Suitability Analysis for Wave Energy Farms off the Coast of Southern California: An Integrated Site Selection Methodology

by

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A Thesis Presented to the
Faculty of the USC Graduate School
University of Southern California
In Partial Fulfillment of the
Requirements for the Degree
Master of Science
(Geographic Information Science and Technology)

December 2018

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Acknowledgements

I would like to express my sincere gratitude to Dr. Wu, my advisor, for her support, guidance, and motivation through the writing of this thesis. I'd also like to thank Dr. Bernstein for helping me find the project that was right for me and for her encouraging words along with Dr. Vos as my thesis committee members. Besides faculty members, I would also like to thank Corey Olfe, a programmer/analyst for the Coastal Data Information Program, for his valuable assistance on a crucial aspect of this project.

List of Abbreviations

AHP	Analytic Hierarchy Process
ASBS	Area of Special Biological Significance
BODC	British Oceanographic Data Centre
CDFW	California Department of Fish and Wildlife
CDIP	Coastal Data Information Program
CF	Capacity Factor
CUZ	Commercially Used Zone
DEM	Digital Elevation Model
EEZ	Exclusive Economic Zone
EFH	Essential Fish Habitat
GIS	Geographic Information System
GRA	Governmentally Regulated Area
GW	Gigawatt
GWh	Gigawatt Hour
MOP	Monitoring and Prediction
MPA	Marine Protected Area
MUZ	Military Use Zone
NDBC	National Data Buoy Center
NMS	National Marine Sanctuary
NOAA	National Oceanic and Atmospheric Administration
OTP	Offshore Power Technology
RE	Renewable Energy

SA	Sensitivity Analysis
SCB	Southern California Bight
SWAN	Simulating WAves Nearshore
TW	Terawatt
TWh	Terawatt Hour
WAM	Wave Model
WEC	Wave Energy Converter

Abstract

Renewable energy is becoming increasingly important as energy prices and air pollution increase globally. Wind and solar power have become more affordable and efficient. However, current renewable energy production cannot bear the weight of the world's growing need for energy unless we can effectively tap the world's greatest source of energy: the ocean. Wave energy converters are technologies designed to harness the energy from the ocean waves. This study aims to help energy resource planners identify the most efficient locations for wave farms near the coast of Southern California. Current studies with the similar goals either only used wave data as the variables during the decision making process or considered other variables but omitted the wave data. Few were found to include both, yet those too are lacking in the full scope.

In this study, wave power data as well as environmental and legal limiting factors were included in wave farm site selection. These limiting factors, along with the wave data, consisted of seven individual layers that were each given weights according to their importance in regards to a PowerBuoy™ wave farm and then combined together using a weighted overlay. The results of this overlay were used to select five areas with the most potential as a suitable location for a wave farm. A simple cost comparison was then conducted to determine which site was the most suitable. It was determined that a site roughly 25 kilometers due south from Point Conception was the best candidate. However, the conditions in the sea off the coast of Southern California are less than ideal for wave farms with the current state of wave energy conversion technology due to a relatively low level of wave power caused by the complex geography of the region.

Chapter 1 Introduction

Recent environmental studies have given much attention to renewable and clean energy due to the increasing energy demands as populations rise (Ozkop and Altas 2017). An increase in rechargeable devices—including automobiles—is further straining the current energy supply. Other studies focus less on local energy demands than they do on the global environmental need of moving away from fossil fuels towards cleaner energy sources. Among the alternative energy research, however, few studies have focused on one of the greatest untapped resources on the planet: the ocean.

Wave energy is the combination of potential and kinetic energy harnessed from ocean waves that is converted into electricity using wave energy converter (WEC) technologies. Compared to solar and wind farms, the development of commercial wave farms has been slow over the last decade. The lack of wave farms in mass production can be attributed to technological, financial, and environmental concerns. This study aims to identify suitable locations for wave farms with little to no commercial or environmental drawbacks. Spatial analysis techniques in ArcGIS were used to identify such locations off the coast of Southern California including the coastline of Santa Barbara, Ventura, Los Angeles, Orange, and San Diego counties.

Limiting factors and wave energy are the two major considerations of wave farm site selection. Limiting factors include any variables that might make a location inappropriate or undesirable for the installation of a wave farm. Wave energy factors refer to the historical pattern of the waves, primarily the average wave height and peak wave period. By using data from the Coastal Data Information Program (CDIP), the wave patterns can be calculated for the entirety of the study area. By combining both the limiting and wave energy factors, this study provides wave energy planners with the information needed to make educated decisions early in the planning process.

1.1. Motivation

Much of the world is turning to renewable energy (RE) sources in the face of climate change, the depletion of non-renewable energy reserves, and a growing need for energy as the global population continues to rise. Advancements in RE technologies continue to grow with a 14.1% increase of global energy production in 2016 coming from renewable sources including wind, geothermal, solar, and biomass (BP 2017). Continued growth is expected in the near future primarily in onshore wind and solar photovoltaic technologies (International Energy Agency 2016). Other contributions to this expected growth include hydropower, bioenergy for power, offshore wind, solar thermal electricity from concentrated solar power plants, geothermal, and ocean power. With over 40% of the world's population living within 100 kilometers of the coast, a concentration on ocean related RE sources could prove most beneficial (IOC/UNESCO 2011).

1.2. Wave Power Potential

Ocean power is comprised of tidal power and wave power. Theoretically, there is also energy potential in the salinity gradient and thermal gradient of the ocean, though these technologies have yet to progress beyond the early developmental stages. Tidal power is a form of renewable energy which is generated from the gravitational and centrifugal forces among the Earth, the Moon, and the Sun (Segura et al. 2017). Wave power, the focus of this study, originates from wind energy which is then transferred to the sea surface when wind blows over large areas of the ocean (Marine and Hydrokinetic Energy Technology Assessment Committee 2013). Although there are no commercial, grid-connected WEC technologies in the U.S. (Lehmann et al. 2017), wave energy is estimated to be able to provide 910 terawatt hours (TWh) annually for the contiguous U.S. (Lehmann et al. 2017; Electric Power Research Institute 2011). Based on the estimate that one TWh of electricity can power 90,000 homes per year, the amount of wave power-generated energy could power nearly 82 million homes if the full potential of wave energy is tapped (Gosnell 2015).

1.3. Benefits of Wave Energy

Compared to other renewable resources, particularly solar and wind, wave energy is beneficial for its predictability (several days in advance) and its consistency (throughout the day and night). Wave energy also consists of significantly higher energy density compared to wind and solar energy (Lehmann et al. 2017). This means that on average, more energy is available per square meter of the ocean surface, in the form of waves, than is available per square meter of land surface, in the form of wind or solar energy. Like these more common renewables, wave energy is sustainable, meaning that it cannot be depleted and can be generated cleanly with no significant harm to the environment as WECs do not produce any forms of emission (Boeker and Van Grondelle 2011; Bento et al. 2014). However, this does not mean that wave energy generation is completely without risks to the environment.

A major environmental concern often raised against the implementation of WECs in the U.S. is the possibility of hydraulic fluid leaks. In response, certain WEC technologies, such as the Pelamis, harden their mechanical components and use biodegradable fluids to minimize the effects should a leak occur (Ilyas et al. 2014). Other environmental concerns include underwater noise pollution and hazardous turbines, both of which could negatively affect sea life in unpredictable ways. Fortunately, unlike designs of tidal energy converters, WECs need neither turbines nor other noisy components.

On the other hand, research has also indicated wave farms as a potential line of defense against beach erosion (Abanades, Greaves, and Iglesias 2014). Using a computer simulation model called Simulating WAves Nearshore (SWAN), researchers identified decreases in wave height and near-bottom orbital velocities leeward of wave farms while other wave dynamics were generally unchanged (Chang et al. 2016). These simulated results were validated by a test site in Lysekil, Sweden, where the reduced energy of the waves leeward of a wave farm also had positive environmental effects. The environment was studied before and after the installment of an array of WECs. According to this case study, 68 species were significantly more abundant in the test site leeward of a wave farm than at the control site and no species were found to be extinct (Ilyas et al. 2014). With this in mind, Marine Protected Areas and other conservation areas are included as limiting factors in this suitability analysis study, but only considered to be entirely restricted for wave farms in accordance with state or federal laws.

Besides environmental concerns, wave energy also faces opposition from commercial interests. Current site selection methods for wave farms do not consider fishing or shipping traffic. More than two-thirds of California’s marine fishing takes place off the coast of southern California between the counties of San Diego and Santa Barbara. The amount of recreational fishing alone in this region results annually in over a $2.5 billion stimulus to the state’s economy (Southwick Associates Inc. 2009). Furthermore, shipping is one of Southern California’s most profitable industries, with an operating revenue of 475 million U.S. dollars in Port of Los Angeles, 355 million dollars in Port of Long Beach, and 169 million dollars in Port of San Diego in 2016 (San Diego Board of Port Commissioners 2017; Long Beach Board of Harbor Commissioners 2017; Los Angeles Board of Harbor Commissioners 2017).

The year of 2016 marked a record breaking year in terms of volume for any Western Hemisphere port with 8.86 million containers passing through the Port of Los Angeles (Los Angeles Board of Harbor Commissioners 2017). Following shortly behind Los Angeles in volume was the Port of Long Beach, which handled a total of 6.78 million containers in 2016. Together they process roughly 40 percent of all imports to the U.S. (Hricko 2006). With these massive industries operating off of the Southern California coast, it is important to consider their areas of operation when identifying potential wave farm locations.

1.4. Trends in Wave Energy

Wave energy has been lagging behind other RE sources due to their high cost and the lack of an optimal design identified for commercialization (Foteinis and Tsoutsos 2017). This uncertainty along with the constant evolution of technologies is responsible for high costs and low commitment rates among potential investors. The current costs of wave energy exceeds those of conventional energy generation technologies such as gas and coal (Astariz and Iglesias 2015). However, like wind energy and solar energy, the cost of wave energy will ultimately drop as resources are no longer spent on inefficient designs but dedicated to a single WEC technology that proves superior to all others. The foreseeable decrease of wave energy costs combined with the potential for the rising cost of conventional energy could make wave energy an economical option in the future.

1.5. Study Area

The study area stretches along the coast from Point Conception (~34.5°N) in the north to San Diego and the Mexican border (~32.5 °N) in the south and westward beyond the Channel Islands (Figure 1). This area covers over 30,000 square miles and is known as the Southern California Bight. It is characterized by shore islands, shallow banks, and deep basins which diminish deep ocean gravity waves (Emery 1960). These features cause wave reflection, refraction, diffraction, and dissipation resulting in a spatially complex wave climate (O'Reilly and Guza 1993).

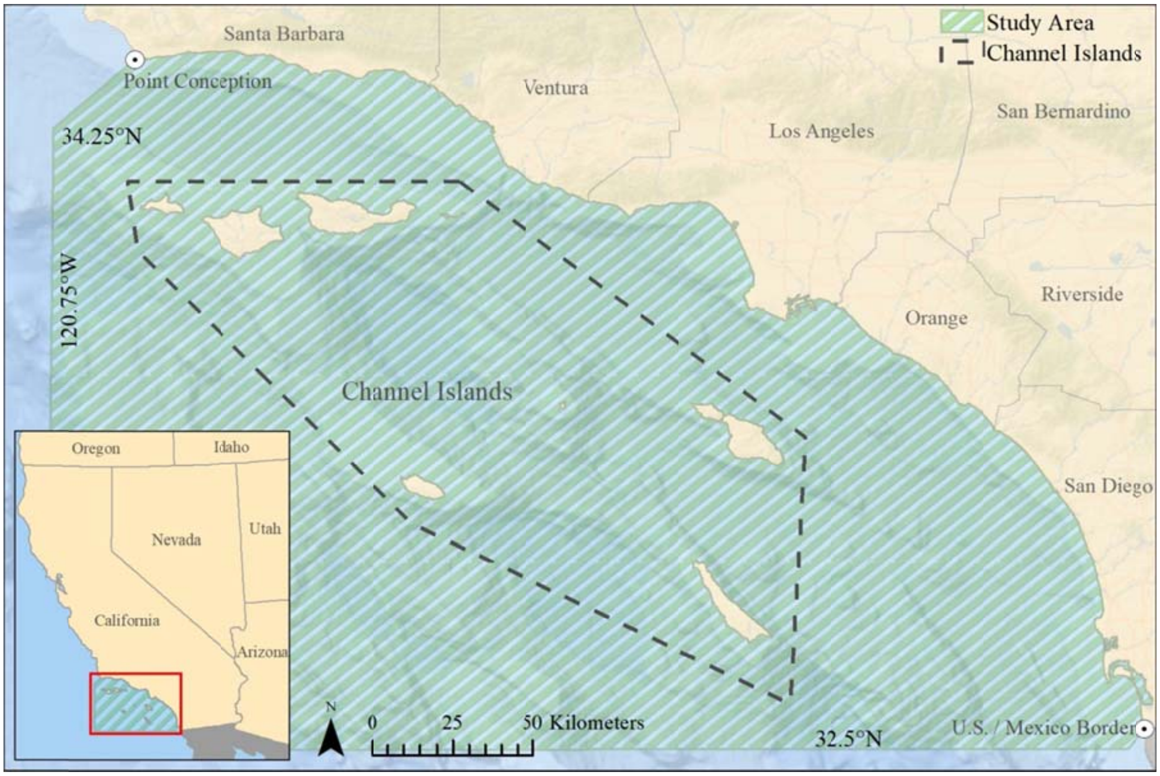


Figure 1 Map depicting the Southern California Bight as the study area

1.6. Thesis Layout

The remainder of this thesis is divided into four chapters. Chapter 2 is a literature review of research pertaining to wave data collection, wave power quantification, WEC technologies, site selection methods, and potential limiting factors. In Chapter 3, the data requirements for this study are introduced and the methods used to conduct the site selection are discussed in detail. The results of the study's analysis are provided in Chapter 4, which is followed by a discussion of these results in Chapter 5 along with any conclusions that were made. As a preliminary step towards site selection, further analysis will be required; and though the study area is limited to the coast of Southern California, the methods described herein can be replicated for any coast given that the required data exists.

Chapter 2 Related Work

To collect wave energy as a power source, we must first understand what we intend to capture. This literature review discusses research papers and technical reports on the most effective means of harnessing the power of the ocean. It begins with an introduction to waves, their attributes, and a summary of wave data collection techniques. The second section focuses on current attempts at quantifying wave power, which is followed by a quick outline of WEC technologies. Lastly, this review discusses the current methods of wave energy farm site selection using nothing but the wave data. Using geographic information systems (GIS), and including other concerning factors alongside wave data, this study ultimately extends the research detailed in this review.

2.1. Wave Data Collection

Waves form by transferring wind energy onto the surface. This energy is measured in kilowatts per meter of wave crest, which is referred to as wave power density (Gunn and Stock-Williams 2012). Important wave parameters include its length (λ) and height (H). When calculating wave energy, the depth of water (h) is also important as roughly 95% of a waves energy exists between the surface of the water and a depth equal to a quarter of the wavelength (Figure 2) (Ilyas et al. 2014). It is important to recognize that most waves are not simple, harmonic or regular. Instead, the vast majority of waves are short-crested and irregular due to the erratic nature of the wind that creates them (Electric Power Research Institute 2011).

To understand the common wave patterns of a specific ocean region for energy collection purposes, it is important to collect massive amounts of wave data in the field. Wave data has been collected by a number of sources over the years; this study focused on two sources that are relevant to Southern California.

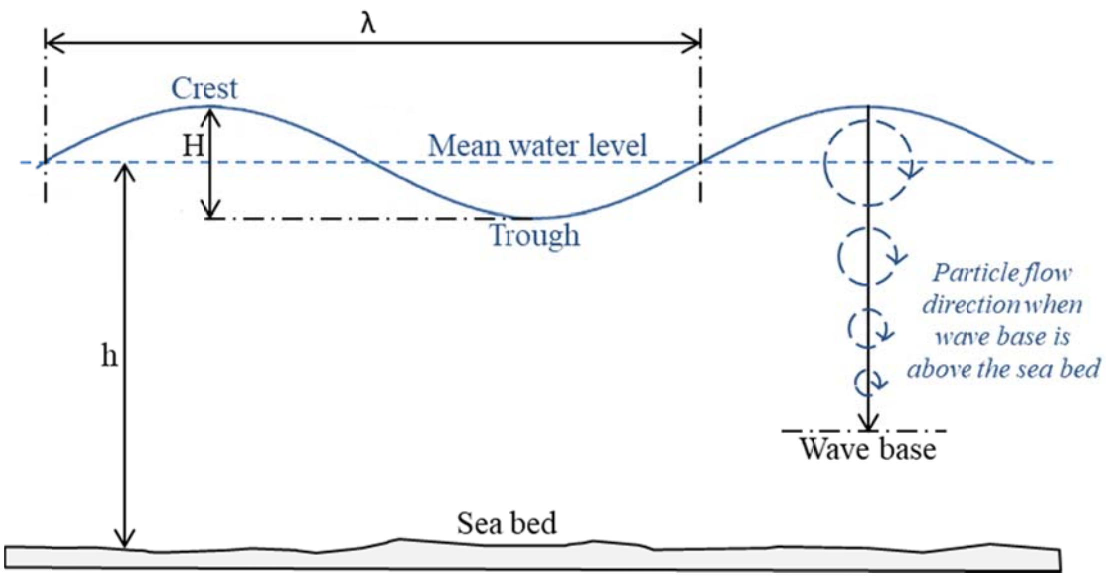


Figure 2 Diagram of wave profile with free orbital motion (adapted from Boström 2011)

Before continuing, it should be noted that the technologies described below in the remainder of Section 2.1 are used for the collection of wave data; they are not and cannot be used to produce wave energy. Energy conducting technologies are covered in Section 2.3.

2.1.1. National Data Buoy Center

The National Data Buoy Center (NDBC) has its roots in the 1960s when the U.S. Coast Guard consolidated approximately 50 smaller ocean-oriented agencies. In 1970, the program was transferred to the newly formed National Oceanic and Atmospheric Administration (NOAA) where it was ultimately placed under NOAA's National Weather Service. By 1979, 26 buoy systems were deployed, 16 of which were in the Pacific.

As of February 2018, there are over 100 moored weather-ocean buoys deployed by the NDBC in the coastal and offshore waters from the Pacific Ocean to the western Atlantic and even in the Great Lakes (Portmann 2016). These buoys are used to record barometric pressure, air and sea temperatures, wind attributes (i.e. direction, speed, and gust), and wave measurements (i.e. significant wave height, dominant wave period, average wave period, and wave direction).

There are four types of moored buoys currently employed by the NDBC: the 3-meter, 10-meter, and 12-meter discus hulls, as well as the 6-meter NOMAD hulls. The larger discus buoys are less portable and more prone to mishaps such as capsizing, while the 3-meter discus and the NOMAD buoys are smaller and generally more durable. The choice of buoy is determined by the deployment location and its intended purpose (National Data Buoy Center 2018).

Wave measurements are calculated for each buoy through a three-part process. First, depending on the buoy model, the heave acceleration or vertical displacement of the hull is measured by the accelerometer or inclinometer, respectively. Secondly, this data is converted from the temporal domain to the frequency domain through the application of a fast Fourier transform using an on-board processor. Lastly, this converted data is cleaned up using a response amplitude operator process to account for electronic and hull noises. The output of these steps includes spectral energy, significant wave height, average wave period, and dominant wave period.

The NDBC also employs a fleet of voluntary observing ships which regularly collect and report wind and ocean data as they conduct their usual business. There are hundreds of such ships. Unfortunately, the majority of these ships do not report wave height or wave period, rendering them unusable for this project.

2.1.2. Coastal Data Information Program

The Coastal Data Information Program (CDIP) began in 1975 with a single underwater pressure sensor used to measure waves near the coast of Imperial Beach, California. With funding from the U.S. Army Corps of Engineers, the program grew to an extensive monitoring network for waves and beaches. Currently, CDIP maintains over 100 wave monitoring stations. Though the bulk of these stations are located along the Pacific and Atlantic coasts, others are located near the Hawaiian Islands, Guam, the Gulf of Mexico, and even in the Great Lakes (Coastal Data Information Program 2018).

Waves are measured by CDIP using a variety of instruments. Fixed underwater sensors include single-point gauges and arrays, both of which measure pressure fluctuations to determine the height and period of waves passing above. A benefit of arrays is that, by linking multiple pressure sensors together, it becomes possible to record the directional component of waves as well. These sensors transmit the recorded data to shore using submerged cables. Surface buoys are free of these cables as they transmit data via radio links using attached antennas, allowing them to be deployed farther from shore. The earlier model of buoys was non-directional, though CDIP has replaced all of these buoys with Datawell Directional Waverider buoys. This advanced model uses a Hippy heave-pitch-roll sensor to measure wave energy attributes as well as the wave direction.

Wave data is transferred from the various instruments to an onshore site to be stored temporarily. This transfer occurs at a continuous interval of one to two transmissions per second. From the onshore site, the data is then transferred to central facility twice an hour where it is recorded, processed, and analyzed. The processing of the raw data is completed using two FORTRAN programs. The first of these programs checks the raw data (rd) files for errors, separates multiple sensor inputs, and calibrates the recorded values based on recorded calibration factors before converting them into diskfarm (df) files. The second program performs a data quality check, completes several complex calculations—such as spectral and directional wave analyses—and produces outputs including spectral (sp) and parameter (pm) files.

2.1.3. Other Wave Data Collecting Organizations

Except for CDIP described in Section 2.1.2, major wave data collecting organizations do not operate close enough to U.S. coasts to be useful for this project. One such association is the Data Buoy Cooperation Panel, which is a joint body of the World Meteorological Organization and the Intergovernmental Oceanographic Commission. They operate the Global Telecommunication System, which disseminates buoy data through the World Weather Watch with a focus on the north Atlantic (Data Buoy Cooperation Panel 2018). Other smaller organizations are dedicated to more specific regions, such as the British Oceanographic Data Centre and MetOcean Solutions that focus on the Southern Ocean near Antarctica. These organizations demonstrate that buoys are the standard tool for collecting wave data around the globe.

2.2. Quantifying Wave Power

Separate attempts to estimate the total wave energy of the world, or even just a specific coastline, result in tremendously different numbers. This variability can be attributed to a number of factors including differences in estimated coast lengths, wave data sources, wave attributes considered, etc. There are no formal agreements upon the methodology for measuring this resource.

Quantifications of the total wave power in an area represent the theoretical potential of the area rather than the actual amount of power which could be harnessed. This wave *power* is typically measured in gigawatts (GW) for areas the size of a continental coastline. Larger extents than that might be measured in terawatts (TW, or 1,000 GW). The practical application of this power is termed wave *energy*, which is measured in GW or TW per hour (GWh or TWh, respectively). Many of the sources in this literature review quantify power annually (GWh/yr and TWh/yr).

The benefits of wave energy technologies on any scale can be inferred from the global quantifications of wave power, dated back to 1965 when Kinsman (1965) estimated 1.87 to 2.22 TW of wave power for the entire Earth. Gunn and Stock-Williams (2012) compiled a table of 11 early global wave power estimates ranging from 800 GW to 2.6 TW using three different methods. They calculated the global nearshore wave power potential to be 2.11 TW, equal to roughly 18,500 TWh of energy per year. Altogether, a broad extent of estimates from different sources ranged from 16,000 TWh/yr all the way up to 32,400 TWh/yr (Reguero, Losada, and Méndez 2015; Mørk et al. 2010).

The most recent calculation of annual global energy consumption by BP placed it at just over 24,800 TWh for the year 2016 (BP 2017). Based on this calculation as well as the estimation of global wave energy, ocean waves alone could meet 65 to 131 percent of the world's energy needs with WEC technologies at an efficiency—or capacity factor (CF)—of 100%. Unfortunately, current WEC technologies max out at a CF of 40%, which equates to a range of only 6,400 to 12,960 TWh per year (26 to 52 percent of the global usage) (Poullikkas 2014). Still, a global array of wave farms with a 40% CF could potentially replace up to 81.5% of the energy produced from oil and coal (BP 2017).

2.3. Wave Energy Converter Technologies

There are many WEC designs currently in use around the world, with many more being developed every year. The number of unique WEC designs is already in the hundreds and continues to grow as more efficient designs are invented (Khan et al. 2017).

2.3.1. Categories of WEC Devices

Categorizing these designs even proves to be a challenge as many do not easily fit into a single group. One method of categorization is by their size and direction of the device in relation to the waves (Figure 3). By this categorization method, there are three main WEC types: point absorbers, attenuators, and terminators (Rusu and Onea 2017). A point absorber generates energy through the vertical movement of the devise as it rises and falls with the passing waves, similar to a buoy rising and falling along the crest. It is the smallest WEC type and can capture wave power from any direction. An attenuator is a longer device oriented horizontally in the direction of the wave and generates energy as the wave passes along the length of the devise. A terminator is also a long device but is positioned with its long front facing the direction of the wave and acts as a breakwater, generating energy as each wave crashes into the device.

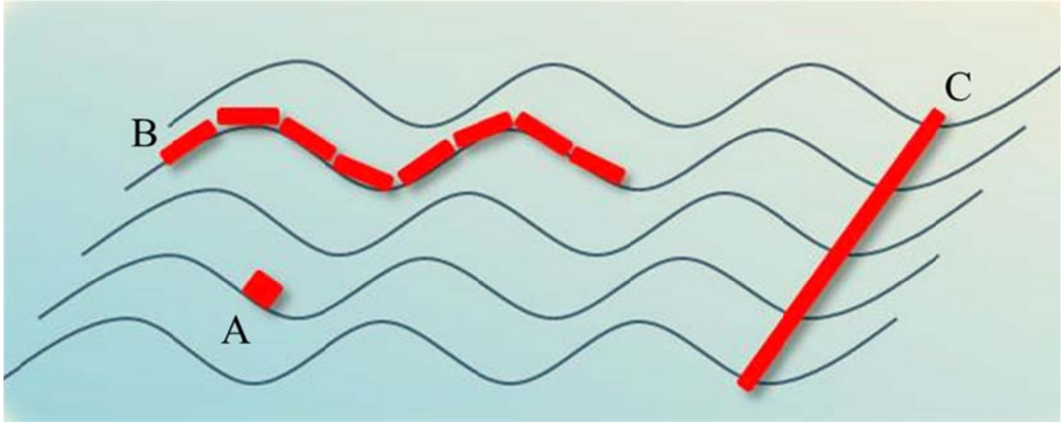


Figure 3 Wave energy converter (WEC) devices categorized by size and orientation to the wave: (A) Point Absorber, (B) Attenuator, (C) Terminator (adapted from López et al. 2013)

The WEC technologies can also be categorized by dividing the devices by the physic principles behind them (Figure 4). There are four major principles regarding WEC design: pressure differential, floating, overtopping, and impact (López et al. 2013). Devices utilizing the pressure differential principle include those employing the Archimedes effect and those operating with oscillating water columns, both relying on pressure differences between wave troughs and crests. Floating structures are those that generate energy through oscillatory motions and can be single or multi-part devices. Overtopping devices rely on waves crashing over the top of the structure, forcing the water to flow through turbines as the water level drops between waves. Lastly, impact devices are positioned against the wave front in order to absorb the wave's impact. There are other devices that do not fall within any of these four categories and there are some that fit into multiple categories depending on the complexity of the design.

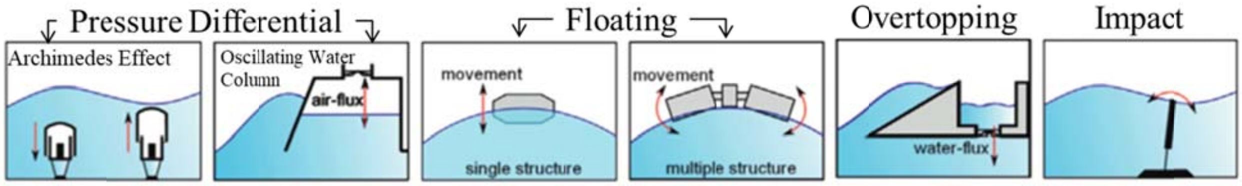


Figure 4 Working principles of WEC devices (adapted from López et al. 2013)

The third method of categorizing WEC technologies is by their proximity to shore upon deployment. There are three groups in this categorization using the corresponding water depths at which the device is designed to be located. Onshore energy converters are those located in waters closest to shore where the waters are roughly 1-10 meters deep; near-shore converters are just beyond that at about 10-25 meters deep; offshore converters are typically the farthest from shore where the waters are over 40 meters deep (Khan et al. 2017). Offshore devices are the most common one being deployed and can include point absorbers, attenuators, and terminators alike. Terminators, however, are uncommon in nearshore locations because of the shorter wavelengths and less predictable wave directions near the coastline. Onshore devices are nearly all terminator type devices.

2.3.2. Current Leading WEC Designs

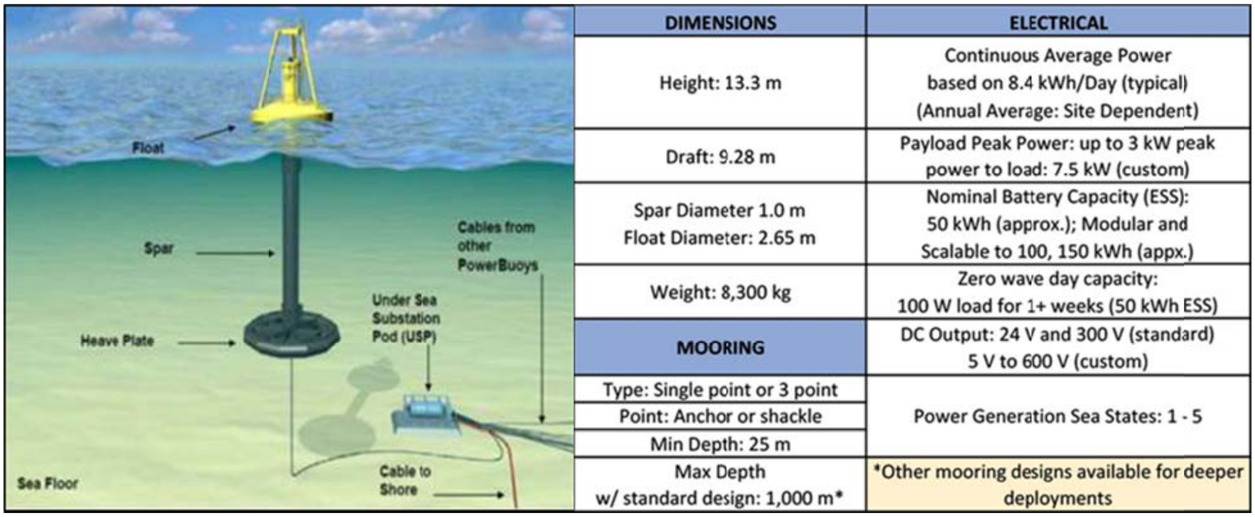
Of the hundreds of current WEC designs, relatively few have made it beyond the research and development phase. Moreover, fewer designs have been deployed to actively generate energy other than for testing purposes. The Pelamis attenuator, originally manufactured by Pelamis Wave Power (now made by Wave Energy Scotland), is among those well-established designs. The world's first commercially active wave farm was a Pelamis wave farm, completed off the coast of Portugal in July 2008 (Poullikkas 2014). Other Pelamis wave farms have since gone into operation in the coastal waters of England as well as Scotland. There are currently no real contending attenuator designs to the Pelamis though there are few in the field testing stage.

As for terminator devices, there have been a couple commercially active designs since the late 1990s. For example, Oceanlinx deployed a blueWAVE terminator in Australian waters and Wavegen deployed one of their LIMPET systems off the coast of the United Kingdom. These onshore designs have since gained competition by Wave Dragon ApS in Denmark (Rusu and Onea 2017). Prior to the Pelamis attenuator becoming the first commercial wave farm, in 2003 the Wave Dragon became the world's first offshore grid-connected WEC, though it only produced local, non-commercial energy (Peter et al. 2006).

None of the aforementioned WEC designs have a solid footing in the U.S. despite multiple attempts to do so over the last two decades (Wang, Isberg, and Tedeschi 2018). However, the U.S. has been actively involved in the field of wave energy conversion during this period. By 2009, the U.S. already boasted more WEC concepts than any other country, though not more than Europe as a whole (López et al. 2013). Currently, the only design with plans for commercial use in the U.S. is the PowerBuoy™, a point absorber, by a New Jersey based company called Offshore Power Technology (OTP). Because of this being the only commercial wave farm in the planning stages in the U.S., the PowerBuoy was selected as the focus for this project.

2.3.3. PowerBuoy Specifications

The design and specifications of the PowerBuoy™ is briefly reviewed in this subsection. The PowerBuoy™ can be described as a two-body floating point absorber. This means there are two main components of the design—the float and the heave plate (Figure 5). The float rises and falls in reaction to the waves while the heave plate resists the pull of the float. This relative motion drives a push rod connected to the float into the spar where this linear motion is converted into a rotary action by a mechanical actuator to drive an electric generator (Mekhiche and Edwards 2014). The table in the right side of Figure 5 describes the dimensions of the device as well as the mooring system and electrical specifications.



DIMENSIONS	ELECTRICAL
Height: 13.3 m	Continuous Average Power based on 8.4 kWh/Day (typical) (Annual Average: Site Dependent)
Draft: 9.28 m	Payload Peak Power: up to 3 kW peak power to load: 7.5 kW (custom)
Spar Diameter 1.0 m Float Diameter: 2.65 m	Nominal Battery Capacity (ESS): 50 kWh (approx.); Modular and Scalable to 100, 150 kWh (appx.)
Weight: 8,300 kg	Zero wave day capacity: 100 W load for 1+ weeks (50 kWh ESS)
MOORING	DC Output: 24 V and 300 V (standard) 5 V to 600 V (custom)
Type: Single point or 3 point	Power Generation Sea States: 1 - 5
Point: Anchor or shackle	
Min Depth: 25 m	
Max Depth w/ standard design: 1,000 m*	*Other mooring designs available for deeper deployments

Figure 5 PowerBuoy™ diagram and specifications (Mekhiche and Edwards 2014)

2.4. Site Selection

Selecting suitable locations for wave farms requires the calculation of wave power potential for the study area as well as a careful consideration of all factors which would limit where a wave farm could be placed.

2.4.1. Modeling Wave Power

Wave power modeling relies on three wave parameters: wave height, peak wave period, and mean direction of the wave (Gunn and Stock-Williams 2012). As mentioned in Section 2.1, the height and length of waves relate directly to the potential wave power. The directional component is a diffusing factor in that wave energy is generally stronger as it flows perpendicular into a shoreline and weaker in the lee of an obstacle. Another diffusing factor is the ocean depth which comes into effect in shallow waters as swell energy, from deep ocean waves, dissipates due to bottom friction and refraction (Wilson and Beyene 2007).

Current wave energy studies rely heavily on wave modeling software that are free of cost. The leading free software for wave modeling is Simulating WAves Nearshore (SWAN), which predicts the growth, decay, and transformation of waves given a set of input physical and environmental parameters (Sørensen et al. 2004). SWAN is a “third generation” wave model that takes into account whitecapping, wave-on-wave interactions, and bottom dissipation (in comparison of those “second generation” models considering only wave interactions). SWAN is unique in including wave-on-wave interactions between three waves as well as depth-induced wave breaking (Booij, Ris, and Holthuijsen 1999). Wave conditions are simulated in the SWAN model using user-input data including the local wind speed and direction, bathymetry, and water boundary. Results of this model are then validated using hindcast data (or backtesting using historical data) as a basis of comparison. In the Southern California Bight (SCB), the validation results of SWAN are typically accurate to about 0.13 meters, with a higher level of error in shallower waters (Rogers et al. 2007; Gorrell et al. 2011).

The Coastal Data Information Program (CDIP) has a wave model called the Monitoring and Prediction (MOP) system which is used to monitor and provide current wave conditions to the public. MOP is a buoy-driven wave model using hindcast data collected from an array of deployed buoys in combination with a wave propagation model to generate wave predictions (O'Reilly et al. 2016). The MOP system generates three standard products: regional swell predictions, inner water sea and swell predictions, and alongshore sea and swell predictions. With expert knowledge on the system, MOP was designed specifically with the complex bathymetry of the SCB in mind. Hindcast validation of this model shows similar errors as those occurring in wind-wave generation and propagation models such as SWAN.

Other wave modeling software exists. Two examples are the Wave Model Development and Implementation Group's WAve Model (WAM) and NOAA's Wavewatch III. Both are third-generation wave models similar to SWAN, but they do not perform as well in validation despite WAM being the first of its kind (Rogers et al. 2007). Alternative model options such as Aquaveo's Coastal Wave Modeling with SMS model developed by the U.S. Army Corp of Engineers offer more customer friendly interfaces available at a steep price.

2.4.2. Assessing Limiting Factors

While wave power is the leading factor in wave farm suitability, a site with optimal wave conditions is only suitable if it is not restricted for use due to legal regulations, current ocean uses, or technical limitations. Legal regulations include laws that prohibit activities affecting natural habitats in the environmentally sensitive areas. Marine Protected Areas, for example, are areas restricting activities for purposes of maintaining biodiversity (Nobre et al. 2009). Areas of international economic exclusivity fall into this group. Certain human activities currently occurring in nearshore ocean waters are also likely to influence where a wave farm can or cannot be placed. Commonly cited limiting factors include oil and gas extraction, military activities, shipping routes, fisheries, and submarine cables and pipelines (Zubiate et al. 2005).

Lastly, WEC devices are designed to be deployed and operate in specific conditions. These technical specifications physically limit where wave farm can be placed based on water depth and seabed slope (Vasileiou, Loukogeorgaki, and Vagiona 2017). A complete list of limiting factors considered for wave farm installations can be found in Appendix A.

2.4.3. Weighted Overlay

Research regarding weighted overlays was conducted specifically for those focusing on wave farm site selection. Possible weights for the layers of limiting factors and wave power were identified through this literature review, providing a range of weighting systems which could be implemented, and each with their own merit. Two sources in particular referenced wave power as a factor in wave site selection.

Vasileiou et al. (2017) gave wave power a weight of 29.2% with other factors including water depth (15%), distance from shore (5%), and vessel density (3.2%). However, this source also used factors such as wind velocity, connection to electrical grid, and population served that were not considered for this study. Wind velocity was given a score of 29.2%, equal that of wave power since this site selection study was for a hybrid wave energy and wind energy farm. Vasileiou's site selection process included an analytic hierarchy process (AHP) with pairwise comparison of the factors to determine these weights, a process requiring an official survey to acquire advanced knowledge from a number of experts.

A second source, again using an array of different factors in their AHP, assigned wave power a weight of 31.5% (Ghosh et al. 2016). This value was actually the sum of two separate categories, wave height and distance between waves, which are essentially the two factors of wave power. Ocean depth (7.9%) and vessel density (4.8%) were also considered in this study. Other factors included water quality, coastal erosion, tourism potential, and more. These factors, and the others, were not considered as they are either difficult to measure, impossible to score, or irrelevant for this study.

Chapter 3 Data and Methods

This chapter lists the datasets and the sources of the data used in this study. It also discusses the methods employed to use this data to identify the most suitable locations off the coast of Southern California where wave farms can be installed with the least environmental, commercial, and social impacts. The identified suitable locations were analyzed for their cost-benefit ratio so that interested parties can have a greater scope of knowledge when selecting potential suitable sites for wave farm installations.

3.1. Research Design and Data Classification

3.1.1. Research Design

The design of this project is summarized in the workflow depicted in Figure 6. It begins with the acquisition of pre-processed data from various sources. This data is then processed separately for vector and raster data types, though with similar steps and identical results. This process includes scoring the data on a one to five (1-5) suitability scale, followed by a process to ensure that each dataset has the same extent boundaries, and ends by converting each into uniform raster datasets of equal extent and cell size. Once this is complete, all data is input into a final output of a single weighted overlay. This process will be discussed in depth in the following sections.

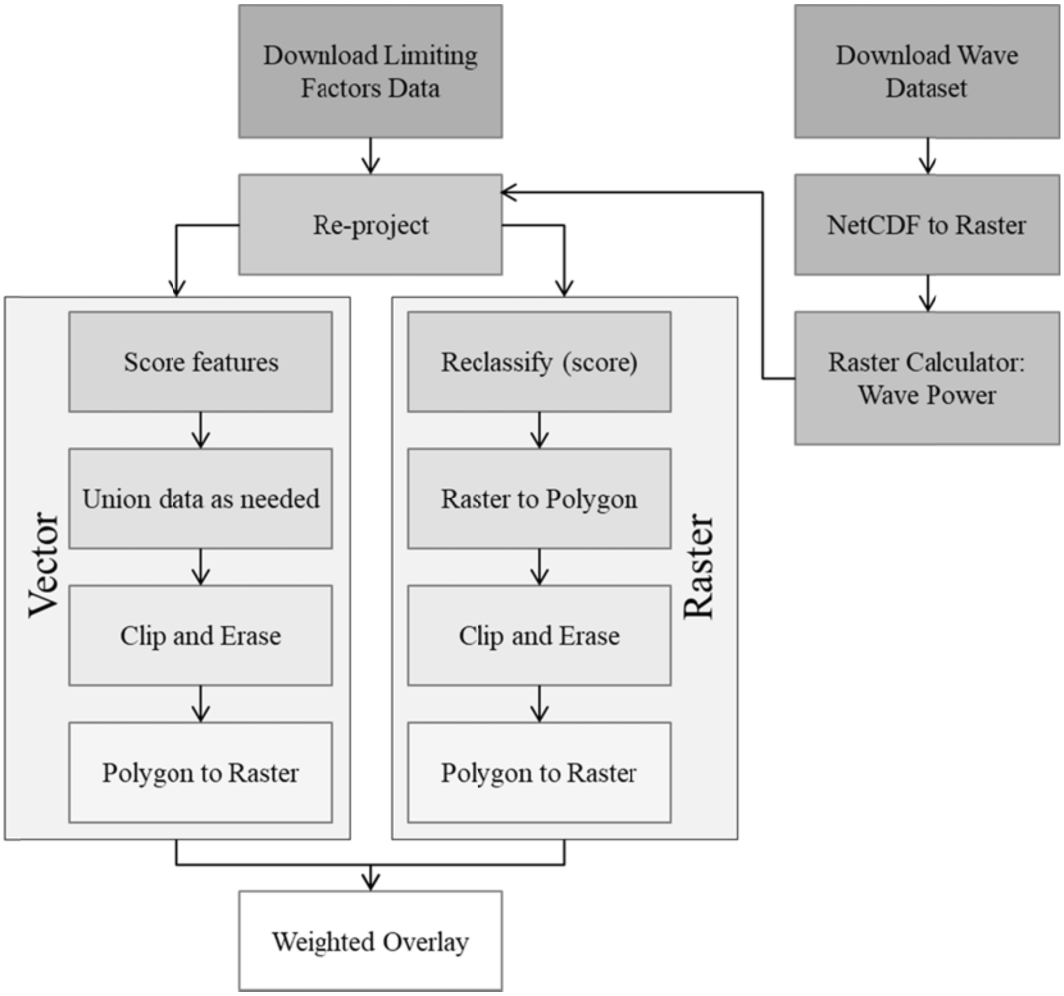


Figure 6 Overview of the method workflow in this study

3.1.2. Data Classification

Data used for the analysis of this study was broken down into two major categories: limiting factors and wave power. Limiting factors restrict or otherwise influence where a wave farm can be installed within the study area. This is an important aspect of the study as it identified areas where wave farms are legally prohibited or physically incompatible. It also takes into account features that do not necessarily prohibit wave farms being installed, yet contain potential technical or political concerns. Wave power, on the other hand, identifies areas with the most and least potential power. It acts as a foundation for the study, which is supplemented by the limiting factors to narrow down the most suitable wave farm locations.

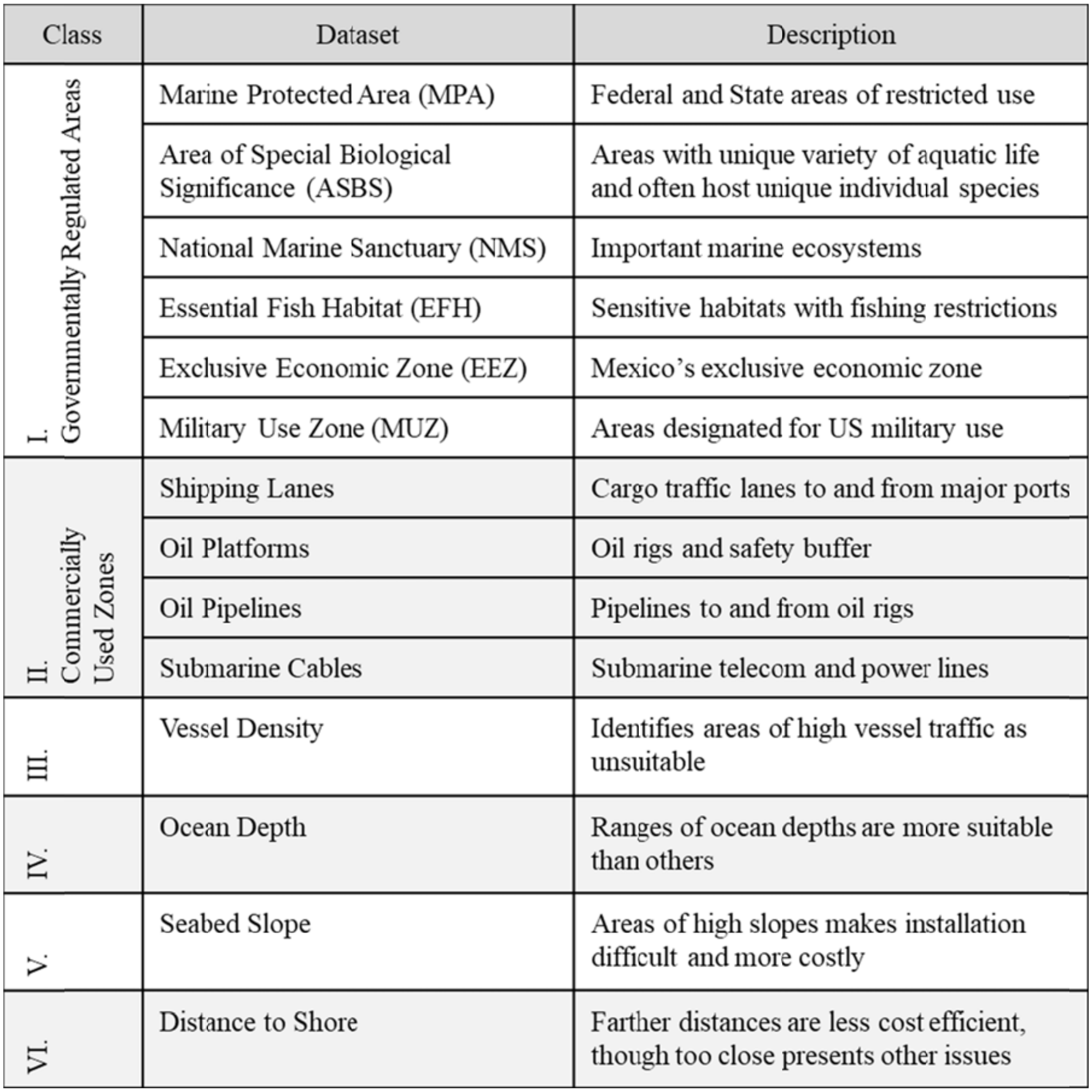
The limiting factors were categorized into six classes, as listed in Table 1 below. Out of the six classes, three represent areas limited by laws and current uses:

I. Governmentally Regulated Areas (GRA): This class includes all regions where a city, state, federal, or military law regulates marine usage;
II. Commercially Used Zones (CUZ): This class includes the regions of significant commercial use;
III. Vessel Density: Vessel density symbolizes the concentration of annual vessel traffic.

These next three classes are self-explanatory and represent areas limited by the physical terrain and distance to shore that influences the cost or effectiveness of the technology:

IV. Ocean Depth
V. Seabed Slope
VI. Distance to Shore

Table 1 The limiting factor categories and datasets included in the wave farm suitability analysis

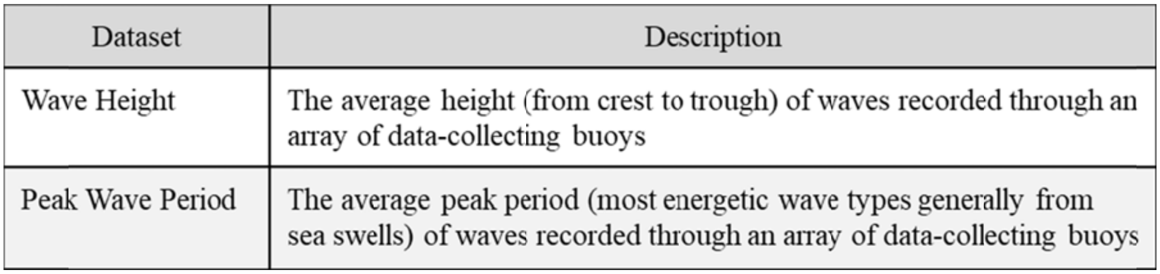


Class	Dataset	Description
I. Governmentally Regulated Areas	Marine Protected Area (MPA)	Federal and State areas of restricted use
	Area of Special Biological Significance (ASBS)	Areas with unique variety of aquatic life and often host unique individual species
	National Marine Sanctuary (NMS)	Important marine ecosystems
	Essential Fish Habitat (EFH)	Sensitive habitats with fishing restrictions
	Exclusive Economic Zone (EEZ)	Mexico's exclusive economic zone
	Military Use Zone (MUZ)	Areas designated for US military use
II. Commercially Used Zones	Shipping Lanes	Cargo traffic lanes to and from major ports
	Oil Platforms	Oil rigs and safety buffer
	Oil Pipelines	Pipelines to and from oil rigs
	Submarine Cables	Submarine telecom and power lines
III.	Vessel Density	Identifies areas of high vessel traffic as unsuitable
IV.	Ocean Depth	Ranges of ocean depths are more suitable than others
V.	Seabed Slope	Areas of high slopes makes installation difficult and more costly
VI.	Distance to Shore	Farther distances are less cost efficient, though too close presents other issues

There were more limiting factors considered but not included in this study. Such factors, including kelp beds, eelgrass beds, aquaculture farms, dive sites, and surf spots, were not included as they fell within the regions already restricted due to shallow water depth. Sand and gravel extraction sites and dredging locations were not included as this data was not readily available for the study area. Fisheries datasets were another factor that was not included as fishing in the SCB is not limited to any specific areas as well as the fact that available fishing numbers are generalized by large grid squares presenting a modifiable areal unit problem in regards to scale. Lastly, attitudinal factors such as public opinions were not included as this data is difficult to quantify. Instead, a simple range of buffers in Class VI was used to represent short distances from shore where wave farms would be most likely to be visible to the public.

Limiting the location of a wave farm is only half of the process. Wave power was used to identify where wave farms would be most effective aside from concerns about limiting factors. As shown in Table 2, the factors necessary to determine the wave power of an area comprise wave height and peak wave period. Together, these variables can be used to calculate wave power.

Table 2 The two forms of the wave data used for calculating wave power



Dataset	Description
Wave Height	The average height (from crest to trough) of waves recorded through an array of data-collecting buoys
Peak Wave Period	The average peak period (most energetic wave types generally from sea swells) of waves recorded through an array of data-collecting buoys

3.2. Data Acquisition

Data for this project was acquired from five different sources as listed in Table 3 below. Details about the source data and their acquisitions are described in the following sections.

Table 3 Data types, resolutions, and sources

Dataset	Data Type	Vector Class / Raster Resolution	Source File Name
California Department of Fish and Wildlife (CDFW) https://www.wildlife.ca.gov/Conservation/Marine/GIS/Downloads			
Marine Protected Areas	Vector	Polygon	/Management/MPA
Special Biol. Significance	Vector	Polygon	/SWQPA
National Oceanic and Atmospheric Administration (NOAA) https://marinecadastre.gov/data/			
National Marine Sanctuaries	Vector	Polygon	NOAA National Marine Sanctuaries
Essential Fish Habitats	Vector	Polygon	West Coast EFH Conservation Areas
Exclusive Economic Zones	Vector	Polygon	200NM EEZ and Maritime Boundaries
Military Use	Vector	Polygon	Danger Zones and Restricted Areas
Shipping Lanes	Vector	Polygon	Shipping Lanes and Regulations
Oil Platforms	Vector	Point	Drilling Platforms
Oil Pipelines	Vector	Polyline	Select Pipelines
Submarine Cables	Vector	Polyline	NOAA Charted Submarine Cables
Vessel Density	Raster	100 m	2013 Vessel Density
British Oceanographic Data Centre (BODC) https://www.gebco.net/data_and_products/gridded_bathymetry_data/gebco_30_second_grid/			
Ocean Depth	Raster	30 arc seconds	Selected by area as a single Digital Elevation Model (DEM)
Seabed Slope	Raster		
U.S. Census Bureau https://www.census.gov/cgi-bin/geo/shapefiles/index.php			
Distance to Shore	Vector	Polygon	2017 Counties (and equivalent)
Coastal Data Information Program (CDIP) http://thredds.cdip.ucsd.edu/thredds/catalog/cdip/model/misc/catalog.html?dataset=CDIP_Models/misc/SoCal_mean_swell_2017.nc			
Mean Wave Height	Raster	0.01 degree	SoCal_mean_swell_2017. NetCDF file provided by CDIP upon request
Mean Peak Wave Period	Raster		

3.2.1. Data Acquired for Limiting Factors

Marine Protected Areas (MPA) and Areas of Special Biological Significance (ASBS) were provided by the California Department of Fish and Wildlife (CDFW), both of which were polygon features downloaded as individual shapefiles that were ready to use. Most of the datasets, however, was acquired from National Oceanic and Atmospheric Administration (NOAA), which vetted and uploaded data from various original sources. The polygon vector datasets from NOAA, according to Table 3, required no formatting and were ready to use. However, oil platforms, as points, and submarine cables and oil pipelines, as lines, required an additional step after download before they could be processed for analysis.

The additional step required for point and line features was to create polygon buffers at significant distances. For the oil platforms, two buffers were created: a 500-meter buffer representing the rigs' minimum safety distance in accordance with standard safety practices and a larger one-kilometer buffer representing the area of increased rig-related vessel traffic. There were no found regulations regarding the minimum safety buffers for pipelines and submarine cables; however, a similar study for wave farm suitability analysis used 500 meters for this buffer distance, matching those of the oil platforms applied in this study (Nobre et al. 2009). Following that example, a 500-meter buffer was used here as well. These buffers were used in lieu of their corresponding points and lines in the data processing step.

These vector datasets contained no metadata about source accuracy. When possible, randomly selected features within each dataset were manually confirmed according to coordinates on official documents or through satellite imagery. MPAs, for example, are each described in detail with exact coordinates in title 14, section 632 of the California Code of Regulations (2017). Similarly, National Marine Sanctuaries (NMS) were confirmed from the Code of Federal Regulations (2009), title 15, sec. 9.922, which provides a general description of the boundaries along with exact coordinates. Other legal or political boundaries could not be as easily confirmed, though any error would be expected to be relatively minor at the scale of this study. Oil platforms were the only features that could be visually confirmed. On the other hand, oil pipelines and submarine cables could not be fully verified. A small level of verification for these features was achieved by the fact that their beginning and end points aligned properly with verifiable locations such as power stations and oil platforms.

Vessel density data was acquired through NOAA as a raster dataset. It was collected by the U.S. Coast Guard for any vessel equipped with an Automatic Identification Systems (AIS) transponder. AIS transponders are required, according to Regulation 19.2.4 of the International Maritime Organization's Safety of Life at Sea (SOLAS) convention, for all internationally voyaging ships of 300 gross tonnage or more, non-internationally voyaging ships of 500 gross tonnage or more, and passenger ships of any size (International Maritime Organization 2007). The transponder sends GPS coordinates, among other data, every two to ten seconds with a positional accuracy of 0.0001 minutes. The National Oceanic and Atmospheric Administration (NOAA) and the Bureau of Ocean Energy Management (BOEM) jointly compiled this data into a raster with 100-meter grid squares for the contiguous United States offshore waters.

The bathymetry data was acquired as a single raster from BODC, a British agency with a global bathymetry database compiled in 2014. This source was chosen for its large areal extent and relatively high raster resolution (30 arc seconds) in comparison to other sources with similar coverage. 30 arc seconds equates to an approximate raster cell size of 30.9 x 25.7 meters at the latitude of the SCB. While this raster file was ready to be used for the ocean depth requirement, it was also processed to create the seabed slope layer using the Slope tool in ArcGIS.

Lastly, the distance to shore feature was creating using the buffer tool on a shapefile of the 2017 version of California counties acquired from the U.S. Census Bureau. The county polygons were first dissolved into a single feature and all islands were removed before the buffers were created. Buffers were set at 1, 2.5, 5, 50, 75, 100, and 150 kilometers according to a logical combination of the values suggested from multiple sources (Nobre et al. 2009; Vasileiou, Loukogeorgaki, and Vagiona 2017).

All limiting factor datasets acquired were the most up-to-date versions available and were representative of the actual features at the time of the analysis (July 2018), with a single exception. Vessel density described the vessel traffic patterns during the year of 2013. This is acceptable, as it represents a historical trend rather than strict legal boundaries, meaning that more recent data would not necessarily predict future vessel density any more accurately than data from 2013.

3.2.2. Data Acquired for Wave Power

To create the wave power layer, a NetCDF file containing the raster layers of the average wave height and the average peak wave period for the year of 2017 was acquired from CDIP. The NetCDF file was created by the team at UC San Diego's Scripps Institute of Oceanography (Scripps) on request. While the two raster layers could have been generated by the wave models using the Monitoring and Prediction (MOP) computer program, there were some technical limitations of installing the MOP program on my personal computer. The request was given with specific parameters for the study area as well as the timeframe for the entire year of 2017 for which the wave data was to be averaged. Rather than an average of a 9-band energy spectra, which is ideal for nearshore waves, the averages of wave height and peak wave period were acquired so that it could be used to more accurately model the waves farther offshore.

While a request like this was happily fulfilled by a team of experts, it is important to understand how the model used for generating the wave data was created. The program used to create these wave models is MOP v1.1, downloadable from the CDIP code access webpage (cdip.ucsd.edu/code_access). The system requirements include a FORTRAN compiler and NetCDF4 packages. The Scripps team recommends using a Linux operating system and provides installation instructions in the MOP download package. With knowledge of FORTAN compilers, MOP can be installed on most modern computer systems.

Running a model in MOP is a two-step process: first, define output sites; and second, create "hindcast predictions" or wave models for that defined site. Defining the output site can be done through R_CA_nc, the first of two tools found within the MOP program. The input values of this tool are the decimal degree coordinates of the CDIP wave data gathering buoys that were selected for the analysis. Next, follow the coordinates with a five-digit site designation, ideally a meaningful prefix followed by the buoy number. An example command would be "% ./R_CA_nc 32.93045 -117.39239 BP100". Running this code results in a NetCDF site definition file that will be used in step two. This should be repeated for each selected buoy.

The second step of running a wave model uses the second of the tools found in the MOP program, the net_model. This tool has many different parameters that allow for customization. The first parameter is the start time (-s), input as 2017010100 for the start of the year 2017. Next is the duration parameter (-h); it can be set for an hour, week, or month. There is a workaround to run this model for longer periods, such as for an entire year, which was necessary for this study. To do this, a new parameter (-z) would be included followed by OWI_hc. This allows the model to be run with multiple start times while the output NetCDF file is appended rather than rewritten each time. The next parameter required is the NetCDF site definition files (-c) created in step one. The initialization parameters file name (-i) comes next, followed by a flag command (-e) that extends the nearshore parameters. The final parameter, another flag command (-O), is used to connect to the THREDDS server to load the buoy data via opendap. This eliminates the need to acquire and store the data on the local machine. An example command would look like this: “`% ./net_model -s 2017010100 -h m -c BP100_32.93045-117.39239_ref.nc -i socal_alongshore_hindcast.INPUT -z OWI_hc -e -O`”; however, there are a number of other options given coastal bathymetry of a different study area.

Running the two-step process above results in the NetCDF file containing the required raster datasets. This is what the Scripps team provided. The Make NetCDF Raster Layer tool in ArcGIS was used to export the imbedded wave data layers into raster datasets (see Figure 7 and Figure 8).

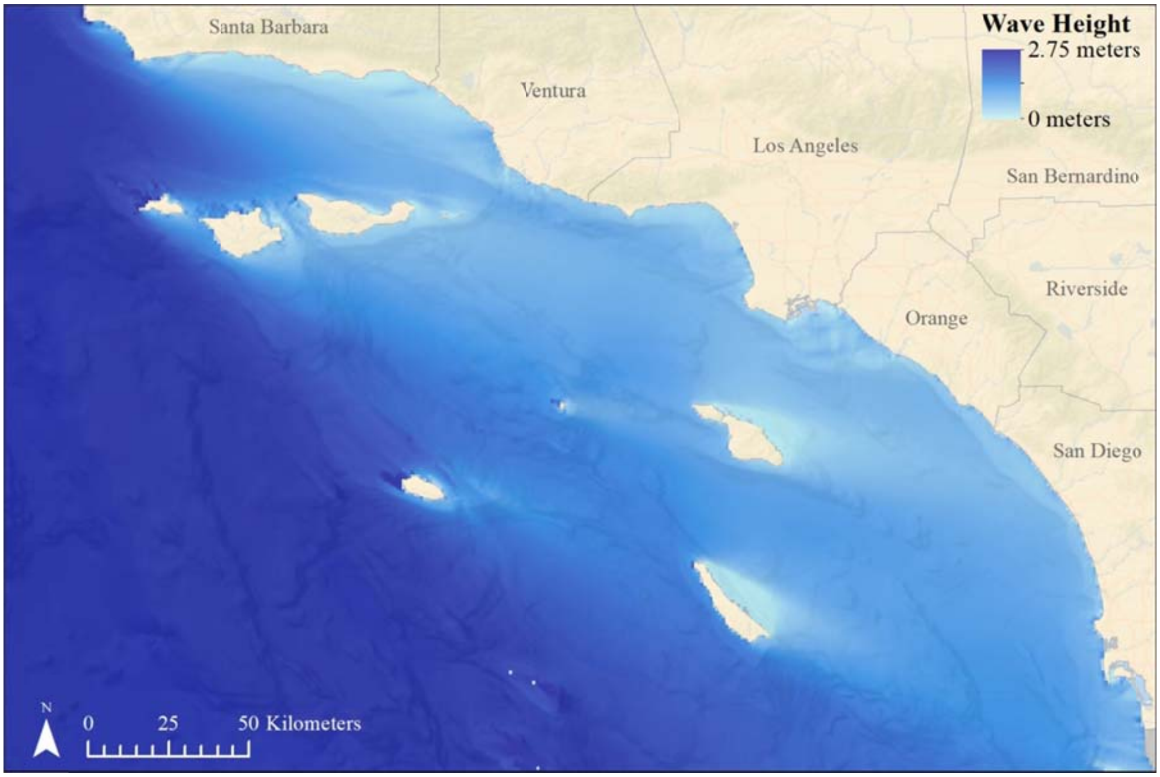


Figure 7 Map of the average wave height for 2017

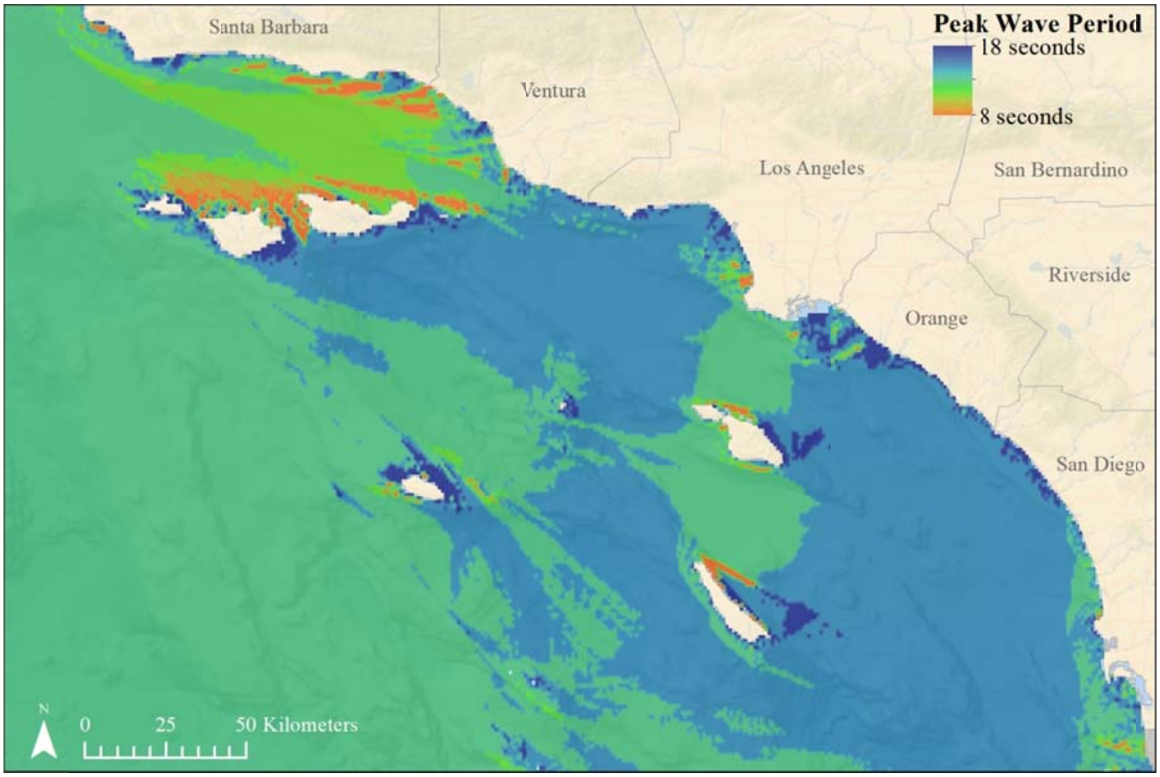


Figure 8 Map of the average peak wave period for 2017

For the two wave data layers to be useful for this project, the two raster layers were combined to create a single wave power dataset. Wave power can be calculated from wave height and peak wave period using the following formula:

$$P = \frac{pg^2}{64\pi} H^2T$$

where P represents wave power (W/m), p represents water density (kg·m^{-3}), g is acceleration due to gravity (m·s^{-2}), H is wave height (m), and T is peak wave period (s). The Raster Calculator tool in ArcGIS was used for this calculation: (1025 * 9.8 * 9.8) / (64 * 3.14) * (“WaveHeight” * “WaveHeight” * “WavePeriod”). While water density can fluctuate due to the variations of water temperature and salinity over a span of the ocean, in a limited area like the SCB, the density gradient is considered very limited. Thus, a value of 1025 kg/m^3 was given (Franzi et al. 2016).

The remaining values in this equation are for acceleration due to gravity at 9.8 m/s^2 and pi which was rounded down to 3.14. The cell values of the resulting raster dataset represent the mean wave power in Watts per meter of wave crest, or wave power density.

3.3. Methods

The analysis of this study consists of two major steps: (1) Process the data in preparation of an overlay and (2) conduct a weighted overlay analysis to produce the final data output. This section breaks down both of these steps so that the study can be replicated for other study areas. All geoprocessing tasks and spatial analyses—except where noted—were completed using ESRI's ArcGIS for Desktop version 10.4.1 running on a Windows 10 laptop with 16 GB of RAM.

3.3.1. Data Processing

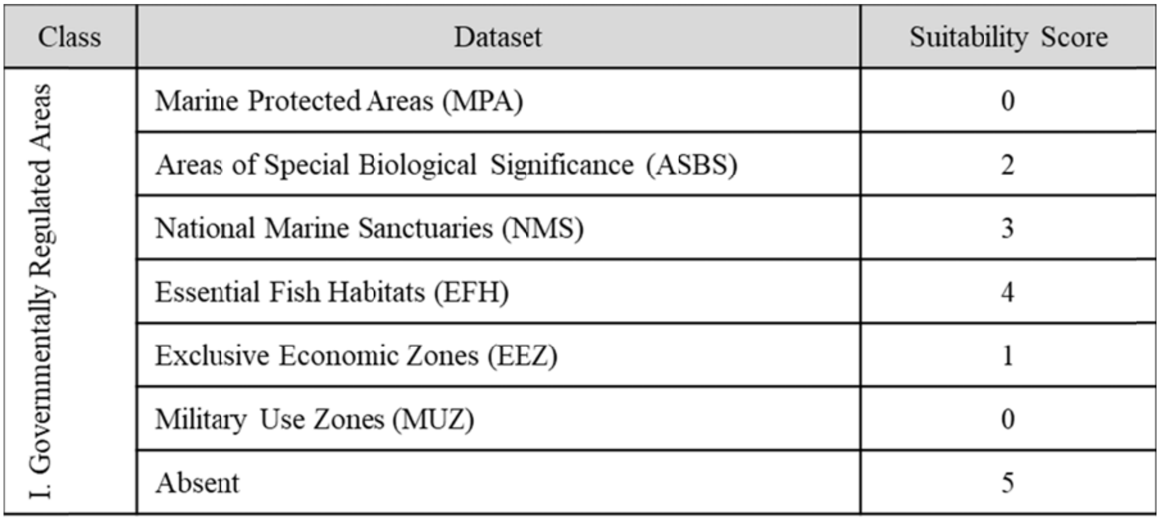
The purpose of this first step is to prepare every dataset to have the same projection, extent, and cell size, ensuring the best results in the weighted overlay. All of the vector and raster datasets were first assigned the same coordinate system—the California Teale Albers projection with the North American Datum of 1983 (NAD 1983 California Teale Albers)—using the Project tool from the Data Management toolbox in ArcGIS. A projected coordinate system was required for accurate areal measurements.

Next, a scoring system for the weighted overlay was established. Each individual feature would be given a suitability score of a value one through five, with one (1) being least suitable and five (5) being the most suitable for wave farm installations. A logical scoring technique was used to score each feature based on their limitations according to the sources referenced. Aside from these features, others were given a restricted score of zero (0) due to technical limitations or legal regulations which completely remove these areas from consideration.

3.3.1.1. Vector Datasets

In this study, the limiting factor datasets were split into six classes (see Section 3.1.2). Table 4 lists the summary of the scores used for the first class, Governmentally Regulated Areas (GRA):

Table 4 Suitability Scores used for Governmentally Regulated Areas



Class	Dataset	Suitability Score
I. Governmentally Regulated Areas	Marine Protected Areas (MPA)	0
	Areas of Special Biological Significance (ASBS)	2
	National Marine Sanctuaries (NMS)	3
	Essential Fish Habitats (EFH)	4
	Exclusive Economic Zones (EEZ)	1
	Military Use Zones (MUZ)	0
	Absent	5

The reasoning of the above scores in GRA for the individual layers is provided below:

- Marine Protected Areas (MPA) are federal and state protected areas which forbid any and all commercial activities. Only certain preapproved research operations may operate in these areas, which does not fit the description of a wave farm therefor all MPAs were given a restricted score of zero (0).
- Areas of Special Biological Significance (ASBS) are not as protected legally, though many prohibit dredging and other seabed altering activities. They are in place to protect the most biologically significant regions, much of which occur within ecosystems sensitive to outside disturbances. Without strict legal restrictions, a score of two (2) was given to these features.

- National Marine Sanctuaries (NMS) have the widest range of area and many MPA and ASBS fall within the extent of these sanctuaries. There are two NMS within the study area: Channel Islands NMS and Cordell Bank. Both regulate the uses of these areas for educational and research purposes as well as to protect maritime heritage and high-risk species. There are, however, no regulations prohibiting wave farms given that the proper protocols and permits are provided. For this reason, NMS were given a suitability score of three (3).
- Essential Fish Habitats (EFH) are areas designated by NOAA as fisheries to help increase the region's fish population. As evident by their boxlike extents, these areas do not strictly represent any habitats, but are placed at strategic locations according to the species of fish being protected. Wave farms would pose little to risk for these fish, though interest groups might protest given that the technology is largely unproven. Therefore a suitability score of four (4) was given to these features.
- Mexico Exclusive Economic Zone (EEZ) is the maritime limit of Mexico's legal claim to economic resources. U.S. based wave farms would face jurisdictional and bureaucratic issues, earning this feature a suitability score of one (1).
- Military Use Zones are designated by the U.S. Air Force and Navy as dangerous due to military activities. Exact regulations pertaining to the legality of wave farms within these extents are unknown, but it was logically determined that they would be considered restricted as well, thus a score of zero (0) was assigned to them.

A new attribute field called “suitability” was created in each layer and was populated with the appropriate suitability score using the Field Calculator. Once scored, each of the six layers was dissolved into a single feature before being merged into a single dataset for Class I (GRA) using the Union tool. Areas of overlapping features had multiple scores assigned to them by the Union tool. This dataset was then clipped to the area of an extent box polygon, created to ensure the same extent used for all datasets in the weighted overlay. Then the dataset was merged with that same extent box polygon, again with the Union tool, to create a feature layer representing the areas where no limiting factor was present within the study area, and was given a score of five (5). Lastly, a land feature polygon dataset from the U.S. Census Bureau including the mainland as well as the islands of California was used to eliminate all areas above sea level to be used in further analysis. Figure 9 depicts the final outcome of this process.

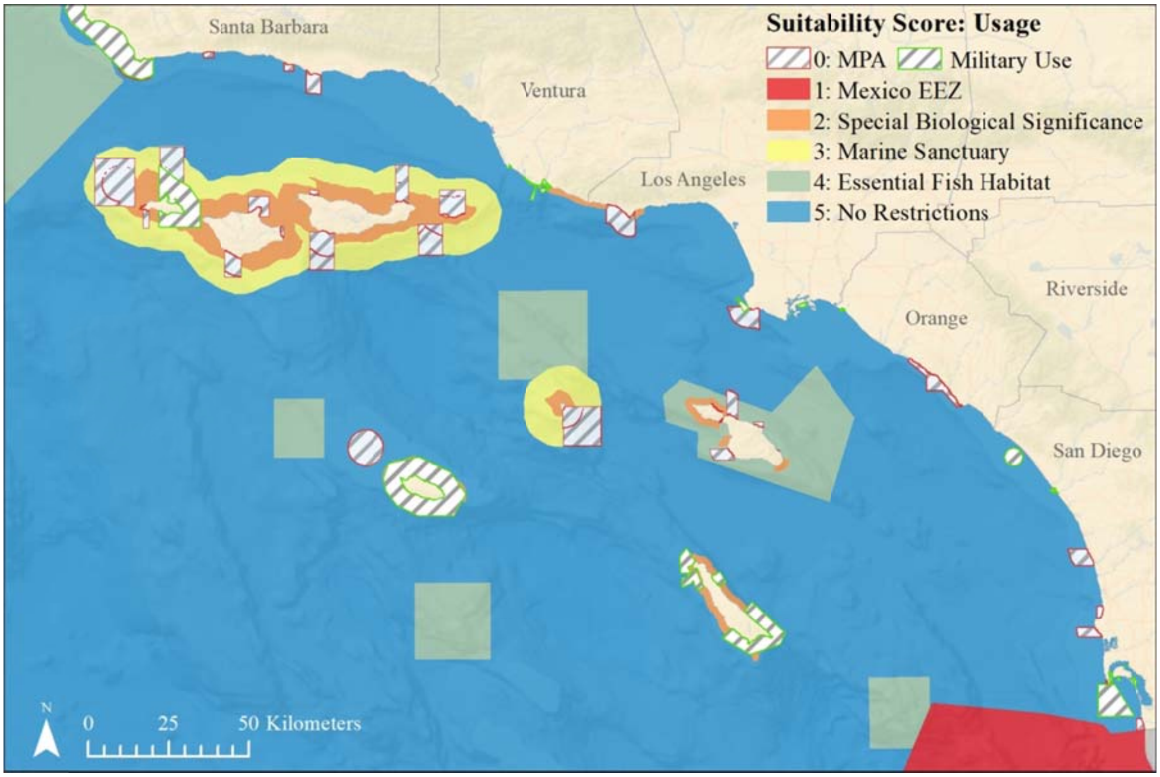
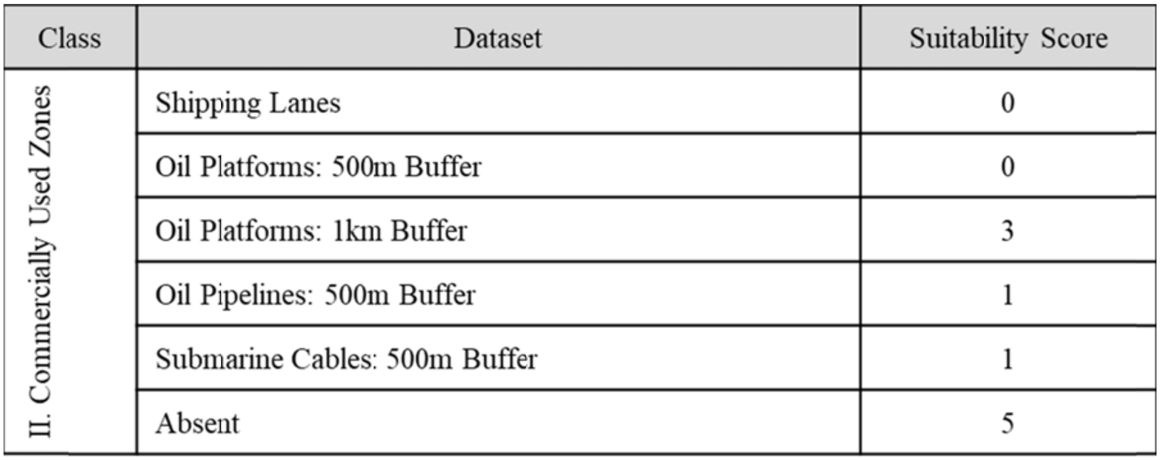


Figure 9 Map of Governmentally Regulated Areas and their suitability score

Commercially Used Zones (CUZ), Class II of the limiting factors, was scored in a similar manner as the GRE (Table 5).

Table 5 Suitability Scores used for Commercially Used Zones



Class	Dataset	Suitability Score
II. Commercially Used Zones	Shipping Lanes	0
	Oil Platforms: 500m Buffer	0
	Oil Platforms: 1km Buffer	3
	Oil Pipelines: 500m Buffer	1
	Submarine Cables: 500m Buffer	1
	Absent	5

The reasoning for the scores assigned in the individual layers is as follows:

- Shipping Lanes are designated in- and out-bound lanes for vessel traffic docking at the ports of Los Angeles and Long Beach. Obstructing these lanes of traffic is strictly prohibited, making a restricted score of zero (0) the only option.
- Oil Platforms have a required 500-meter safety buffer for any anchoring vessels due to the length of the oil platform’s anchor cables and possible contact between the two. Wave farms would be equally at risk thus they were scored as restricted (0). A larger buffer of one kilometer was also included to represent a larger emergency related safety zone. This buffer is less restrictive and, in a judgment call, a suitability score of three (3) was chosen.
- Oil Pipelines require regular checks and maintenance making a clear path above water but also along the sea floor. A 500-meter buffer was chosen to represent this path and was given a suitability score of one (1).

- Submarine Cables, like oil pipelines, require regular checks and maintenance so the same buffer distance and suitability score of one (1) were given to those features.

Like the GRE dataset, these CUZ features were dissolved and then merged together using the Union tool. They were also joined with the extent box to represent areas free from restrictions which was given a suitability score of five (5). The areas above sea level were erased from this dataset as well. Figure 10 shows the final outcome of this process.

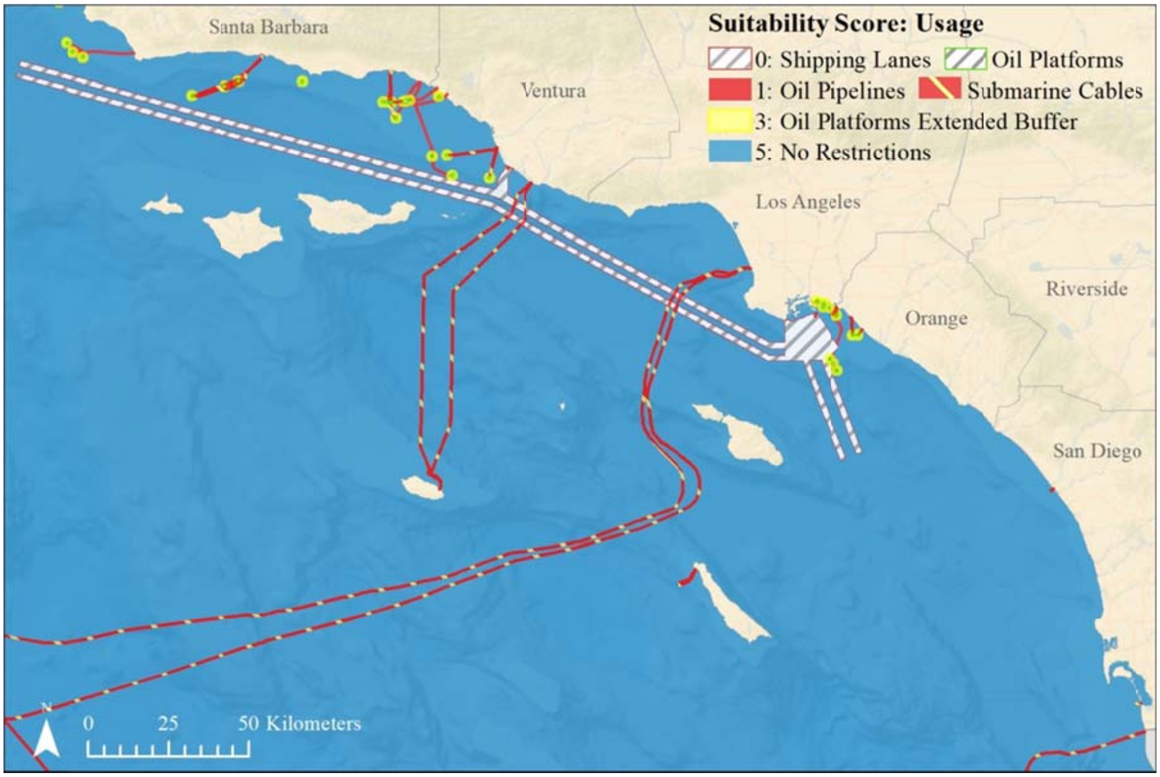


Figure 10 Map of Commercially Used Zones and their suitability score

The final vector layer is Class IV, Distance to Shore. All remaining datasets (classes III, IV and V) are in raster format and will be discussed in the next section. Distance to Shore was broken down into the five categories as described in Table 6. Economics and aesthetics are the two primary considerations when creating and scoring these buffers distance to the coastline.

Table 6 Suitability Scores used for Distance to Shore

Class	Value Range	Suitability Score
VI. Distance to Shore	>150 km	1
	<1 km & 100 - 150 km	2
	1 - 2.5 km & 75 - 100 km	3
	2.5 - 5 km & 50 - 75 km	4
	5 - 50km	5

The economic concern is in regards to the cost of cable per kilometer between the shoreline and the potential wave farm location. For these reasons, any location beyond 150 kilometers was given for a score of one (1) for the least suitability, considering anything beyond that distance to shore would be very costly. Between the distance of 100 and 150 kilometers to shore, the cost for cable infrastructure is still on the high end so it scored a two (2) on the suitability scale. The cost for cable infrastructure for the next two ranges—between 75 to 100 kilometers and between 50 to 75 kilometers to shore—becomes moderately economical, so these ranges were given the suitability scores of three (3) and four (4), respectively. Anywhere below 50 kilometers from the shoreline, except where aesthetics come into play, is considered the most suitable for the cable cost, and therefore earning the maximum score of five (5) in this class.

As for the aesthetics concern, it involves the potential negative impacts on human experiences due to wave farms being seen as eyesores. Since unpleasant aesthetics would not strictly prohibit wave farm placement, no ranges of distance to human development (in this case, to the coastline) were scored as restricted (0) or even the least suitable (1). However, a wave farm within a kilometer of the shoreline would be highly contested for visual aesthetic as well as for some recreational concerns since many human activities occur in region. Thus, a suitability score of two (2) was assigned for the distance of one kilometer to shore in this category. From there, the farther offshore, the higher the suitability score would get. A score of three (3) was given to the range between 1 and 2.5 kilometers to shore and a score of four (4) was given to the range between 2.5 and 5 kilometers. The distance to shore greater than 5 kilometers was considered beyond the range of recreational activities and therefore was given a score of five (5), except the ranges mentioned above for the economic concerns.

After the suitability scores were applied to the appropriate value range, this Distance to Shore dataset was clipped to the study area extent. The areas above sea level were removed from the raster dataset using the same approach mentioned as that for both the GRA and CUZ datasets. Figure 11 shows the final outcome of this reclassified suitability for Distance to Shore.

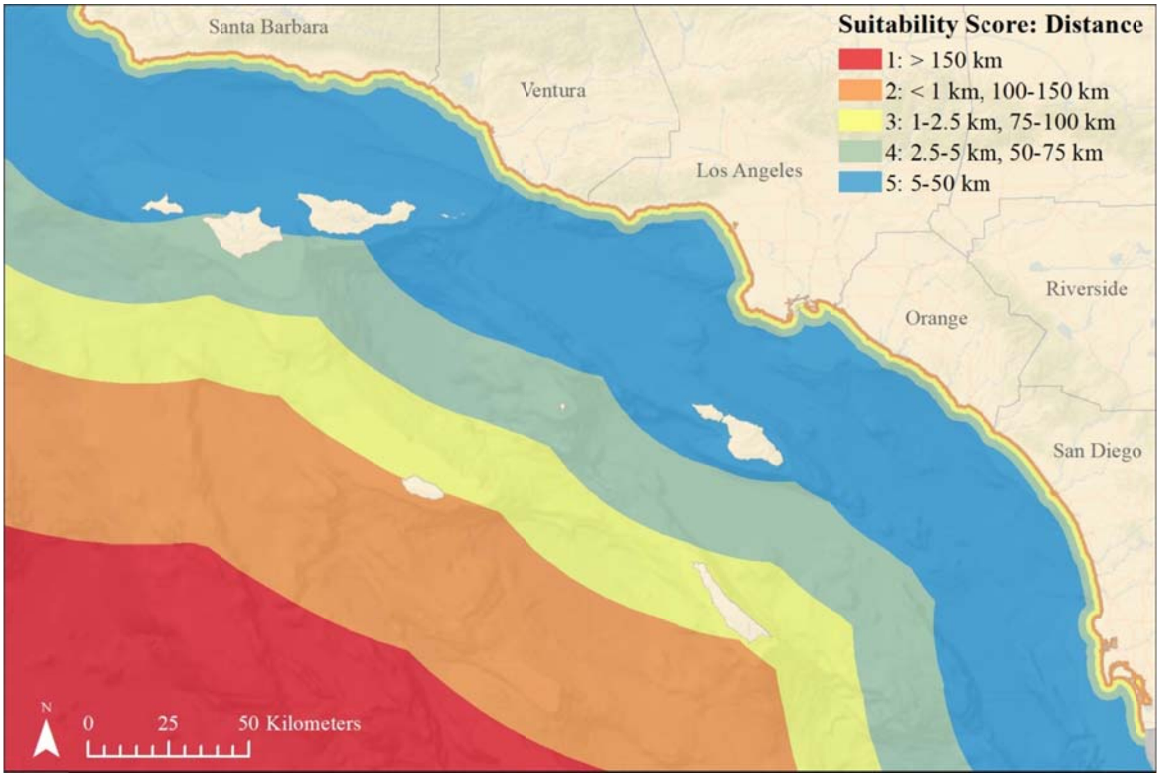


Figure 11 Map depicting the Distance to Shore in assigned suitability scores

In preparation of the weighted overlay, these vector datasets were converted into raster layers using the Polygon to Raster tool from the Conversion Tools toolbox in ArcGIS. Each dataset was converted individually, but with identical parameters as follows. For each, the suitability score was selected as the Value field, the Cell Assignment Type was left with the default CELL_CENTER, the Cellsize was set to 100 (meters), and no Priority field was selected.

3.3.1.2. Raster Datasets Preparation

The process of preparing the raster datasets was more complicated than working with vector datasets. Because the raster datasets acquired are floating type rasters that naturally do not contain attribute information, the process of assigning suitability scores was completed through reclassifying each raster into an integer type raster with the desired classification. The Reclassify tool in the Spatial Analyst extension in ArcGIS was used to perform this task.

Vessel Density, Class III of the limiting factors in this study (See Section 3.1.2), represents the density of boat traffic for 2013. According to the metadata of this raster layer, the cell values for the dataset do not represent the actual number of vessels and should be treated as a high-low density scale. These values were classified into five suitability score categories using the Standard Deviation classification method in ArcGIS. The Interval Size was set to “1 Std Dev” resulting in four value ranges of one standard deviation. Those areas in the highest vessel density range were given a score of one (1) and those that fell into the category with the lowest density were given a score of four (4). Suitability scores of two (2) and three (3) were given to the two categories falling in between. The areas absent of vessel density values were assigned a score of five (5). Table 7 lists the range of the values and their assigned scores.

Table 7 Vessel Density suitability scores assignment

Class	Value Range (Based on 1 Standard Deviation)	Suitability Score
III. Vessel Density	1.405 - 141.356	1
	0.855 - 1.404	2
	0.305 - 0.854	3
	0.001 - 0.304	4
	Absent	5

Once reclassified, the Vessel Density raster layer was converted into a polygon feature layer using the Raster to Polygon tool in ArcGIS. From there, the same procedure applied to the vector datasets of clipping to the extent polygon and erasing the land features was completed. Figure 12 shows the final output of this vessel density layer.

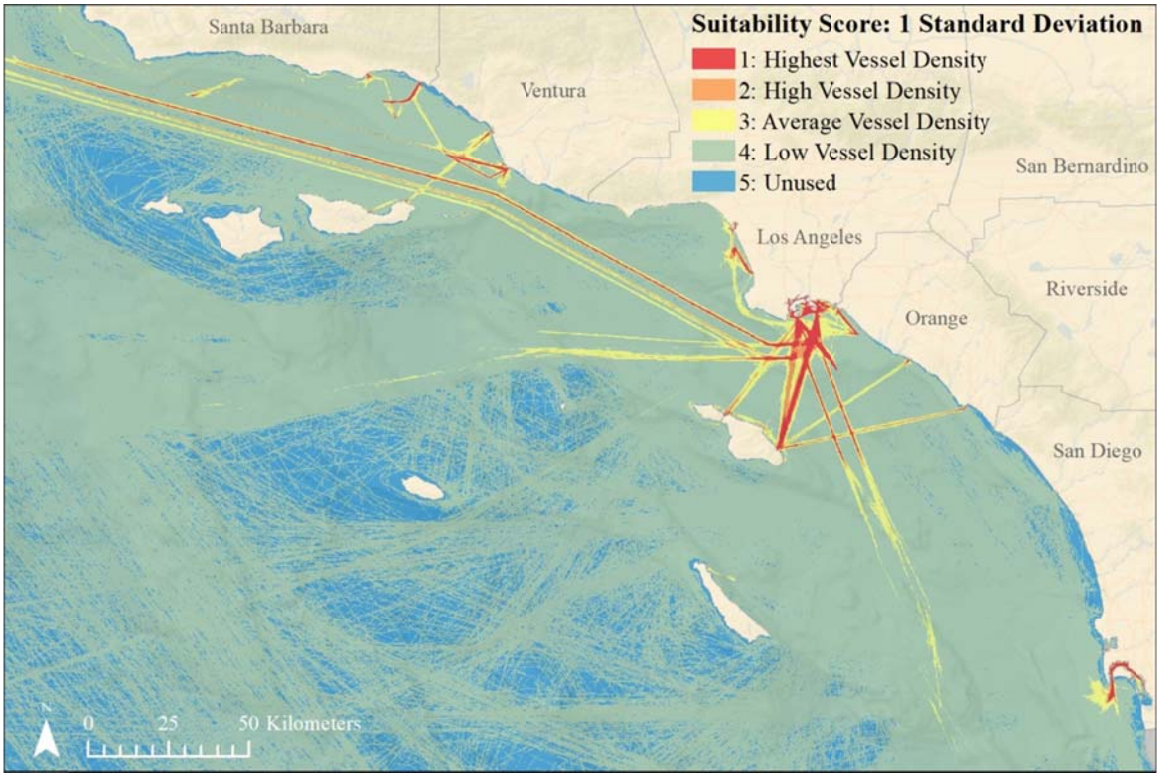
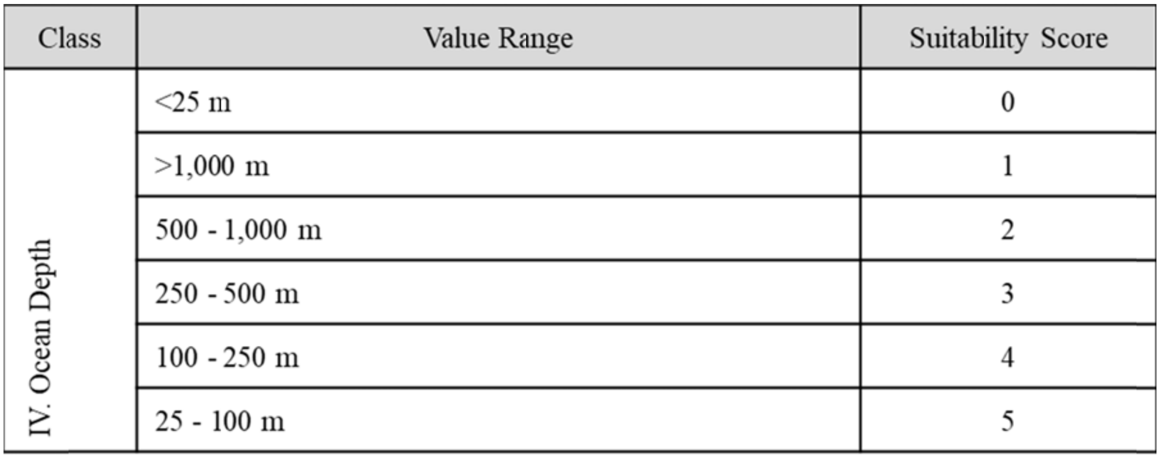


Figure 12 Map of Vessel Density in assigned suitability scores

Ocean Depth, Class IV of the limiting factors (See Section 3.1.2), was reclassified from a Digital Elevation Model (DEM) and was scored based on two factors: WEC capabilities and economics. Because the only WEC technology currently planned for installation in the U.S. is PowerBuoy™, the ocean depth suitability was categorized based on the recommendations for this technology (Mekhiche and Edwards 2014). Table 8 shows this breakdown of depth ranges and corresponding scores.

Table 8 Ocean Depth suitability scores assignment



Class	Value Range	Suitability Score
IV. Ocean Depth	<25 m	0
	>1,000 m	1
	500 - 1,000 m	2
	250 - 500 m	3
	100 - 250 m	4
	25 - 100 m	5

According to the manufacturer's specifications, the PowerBuoy™ design has an operating depth ranging between 25 meters and one kilometer. Depths below 25 meters were therefore assigned a suitability score of zero (0) for restricted. Depths beyond one kilometer, however, were assigned a score of one (1) as the source also notes that costly adjustments can be made to account for greater depths. Due to the increases in the initial cost of installation as well as the ongoing maintenance, the next two categories—500 meters to one kilometer and 250 meters to 500 meters—were given the suitability scores of two (2) and three (3), respectively. At a depth range between 100 meters and 250 meters, a balance between cost and estimated wave energy potential is met. This range was given a suitability score of four (4), reserving the score of five (5) to the range of 25 meters to 100 meters for its lowest initial cost within the ideal depth range of wave potential.

The source DEM integrated ocean bathymetry and land topography data. To account for this land topography, all cell values above sea level (elevation > 0) were reclassified to zero (0). The raster was then converted into a polygon dataset and removed in a feature editing session in ArcGIS. Lastly, the dataset clipped to the proper extent with all unwanted remnants of the land topography removed using the Erase tool. The final output is displayed below in Figure 13.

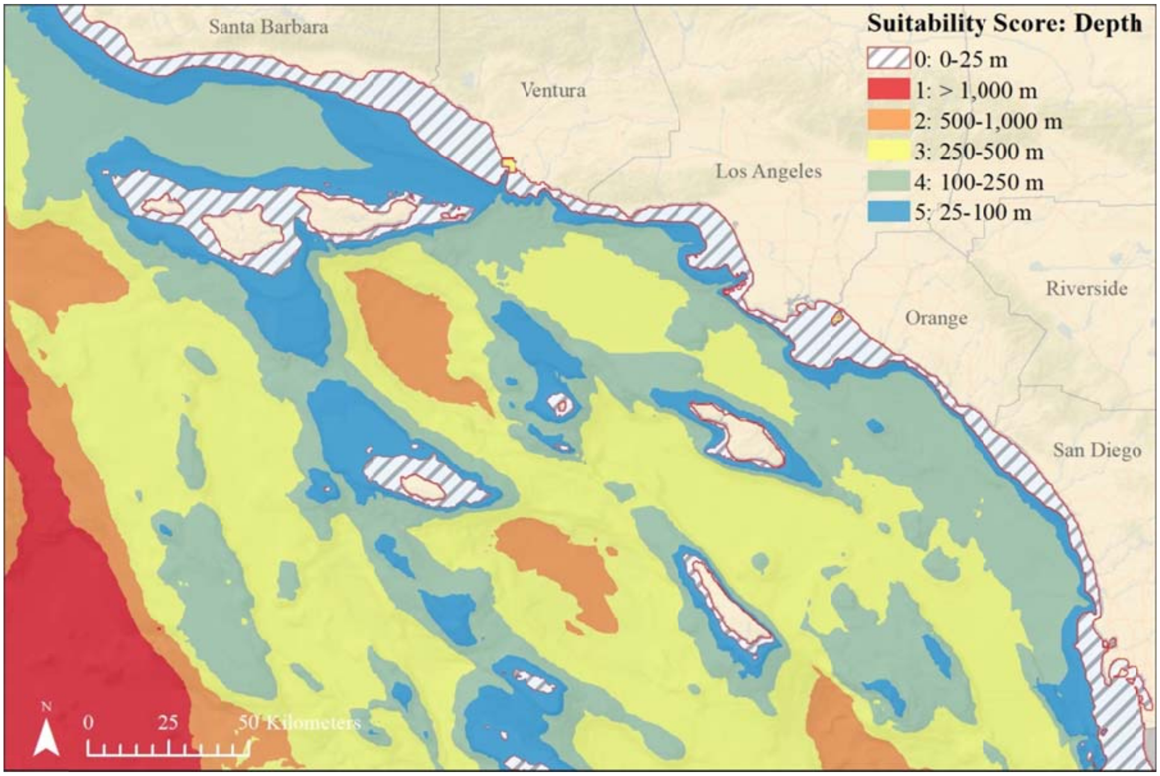
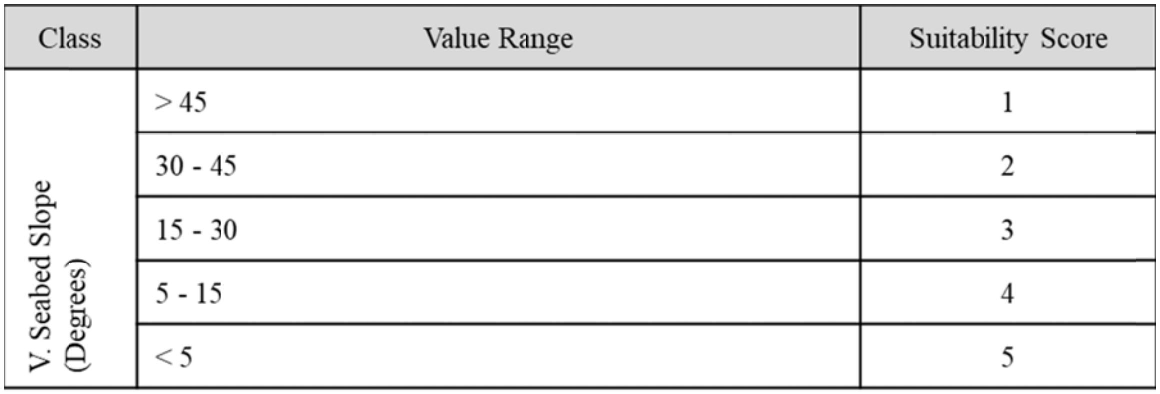


Figure 13 Map of Ocean Depth in assigned suitability scores

As to Class V, the final class of the limiting factors (See Section 3.1.2), the suitability scores of Seabed Slope were based on the levels of the difficulty to install PowerBuoys™ on the sea floor. As a rule, the more even the terrain is, the easier and more cost effective the installation will be. Slopes above 45 degrees (°) were considered to be too steep for the standard mooring procedure. Alternative methods increase costs, earning this category a suitability score of one (1). Steep slopes between 30 and 45 degrees (º) were considered marginally acceptable for the standard mooring procedure and were given a score of two (2). Within this slope range, the water depth changes rapidly in a small area, causing rising difficulties for wave farm installation. Slopes between 15 and 30 degrees are still steep enough to affect planning, though to a much lesser extent and therefore were given with a score of three (3). Any slope below 15 degrees is preferred for wave farm installations. Within this range, those seabed slopes between 5 and 15 degrees were given a score of four (4) while areas below 5 degrees where given a score of five (5). Table 9 lists these slope ranges and their suitability scores.

Table 9 Seabed Slope suitability scores assignment



Class	Value Range	Suitability Score
V. Seabed Slope (Degrees)	> 45	1
	30 - 45	2
	15 - 30	3
	5 - 15	4
	< 5	5

The slope dataset was created from the same DEM that was used for Ocean Depth so it had to go through the same process to remove the values above sea level. After converting this raster into a polygon dataset, it was clipped and erased to match all previous datasets. The final product of this process can be seen below in Figure 14.

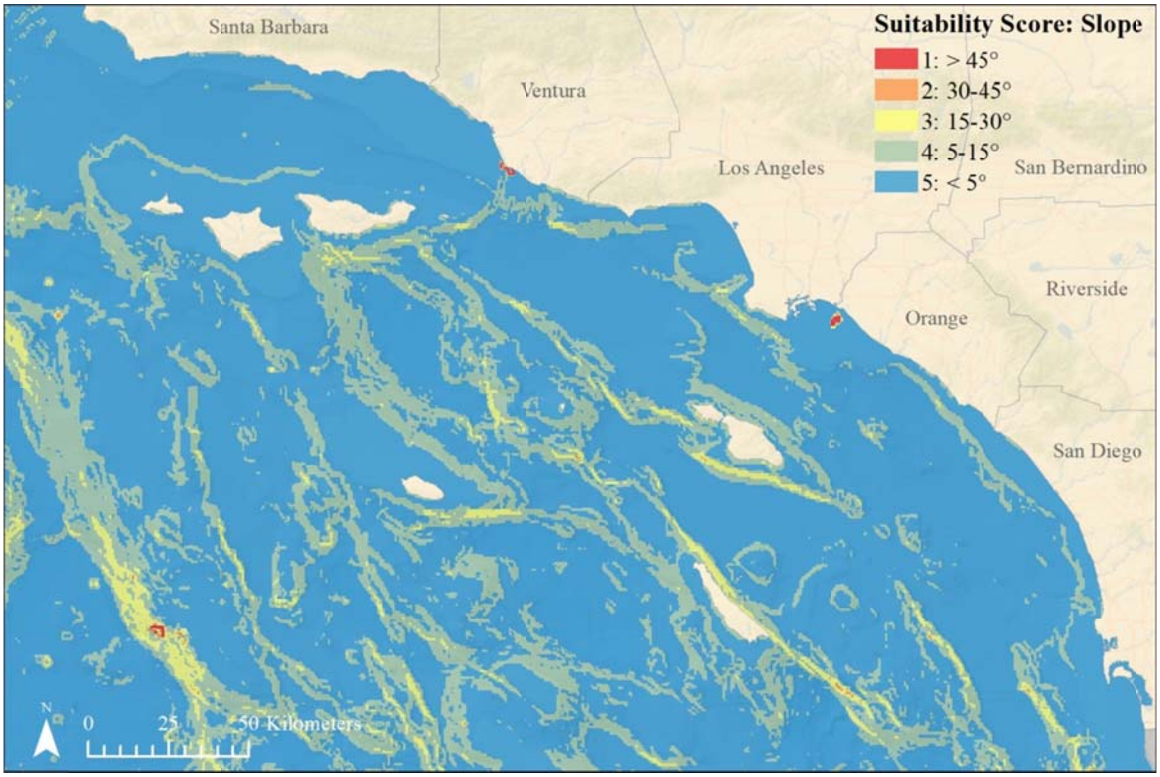


Figure 14 Map of Seabed Slope in assigned suitability scores

The final step in preparing the datasets in this section for the weighted overlay was to convert each back into raster format. Like the original vector layers from Section 3.3.1.1, these were converted using the Polygon to Raster tool with the same input parameters. Recall that for each, the suitability score was selected as the Value field, the Cell Assignment Type was left with the default CELL_CENTER, the Cellsize was set to 100 (meters), and no Priority field was selected. Once completed, all six classes had the same coordinate system, extent, and cell size.

It is important to note that the potential for errors occurring from the conversion of raster layers into polygons and then back into rasters was carefully considered. The potential errors were found to be acceptable for three reasons. One, this process was performed after the layers were reclassified into discrete values. Two, the CELL_CENTER cell assignment type was used when returning the feature to raster layers thus preserving the discrete values. And three, at a cell size of 100 meters, any shift of cells to align to the new extent were within the error limits of the original cell sizes. At such a scale, the maximum shift of less than 50 meters is negligible.

3.3.1.3. Wave Power Dataset Preparation

Wave Power Density was treated differently than other datasets in this suitability analysis since the values vary dramatically by region. Because the range of wave power density is unique to the study area, the suitability scoring system would not be generally applicable for most regions outside of the SCB. While the highest values of wave power density were greater than 50 kW/m in the SCB, more than 99% of the wave power density was below 25 kW/m. Using that value as the upper limit, an adjusted mean for the wave power density in this region was obtained and divided into five categories, each with a 5 kW/m range (Table 10).

Table 10 Wave Power Density suitability scores assignment

Dataset	Value Range	Suitability Score
Mean Wave Power Density	< 5 kW/m	1
	5 - 10 kW/m	2
	10 - 15 kW/m	3
	15 - 20 kW/m	4
	> 20 kW/m	5

The values below 5 kW/m were scored a one (1) for least suitability. From there, the next three range from 5 to 10 kW/m, 10 to 15 kW/m, and 15 to 20 kW/m were given the suitability scores of two (2), three (3), and four (4), respectively. The last suitability class of wave power density was comprised those of 20 kW/m and above, including some cells with high wave power density values above 25 kW/m. These high wave power density values existed only in small groupings on the windward side of the two western most islands in both the northern and southern chain of islands within the SCB (Figure 15) and were not given a separate suitability class. Note that the values depicted are for reference purposes only and were not used in any analyses.

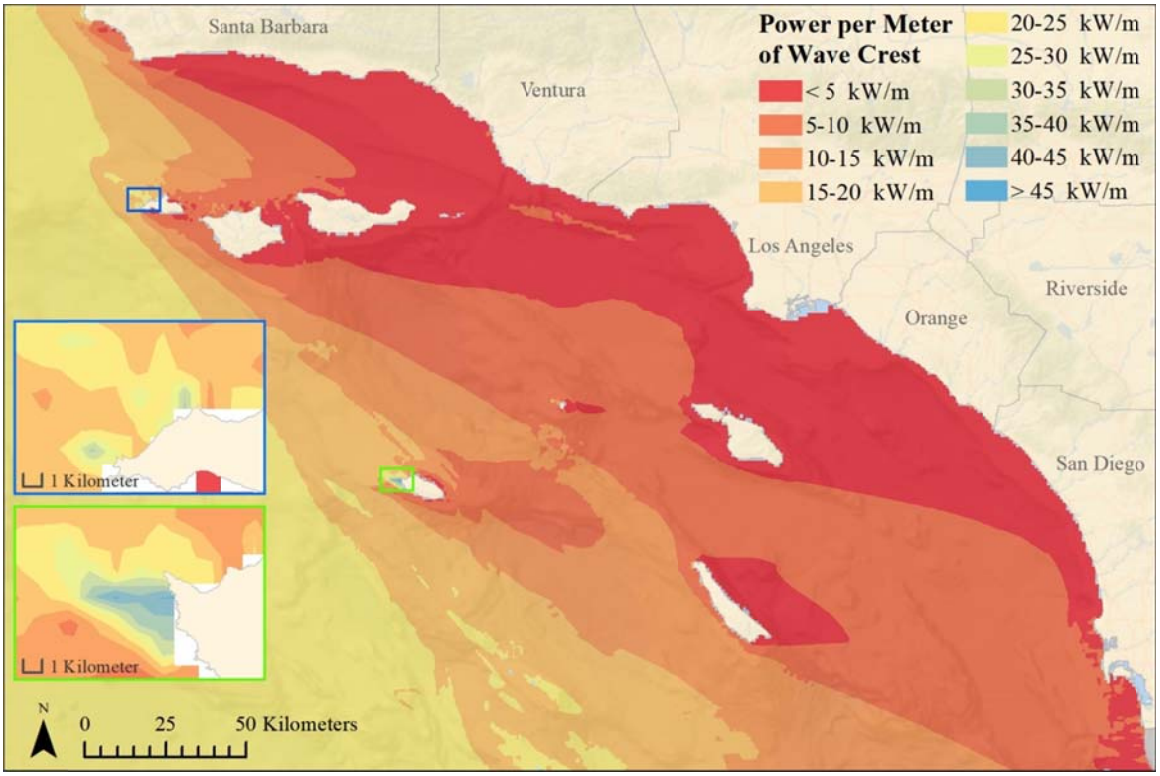


Figure 15 Map depicting the distribution of wave power density with insets focusing on the limited areas with power densities greater than 25 kW/m

The process of converting the raster into polygon was performed with the previously calculated wave power data (see Section 3.3.1.2). The newly created polygon feature was clipped to the proper extent and any areas overlapping land features were eliminated from the feature. The suitability score map of wave power can be seen in Figure 16.

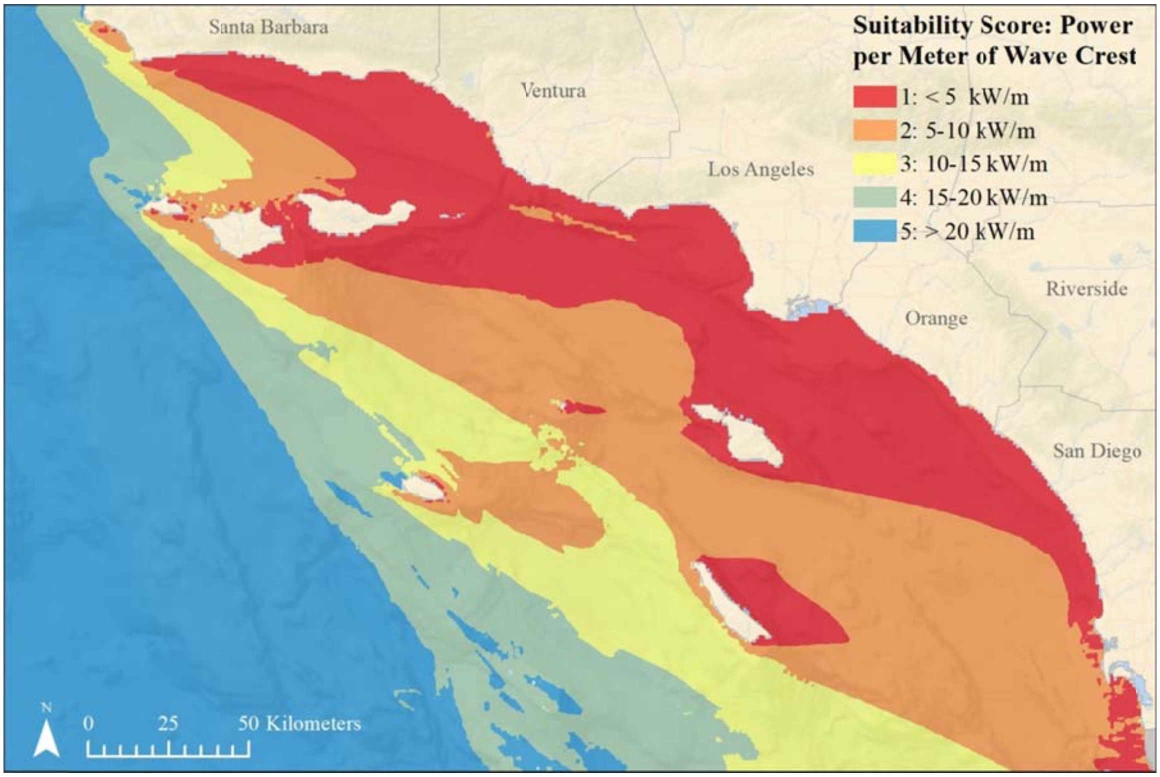


Figure 16 Map of Wave Power Density in assigned suitability scores

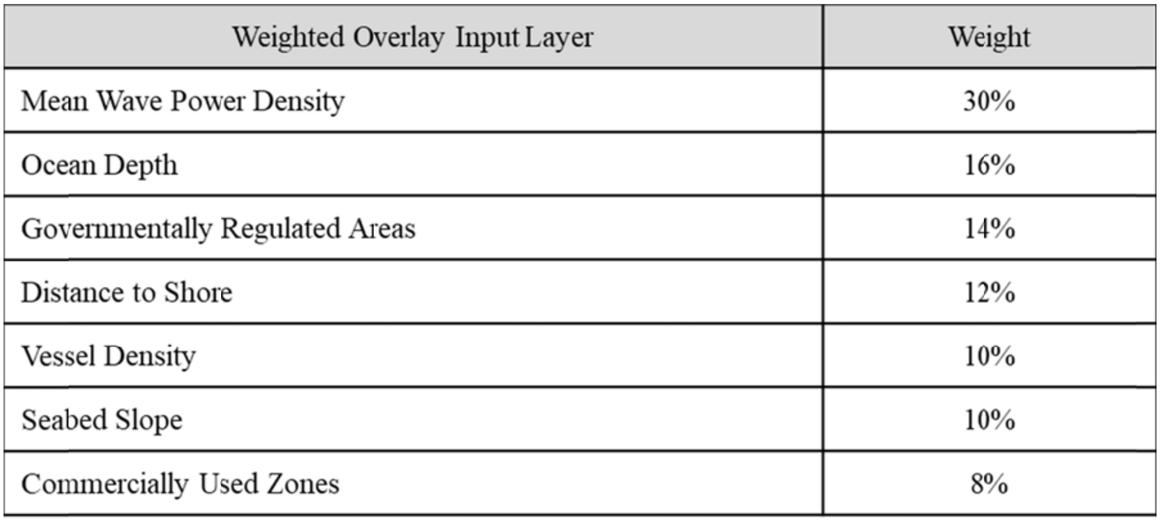
The final step in preparation of the weighted overlay was to convert the Wave Power Density vector dataset back into raster format using the Polygon to Raster tool with the same input parameters used for the previous six datasets. Once completed, all seven datasets prepared for the weighted overlay had the same coordinate system, extent, and cell size.

3.3.2. Weighted Overlay

The Weighted Overlay was the method chosen to combine the limiting factors and mean wave power in order to determine areas of high and low suitability for wave farms. The Weighted Overlay tool uses a common measurement scale to overlay multiple rasters each weighted according to its importance.

Both sources cited in the literature review in Chapter 2 had additional layers in their weighted overlay which were not used in this study and were lacking other layers which were included. This made a one-to-one comparison of the weights impossible. However, borrowing from these sources and logical conclusions based on personal knowledge acquired through research for this project, a fair table of weights was developed (Table 11).

Table 11 Weight designation of the wave farm suitability



Weighted Overlay Input Layer	Weight
Mean Wave Power Density	30%
Ocean Depth	16%
Governmentally Regulated Areas	14%
Distance to Shore	12%
Vessel Density	10%
Seabed Slope	10%
Commercially Used Zones	8%

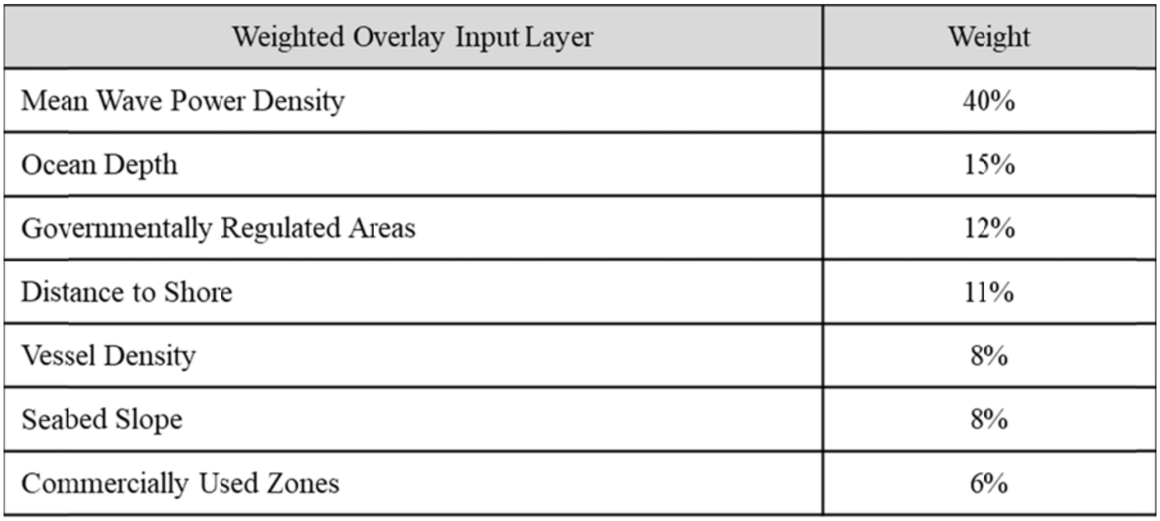
As with the other studies mentioned, wave power was determined to hold far more importance than other factors, thus Wave Power Density was assigned a weight of 30%. The remaining values were closer in weight, with Ocean Depth outweighing them all at 16% because of how depth affects the effectiveness of the WECs. This was followed by the GRA layer at 14% as they represent the legal and public concerns, both of which play a major role in the success or failure of such projects. Next, Distance to Shore was weighted 12% due to economic concerns, which are not as pressing as higher weighted factors, but can still complicate financing for a project. Tied at 10% each are the Vessel Density and Seabed Slope layers, neither of which offers any legal restrictions or much risk of increasing installation costs beyond budget. Lastly, the lowest weighted layer is the CUZ at 8% due to the fact that most features within the layer are automatically restricted. Only the extended one-kilometer buffer is being weighed in this instance, which is a minor overall concern.

These layers and values were entered into the Weighted Overlay tool in ArcGIS. The “1 to 5 by 1” Evaluation scale was selected so that it would match the Suitability Score scale of 1 through 5. This automatically filled in the Scale Value field to match the Field (Suitability Score) value so that all Scale Values matched the feature’s Suitability Score. For any features with a suitability score of 0, the corresponding Scale Value was set to Restricted. This option overrides the Weighted Overlay calculations and gives those cells a restricted value in the final output regardless of the cell values of overlapping input rasters. This essentially omits these features from all of the weighted overlay calculations.

3.3.3. Sensitivity Analysis

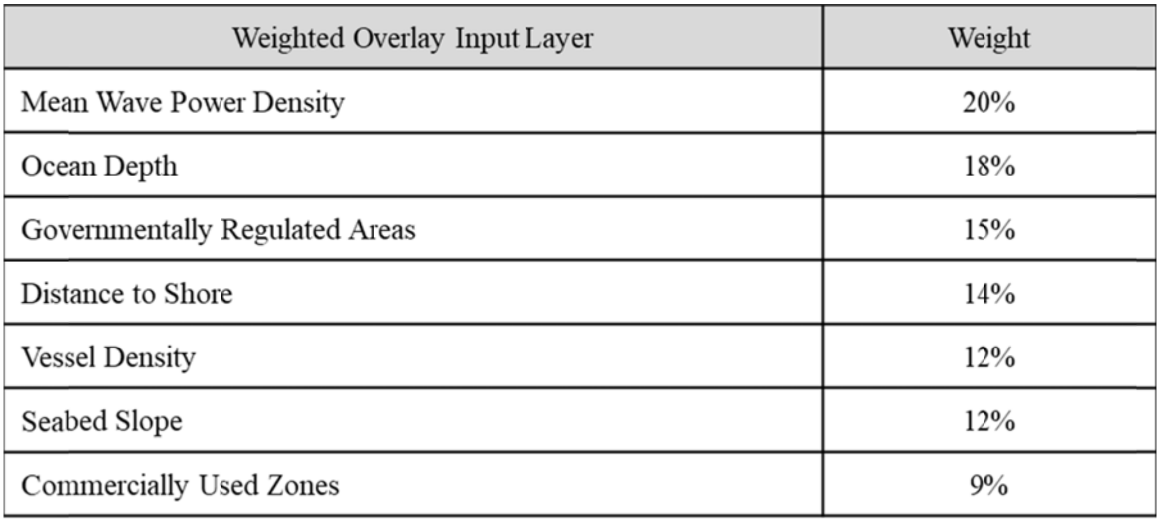
A sensitivity analysis (SA) was performed to determine how much the results vary depending on the importance given to wave power in the weighted overlay. For this SA, the original (primary) weighted overlay was replicated twice, once with Wave Power Density being assigned a higher weight at 40% and once with it being assigned a lower weight at 20%. The remaining weights were adjusted as evenly as possible so that the total weights again equaled 100%. Since the difference in 10% could not be evenly distributed between six categories, a judgment call was made to account for the difference. Table 12 and Table 13 show the altered weights for these two SA overlays.

Table 12 Weights used for Sensitivity Analysis 1 (40%)



Weighted Overlay Input Layer	Weight
Mean Wave Power Density	40%
Ocean Depth	15%
Governmentally Regulated Areas	12%
Distance to Shore	11%
Vessel Density	8%
Seabed Slope	8%
Commercially Used Zones	6%

Table 13 Weights used for Sensitivity Analysis 2 (20%)



Weighted Overlay Input Layer	Weight
Mean Wave Power Density	20%
Ocean Depth	18%
Governmentally Regulated Areas	15%
Distance to Shore	14%
Vessel Density	12%
Seabed Slope	12%
Commercially Used Zones	9%

3.3.4. Cost-Benefit Analysis

A cost analysis can help prioritize the potential wave farm locations identified above. One method of conducting a cost analysis is to compare the cost of installing a wave farm with the average wave power available at each site. For this analysis, the cost of a wave farm's installation was simplified to only include distance to shore as this is the primary variable affecting cost. Ocean depth also affects cost, but the extent of this effect could not be estimated so it was left out of this cost analysis. Other values are constants, including cost per WEC device, cost per kilometer of submarine cable, and the number of WEC devices per site. Since constants apply to every site equally they do not affect the results of the cost analysis and can be omitted from this calculation. The simplified fraction between cost and wave power is therefore used as the cost analysis score:

$$\text{Cost analysis score} = D / P$$

where D is the distance from site to nearest power station in kilometers and P is the average wave power per meter of wave crest. For the full cost analysis formula from which this was simplified, refer to Appendix D.

This cost analysis requires a few assumptions to be met: The wave farm will be connecting into an existing substation, each WEC device has the same installation cost, and the full length of the cable to shore will be installed despite preexisting submarine cables. Furthermore, the number of WEC devices per site is assumed to be a constant and each potential wave farm site will be large enough to accommodate over 100 PowerBuoys™.

Chapter 4 Results and Discussion

The results of the weighted overlay are reported and discussed in three parts in this chapter. First, a map created from the primary output raster shows the breakdown of final suitability for wave farms. Second, the sensitivity analyses compared the primary results with the alternates. Bar graphs depict the percent breakdown per suitability score for each of the three outputs to compare the variance resulting from a 10% shift in the weight of Wave Power Density in the weighted overlay. Third, a simple cost-benefit analysis compares the mean wave power of individual potential wave farm locations along with the distance of each location to the nearest onshore power station.

4.1. Weighted Overlay Results

The output raster layer from the weighted overlay was broken down into five categories of suitability, with an increasing score of suitability from Category 1 (least suitable) to Category 5 (most suitable). Category 0 was also included representing restricted areas. A map was produced for visualization purposes which depicts the layout of these values (Figure 17).

Upon the initial inspection of Figure 12, one might notice that Category 1 is completely absent from these results. This was due to the fact of relatively few features given this score which might have been overpowered by multiple layers of higher suitability scores. Category 2 is the least prominent of the remaining categories with only 200 raster cells grouped together near the Los Angeles County / Orange County border, nearly indiscernible at the scale used. Next, Category 3 cells make up several large regions near the center of the study area. Lastly, the restricted Category 0 falls mainly along the coastline of the mainland as well as each of the Channel Islands. These first four categories are considered undesirable, if not completely restricted, for this study.

The more suitable areas fall within the 4th and 5th suitability categories. Category 4 alone makes up nearly 75% of the cells in this raster layer (Figure 18). The abundance and distribution of these cells, in the map as well as the histogram, suggests that Category 4 should be considered as the neutral class, whereas those scored below 4 (Category 0 to Category 3) are undesirable and Category 5 is alone in consideration for potentially suitable wave farm locations. The cells in Category 5 are mostly grouped together to the northwest of the study area, with several smaller groupings spread out beyond the Channel Islands. Because wave power was given a relatively high importance compared to the other variables, the majority of Category 5 raster cells fall within the area where Wave Power Density was also scored 5. It is worthwhile to note that there are no Category 5 cells that fall within areas where wave power was scored below 4.

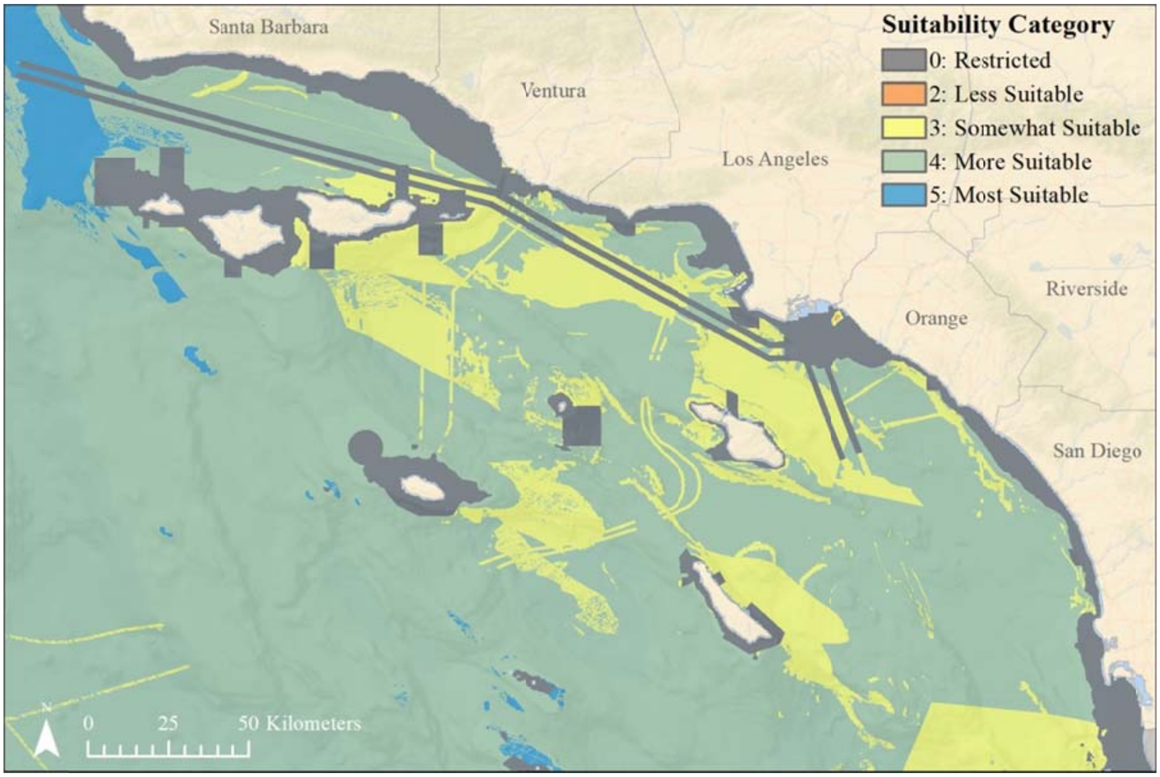


Figure 17 The primary wave farm suitability result

There are areas along the shore that are noticeably lacking any values in the results of the weighted overlay. These cells are withheld from the weighted overlay and are not relevant to any statistical analysis. Prominent examples include San Diego Bay, Mission Bay, and San Pedro Bay (Figure 16). There is also a small strip of missing cells along the coast and surrounding each island. These missing cells are caused by a lack of original data in the wave energy model and were therefore assigned no values. Without suitability scores, these areas are omitted from consideration of wave farm suitability.

Besides above mentioned characteristics in category breakdown (Category 4 and Category 0, Figure 18 also shows that no cells fall into Category 1 and only 0.003% of the cells fall into Category 2, essentially 0% as shown in this graph. With these first three categories excluded, the data appears more normally distributed.

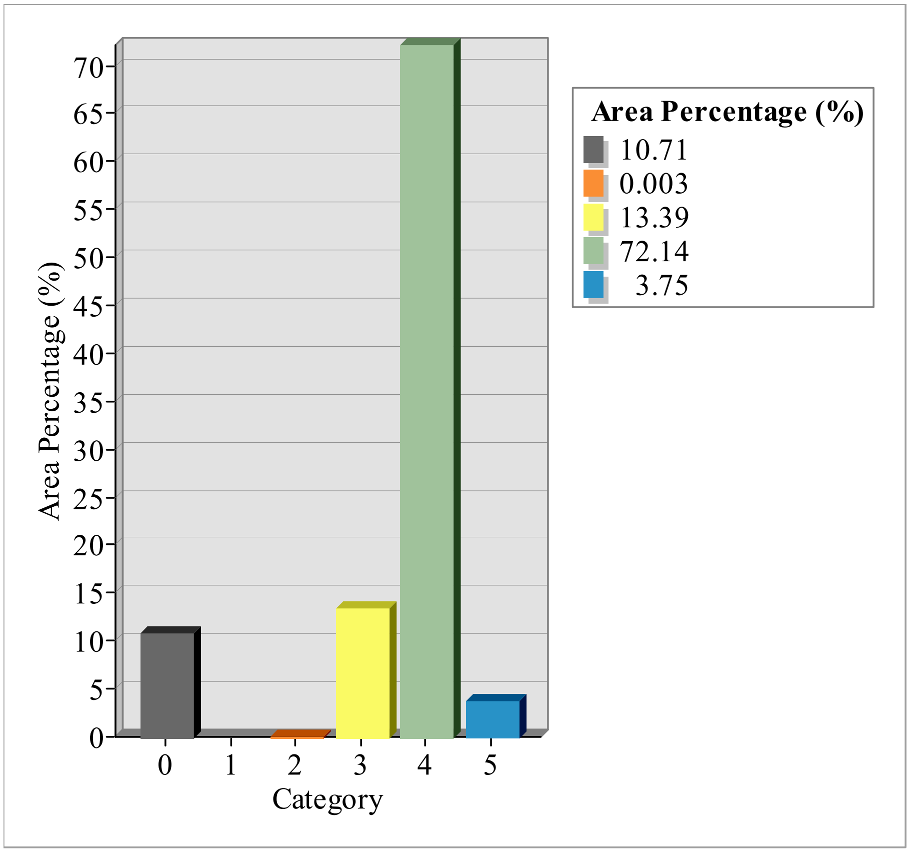


Figure 18 Category breakdown for wave farm suitability by area percentage

4.2. Sensitivity Analysis Results

Two additional weighted overlays were run, each using a different weighting scheme primarily to measure the sensitivity of the weight assigned to the wave power input. The results of these weighted overlays were compared to the results of the primary weighted overlay. The particular interest was any differences in the percent breakdown of cells between each category as well as the changes in the spatial distribution of these cells.

4.2.1. Breakdown of Suitability Categories

The first of these weighted overlays (Sensitivity Analysis test 1, or SA1) raised the weight of wave power density from 30% to 40%. The result was a drastic shift between Categories 3 and Category 4 (Figure 19). The area percentage of Category 3 rose 18% and that of Category 4 dropped 18.35%. The other categories combined made up less than a 1% change, with Category 5 rising only 0.35% and Category 2 rising about 0.017%. There was no change in the absence of Category 1 cells. Since Category 0 is made up of restricted cells omitted from the weighted overlay process then the percentage of cells in this category should always remain constant. In summary, increasing the weight of wave power density decreased the overall suitability of the results. However, the bulk of this change occurred between two categories of lesser importance than Category 5, which saw only a marginal increase.

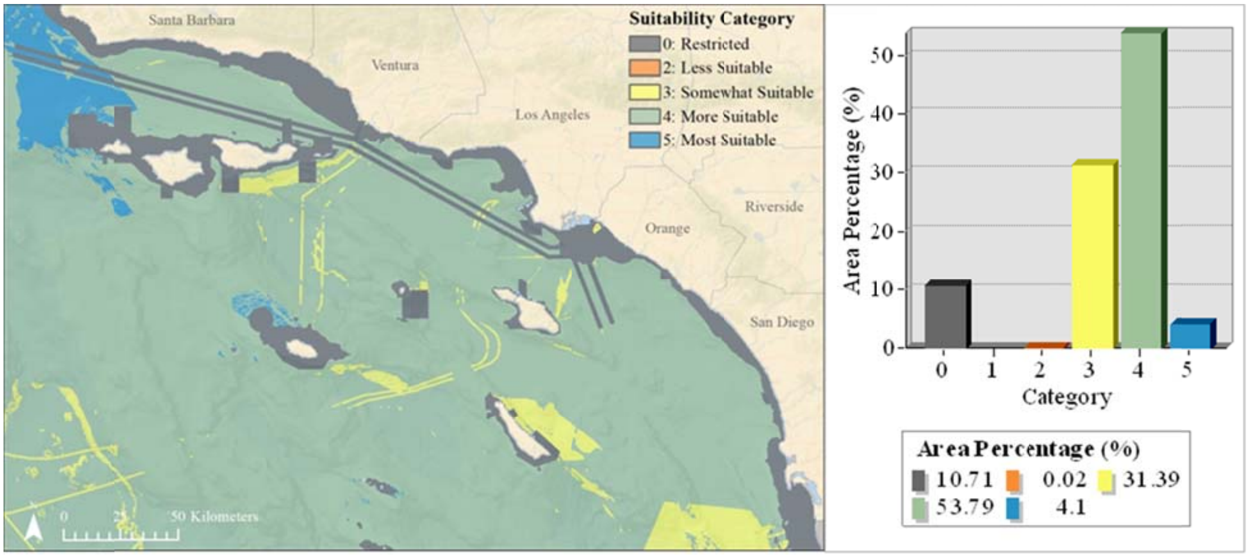


Figure 19 Sensitivity Analysis 1: Map and suitability breakdown with 40% weighted wave power

For the second weighted overlay in sensitivity analysis test (SA2), the weight of wave power density was reduced from 30% to 20% (Figure 20). These results showed less extreme shifts in the weights, with the greatest change being in Category 3 as its raster cell count dropped 7.6%. This decrease was almost entirely compensated by an increase of 7.26% in Category 4. The remainder of the difference was accounted for by a rise in Category 5's count by 0.32%, with an insignificant drop of 0.001% in Category 2. Again, no changes were seen in Category 1 and Category 0 as expected. In contrast to the SA1 weighted overlay results, these showed a trend towards a higher rate of suitability. Similar to those results, however, is the limited growth in Category 5.

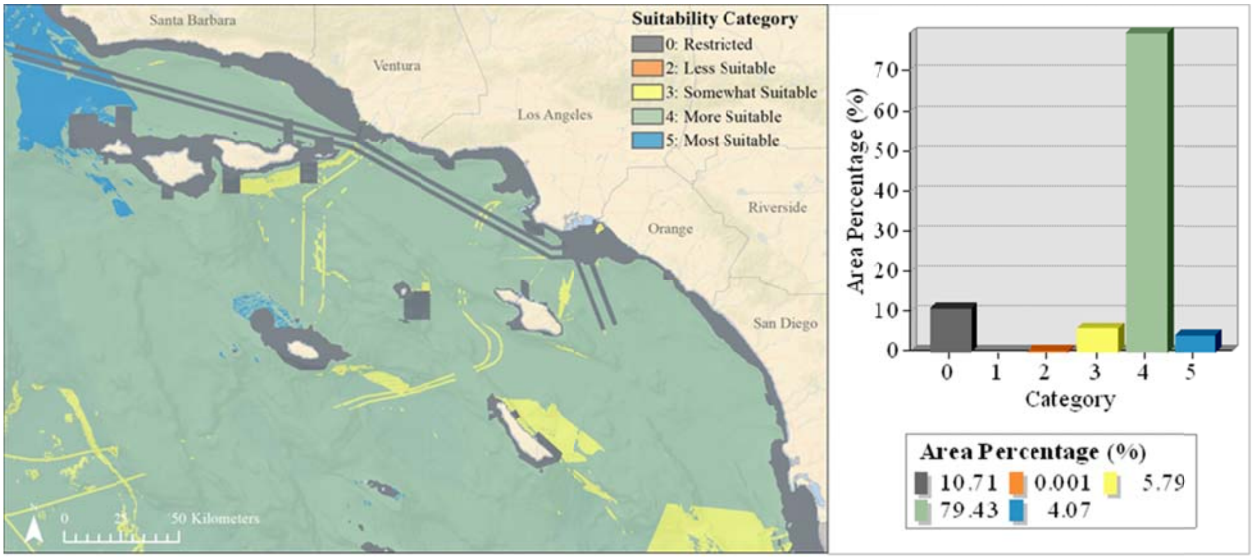


Figure 20 Sensitivity Analysis 2: Map and suitability breakdown with 20% weighted wave power

The increase of area percentage in Category 5 in either of the weighted overlays is very minor, both with less than 1% increase. However, such a seemingly insignificant change in the overall percentage of the raster equates to a much larger change relative to the percent growth of Category 5. In the SA1 weighted overlay the 0.35% overall change in Category 5 increased its percentage from 3.75% to 4.1%, which is a 9.3% relative increase of cells in Category 5. Similarly, the increase of Category 5 cells by 0.32% in the SA2 weighted overlay resulted in an increase from 3.75% to 4.07%, a relative increase of 8.5%. With the limited area of Category 5 in the primary weighted overlay, this extra 9.3% and 8.5% could be used as areas of secondary consideration given the need to expand the potential site selection area.

4.2.2. Change in Spatial Distribution

As described above in Section 4.2.1, the SA1 weighted overlay using a 40% weight for wave power had a drastic decrease in overall suitability. This can be visualized in Figure 21 classified as the -1 Category in red. These areas were identified by the Difference tool, in ArcGIS, as being one category lower in the SA1 weighted overlay than in the primary weighted overlay. All +1 Category areas, in green, are where the categories increased from the primary to SA1 weighted overlay. All other areas not falling into either of these classes are areas which were unchanged in the SA1 overlay.

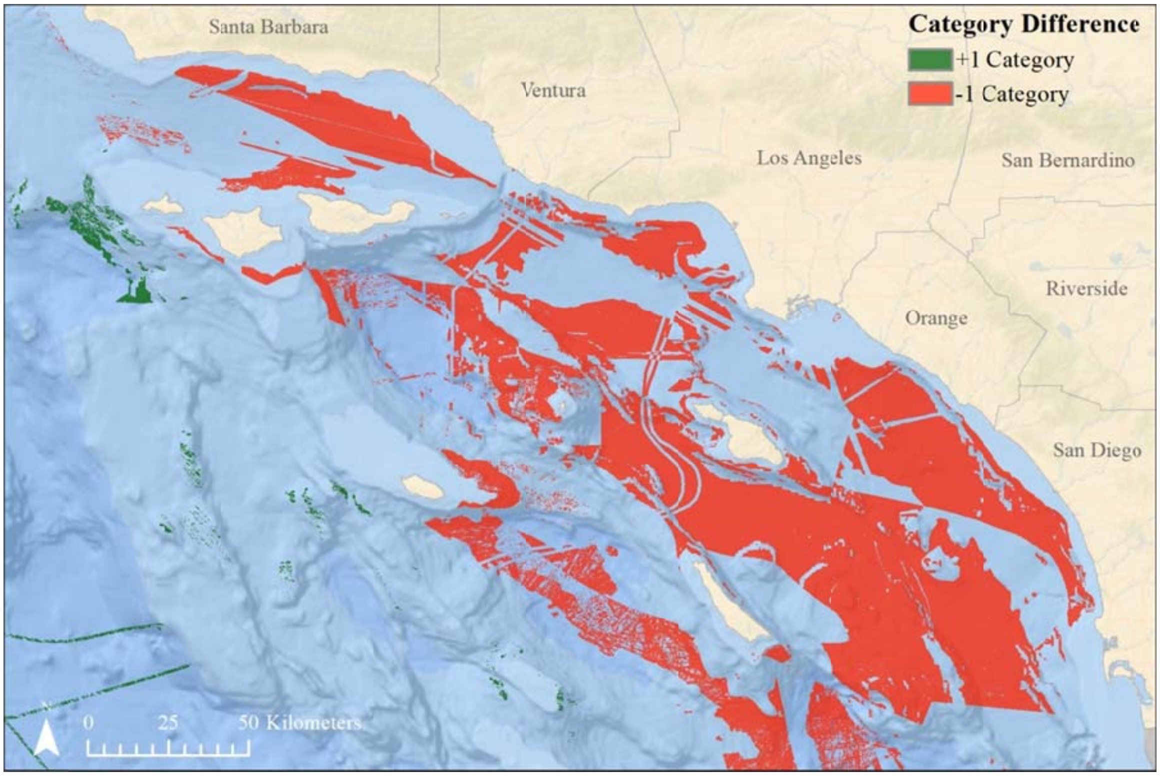


Figure 21 Category changes from the primary overlay (30% weight for wave power) to first sensitive analysis (40% weight for wave power)

Opposite yet similar pattern changes can be seen by comparing the spatial distribution of categories in the SA2 weighted overlay with that of the primary overlay (Figure 22). With the weight increase in wave power density, regions southwestward beyond the Channel Islands showed an increase in category, if any change at all, in SA1. With the decrease in wave power density weight in SA2, the areas beyond the islands that showed change instead decreased one category of suitability.

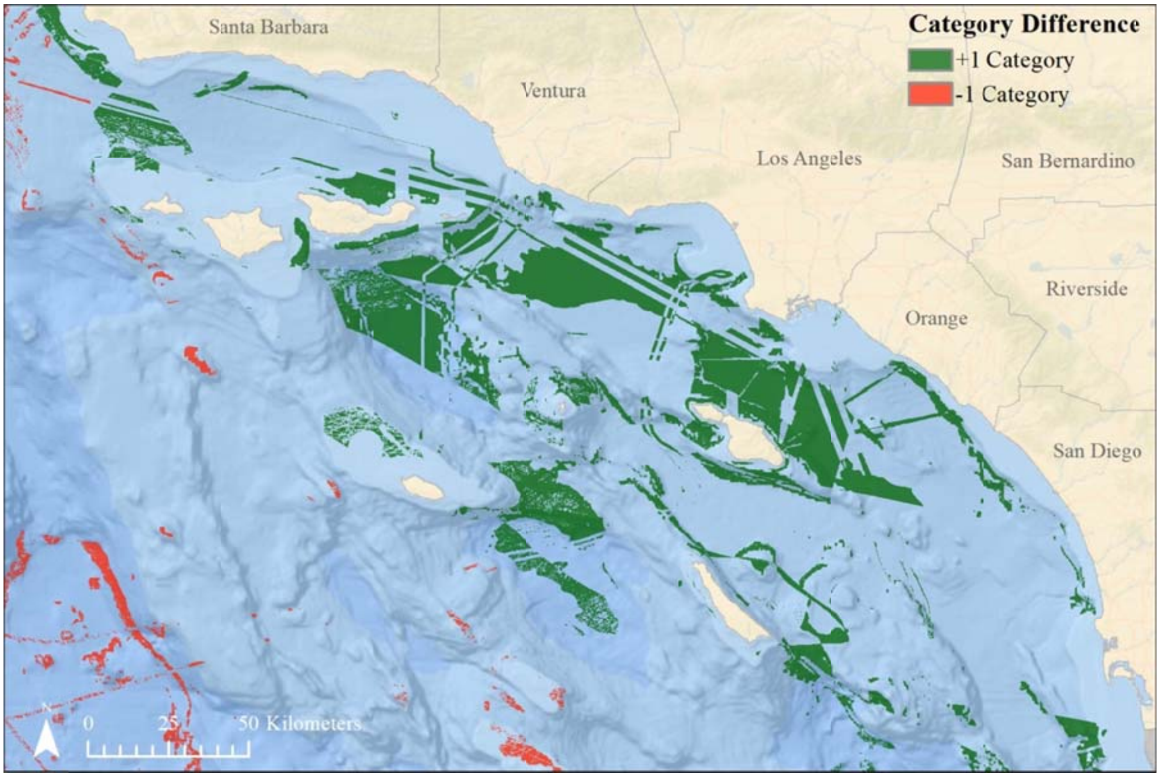


Figure 22 Category change from the primary overlay (30% weight for wave power) to second sensitive analysis (20% weight for wave power)

A clear divide can be seen in both of these maps between the classes as the red and green values do not intermingle. On one side of the divide the category level rises while on the other side of the divide they decrease. A comparison between the wave power density map from Chapter 3 (Figure 16) and these maps shows that this clear divide aligns with the division between suitability scores of 4 and 5 in the wave power layer. This shows that the increase or decrease of wave power density weight primarily affects areas of lesser energetic waves. It is also important to note that neither SA1 nor SA2 resulted in an increase or decrease of more than one category.

4.3. Cost Analysis

For cost analysis, five potential wave farm locations were chosen based on their suitability result in the primary weighted overlay (Figure 23). Site 1 is an area of Category 5 cells in the northwest region of the study area. Site 2 and Site 3 are neighboring groups of Category 5 cells to the south of San Miguel Island. Site 4 is an area of Category 4 cells near Los Angeles. Site 5 is an area of Category 4 cells adjacent to a restricted area near San Nicolas Island. Each site was chosen for specific reasons explained further below, and measured for their distance to shore and average wave power. Distance to shore was more specifically measured by the distance to the nearest onshore power plant while navigating around MPAs and areas restricted by military use. For this analysis, the lower scores represent more ideal conditions.

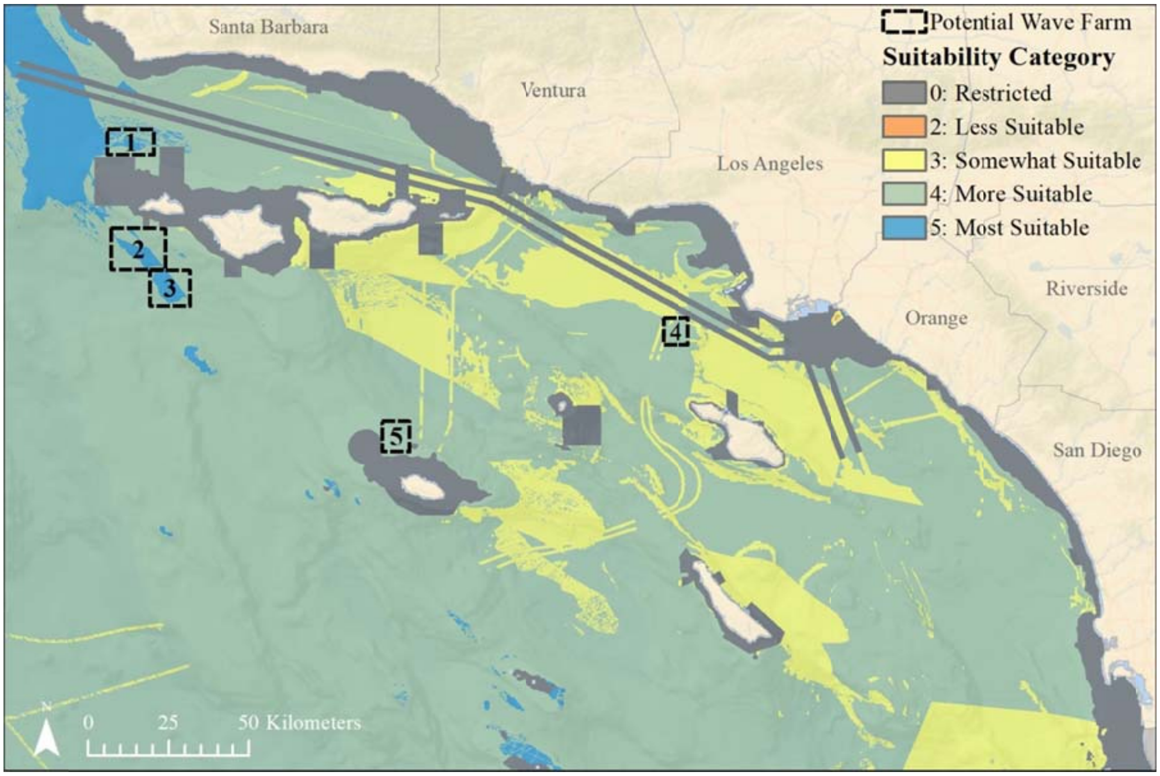


Figure 23 Five potential wave farm locations chosen for cost analysis

Site 1 was selected as it is the closest large grouping of Category 5 cells within the study area; note that the large Category 5 site to the west is beyond the western limits of the Southern California Bight. The proximity of Site 1 to this large grouping is beneficial as it could represent a potential expansion zone to accommodate future growth of the wave farm. This site is 30 kilometers from the nearest power station and has an average wave power of 19.1 kilowatts per meter of wave crest. Inputting these variables into the cost analysis resulted in a score of 1.57.

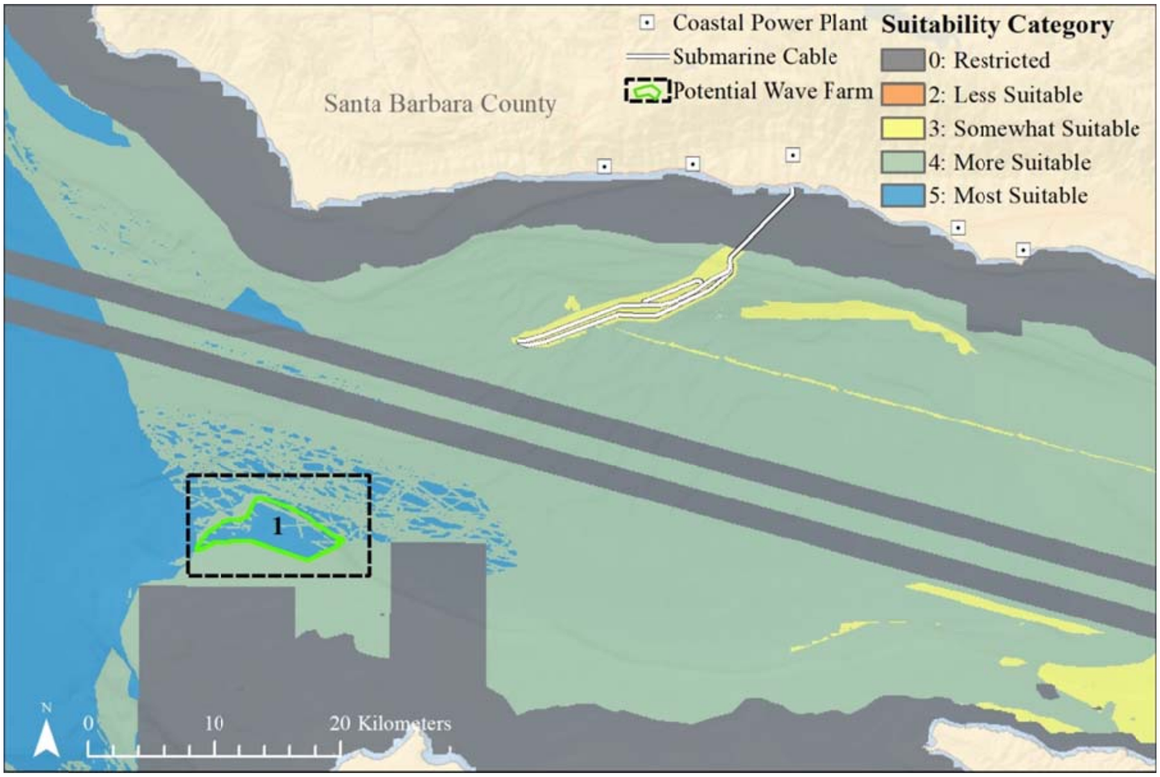


Figure 24 The potential wave farm Site 1 location with primary weighted overlay

Site 2 was selected as it is a large grouping of Category 5 cells falling within the highest range of wave farm power in the study area. It is farther from shore than would be desirable, yet it is still within an acceptable distance. This site is 90 kilometers from the nearest power station and has an average wave power of 20.3 kilowatts per meter of wave crest. Inputting these variables into the cost analysis equation resulted in a score of 4.43.

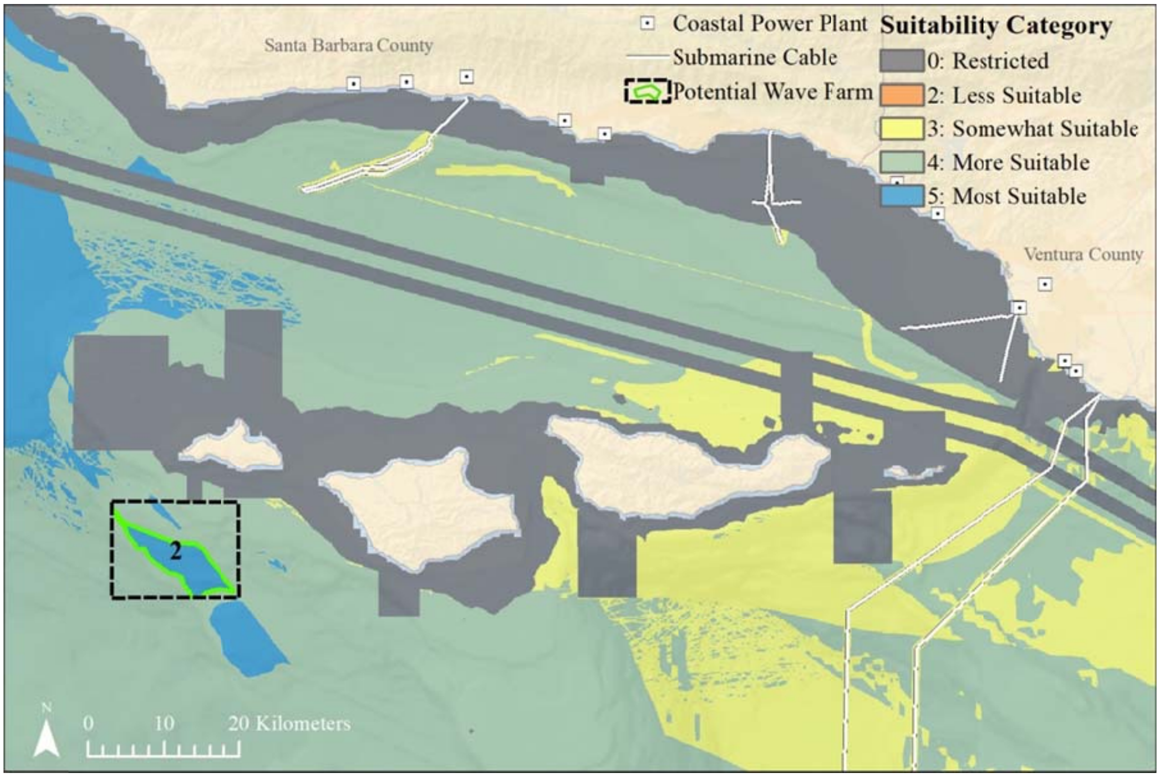


Figure 25 The potential wave farm Site 2 location with primary weighted overlay

Site 3 was chosen as an alternative to Site 2. They are nearly identical in wave power potential and in size, but Site 3 is farther from the nearest power stations. Regardless, Site 3 was selected to give decision makers the option in the event that the distance to shore is less important than proximity to population centers. In this case, Site 3 would be beneficial as it is closer to the Los Angeles metropolitan area. With this in mind, distance to the nearest power station was calculated for the nearest station to the east of the Channel Islands, near Los Angeles. This site is 120 kilometers from the nearest power station to the east and has an average wave power of 20.3 kilowatts per meter of wave crest. Inputting these variables into the cost analysis equation resulted in a score of 5.91.

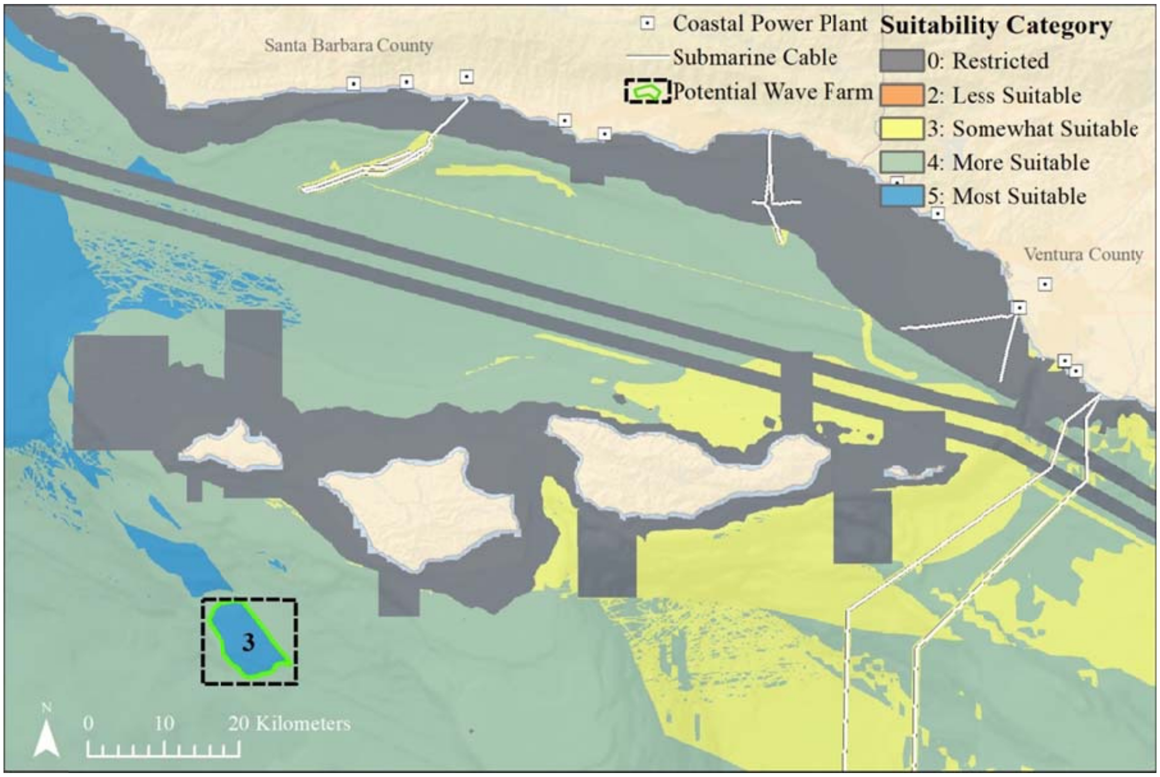


Figure 26 The potential wave farm Site 3 location with primary weighted overlay

Site 4, despite being a Category 4 grouping, was selected because of its proximity to Los Angeles. Because this Category 4 area was more confined in the SA1 weighted overlay compared to the primary weighted overlay result, Site 4 was narrowed down to that specific area (Figure 27). Another benefit of this site is the adjacent preexisting submarine cable corridor which has the potential to ease the planning and permitting processes. This site is 35 kilometers from the nearest power station and has an average wave power of 5.2 kilowatts per meter of wave crest. Inputting these variables into the cost analysis equation resulted in a score of 6.73.

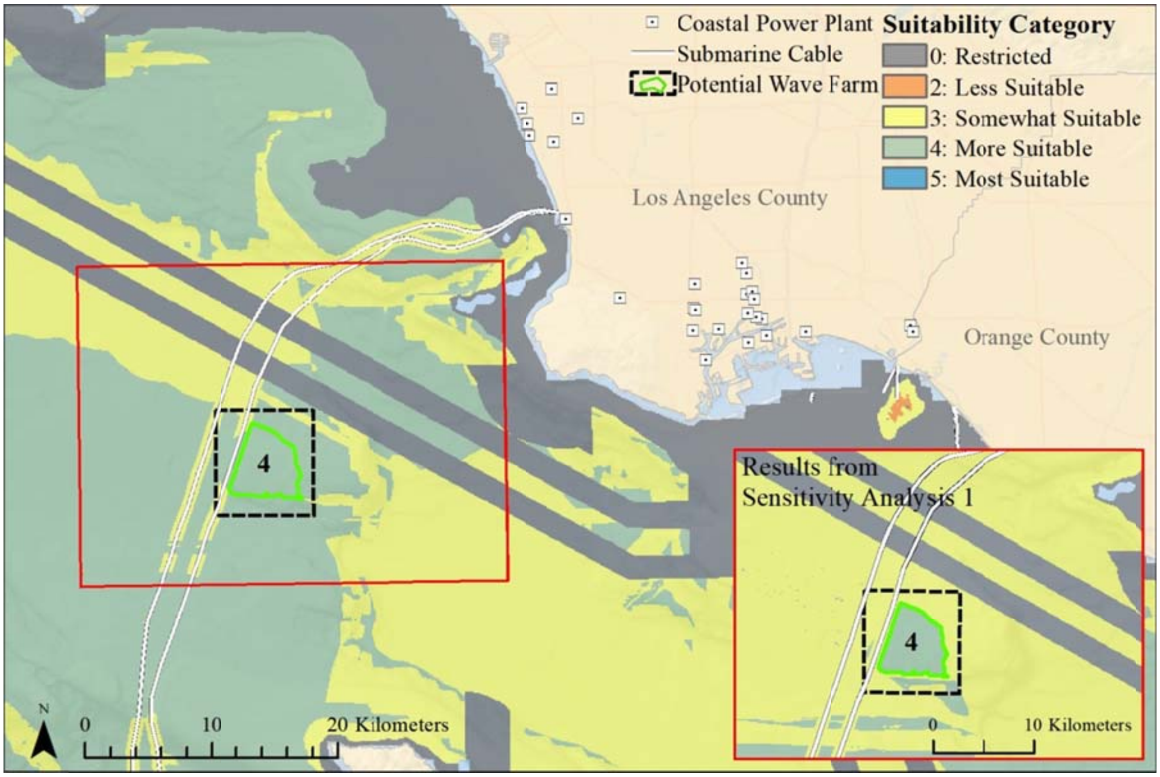


Figure 27 The potential wave farm Site 4 location with primary weighted overlay (main map); the boundary of Site 4 was defined based on sensitivity analysis 1 result (inset map)

Site 5 was selected due to its proximity to the induction point of a preexisting submarine cable corridor. Besides, despite being a Category 4 area in the primary weighted overlay, this site is considered Category 5 when the weight of wave power was dropped to 20% in SA2. This site is 100 kilometers from the nearest power station and has an average wave power of 15.6 kilowatts per meter of wave crest. Inputting these variables into the cost analysis equation resulted in a score of 6.41.

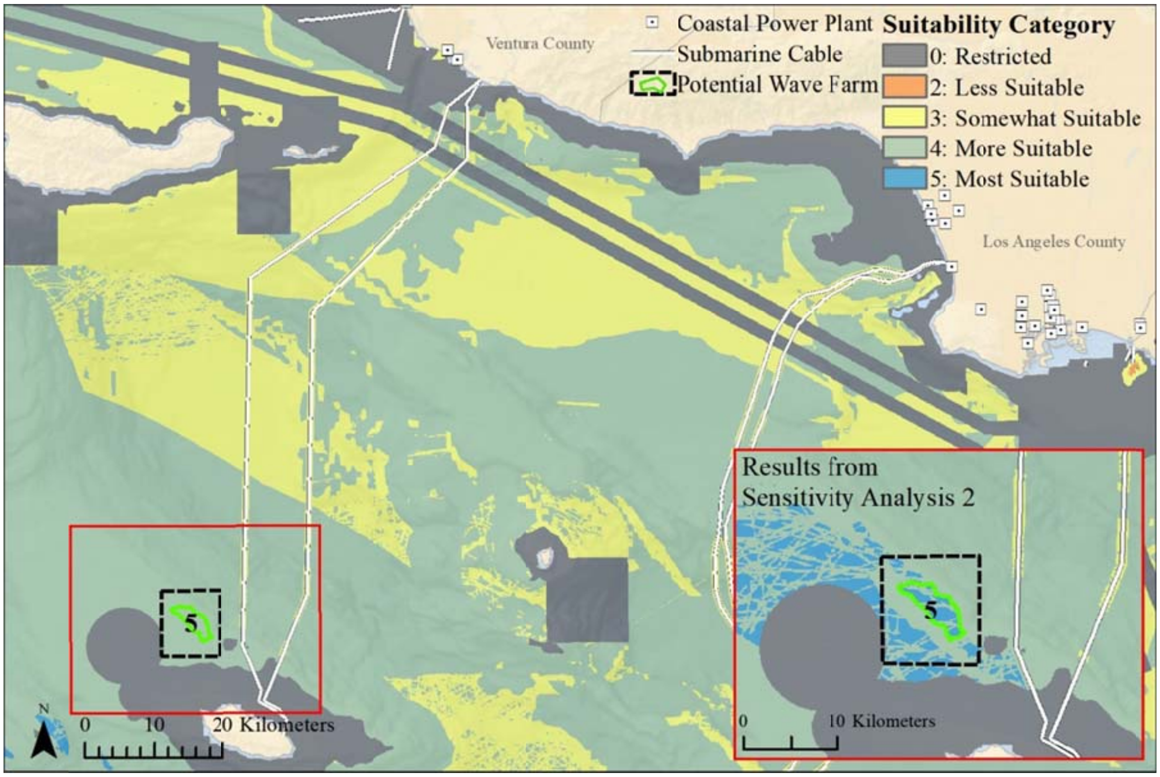
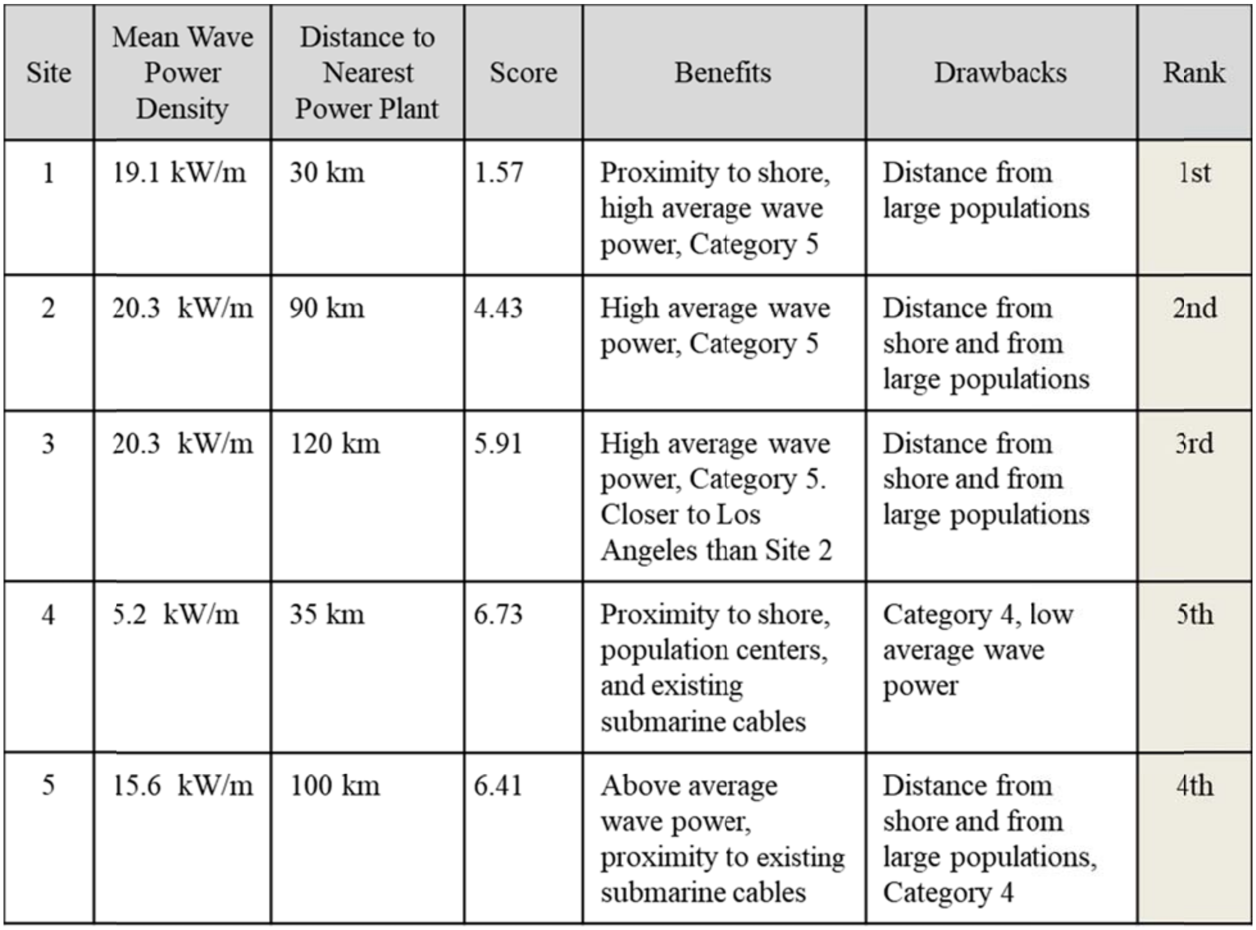


Figure 28 The potential wave farm Site 5 location with primary weighted overlay (main map); this location becomes Category 5 when the weight of wave power decreases to 20% (inset map)

The overall cost-benefit analysis results can be seen in Table 14. Site 1 was the most ideal due to its proximity to shore as well as the high average wave power compared to other sites. Site 2 and Site 3 were ranked second and third, respectively, as they had similar average wave power potential as Site 1, but a significantly greater distance from shore. Site 5 is ranked fourth due to the higher cost of it being much farther from shore, but it still had a higher wave power potential than Site 4. Lastly, Site 4 suffers in its ranking due to its low average wave power relative to the other sites.

Table 14 Cost analysis for wave farm site suitability



Site	Mean Wave Power Density	Distance to Nearest Power Plant	Score	Benefits	Drawbacks	Rank
1	19.1 kW/m	30 km	1.57	Proximity to shore, high average wave power, Category 5	Distance from large populations	1st
2	20.3 kW/m	90 km	4.43	High average wave power, Category 5	Distance from shore and from large populations	2nd
3	20.3 kW/m	120 km	5.91	High average wave power, Category 5. Closer to Los Angeles than Site 2	Distance from shore and from large populations	3rd
4	5.2 kW/m	35 km	6.73	Proximity to shore, population centers, and existing submarine cables	Category 4, low average wave power	5th
5	15.6 kW/m	100 km	6.41	Above average wave power, proximity to existing submarine cables	Distance from shore and from large populations, Category 4	4th

Chapter 5 Conclusions

The most suitable areas for wave farms within the Southern California Bight (SCB) were identified based on an extensive set of criteria, including not only wave power but also limiting factors such as governmentally regulated areas, commercially used zones, vessel density, ocean depth, seabed slope and distance to the shoreline. This approach assures that the most crucial elements are considered and weighted according to their importance for the selection of wave farm sites. Three sites were identified within the SCB during the initial weighted overlay and two others were selected from the results of the sensitivity analyses. These five potential wave farm sites were compared against one another and ranked according to their initial cost versus the estimated average power. A location in the northwestern region of the study area near Point Conception was selected above the others, primarily due to the higher wave power in that region along with the site's proximity to shore. A lack of low scoring limiting factors at this location earned it a Most Suitable status as Category 5. The only downside of this location is its distance from major population centers such as Los Angeles and San Diego.

While the Point Conception site and the other four potential wave farm sites scored highest among the remainder of the study area, the SCB overall is not an ideal location for wave farms. Due to the average south-southeasterly wave direction of the North Pacific, the SCB is shielded from much of the ocean's most powerful waves as pictured in Appendix B. Yet, the SCB is still moderately suitable only because of the large population that a local wave energy farm would serve. The limitation in wave power makes a site suitability analysis a critical process for decision-making in the region.

The International Electrotechnical Commission (IEC) is responsible for creating International Standards for all electronic or electric related technologies. Their technical specifications for wave resource assessment require a three-part process: preliminary reconnaissance to identify potential sites, a feasibility assessment of the identified sites, and a detailed wave farm design plan (Cornett et al. 2014). The process discussed in this thesis should fall within the first step of this decision making process. Further multi-criteria analysis should be performed to assess identified locations individually for their quantifiable energy production potential and economic feasibility. Together, these two analyses will precisely evaluate the actual suitability and production value of the sites. This process is not limited to the SCB; the methodology applied in this study can be replicated for any shoreline locations, given the availability of the necessary data.

5.1. Limitations

There were a few limitations faced within the methods of this study including limitations of the data, software, and even the status of WEC technology.

One of the major limitations regarding data is the fact that there are so many different factors to consider for a wave energy farm. Scouring through related research revealed a fair number of limiting factors yet no source included an array of factors as extensive as those considered in this study. Even so, there are bound to be at least a few factors which were unfortunately overlooked. Some factors, on the other hand, were intentionally excluded. For example, fisheries were not included as the data is not readily available. Commercial fish take, as an alternative option, was not included in this study because the take tonnage is calculated in a large grid pattern and would not be useful at the scale of this study. Instead, vessel traffic somewhat compensated for this gap in the data.

Another limitation with the data was the difficulty in weighing the classes for the weighted overlay. Research showed that an extensive analytic hierarchy process (AHP) involving a panel of experts given a formal survey showed little promise over a weighted overlay given equal values to each class. The sensitivity analysis conducted in this study showed that a moderate change in weighted values could have a large effect on the results. Fortunately, in this case the changes had a minor effect on the most suitable class (Category 5).

The number of different data sources also presented a problem in this study. Aside from the difficulty of having to find all required datasets, having multiple sources also made unifying the data for analysis difficult and time consuming. Differences in coordinate systems, cell sizes, and extents had to be resolved prior to proceeding. Different sources also held different standards of accuracy, scale, and completeness that had to be considered along with the issue of dated data. Some datasets have not been updated in years while others are current. Lastly, others attempting to replicate this study for a different region might find that all of the data is not globally available. Wave data, for example, was modeled using a U.S. based array of data buoys meaning that a different wave modeling technique might be required for projects outside the U.S.

ArcGIS provides many tools and extensions for a broad range of purposes yet wave modeling is not yet among them. An attempt was made to utilize the Spline with Barriers tool in ArcGIS as an alternative to a third party wave modeling software, but the results were inadequate, as shown in Appendix C. This was attempted by using the average wave heights for each buoy location as the input value points and the land (above sea level) layer to act as barriers. If the results were promising, the peak wave period values would have been modeled using spatial interpolation as well. Advanced spatial interpolations available in the Geostatistical Analysis Tools toolbox in ArcGIS might have generated more suitable results, but these were not tested.

The unsuitable spatial interpolation result of wave power deemed a third party modeling software to be required, yet this provided its own set of limitations. All promising wave modeling software was either vastly expensive for a site suitability project like this one, or was not fully developed into a user-friendly application. Only two free models were found for consideration: SWAN and MOPS. Both required an advanced level of computing skills (e.g. FORTRAN) to operate without a graphical user interface (GUI). For this project, it was fortunate that the creators of the MOPS model were able to assist in running the model themselves and providing the resulting wave energy rasters.

Choosing the most likely WEC technology that would be selected for use in the SCB required much research. The state of WEC technology is still a constant flux as more efficient and less expensive designs are continuously being developed. The most commonly deployed design is the Pelamis Wave Power attenuator making it the original focus of this study until more research exposed the fact that all proposed wave farms in the U.S. plan to use the PowerBuoy™ by the company OPT. In another year or two, I expect these designs to evolve or be replaced completely. With different operating specifications for newer devices, it will likely become necessary to update the limiting factors—primarily ocean depth—in future projects.

5.2. Improvements and Future Work

This study succeeded where it was meant to. Nevertheless there is always room for improvement. Apart from the limitations described in the previous section, there are several additions that might be included in future studies.

One thing that became apparent while conducting research was that wave farms are not limited to generating energy from waves alone. The terms “hybrid farm” or “dual wind and wave energy” were used by many different sources in reference to devices which could harness both wind and wave power to generate energy. It was found that the California coast would benefit greatly from combining these technologies by reducing the idle time during periods of low resource availability (Stoutenburg, Jenkins, and Jacobson 2010). This might not prove true in the SCB with its unique wave states as the benefit is minimal in regions with a strong temporal correlation between resources (Fusco, Nolan, and Ringwood 2010). However, future studies might consider conducting a site suitability analysis for such a dual-use device by considering additional limiting factors for wind energy.

Given more time, another addition to this study would be an official survey of experts in order to conduct a more thorough AHP for the weighting of the site selection factors. The results would not be expected to vary much, though it would eliminate the impression of guesswork. Another option would be an extended sensitivity analysis developed to test the effects of altering the weights of each class rather than just that of wave power.

The cost analysis in this study was effective yet overly simplified. A much more extensive cost analysis was originally designed to estimate the number of months it would take for each site to cover the costs of the initial installation of a ten-unit wave farm. Unfortunately, this cost analysis was exceptionally complex. A more in-depth cost analysis would also require an engineering feasibility study, for which this project has provided the foundation. In the future, this in-depth cost analysis can be conducted to provide more accuracy in evaluating the potential wave farm sites.

One final thought on the improvement of this study would be a more detailed documentation of the MOP wave model. The instructions provided in this model are limited in their usefulness. This process thus had to be completed by the scientist team who created the model. For follow-up studies on wave energy farm site selection, it would be beneficial to gain a better understanding about the modeling software in order to complete the models without this third party request. A more complete step-by-step tutorial than the brief description provided would be required.

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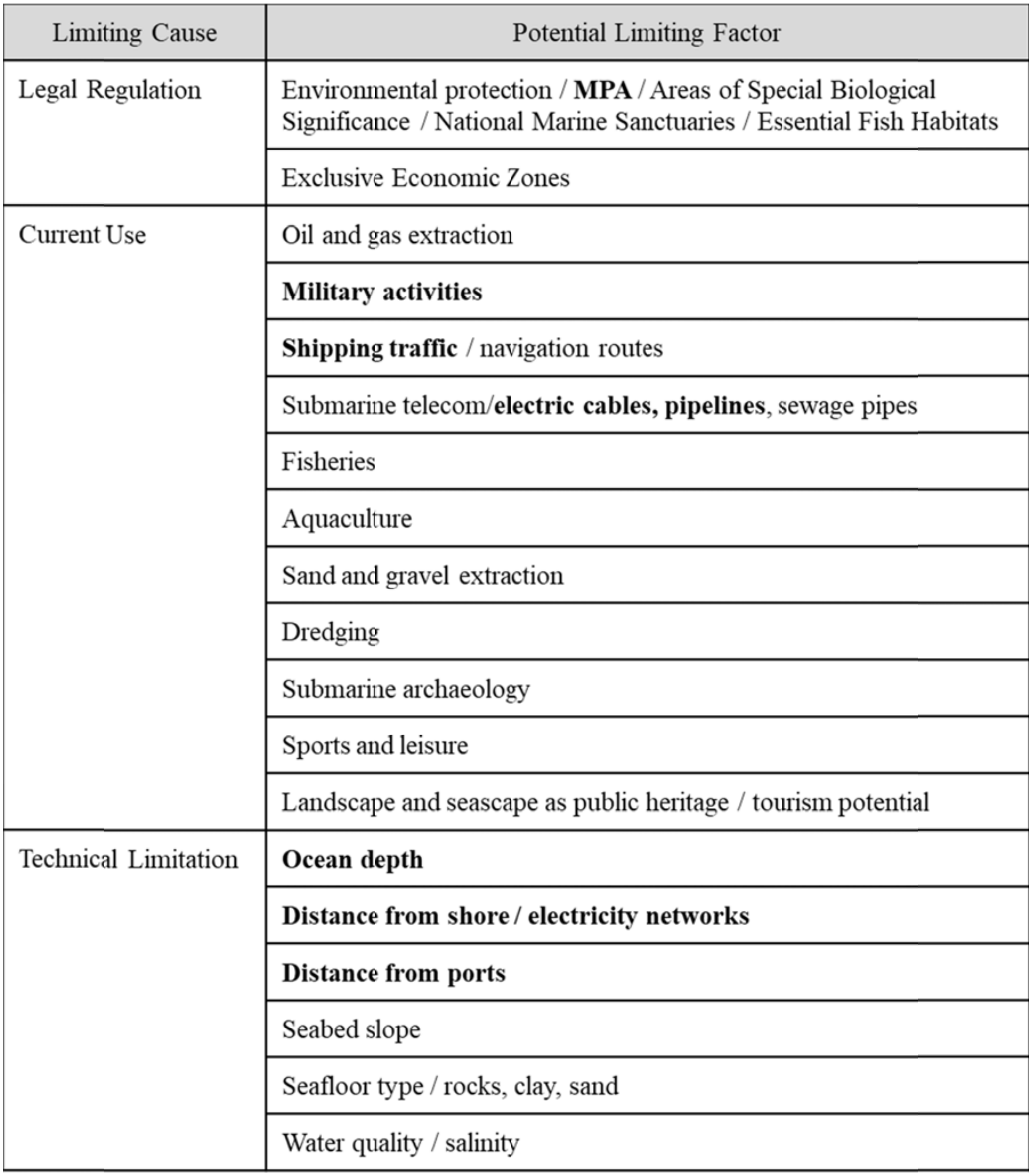
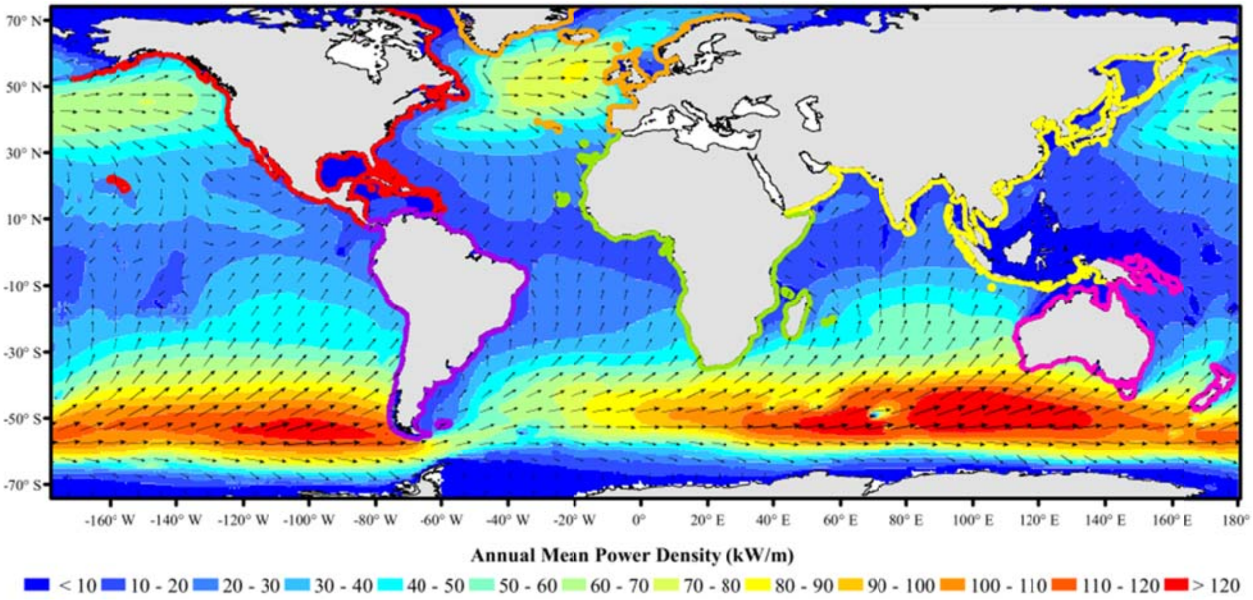
Appendix A. A Complete list of potential limiting factors considered by all acquired sources



Limiting Cause	Potential Limiting Factor
Legal Regulation	Environmental protection / **MPA** / Areas of Special Biological Significance / National Marine Sanctuaries / Essential Fish Habitats
	Exclusive Economic Zones
Current Use	Oil and gas extraction
	Military activities
	Shipping traffic / navigation routes
	Submarine telecom/**electric cables, pipelines**, sewage pipes
	Fisheries
	Aquaculture
	Sand and gravel extraction
	Dredging
	Submarine archaeology
	Sports and leisure
	Landscape and seascape as public heritage / tourism potential
Technical Limitation	**Ocean depth**
	Distance from shore / electricity networks
	Distance from ports
	Seabed slope
	Seafloor type / rocks, clay, sand
	Water quality / salinity

Features in **bold** are those considered by multiple sources.

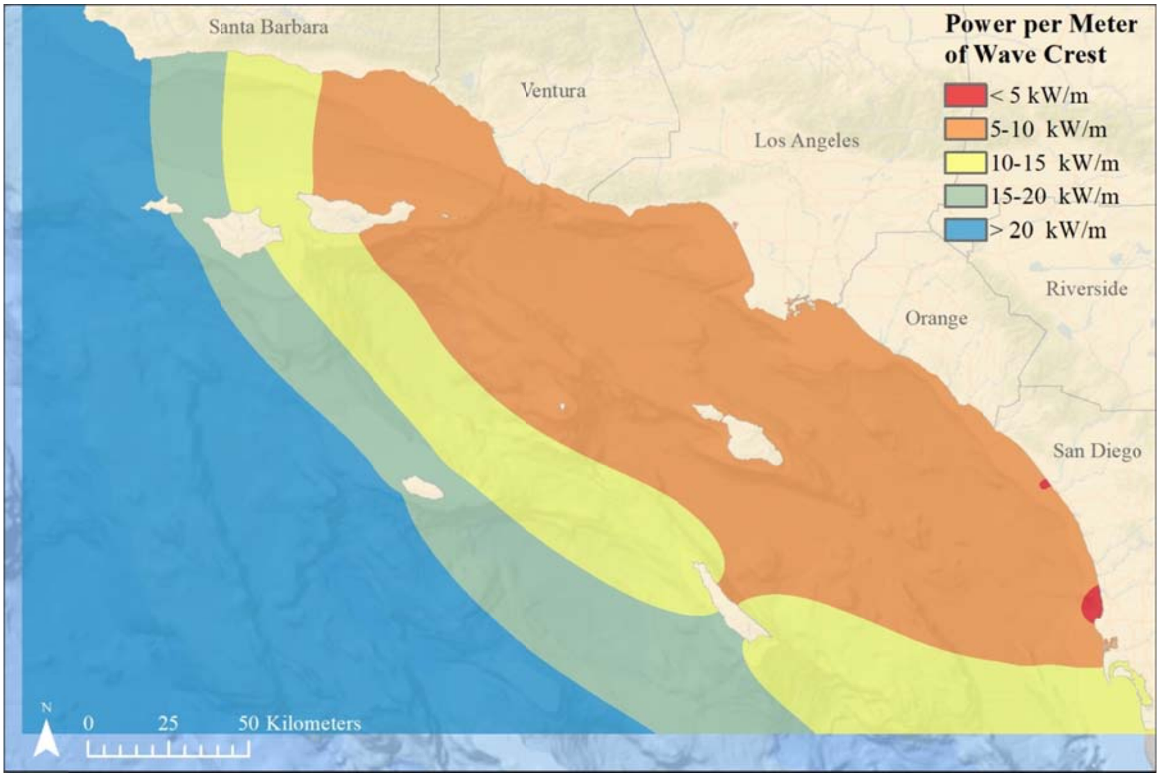
Appendix B. Global distribution of annual mean wave power and annual mean wave direction



Wave power marked by color; annual mean wave direction marked by arrows

(Source: Gunn and Stock-Williams 2012)

Appendix C. Map of wave power density interpolated from CDIP buoy data using the Spline with Barriers tool in ArcGIS



Appendix D. Detailed Return of Investment equation originally intended for the cost-benefit analysis

$$T = \frac{(U * N) + (D * M) + (O * A)}{P * N * V * H}$$

Where:

T: Number of months until wave farm pays of cost of installation

U: Cost per WEC device = \$6 million

N: Number of WECs to be installed = 10

D: Distance from proposed wave farm to shore = Variable

M: Cost of energy transmission cable per meter = \$35

O: Average ocean depth of each site = Variable

A: Cost of anchoring cable per meter = Unknown constant

P: Energy produced per hour, dependent on Wave Power = Variable

V: Value of energy per hour at a local rate = 0.178 per kWh

H: Number of hours in a month = 24 × 365 ÷ 12 = 730

Appendix E: Definitions

Capacity Factor: The ratio of the actual energy produced by a wave energy converter divided by the amount of energy that could theoretically be produced from the full-time operation of that device at its rated capacity (URS 2009).

Clean Energy: Energy sources which minimalize air, water, and land pollutant emissions (Gosnell 2015). This term is most often related renewable energy sources, but also includes bio-fuels and nuclear energy as well.

Diffraction and Reflection: Waves interacting with ocean barriers, natural or manmade, will bend around and behind those objects in what is called diffraction. They also bounce back, or reflect, off of those barriers. These interactions slow and/or change the direction of the waves without influence from the seabed (Thorpe 1999).

Peak Wave Period: The time period, in seconds, between waves with the highest spectral density; as opposed to average wave period which is the average time between each wave indiscriminate of wave height (Robertson et al. 2016).

Refraction: Waves interact with the seabed as they propagate into coastal shallow waters. This interaction causes the waves to slow and change direction, bending to conform to the shape of the underwater terrain (Thorpe 1999).

Renewable Energy: Inexhaustible energy sources are called renewable (Boeker and Van Grondelle 2011). Examples of renewable energy sources include solar radiation, wind, and water (rivers and ocean) as these sources are not depleted by human use.

Sustainable Energy: Energy sources which fulfill the energy demands of today without compromising future generation's ability to meet their energy needs as well (Boeker and Van Grondelle 2011). Renewable energy and energy efficiency are two main components of sustainable energy.

Wave Energy: Wave energy is the amount of wave power per a unit of time. It is expressed in units such as kilowatts per hour (kWh). For example, 1,000 watts per hour for 1 hour is equal to 1 kWh. Note that 1 watt per hour for 1,000 hours is also 1 kWh.

Wave Power: Wave power is the power generated by ocean waves which can be converted into useable energy. The unit of measurement is Watts (W). In the wave energy example, 1,000 watts has 1,000x more power and therefore generates the same energy 1,000x faster.

Wave Power Density (aka Wave Energy Flux): Power in waves is concentrated linearly along the wave crests (Figure 2). This calls for the need of a linear measurement of wave power, watts per meter of wave crest (Electric Power Research Institute 2011).