests to California fish ecology. The biogeography of California fishes is reviewed by Horn et al. (2006).

Fish Behavior

The immediately observable effects on fish from WEC installation, operations and maintenance, and decommissioning, will be behavioral. Fishes respond to acoustic, mechanosensory, visual, chemosensory, magnetic and electrical stimuli. Species- and context-specific behavioral responses, assuming sensitivity, to these cues may range from attraction to aversion.

Fishes are sensitive to underwater acoustic or mechanosensory stimuli whether natural or of anthropogenic origin (Kalmijn 1989; Myrberg 1990). Noise associated with WEC installations may affect fishes directly or indirectly; for example, the noise could interfere with acoustic communication (Myrberg 1990). Although construction is a short-term activity, fish respond to and may exhibit lasting negative physiological effects due to underwater construction noise (Engås et al. 1996; Popper et al. 2005). Boat noise, for example, has been shown to affect fish behavior: Bluefin Tuna (*Thunnus thynnus*) schools showed reduced coordination and altered their swimming direction in response to vessel activity (Sarà et al. 2007).

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47 The MLPA mandates a network of marine reserves in California waters California Department of Fish & Game (2008) Master Plan for Marine Protected Areas, Revised Draft. California Department of Fish & Game, Sacramento.

Visual responses are likely to be primarily positive. The attraction to Fish Aggregation Devices (FADs), within range, is thought to be partially or largely visual (Rountree 1989; Dagorn et al. 2000; Dempster and Kingsford 2003). For example, fishes orient to flotsam and FADs using visual cues (Atz 1953; Senta 1966; Hunter and Mitchell 1967), but vision is insufficient to explain their long-term association, often at distances beyond what water clarity would permit (Nelson, personal observation; Dempster and Kingsford 2003).

Olfactory cues may complement vision, functioning at greater distances. When a fouling community develops on the exposed surfaces of a WEC installation, olfactory cues may recruit and orient fish. Nelson (2003) found that FADs with a fouling community attracted larger fish assemblages than FADs lacking a fouling community. Mitamura et al. (2005) demonstrated that olfaction was necessary to successful homing in the reef-associated rockfish, *Sebastes inermis*. Nonetheless, potential response to anthropogenic chemosensory signals is poorly understood, and most research has been conducted on freshwater rather than marine species (Blaxter and Hallers-Tjabbes 1992); however, pollutant compounds have been demonstrated responsible for changes to marine and freshwater fish behavior (Wibe et al. 2001; Johnson et al. 2007).

Electrical or magnetic fields are referred to collectively as “electromagnetic fields” (EMFs). EMFs are associated with communication, navigation, and feeding in a broad variety of fishes (Kalmijn 1974; Kalmijn 1982; Walker et al. 1997; Sisneros and Tricas 2002; Miller 2005; Lohmann et al. 2008). Due perhaps to the paucity and complexity of field experiments, and to the assumption that electrical transmission cables will be sufficiently shielded, some reports have been dismissive of the potential EMF impact associated with ocean energy projects (e.g., Valberg 2005). However, mesocosm experiments testing elasmobranch behavioral response(s) to WEC-associated EMF have been planned, and results should soon be available (Gill et al. 2005; Gill and Wearmouth 2007). Methods have also been developed for testing sensitivity to electrical changes (e.g., Kajiura and Holland 2002) and magnetic fields (Meyer et al. 2005) for fishes.

Life History and Temporal Patterns

Many marine and anadromous fishes undergo diel, seasonal, ontogenetic or reproductive migrations (Hobson et al. 1981; Gunderson et al. 1990; Mazeroll and Montgomery 1998; Arendt et al. 2001; Lindley et al. 2008) that may result in or affect the timing of their interactions with WEC arrays. Detailed life history information is lacking for many marine species, but seasonal, nearshore occurrence patterns for select Northern and Central California species are known (Table 5.2). While commercial or regional WEC installations are functionally permanent structures compared to the life span of some fish, construction, operation, and maintenance are periodic and should be considered in the context of fish life history. For example, the presence of a WEC array is inconsequential in the fall to Coho Salmon (*Onchorhynchus kisutch*) smolts but may have effects during the spring outmigration. Installation, maintenance, and decommissioning could be scheduled to reduce impacts on sensitive species.

Directed movement patterns may cause fishes to encounter WEC arrays. Some fishes make migratory movements on a diel or seasonal basis. Other fishes shift habitat in response to ontogeny or to changes in environmental conditions, for example, some rockfish species move with the onset of winter storms (Love et al. 2002). Reproductive or feeding aggregations may also draw fishes to a location defined by habitat or by food resources. Green Sturgeon (Acipenser medirostris, Erickson and Hightower 2007; Lindley et al. 2008) and salmonids (Loch and Miller 1988; Brodeur et al. 2004; Krutzikowsky and Emmett 2005; Melnychuk et al. 2007), in particular, are known to migrate through nearshore habitat likely to overlap with WEC arrays. Other fishes also exhibit directed movements or form aggregations that may cause them to encounter these arrays, but the detailed information required to anticipate such impacts is lacking.

Table 5.2. Relative frequency of occurrence by month in nearshore waters of selected central and northern California coastal fishes

Darker shades indicate a greater likelihood of encounter than lighter shades.

		Month											
Species	Life stage	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Chinook salmon, spring-run	Smolt												
	Adult												
Chinook salmon, fall-run	Smolt												
	Adult												
Coho salmon	Smolt												
	Adult												
Steelhead	Smolt												
	Adult												
Dungeness crab	All												
Black rockfish	All												
Blue rockfish	All												
Bocaccio	All												
Copper rockfish	All												
Cabezon	All												
Kelp greenling	All												
Lingcod	All												
Sand sole	All												
English sole	All												
Pacific halibut	All												
Big skate	All												
Spiny dogfish	All												
Leopard shark	All												
Soupfin shark	All												
White shark	All												

Source: Nelson

Types of Interactions

Interactions between fish and WEC arrays may range from direct and physical effects of WEC devices on the behavior or physiology of an individual fish, to indirect effects that manifest at the regional or population level (Table 6.3). Some factors are likely to have positive effects, at least with regard to select species (Table 6.3). For example, on the California North Coast, the addition of vertical relief will likely attract reef species such as Pile Perch (*Rhacochilus vacca*) or Black Rockfish (*Sebastes melanops*). Impact types may be divided into direct and indirect impacts. An example of a direct impact is the creation of flow refugia (places of reduced current where fishes can reduce their energetic cost of maintaining a position) that provide microhabitat immediately accessible to fishes. An indirect impact example is scour or deposition around anchor footings that may not affect fish habitat, but does affect benthic infaunal prey resources. These effects are assumed to be manifest across a range of spatial scales, some limited to the local vicinity (within 1 km) to a regional (100s of km) but not oceanographic (1000s of km) scale.

Table 5.3. WEC potential effect type and area, affected species and study priorities

WEC component or effect created by WEC	Distance over which effect occurs	Effect type (direct or indirect)	Minimum project size for effect	Affected species	Potential affect on fish	Study priority
Introduction or increase in fouling community	0 to 1 km	Direct	Commercial	Fishes associated with reef-like substrates; planktonic larvae cuing on "reef"	Change in settlement patterns	
Limits on commercial and sport fishing	0 to 1 km	Direct	Commercial / regional	Targeted and bycatch fish species	Local fishing mortality / fisheries impact	Monitor
Water quality changes due to anti-fouling compounds	0 to 1 km	Direct	Commercial	Fishes that bioaccum-ulate metals or other organics in anti-fouling fluids	Chronic toxicity effects	
FAD effect	0 to 1 km	Direct	Pilot	Fishes associated with Fish Aggregating Devices (FADs)	Change in distribution of select species	Monitor
Flow refugia	0 to 1 km	Direct	Pilot	Fishes associated with Fish Aggregating Devices (FADs)	Local refuges	
Electro-magnetic field (EMF)	0 to 1 km	Direct	Pilot?	Agnatha, Chondrichthyes, Acipenseriformes, Salmonidae, others?	Possible difficulty in navigation and foraging patterns	High study priority because effects are not understood, but see Figure 5.2
Artificial reef effect	0 to 1 km	Direct	Pilot	Fishes associated with artificial reefs	Change in community ecology	Medium study priority because effects are likely to occur but significance is not known
Scour/deposition around pier or anchor footings	0 to 100 km	Indirect	Commercial	Fishes that forage on benthic infauna	Local foraging patterns	

Seepage of hydraulic fluids	0 to 100 km	Direct	Commercial	Fishes that bioaccumulate metals or other organics in hydraulic fluids	Chronic toxicity effects	
Creation of a *de facto* marine reserve	0 to 10 km	Indirect	Commercial	Fishes associated with artificial reef & FAD	Local abundance pattern	Yes
Ecological effects	0 to 10 km	Indirect	Commercial	All fishes; predation may disproportionately affect special status species	Community ecology; predation	Yes
Increase in connectivity between habitats, demes	10 to 100s of km	Indirect	Regional	Fishes exhibiting low dispersal potential	Population genetics	Monitor
Creation of wave shadow	0 to 100 km	Indirect	Commercial	Fishes that inhabit the surf zone	Local abundance pattern	Monitor
Spill of diesel fuel or other oils associated w/ vessel accident	Dependent on magnitude of spill	Direct	Pilot	Fishes that cannot swim distance to escape spill effects	Respiration difficulty, chronic toxicity effects	
Underwater noise and sound pressure	0 to 100 km	Direct	Pilot	Fishes with hydrostatic organs	Assemblage composition	Yes
Habitat conversion	100s of km	Indirect	Regional	Fishes associated with artificial reef & FAD	Stock status, relative biomass or diversity of all affected species	Yes

Source: Nelson

Knowledge Gaps and Research Priorities

Several potential effects were identified as priorities for future research or monitoring (Table 6.3). In some instances (e.g., potential EMF effects), experimental research may be warranted; in others, monitoring may be sufficient. Study priorities were chosen by considering the expected magnitude of an effect, effect quality (perceived negative versus positive aspect), degree of risk (interaction of concentration and exposure), availability of scientific background information, and the potential to involve a special status species. These criteria are not intended to be definitive, but serve as a starting point for discussion.

Assessing the effects of potential stressors (such as noise or EMFs) should follow a logical sequence (Figure 5.2). Predicting and then establishing the characteristics of these stressors is an essential first step to avoid wasted effort. Subsequent experimental work may then focus on potential behavioral responses to stimuli within a known or expected range of parameters and on the species most likely to be affected.

EMFs are a study priority due to the uncertainty of their strength and range as associated with WEC technology, and due to their broad range of potential impacts. For example, EMF levels may be insignificant or may be manifest as a highly localized source of irritation, or it could substantially interfere with fish navigation. In addition, several special status species in California waters are likely to be sensitive to low levels of EMFs including Pacific Lamprey (*Lampetra tridentata*), White Sharks (*Carcharodon carcharius*), Green Sturgeon (*Acipenser medirostris*) and salmonids (*Onchorhynchus* spp). These species also make extensive use of inshore habitats where WEC installations are likely to be located (Beamish 1980; Brodeur et al. 2004; Quinn 2005; Erickson and Hightower 2007; Weng et al. 2007; Lindley et al. 2008). For these reasons, a careful study of the fields associated with WEC installations (i.e., not only around the electrical transmission cable) should be a high priority, and controlled, experimental studies like Gill and Wearmouth (2007), Kajiura and Holland (2002), and Meyer et al. (2005) should be considered.

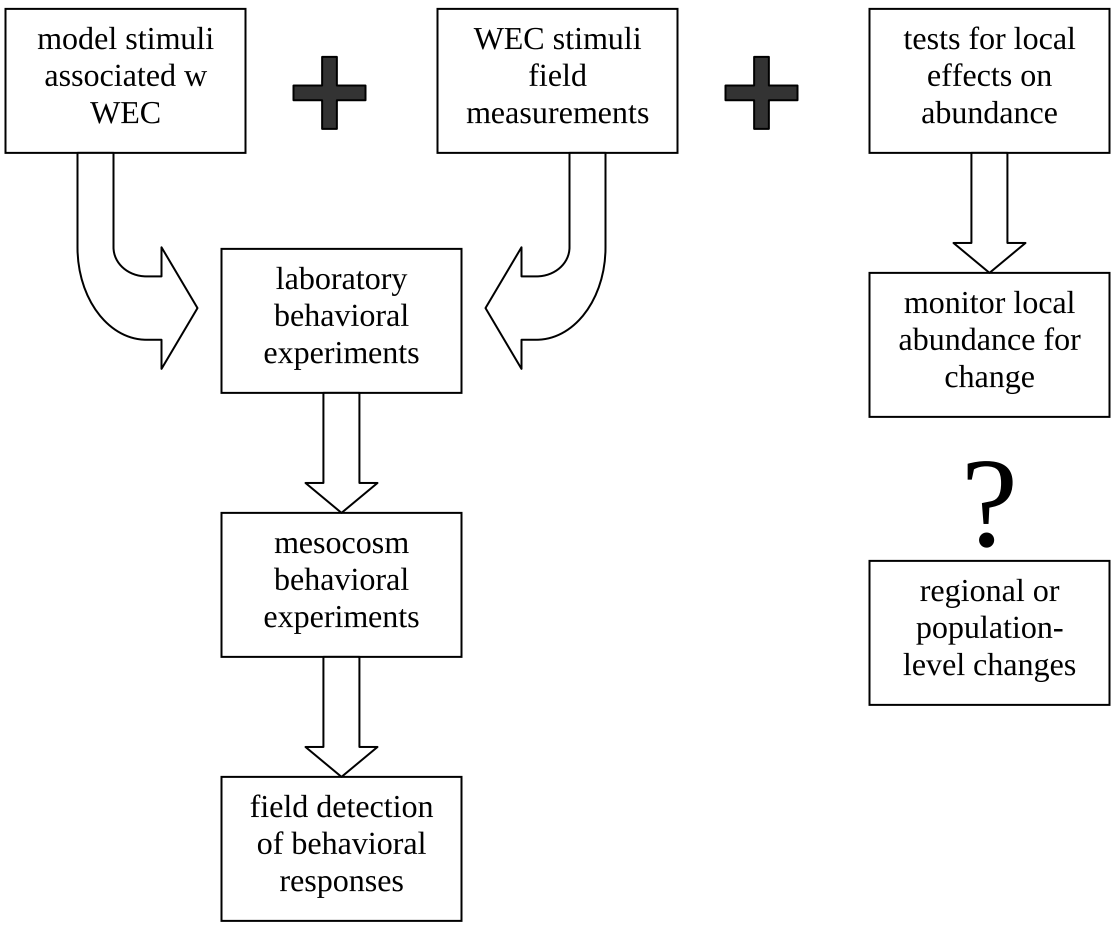

Figure 5.2. Process for anticipating and assessing potential effects at the behavioral and ecological levels

Moving from top to bottom need not depend on initial results, but should be informed and focused by them.
Source: Nelson

Underwater noise and vibrations could take a wide variety of forms; their importance in the context of WEC technology depends on their characteristics. New information specific to WEC-generated sounds may suggest that underwater noise and sound pressure are not a cause for concern, but without such information, there is potential for significant effects on fish physiology and behavior. Figure 5.2 suggests a sequence for assessing potential impacts that could be applied to these stimuli.

Assessing artificial reef effects, such as distinguishing between attraction and production (Grossman et al. 1997; Pickering and Whitmarsh 1997; Leeworthy et al. 2006), must involve comparisons with natural reefs (Carr and Hixon 1997). 'Attraction' and 'production' are not inherently clearly positive or negative in terms of conservation, although a potential decrease in available stocks may impact sport and commercial fishermen. Because public access (including fishing access) to WEC sites is likely to be curtailed for safety reasons, these sites will probably function as *de facto* marine reserves, with fisheries management and conservation implications. These abundance and redistribution effects will be important to understand because they are relevant to human use patterns and economics (Hackett Chapter 2), environmental effects—broadly speaking—that also merit attention.

'Ecological effects' (Table 5.3) include the possibility that WEC-associated fish assemblages substantially increase predation on outmigrating salmonids. This is not the only group of fishes that could be similarly affected, but salmonids are species of concern due to their conservation status and importance to recreational and commercial fisheries. While salmonids have evolved in the presence of many predators and have a variety of means for avoiding predation, a WEC array positioned close to a river mouth where encounters are likely may affect a species or a particular salmon run that is already compromised by other factors. Because of the conservation status of California salmon stocks, this possibility deserves consideration.

'Habitat conversion' (Table 5.3) associated with regional WEC development may have substantial, population-level effects. The modification of comparatively flat, soft bottom habitat to something similar to a rocky reef by introducing vertical relief and hard substrate may be regarded as a positive development, for example by contributing to the recovery of depressed rockfish stocks (e.g., Love et al. 2006; Love et al. 2007), but may also result in the loss of commercial crabbing grounds. Altering marine habitat on a regional scale may also have unanticipated, nonlinear effects to coastal ecological communities (Lohse et al. Chapter 4). Ideally, initial observations of pilot- and commercial-scale WEC development will inform future assessments of the potential for population-level effects of habitat conversion.

Most of the factors that are recommended for monitoring—fishing, FAD effects, and wave shadow—are assumed to have relatively smaller impacts (Table 5.3). 'Connectivity' could have more serious results, but the likelihood given our present knowledge seems low. Other potential impacts are also likely to be observable only with larger project sizes. For example, a wave shadow effect may require a commercial WEC installation to impact the local distribution of surf zone fishes. Table 5.3 includes the expected response to each factor and some description of the species likely to be affected. With increasing levels of spatial and ecological scale, the degree of uncertainty of WEC effects on fish increases, and impacts at the ecosystem level, currently, are so speculative they are not considered here.

Tests for ecological effects should follow a multiple BACI (Before-After-Control-Impact) design; without pre-development, baseline information, project impact cannot be properly assessed (Underwood 1994; Keough and Mapstone 1997), and multiple control sites (Kingsford 1999) should be included if at all possible. With increasing levels of spatial and temporal scale of the WEC installations, the degree of uncertainty; impacts at the ecosystem level (for example, the potential impacts of increased abundance versus redistribution) are discussed strictly on a qualitatively basis.

Summary and Conclusions

WEC installations will principally result in converting or altering habitat; they will likely act as artificial reefs by adding vertical relief attractive to reef-associated fishes. The WEC installations will furnish additional hard substrate for algae and invertebrates, which in turn may offer habitat for fishes and for prey species. Mid-water and surface components of a WEC installation may also form the nucleus for fish aggregations, serving as FADs (Fish Aggregation Devices). These combined effects could either increase fish biomass or simply re-distribute local fish biomass, a dichotomy that is recognized and associated with purpose-built artificial reefs (Grossman et al. 1997; Pickering and Whitmarsh 1997). Fish biomass redistribution may have significant negative effects if this condition reduces the stock accessible to local fisheries (Grossman et al. 1997; Brickhill et al. 2005). This potential impact on fisheries may be offset by positive effects associated with these *de facto* marine reserves (Kaiser et al. 2007; Tupper 2007), the result of WEC-supported fish assemblages where fishing is limited or prohibited altogether. Positive or negative effects will probably depend on the independence of WEC-associated fish communities from natural reefs, largely determined by distance and intervening habitat characteristics (Carr and Hixon 1997).

Electromagnetic field (EMF) effects present broad potential concerns on fish orientation, navigation, and possibly feeding. However, these concerns are partially due to our incomplete knowledge of fish sensitivity and response to EMFs, as well as our unanswered questions on how EMFs may be manifest around WEC arrays. Given the paucity of information, measurements of WEC-induced EMFs and controlled experiments on EMF effects should be research priorities.

Indirect ecological effects include a reduction in fish densities at nearby natural reefs or a predation risk substantially increasing for special status species, but they would be difficult to measure and detect. The potential scale of WEC installations on the U.S. Pacific coast offers an opportunity for informing the attraction versus production debate (Brickhill et al. 2005); such studies could also advance our understanding of habitat limitation and movement patterns. FAD effects in temperate waters have not been well studied and WEC installations offer an opportunity for studying such effects. Effects on special status species should certainly be a priority, with research strategies tailored to the species' natural histories and those factors of greatest concern.

Clearly negative effects of WEC technology on marine and anadromous fishes are difficult to anticipate, but judging by the expected magnitude of the response, reef-associated fishes are likely to respond most strongly to WEC technology. Otherwise, study priorities should probably be assigned by considering individual species' ecologies. Salmonids should be considered due to their potential sensitivity to EMF (Quinn 1980), the conservation status of the California runs, and the potential for negative ecological interactions if WEC installations do result in high predation of outmigrating smolts. Site selection and project scale are critical factors in anticipating these potential effects.

To evaluate and mitigate ecological effects of WEC technology, good use of pilot projects and other small-scale efforts should be emphasized, in California and elsewhere. Models and laboratory experiments may be important first steps, but ultimately some field installation of WEC technology is necessary to truly understand its effects. Finally, baseline information from individual project sites is crucial to any rigorous test of how WEC technology interacts with the ecology of California fishes.

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6.0 Wave Energy Conversion Technology Development in Coastal California: Potential Impacts on Marine Birds and Mammals

Sarah Ann Thompson, Jim Castle, Kyra L. Mills, William J. Sydeman

Farallon Institute for Advanced Ecosystem Research

Abstract

We summarize information on the distribution and abundance, life history attributes, and habitat-use patterns of marine birds and mammals to evaluate how and when these species may interact with wave energy converters (WEC) and hydrokinetic energy facilities ("wave parks") in California. We assume scale-dependent interactions: there should be fewer interactions with test-scale operations (one or few WEC), and increasing interactions with fully-arrayed commercial operations. For seabirds, concerns include collision, disturbance to local breeding colonies, fouling by release of oil or hydraulic fluids, and changes in prey base. Various species may be affected at different times of year, but year-round residents, such as Common Murres (*Uria aalge*), cormorants (*Phalacrocorax penicillatus and P. pelagicus*) and Marbled Murrelets (*Brachyramphus marmotus*) have the greatest chance of negative interaction. WEC/wave energy parks may increase or decrease food availability for seabirds. Potential disturbance to cormorant and murre colonies is of concern. For mammals, concerns include collision, disruption of migratory pathways, chemical fouling, changes in food availability, disruption of sensory systems, and disturbance to haul-outs and local rookeries. Like seabirds, the species to be affected will vary seasonally. Numerous large-scale wave parks along the California coast could block the migratory pathway of the entire population of eastern gray whales (*Eschrichtius robustus*); this appears to be one of the most significant concerns. Research into potential interactions between marine birds and mammals and WEC and wave parks is needed; the potential impacts of each planned hydrokinetic facility will need to be assessed on a case-by-case basis. Research should include retrospective analyses on distribution and abundance to more fully evaluate the potential for interactions due to habitat overlap, and studies of avoidance devices, such as visual or acoustic alerts (e.g., "pingers"), which could be used to minimize interactions. Moreover, before small (test) or large-scale (commercial) hydrokinetic energy parks are deployed, local marine bird and mammal populations should be inventoried and monitored with enough precision to conduct an impact evaluation following installation. In conclusion, WEC/wave parks could have impacts on California's marine birds and mammals, though few species are likely to be seriously affected. Nonetheless, effects could be substantial for some species and in some locations; therefore, as the technology and hydrokinetic energy industry develops, the potential for impacts with seabirds and marine mammal populations should be carefully evaluated.

Introduction

Hydrokinetic (wave and tidal) energy production in the ocean offers a number of compelling advantages over conventional hydrocarbon-based energy production. However, as with all developing technologies, there are environmental concerns that must be considered in the design, testing, and ultimate implementation of hydrokinetic energy facilities. In this chapter, we consider potential interactions between wave energy converters (WEC) and marine birds and mammals in the northern and central California nearshore coastal marine environment.

We have taken the following approach to our assessment. First, we examine marine bird and mammal species-occurrence patterns in the region. Second, we consider which species are most likely to interact with wave energy devices based on their distribution at sea (e.g., water depth preferences), other habitat preferences, relative abundance, and life history and behavioral attributes. Third, we evaluate potential impacts regarding species' movements and feeding behaviors.

To conduct this initial assessment, we made a number of assumptions. We assume that wave energy projects would be tested in relatively small plots containing few WEC devices. In contrast, we assume that commercially-viable wave energy parks would be of considerable size, encompassing upwards of 1-square mile of ocean habitat and producing up to 40 megawatts of electricity (Nelson 2008a). We assume that there would be a trade-off in the locations of wave energy parks, and that industry would prefer to locate devices relatively close to shore to facilitate transmission of electricity. Therefore, we surmise that most of the activity would take place nearshore, on the continental shelf in waters ~30-100m in depth. Finally, we assume that wave energy parks, should they be developed, would occur primarily in the region between Point Conception, California and Cape Blanco, Oregon, where wave activity is substantial.

6.1.1 Seabirds

Seabirds are a diverse and populous group along the California coastline. Notable characteristics of seabirds include their movements and foraging behaviors, their migratory status (some species migrate while others are resident year-round), and their breeding locations (some species nest on coastlines or offshore rocks while others breed near lakes or estuarine habitats).

Seabirds that occur along the California coastline that could interact with wave energy facilities are listed in Table 6.1 with a notation of low, moderate or high likelihood of interaction of WEC; their conservation status is also presented. Hereafter, we use common names in the text; scientific names can be found in Table 6.1.

Potential negative interactions between seabirds and WEC include:

1. Collision with devices above or below the surface of the water, or with the associated anchoring systems or transmission cables.

2. Fouling and/or poisoning by leaked oil, hydraulic fluid, or other chemical compounds.

3. Disruption of food resource availability.

4. Disturbance to breeding colonies during WEC deployment and maintenance.

Potential positive interactions between seabirds and WEC include:

1. Enhanced food resources if WEC and anchoring systems serve as fish attractants or create reserve-like areas where fishing efforts are prohibited.

2. Resting (roosting) or nesting sites for some species.

All of these interactions are described and discussed in greater detail below.

6.1.2 Marine Mammals

Like seabirds, marine mammals are diverse and abundant within the study region. There are three marine mammal groups that could interact with WEC: cetaceans (whales and dolphins), pinnipeds (seals and sea lions), and sea otters. There are no dugongs or manatees in the region.

Marine mammals that occur along the California coastline that could interact with wave energy facilities are listed in Table 6.2 with a notation of low, moderate or high likelihood of interaction, and their conservation status. Hereafter, we use common names in the text; scientific names can be found in Table 6.2.

Many of the species discussed here are highly migratory, visiting the region seasonally, while others are found in the area year-round. Generally, we believe resident species are more likely to show negative interactions with WEC than migratory species, though this is not always the case. For example, gray whales migrate extensively through the nearshore environment, and could be subjected to various encounters with WEC and wave energy parks. The habitat overlap between gray whales and potential wave energy parks could be substantial.

Potential negative interactions between marine mammals and WEC include:

1. Collision and/or entanglement with devices, associated anchoring systems, or transmission cables below the surface.

2. Disruption or exclusion from preferred migration and movement routes.

3. Exclusion from preferred feeding habitats.

4. Damage to sensory or physiological systems due to noise pollution (during construction or operation and dismantling of wave parks.

5. Electromagnetic field (EMF) disruption.

6. Decreased prey resource availability or detection due to increased sedimentation "down-stream" from or beneath wave parks.

7. Poisoning and fouling of fur and skin by oil, hydraulic fluids, or other chemical compounds leaked from WEC.

8. Disturbance to local resting or breeding sites (haulouts and rookeries).

Potential positive interactions include:

1. For pinnipeds, increased resting and haul-out locations provided by the WEC or other associated structures.

2. Enhanced food resources if WEC and anchoring systems serve as fish attractants or create reserve-like areas where fishing efforts are inhibited.

All of these potential interactions are described and discussed in greater details below.

6.1.3 Methods

A comprehensive database and assessment of marine bird and mammal distributions were recently prepared by the National Oceanic and Atmospheric Administration (NOAA). This document, entitled "*A Biogeographic Assessment off North/Central California: In Support of the National Marine Sanctuaries of Cordell Bank, Gulf of the Farallones and Monterey Bay. Phase II: Environmental Setting and Update to Marine Birds and Mammals*" (NCCOS 2007), forms the backbone of our assessment on species mostly likely to be affected and the potential interactions between WEC and marine birds and mammals of the region. Additionally, the U.S. Pacific Marine Mammal Stock Assessment: 2007 (Carretta et al. 2007) was consulted for information regarding the population size and distributions of marine mammal species.

Current Knowledge and Knowledge Gaps

Herein, we will first discuss potential impacts and interactions between marine birds and mammals and WEC in a general overview before moving on to a species by species assessment (species accounts). Our current state of knowledge is based on general information on distribution and abundance, life history attributes, and habitat-use patterns of these species in the study region. To our knowledge, there are no studies that directly investigate WEC-bird and mammal interactions in California.

6.1.4 Potential Interactions with WEC Devices

6.1.4.1 Predator-Prey Relationships

WEC structures may have both positive and negative effects on seabird and marine mammal prey resource availability. For example, it is well known that man-made structures, such as active and derelict oil platforms, attract and support substantial fish communities, and that these structures may be important as nurseries for juvenile fish populations (Carr 1989; Carr 1994; Kingsford 1995a; Love et al. 2005; Neira 2005; Love and York 2006). Structures may also be important at the local scale (tens of meters) as they provide unintended refugia for fish in that fishing is often curtailed or eliminated in the vicinity of large structures (Love et al. 2000), which could also provide reduced disturbance from these activities. Positive effects of man-made structures on fish assemblages may occur rapidly; increased diversity in fish communities was evident within a year of the installation of gas platforms in the Adriatic Sea (Fabi et al. 2004). Many types and life stages of fish, including their juvenile and larval stages, are supported by these habitat-forming structures and may provide food for various seabirds and marine mammals.

An array of WEC, if large enough, may substantially inhibit the ability of some marine mammals to pursue their prey, particularly those that feed on schooling fish or dense aggregations of small crustaceans, such as krill or mysids. These prey groups often have a patchy distribution, and those mammals that feed on them may require large amounts of space for their pursuit and capture. In this case, the refugia offered to the grouping prey by a WEC array may not lead to positive effects for their mammalian predators if they cannot maneuver through and around the WEC while hunting.

For seabirds, the structure, density, and arrangement of WEC are likely important in the potential to provide food resources. Floating buoys may provide shelter similar to a kelp raft, and an array of mooring cables may imitate the fundamental form of a kelp forest. In particular, if the shelter provided by WEC serves as a nursery ground for juvenile forms of large fish, such as juvenile rockfish (*Sebastes* spp.), or serves to attract forage fish, such as coastal pelagic species such as northern anchovy (*Engraulis mordax*), pacific sardine (*Sardinops sajax*) or pacific herring (*Clupea pallasii*), food resources for seabirds and marine mammals could be enhanced. However, we do not know if WEC would serve to attract fish (presumably they will), or if the species-specific preferred size classes or species of fish (small, prey species) would be attracted, which could then be of benefit to marine birds and mammals.

Furthermore, should the WEC lead to enhanced food resources for seabirds and marine mammals, they could likewise lead to the attraction of their predators. For example, sharks prey upon sea lions, and are known to frequent areas near sea lion haulouts, such as the Farallon Islands or Año Nuevo Island. A congregation of sea lions on or around a buoy (whether it be used as a food resource or resting platform) may increase these types of predator encounters.

In summary, predator-prey relationships and effects across trophic levels and interactions are complex and deserve additional research and consideration.

6.1.4.2 Collision and Entanglement Risks

Collision between marine mammals or seabirds is defined as direct contact with WEC. Collisions may occur when birds or mammals interact with WEC or their anchoring/mooring systems. The likelihood and nature of collisions will depend on species occurrence and behavior, relative position of the device in and above the water column, and light availability. Several factors may decrease the visibility of WEC for seabirds and marine mammals that could increase the chance of collision. Tidal mixing or surface waves interacting with the WEC could produce air bubbles that could obscure the vision of some animals, leading to underwater collisions. WEC placed near tidal streams may result in an increased risk of collision due to increased turbidity in the water (Weiffen et al. 2006). Time of day, tidal height, and general weather conditions would also affect light availability and influence visual acuity and the risk of collision both under and above the surface of the water. The color of the WEC device may also factor into the potential for collision: blue-green colors are more recognizable to marine mammals that rely on sight (Scottish Government 2007). Additionally, consideration must be given to animals simply being unaccustomed to the presence of WEC or having limited swimming abilities (e.g., juvenile marine mammals). Some marine mammals use sonar and echolocation to sense their surroundings, and may be able to use this sense to avoid colliding with WEC structures. Pinnipeds can use their vibrissae (whiskers) to sense objects (Dehnhardt 1994) and changes in hydrodynamic flow (Schulte-Pelkum et al. 2007), but it is unclear how well this would assist them in sensing an object like a WEC.

Some pinnipeds may haul out onto WEC buoys, and seabirds could also rest or roost on them. The potential risk to these mammals includes injury from the buoy, entanglement with cables and associated anchoring hardware, and injury from other mammals competing to occupy the platform. Risk of injury to birds from this activity is not evident at this time. Further effects of pinnipeds hauling out onto WEC could be damage to the WEC itself, though the extent of this damage is difficult to forecast without knowledge of the detailed structure of the WEC and exposed equipment located on it. Further damage to WEC could also result from pinnipeds and seabirds excreting onto them, and it is unknown whether the chemical makeup of the waste could damage the outer coating (if any) of the WEC or any instruments located on it.

If WEC and wave parks provide food resources for marine birds and mammals, this could also be detrimental because the attraction of foraging animals could increase the probability of collisions with buoys or other subsurface structures (cables, etc.). The physical structure of the WEC may be obstacles to feeding and foraging efforts of birds and mammals. Seabirds and marine mammals forage by a variety of methods: almost all seabird species find prey visually, and marine mammals locate prey visually, through the use of sonar, and with the help of vibrissae (whiskers). Seabirds often fly near the surface of the ocean and plunge-dive from the air into the water to catch prey (e.g., terns and pelicans). Other species (murres and cormorants) dive from the surface and swim (with a flying motion) underwater while attacking potential prey. While floating on the surface, seabirds would not be affected to a large extent by the presence of buoys, but mid-air collision with buoys during flight or hard-to-see mooring cables during diving is a risk of greater concern. Dolphins, porpoises, toothed whales and pinnipeds engage in a swimming pursuit of fish, while baleen whales engulf swarms of small invertebrates, such as krill. All have the potential of collision with cables and anchoring structures of WEC.

The shape and structure of individual WEC will have considerable effect on the potential for interaction with marine birds and mammals. A simple buoy WEC, with a single mooring line attached to the bottom, would lessen the potential for harmful interactions compared to a device with moving components (such as the prototype artist's rendition on the title page of this chapter) or sequentially-attached WEC devices. Devices with moving structures could create increased risks of collision if the animals cannot detect or perceive moving parts that might strike or entrap them. Furthermore, devices with propeller-like structures could also create eddies, which could trap and potentially injure animals (particularly small ones like birds). However, concerns about potential negative impacts of collision for marine birds and mammals can be addressed and possibly minimized during the design of WEC. For example, visual and acoustic alerts (e.g., pingers) may be deployed on WEC that may lessen the likelihood of entanglement and collision (Kraus et al. 1997; Melvin et al. 1999).

6.1.4.3 Migration/Movement Route Disruption

Migrating marine mammals may experience disruption in their pattern of migration that may lead to disrupted breeding cycles, habitat exclusion, increased energetic cost and different predator threats (Reynolds and Rommel 1999, 2007). Most gray whales and humpback whales migrate between feeding grounds in Alaska and breeding grounds in Mexico and large wave parks may cause the migrating whale to choose a different route in order to circumvent the obstacle. This occurrence may create issues by delaying the arrival to the breeding or feeding grounds. Additionally, diverting around wave parks may cause mammals to move into deeper water, exposing them to greater threats from predators they may otherwise avoid in shallow waters, such as great white sharks and killer whales. To complicate this issue, delays may force whales to search for other food sources or prevent them from using their primary habitat (habitat exclusion), producing an additional energetic cost. In the spring, mother whales escort their babies from breeding grounds northward, and both mother and offspring may be even more susceptible to all of these risks.

Some migrating marine mammals feed minimally on their routes, but marine mammals that do not migrate may experience a disruption of food availability in their foraging grounds or their ability to pursue prey (detailed above). Other possible effects on non-migrating species would be interference with movement corridors and breeding, and increased energetic costs and threat of exposure to predators.

Wave energy parks or arrays are not likely to disrupt seabird migration since these occur by flight.

6.1.4.4 Disturbance to Seabird Breeding Colonies and Pinniped Haulouts and *Rookeries*

Seabirds and marine mammals, specifically pinnipeds, gather at specific sites for resting (termed “haulouts” for pinnipeds) and reproduction (“colonies” for seabirds and “rookeries” for pinnipeds). The number of animals gathered at these sites may range from tens to hundreds of thousands (for some seabirds). In these concentrations, seabird and pinniped populations are susceptible to disturbance from a variety of sources. Human disturbance of colonies and rookeries is a serious conservation issue for marine birds and mammals in California (Carney and Sydeman 1999). Generally, seabirds and mammals have an “effective detection distance” for human activities, including noise, beyond which no discernable effect would be observed. However, during certain activities, human disturbance may be more or less likely to occur. For example, when seabird colonies are forming, the animals are most likely to respond to disturbance by abandoning the sites. Similarly, pinnipeds are susceptible to disturbance and may abandon rookery sites. This may be of greater concern during pupping season, when the evacuation of mothers from a breeding site may result in separation from pups. Even after the initial stages of reproduction, human disturbance may be harmful: birds and pinnipeds with dependent offspring may flush from colonies and/or rookeries trampling young in the process or exposing them to predation. For example, murre eggs and chicks exposed after adults have flushed are often taken by predators, such as gulls or ravens (Thayer et al. 1999). Potential for these types of disturbances can be highly reduced by thoughtful placement of the WEC.

6.1.4.5 Sound and Light Disturbance

Sources of anthropogenic noise include explosions, commercial shipping, seismic exploration, military operations (i.e. sonar) and industrial activities (offshore drilling, construction, wind farms, etc.) (Hildebrand 2005). Sound transmission and amplitude are affected by depth, salinity and temperature (Nowacek et al. 2007). During the deployment (construction) and decommissioning phases of wave park installations, the effect of noise produced during placement and removal of the WEC, moorings, and anchoring systems on marine mammals may be of concern. Studies indicate that anthropogenic sounds produced from a variety of sources affect marine mammals differently depending on the species, physical conditions of the site (depth, salinity and temperature), and distance from the source of noise (Nowacek et al. 2007).

Marine mammals perceive sound in two ways: ambient sound is heard by the mammal directly, and animals also use active and passive bio-sonar to detect prey, obstacles, etc. (Reynolds and Rommel 1999, 2007). The impacts of noise on marine mammals may disrupt behavior, including the ability to sense obstacles in migratory corridors or impacting their ability to capture prey. Noise can also cause permanent or temporary damage and discomfort to sensory systems. A more serious effect of noise pollution can be stranding, in which the animal(s) beach themselves, which can be fatal (Simmonds and Lopezjurado 1991). Although there is debate about the relationship between noise disturbance and stranding, there is support in the literature for this idea (Weilgart 2007).

Studies have shown that seals and cetaceans may be able to hear some noises (i.e., setting pilings into the ocean floor) at a distance of up to 80 km and show behavioral responses at 20 km (Government 2007). Seals and harbor porpoises have experienced permanent hearing loss from severe anthropogenic noise disturbances (at 400 meters and 1.8 kilometers, respectively) (Scottish Government, 2007). Bottlenose dolphins demonstrated a behavioral change in response to noise in an experimental study (Nowacek et al. 2007). Three species of pinnipeds (harbor seal, California sea lion and northern elephant seal) were exposed to octave-band noise at 60-75 dB (the noise levels were referenced to sensation level, or the animal’s baseline threshold) for 24 hours and the results induced a temporary threshold shift (the reversible elevation in auditory threshold that may occur following overstimulation by a loud sound) (Kastak et al. 1999).

Cetaceans communicate with each other underwater through the use of sound. There is evidence that noise pollution in the ocean can lead to communication disruption or habitat exclusion as the animals attempt to avoid the noise (Tyack 2008). Alternatively, some noise has been shown to have little or no negative impacts on cetaceans. Low-frequency sound (130-160 Hz) had a non-significant effect (no response and continued foraging) on *Balaenoptera* whales (Croll et al. 2001). Sperm whales demonstrated no response to sound of less than or equal to 179 dB rms 1μPa (Nowacek et al. 2007). Humpback whales, sighted 3 to 9 km from an explosion that generated 140-153 dB rms 1μPa at 1.8 km, demonstrated no changes in behavior or physiology (Nowacek et al. 2007).

Seabirds can be attracted to lights (particularly young birds), and lights on WEC (although intended to prevent collisions with boats) may actually serve to increase the probability of collision between structures and migratory birds (Montevecchi 2006). Seabirds also have acute hearing, but little is known about whether noises disturb birds at sea or if they are otherwise adversely affected by noise pollution (Scottish Government 2007). Placement of WEC far from nesting colonies may serve to reduce this type of risk.

6.1.4.6 Electromagnetic Field (EMF) Considerations

Electromagnetic fields (EMF) have been shown to affect a host of higher vertebrates (Kirschvink et al. 2001), though little is known about the effects of EMF on marine mammals. Some studies indicate dolphins, porpoises and whales respond to the magnetic portion of an electromagnetic field (Scottish Government 2007). Based on this information, the primary concern may be for the physiological effects of EMF and/or if the marine mammals occupy an area around wave energy converters (Fernie and Reynolds 2005). Further investigation is needed in this area.

6.1.4.7 Chemical Compounds

Since most WEC house interior hydraulic systems and/or electric turbines, they contain oil and/or hydraulic fluids. WEC will face the possibility of collision with other free-floating objects in the ocean, such as logs or boats, which could damage these structures (the WEC or vessel) and release fluids into the water. A potentially serious concern for seabirds floating on the surface in the vicinity of WEC is the possibility of injury resulting from contact with such plumage-fouling compounds. All seabirds are susceptible to plumage-fouling from hydrocarbon compounds because they traverse the water-air interface, but some species are more susceptible than others due to their tendency to sit on the water in large numbers for long period of time (e.g., murres). Seabirds can be negatively affected by contact with petro-chemicals in a number of ways, including (1) hypothermia, when oil interferes with the waterproofing of feathers and allows skin to contact water; (2) starvation, if birds beach themselves to avoid hypothermia and are therefore unable to feed at sea or due to excessive preening; and (3) ingestion of toxic compounds during preening efforts (Mazet et al. 2002).

Marine mammals are also susceptible to oil and other chemical compounds. Cetaceans lack an olfactory system, which could possibly make it difficult for them to detect oil in the water (Matkin et al. 2008). Marine mammals are susceptible to injury or death from the inhalation or ingestion of oil, and in the case of some pinnipeds and sea otters, it can also mat their fur and expose them to hypothermia. Gray whales, harbor porpoises, Dall’s porpoises and orcas were seen in the oil slick from the Exxon Valdez (Matkin et al. 2008), and long-term effects on populations are suspected.

6.1.5 Potential Interactions with WEC Devices by Species

Impacts of WEC devices on marine mammals and seabirds will largely depend on the species' distribution, patterns of behavior (breeding, local vs. migratory) and, in some respects, status of the population in the region. The following tables and species accounts summarize potential impacts of WEC impacts by species.

Table 6.1 and 6.2 summarize seabird and marine mammal species found in the WEC development region of California, their patterns of seasonal occurrence, conservation status, other endangered species listings, and a simple rating score for potential interactions with WEC/wave parks in California.

Table 6.1. Summary of seabirds of California that may interact with WEC devices.

COMMON NAME	SCIENTIFIC NAME	SEASON	IUCN STATUS	OTHER LISTINGS§	POTENTIAL INTERACTION RATING
Pacific Loon	*Gavia pacifica*	Non-breeding	Least Concern		Moderate
Western Grebe	*Aechmophorus occidentalis*	Year-round	Least Concern		Moderate
Clark's Grebe	*Aechmophorus clarkia*	Year-round	Least Concern		Moderate
Black Scoter	*Melanitta nigra*	Non-breeding	Least Concern		Moderate to Low
Surf Scoter	*Melanitta perspicillata*	Non-breeding	Least Concern		Moderate to Low
White-winged Scoter	*Melanitta fusca*	Non-breeding	Least Concern		Moderate to Low
Laysan Albatross	*Phoebastria immutabilis*	Non-breeding	Vulnerable		Low
Black-footed Albatross	*Phoebastria nigripes*	Non-breeding	Endangered		Low
Northern Fulmar	*Fulmarus glacialis*	Year-round	Least Concern		Low
Pink-footed Shearwater	*Puffinus creatopus*	Summer	Vulnerable		Low
Buller's Shearwater	*Puffinus bulleri*	Fall	Vulnerable		Low
Sooty Shearwater	*Puffinus griseus*	Spring-Fall	Near Threatened		Moderate to High
Black-vented Shearwater	*Puffinus opisthomelas*	Winter	Near Threatened		Low to None
Fork-tailed Storm-Petrel	*Oceanodroma furcata*	Spring-Summer	Least Concern		Low to None
Leach's Storm-Petrel	*Oceanodroma leucorhoa*	Spring-Summer	Least Concern		Low
Ashy Storm-Petrel	*Oceanodroma homochroa*	Spring-Fall	Endangered		Low
Black Storm-Petrel	*Oceanodroma melania*	Spring-Fall	Least Concern		Low
California Brown Pelican	*Pelecanus occidentalis californicus*	Year-round	Least Concern	CSE	High
Brandt's Cormorant	*Phalacrocorax penicillatus*	Year-round	Least Concern		High
Double-crested Cormorant	*Phalacrocorax auritus*	Spring-Summer	Least Concern		High
Pelagic Cormorant	*Phalacrocorax pelagicus*	Year-round	Least Concern		High
Red-necked Phalarope	*Phalaropus lobatus*	Spring-Fall	Least Concern		Low to Moderate
Red Phalarope	*Phalaropus fulicarius*	Year-round	Least Concern		Low
Heermann's Gull	*Larus heermanni*	Year-round	Near Threatened		Moderate
Western Gull	*Larus occidentalis*	Year-round	Least Concern		High
Glaucous-winged Gull	*Larus glaucescens*	Non-breeding	Least Concern		Low
Sabine's Gull	*Larus sabini*	Spring-Fall	Least Concern		Low
California Gull	*Larus californicus*	Year-round	Least Concern		High
Black-legged Kittiwake	*Rissa tridactyla*	Non-breeding	Least Concern		Low
Arctic Tern	*Sterna paradisaea*	Spring-Fall	Least Concern		Low
Caspian Tern	*Sterna caspia*	Spring-Fall	Least Concern		Low
Elegant Tern	*Sterna elegans*	Spring-Fall	Near Threatened		Low
Common Murre	*Uria aalge*	Year-round	Least Concern		High
Pigeon Guillemot	*Cepphus columba*	Year-round	Least Concern		High
Cassin's Auklet	*Ptychoramphus aleuticus*	Year-round	Least Concern		Moderate
Rhinoceros Auklet	*Cerorhinca monocerata*	Year-round	Least Concern		Moderate
Tufted Puffin	*Fratercula cirrhata*	Spring-Summer	Least Concern		Low
Marbled Murrelet	*Brachyramphus marmoratus*	Year-round	Endangered	FT, CSE	High
Xantus' Murrelet	*Synthliboramphus hypoleuca*	Non-breeding	Vulnerable	CST	Low
Craveri's Murrelet	*Synthliboramphus craveri*	Spring-Fall	Vulnerable		Low

Source: Thompson et. al.

Table 6.2. Summary table of marine mammals of California that may by interact with WEC devices.

COMMON NAME	SPECIES NAME	IUCN STATUS*	OTHER LISTINGS§	POTENTIAL INTERACTION RATING
Blue Whale	*Balaenoptera musculus*	Endangered	FE	Low to Moderate
Humpback Whale	*Megaptera novaeangliae*	Vulnerable	FE	Moderate
Killer Whale (Orca)	*Orcinus orca*	Lower Risk	FE	Low
Fin Whale	*Balaenoptera physalus*	Endangered	FE	Low
Gray Whale	*Eschrichtius robustus*	Lower Risk	(Delisted FE and CSE)	High
Sperm Whale	*Physeter macrocephalus*	Vulnerable	FE	Low
Short-finned Pilot Whale	*Globicephala macrorhynchus*	Lower Risk		Low
Baird's Beaked Whale	*Berardius bairdii*	Lower Risk		Low
Blainville's Beaked Whale	*Mesoplodon densirostris*	Data Deficient		Low
Perrin's Beaked Whale	*Mesoplodon perrini*	Not Listed		Low
Lesser Beaked Whale	*Mesoplodon peruvianus*	Data Deficient		Low
Gingko-toothed Beaked Whale	*Mesoplodon gingkodens*	Not Listed		Low
Hubbs' Beaked Whale	*Mesoplodon carlhubbsi*	Data Deficient		Low
Cuvier's Beaked Whale	*Ziphius cavirostris*	Data Deficient		Low
Pygmy Sperm Whale	*Kogia breviceps*	Lower Risk		Low
Dwarf Sperm Whale	*Kogia sima*	Lower Risk		Low
Bryde's Whale	*Balaenoptera edeni*	Data Deficient		Low
Sei Whale	*Balaenoptera borealis*	Endangered	FE	Low
Minke Whale	*Balaenoptera acutorostrata*	Lower Risk		Low
Bottlenose Dolphin (coastal)	*Tursiops truncates*	Data Deficient		Moderate
Short-beaked Common Dolphin	*Delphinus delphis*	Lower Risk		Low
Long-beaked Common Dolphin	*Delphinus capensis*	Lower Risk		Low
Dall's Porpoise	*Phocoenoides dalli*	Lower Risk		Moderate
Harbor Porpoise	*Phocoena phocoena*	Vulnerable		High
Northern Right Whale Dolphin	*Lissodelphis borealis*	Lower Risk		Low
Pacific White-Sided Dolphin	*Lagenorhynchus obliquidens*	Lower Risk		Low
Risso's Dolphin	*Grampus griseus*	Data Deficient		Low
Striped Dolphin	*Stenella coeruleoalba*	Lower Risk		Low
California Sea Lion	*Zalophus californianus*	Lower Risk		High
Harbor Seal	*Phoca vitulina*	Lower Risk		Low
Nothern Elephant Seal	*Mirounga angustirostris*	Lower Risk		Low
Steller Sea Lion	*Eumetopias jubatus*	Endangered	FT	Moderate
Northern Fur Seal	*Callorhinus ursinus*	Vulnerable		Low
Guadalupe Fur Seal	*Arctocephalus townsendi*	Vulnerable	FT, CST	Low
Southern Sea Otter	*Enhydra lutris*	Endangered	FT	Low

*The IUCN conservation status for marine mammals has not been updated from the 1994 to the 2001 classification scheme. The "Lower Risk" category was broken up for the 2001 scheme, containing both "Near Threatened" and "Least Concern" (as seen in Table 6.1).

§FE: Federally Endangered; FT: Federally Threatened; CSE: California State Endangered; CST: California State Threatened. From the U.S. Fish and Wildlife Endangered Species Program (http://www.fws.gov/endangered/) and the California Department of Fish and Game State and Federally Listed Endangered and Threatened Animals of California report, May 2008 (http://www.dfg.ca.gov/biogeodata/cnddb/pdfs/TEAnimals.pdf).

Source: Thompson et. al.

To further identify potential interactions with WEC and their arrays, we developed the following species accounts for 34 seabird species and 35 species of marine mammals   For each species, we ranked the potential for interaction as low, moderate, or high based on the following criteria:

1. Seasonal patterns of occurrence and relative abundance off the coast of central and northern California.
2. Potential overlap in habitat use with presumed locations for WEC and wave parks (e.g., distance from shore, preferred water depth, etc.).
3. Species-specific behavior that might influence WEC interactions, including prey preferences and foraging behaviors, and for seabirds: diving style and depth, flight speed and abilities, time spent sitting on the water column, and attraction to lights.
4. Known susceptibility to contamination by petro-chemicals.

In addition, we have considered the conservation status for each species; for this assessment we have used the International Union for the Conservation of Nature (IUCN 2007) criteria for all species, and have reported "Endangered" or "Threatened" listings at the U.S. federal or California state level for those species listed as such.

6.1.5.1 Seabirds

Pacific Loon: Potential for interaction: Moderate

This species overwinters on the coastal ocean of western North America, but breeds in the Arctic. Migratory birds may travel in groups and fly rapidly and low over the water; they are most abundant during the winter and are found relatively close to shore. Due to its rapid flight speed, there is potential for collision with WEC. Interactions are also likely to occur during the months of April/May and September/October when the birds are migrating. This species is also susceptible to plumage-fouling.

Western and Clark's Grebes: Potential for Interaction: Moderate

These species are commonly found over nearshore waters up to 100 meters depth; they also occupy protected bays, marshes, and lake habitats of the coastal environment. The potential for interaction includes mid-air collision during flight as well as susceptibility to plumage-fouling.

Black, Surf and White-winged Scoters: Potential for interaction: Moderate to Low

Wintering scoters (mostly Surf) are found in nearshore areas slated for wave energy parks in California, but in comparison with the grebes, are restricted to habitats closer to shore, and in protected bays and estuaries. Breeding for all three species occurs in the Arctic. We rate the potential for interaction as moderate to low as there is not much likelihood for collisions with WEC and these species typically occur in very shallow waters. But, these species could be vulnerable to plumage-fouling in the event of hydraulic fluid or oil releases.

Laysan and Black-footed Albatrosses: Potential for interaction: Low

These species rarely occur in the nearshore habitats slated for WEC and wave park installations in California. When found near the coast, these species (particularly the Black-footed albatross), are normally located over deeper waters of canyons that reach towards shore (e.g., Monterey Canyon), or near centers of upwelling (such as Point Arena). There is low potential for interaction due to habitat segregation between these species and the likely locations of WEC and wave parks.

Northern Fulmar: Potential for interaction: Low

While this species is relatively common off the coast of California, it prefers somewhat deeper waters rather than nearshore areas. Numbers in nearshore regions are greatest November through March. There is a low potential for interaction with WEC due to habitat segregation between this species and probable wave energy park locations.

Pink-footed Shearwater: Potential for interaction: Low

While this species is relatively common off the coast of California, it occurs mostly over deeper waters in the spring, summer and fall. There is a low potential for interaction due to habitat segregation between this species and the probable location for wave parks.

Buller's Shearwater: Potential for interaction: Low

Although common seasonally offshore of California, this species frequents deeper waters and is not often found in the nearshore environment. There seems to be an association between this species and albacore tuna (*Thunnus albacores*); the occurrence of tuna near or on the continental shelf varies interannually, which may explain the occasional presence of Buller's shearwater in nearshore environment. Overall, there is a low potential for interaction with WEC due to habitat segregation.

Sooty Shearwater: Potential for interaction: Moderate to High

This species often occurs in very large aggregations in the nearshore environment where it plunge-dives for food. Though very abundant, especially in certain locations such as Monterey Bay, this bird occurs primarily during the summer and fall migration periods; breeding takes place in the southern hemisphere. Potential interactions include collision with WEC, both above and under water. We rate the potential for interaction as moderate-high because this species is normally found in very large concentrations. While interactions could be infrequent, when interactions occur, many birds could be involved.

Black-vented Shearwater: Potential for interaction: Low-None

This species is present off of the coast of southern California seasonally, and then in relatively small numbers during winters. It is rarely seen north of Pt. Conception, therefore we foresee no potential interactions with WEC.

Fork-tailed Storm-Petrel: Potential for interaction: Low-None

This species is uncommon in California south of its small breeding colonies in Humboldt County. This species is almost always observed over deep water, therefore we see no potential for interactions with WEC.

Leach's Storm-Petrel: Potential for interaction: Low

This species is common in California where there are some fairly large breeding colonies, but it frequents deep waters over the continental slope and pelagic zone. Many birds sighted off the California coast are migrating. There is a low potential for interaction due to habitat segregation with areas slated for WEC/wave park development. However, there are small breeding colonies of this species along the coastline which may increase the potential for interaction depending on siting of wave energy parks.

Ashy Storm-Petrel: Potential for interaction: Low

Although this species is common in California and endemic to the California Current System, these birds occur over waters of the continental slope when not at colonies, and rarely frequent nearshore waters. There is a low potential for interaction due to habitat segregation. However, both Ashy and Leach's storm-petrels (noted above) can be attracted to lights (particularly when young), in which case the potential for interaction may increase.

Black Storm-Petrel: Potential for interaction: Low

This species is uncommon off the coast of California, which is the northern extent of its range. These birds are also rarely seen in the nearshore, preferring deeper waters over the shelf-break and slope. There is a low potential for interaction due to habitat segregation.

California Brown Pelican: Potential for interaction: High

This species frequents the nearshore environment for feeding and rarely occurs beyond the shelf-break in waters greater than 200m. Prey (forage fish; notably northern anchovy) are caught by plunge-diving, leading for the potential for collision with underwater WEC structures and transmission lines. These birds often fly and glide just above the surface of the water, and are also susceptible to plumage-fouling. The potential for interaction is high through direct interactions with buoys during flight or feeding, and fouling due to chemical releases. Pelicans may also roost on the above-surface portions of WEC. This species is listed by the State of California as "Endangered", though petitions to de-list this species are in process.

Brandt's Cormorant: Potential for interaction: High

This species is abundant in California, and spends nearly all of its time in the nearshore environment. Coastal breeding colonies are found from Cape Blanco to Point Conception, with most in central-northern California. This species flies low over the water along shorelines, and swims to pursue prey, often near the seafloor. The potential for interaction is high, with collision with buoys while flying (including taking off and landing) and interaction with subsurface structures while swimming. Disturbance to breeding colonies and oiling are also potential issues. This species may roost on WEC buoy structures.

Double-crested Cormorant: Potential for interaction: High

This species is common off the coast of California and occupies habitat where there are potential interactions with WEC. These birds fly low over the water with limited agility, and are foot-propelled divers, pursuing prey in shallow waters. Direct interaction with buoy moorings during foraging and collision with buoys at the surface during flight is possible. This species may be indirectly affected by WEC through potential prey distribution changes. Oiling is a potential issue as well.

Pelagic Cormorant: Potential for interaction: High

This species is common off the coast of California, and occurs regularly in the nearshore environment where there is potential for interaction with WEC. Numerous small breeding colonies along the coastline are common. These birds fly low over the water with limited agility, and are foot-propelled divers. Direct interaction with buoy moorings during foraging and collision with buoys at the surface during flight is possible. Primary food resources include benthic fish that may be affected by WEC anchors, cables, etc.

Red-necked Phalarope: Potential for interaction: Low to Moderate

This species is common in large flocks off the California coast during its migrations. During these times, the birds generally are not found in close to shore, but do occur over the continental shelf particularly near areas of intense upwelling. These birds have been known to collide with lighted structures. Considering the large concentrations and susceptibilities of this species to lighting, we believe that the potential for direct interaction with WEC is low to moderate.

Red Phalarope: Potential for interaction: Low

This species is common off the California coast during migrations, but remains further offshore primarily over the deep waters of the continental slope. Though this species occasionally collides with lighted structures, there is a low potential for interaction due to habitat separation with WEC/wave energy parks.

Heermann's Gull: Potential for interaction: Moderate

Though not particularly numerous, this species is often found in nearshore environments where its food is located, often in association with kelp or rocky intertidal habitats. Migration takes place offshore. This species often attempts to steal food from other birds, such as the Brown pelican, and sea lions, and can often be found in association with those species. Potential for direct interaction with WEC is possible. This species will probably use WEC as roosting (resting) sites as well.

Western Gull: Potential for interaction: High

This species is abundant in California, occurs year-round, has numerous breeding colonies, and frequently occurs in the nearshore environment. This species is a generalist feeder, will eat anything it finds edible on the surface, scavenge around other species, and forage in the rocky intertidal. Potential for interaction with buoys includes many direct interactions including use of WEC for roosting and possibly nesting sites. It is likely that Western gulls will be positively affected by WEC and wave energy parks in the marine environment.

Glaucous-winged Gull: Potential for interaction: Low

This species, though not particularly numerous, is found occasionally in the nearshore environment and more often over waters of the outer-shelf to mid-continental slope. Potential direct interactions between these birds and buoys exist at the surface of the water. As with other gulls and terns, these birds will probably use WEC for roosting.

Sabine's Gull: Potential for interaction: Low

This species is uncommon in nearshore areas of California, as it migrates offshore and occurs over the waters of the continental slope. There is a low potential for interaction due to the habitat segregation.

California Gull: Potential for interaction: High

This species is common off the California coast, and inhabits many niches in the nearshore environment. These gulls are opportunistic feeders, consuming anything edible that comes their way. Potential for direct interaction with WEC buoys at the surface of the water exists due to the relative abundance of this species. California gulls may roost or nest on WEC.

Black-legged Kittiwake: Potential for interaction: Low

This species spends its non-breeding season off the California coast. It primarily occurs over the continental slope and is rarely found in nearshore regions except where the shelf is narrow. There is a low potential for interaction due to habitat segregation.

Arctic Tern: Potential for interaction: Low

This species migrates off of the California coast, and can be found over the deep waters of the continental slope. There is a low potential for interaction due to habitat segregation.

Caspian and Elegant Terns: Potential for interaction: Low

These species are uncommon in California and often occupy protected waters such as bays and estuaries. There is a low potential for interaction due to habitat segregation, but where they might overlap in space, the birds might roost on WEC.

Common Murre: Potential for interaction: High

This species is very common in California year-round and occurs regularly in nearshore waters within the depth range of potential WEC facilities and parks. There are also many breeding colonies, some numbering in the tens of thousands which occur along the coastal margin. These birds rest on the surface of the water, and dive (wing-propelled) to pursue prey. An indirect effect that could be of concern is prey distribution disruption. There is high potential for collision with buoys on and below the surface as birds fly near the surface, float and dive. This species is typically one of the species to be most affected by petroleum pollution in the marine environment in California. Disturbance to breeding colonies during WEC installation and maintenance activities is also potential issue.

Pigeon Guillemot: Potential for interaction: High

Common in California, this species has numerous colonies and occupies nearshore waters (<50 meters depth). These birds hunt benthic organisms on rocky substrates. There is potential for collision with buoys at the surface as birds fly with great speed and limited agility, and interaction below the surface is possible as the birds are wing-propelled divers. Breeding colony disturbance may be an issue.

Cassin's Auklet: Potential for interaction: Moderate

This species is common off the California coast, though often occupies deeper water habitats of the continental shelf-break and upper slope. This species is known for its tremendous swimming agility while pursuing prey, though it has poor maneuverability while flying, and there are many accounts of these birds colliding with vegetation and buildings. Moderate potential for interactions with WEC exist due to this species' high relative abundance and known habit of colliding with structures during flight. This species is also sensitive (attracted) to light, which could increase the potential for interactions with WEC.

Rhinoceros Auklet: Potential for interaction: Moderate

This relatively common species can be found in nearshore waters of California year-round, but mostly occurs over the continental slope. These birds are strong wing-propelled divers, but are poor fliers and fly fast near the surface of the water. There is potential for collision with buoys at the surface of the water and interaction below the surface. This species is also sensitive to lighting.

Tufted Puffin: Potential for interaction: Low

This species is uncommon in California and when present occurs in deep water over the continental slope. There is a low potential for interaction due to habitat segregation.

Marbled Murrelet: Potential for interaction: High

There is high potential for interaction with WEC as this species frequents the nearshore environment. Murrelets fly fast and low over the water, but are agile. Nonetheless, collision potential is high. The population in northern California is highly imperiled, and this species is federally listed as "Threatened" and California State listed as "Endangered".

Xantus' and Craveri's Murrelets: Potential for interaction: Low

These species are rarely found in the nearshore, preferring warmer waters outside the coastal upwelling region. There is a low potential for interaction due to habitat segregation. Xantus' Murrelets are listed by the State of California as "Endangered".

6.1.5.2 Marine Mammals

Population estimates for marine mammals can be found in the U.S. Pacific Marine Mammal Stock Assessment report, 2007, produced by the National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Southwest Fisheries Science Center.

Blue Whale: Potential for Interaction: Low to Moderate

California supports a population of approximately 1,200 individuals. Most commonly found along the continental slope, this species occasionally frequents the nearshore, and there is some evidence that the year-round feeding population in Californian waters is increasing. Blue whales are susceptible to ship strikes, and there is also concern that they are sensitive to anthropogenic noise. We rate this species' potential for interaction with WEC as low to moderate due to the susceptibility of this animal, occasional occurrence in potential WEC sites, and low population estimates. The blue whale is federally listed as "Endangered".

Humpback Whale: Potential for Interaction: Moderate

There are approximately 1,400 humpback whales found off California. Humpbacks often travel and feed relatively close to coastline, even close enough to be spotted and identified by shore-based observers. Additionally, mothers swim with calves along coastal routes between nursery and feeding grounds. There is some concern about the effect of noise disturbance on this species, such as that produced by shipping traffic, so consideration should also be taken regarding the installation of WEC. Because of the patchy nature of krill, humpbacks' main food source, these whales may be indirectly affected if WEC interfere with the accessibility of krill. Due to the frequency of this whale in coastal waters and their migratory nature, but considering the relatively low numbers of this species, we rate the potential for interaction with WEC as moderate. The humpback whale is federally listed as "Endangered".

Killer Whale (Orca): Potential for Interaction: Low

This species is found in variable water depths and temperatures worldwide. While killer whales occasionally occupy nearshore habitat for foraging, they remain largely transient. Due to their relatively low numbers (conservative estimates in the hundreds for offshore animals on the West Coast), transitory nature, and adept swimming abilities, we rate the potential for interaction as low. Killer whales are federally listed as "Endangered".

Fin Whale: Potential for Interaction: Low

Fin whales can occur in coastal, nearshore shelf waters, but are more likely to be found outside 100m in depth. Like blue whales, there may be potential for interaction during construction due to low-frequency noise, but direct interactions with WEC/wave parks are unlikely to occur due to habitat segregation. Fin whales are federally listed as "Endangered".

Gray Whale: Potential for Interaction: High

Gray whales are one of the most commonly sighted whales off California with approximately 18,000 individuals migrating or resident in nearshore waters. The entire northeastern Pacific population of gray whales may migrate through or reside within habitat slated for WEC/wave parks in California. The potential for interaction is high due to this extreme habitat overlap. Potential interactions include entanglement and subsurface collision potential with WEC and associated supports, increased vulnerability to predation, changes to prey availability, and foraging behavior (of resident whales). Gray whales were formally listed as "Endangered", but have been delisted.

Sperm Whale: Potential for Interaction: Low

These whales are generally found in deeper waters of the continental slope and also occupy canyons and open ocean habitats. Potential for interaction is low due to habitat segregation. This species is federally listed as "Endangered".

Other Whales: Potential for Interaction: Low

Due to low population numbers and infrequent use of nearshore waters, we rate the following species as having low potential for interaction with WEC:

- Short-finned pilot whale
- Baird's beaked whale
- Mesoplodont beaked whales (including Blainvilles' beaked whale, Perrin's beaked whale, Lesser beaked whale, Gingko-toothed beaked whale, and Hubbs' beaked whale)
- Cuvier's beaked whale
- Pygmy sperm whale
- Dwarf sperm whale
- Bryde's whale
- Sei whale
- Minke whale

Bottlenose Dolphin (coastal): Potential for Interaction: Moderate

The coastal population of at least 300 bottlenose dolphins (found within 1 km of shore) exhibit north-south movements, and their range expanded northward to San Francisco Bay following the 1982-83 El Niño event. A separate, larger population of bottlenose dolphin also occurs in offshore waters of California, Oregon, and Washington. There is moderate potential for interaction with WEC due to the low numbers of this coastal stock, but the high habitat overlap with areas appropriate for WEC.

Short-beaked Common Dolphin: Potential for Interaction: Low

This dolphin is abundant, with more than 400,000 individuals, but they are primarily found in nearshore areas only south of Point Conception. In Central California, these dolphins occasionally occur in nearshore waters, particularly during warm water periods. Mostly frequenting the outer continental shelf and pelagic waters in Central California, the potential for interaction is low due to habitat segregation.

Long-beaked Common Dolphin: Potential for Interaction: Low

This dolphin has been only recently recognized as a distinct species, and the population has been estimated at approximately 1,800 individuals. This species occurs primarily south of Point

Conception, and occasionally in Central California waters. Potential for interaction is listed as low due to this species' low numbers and limited overlap of its distribution with potential WEC installation areas.

Dall's Porpoise: Potential for Interaction: Moderate

Dall's porpoises are abundant, with a widely-distributed population, and frequent waters of variable depths. The potential for interaction is moderate due to some habitat overlap, and if WEC/wave parks were established in waters deeper than 100 meters, there may be an increased likelihood of underwater collisions due to the fast-swimming and group foraging behaviors of this species.

Harbor Porpoise: Potential for Interaction: High

The population of the harbor porpoise is at least 29,000 for the Central California and Southern Oregon stocks (all stock estimates combined for this region). This species is non-migratory and is found exclusively in nearshore habitats, therefore, the potential for interaction with WEC/wave parks is high. Interactions may include collision, entanglement (although less likely) and changes to their prey base if WEC/wave parks serve to attract fish. Harbor porpoise are also known to be very sensitive to noise and vessel disturbance and WEC/wave parks could cause displacement from foraging areas or other important habitat.

Northern Right Whale Dolphin: Potential for Interaction: Low

There are approximately 12,000 northern right whale dolphins found off the west coast of North America. These dolphins occur in large groups (hundreds) and are primarily found in shelf to slope waters, though there can be occasional sightings in nearshore waters. We rate the potential for interaction as low due to minimal habitat overlap with possible WEC/wave park installations.

Pacific White-sided Dolphin: Potential for Interaction: Low

These dolphins are abundant (~25,000 in continental U.S. waters), and their population is widely distributed. Not commonly found in nearshore waters, the potential for interaction is low due to minimal habitat overlap with potential WEC areas.

Risso's Dolphin: Potential for Interaction: Low

Risso's dolphin is abundant, and its population is stable and widely-distributed, with approximately 12,000 individuals found off the west coast of the U.S. Though they may occasionally pursue prey into shallower waters, these dolphins prefer the open ocean and deeper waters, and as such the potential for interaction is low due to habitat segregation.

Striped Dolphin: Potential for Interaction: Low

Striped dolphins are abundant (~23,000), but generally occur too far offshore to warrant much chance for interaction with WEC. The potential for interaction with WEC is low due to this habitat segregation.

California Sea Lion: Potential for Interaction: High

California sea lions are abundant, widely-distributed in California, and have an increasing population exceeding 238,000 animals in the U.S. stock. This species is found nearshore along the California coastline, and the potential for interaction with WEC/wave parks is very high. Negative interactions can include entanglement since sea lions are often found entangled in fishing nets. There is minimal risk of underwater collision with WEC since sea lions are extremely agile swimmers. Since there are many known instances of California sea lions utilizing manmade structures like buoys and docks for haulout sites, it is likely that sea lions will haul out on and use WEC for resting.

Harbor Seal: Potential for Interaction: Low

Harbor seals are abundant, widespread, and have a population in California of at least 30,000 animals. This species is found in the nearshore environment, and would therefore occur where WEC/wave parks are planned. The potential for direct interaction is low since these seals are extremely agile swimmers, which might minimize the possibility for entanglement and/or collision. If WEC/wave parks serve to attract fish, however, the prey base for harbor seals may be locally increased (which, in turn, could lead to increased potential for direct interaction). It is doubtful, although possible, that harbor seals would rest on WEC. The greatest concern may be disturbance to harbor seal rookeries during installation or maintenance of WEC. The distance between proposed WEC/wave park installations and breeding sites should be carefully evaluated. During pupping and pup rearing, harbor seals are susceptible to human disturbance, and this could result in mother-pup separation and mortality of pups.

Northern Elephant Seal: Potential for Interaction: Low

Once thought to be extinct, the population of this seal is increasing and currently has more than 120,000 individuals. The potential for interaction is low as this seal forages offshore and largely in the Gulf of Alaska, but consideration should be given to known haulout beaches along the coast, as well as expanding breeding rookeries. While not particularly sensitive to disturbance, WEC/wave parks could interfere with this species establishing new rookeries along the coastline as those currently occupied reach carrying capacity.

Steller (Northern) Sea Lion: Potential for Interaction: Moderate

This sea lion's population has been declining across much of their range, and the cause continues to be under investigation. In California, the population is depleted, and this species is federally listed as "Threatened". The potential for interaction is moderate owing to overlap in foraging habitat (continental shelf) and known use of coastal islands and islets as haulouts and rookeries. Steller sea lions may use WEC to rest, but because their population is much reduced, the potential for this specific interaction would be less than that for the California sea lion. Steller sea lion food resources may also be enhanced if WEC/wave parks attract fish. Potential disturbance to haulouts and rookeries should be considered.

Northern Fur Seal: Potential for Interaction: Low

The northern fur seal has two breeding areas, one in Alaska and the other in on San Miguel Island in Southern California, and therefore has an overlapping range with the potential areas for WEC. Haulout sites include offshore islets. The population continues to recover from the hunting efforts of the previous century and is conservatively estimated to be approximately 5,000 for the San Miguel Island stock, but can be severely impacted by El Nino events. We rate the potential for interaction with WEC as low due to the low population numbers of this species and the relatively infrequent occurrences at mainland haulout sites.

Guadalupe Fur Seal: Potential for Interaction: Low

Though occasionally seen in Central California, this species breeds in Mexico and is primarily found to the south of the proposed area for WEC. This species is federally and California State listed as “Threatened”.

Sea Otter: Potential for Interaction: Low

Listed as endangered with a small California population (approximately 1,700; federally listed as “Threatened”), sea otters could potentially interact with WEC/wave parks. This species is regularly found in the nearshore environment along the California coast, mostly south of San Francisco. The potential for negative interaction is primarily by fouling of fur by petroleum products. This is of concern because otters are insulated by their fur and not by a blubber layer as are pinnipeds. Entanglement or collision with WEC and associated support structures is not likely since otters are extremely agile swimmers. Rarely occurring in wave-exposed habitats and often found in kelp forests, otters exist with no apparent problems with becoming entangled there. Due to the consistent use of certain nearshore locations and the ease of observation, it should be possible to determine where otters and WEC might overlap spatially.

Priority Research Needs

We have taken a broad approach with this review, and presented general information on the types of interactions that may impact marine birds and mammals in relation to the deployment and maintenance of WEC and wave energy parks in California. We have argued that a variety of potential impacts may occur, but without specific information on the exact type of WEC to be deployed, or the size or siting criteria of wave energy parks, we cannot provide definitive answers, and even with this information there would remain a great deal of uncertainty without direct field studies. With little doubt, some marine birds (e.g., gulls and cormorants) and mammals (e.g., sea lions) will use WEC for resting and possibly nesting, as they do with larger moorings and buoys in the marine environment. However, we actually know little about the possibility of collision or entanglement, and this cannot be investigated thoroughly until WEC are deployed, in groups, and over the large swaths of the ocean required for a commercially-viable hydrokinetic energy facility. In short, the potential for impacts of commercial- or network- scale deployments has not been addressed for this ecosystem or for these species, and information from other locations may or may not be applicable.

We have focused on species that will likely co-occur spatially with WEC/wave energy parks, i.e., those inhabiting the nearshore or inner continental shelf, and have highlighted these species are the ones most likely to show interactions. We believe this part of the assessment is robust, but note that we cannot predict with certainty that these will be the only species to show interactions.

Overall, as with other types of industrial development projects in marine and terrestrial environments, we suggest that a “BACI” (Before and After Control Impact) study design would be of value to understand impacts. Study designs should be addressed once potential WEC and wave park sites have been identified. This will provide knowledge about the organisms that are present prior to installation, and what type of effect (if any) installation activities or the presence of WEC will have on those organisms.

Lastly, some risk of interaction between WEC and marine birds and mammals may be reduced by careful design on the placement of devices and wave energy parks. Wave park siting that avoids breeding colonies of seabirds and haulouts for pinnipeds would help to minimize potential interactions. Placement of WEC/wave parks far from these sites would also serve to reduce the number of animals that may co-occur in that area. For individual WEC devices, a design with minimal moving parts may reduce the potential for strikes with animals underwater. Above-water structures, if tall, would increase the risk of collision with flying birds, so shorter structures may be optimal. Dense aggregations of WEC and support structures may reduce the ability of animals to avoid contact than less dense aggregations, but dense WEC would, presumably, have less of an overall “footprint” in the marine environment. Visual and acoustic alerts should also be considered to minimize the potential for interaction; research into these devices is needed. Finally, numerous boats, ships, barges, or other machines will be present for the installation of WEC/wave parks and possibly for maintenance of the devices. This activity should be carefully supervised for effects on surrounding marine life. In particular, observers could be present to alert installation crews of the presence of marine mammals in the area. Considerate installation should help to reduce potential immediate negative impacts.

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7.0 Tools and Approaches for Detecting Ecological Changes Resulting from WEC Development

Greg Crawford, Humboldt State University,

Rani Gaddam and Peter Raimondi, University of California Santa Cruz

Peter Nelson, H. T. Harvey & Associates

William Sydeman, Farallon Institute of Ecosystem Research

Abstract

Ocean observing systems (OOS) are coordinated networks of oceanographic sampling devices and surveying systems. Currently, such systems are supported through federal (e.g., NOAA), state, or private funding. These include real-time two-dimensional wave spectra, ocean surface current mapping, bathymetric surveying, and a variety of water quality measurements (e.g., temperature, salinity, dissolved oxygen, turbidity, chlorophyll, nutrients). Coupled wave-current-sediment transport models, in conjunction with bathymetric maps and climatological OOS wave and current data, will be useful in assessing the suitability of potential WEC sites (including potential environmental impacts). Furthermore, operational models and near-real-time data may be useful in assessing both real and potential environmental impacts for operational WEC sites. Water quality observations may be necessary to identify environmental changes and help determine causal influences, particularly in sensitive ecological habitats such as estuaries.

Ecological monitoring programs can complement efforts to track physical processes, and are critical to establishing baselines for assessing biological changes. This twin approach offers the means to test WEC-induced environmental changes for biological effects, and distinguish between anthropogenic impacts and natural fluctuations in ecological systems. Partnership agreements between OOS organizations, ecological monitoring programs, and the WEC industry, including sharing of observational data and a commitment to use standardized instruments, formats and QA/QC protocols, would benefit all stakeholders.

Introduction

Earlier chapters have identified the need to monitor and predict potential environmental and ecological impacts of WEC installation, operation and decommissioning. The required measurements and modeling tools to assess real and potential impacts can be supported as part of ocean observing systems, or OOS. The OOS concept is one that has been adopted regionally, nationally, and internationally. OOS can provide critical baseline information for sites considered for WEC project development (sea floor maps, wave climates). They can provide methods for gathering information on ecosystem changes and determining the probability of causation by WEC device deployment or larger environmental changes. Furthermore, they can provide tools for monitoring environmental conditions around these WEC systems and build data for informing the adaptive management of these areas.

Here we review the OOS concept and discuss some of the key OOS resources and infrastructure currently in place, as well as some that will be necessary, to support WEC projects. The first part of this chapter focuses on the physical data collected by the OOS network. The second half outlines "observing systems" designed to track temporal changes in the biological community. It should also be noted that all the current assets should not be assumed to be permanent. For any particular WEC project, the support for ocean observing assets deemed critical should be assessed and addressed.

Background

"Ocean observing systems" is a term used to describe a hierarchy of programs, methodologies, and instrumentation for monitoring and forecasting various ocean characteristics. These systems are designed to help address a wide range of local, regional, national, and international issues. At the international level stands the Global Ocean Observing System (GOOS; http://www.ioc-goos.org), which represents the ocean component of the Global Earth Observing System of systems (GEOSS). Co-sponsored by the Intergovernmental Oceanographic Commission (IOC) of UNESCO, the United Nations Environment Programme (UNEP), the World Meteorological Organization (WMO), and the International Council for Science (ICSU), GOOS has several core objectives: (1) monitor, understand and predict weather and climate; (2) describe and forecast the state of the ocean, including living resources; (3) improve management of marine and coastal ecosystems and resources; (4) mitigate damage from natural hazards and pollution; (5) protect life and property on coasts and at sea; (6) enable scientific research. The actual implementation of GOOS is undertaken by member states (nations) through government agencies and oceanographic agencies working together on key themes and in regional alliances.

In the US, the implementation of GOOS falls under the auspices of IOOS (Integrated and Sustained Ocean Observations; http://www.ocean.us). IOOS is defined as "a system of systems that routinely and continuously provides quality controlled data and information on current and future states of the oceans and Great Lakes from the global scale of ocean basins to local scales of coastal ecosystems." IOOS supports the development and operation of monitoring and forecasting efforts in support of seven societal goals: (1) improve the safety and efficiency of marine operations; (2) more effectively mitigate the effects of natural hazards; (3) improve predictions of climate change and its effects on coastal populations; (4) improve national security; (5) reduce public health risks; (6) more effectively protect and restore healthy coastal marine ecosystems; (7) enable the sustained use of marine resources. We note that societal goals (6) and (7) address directly issues associated with WEC development. Furthermore, four of the 16 research priorities identified by the Joint Subcommittee on Ocean Science and Technology

(2007) support the need for effective characterization and monitoring of environmental and ecological conditions in regions potentially influenced by WEC systems. Those research priorities include: understand the status and trends of resource abundance and distribution through more accurate, timely, and synoptic assessments; apply advanced understanding and technologies to enhance the benefits of various natural resources from the open ocean, coasts, and Great Lakes; understand and predict the impact of natural and anthropogenic processes on ecosystems; apply understanding of marine ecosystems to develop appropriate indicators and metrics for sustainable use and effective management.

To develop and manage regional coastal ocean observing systems around the US, eleven regional associations have been developed. These associations include representation from academic institutions, local, state and federal agencies, marine-related businesses, and NGOs (non-governmental organizations). For the California-Oregon-Washington domain, these associations include SCCOOS (Southern California Coastal OOS; http://www.sccoos.org), CeNCOOS (Central and Northern California OOS; http://www.cencoos.org) and NANOOS (Northwest Association of Networked Ocean Observing System; including British Columbia, Washington State, Oregon, and overlapping with northern California; http://www.nanoos.org).

CeNCOOS (2008) defines its mission as "… to provide the leadership and coordination necessary to develop the Integrated Ocean Observing System (IOOS) in Central and Northern California. The IOOS will improve understanding and monitoring of our oceans by implementing the observational framework necessary to monitor the state of the coastal waters in real time. The basic data and value-added products will be made available to all marine users and managers for the benefit of the public good and conservation of our resources." NANOOS' mission is "to coordinate and support the development, implementation, and operation of a regional coastal ocean observing system … and to provide data and data products regarding the ocean to a diversity of end users in a timely fashion, on spatial and temporal scales appropriate for their needs" (NANOOS, 2005). They have identified mitigation of coastal hazards (including coastal erosion) and ecosystem impacts among their top priorities (Newton, 2007).

The national effort is also supported by: a "national backbone" of monitoring systems, representing both *in situ* (e.g., in-water) and remotely sensed (e.g., satellite) measurements; a data management and communications (DMAC) system; and a modeling and analysis system. These systems, along with the coastal OOSs, are all in various stages of development and deployment. For example, one contribution for the national backbone currently development is PaCOOS (Pacific Coast Ocean Observing System; http://www.pacoos.org), a system for monitoring the California Current Large Marine Ecosystem. The specific focus is on the U.S. Exclusive Economic Zone off Washington State, Oregon and California, with additional collaborations with west coast marine scientists and managers in Canada and Mexico. The PaCOOS system has not yet been fully designed, but is expected to focus on large scale monitoring of the environmental variability, climate change, fisheries resources, and various protected marine species associated with the California Current. This system will provide critical information on large scale environmental and biological conditions along with observations that could help determine changes and causes of change (whether due to WEC, climate variation, or other influences.) Data and analyses from the PaCOOS program will be able to provide key baseline information on the marine environment and ecosystem over the continental shelf, particularly over the relatively poorly studied north coast of California. Furthermore, long-term monitoring by PaCOOS will help with the identification and causal determination of larger ecosystem changes. Such information will help with WEC site selection and adaptive management schemes. Similarly, WEC-related environmental monitoring data should be assimilated into the broader PaCOOS monitoring to provide a greater detail of understanding of coastal conditions and the ecosystem response.

Relevant Physical Ocean Observing System Assets in California

Figure 7.1 depicts core, contemporary physical ocean observing assets along the west coast of North America, from Washington State to roughly Point Conception in California. Figure 7.2 focuses specifically on the resources between roughly the California-Oregon border and Cape Vizcaino, while Figure 7.3 covers the region from Cape Vizcaino to roughly San Simeon and Point Piedras Blancas, California. Here we focus primarily on moored buoys and coastal stations that make automated measurements of meteorological and oceanographic conditions.

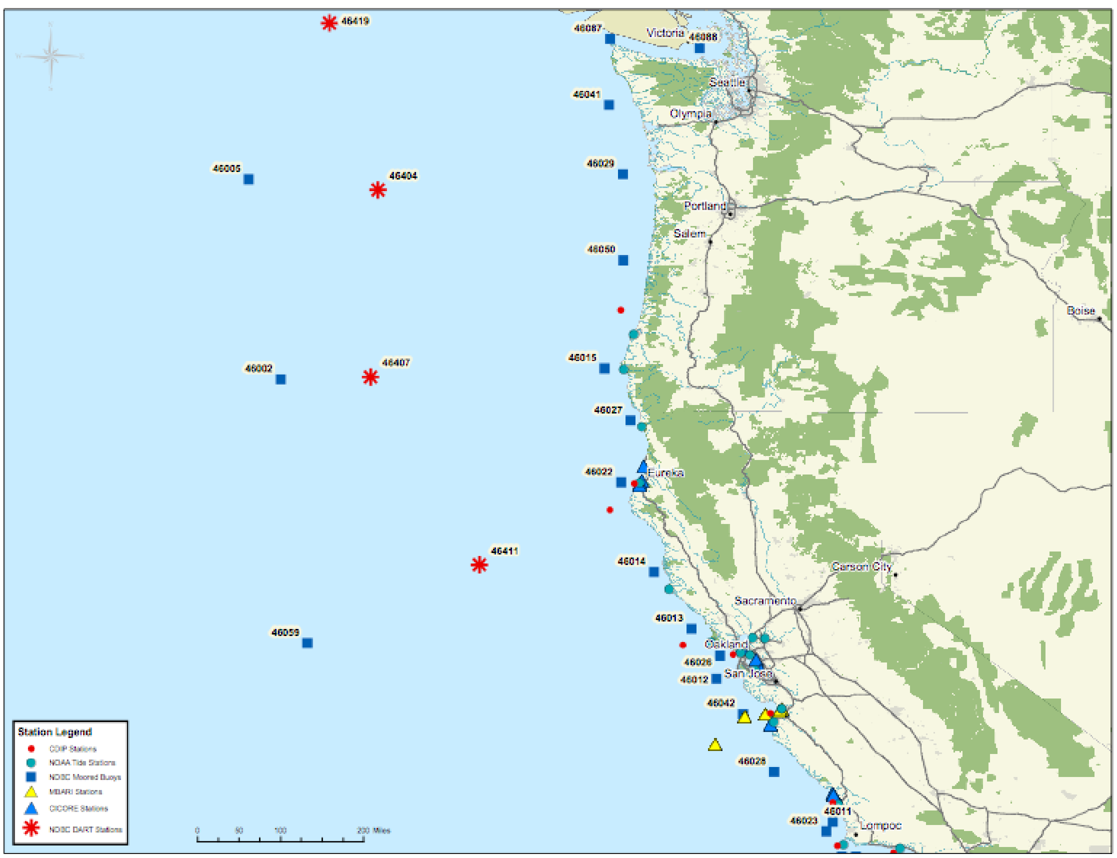

Figure 7.1. Marine and estuarine data buoys and coastal observing systems along Washington, Oregon, and northern and central California

Source: Crawford et. al.

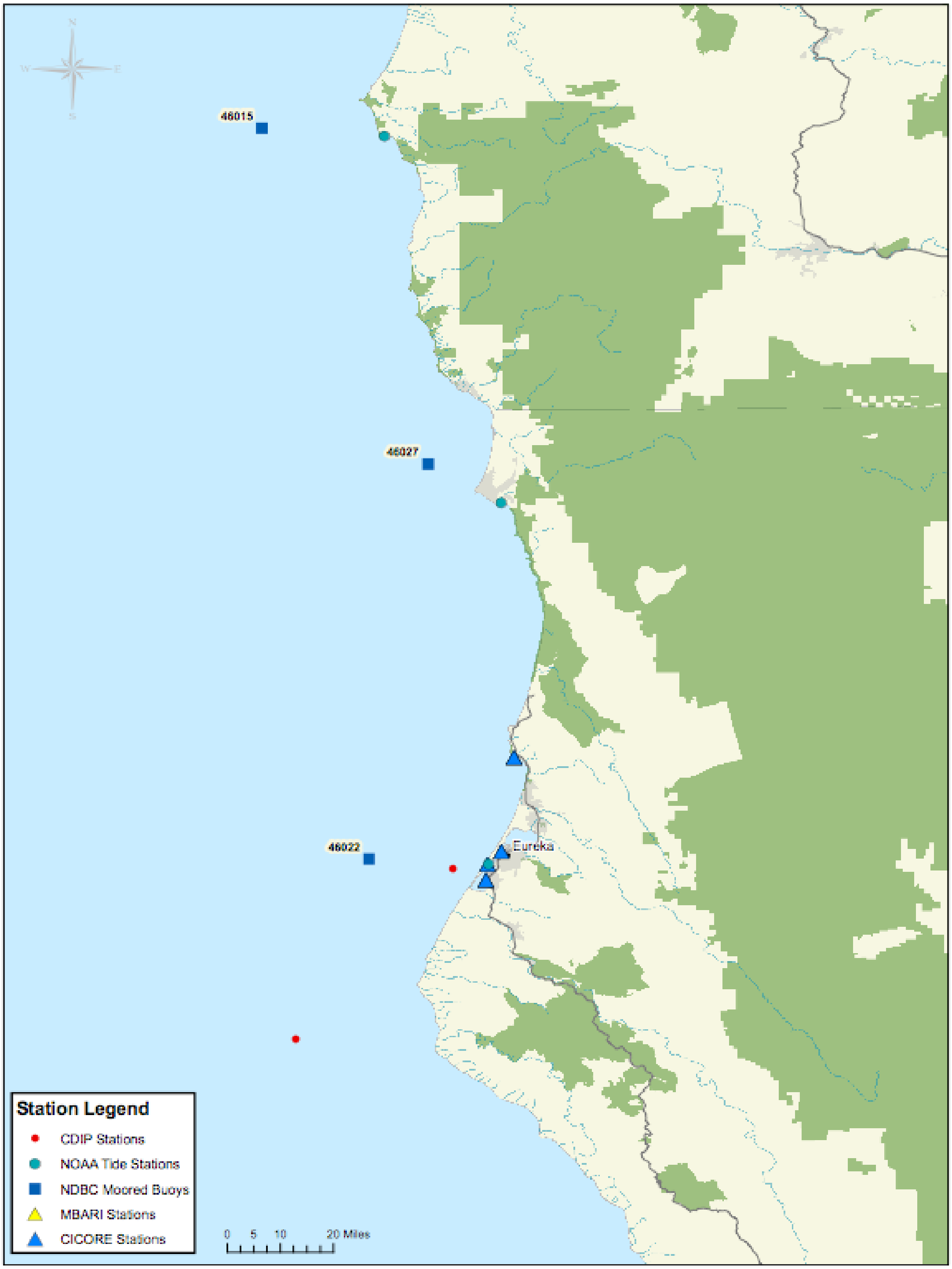

Figure 7.2. Nearshore and estuarine data buoys and coastal observing systems from the California-Oregon border to Cape Vizcaino, California

Source: Crawford et. al.

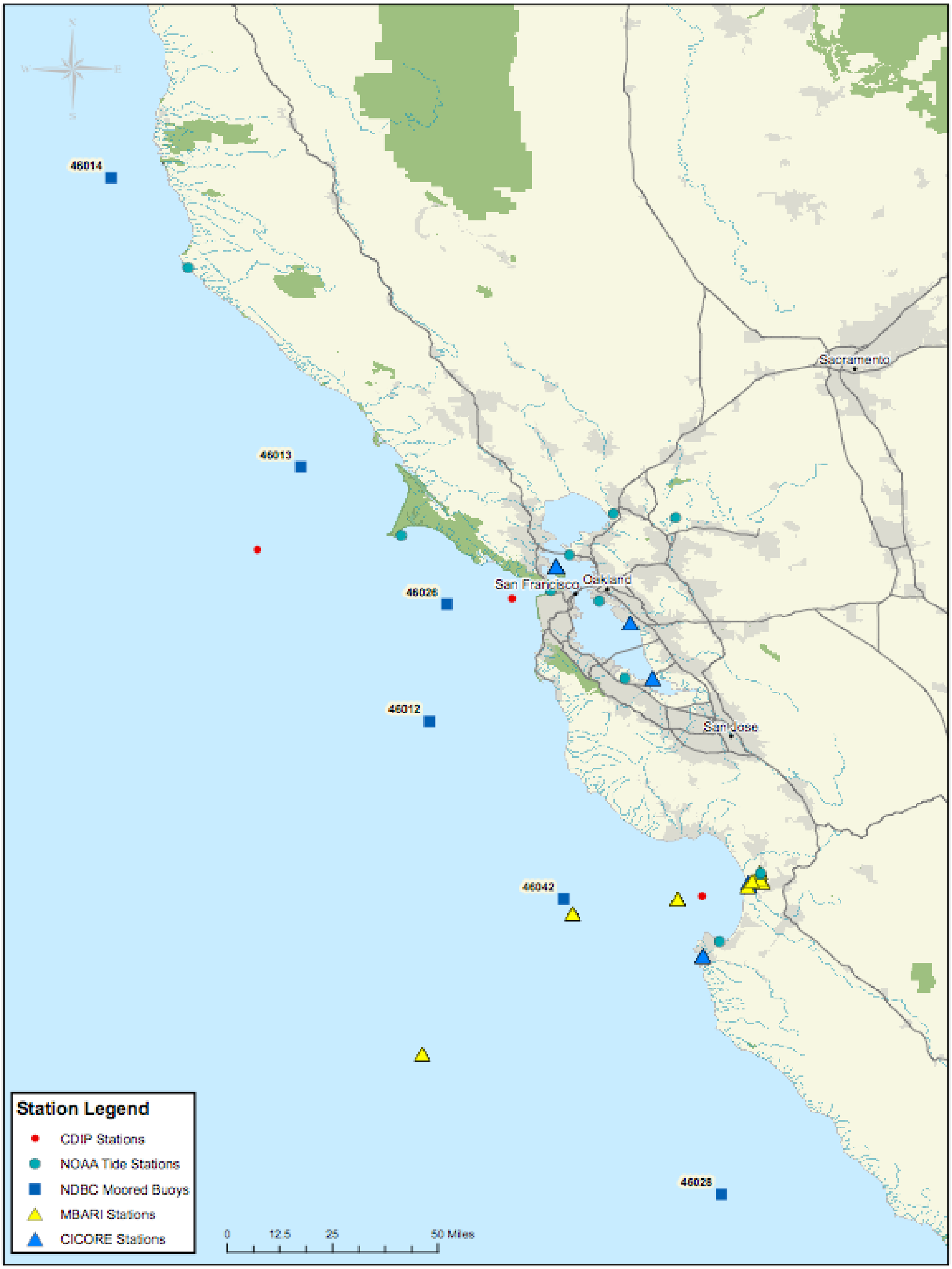

Figure 7.3. Nearshore and estuarine data buoys and coastal observing systems from Cape Vizcaino to Pt. Piedras Blancas, California

Source: Crawford et. al.

7.1.1 Measurements from Moored Buoys

A number of key physical variables to support WEC site selection and operation, including waves, winds, and current profiles, can be measured routinely from moored coastal buoys. NOAA and others have maintained a network of instrumented marine buoys that can provide both historical and contemporary data on marine conditions. For example, long term historical records of wave spectra can be used to identify areas where WEC systems may be most effective (Nelson and Woo Chapter 1). Contemporary measurements of wave spectra can be used to drive wave and sediment transport models in the presence and absence of WEC systems, thereby providing guidance on potential WEC impacts. Similarly, long term wind records can be used to provide climatological perspectives on storm frequency and intensity, and thereby aid in the development of safety precautions. Furthermore, the maintenance of a network of real-time observations from moorings can aid in the forecasting skill for major storms and in the appropriate response by WEC system operators. On the other hand, the present distribution of instrumented moorings may not, of course, be ideal for any specific WEC site, nor are there specific guarantees on the long term maintenance of this current network.

Automated wave observations typically come in one of two forms: one-dimensional or two-dimensional. Most of the NOAA meteorological buoys use sensors that measure one-dimensional (1D) wave spectra, which provide information on wave heights and wavelengths but not the direction of wave propagation. Buoy systems that provide two-dimensional (2D) wave spectra describe wavelengths, waveheights, and wave direction. These systems are more specialized and expensive and, therefore, less prevalent. Two-dimensional wave spectra would be particularly valuable in front of a WEC system, in order to characterize how the wave shadow may shift in relation to the location of the source of the waves.

NOAA maintains a network of ocean buoys around the country, usually identified by their serial number. Currently, off northern and central California, the relevant nearshore buoys are 46027, 46022, 46014, 46013, and 46026; in the offshore region, the relevant buoys are 46002 and 46059 (Figures 7.1-7.3). These buoys measure winds and one-dimensional wave spectra, and water temperature, along with a variety of meteorological measurements. These measurements are recorded hourly and are available in near-real time; archived data are posted on NOAA's NDBC (National Data Buoy Center; http://www.ndbc.noaa.gov) website.

CDIP (the Coastal Data Information Program; a program operated by the Scripps Institution of Oceanography and co-funded by the US Army Corps of Engineers and California Department of Boating and Waterways) maintains a number of Waverider buoys that measure 2D wave spectra (as well as surface temperature). As such, these buoys can provide the best source of wave information for defining wave climatology and the implications for WEC instrument siting. There are three such buoys off the north coast of California: one near the entrance to Humboldt Bay, one off Cape Mendocino, and the third west of Point Reyes. Additional CDIP buoys are found near San Francisco Bay, Monterey Bay, Morro Bay, and Pt. Conception (see Figures 7.1-7.3).

Regional institutions maintain a handful of additional buoy stations. Monterey Bay Aquarium Research Institution (MBARI), for example, maintains three buoys offshore of Monterey Bay that measure atmospheric conditions, along with water column profiles of temperature, salinity, and (usually) current velocity (Figure 7.3). Meteorological data are available from the NDBC website; water column data are accessible through MBARI's Monterey Ocean Observing System (MOOS) website (http://www.mbari.org/oasis/index.html).

UC Davis has maintained a mooring on Cordell Bank, in support of the National Marine Sanctuary Program there, however it has been missing since January 2008. The platform has historically provided temperature, salinity, fluorescence, transmittance, and current profile information.

NOAA also maintains a collection of DART (Deep-ocean Assessment and Reporting of Tsunamis) buoys in the Pacific Ocean, as a key component of the NOAA Tsunami Program. These buoys, in concert with seismic stations and coastal tide gauge stations around the Pacific Rim (including NOAA's own National Ocean Service tide stations), provide critical data to support the West Coast / Alaska Tsunami Warning Center's tsunami assessment and warning efforts. Thus, while DART buoy data may not be used directly for WEC operations, these ocean observing assets support tsunami hazard assessment and therefore may help WEC managers to save property and lives along the northeastern Pacific coast. The principal DART buoys are 46404, 46407 and 46411 (Figure 7.1).

7.1.2 Surface Current Radar

The State of California has invested in the development of a state-wide network of high frequency coastal radar systems that can provide hourly maps of ocean surface currents (speed and direction) up to 140 miles (220 km) offshore (Figure 7.4). This network, consisting of radar systems mounted along the coastline, will complement a similar system in Oregon and elsewhere around the nation. These radar systems are currently operational from southern California up to Bodega Bay, and between Crescent City and Trinidad Head; the remainder of the state is expected to be covered by March 2009. Data from these instruments will provide near-real-time observations. Furthermore, they may eventually be used to provide current and wave forecast models with the most up-to-date conditions (a process referred to as data assimilation), thereby increasing model forecast skill.

The radar instruments are SeaSondes, manufactured by Codar Ocean Sensors. They are designed to measure and map, in near-real-time, ocean surface currents. The SeaSondes come in three configurations: a high-frequency, high resolution system (with range resolutions of 500 m – 3 km and spatial ranges of 20-75 km), a standard system (13 MHz; 200-500 m resolution, 15-30 km spatial range), and a low-frequency, long-range (4-5 MHz, 3-12 km resolution, 100-220 km spatial range). The entire California coastline will be covered with long-range SeaSondes. In addition, a number of key locations (e.g., Monterey Bay, San Francisco Bay, the Southern California Bight) are instrumented with a variety of standard and high-resolution systems to provide greater detail.

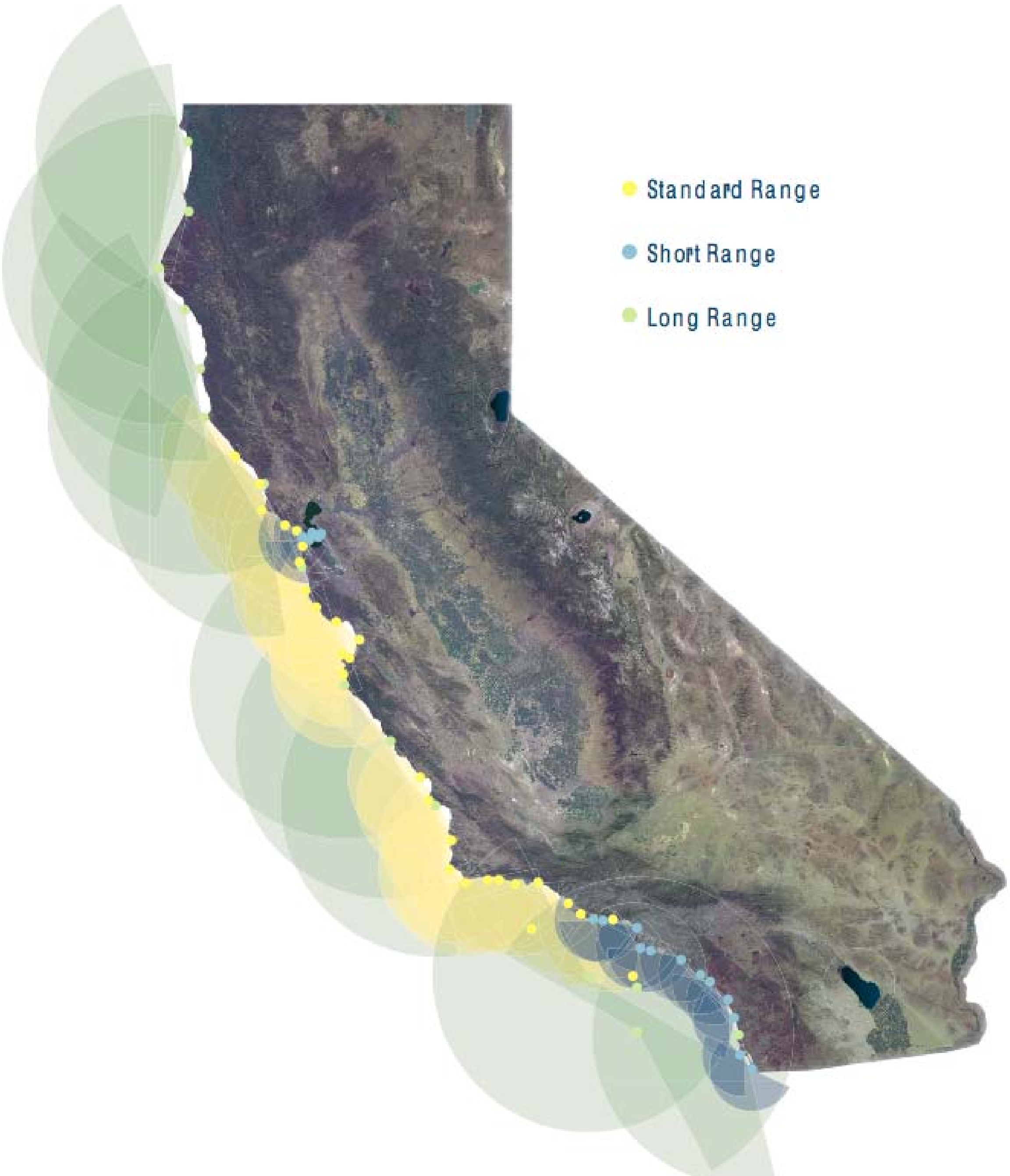

Figure 7.4. Map of the planned high-frequency radar coverage for California, as a part of the state's COCMP (Coastal Ocean Current Monitoring Program)
Source: Crawford et. al.

The SeaSondes also have some capacity to monitor directional ocean wave spectra as well, using a combination of radar data and models for wave spectra. There are, however, tradeoffs with the three SeaSonde systems. All ocean HF radar systems have difficulty in resolving ocean wave spectra when the significant waveheight approach a threshold value (e.g., Lipa and Barrick, 1982). The threshold value depends on the radar frequency (e.g., for the standard range system, the maximum threshold for significant waveheight is 7.4 m; for the long-range system, the threshold is 20 m). In addition, lower-frequency radar systems are less sensitive to smaller waveheights. (We note that Lipa and Nyden (2005) suggest the development of a new radar system that could adjust operating frequencies to obtain the best possible wave measurements.) Thus, the COCMP long-range SeaSonde network may prove useful for providing supplemental wave spectra information, although it remains to be seen how well the methodology works in the presence of multiple wave systems (e.g., swell from a distant storm, coupled with locally-generated wind waves).

Lipa et al. (2005, 2006) have also conducted numerical simulations to show that a SeaSonde system also has the potential to detect a tsunami before it strikes the coast. The concept relies HF radar detection of relatively high orbital velocities of moderate tsunamis over the continental shelf. Codar Ocean Systems is presently collaborating on a project in India to further develop and test this approach (D. Barrick, pers. comm.).

7.1.3 Measurements at Coastal Stations

As indicated in Chapter 3 and 4, estuarine monitoring of physical and environmental variables, using buoys and coastal stations, is key to interpreting real and potential environmental and ecological impacts, particularly in sensitive locations like estuaries.

A number of shore-based stations collect marine information. NOAA's National Ocean Service (NOS), for example, maintains a network of tide gauge stations around the U.S. Most of these sites also provide water temperature data. In the major harbors (San Francisco Bay, Los Angeles/Long Beach), additional data are also provided, including meteorological and ocean current measurements, as a part of NOAA's PORTS (Physical Oceanographic Real Time System). All these data are available in near-real-time through the NOAA NOS Tides and Currents webpage (http://tidesandcurrents.noaa.gov).

Several coastal stations have been established along the California coastline and embayments as a part of the NOAA-funded CICORE program (California Center for Integrative Coastal Observation, Research and Education; see Figs. 1-3). Most of these sites measure characteristics sometimes associated with water quality, including temperature, salinity, pH, dissolved oxygen, turbidity, chlorophyll, and water level (e.g., tidal height). These data may be critical in the interpretation of any observed habitat or biological community changes in the vicinity of WEC systems. (In order to assess changes in mixing and SST in the nearshore environment, as discussed in Chapter 4, it would be necessary to measure properties like temperature at a variety of depths. Furthermore, an estuarine or nearshore buoy would be less influenced by "edge effects" than most shoreline stations.)

Long term oceanographic data, including sea-surface current velocity, salinity, temperature and biogeochemical parameters, should be used to inform managers, developers and stakeholders whether the offshore infrastructure or a natural event is responsible for biological change. Possible alterations include beach erosion or a change in the migratory patterns of whales.

7.1.4 Bathymetric and Shoreline Mapping

Maps provide substantial baseline information for siting including sensitive habitats and substrate information for device mooring. In addition, routine mapping can determine benthic habitat changes, large sediment movement and changes, and estuarine breaching changes.

The California Seafloor Mapping Program (CSMP) calls for detailed surveying of all California waters, including bathymetric, substrate, and marine habitat mapping. In 2006, the Ocean Protection Council authorized up to $15M to implement the Seafloor Mapping Plan. A university-industry-agency collaborative effort is expected to be complete within the next few years.

While the CSMP is intended as a one-time survey of California waters, the data and methodology can certainly be viewed as an ocean observing system. (Indeed, several small sections of the coast were mapped in detail already, as a part of the NOAA-funded ocean observing program, CICORE; see http://www.cicore.org/bathymetry.htm).

Ship-mounted acoustic multibeam systems represent a core technology for this surveying effort (e.g., Smith et al., 2005; Xu et al., 2007). In very shallow waters, a narrow-beam echosounder may be preferable. In the surf zone, close to shore, operations of small vessels can be a major challenge. In some cases, marine scientists have measured the nearshore bathymetry using echosounders mounted on jet skis or similar rapidly-moving platforms (e.g., Dugan et al., 2001).

In locations where significant coastal erosion may already be a concern, coastal elevation data can be obtained using airborne topographic mapping (ATM). ATM is typically undertaken using one of two different technologies: LIDAR (Light Detection and Ranging) and IfSAR (Interferometric Synthetic Aperture Radar). NOAA’s Coastal Services Center maintains an archive of available data from around the country.

Relevant Biological Ocean Observing System Assets in California

The Integrated Ocean Observing System (IOOS) focuses largely on the physical parameters of the marine environment, but there are also “observing systems” designed to track temporal changes in the biological community. These generally do not have the geographic range of the OOSs, but can be more directly applicable to evaluating the ecological effects of WEC systems. Funded monitoring programs along the length of the California coastline would provide useful methods for tracking key biological parameters sensitive to potential WEC impacts. A subset of existing California marine ecological monitoring programs that provide validated models for biological observing are described below. Here, the authors jointly outlined model ecological observing approaches from the standpoint of evaluating WEC.

7.1.5 Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO)

PISCO researchers on an ongoing basis conduct long-term biological monitoring surveys. Intertidal biodiversity surveys are conducted at sites ranging from Southeast Alaska to Baja California Sur, and intertidal community structure surveys are conducted at sites ranging from Oregon to Southern California. Subtidal community structure surveys are conducted at sites ranging from Santa Cruz to Los Angeles. For more information regarding PISCO survey protocols, see http://cbsurveys.ucsc.edu/sampling/sampling.html, http://www.marine.gov/sampling-methods.htm, and http://www.piscoweb.org/research/community/subtidal/protocols.

Some sites being considered for WEC may be located near intertidal or subtidal PISCO monitoring sites; therefore existing survey information can be used as a baseline for community structure in these areas. In addition, these data can be used to assess changes to the biological community as a result of WEC. However, many areas being considered for WEC are not near existing monitoring sites; therefore additional survey sites could be established to obtain baseline data and to be able to assess changes in these communities.

Regular measurements of nearshore and onshore wave energy could also be made at existing PISCO survey sites. Measuring wave energy and community structure in the same geographical area and analyzing how community and exposure co-vary could provide a helpful tool in planning for WEC. Additional sites will likely need to be established to encompass a full spectrum of wave energy gradients for a given area. For subtidal survey sites, community structure data can also be linked to swell models to provide additional comparisons between wave energy and biological communities.

7.1.6 Remotely Operated Underwater Vehicle (ROV) Surveys

ROV surveys of deep rocky reefs offer an alternative to SCUBA surveys in habitats that preclude safe diving conditions and where depths limit SCUBA bottom time. These methods have been used successfully on the Pacific coast (Starr et al. 1996; Yoklavich and O'Connell 2008), and have recently been implemented for use in the MLPA (Marine Life Protection Act) Initiative baseline assessment. As with other visual survey methods (see 7.5.1.), the information from these surveys can be used as baseline data for sites being considered for WEC. In addition, the expansion of MLPA surveys to sites in Northern California would help to establish additional baseline data for the direct effects of WEC on benthos.

7.1.7 Collaborative Fisheries Research

Existing partnerships with sport and commercial fishermen have been extended to monitor California nearshore fisheries resources (Rick Starr, personal communication, August 25, 2008). These types of partnerships are applicable throughout California state waters, and make effective use of Local Ecological Knowledge (LEK) in designing and conducting ecological surveys. This information can be used as baseline data for sites being considered for WEC, as well as an assessment of change for sites where ongoing monitoring is being conducted. Collaborative efforts and citizen science type approaches are likely to prove the most efficient method to sample much of the north coast for the nearshore effect of WEC devices; however this is dependent on the number of fisherman available to conduct these surveys.

7.1.8 Spatial Intertidal Surveys

Schoch et al. (2006) conducted annual rocky intertidal surveys from 2001-2003 at sites from Washington to Mexico (including the central and northern CA coastline). These sites are not currently being sampled, but could be used as an additional source of baseline data for sites being considered for WEC.

7.1.9 The Cooperative Research and Assessment of Nearshore Ecosystems (CRANE)

The CRANE program is a collaborative effort between the California Department of Fish and Game and research and management scientists. The objective is to "...gather and report data for fishery management and performance of marine protected areas" (http://www.dfg.ca.gov/marine/fir/sss.asp, accessed August 22, 2008). CRANE covers shallow, rocky habitats from Monterey to San Diego, including the Channel Islands, collecting data on habitat, macroalgae, invertebrates and fishes. A one-time funding opportunity in 2004 provided the means to collate data from diverse on-going monitoring efforts, some with a history measured in decades. The data are still collected, but there have not been any means for pulling these records together subsequently. The data are collected by diver surveys and are dependent on local conditions. Despite this limitation, and the geographic and habitat restrictions, the CRANE data represent an invaluable resource for assessing WEC impacts from nearby sites.

7.1.10 Reef Check California

Reef Check California (RCC) is a network of trained, volunteer SCUBA divers who survey selected nearshore marine species. The program is intended to track changes in the abundance and size distribution of target species (macroalgae, invertebrates, fishes), sampling fixed transects at core sites two times per year. Additional transects are also sampled and include the collection of basic substrate type data (e.g., sand/silt/clay, cobble, etc.) By accessing the growing number of recreational divers in California, as well as visiting divers from outside the State, RCC is able to gather significant quantities of data for comparatively little cost. RCC has a carefully designed training program for its volunteers and a data quality assurance/control procedure for vetting their data. Like the CRANE data, this program has its limitations, but offers a unique and important resource for monitoring environmental changes in nearshore rocky habitat. It has the added benefit of including public volunteers, building a sense of stewardship and contributing to public education.

7.1.11 Biogeographic Information & Observation System (BIOS)

The California Department of Fish and Game (CDFG) maintains a system called the Biogeographic Information & Observation System (BIOS). This is an on-line GIS database of biological information collected by CDFG and its partner organizations. While BIOS is not a monitoring system per se, it does offer a means for locating spatially linked information, and may be useful for identifying or locating spatially explicit marine data relevant to WEC development.

7.1.12 The University of Washington's Coastal Observation and Seabird Survey Team (COASST)

The COASST project operates in Northern California, Oregon, Washington and Alaska, monitoring well over 350 sites for beach-cast seabird carcasses (http://www.coasst.org). COASST trains volunteers to monitor marine ecosystem health by tracking the number, species and phenology of marine birds along a large portion of the US Pacific coastline. These data are used to create a baseline for tracking populations of marine birds, and by extension the effects of, for example, changing oceanographic conditions, fluctuations in prey abundance, biotoxin levels or pollution. COASST involves the public directly in marine science, teaches volunteers about ecological processes and how science works, and offers an inexpensive and powerful tool for the ecosystem-based management of the California Current system and nearshore coastal environments. Ideally, this program would be extended southward at least to Point Conception. Data collection protocols from comparable programs (e.g., BeachCOMBERS) could be developed to ensure data compatibility with COASST. This citizen science effort, like Reef Check, has real potential for tracking environmental changes as indicated by marine species with the additional benefit of directly involving members of the public.

7.1.13 The California Cooperative Oceanic Fisheries Investigations (CalCOFI)

CalCOFI are a scientific partnership that monitors the physical and chemical properties and the populations of marine organisms from phytoplankton to upper trophic level predators of the California Current system. Because the emphasis is on oceanic parameters, a direct link between WEC and the systems monitored by CalCOFI is unlikely. However, the data collected by CalCOFI represents an invaluable source of baseline information and a means of identifying oceanographic and ecological changes that may in turn affect WEC impacts on nearshore systems.

7.1.14 California Ocean Science Trust, Marine Protected Area Monitoring Enterprise

The MPA Monitoring Enterprise has recently been created to develop a collaborative approach to the monitoring of the network of marine protected areas (MPAs) currently being established under California's Marine Life Protection Act (MLPA). The Monitoring Enterprise will work with agency, academic and independent scientists, as well as stakeholders and interested members of the public to design a science-based and cost effective approach to monitoring. The results are intended for direct application to the management of California's marine protected areas. Given the detailed ecological and socio-economic information necessary for tracking the effectiveness of the MPAS in meeting the MLPA goals, this monitoring effort may offer both baseline and long-term data relevant to evaluating the impacts of WEC.

This list is not a comprehensive description of all ecological observing tools applicable to evaluating WECs, but an effort by the authors to recognize biological observation techniques and programs that could aid in detecting ecological changes resulting from WEC development. Several of these biological observing tools are being utilized and refined for collecting baseline and monitoring data for the establishment of marine reserves in California's waters. These methods are useful for detecting site specific habitat and population changes, as well as identifying broad ecosystem changes in a region. Considering the uncertainty surrounding WEC development and potential environmental impacts, biological observing tools will be essential to conducting WEC baseline research and detecting potential nearshore and ecological changes during WEC operation.

Relevant Forecasting Model Assets in California

The installation, operation, and removal of WEC systems will require the use of accurate forecasts of waves and currents in the coastal ocean. Some forecasting resources and infrastructure are already well-developed, but specific forecasting tools should be developed to support WEC projects to maximize safe and efficient operation.

7.1.15 Ocean Wave Forecasting

A number of ocean wave forecasting models exist for the world's ocean. For the deep Pacific Ocean (beyond the continental shelf), the most valuable tend to be the NOAA Wavewatch III (Tolman 1997, 2002) deep water wave model. More sophisticated models are required, however, to predict wave conditions as waves from the deep ocean propagate over the continental shelf. For example, in southern and central California, a spectral refraction-diffraction model, REFDIF (Kirby, 1986) is used to predict wave spectra (e.g., O'Reilly and Guza, 1993) up to three days in advance, using Wavewatch III predictions for input, although locally generated wind waves are not considered. The approach used here is, in a computational sense, fast and efficient because numerical solutions for a wide range of offshore wave conditions are solved before the CDIP swell forecasting model becomes operational. Thus, for a given set of offshore conditions, the forecasting model essentially looks up the appropriate solution instead of having to calculate solutions anew.

The National Weather Service Forecast Office in Eureka, California has taken a more detailed and numerically intensive approach. They have implemented the public-domain SWAN (Simulating Waves Nearshore) model and are producing detailed, gridded two-dimensional wave spectra (e.g., Nicolini et al., 2005). This model includes both swell propagating in from the deep ocean and waves generated by local winds. The predictions are then converted into visual and text products that describe hazard conditions for mariners. Their approach is currently being deployed at other NWS Forecast Offices around the country (T. Nicolini, pers. comm.).

7.1.16 Ocean Current Forecasting

Prediction of ocean currents is also important for determining stresses on instrumentation, as well as the net ocean flow. Such circulation models often come in two varieties: those that predict tidal flows (driven by the gravitational forces of the sun and moon on the earth) and those that predict flows that arise as a consequence of wind forcing. Over much of the continental shelf, wind-driven flows dominate. In the vicinity of river mouths and embayments, such as San Francisco and Humboldt Bay, however, tidal currents can be substantial as well. Furthermore, the interactions between currents and waves can be complex and nonlinear. For example, currents can cause waves to change their wavelength and/or direction of propagation; waves, in turn, can apply an effective force (the radiation stress) that can modify currents.

Operational current forecasting of coastal California waters is, at present, very limited. The Jet Propulsion Laboratory of NASA has developed a 1-km resolution operational ocean forecasting system for the Monterey Bay region (spanning from roughly San Mateo to Morro Bay), based on the three-dimensional Regional Ocean Modeling System (ROMS); a similar model exists for the

Southern California Bight. Boundary conditions are provided from a larger (15 km resolution) ROMS model for the entire west coast of the U.S. The model forecasts temperature, salinity and currents. Satellite data and *in situ* observations are regularly assimilated into the model. The model and results are described at the JPL website, http://ourocean.jpl.nasa.gov/MB. It is likely that any WEC project off northern California would benefit from the development of a circulation model similar to the JPL model for Monterey Bay.

The NWS SWAN wave modeling effort in northern California includes an implementation of the tidal current model ADCIRC, which allows prediction of wave hazard conditions in and around the vicinity of the entrance to Humboldt Bay, California as a consequence of wave-current interactions and wave shoaling. The model output is currently limited to graphical representations of the wave and current conditions around the bay entrance (see http://www.wrh.noaa.gov/eka/swan).

7.1.17 Tsunami Forecasting

A large tsunami could potentially damage a wave energy system in shallow water. NOAA's West Coast and Alaska Tsunami Warning Center (WCATWC) has the national responsibility of issuing tsunami watches and warnings, based on seismic and tide gauge measurements around the Pacific Rim, as well as historical documentation of tsunami sources and impacts. WEC projects will likely desire rapid communication of tsunami watches and warnings in order to prepare their instrumentation as best as possible.

Recommendations

- A well-validated, coupled wave-current-sediment transport model, along with accurate bathymetry, sediment characterization, and historical wave and current observations, has the potential to predict potential morphological changes, as well as associated ecological impacts, resulting from WEC development. The analysis would be useful for validation of present conditions (without WEC installation) and prediction of future conditions in the presence of WEC development and operation. In particular, such modeling could be used to assess potential impacts as a part of WEC site consideration, focusing on climatological conditions, and in a continuously-running operational setting, to predict nearshore impacts resulting as a consequence of actual environmental conditions. OOS efforts, such as COCMP, CDIP and NOAA NDBC, can help support such efforts through provision of data where and when possible.
- Monitoring of nearshore impacts related to wave energy shadows and nearshore energy reductions (see chapter 3 and 4) will require, at minimum, near-real-time, two-dimensional wave spectra measurements from at least two locations: within the shadow zone of the WEC system and outside (but within no more than 10-20 km of) the shadow zone. Coastal ocean currents (for example, using shore-based, high-resolution high-frequency radar systems) are also an important element of modeling these nearshore environments. Again, OOS efforts such as COCMP, CDIP and NOAA NDBC would provide data to support such efforts. The IOOS community and industry should assess the availability of OOS resources

at potential WEC sites and determine how those resources might be modified or enhanced (e.g., higher resolution SeaSondes near WEC sites) to help meet an increased need for information.

- Supplemental observations of wave conditions, water circulation and sediment transport would be valuable, particularly in regions near estuaries. Furthermore, it would be useful to monitor water quality characteristics around estuaries in the vicinity of WEC sites in order to help interpret potential environmental and ecological changes in these important and ecologically sensitive areas.

- Bathymetric/topographic surveys of the local littoral cell, up to and including any backshore region, provide a method for assessing erosion/deposition issues. They can also provide a method for validating predictions derived from modeling efforts. Currently, the bathymetry of much of the California nearshore environment is poorly mapped. Since it is expected that most WEC systems would be sited within 1-3 miles of the coast, baseline bathymetric surveys of this region should be a high priority. Furthermore, it would be valuable to conduct regular bathymetric surveys in the vicinity of the instrumentation, the cable, and along the nearshore region to monitor changes.

- WEC site developers and operators should share their own environmental and ecosystem monitoring data with the larger OOS community in a timely way, using standardized protocols and data formats as much as possible. Partnerships should be developed between industry and IOOS partners to ensure the maximum benefit for all.

- Ocean observing systems such as COCMP, CDIP and NDBC provide useful physical long-term data sets for both WEC site selection and operation. Ecological surveys, coupled with oceanographic observations will provide valuable parameters for detecting environmental and ecosystem change and management of WEC projects. Correlating physical processes with biological effects offers a valuable first step in understanding ecological processes, including how WEC development may impact marine ecology. Development of standardized monitoring plans with rigorous quality assurance and control procedures would greatly improve the current situation of multiple, independent surveys with little or no coordination among efforts. Developing and maintaining the funding for these systems will be in the interests of resource managers and industry alike.

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