Oceans Fueling Our Future: Optimizing Placement of Marine Hydrokinetic Energy Along the California Coast

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ABSTRACT

The California coast contains 840 miles of coastline and strong year-round wave patterns exhibiting the potential for ocean energy extraction. Ocean energy is attractive due to its superior reliability and predictability in comparison to other renewable energy sources such as solar and wind. Many locations in California provide ideal conditions for placement of marine hydrokinetic energy devices but there has been a lack of multi-device statewide models. As marine hydrokinetic energy optimization is determined by ocean currents steam flow and wave pitch, roll and heave (horizontal and vertical changes), site selection significantly impacts overall energy output (Dallman, 2014). This study developed three optimization models to illustrate potential spatial distribution of the two main categories of marine hydrokinetic energy devices: wave energy converters and rotating turbines. Using a GIS suitability analysis, and specifications provided by the most commercially available marine hydrokinetic energy devices I tested locations for optimal conditions needed for implementation. Using crucial variables I created binary, ranked and weighted models. Within the study sample of potential locations, approximately half of the locations were rated highly suitable for wave energy converters while very few locations were rated suitable for rotating turbine devices. This is due to variations in wave height and due to California Current's peak strength being located too far off the coast for device construction. The wave patterns of California provide immense power and with further device placement optimization models, marine hydrokinetic energy can help continue to push California towards its goal of a transition to renewable energy.

KEYWORDS

Ocean Energy, Wave Energy Converters , Rotating Turbine Current Energy, Wave Power Parameters, Geographic Information Systems (GIS) Suitability Analysis

INTRODUCTION

Increasing focus on global energy consumption has led to a growing interest in renewable energy development. With 71% of the earth's surface covered in water, 327,000 miles of coastline and an estimated 2,610 TWh/yr of total wave energy power in the United States, the oceans may be the world's largest untapped resource (Hagerman, 2011). Estimates of the potential energy of the continental United States are enough to power over 67 million homes, equivalent to replacing 22 coal fired power plants-avoiding 86 million metric tons of carbon dioxide annually (Berdard, 2007). Marine hydrokinetic energy technology has widened the possibility of extracting renewable electricity from the ocean's dynamic movement of waves, tides, and currents. With one third of the total human population living within 60 miles of the coast, there is a significant possibility of linking this energy source to coastal populations. In these locations it is difficult to implement other renewable energy options such as solar or wind due to limitations presented by coastal fog patterns and coastal topography.

There are many components to hydrokinetic energy that make it a promising alternative to fossil fuels and other renewable energy options. In contrast to the limited availability of coal oil and natural gas, ocean energy is continuously created and does not produce harmful byproducts or emissions. Ocean energy is especially attractive due to its superior reliability and predictability in comparison to other renewable energy such as solar and wind. Water is 832 times denser than air, which enables marine energy to produce a greater energy potential in a given stream flow compared to wind energy. For example, energy contained in a 12mph water flow is equivalent to an air mass moving at 100mph (Zarubin, 2015). In addition, a significant argument against the use of renewable energy is the variability of wind and solar energy over a 24 hour period; however, marine hydrokinetic energy output is fairly uniform due to the consistency of ocean currents and waves. These ocean energy patterns can be predicted months in advance due to accurate climate and earth data. With effective development marine hydrokinetic devices can consistently capture and transfer clean, reliable power while many other renewable energy options are not able to operate.

Previous research on the implementation of hydrokinetic energy devices to calculate projected power output has been on a narrow device specific basis, preventing large scale multi-device proposals to be made. This lack of a system wide understanding has created a complex and contradictory marine hydrokinetic field, as each project creates their own individual ocean models and parameters determined by their specific device requirements. Accurate, comprehensive device projections determined by energy optimization due to oceanography patterns are essential to convince policy makers and investors to fund, develop and implement a mixture of these devices on a statewide scale. In order to construct a more credible and convincing argument for the potential of ocean energy, these models must be consistent. As marine hydrokinetic energy optimization is determined by an ocean current's steam flow and a wave's pitch, roll and heave (horizontal and vertical changes), site selection significantly impacts energy output for this technology (Dallman, 2014). However, during the development of hydrokinetic device operations and mechanics it is difficult to predict large-scale costs and energy output due to the lack of robust site-specific models. Without these accurate multi-device characterizations, marine hydrokinetic data models are limited at a larger geographic context.

In this study I developed three optimization models to illustrate the potential spatial distribution of the two main categories of marine hydrokinetic energy devices: wave energy converters and rotating turbines. Using a GIS suitability analysis, and specifications provided by the most commercially available marine hydrokinetic energy devices, I tested locations for optimal conditions needed for implementation. Using crucial variables such as wave significant height, wave density, wave period, ocean current speed, ocean current power, bathymetry and federal and state marine protected areas, I created binary, ranked and weighted models. The outputs of these models constructed a comprehensive overview of the optimal distribution of marine hydrokinetic devices on a state-wide scale for maximum power output. To perform this analysis, I determined the ideal conditions for each type of hydrokinetic energy device (rotating turbines versus wave energy converters) and considered restrictions on installation due to environmental impacts. This research addresses the potential for multi-device implementation as well as the need for additional funding for continued development in order to reduce device costs. Large scale models examining specific elements of harnessing marine hydrokinetic energy are essential in allowing ocean energy to play a significant role continuing our global transition towards a renewable energy future.

BACKGROUND

Physical Factors Influencing Wave Energy Outputs

Waves begin as small ripples and then increase in size due to wind energy speed, wind duration and wind fetch (area over which wind is blowing). Wave swells can travel long distances gaining momentum until they crash onto shore or reaching their breaking point (when steepness ratio is too great). The strength of the waves of the west coast provide much more potential than the waves on the east coast due to three main factors: their prevailing winds, the continental shelf and the ocean fetch. On the west coast inward prevailing winds increase wave energy due to blowing at the same orientation of the waves and the narrow, steep continental shelf in theses locations allows larger waves to maintain energy to shore (Brian, 2012).

Physical Factors Influencing Ocean Current Outputs

The major driving forces for large scale ocean currents include earths rotation (or Coriolis), gravity, wind stress, temperature and salinity differences. Small scale currents are driven by tides, pressure gradients and bottom friction (Hass, 2013). The patterns of ocean current energy in California are driven by the south to north flowing California current, the seasonal north to south Davidson counter current and the subsurface undercurrent. The California Current System can be described by four district features: “an offshore equatorward flow (California Current) located approximately 300 km from the coast, an inshore surface (Inshore Countercurrent) and sub-surface (California Undercurrent) poleward flow, and a region of cyclonic circulation (Southern California Eddy) that connects the inshore and the offshore circulation” (Lorenzo, 2013). The California Current flow derives from the North Pacific Current and the coastal jet running from Washington to Baja California (Checkly, 2009). The Davidson Current runs from San Diego to Washington and is closer onshore than the California Current. Both these current systems are far offshore making extracting their energy through rotating turbines relatively difficult. The suitable locations with respect to current speed and energy in general are far beyond the parameters set for optimal ocean depth to build these devices.

Marine hydrokinetic energy devices

There are two categories of marine hydrokinetic devices to capture ocean energy. First, wave energy converters (non-turbine systems) which include devices such as oscillating water columns, point absorbers, attenuators, overtopping devices, and oscillating wave surge converters; all of which utilize the oscillating motion of ocean waves to generate power by taking advantage of changes in height and/or pressure (Güney, 2010). Descriptions of these devices and figures reflecting their design are illustrated in Appendix A. Second, rotating devices (or turbine systems) includes various types of tidal turbines which -- similar to the wind turbines on land -- harness the power of currents to rotate the blades of the device mounted on an axial (horizontal) or cross-flow (vertical) shaft connected to a rotor therefore allowing the generator inside to create electricity (Lago, 2010) (Kahn, 2009) (Appendix A, Figure 6). Currently the most successful devices are various configurations of rotating turbines due to our access of well-developed wind turbine designs as well as advanced computational fluid dynamic models. For these reasons, rotating turbines comprise over 90 percent of today's marine kinetic capacity totals (Crawford, 2013) (Miller, 2010). By engineering devices to reverse wave motion and current flow relationships, basic marine hydrokinetic technology such as electromagnets, hydraulic pistons, generators and hydro-turbines can convert this movement into energy (Miller, 2010).

Political and economic context

Perhaps the largest hurdle to overcome in order for hydrokinetic energy to make an impact on global energy is lowering the associated overhead costs of device implementation through further funding for research. In order to lower costs, these devices must receive grant money for continued technological developments. To do this, companies must illustrate to policy makers the potential of these devices by using accurate ocean energy models to predict energy output on a state and national level. The economics of these devices must make the financial returns comparable to other alternative energy sources and greater than those of the traditional fossil fuels (what is also known as approaching its grid parity). Factors such as preliminary costs, construction, operation, maintenance and decommissioning cost are incorporated in the overall levelized cost which can then be offset by energy produced. By using accurate predictions of ocean energy potential to forecast expected costs of implementation, more effective development can induce prices to drop.

The actual levelized cost of one of these devices is difficult to determine because of high variation depending on location and category of device being implemented, a field which as stated above currently does not have consistent data present. This research will attempt to make progress towards more consistent models because without accurate predictions of the cost and energy harnessing capacity, it will be difficult to assess a cost benefit analysis. By creating models and parameters based on commercially available hydrokinetic devices through GIS software, I hope to improve the research and provide companies with the tools they need to illustrate to policy makers and potential investors the promise of this rapidly developing technology.

METHODS

Justification for suitability analysis

To determine California's coastal ocean energy potential and examine where marine hydrokinetic energy devices are most suitable I executed a GIS suitability analysis using binary, ranked and weighted models as well as checked my outputs by comparing to a reclassified and weighted overlay model. This identifies the most suitable sites by applying a set of individually weighted criteria. This is the optimal tool due to the flexibility of layering and incorporating certain variables to visualize an output. While there are many obstacles to overcome in order to effectively implement this new technology, the models I created will allow for interpretation of the potential of these devices at a larger spatial scale than currently present in the literature. I use a suitability analysis because it can incorporate the many parameters that must be considered when developing hydrokinetic projects such as potential energy output and distribution. The presence of multiple criteria allows the process of determining suitability at a particular location to become increasingly accurate due to integrating many variables that play a role in the predicted success rate. This suitability analysis technique for testing locations along the coast of California is ideal because by creating various layers within ArcGIS it allows for adding or eliminating specific layer types depending on what factors need to be highlighted.

Base layer data and descriptions

Table 1. Summary of oceanographic variables used for suitability analysis. Data collected from agencies such as the National Renewable Energy Laboratory (NREL), United States Geologic Survey (USGS), National Oceanic and Atmospheric Administration (NOAA) and California Department of Fish and Wildlife Service.

Variable/Parameter	Data Characteristics	Data Source	Variable Type
Ocean Depth	• Units: Meters • Ocean Depth Categorically	National Renewable Energy Laboratory	Categorical
Wave Energy Period	• Units: Seconds • Time taken for one wave to pass a fixed point	National Renewable Energy Laboratory	Continuous
Wave Significant Height	• Units: Meters • Distance between wave crest and wave trough	National Renewable Energy Laboratory	Continuous
Wave Power Density	• Units: kW/m • Power with which wave crest width are moving past a fixed point	National Renewable Energy Laboratory	Continuous
Ocean Current Mean Speed	• Units: m/s • Kinetic speed of moving ocean currents	National Oceanic and Atmospheric Administration	Continuous
Ocean Current Mean Power	• Units: Watts/m^2 • Ocean current mean kinetic power density annual average	National Oceanic and Atmospheric Administration	Continuous
Federal & State Marine Protected Areas (MPA)	• ESRI Shape files • GIS shape files of federal and state restricted zones	California Department of Fish and Wildlife	Categorical
Ocean Bathymetry	• Units: Meters • Ocean depth	California Department of Fish and Wildlife	Continuous

National renewable energy laboratory data

The data from the National Renewable Energy Laboratory was measured out to 50 nautical miles from shore (92600 meters) with measurements taken every three hours at resolution of a US Coastal 4-minute x 4-minute grid. It was collected using a 51-month (March 2005 to May 2009) Wavewatch III hindcast database developed by the National Oceanographic and Atmospheric Administration's (NOAA's) National Centers for Environmental Prediction (Hagerman, 2011). I then used the average annual and 12 monthly average measurements.

Wave depth: This data is a categorical measurement of depth zone at each location. It does not account for inland data such as the San Francisco bay. It uses the NMWW3 coastal grid accurate to 4'X4' minutes (Hagerman, 2011). I used this data to visualize potential placements in the discussion section as this data was tied to the wave energy converter data. I did not use this data in my suitability models because I used continuous ocean bathymetry data. See the categorical breakdown of depth in Appendix section B.

Wave Energy Period: Wave energy period is calculated as the time taken for a subsequent wave crests to pass a fixed point. In general this is measured as the variance weighted mean period of the one dimensional period variance density spectrum. This is an overall sea state parameter that is calculated from spectral moments (Hagerman, 2011).

Wave Significant Height: This measurement in meters is the average amplitude for waves at a certain location as measured from crest to trough. It is crucial variable for determining best geographic placement for wave energy converters such as the attenuator or wave overtopping device. The time series derived height takes the average of the highest third of the waves (Hagerman, 2011) which directly corresponded to the methodology of the national Buoy Center who archives significant wave height as average of highest one-third of all wave heights measured during 20 minute sampling period. This data also depends on calculations of special moments (Hagerman, 2011).

Wave Power Density: Wave power density of the sea surface in killowatts per meter of wave crest width across a unit diameter circle. In the waves used to derive this data, half of the energy was stored in potential form "associated with the vertical rise and fall of the water surface from its still-water, undisturbed condition" (Hagerman, 2011) while the other half comes from the kinetic energy "associated with the orbital motion of water particles beneath the water surface" (Hagerman, 2011). According to the Electric Power Research Institute this approach is fully consistent with accepted global practice and "includes the resource made available by the lateral transfer of wave energy along wave crests, which enables densities within a few kilometers of a linear array, even for fixed terminator devices" (Hagerman, 2011). Since this measure of wave power density is the rate at which wave energy "propagates across a unit diameter circle", it is used to dictate the potential and kinetic energy that could be harvested by a vertical cross section of a wave energy device oriented perpendicularly to the wave. These calculations are well defined for a field of regular single frequency waves, but the equations somewhat break down when multiple long irregular waves are present. For this reason I am testing suitability for single frequency waves.

About National Oceanic and Atmospheric Administration Data

The current data used to estimate suitability for rotating turbines comes from the partnership between NOAA and the National Ocean Partnership program. This data was collected as part of the Hybrid Coordinate Ocean Model or HYCOM global data. The spatial coverage is measured for the East and West coasts of the United States along with Alaska with a spatial resolution of 7km. Data for the current mean power and current speed was collected between the years 2004-2008 with a time step of one day (Hass, 2013).

Ocean current mean speed: The average current speed off the coast of California is measured as the average current speed in meters per second accumulated over the 12-month values. Over the entire area the maximum ocean current speed was measured at .308 m/s while the minimum value was 0.042 m/s. The mean over the entire area was 0.201 m/s with a standard deviation of 0.037. These values are relatively low in comparison to currents such as the Gulf Stream.

Ocean current mean power: The measurement in Watts/meter^2 of ocean current mean kinetic power density is according to the annual average accumulated over the 12-month values. Power density is used to quantify “amount of available undisturbed kinetic power” (Hass, 2013). This value is directly correlated with the average current speed because the velocity of the current speed was used to calculate power with the addition of using the water density data. The annual mean power density was calculated using the depth integrated average power density between the surface and the top 200m of the water column.

Federal and state marine protected areas: Using data from the California Department of Fish and Wildlife Service in their marine database I was able to obtain ESRI shape files for federal and state marine protected areas. I used the merge function in ArcGIS to combine both into one shape file. This data set outlines areas that are at risk and/or have sensitive and protected ecosystems eliminating these locations to the placement of marine hydrokinetic energy devices. There are 155 polygon shape files that compile both federal and state protected areas. If the shape file is present, the location is unsuitable so I overlay these on top of my output maps. Combined the marine protected areas summed to a total of ~2,627 km^2 (263,000 hectares). From here I assigned a new variable to the attribute table called "Present" and gave each protected location a value of 0 and then used polygon to raster to create a raster layer of all the marine protected areas.

Setting suitability parameters

Data to determine the parameters for hydrokinetic devices are found in publications from marine hydrokinetic energy firms and the suitability parameters they specify for each device design. In examining for suitability I am establishing parameters according to the most commercially available devices that have already been developed, built and formally tested in the ocean (compared to devices with strictly lab based testing). The main devices I based my parameters are described in Table 2 with parameter suitability range summarized in Table 3.

In order to describe the technically recoverable resource, there are three engineering characteristics that indicate the success of a mechanical device such as wave energy converters or rotating turbines. The first is the threshold operating condition (TOC), the second is that rated operating condition (ROC) and the last is the maximum operating condition (MOC). These are most often used for wind-turbine generators but can be used here to establish the conditions needed for effective power output. The threshold operating condition is the minimum cut-in speed/power needed for sufficient movement of the device which establishes the lower limit of my suitability scale. Below this value the wave power density or ocean current speed is "insufficient to motivate the 'wave to wire' power conversion mechanism so the device is idle" (Hagerman, 2011). The maximum operating condition is the upper limit for my suitability scale as values above these mean the device is entering "survival mode" as it stops generating electricity and simply tries to limit "maintenance and repair costs" (Hagerman, 2011). The rated operating condition is when the device is capturing energy from ocean currents or waves and converting it into energy with output energy values depending on the specific conditions present.

Table 2: Marine Hydrokinetic Energy Device Companies

Company	Device
Ocean Power Technology	Power Buoy PB3
Wave Dragon	Wave Overtopping Device (floating, slacked moored)
Wave Star	Half Submerged Buoy System
Pelamis Wave Power	Attenuator Device
Scotrenewables Tidal Power Ltd	SR 2000 Horizontal Turbine
Atlantis/Lockheed Martin	SeaGen S & AR1500 Turbines
Waterotor Energy Technologies	Waterotor Low Speed Unidirectional Turbine
Tidal Energy Ltd.	Delta Stream Technology Tubine
Open Hydro Naval Energies	Open Center Turbine

Table 3. Parameters and Suitability Data. Data to determine the parameters for each hydrokinetic device are defined by a suitability range according to currently available marine hydrokinetic energy devices.

Variable	Device	Suitability Range	Company Devices to Set Parameter
Wave Significant Height	Wave Energy Converters	.5-4 meters	• Wave Star: 1m-3m • Ocean Power Tech Buoy: .1-4m
Wave Power Density	Wave Energy Converters	.4-48 kW/m	• Wave Dragon: .4-48 kW/m
Wave Energy Period	Wave Energy Converters	5-10 seconds	• Wave Star: 5-10 seconds
Ocean Depth	Wave Energy Converters	10-1000m	• Wave Star: 10-30m • Wave Dragon: 30m-100m • Pelamis Wave Power: Minimum 50m • Ocean Power Technology: 20-1000m
Current Speed	Rotating Devices	.2-5 m/s	• Waterotor: .8m/s • Scotrenewables: 1-4.5m/s • Atlantis SeaGen: 1-2.5m/s • Atlantis AR1500 High Flow: 3-5 m/s • See notes below on assumptions to set suitability range for rotating devices
Current Power	Rotating Devices	4kW/m	• See notes below on assumptions to set suitability range for rotating devices
Ocean Depth	Rotating Devices	20-130m	• Waterotor Energy and Technology: minimum 20m • Scotrenewables: Minimum 25m • Open Hydro: Minimum 25m • Atlantis: Minimum 30m • Triton 6: max 130m
Federal and State Marine Protected Areas	Wave Energy Converters Rotating Devices	If present, unsuitable	NA

Parameters for Wave Energy Converters

As summarized above I set my suitability range according to device descriptions. When testing my models I observed a majority of locations completely suitable for wave energy converters. To be more specific regarding the most optimal distribution I tightened the stuiability range for Wave Energy Converters to observe locations with the highest potential energy output. To do this I changed the wave power density cut-off from .4 to 10. And changed wave significant height from .5 meters to 1.5 meters.

Parameters for Rotating Turbine Devices

Current speed parameter Since the measurements of ocean current speed are seasonal, the annual average calculations are significantly lower than the current speeds observed during the spring and summer months (February through July). During these months a majority of the maximum ocean current speeds increase. This is especially demonstrated in locations with high speeds as they increase from .3 m/s to .4 m/s (National Renewable Energy Laboratory, Marine Hydrokinetic Energy Atlas). Due to these seasonal patterns, the analysis of the average annual current speed under predicts the locations suitable for rotating turbine energy extraction. To counteract this I lowered my cut-off value for minimum current energy speed. Since the most advanced rotating devices still require a minimum of .8m/s, I tested with the assumption that technologic developments will be made to expand rotating devices capabilities to extract energy at a rate .2m/s. Again, this lowered cut-off is used because the yearly average discounted for the spring and summer months when the speeds will be around .1-.2 m/s greater.

Current power parameter Again since most of the mean power off the coast of California is below the minimum cut-off needed to run the most advanced rotating turbines, I am setting my parameter with respect to the assumption that the technology will be further developed to extract lower power densities. According to the minimum operational speed of .2m/s I set the minimum ocean mean power at 4kW/m.

Ocean Depth Parameter The depths suitable for marine hydrokinetic devices vary between specific device design and construction. The most important aspect to determine suitable depth is the length of the individual rotors in horizontal axis devices and total vertical length of the rotor system in vertical axis devices. The slow moving vertical axis turbine system from Waterotor

Energy and Technology along with the Triton S with blades 4-4.5 meters are the smallest devices able to operate in locations with ocean depths at a minimum of 25 meters.

With regard to the maximum depth this again is determined by the length of the rotors. Some of the largest single rotors are around 25-30 meters long. These devices use of a main tower that can function in areas of around 100m (such as the Triton 6). Other devices use mooring cable that extend from the seafloor and hold the rotating turbine device in the stream flow. These devices can be placed much further offshore up to 130 meters.

Data Analysis and Preparation

To analyze the ideal geographic placement and distribution of hydrokinetic devices off the coast of California I used ArcGIS version 10.5.1 through the process of a suitability analysis using tools such as polygon to raster, extract by mask, clip, various forms of raster calculators, reclassify and weighted overlay analysis. As stated above I determined the potential energy conversion calculations due to ocean patterns by reading through literature on current devices being developed. I then established the variables and parameters associated with energy output and distribution and obtain ocean data.

Step 1:

I am working in USGS map scales of 1:24,000 and working in California projection UTM Zone 10. For my binary, ranked and weighted analysis I imported each data layer as a shape file. I then used the data management projection tool as well as the polygon to raster tool within the conversion toolbox to take the collected geo-referenced databases and convert them from vector files to raster format with a projection of GCS_WGS_1984. I choose this coordinate system in order to keep uniformity with the National Renewable Energy Data.

Step 2:

I used the clip function for polygons and the extract by mask function for raster's to isolate California data by extracting my input datasets overlaying my California clip features. From here I used the iterations tool in model builder to clip the data. I set the input raster and then spatially masked off California using my study area as the mask file. To save the output and keep the original file name I used %Name%_C so my new raster's would be the clipped files.

Step 3:

I then used literature and specifications of current marine hydrokinetic energy devices to set parameters and calculate the ideal power output conditions for each of these devices. My models incorporate wave power density, wave significant height, wave depth, bathymetry, current speed, current power and protected environmental zones as illustrated in Table 3 above. In the published literature, there are no studies combining all these variables together using weighted scales.

Step 4:

Using raster calculators and the suitability parameter set above in step 3, I created a constraint layer regrouping all the unsuitable areas. These layers are composed of locations with values above or below the set suitability range. The map algebra function of ArcGIS was used to merge and reclassify all the layers by dividing the data into subcategories. The unsuitable areas were attributed by a value of 0 and the suitable areas given a value of 1.

Step 5:

Using model builder I was able to incorporate each of these variables into my suitability models. My models used differing calculator functions to combine variable layers to create a comprehensive output map. These flexible maps reflect the suitability of various devices according the specified layers being incorporated. The output maps use categorical color scale to visualize this spatial distribution. I will now expand upon my three models below.

Output Suitability Maps

Using model builder I was able to incorporate variables into my suitability models. I used three models for each of the two device categories to produce a total of 6 graphs. Using the parameter clipped files I employed spatial analysis raster calculators.

Parameters for wave energy converter raster calculator are as follows:

- [("%Depth%" >= -1000) & ("%Depth%" <= -10)]

- [("%Wave Energy Period%" >= 5) & ("%Wave Energy Period%" <= 10)]
- [("%Wave Significant Height%" >= .5) & ("%Wave Significant Height%" <= 4)]
- ("%Wave Power Density%" >= .4) & ("%Wave Power Density%" <= 48)

Parameters for the rotating turbine raster calculator are as follows:

- ("%Mean Current Speed%"> .2) & ("%Mean Current Speed%"<5)
- ("%Mean Current Power%" > 4)
- ("%Depth%">20) & ("%Depth%"<130)

A) Binary model

From here I added an additional raster calculator to combine all the layers using the multiplicative binary expression. Since each of these parameter calculations are multiplied together to give an output then if one parameter is unsuitable, then by default the location in deemed unsuitable. For this model each parameter must be fulfilled in order for a location to be considered suitable. See Figure 2 and Figure 3. See Appendix C for input commands.
Example: Parameter 1 * Parameter 2 * Parameter 3.

B) Ranked Model

The ranked method takes a similar approach but rather than being multiplied, each parameter value is added to create a suitability scale. The more parameters fulfilled, the more suitable the location. This equation is additive based on binary datasets and the output will be a set of ranked integers from 0 (unsuitable) to 10 (highly suitable). Each parameter was treated as the same value and added up to determine how suitable or unsuitable a specific location was. Each layer has a value of 1 and you add up the values of the suitable layers. If there are 10 layers a value of 0 means none of the layers are suitable in that location while a value of 10 means all the layers provide good level of suitability. See Figure 2 and Figure 3. See Appendix C for input commands.
Example: Parameter 1 + Parameter 2 + Parameter 3.

C) Weighted Model

The weighted model is an expansion on the ranked model in that you assign a rank to each parameter in order of importance (such as 10: most important, 1: least important). For weighted model I added another raster calculator but this time for each unit there is an added variable weight multiplied to it in order to reweigh the data with respect to importance. See Figure 2 and Figure 3. See Appendix C for input commands.
Example: (Rank * Parameter 1) + (Rank * Parameter 2) + (Rank * Parameter 3)

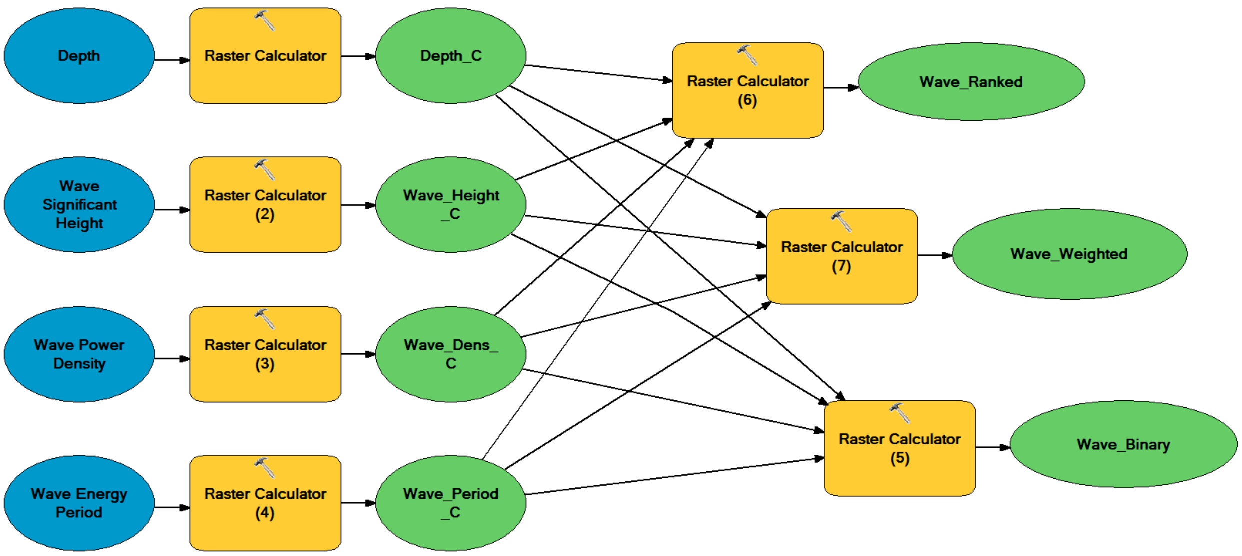

Figure 2. Model Builder for Wave Energy Converters

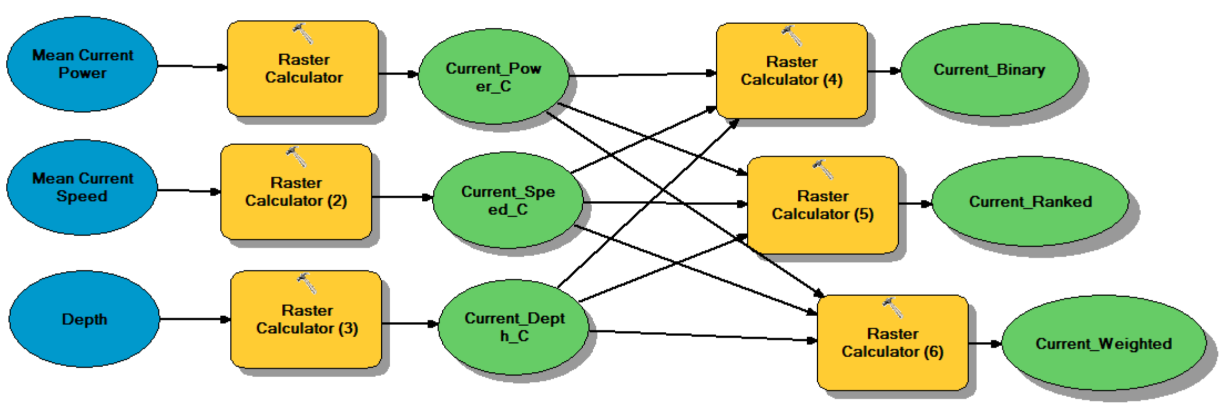

Figure 3. Model Builder for Rotating Turbine Devices

7) Reclassified Model

For the reclassified and overlay analysis I used a cartographic model for suitability analysis with ordinal suitability classifying low suitability ranked 0-3, medium suitability ranked 4-7 and high suitability ranked 8-10. I used the reclassification tool for each of my different parameters to change the values in a raster (pairwise comparison matrix). This assigned numerical values to classes within each map layer depending on this new suitability scale for marine hydrokinetic energy devices. To do this I used the weighted overlay tool that begins with reclassification to evaluate the scale of suitability or preference. I then added the resulting cell values together to create an output raster. This allowed me to create an even more detailed output map with a more comprehensive suitability scale.

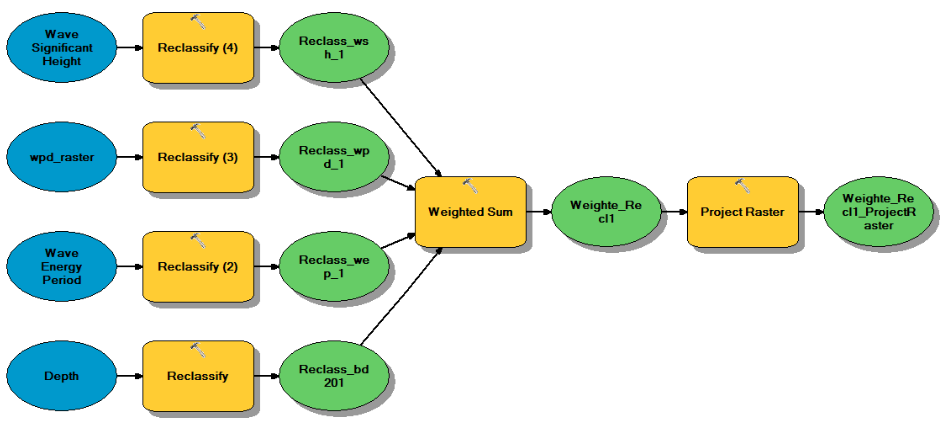

Figure 4. Model Builder for Reclassified and Weighted Overlay

RESULTS

Using the methodology described above I passed the essential parameters with suitability cut-offs through my three models. From these models I created output maps to visualize the most optimal distribution of these devices. The output maps demonstrate to what extent each area tested fulfills the required parameters for a suitable placement of a marine hydrokinetic energy device. Each area tested is a consistent geographic unit determined by the specificity of the coarsest data set. The graphs indicating “count” reflect the grouping of each individual location tested according to their level of suitability. Each model (binary, ranked, weighted) incorporates variable values in a slightly different way so I am be able to compare and interpret the output maps for each distribution in my discussion. In general I define Northern California as the region south of the Oregon boarder to Monterey, Central California as the region between Monterey and around Santa Barbra, and Southern California the region from Santa Barbra to Mexico.

1) Wave Energy Converter Binary Model

This output model uses a multiplicative approach therefore if one of the variables tested was not suitable, then the entire area of that location is considered unsuitable making these models exclusionary. This is due to each parameter being given a value of 0 or 1 and then being multiplied together. When multiplying since it only takes one 0 (one parameter unsuitable) to multiply for an output of 0, each parameter must be fulfilled in order for a location to be considered suitable in a binary map. For each of the following models purple represents an area that is unsuitable for the specific device being tested while teal indicates an area suitable.

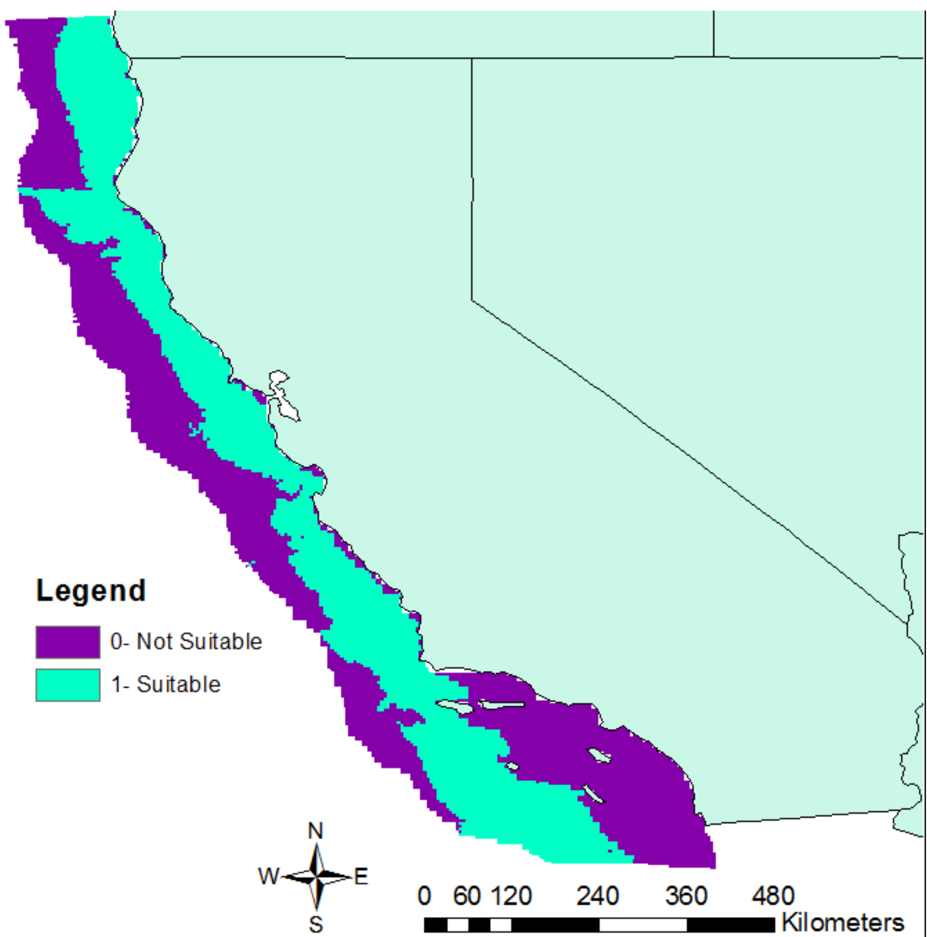

Figure 5. Binary Map of Suitability for Placement of Wave Energy Converters.

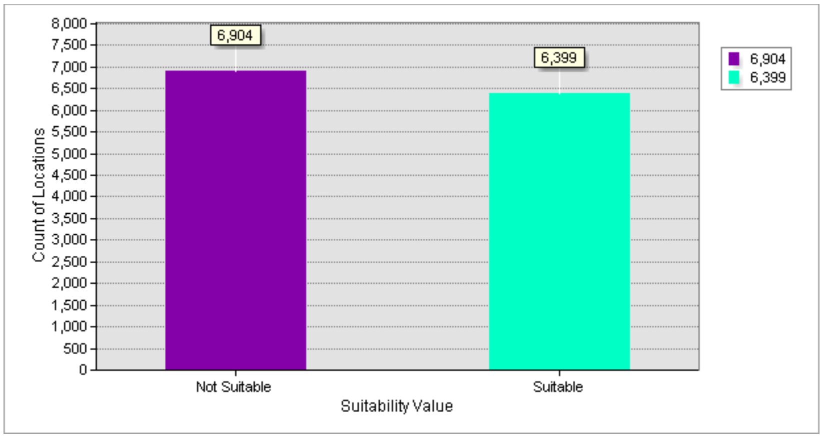

Figure 5.A. Binary Graph of Suitability Distribution of Wave Energy Converters. Graph demonstrates the number of tested locations suitable or unsuitable for wave height, wave power density, wave energy period, and depth.

Table 5. Binary Analysis Suitable and Unsuitable Areas

Suitability	Count	Percent Area
Unsuitable	6904	51.9%
Suitable	6399	48.1%

The binary suitability model illustrates a majority of suitable locations clustered around areas off the California coast in northern and central California where there is an abundance of wave height differences. In southern California there were many locations limited due to the low wave significant height. As categorized in table 1 above the binary model of the marine hydrokinetic energy suitability map generated 51.9% of the study area permanently unsuitable for marine energy and 48.1% suitable.

2) Wave Energy Converter Ranked Model

This output model uses an additive expression to arrive at the ranked output map. Using the additive approach each variable maintains the same weight (with a unit of 1), and then they are added up to reach a final output suitability number. The higher the number the more parameters are fulfilled indicating a higher suitability. This equation is additive based on binary datasets and the output will be a set of ranked integers from 0 (not suitable) to 4 (most suitable). The distribution of suitable locations is demonstrated below in Figure 6.

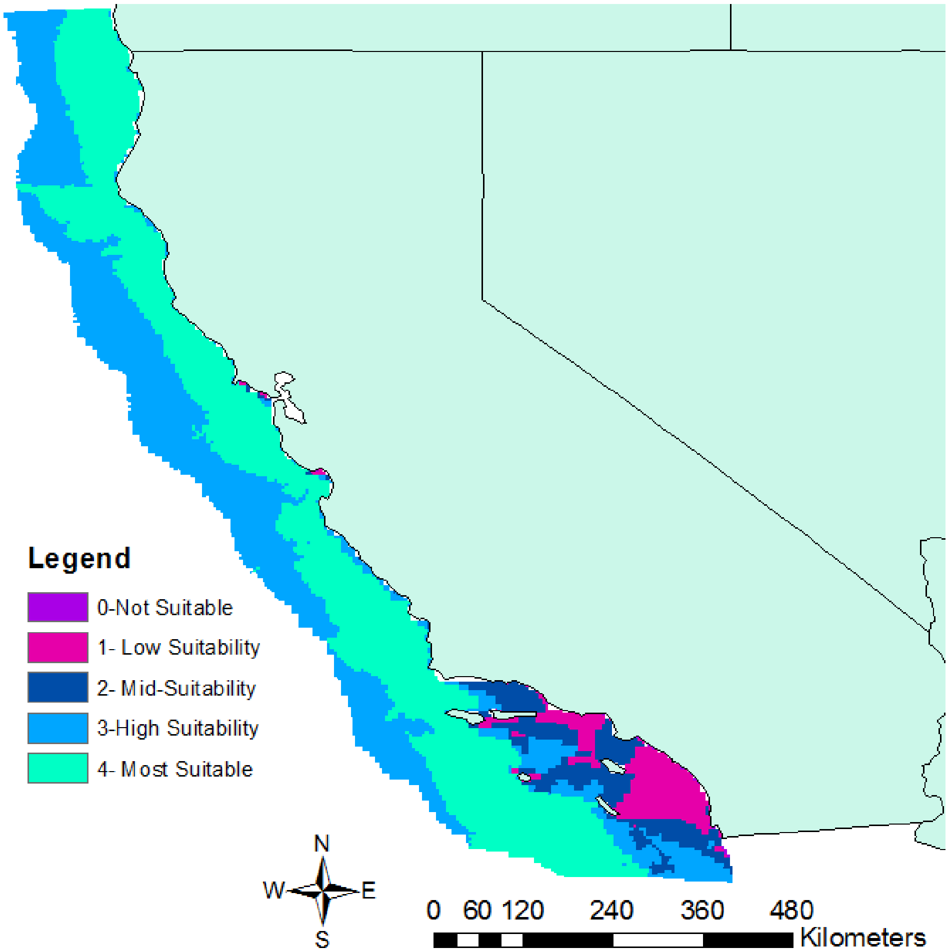

Figure 6. Ranked Map of Suitability for Placement of Wave Energy Converters.

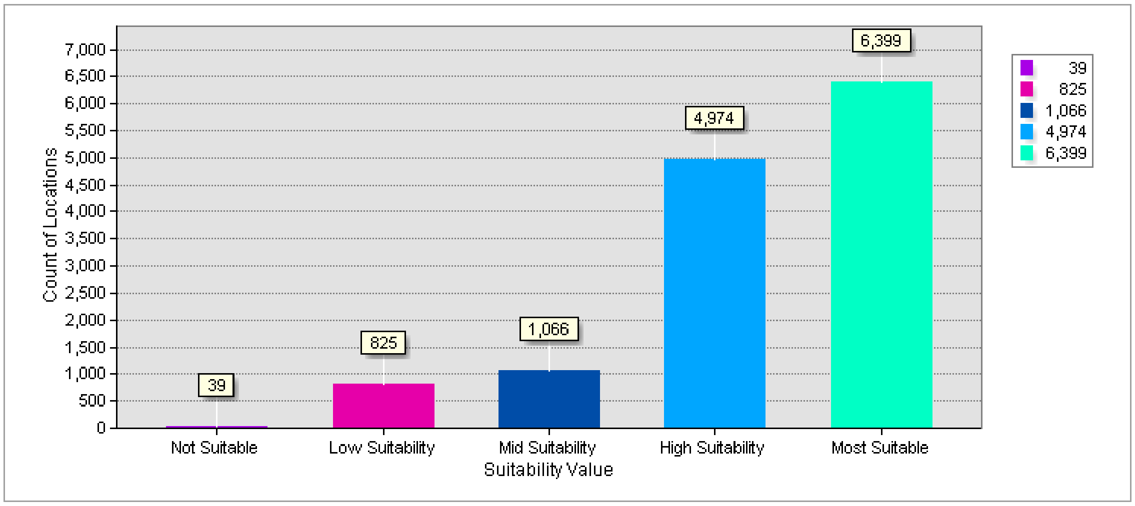

Figure 6.A. Ranked Graph of Suitability Distribution of Wave Energy Converters. Graph demonstrates the number of tested locations suitable or unsuitable for wave height, wave power density, wave energy period, and depth.

Table 6. Ranked Analysis Suitable and Unsuitable Areas.

Suitability	**Count**	**Percent Area**
Not Suitable	39	2.9%
Low Suitability	825	6.2%
Mid Suitability	1066	8.0%
High Suitability	4974	37.4%
Most Suitable	6399	48.1%

On viewing the ranked suitability model a majority of the suitable locations clustered around areas near the coast North of the Point of Conception (between Santa Maria and Santa Barbra) due to shallow ocean depth and high wave heights. Mid-suitable locations appear in areas beyond the regions near the coast due to deeper waters and mid power output from wave energy. The lowest suitability areas are directly off the coast south of Santa Barbra due to low measures of wave energy and wave height.

According to the ranked model of the marine hydrokinetic energy suitability map generated and summarized in Table 2, it was determined that, while 2.9% of the study area is not suitable for marine energy, 6.2% has low suitability, 8.0% has mid suitability, 37.4% has high suitability and 48.1% is the most suitable according to my parameters.

3) Wave Energy Converter Weighted Model

The weighted model is an expansion on the ranked model but for each parameter value (1: suitable, 0: unsuitable) there is a variable weight multiplied to it. For wave energy converters higher values were given to wave significant height and wave power density. Adding up the values for this model created a larger spread of suitability values.

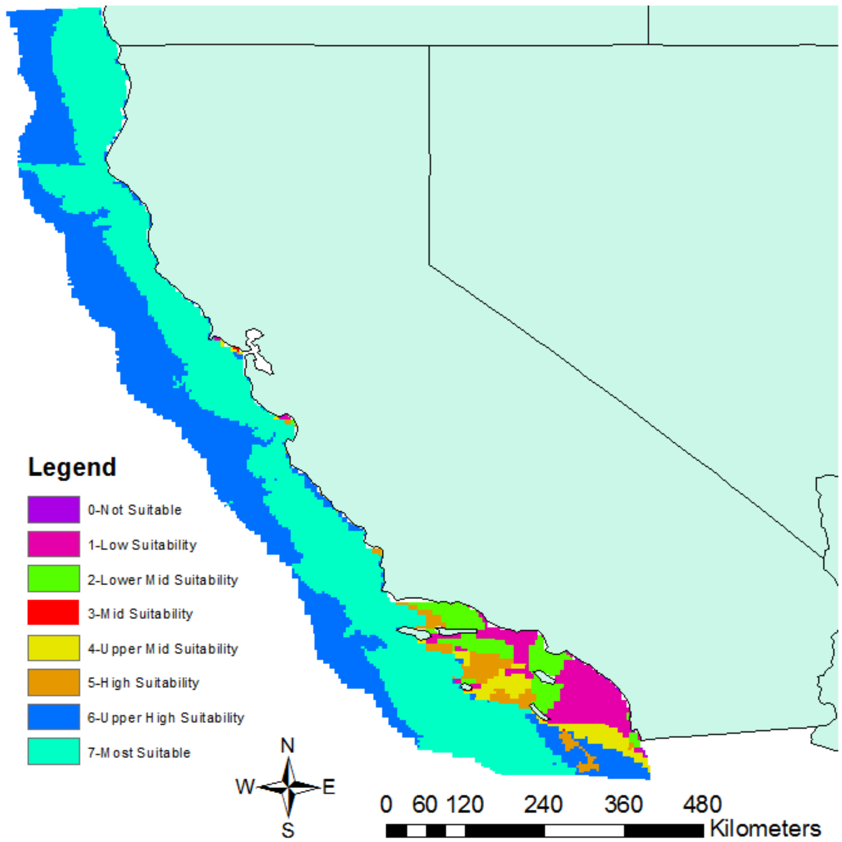

Figure 7. Weighted Map of Suitability for Placement of Wave Energy Converters.

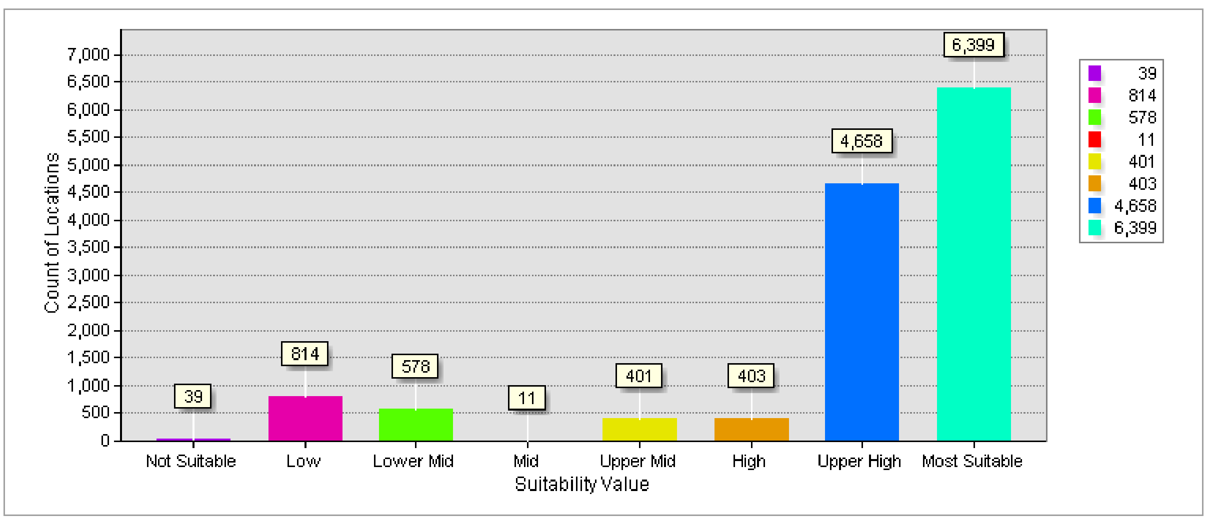

Figure 7.A. Weighted Graph of Suitability Distribution of Wave Energy Converters. Graph demonstrates the number of tested locations suitable or unsuitable for wave height, wave power density, wave energy period, and depth.

Table 7. Weighted Analysis Suitable and Unsuitable Areas

Suitability	Count	Percent Area
Not Suitable	39	.1%
Low Suitability	814	6.1%
Lower-Mid Suitability	578	4.3%
Mid Suitability	11	.083%
Upper-Mid Suitability	401	3.0%
High Suitability	403	3.0%
Upper High Suitability	4658	35.0%
Most Suitable	6399	48.1%

On viewing the weighted suitability model we see a majority of the highly suitable locations clustered again around areas directly off the coast in northern and central California. Some of the midrange suitability locations are centered near southern California possibly due to mid level wave measurements. Many of the unsuitable locations are in areas directly off the coast of southern California again due to the lack of wave power and wave height.

According to the weighted model of the marine hydrokinetic energy suitability map generated, it was determined that unsuitable locations to mid suitable locations make up only 10.6% of total locations tested. Upper mid suitability to high suitability made up an additional 6% of locations. This leaves 35% of locations tested registering as upper high suitability while 48.1% were calculated as the most suitable indicating almost half of locations tested had measurements of optimal conditions for energy extraction by wave energy converter devices.

4) Rotating Turbine Binary Model

Same methods as described above but now testing for rotating turbine suitability using the binary model. Again it must be noted that the minimum suitability scales were lowered in order to test for optimal locations given that rotating turbine devices will be developed to operate at lower speeds.

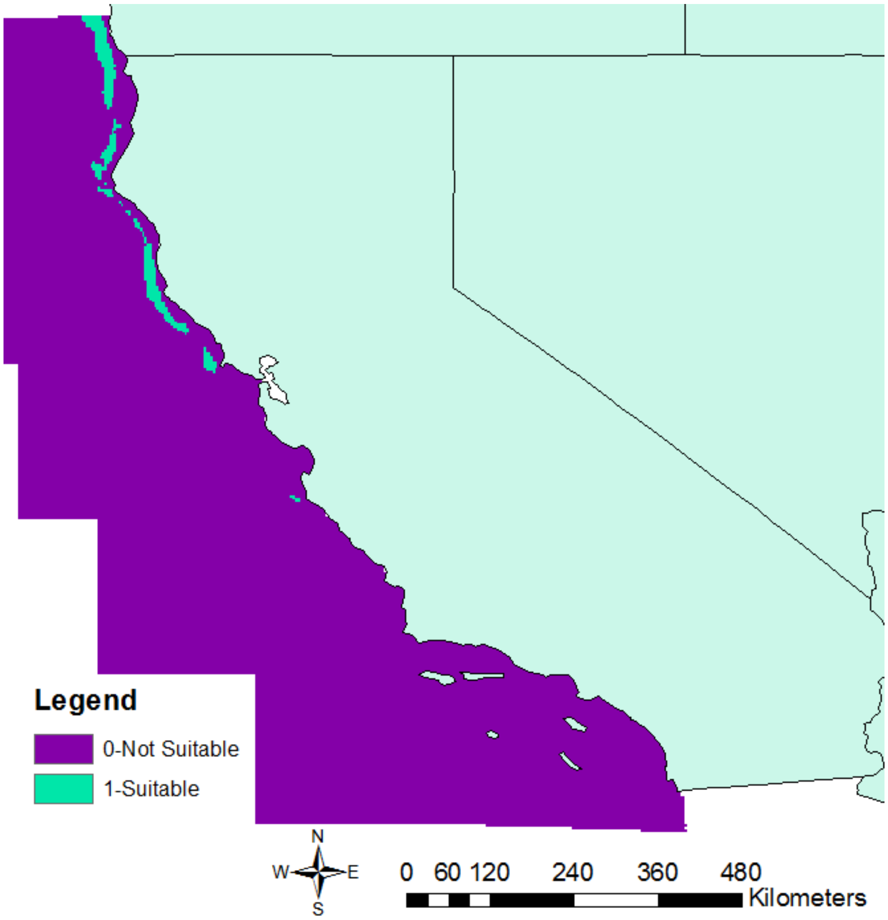

Figure 8. Binary Map of Suitability for Placement of Rotating Devices.

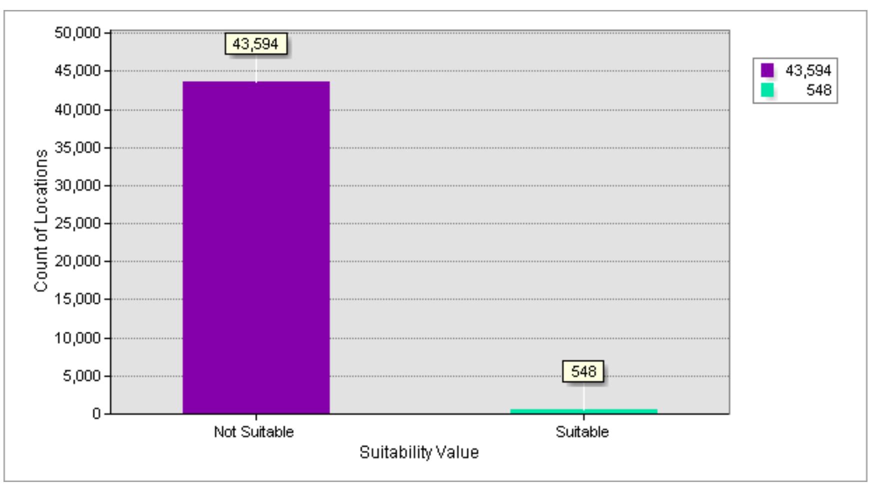

Figure 8.A. Binary Graph of Suitability Distribution of Rotating Turbines. Graph demonstrates the number of tested locations suitable or unsuitable for wave height, wave power density, wave energy period, and depth.

Table 8. Binary Analysis Suitable and Unsuitable Areas

Suitability	Count	Percent Area
Unsuitable	43594	98.8%
Suitable	548	1.2%

The binary suitability model illustrates a small sliver of suitable locations clustered around areas off northern California where there is a strong current power and fast current speeds. For rotating turbines a vast majority of the locations tested were unsuitable for energy extraction. According to the binary model 98.8% of the study area is unsuitable for rotating turbines devices while only 1.2% is suitable.

5) Rotating Turbine Ranked Suitability Model

Same methods as described above but now testing for rotating turbine suitability using the ranked model.

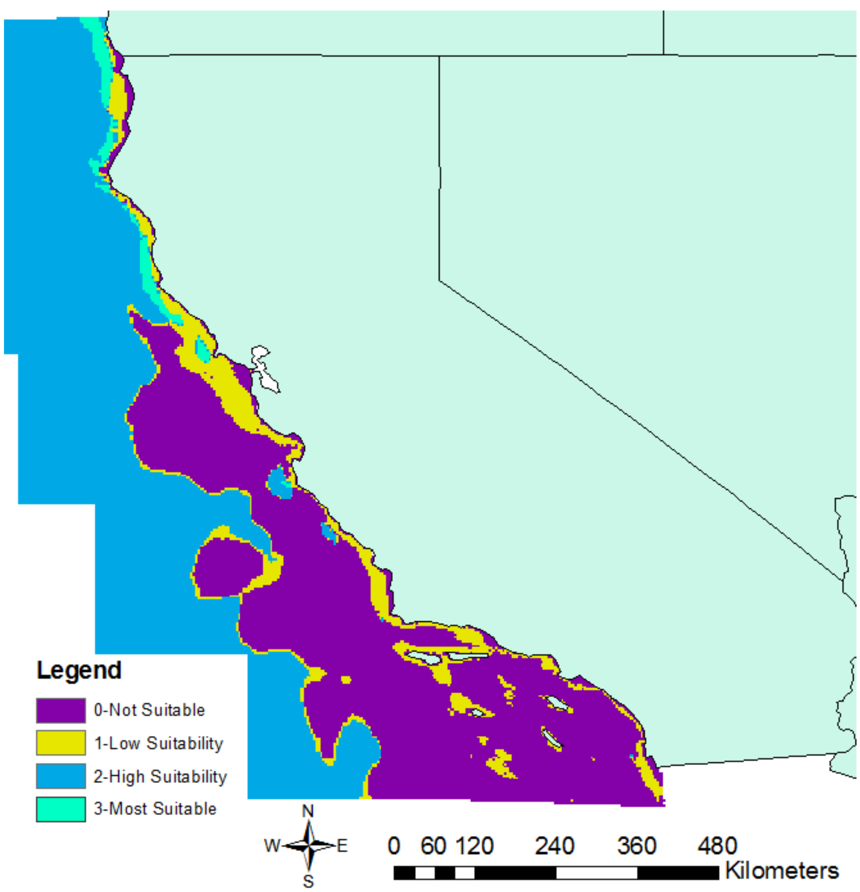

Figure 9. Ranked Map of Suitability for Placement of Rotating Devices.

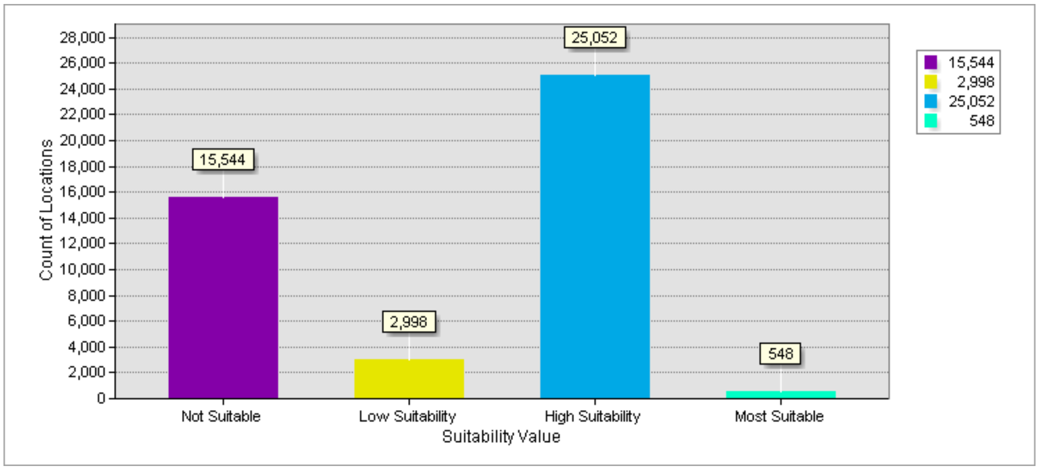

Figure 9.A. Ranked Graph of Suitability Distribution of Rotating Turbines. Bar graph reflecting the number of locations tested in relation to their level of suitability.

Table 9. Ranked Analysis Suitable and Unsuitable Areas.

Suitability	Count	Percent Area
Not Suitable	15544	35.2%
Low Suitability	2998	6.8%
High Suitability	25052	56.8%
Most Suitable	548	1.2%

On viewing the ranked suitability model a majority of the suitable locations clustered close to the shore north of the Bay Area and far from the shore south of the Bay Area. This is due to the California current being far from shore. There are still very few locations which are perfectly suitable for rotating turbine devices due to slow ocean current speeds.

According to the ranked model of the marine hydrokinetic energy suitability map generated, it was determined that, 35% of the study area is permanently unsuitable for marine energy, 6.8% has low suitability, 56.8% has high suitability (it is not suitable for one crucial parameter), and only 1.2% is perfectly suitable.

6) Rotating Turbine Weighted Suitability Model

Same methods as described above but now testing for rotating turbine suitability using the weighted model.

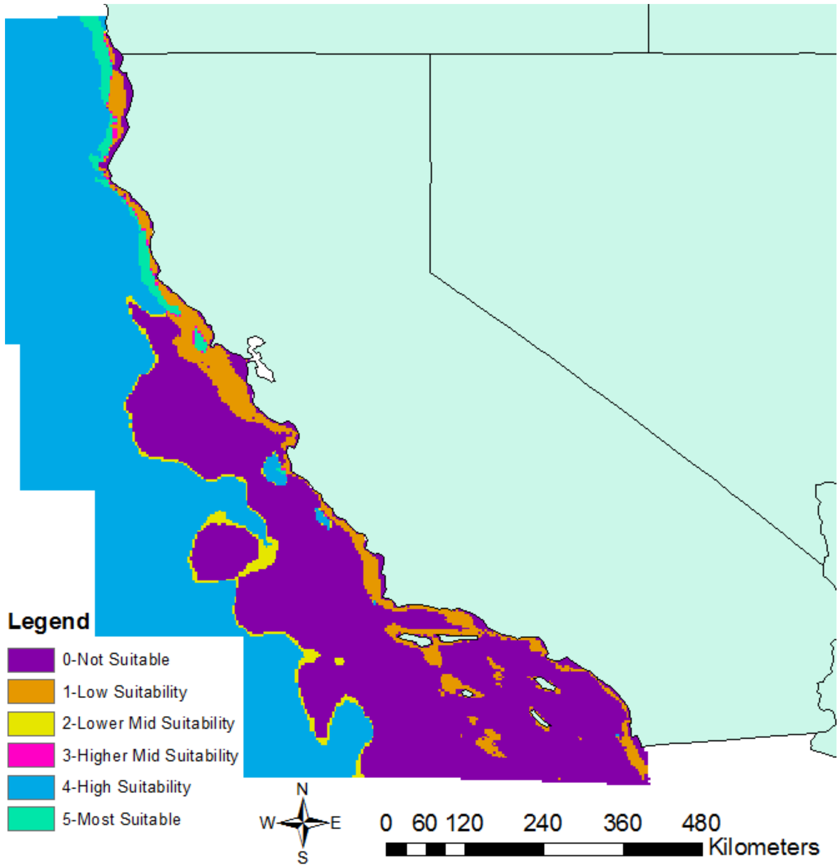

Figure 10. Weighted Map of Suitability for Placement of Rotating Devices.

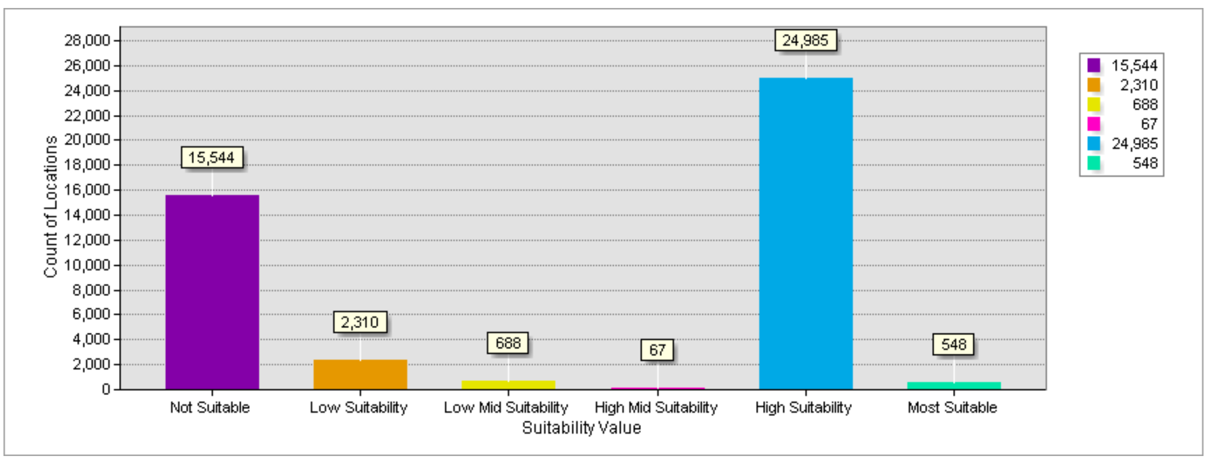

Figure 10.A. Weighted Graph of Suitability Distribution of Rotating Turbines. Bar graph reflecting the number of locations tested in relation to their level of suitability.

Table 10. Weighted Analysis Suitable and Unsuitable Areas

Suitability	Count	Percent Area
Not Suitable	15544	35.2%
Low Suitability	2310	5.2%
Lower-Mid Suitability	688	1.6%
Higher-Mid Suitability	67	0.2%
High Suitability	24985	56.6%
Most Suitable	548	1.2%

On viewing the weighted suitability model we see almost the exact same pattern illustrated in the ranked model with just the mid range suitability being broken down into subsections. The percentages reflect that of the ranked map and are summarized in Table 6.1.

Factoring in Marine Protected Areas

Given that my models indicated only wave energy converters as suitable for implementation off the coast of California, I focused on the limitations of marine protected areas for these devices. To do this I overlaid the Federal and State Marine Protected Areas on the wave energy converter weighted map indicated by the same characteristics as "Not Suitable" locations.

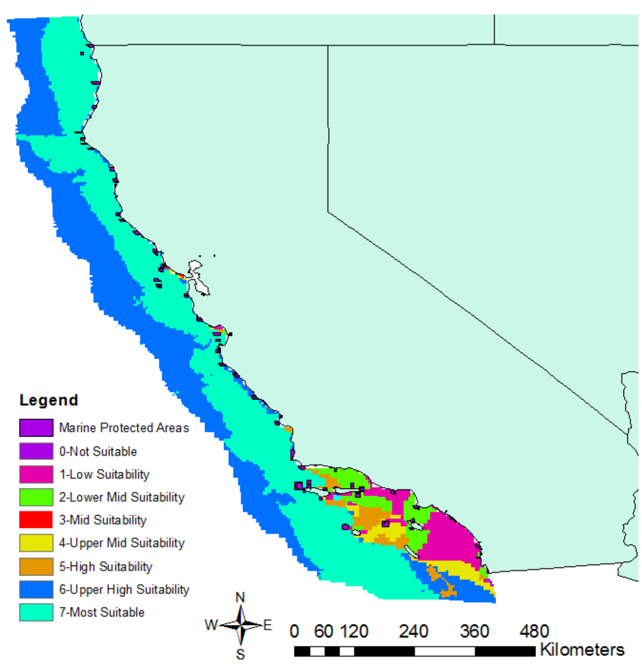

Figure 11. Marine Protected Areas on Wave Energy Converter Weighted Map

As indicated above in Figure 11, while marine protected areas are present in some suitable locations for wave energy converters, overall they do not impose a large barrier on the potential placement of these devices.

Testing Accuracy According to Reclassified Model

As stated in the methods section on reclassified and weighted overlay models, I carried out an additional test to compare to my weighed output for wave energy converters. The output maps were similar and had consistent patterns in terms of suitable and unsuitable locations.

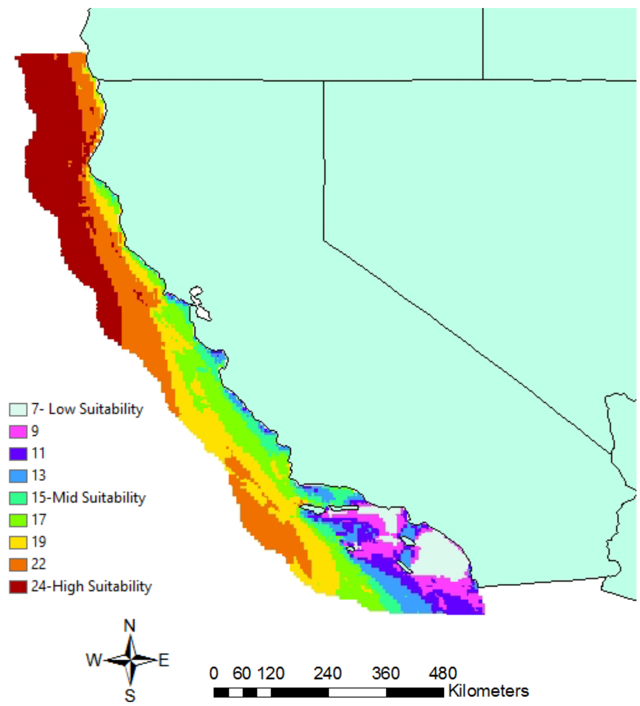

Figure 12: Wave Energy Converter Reclassified Model

DISCUSSION

For each type of marine hydrokinetic device, the ideal conditions I outlined in my model parameters are demonstrated in my output Binary, Ranked and Weighted distribution maps. These maps illustrate the potential locations for implementation, with each map demonstrating varying outcomes. As depicted in my results the potential for wave energy converter energy is high while the potential for rotating devices is low.

Distribution of Wave Energy Converters

The major factors considered for wave energy converters according to the models are wave height and ocean depth. These physical factors played a significant role in determining the suitability outcomes. Across all models around half of all locations tested for wave energy converters fulfilled every parameter needed for optimal suitability. The overall distribution for wave energy converter devices according to the binary model reveals that a majority of suitable locations are clustered directly off the coast ranging from around San Louis Obispo all the way up to the Oregon boarder. This is also demonstrated in the ranked and weighted models. As the suitability scale widened and more differences within the mid-suitable range were revealed, it is demonstrated that a majority of locations tested were completely suitable up to a depth of 1000 meters below sea level. Beyond this depth it is too deep to place wave energy converter devices and thus ocean depth is a major restriction to implementing these devices. This pattern can be identified by observing the line dividing the suitable and not suitable locations in the binary model. The locations shifted from suitable to unsuitable according to their depth.

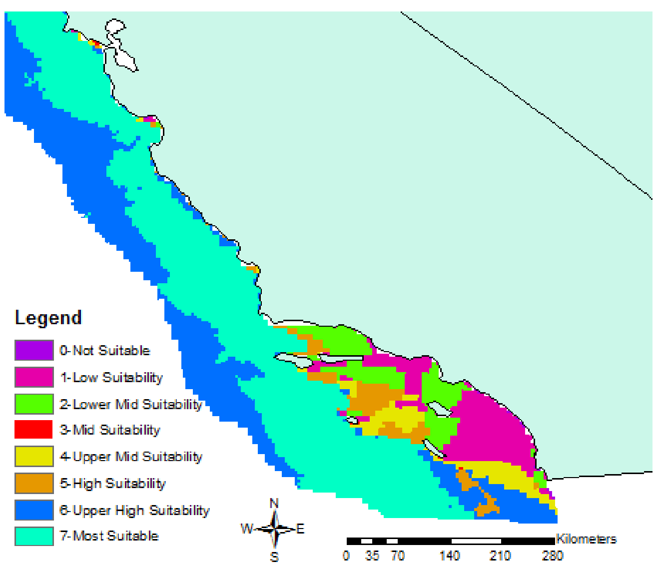

Figure 13. Southern California Wave Energy Converter Suitability Enlarged

In the Southern California region south of Santa Barbra, the suitability scale ranges from low suitability to high suitability, with locations directly off the coast registering as the least suitable of all locations along the California coast. A majority of the unsuitable patterns are clustered around places with low values of wave significant height and wave power density, this due to the weight given to both these data layer sets. The lowest suitability regions are clumped between Ventura and Santa Monica as well as the coast between San Diego and Long Beach. The trend is demonstrated throughout each model illustrating the importance of placing these models in locations with significant wave height in order to reach maximum suitability. When comparing these outputs to my reclassified and weighted overlay models there were parallel results in that suitable locations in the binary, ranked, and weighted models matched those of the reclassified model.

Comparisons to Other Models

When comparing my output models to research from the California Energy Commission there are many similarities and some differences. In their report on California's wave energy resource they classified primary sites as expected to yield optimal energy outputs according to "locations with excellent wave conditions and water depth greater than 50 meters within 10 miles of the coast" (Kane). These primary locations matched my outputs as they ran from the Point of Conception (between Santa Maria and Santa Barbra) north to the Oregon boarder. Their wave patterns also reflected my data with wave energy flux peaking between the months of November and March. A difference in this model is that the region from 35.5° to 38° north latitude (which encompasses the Bay Area) is downgraded to secondary due to the presence of marine sanctuaries (Kane).

In this California Energy Commission study, their secondary locations also match my models. South of the Point of Conception they regard the magnitude of the resource less optimal due to a steep drop in wave significant height and wave energy flux density. The variables in this study slightly differed from mine in that they factored in permitting feasibility, and locations deeper than 50 meters while I factored in and federal and state marine protected areas and depths between 20 and 1000 meters.

In relation to a 2011 Electric Power Research Institute Technical Report my results of wave energy converter distribution also match their predictions. Both studies tested a majority of suitable locations concentrated in northern and central California while little potential for implementation in southern California south of Santa Barbra. Their study indicates potential available wave energy along both the inner and outer shelf of 110 TWh per year in northern California, 333TWh per year in central California and only 55 TWh per year for southern California (Hagerman, 2011).

Distribution of Rotating Turbines

The major factors that must be considered for rotating turbines according to the models are ocean current speed and power. These physical factors played a major role in determining the suitability outcomes. The overall distribution for rotating turbine devices according to the binary model reveals only a few suitable locations off the coast of Northern California. Again since the suitability cut-offs assumed developments for rotating turbines to extract slower speeds, these are the suitable locations for technologies beyond what is available today. The wider suitability ranges in the ranked and weighted models demonstrate a majority of the locations only fulfilling one or two of the tested variables making it difficult to implement on a wide scale. A majority of suitable locations are clustered along a small sliver far off the coast between Mendocino and the Oregon boarder matching with the ranked and weighted models. This long distance to areas of with high ocean current speeds makes it difficult to install these devices and transport the energy to shore. The trend demonstrated throughout each model illustrates the importance of placing these models in locations with strong currents in order to reach maximum suitability.

Comparisons to Other Models

There are many similarities when comparing my output results to other models in the industry such as "Ocean Current Energy Resource Assessment for the United States" from the Center for GIS at Georgia Tech (Yang, 2013). In their study a majority of the ocean current potential is held in the Florida Current while there is relatively low potential for rotating devices off of the California Coast.

Binary ranked and weighted model comparison and utility

While each map incorporates the same parameters, each can be used in a different setting in order to illustrate and analyze the potential geographic distribution of these marine hydrokinetic energy devices.

Binary Model

This general model can be used as a basic guideline to illustrate the potential distribution of these devices without getting too detailed into the parameters used. It is easy to interpret so it is great for advocacy and basic policy pitches highlighting the potential of these devices quickly and concisely. As illustrated in both the wave energy converters and rotating turbine outputs, the distinction between suitable and unsuitable locations is extremely clear and easy to differentiate. One factor that must be considered is that as the number of parameters considered increases, the need for them to all be fulfilled as suitable also increases (because if one is unsuitable then location is deemed unsuitable). These models are detailed enough to follow the patterns of suitability and extrapolate based on knowledge of parameters used.

Ranked Model

The ranked model provides an output more reflective of each parameter without getting as detailed as the weighted model. It is fairly easy to interpret and explain so it can be used to address people outside of the marine hydrokinetic energy industry. This is best suited for more extensive arguments for further funding, continued research and investors who are attentive to the scale and distribution. For the rotating turbines the ranked model was very similar to the weighted due to a lack of suitable locations. Further expanding with a more detailed analysis in this case did not provide any further information therefore the ranked model would be reasonable to present to more advanced scientists. For wave energy converters the ranked model was fairly limited in its detail as illustrated by the difference between the ranked and weighted model for locations in Southern California. The ranked model had a range of suitability outputs of three while the weighted had a range of six.

Weighted Model

The weighted model is the most detailed and extensive model for marine hyrokinetic energy devices as it reflects each parameter with its specific weighted value. Re-weighing the parameters gives the most accurate results as its spreads the suitability scale to include more categories. It must also be considered that the weight assigned to each layer is based upon interpretation so models at the weighted level may differ between studies. Weighted models are good for device developers, engineers and industry managers who value each parameter and layer individually. Extensive distributions can help develop more efficient designs and therefore increase energy output. Weighted models also allow for a detailed suitability output map to be created for one individual layer. As stated above, the weighted map for the rotating devices did not provide too much additional information when compared to the ranked model, but for the wave energy converter output map it was crucial in differentiating the suitability in southern California.

Reclassified and Weighted Overlay Models

This last model I used to compare and test my accuracy between the weighted model and this reclassified model. This model is even more detailed than the weighted model and provides a more extensive suitability scale to examine locations. Similar to the weighted model this model would also be crucial for device developers, engineers and industry managers who can test variations in their device and visualize the potential suitability output.

Potential Composite of Both Wave Energy Converters & Rotating Turbines

Examining a composite of a weighted wave energy converter map and a weighted rotating turbine map demonstrates the overall optimal potential distribution of marine hydrokinetic energy devices. As illustrated, the most suitable locations for potential implementation of either type of ocean energy device are in northern and central California with a majority of locations only suitable for wave energy converters. In general Southern California locations are not suitable for either type of marine hydrokinetic device due to a lack of strong currents and low wave significant height.

Limitations and Future Directions

Sub-Device Variables

While this study incorporated seven variables to interpret the geographic distribution of these devices, there are many other factors that could have been taken into consideration when developing these models. Each specific device construction has a variation in parameters such as the different conditions needed for a buoy device versus a wave surge converter. There is also the potential to extrapolate these variables to provide additional information such as the directional flow along with current speed or sea floor type along with depth. Additional factors include distance to substation, (needed to transform the voltage collected by the hydrokinetic energy devices from either high to low or low to high in order to incorporate it into California's generation, transmission and distribution system), along with peak wave period (highlighting the dominate wave period by taking the inverse of the frequency at a waves highest density and the mean direction of spectral peak energy) to measure the directionality of the waves (Hagerman, 2011).

Comparison to other studies In comparing my variables to other research I found some discrepancies in the measurements of the currents. In examining the Coastal Ocean Currents Monitoring Program (COCMP) and their ocean current data, there are some cases where my data underestimates current speed and power. This may be due to the physical level and season at which the current measurements were quantified. Other studies also examined surface level currents such as those exiting the San Francisco bay. I did not include this data due to a measured current speed too slow to be harvested (the average ranged between .1-.2 m/s), and furthermore the large commercial devices I was examining would not be feasible to place in bay-like conditions as they would obstruct main shipping routes. Additional ocean energy conversion devices that were not included in this study could be considered for future research efforts. This includes Ocean Thermal Energy Conversion, which uses movement of vertical mixing due to ocean heat to run an engine creating electricity. Tidal energy, capturing energy from the rise and fall of shoreline tides, could also be considered for an assessment of ocean energy. Both of these devices expand the capabilities of ocean energy along the coast of California.

Assumptions Made

My models assume all of the devices examined to establish parameters will continue to develop to a point where it would be cost effective (levelized Cost Of Electricity low enough) in order for widespread implementation. While this was a reasonable assumption necessary to set my parameters, the market-based economy may make it difficult to continue to develop projects if funding is not available. To alleviate this obstacle I set parameters according to devices that are currently the most advanced and successful for each particular category. For example the category of rotating turbines has hundreds of companies across the globe investing and developing these technologies. Due to this there are vast numbers of different designs so it is safe to assume that even if one company is not successful there will be others in the market. An example from this study is the use of the Ocean Power Technology Buoy PB3 to set parameters. Even if this specific device is not entirely successful, there will be others in which the results of potential spatial distribution from this research will apply.

An additional limitation is that my models are using the average values of the entire year (for example average wave significant height or average ocean current speed). Many of these measurements vary seasonally with much larger values being measured in the winter and spring months. To prevent the creation of 12 monthly output maps for both devices, each with a binary, ranked and weighted maps (which would sum to a total of 72 maps), I took the yearly average of to create 6 total outputs. Smoothing out the data limits an analysis on seasonal distribution. In general this does not make a significant impact on my study because for ocean data the energy increases are distributed equally across all areas. To confirm this I used the map viewer of the department of energy's Marine and Hydrokinetic energy interactive maps.

Further Challenges

Technical Challenges

With regard to device design more research must be made on creating devices able to withstand the constant pounding of waves, the corrosive nature of salt water, and the concern of marine growth build up. Many management methods used by offshore oilrigs can be employed to help overcome these challenges. Consideration also must be given to the impact these devices will have on shipping routes and recreational zones. An additional consideration is the impacts certain devices will have on energy absorption of surrounding devices. An example of this is the influence an individual isolated buoy can have on incident wave energy flux on each successive surrounding buoy (Hagerman, 2011). Finally more studies must be made on the difference between regular simple harmonic wave motion versus long created irregular waves which must be broken down using Fourier analysis into individual harmonic components (Hagerman, 2011).

Moving forward in the advancement of these devices will require a continued development of increasingly accurate models for distribution and energy output. This will include very specific models to be created for each new device that is created. With models established for each device, policy makers can sum all these individual models together to create a multi-device map. The need for these increasingly accurate models is necessary to receive more public and private funding for future development to get operating and implementation costs down.

Environmental Challenges

Impact of marine hydrokinetic devices on marine ecosystems and species has been researched extensively with an overall consensus of limited effects. Most devices move slow enough to avoid major impacts, "the sensory systems of these animals are good enough to detect and avoid the turbines… the blades themselves would be slow moving and have gaps large enough for most creatures to swim through" (Lewis, 2014). Device developers are factoring environmental impacts as they design these devices by considering species protection measures such as slow moving blades, acoustic detection and possibly sonar breaks, all of which have been implemented by Delta Stream Technology. They also increased the length of the rotors on their turbines in order to slow their movement down to 10 RPMs. In California the most complex habitats are located directly offshore in slow moving water, but since suitability is determined by locations with fast moving water this issue may possibly be avoided. The especially fragile communities often reside in ecological "hot-spots" and are in abundance in Southern California. Again since neither rotating devices nor wave energy converters have high suitability in these locations, they should not provide a threat.

Economic Challenges

Regarding economic and political feasibility there are many factors that must be taken into account. The first would be the need for infrastructure integration as to establishing underwater transmission lines to connect within the grid system increasing the already pricy overhead cost of these devices. Once these devices are in place the cost would be marginal to the consumer in the long term, as you would simply need routine maintenance. One promising component of ocean energy is there are many proposed plans to implement offshore wind energy especially off the coast of Northern California by EDP Renewables along with other large investors such as Google (Malone). Such projects could allow a combination of offshore wind energy and marine hydrokinetic energy to exploit the same energy transfer infrastructure.

Other considerations that must be made for the success of these devices include who should be investing in these projects and who should set regulations. Should federal and state governments help with funding for further development or should private companies maintain control of the development and implementation. If these devices do make it on a wide scale should taxpayers be required to help with maintained costs and continued expansion in return for subsidies for using ocean energy? When attempting to expand in the market should the government intervene to maintain a competitive market between distributors in order to lower the cost of electricity to the consumer or should the government allow an individual company to dominate essentially establishing a monopoly on ocean power. All these factors must be considered as these devices become increasingly advanced and near entry into California's energy market.

Future Directions

Currently there are around 300 marine hydrokinetic energy companies developing marine hydrokinetic energy devices all across the world. The need for modeling potential placement will be ongoing as long as there is continued technological development. This remote method of testing locations prevents the need to spend millions of dollars in physically going to a particular location and testing the devices. This research can be used by utility operators, advocates, devices makers because models help highlight the potential locations where we should push forward in the development and testing of these devices. Currently these devices are much too expensive to construct and deploy so more models must be made in order to reveal to policy makers the potential of these devices are worth the investment. Without models illustrating the potential of these devices, essential funding will be difficult to acquire for further development to get levelized costs down.

The state of our current energy climate as a whole will be improved with the addition of marine hydrokinetic energy. We must continue with the notion that we are partaking in a crucial moment in the history of our planet, and recognize that there are solutions to enact change. We must not simply give into the effects of fossil fuels but rather continue to explore, locate, develop and implement new technological devices, making use of untapped sources of energy yet to be discovered. California, as a leader in renewable energy development with a long coastline, has the potential to incorporate marine energy into its electricity grid through the use of a vast assortment of wave energy converter designs. As wind and solar are fairly variable, ocean energy can fill in the gaps with consistent energy output. This reliability is crucial if we as a society are to have a successful transition away from fossil fuels. When examining geographic distribution of marine hydrokinetic energy in the socio-economic and political sense, the locations with highest energy demand are the ones who will benefit most with the implementation of these devices. With the introduction of marine hydrokinetic energy into our collection of solutions to solve our energy crisis, it appears we may perhaps be taking the necessary step to eliminate the need for fossil fuels in our future. Marine hydrokinetic energy is the future of our renewable energy developments and can ultimately transform the worlds energy systems. With the right support and a recognition of their potential as predictable and consistent forms of renewable energy, marine hydrokinetic devices can be employed as another piece in our renewable energy puzzle.

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ESPM 164 Lab 9: Suitability Analysis & Model Builder (Kelly Easterday)

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APPENDIX A: Figures of Marine Hydrokinetic Devices

Source: Union of Concerned Scientists

Figure 1: Oscillating Water Column

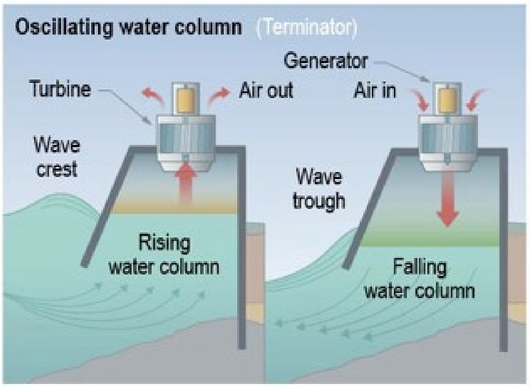


Figure 2: Point Absorber

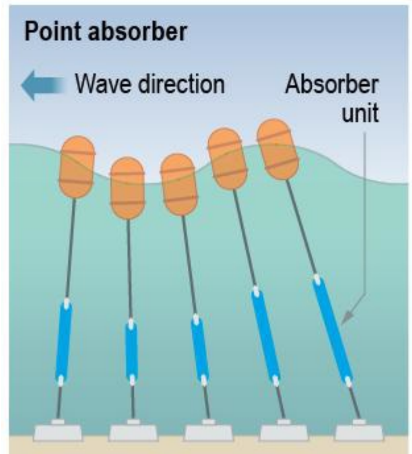


Figure 3: Attenuator

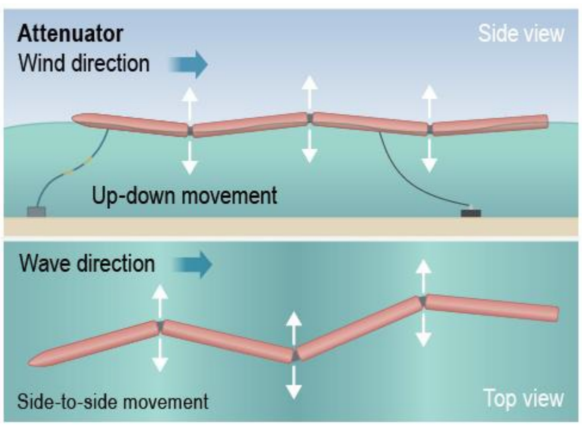


Figure 4: Wave Overtopping Device

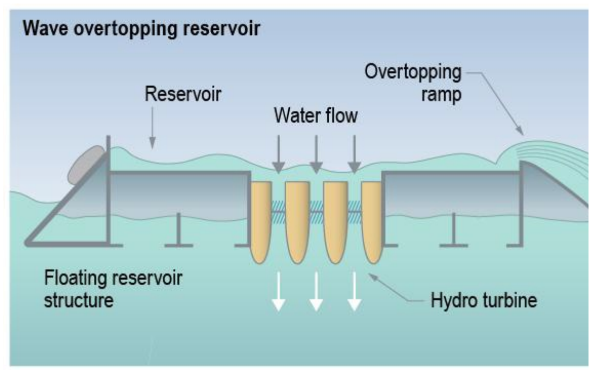


Figure 5: Oscillating Wave Surge Converter

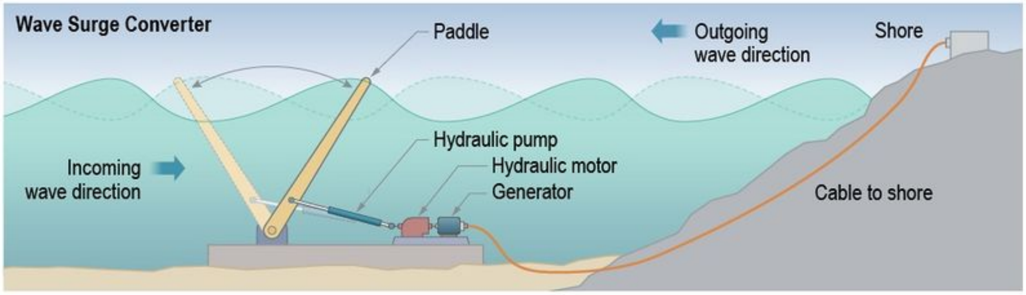
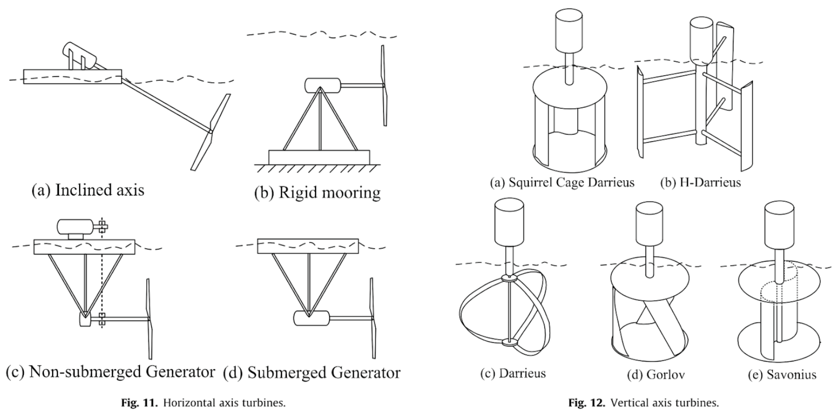


Figure 6: Rotating Turbine Devices (Khan, 2009)



The oscillating water column is a partially submerged apparatus enclosing a column of air and water sitting on the surface of the ocean. As waves enter and exit the bottom there is a change in air pressure, forcing the air in and out of a turbine connected to a generator (Appendix A, Figure 1). The point absorber uses the up and down motion of a floating buoy, which is anchored to the ocean floor, to move magnets up and down inside a coil, generating a current (Appendix A, Figure 2). The attenuator is a design that allows for floating structures parallel to the wave direction, anchored in certain places, to move radially with the rise and fall of the waves at its many "joints", which transfer energy through a hydraulic piston moving a motor connected to a generator (Appendix A, Figure 3). The overtopping device that is placed so that waves break right on top of it creating a reservoir higher than the level of the ocean, allowing gravity to pull the water back down through the hydraulic turbine to its original level (Appendix A, Figure 4). The last wave energy converter is the oscillating wave surge converter, which is simply a flap perpendicular to the wave direction, moving a hydraulic pump as it oscillates (Appendix A, Figure 5).

APPENDIX B: Breakdown of Ocean Depth

Table A. Categorical Breakdown of Depth

1. Depth Zone A: Grid points 0- 19 meters
2. Depth Zone B: Grid points 20 to 49 meters
3. Depth Zone C: Grid Points 50 to 199 meters (station on shelf)
4. Depth Zone D: Grid points 200 to 999 meters (station on shelf)
5. Depth Zone E: Grid points 1000+ meters → deep water station (beyond shelf edge)

Table B. Hindcast Grid Point Breakdown by Region and Depth Zone (Hagerman, 2011)

	Zone A	Zone B	Zone C	Zone D	Zone E	Total
Pacific Northwest	25	84	768	707	1,045	2,629
Central California	5	44	212	414	1,198	1,873
Southern California	15	22	119	733	849	1,738

Appendix C: Raster Calculator Inputs

-Input for binary raster calculator 5 wave energy converters:

"%Depth_C%" * "%Wave_Height_C%" * "%Wave_Dens_C%" * "%Wave_Period_C%"

-Input for binary raster calculator 4 rotating devices:

"%Mean Current Speed_C%" * "%Mean Current Power_C%" * "%Current_Depth_C%"

-Input for ranked raster calculator 6 wave energy converters:

"%Depth_C%" + "%Wave_Height_C%" + "%Wave_Dens_C%" + "%Wave_Period_C%"

-Input for ranked raster calculator 5 rotating devices:

"%Mean Current Speed_C%" + "%Mean Current Power_C%" + "%Current_Depth_C%"

-Input for weighted raster calculator 7 wave energy converters:

"%Depth_C%" + (3* "%Wave_Height_C%") + "%Wave_Dens_C%" + (2* "%Wave_Period_C%")

-Input for weighted raster calculator 6 rotating devices:

(3 * "%Mean Current Speed_C%") + (2 * "%Mean Current Power_C%") + "%Current_Depth_C%"