Site Suitability Analysis for Implementing Tidal Energy Technology in Southern California

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Dedication

Dedicated to my closest friends and family.

Acknowledgements

I would like to extend a special thank you to my closest friends and family. To my oceanography friends: thank you for the kind words of encouragement and constant laughs. To my boyfriend: thank you for being with me every step of the way. Finally, to my parents: thank you for believing in me and providing your constant support.

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Table of Contents

List of Tables

List of Figures

List of Abbreviations

ADCP	Acoustic Doppler Current Profiler
ASBS	Areas of Special Biological Significance
AWEA	American Wind Energy Association
CO-OPS	Center for Operational Oceanographic Products and Services
CSV	Comma-Separated Values
EEZ	Exclusive Economic Zone
EFH	Essential Fish Habitat
EIA	U.S. Energy Information Administration
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
GIS	Geographic Information System
IDW	Inverse Distance Weighted
IPPC	International Panel on Climate Change
IRENA	International Renewable Energy Association
JSON	JavaScript Object Notation
MPA	Marine Protected Area
NAD	North American Datum
NASA	National Aeronautics and Space Administration
NCEI	National Center for Environmental Information
NMS	National Marine Sanctuary
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory

NREA	National Renewable Energy Association
NTSFL	National Tide and Sea Level Facility
OIST	Okinawa Institute of Science and Technology
RBF	Radial Basis Function
ROMS	Regional Ocean Modeling System
TXT	ASCII-Text Formatted Data
UTM	Universal Transverse Mercator
WEC	World Energy Council
XML	Extensible Markup Language

Abstract

Traditional sources of energy are outdated and destructive. There is a clear need for new and more sustainable energy sources, creating a huge market for innovative research and technology within the energy industry. The use of the world's oceans to generate energy is pioneering and provides many enticing benefits including cleaner and more consistent energy generation. Tidal energy converters harness the power of moving water generated by the tides and is a huge source of untapped energy. This study analyzed the parameters most important to successful tidal energy generation in order to determine the most suitable sites for implementing this technology in southern California. Using data from various sources, two different interpolation methods were used to create a continuous raster surface of tidal range values that, along with other variable fields related to tidal energy, were used to perform two different types of analysis, a weighted overlay and fuzzy overlay analysis. The results of these two different analysis methods were compared and this methodology provided a conclusive map showing the most effective sites for successful use of tidal energy converters in southern California. An analysis was also completed to look at the distance of suitable sites to nearby onshore energy facilities. This research builds upon previous renewable energy studies in southern California and provides insight into how the region can reduce its fossil fuel emissions and convert to cleaner, more sustainable energy sources.

Chapter 1 Introduction

This study sought to determine suitable sites for the implementation of tidal energy technology off the southern coast of California. Tidal energy converters use new technology to harness usable energy from the water motion and currents produced by the tides. This form of renewable energy has many benefits not seen in traditional renewables such as wind and solar and is much cleaner and better for the environment than current fossil fuel sources. This study uses GIS to look at different parameters that influence the success of tidal energy converters such as tidal range, strength of tidal currents, and seafloor bathymetry. Classifying these variables and then performing a weighted analysis provides a detailed map showing the most suitable sites for implementing tidal energy technology in southern California.

1.1. Climate Change

One of the largest problems the planet currently faces is the issue of climate change. Over the period between 2006 and 2015, there was an increase in the global mean surface temperature of approximately one degree Celsius, which can likely be attributed to human activity (IPCC 2018). Certain areas of the Earth such as the Arctic, and areas covering large amounts of land have seen warming at even higher rates than the global average (IPCC 2018). The effects that can be seen on the planet due to rising temperature are very serious. One of the main effects of global temperatures increasing is sea level rise. Warmer temperatures cause thermal expansion of water molecules, and also lead to melting of glaciers and ice sheets (Nuccitelli 2018). These phenomena play a significant role in raising the sea level, with estimates that there could be an increase of up to five feet by the year 2100 (Nuccitelli 2018). The effects of sea level rise include flooding, coastal erosion, and habitat destruction, all of which are costly and dangerous (Nicholls

2011). Another destructive effect of global temperatures rising is the slow-down of global ocean circulation. Thermohaline circulation plays a large role in global ocean circulation and includes the mass flux of seawater that is caused by differences in density, mostly due to the heating and cooling of water. After water is moved to the poles by wind-driven surface currents, it is cooled at the high latitudes. Cooler water molecules are denser than warmer water molecules, which causes the cold-water particles to sink, driving large-scale circulation (Wunsch 2002). When global temperatures rise, the differences in ocean water at the equator and high latitudes decreases, which leads to a decrease in the velocity of the global ocean circulation (NOAA 2019b).

1.2. The Use of Fossil Fuels

Rising global temperatures have been attributed to human activity, mostly due to the emissions generated from using fossil fuels. Fossil fuels are considered to be any source of fuel such as coal, oil, or natural gas that are formed from natural processes such as anaerobic decomposition of ancient dead organisms. Greenhouse gasses are the resulting by-product of burning these fossil fuels and are considered to be one of the largest contributors to global climate change. Greenhouse gasses work by trapping heat in the Earth’s atmosphere, which contributes to the warming of our planet (EPA 2019). The global warming trend, which has been observed by many scientists, has already begun to affect our climate by increasing temperatures. This, in turn, causes phenomena such as melting glaciers, warming oceans, and more extreme weather (NASA 2019a). In 2017, the United States totaled 6,456.7 million metric tons of emissions from carbon dioxide equivalents that stem from the use of fossil fuels.

Most of the electricity generated in the United States comes from fossil fuels. A report provided by the U.S. Energy Information Administration (EIA 2019a) found that 62.9% of electricity in the United States comes from these sources. The same study found that natural gas provided the largest source of energy within the fossil fuel category, with coal and petroleum not far behind (EIA 2019a). The report also mentioned the use of renewable energy, which found that approximately 17% of energy in the U.S. came from renewable sources, mainly hydropower plants.

1.3. Renewable Energy

Renewable energy is a more sustainable and clean solution for the generation of electricity and includes energy that comes from sources that are naturally replenished on human timescales. This includes phenomena such as wind, sunlight, tides and waves, or geothermal heat. Renewable energy research and implementation has made much progress in recent years as more information about the negative effects of traditional energy sources has become available. A study conducted by the National Renewable Energy Laboratory found that renewable energy generation from today's technologies and a few emerging technologies could adequately supply 80% of the U.S.'s energy needs by 2050 (NREL 2019). This would reduce greenhouse gas emissions from electricity by almost 81%, which would help to reduce harmful emissions.

One of the most common forms of renewable energy comes from the wind. Wind turbines are rotated by naturally occurring winds in the Earth's atmosphere, which is converted into mechanical energy that can be used for a variety of applications (AWEA 2019). In 2016, wind energy accounted for 8% of the operating electric energy capacity of the United States, which was more than any other renewable energy source (EIA 2019c). While not as economically competitive as other traditional sources of energy, wind energy is one of the lowest cost sources of renewable energy at approximately 2 to 6 cents per kilowatt-hour (U.S. Department of Energy 2019a). One of the main disadvantages of wind energy is that the suitable locations for implementing the technology are often far from areas that would benefit from the energy production, such as large cities or residential neighborhoods. Another disadvantage is that wind is not a constant phenomenon. Because of this, traditional energy sources must be kept in place for reserve power when there is not an abundance of wind (OIST 2016). This practice is costly and contradicts the positive aspects of using wind as a renewable energy source.

The second most common form of renewable energy comes from the sun. Solar photovoltaic devices convert direct sunlight into mechanical energy that can be used to power different applications (EIA 2019a). Solar power has become more accessible and affordable in recent years, with prices for installing commercial solar panels dropping by nearly 50% since 2014 (U.S. Department of Energy 2019b). A report by the National Renewable Energy Laboratory found that solar represented 22% of new electric generation capacity for the U.S. in 2018, with the state of California generating 19% of their energy from solar power (Feldman and Margolis 2019). Similar to wind power, solar power has its drawbacks. Solar radiation is not always constant and can produce varying levels of energy depending on the amount of cloud cover, the location, or the season (EIA 2019a), all of which contribute to the amount of energy that can be produced.

1.4. Hydrokinetic Energy

A newer from of renewable energy that has recently become more prevalent comes from the ocean. Hydrokinetic energy encompasses a wide range of technologies that are able to harness and convert energy from the ocean, whether it be through the oscillating motion of waves, the flow of water through tidal currents and streams, or by thermal and osmotic processes (Esteban and Leary 2012). The theoretical potential energy generation from the ocean is estimated to be between 20,000 and 90,000 terawatt-hours per year, although it is unlikely that any one technology will be able to extract the full potential (Soerensen and Weinstein 2008). There are many types of technology that utilize processes from the ocean to generate energy, with waves and tides being the most effective.

The greatest potential for harnessing renewable energy from ocean waves is located where the surface winds are the strongest, which occurs between the latitudes of 40 and 60 degrees north and south of the equator, and on the eastern boundaries of oceans (Pelc and Fujita 2002). According to the World Energy Council, wave energy has the potential to provide two or more terawatts of electricity, which is approximately one fifth of the world energy demand (WEC 1993).

The main attraction of harnessing and converting energy from tidal systems versus wave systems is predictability. Waves in the ocean are controlled by a variety of external factors such as wind and seafloor bathymetry, which make them unpredictable and difficult to forecast. Tides, on the other hand, are controlled by the consistent gravitational pull of the moon and sun, which can be predicted with high accuracy years into the future. Because of the standard factors controlling the tides, the flow of water from which energy is harnessed is forever in motion. This allows for consistent harnessing of power that can be directly sold as firm power to an energy grid, reducing the need for reserve power sources (Bedard et al. 2007). The potential of implementing tidal energy is immense, hence the importance of continued exploration into the development and use of this technology.

1.5. Thesis Structure

The following sections of this document provide a comprehensive review of related literature, the methodology used in this analysis, and the results of the suitability analysis. The literature review includes relevant information regarding renewable energy technologies, the use of GIS in site suitability analyses, and how GIS is used in relation to tidal energy technology. The methods section reviews the data manipulation and editing required for this analysis, as well as the workflow used to perform two different kinds of overlays. The results section is followed by a discussion of the results and their implications. This document concludes with an analysis of the project and how it may be applied to future work.

Chapter 2 Related Work

To harness the full potential of tidal energy through appropriate site-suitability analysis, it is important to understand: (1) the processes through which tidal energy is generated and how it is utilized; and (2) the methodologies and results from similar studies looking to find sites that are most appropriate for wave energy. The following review investigates research reports, academic articles, and technical documents regarding tides, tidal energy technology, and site suitability analyses of tidal energy in various locations conducted to date.

2.1. Ocean Energy

Ocean energy sources are increasingly becoming a part of the global renewable energy mix. There are many types of technology that utilize processes from the ocean to generate energy, with wave and tidal energy being the most effective. Ocean energy, alternatively called hydrokinetic energy, encompasses a wide range of technologies that harness and convert energy from the ocean, through the oscillating motion of waves, the flow of water through tidal currents and streams, and thermal and osmotic processes (Esteban and Leary 2012). Theoretically, the potential energy generation from the ocean could be between 20,000 and 90,000 terawatt-hours per year, although it is unlikely that any one technology will be able to extract the maximum amount possible (Soerensen and Weinstein 2008). Hydrokinetic energy will become an increasingly important part of our energy future.

2.1.1. Wave Energy

Wave energy is the potential and kinetic energy harnessed from ocean waves that is combined and then converted into electricity using wave energy converter (WEC) technologies (Williams 2018). Over the last decade, the development of commercial wave farms has been slow when compared to solar and wind farms. This is attributable to technological, financial, and environmental concerns. Compared to other parts of the world, especially Europe, WEC technology is still not widely recognized in North America as an alternative source of renewable energy (Beyene and Wilson 2014). A lack of funding and little research support has kept the estimated cost of installation and operation relatively high, which has kept interest in WECs very low. Additionally, research on the environmental impacts of installing WECs is scarce, but initial findings point to potential changes in sediment transport due to a change in wave hydrodynamics, the creation of artificial habitats, and a change in migration routes for marine mammals (Beyene and Wilson 2014).

The greatest potential for harnessing renewable energy from ocean waves is located where the surface winds are the strongest, which occurs between the latitudes of 40 and 60 degrees north and south of the equator, and on the eastern boundaries of oceans (Pelc and Fujita 2002).

There are many different approaches to capturing wave energy in various stages of development and deployment. WECs utilize the motion of surface ocean waves either at the surface or at some depth in the water column. There are three different types of wave energy converters (Rusu and Onea 2017). The first are point absorbers, which generate energy through the vertical displacement of the device as it rises and falls with the passing waves. It is the smallest WEC type and can capture wave power from any direction. The second are attenuators, which are larger devices oriented parallel to the direction of wave travel that generate energy as the wave passes along the length of the device. Lastly, the third option, a terminator is similar to an attenuator but is positioned lengthwise facing the direction of the wave, generating energy as each wave crashes into the device.

Theoretically, the wave energy potential on the west coast of the United States is more than twice the wave energy potential of the east coast (Lehmann et al. 2017). The Electric Power Research Institute (EPRI) reports the total available wave energy along the inner shelf of California is 205 TWh/yr and the Pacific Gas and Electric Company (PG&E) reports that the total energy consumption of California in 2005 was 272 TWh (Lehmann et al. 2017). Clearly wave energy has the potential to generate large amounts of usable energy, but it is also limited by various factors as discussed above.

2.1.2. Wave energy compared to tidal energy

Wave and tidal energy are two types of hydrokinetic energy, which are sometimes confused with one another. The main difference is their requirements with respect to their installation location, and both have benefits and drawbacks. Both types of hydrokinetic energy show strong potential, but the focus of this study is tidal energy, which is relatively less researched. However, since they contain many of the same criteria for determining site suitability, a comparison of their characteristics and strengths and weaknesses is offered below.

With respect to wave energy potential, wave height is dependent on the strength of the winds and seafloor bathymetry. Surface winds can only be predicted a few days in advance and vary in strength. This poses challenges for wave energy, insofar as predicting strong waves well in advance is challenging. Conversely, tides are dependent on the constant gravitational forces of the sun and moon, which provide a continuous movement of water. This translates to constant energy production that can be predicted years in advance.

Another limiting factor of wave energy converters are their physical locations. Most wave energy converters operate at the surface of the ocean, making them susceptible to any surface traffic from boats and other recreational activities. This reduces the areas in which wave energy converters can be implemented, which negatively impacts their potential energy production. Williams (2018) identified five locations for the implementation of wave energy farms in southern California. These locations were generally far offshore, in areas where wave power density was high. Tidal energy converters generally operate below the sea surface and are anchored to the seafloor. This allows them to avoid any disruptions that may be caused at the surface and also avoids the visual disruption that might occur. The differences in geography allow for both tidal and wave energy technology to be operational in their own regions without any overlap between the two.

2.2. Tides

Siting tidal energy turbines correctly is contingent on a detailed understanding of the tides. Ocean tides are directly related to the gravitational pull of the Moon and Sun on the Earth (NOAA 2019d). The gravitational forces create a "bulge" of water on the sides of the Earth nearest and farthest from the Moon, which causes the differences in sea level associated with the tides (NOAA 2019d). Tidal cycles vary by geographic location. One tidal cycle takes approximately 24 hours and 50 minutes, with high tides occurring 12 hours and 25 minutes apart. Diurnal cycles refer to a pattern of one high and one low tide per cycle, while semi-diurnal tidal cycles produce two highs and two low tides per cycle. Mixed semi-diurnal tidal cycles, which are prominent on the west coast of the United States, produce two high and two low tides per day that differ in their height (NOAA 2019d). Choosing the appropriate type of tidal energy technology and identifying the proper location must take these tidal patterns into account on a location-specific basis.

The magnitude of the tidal range determines how much energy can be generated from the tides. Tidal range refers to the difference in height between high and low tides. The height of the tides is dependent on the locations of the Sun, Moon, and Earth, and differs throughout the lunar cycle. Spring tides occur when the largest difference between high and low tide is observed, usually occurring after a full moon when the Sun, Earth, and Moon are aligned. Neap tides occur when the smallest differences between high and low tide are observed, which is usually in the first or third quarter of the lunar cycle when the Sun, Earth, and Moon form a right angle (NTSLF 2019). Other factors that dictate the height and extent of the tides include areas with large continental margins, which magnify the tides, while narrow inlets and bays can also exaggerate the tidal height (NOAA 2019d). Wind and weather patterns associated with different climates can also magnify or reduce the magnitude of the tides. Figure 1 shows the tidal energy across the globe, highlighting the differences in tides at different latitudes and longitudes. Any sitting of tidal energy turbines must optimize the tidal trends in a particular area over time. The suitability of tidal energy technologies such as tidal turbines will be heavily influenced by the magnitude of the tides, as larger tidal ranges will produce a greater volume and flow of water that can be optimized by the tidal energy converters.

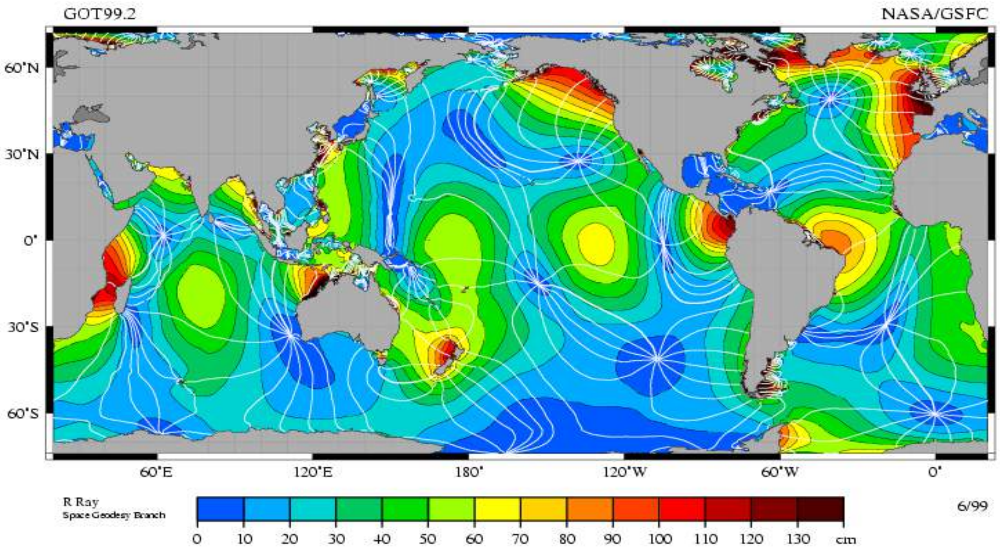


Figure 1. Map showing the tidal energy around the world calculated from the TOPEX/Poseidon satellites. Red colors indicate the strongest tides, while blue indicates the smaller tides (NASA 2019b)

Southern California has a semi-diurnal tidal cycle, meaning that there are two high tides and two low tides per day, each at differing heights. The tidal range between the lowest low tide and highest high tide is between approximately 1 and 2 meters. The tidal range has increased over the last century, which is consistent with mean sea level rise (Flick et al. 2003), indicating that the tidal range in southern California has the potential to increase in magnitude in the future which would be beneficial to tidal energy technologies. Southern California has varying tidal ranges that are heavily influenced by geography, insofar as they follow a pattern of increasing magnitude as the geographic location moves south, and also show large magnitudes in areas where the topography is more enclosed.

2.2.1. Tidal Currents

Tidal currents affect the suitable locations for tidal energy turbines depending on how strong the flow of water is at a specific site. Tidal currents occur with the rise and fall of the tides, which results in a sub-surface flow of water (NOAA 2019a). When the tides are rising and moving towards the shore, the resulting current has a net flow towards land and is considered to be “flooding”. When the tides recede and move back towards the ocean, the resulting current has a net flow towards the ocean and is considered to be “ebbing” (NOAA 2019a). Tidal currents vary in strength depending on the relationship between the Sun, Moon, and Earth. During neap tides, tidal currents are weaker and during spring tides tidal currents are stronger. In a standing wave model, slack water will occur at the same time as the high and low tides, with the maximum flood and ebb currents occurring between the high and low tides. In a progressive wave system, which characterizes most coastal areas, the tidal current will be strongest at the high and low tides with little or no current occurring between the two extremes (NOAA 2019a). The relationship between tides and tidal currents is unique to every location on Earth, so while the two can be measured and derived using similar methods, they are most often calculated separately to account for any differences in physical environment. With respect to southern California specifically, tidal currents off of the coast are relatively slow with an average velocity of 0.1 to 0.5 meters per second. These tidal currents are barotropic, meaning the flow travels in the same direction throughout the water column. This type of flow is beneficial for tidal turbines because it allows for the full capture of water flow, which can result in higher energy capture.

Due to the velocity of water flow they create, tidal currents are important for tidal energy technologies such as tidal turbines. Tidal currents are the source of water movement, which turns the arms of the turbine. Faster tidal currents will spin the tidal turbines quicker, which will result in higher energy production. Since tidal currents move both towards and away from the shore, they can move tidal turbines in both directions meaning a greater potential for energy production. The implications of slower tidal currents in southern California indicate less suitability for tidal turbines, but there is still potential for these technologies in the region.

2.2.2. NOAA Tidal Data Collection

This study used data from the National Oceanic and Atmospheric Administration (NOAA). NOAA is the leading producer of oceanographic data and sets many of the standards used for collecting tidal data. The Center for Operational Oceanographic Products and Services (CO-OPS) at NOAA operates a network of buoys and water level stations across the United States that are used by NOAA to create accurate tidal predictions. There are over 3,000 locations where tidal information is collected, with 27 stations located within the study site in Southern California. Each station is designated as harmonic or subordinate, meaning the station predicts tidal levels using either a harmonic constant that physically measures the tide (harmonic) or a mathematical prediction based on a separate harmonic constant (subordinate). Each station produces a chart containing the times and heights of the two high and two low tides per day.

This free data set includes a variety of metadata. Variables include date, day of the week, time, predicted height, and high or low tide. To use these data, a date range must be specified in addition to the units for each parameter. The data can be downloaded in 30-day increments. The website also includes options for historical data, which can be downloaded at larger temporal scales. Export options include XML, TXT, JSON, or CSV format. This data set is not only comprehensive, but also well vetted and easily imported into ArcGIS. The National Ocean Survey, a component of NOAA and the U.S. Department of Commerce, maintains a continuous control network of approximately 140 tide gauges which are located along the coasts and within the major embayments of the United States, ensuring the accuracy of CO-OPS tidal data (NOAA 2019c).

NOAA also produces tidal current predictions for a number of locations in the United States including sites in southern California (Figure 2). This information is calculated from the CO-OPS stations and is available for download. The data shows the ebb and flow tidal current speeds over a weeklong period for each location.

Additionally, NOAA and CO-OPS host a GIS data portal. The CO-OPS Station map service includes current and historical spatial data, which includes most of the products and data produced by the CO-OPS program. This information can be easily accessed in ArcGIS JavaScript, ArcMap, and ArcGIS Online. This simplified the data importing process in ArcGIS while working on this project.

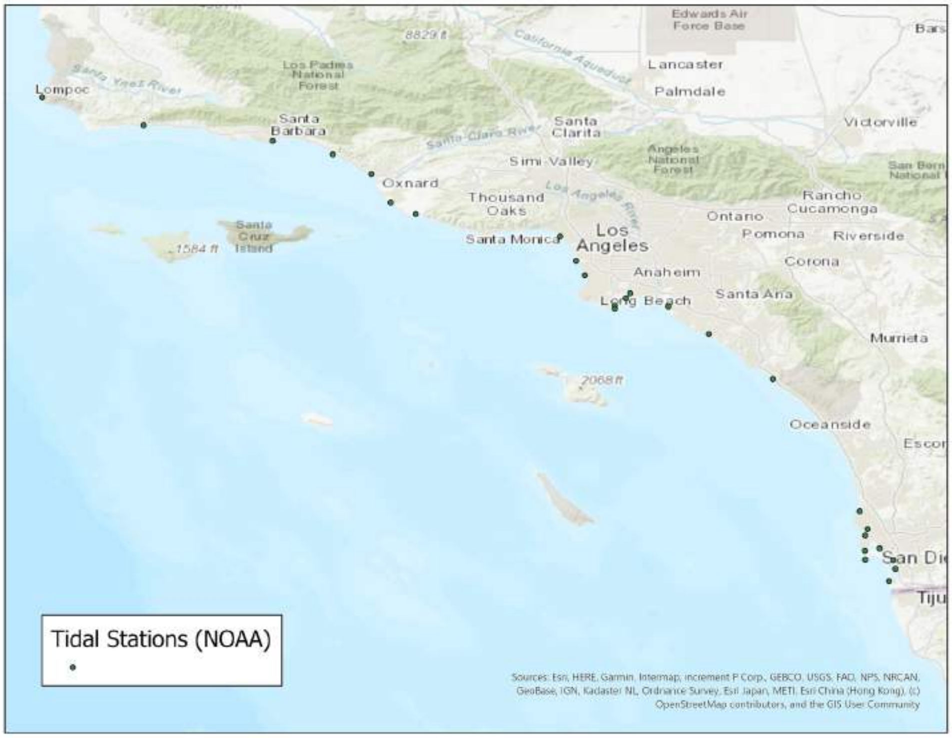


Figure 2. Map depicting the tidal stations derived from CO-OPS used in this study.

2.3. Tidal Energy Technology

Tidal energy has evolved significantly over the last 20 years, increasing its potential for it to be a core part of the alternative energy portfolio. Currently, there are two main technologies used to harness and convert tidal energy, each of which has applicability in different scenarios. The first, tidal range technology, uses barriers or dams to generate power from the height difference between high and low tides. Tidal turbines are installed in the barrier, which rotate and generate power when water flows through them during the ebb and flow tides (IRENA 2014). Currently, the largest tidal barrage system is located in South Korea at the Sihwa Lake Tidal Power Station, which generates up to 255 megawatts of electricity (EIA 2019b). The drawbacks of implementing tidal barrage systems is that they create barriers for natural migration of marine wildlife and increase sediment deposits which is detrimental to many organic processes (Uihlein and Magagna 2016). There are certain areas where a tidal barrage system may function efficiently in southern California, such as at entrances to bays or at river mouths, but because of the drawbacks mentioned above, and the many protected areas on the southern California coast, tidal barrage systems were not considered for this study.

The second type of technology is called tidal stream or tidal current technology. This technology utilizes turbines similar to wind turbines that are moved by the currents that result from tides. The flow of water rotates the arms of the turbine, which turns kinetic energy into mechanical energy that can be harvested and used (IRENA 2014). Tidal turbines are more expensive to develop due to the harsh nature of the ocean but cause less damage to the ecology and potentially have higher energy outputs (EIA 2019b). Tidal turbines also have higher power densities that allow them to produce higher energy outputs while maintaining a smaller size (Roberts et al. 2016), which in comparison to wind turbines makes them much more efficient.

Tidal turbines are an ideal candidate for further study in southern California. In addition to expansive miles of coastline in which these turbines can operate, the bathymetry and tidal range prove ideal for tidal turbines. Tidal turbines are very similar to wind turbines, which are common in southern California. The existing wind energy grids in the region can be used as a foundation for implementing tidal turbines. Additionally, California has strong environmental regulations, so tidal turbines are ideal due to their reduced environmental impact. Due to their efficiency and minimal environmental impact, tidal turbines were the focus of this study.

The connection between wind and tidal energy may not be readily apparent, but they work in conjunction. A critical aspect of the success of tidal technologies is their ability to be integrated into the energy grid. Tidal energy technologies can build upon previous work on wind turbines as they contain similar mechanisms. Further, the integration strategies can be easily transferred to the newer technologies (Blavette et al. 2011). The existing wind energy grids in the southern California region can be used as a foundation for the implementing tidal turbines and their resulting energy grids.

Chapter 3 Design and Methods

The goal of this study was to identify suitable areas off of the coast of southern California for implementing tidal energy technology. Southern California was selected because of the potential for tidal energy development, the state's interest in renewable energy, and the large expanse of coastline available for installation. The northern end of the study area was Point Conception, California (34.447490, -120.471715) and the southern boundary was the California-Mexico border (32.534425, -117.122903). Between the northern and southern points, a 2,000 m buffer from the coastline constituted the study area. The methodology included data classification, weighted overlay analysis, fuzzy overlay analysis, and distance analysis.

3.1. Methodologies Used to Assess Site Suitability

Multiple studies have explored the suitability of various sites for harvesting tidal and wave energy. In South Carolina, physical data observation was used with 3-D modeling to perform a site assessment for tidal stream energy (Work et al. 2012). The authors used the Regional Ocean Modeling System (ROMS) to numerically simulate tidal flows, but also took physical measurements of tidal velocities using Acoustic Doppler Current Profilers (ADCPs). Using both the simulated and the physical data allowed the authors to validate the data model. This study demonstrates the use of multiple data sources to assess tidal energy technology potential. While this study focused on one specific location, the methodologies could be expanded to larger spatial areas.

Defne et al. (2011) examined the potential of tidal stream power in Georgia using a GIS-based multi-criteria assessment. The authors gathered geospatial data that was categorized into three layers: the physical realization layer, the environmental constraints layer, and the socioeconomic constraints layer. Breaking up the data into these three categories allowed for the separation of parameters into like categories, which aided in identifying suitable areas. This study selected areas based upon the three categorical layers but did not utilize overlay techniques. The methods used in the Georgia study were modified for this study namely through the categorization of data into a physical layer, an environmental layer, and a socioeconomic layer.

The issue of locating alternative energy facilities, specifically in the marine environment, has been addressed in studies. Williams (2018), for example, conducted a site suitability analysis for wave energy farms off the coast of southern California. The study identified five different sites that were suitable for wave energy farms based on the natural environment, government and legal constraints, and cost effectiveness. The methodology considered Marine Protected Areas, military zones, and wave power density, and used a weighted overlay analysis to delineate five areas in which wave energy could be harvested. This study showed that hydrokinetic energy is well suited to many locations in California. Using a very similar methodology to Williams (2018), this study utilizes similar approaches to data management and data type but applies it to tidal energy. Many of the same parameters are utilized but modified to better represent the specific requirements of tidal energy technology.

Another study that was conducted in Greece used multi-criteria decision-making methods as well as GIS to locate suitable marine areas for the deployment of Hybrid Offshore Wind and Wave Energy Systems (Vasileiou et al., 2017). The authors of this study developed a GIS database that produced thematic maps representing exclusion criteria based on economic, technical and social constraints. They next used these maps to analyze eligible marine areas not satisfying exclusion criteria and ranked them using a hierarchy process developed from the evaluation of criteria related to economic, technical and socio-political factors. The use of GIS to create databases relating different factors that impact wind and wave energy systems in a marine environment was beneficial in creating spatial representations of suitable areas that could support these technologies.

Each of the studies reviewed here contributed to a better understanding of the siting of energy technologies. However, none of them have applied geospatial technologies to the siting of tidal energy turbines in Southern California. This study provides an initial attempt to address this research question.

3.2. Data

The data were broken up into three categories: physical, government regulation, and commercial use. Each category consisted of various datasets that were derived from different sources and had different spatial resolutions. The data were manipulated so that each dataset had the same spatial extent and scale and the classification and subsequent overlay analyses would be accurate. For this analysis, each dataset was projected, edited, and formatted using the North American Datum of 1983 and Universal Transverse Mercator (UTM) Zone 11. The data was also set to a uniform cell size of 100 m.

Once all of the data had been classified and set to the correct spatial extents, it was further categorized into hard and soft criteria. Mierzwiak and Calka (2017) outlined the use of multi-criteria analysis to assess solar farm location suitability. The use of hard and soft criteria was implemented to define areas that strictly met or did not meet the criteria (hard) or to define areas that had varying levels of suitability based on specific criteria (soft). Applying this logic to the data related to tidal energy technology allowed for further classification of the data resulting in a better suitability analysis.

3.2.1. Physical Data

To define the study area, national shoreline data for the California region were downloaded from the NOAA National Shoreline Data Explorer. These data were collected by the National Geodetic Survey. Shoreline data was imported into ArcGIS Pro and clipped to the extent of the study area running from the California-Mexico border north to Point Conception. A 2,000 m buffer was then applied to the clipped shoreline polygon to create a new polygon consisting of the study area. Then, a land feature polygon dataset from the U.S. Census Bureau was used to clip and eliminate all land areas. Table 1 lists the different data sources.

Table 1. Data used in this study to define the study area.

Data	**Source**	**Year**	**Spatial Reference Information**	**Description**
National Shoreline	NOAA / National Geodetic Survey, 2011	2011	NAD 1983	Vector, line data mapping the national shoreline.
U.S. Country Boundary	Esri, Living Atlas	2018	WGS 1984	Vector, Polygon data defining USA country boundary.

Physical data for this analysis consisted of tidal range and bathymetry data. Tidal range quantifies the extent of high and low tides within the study area and is the most relevant parameter to tidal energy technology as the flow of water produced by the tides is what powers the technology. NOAA’s CO-OPS produces an interactive data map containing every tidal station in the United States. For each station within the study area, annual prediction tide tables for a two-year period between January 1st, 2018 and December 31st, 2019 were downloaded as a TXT file. As mentioned in Chapter 2, tidal range does not change much over small time scales, so a two-year data duration was deemed appropriate. Once the data were downloaded, each station's file was imported into Excel. A simple formula was used to calculate the distance in meters between each high and low tide (high tide minus low tide) during the two-year period. The calculated distances were then averaged to obtain the average tidal range for the two-year period. This methodology was applied to each of the 27 stations. The average tidal range calculations were compiled into a spreadsheet containing the station name, latitude and longitude coordinates, and the average tidal range of each station. This Excel spreadsheet was imported into ArcGIS Pro as XY point data.

3.2.2. Interpolation of Tidal Range

Using ArcGIS Pro and NOAA's tidal range data set, interpolation was used to create a continuous surface depicting tidal range within the study area. Data was taken from tidal stations, averaged, and then interpolated to create a continuous surface. There are different types of interpolation methods that are available in ArcGIS Pro. Each method type has different qualities and provides different information.

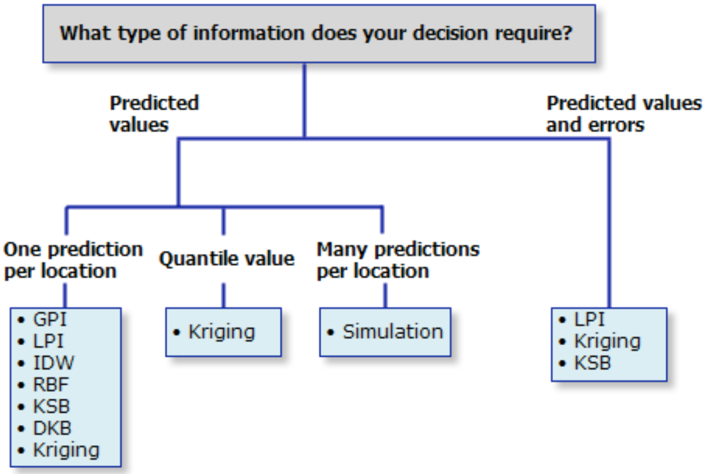


Figure 3. Classification tree provided by ArcGIS Pro to help determine which type of interpolation method to use. Esri (2020a).

It was decided that to create a surface of tidal range data, an interpolation method that provides one prediction per location would be necessary. The Inverse Distance Weighted (IDW) and Radial Basis Function (RBF) methods were selected as the most appropriate interpolation types. RBFs are used to produce smooth surfaces from a large number of data points. The functions produce good results for gently varying surfaces and pass through the original data points making it an exact interpolator (Esri 2020d). IDW is also an exact interpolator and uses the measured values surrounding the prediction location to predict a value for any unmeasured location (Esri 2020c). The measured values closest to the prediction location have more influence on the predicted value than those farther away. The IDW method is prone to clustering but is a simple method for predicting values. Both of these interpolation methods are suitable for producing a raster dataset containing a surface of tidal range values and are used in the analysis.

To create a raster dataset of tidal range values, two different interpolations were used. First, an IDW interpolation was performed using the tidal range point data. This method was chosen because it uses the proximity of surrounding values to predict a new location's value, which seemed appropriate for this type of data. For the interpolation, the input point features constituted the tidal range data, the Z value field was set to 'average', which was the average tidal range of each station, and then the remainder of the parameters were kept as default values to ensure a classic IDW interpolation. The extent of the interpolation matched the study area polygon. To further clip the interpolated data to the study area, and to eliminate any "no data" cells, the "extract by mask" tool was used with the study area polygon as the mask.

An RBF interpolation was also performed to create a different raster surface of tidal range data. As mentioned in Chapter 2, the IDW interpolation does have limitations on data that is clustered, so another interpolation method was used to see how the results would change. An empty raster dataset was created to house the RBF interpolation. The Radial Basis Function tool in ArcGIS was used with the tidal range data as the input feature, the Z value set to ‘average’, and the output raster set as the empty raster. The extent and snap rasters were set to the IDW raster and default values were used for the remainder of the parameters. The multi-quadratic radial basis function was selected because it could predict values that may be higher or lower than the original data’s maximum and minimum value in the source dataset. This allowed for a greater field of values to be estimated and for a smoother surface to be created. To further clip the interpolated data to the study area, and to eliminate any no data cells, the “extract by mask” tool was used with the study area polygon as the mask.

The two tidal range rasters were classified into 5 different classes based on their suitability for tidal energy technology. Using the reclassify tool, natural breaks were used to separate the data into 5 sections of tidal range, and then a value of ‘1’ was assigned to the smallest tidal range class and a value of ‘5’ was assigned to the largest tidal range class.

Another piece of physical data needed for this analysis was bathymetry. Bathymetry refers to the measurement of the depth of the ocean relative to sea level. Data were downloaded from NOAA’s National Center for Environmental Information (NCEI) coastal relief model. This model combines bathymetry with land topography to provide detailed measurements along the coast. Data can only be extracted at certain maximum extents, so four custom grids were downloaded as GeoTIFF files with a resolution of 1 arc-second encompassing the study area. The four GeoTIFF files were imported into ArcGIS Pro and then the mosaic tool was used to combine the data into one continuous raster. This raster used the same NAD 1983 datum and UTM Zone 11 projection as the other rasters in this study, the pixel type was set to 16-bit signed to account for negative bathymetry values, and the minimum mosaic operator type was adopted.

The new mosaic raster was then clipped using the extract by mask tool with the study area polygon as the mask and the IDW tidal range raster as the extent and snap raster parameters.

For the bathymetry data, the reclassify tool was used to divide the data into three classes. The ideal class range was set to a range of -50 to -15, accounting for the water depth in which tidal energy technology can be installed. This range was chosen based on the pre-feasibility assessment of tidal energy systems performed by Khare et al. (2019). The ranges accompanying either side of the ideal range were broken into two classes, one being -322 to -51 and the other being -14 to +435. These ranges encompassed the entirety of the bathymetry data. The ideal bathymetry range was given a classification of '1' while the two less than ideal ranges were given a classification of '0' so that the ideal bathymetry values could be easily identified and be applied in the suitability analysis. Figure 4 illustrates the workflow used in manipulating the bathymetry and tidal range data while Table 2 highlights the data properties.

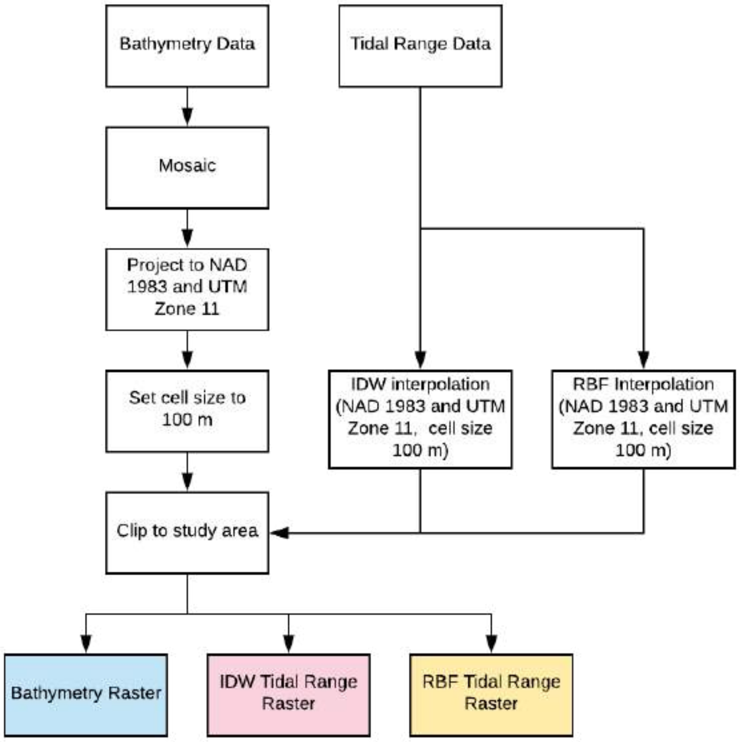


Figure 4. Flowchart depicting the data organization for the physical datasets.

Table 2. Data used in this study relating to the physical limitations of tidal energy technology.

Physical Data	Source	Year	Datum	Description
Tidal Range	NOAA / Center for Operational Oceanographic Products and Services, 2018 - 2019	2018-2019	WGS 1984	Vector, Point data consisting of tidal stations. Each station has an average tidal range measurement.
Bathymetry	NOAA / National Center for Environmental Information, 2003	2003	WGS 1984, 1 arc-second	Raster, Coastal relief model combining bathymetry and topography. Southern California region was used.

3.2.3. Government Regulation Data

Building upon work by Williams (2018), government regulation data were processed and edited so that it had the correct spatial scale and extent, by projecting the data to the NAD 1983 datum and UTM Zone 11 projection and clipping it to the study area. The government regulation data included Marine Protected Areas, Areas of Special Biological Significance, and Military Use Zones as noted in Table 3. Each of these datasets was imported into ArcGIS Pro in their original formats. A system was established to score each dataset based on its suitability for tidal energy technology. Each feature was given a suitability score consisting of a value of 1 through 5, with 1 being least suitable and 5 being the most suitable for tidal energy technology. Some features were given a restricted score of zero accounting for technical limitations or legal regulations, which would warrant classifying these areas as completely unsuitable for tidal energy technology.

The scoring system used to give each dataset a suitability score was chosen based on the extensive background research completed for this project. The scoring system for government-regulation data is described below:

Table 3. Data used in this study relating to the government use limitations of tidal energy technology.

Government Regulation Areas	Source	Year	Datum	Description
Marine Protected Area	NOAA Marine Protected Areas Inventory, 2017	2017	WGS 1984	Vector, polygon data outlining areas designated as Marine Protected Areas.
Areas of Special Biological Significance	California Water Boards GIS Rest Services, California Government, 2005	2005	WGS 1984	Vector, Polygon data showing boundaries of areas of special biological significance
Military Use Zones	Department of Commerce, NOAA Office for Coastal Management	2017	NAD 1983	Vector, Polygon data showing boundaries of danger zones and restricted areas used by the U.S. Military
California State Parks	California Department of Parks and Recreation	2020	WGS 1984	Vector, Polygon data showing boundaries of state parks in California.

- Marine Protected Areas (MPAs): Federal and state regulated waters that serve to achieve the long-term conservation of nature with associated ecosystem services and cultural values, which are managed by legal or other affective means (Day et al., 2008). MPAs prohibit all commercial activities but do allow some pre-approved research operations. Tidal energy installation is not considered a pre-approved activity therefore MPAs were given a suitability score of 0 as well.
- Areas of Special Biological Significance (ASBS): A subset of state water quality protection areas that protect important ecosystems from any undesirable alteration in natural water quality (NOAA 2019c). These areas prohibit pollution from water runoff as well as dredging of the seafloor. Because tidal turbines are most often secured to the seafloor, ASBS were given a suitability score of 0.
- Military Use Zones: Danger zones and restricted areas within coastal and marine waters used by the armed forces. Restricted areas generally provide security for Government property and/or protection of the public from the risks of damage or

injury arising from the Government's use of that area (NOAA OCM 2017). Because of these heavy restrictions it was logically assumed that tidal energy technology could not be installed in these areas and was therefore given a suitability score of 0.

- California State Parks: State parks are managed by the California Department of Parks and Recreation. State parks have many allowances for recreational use, although there are some restrictions regarding the disturbance of wildlife and natural habitats. No literature could be found about the prospective installation of energy systems within state parks, therefore it was inferred that government permission could be sought out for the implementation of tidal energy technology in these areas. A suitability score of 3 was chosen to reflect these findings, and also to account for the high level of recreational use in these areas.

This project omitted other protected areas that could limit the installation of tidal energy technology. Essential Fish Habitats (EFH), National Marine Sanctuaries (NMS), and Exclusive Economic Zones (EEZ) are federally and state regulated areas that would impose restrictions on projects such as tidal energy installation. Because there were no instances of these areas within the study area, they were omitted from the analysis. Table 3 highlights the data sources and their properties for all of the Government Regulation data.

A new attribute field called “suitability” was created in each government data layer (MPA, ASBS, Military Use Zones, State Parks) and was populated with the corresponding suitability score as described above. Once scored, each of these government regulation data layers were individually dissolved into a single feature using the Dissolve tool in ArcGIS Pro. The datasets were then clipped to the extent of the study area. Then, the dataset was converted into a raster using the Polygon to Raster tool. The extent and snap rasters were set to the tidal range raster to ensure that the new raster would overlay the others perfectly. Each cell was populated with its corresponding suitability score as described above. Areas considered ‘no data’ were reclassified to a value of 0 to represent areas that were not identified by the parameter. This process was repeated for each dataset in the government use category resulting in a raster for each parameter.

3.2.4. Commercial Use Data

Commercial use data were also processed and converted to the NAD 1983 datum and clipped to the study area. Commercial use data included shipping lanes, oil pipelines, and submarine cables (Table 4). While oil pipelines are considered in the analysis, oil platforms were excluded from this study because they are located very far from the study area, and also would have little impact on tidal turbines installed on the seafloor.

Table 4. Data used in this study relating to the commercial use limitations of tidal energy technology.

Commercial Use Data	Source	Year	Datum	Description
Shipping Lanes	NOAA, Office of Coast Survey	2015	WGS 1984	Vector, Polygon data showing boundaries of major shipping lanes in the U.S.
Oil Pipelines	NOAA, Office of Coast Survey	2018	WGS 1984	Vector, Line data mapping the location of oil pipelines.
Submarine Cables	NOAA	2019	WGS 1984	Vector, polygon data showing the locations of various submarine cables.
Marinas	California Department of Fish and Game, Marine Region GIS Lab	2020	NAD 1983	Vector, Point Data consisting of coastal and marine related boat marinas.

Similar to the government use data, each dataset in the commercial use category was scored based on its suitability for tidal energy technology. Below is the description and reasoning for the suitability scores for commercial use data.

- Shipping Lanes: Designated lanes for commercial and private vessel traffic. Blocking these lanes is strictly prohibited. Because tidal turbines are installed on the seafloor, they would not directly block shipping lanes. Subsequently, this category does not need to be restricted. However, movement from large shipping vessels on the surface could have an impact on the water flow beneath, interfering with the tidal flow that powers turbines. Because of this, the shipping lane data was given a suitability score of 2.
- Oil Pipelines: Pipelines running along the seafloor for the transport of oil. Because these pipelines are installed into the seafloor, they would directly impact the installation of tidal turbines. For this reason, oil pipelines were given a restricted suitability score of 0.
- Submarine Cables: Cables running along the seafloor used for a variety of commercial and governmental purposes. Similar to oil pipelines, these cables would directly impact the installation of tidal turbines and were therefore given a restricted score of 0.
- Marinas: Areas consisting of public and private marinas. While no specific literature discusses the limitation of marinas, an assumption that tidal energy technology would not be allowed for installation in these areas was made. A restricted suitability score of 0 was given. A 100 m buffer was applied to all marina data points to account for these areas.

A new attribute field called "suitability" was created in each data layer, following the same methodology as the government regulation data described in section 3.1.2, and was populated with the corresponding suitability score. Once scored, each of these commercial use data layers were individually dissolved into a single feature using the Dissolve tool in ArcGIS Pro. The datasets were then clipped to the extent of the study area. Then, the datasets were converted into a raster using the Polygon to Raster tool. The extent and snap rasters were set to the tidal range raster to ensure that the new raster would overlay the others perfectly. Each cell was populated with its corresponding suitability score as described above. Areas considered 'no data' were reclassified to a value of 0 to represent areas that were not identified by the parameter. This process was repeated for each dataset in the commercial use category resulting in a raster for each parameter. Figure 5 depicts the workflow used to process this data while Table 4 lists the data properties.

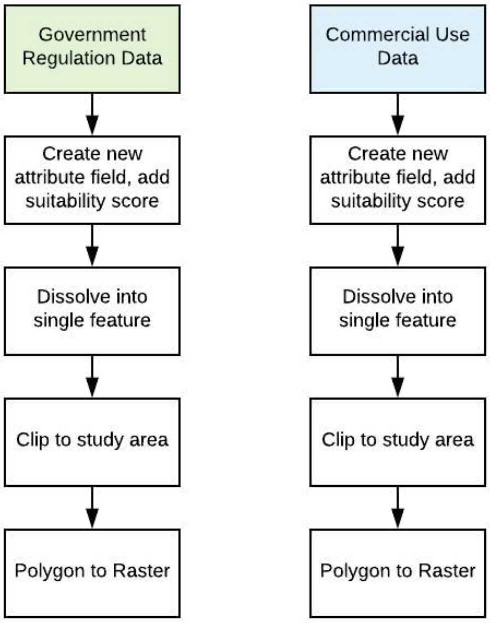


Figure 5. Flow chart depicting the data pre-processing for the government and commercial use datasets.

3.2.5. Power plants

Information about power plant locations in southern California was also utilized. The California Energy Commission runs a Critical Infrastructure GIS data portal that has an ArcGIS feature layer containing information about all of the power generating facilities located in California and their source of energy. This layer was imported into ArcGIS Pro where it was then clipped to the study area. Next, all locations that were appointed as hydro, wind, or solar energy were selected to identify renewable energy sites. These were chosen because hydro, wind, and solar energy processes are similar in nature to tidal energy, meaning these facilities will be somewhat more prepared to handle and convert tidal energy since they are already processing renewable energy.

3.3. Hard and Soft Criteria

The ways in which the data themes were reclassified to fit the needs of this study in Section 3.2 provided two groups of variables comprised of hard and soft criteria. The themes with Boolean outcomes (0/1) served as hard criteria because the areas rated 0 would not support the implementation of tidal energy technology. There was six such variables as follows:

- Marine Protected Areas
- Areas of Special Biological Significance
- Military Use Zones
- Marinas
- Oil Pipelines
- Submarine cables

The second group behaved like soft criteria because they supported varying levels of suitability in terms of the implementation of tidal energy technology. There were four such variables as follows:

- Tidal Range
- Bathymetry
- California State Parks
- Shipping Lanes

The conceptualization of the criteria in these two ways meant that the computational effort required to perform the various kinds of overlays described in Sections 3.4 and 3.5 could be minimized by introducing each criterion in the aforementioned order because the first set could be used iteratively to reduce the area of interest.

3.4. Overlay Analyses

Two different analysis types were used to determine site suitability. The first was a weighted overlay analysis. A weighted overlay analysis uses a workflow in which all data is first reclassified to a scale based on suitability or preference, then each cell is multiplied by its weight of importance, and finally all of the cell values are added together to produce a raster dataset (Esri 2020e). This method allows for more impactful parameters to be given a larger importance in determining which areas are suitable. Weighted overlay is appropriate for investigating tidal energy technology because the inputs, such as tidal range, can be more heavily weighted to influence the overall results.

A fuzzy overlay analysis has a similar workflow to weighted overlay analysis but differs in how it classifies the data. Fuzzy overlay is based on the fuzzy membership, which transforms a dataset into a 0 to 1 scale indicating how likely a cell belongs to a specified set (Esri 2020b). This classification principle allows for more leniency when deciding how a cell is classified, operating under the assumption that boundaries between different classes may not be so strict. Fuzzy membership has many different types including Gaussian, Large, Linear, Small, Near, MS Large, and MS Small. Each type dictates how the data is transformed and is appropriate for particular types of data. Once data has been classified using the fuzzy membership principles, it is used in a fuzzy overlay. The fuzzy overlay process uses all of the input values to determine what sets the phenomenon belongs to. There are many different overlay types to use with the fuzzy overlay process. For this study the ‘And’ operator was chosen. This operator type returns the minimum value of the sets the cell location belongs to, so for tidal energy technology the analysis will result in suitable locations that have a high probability of matching all of the input criteria.

3.5. Weighted Overlay Analyses

The weighted overlay analysis was performed in ArcGIS Pro and was separated into two phases. The first phase of the weighted overlay used the hard criteria defined in Section 3.2 to eliminate all areas that were not available for the implementation of tidal energy technology. This resulted in a map of restricted and non-restricted areas. The second phase of the weighted overlay analysis used the soft criteria defined in Section 3.2 that used physical, government regulation, and commercial use data to perform a weighted overlay analysis on the non-restricted areas to identify suitable sites for tidal energy technology.

3.5.1. Hard Criteria

The first step in the weighted overlay analysis process was to eliminate all of the areas that were completely off-limits for tidal energy technology. Using the parameters assigned to the hard criteria class defined in Section 3.2, the union tool was used to dissolve all of the features into a single class. Areas of overlapping cells were given the lowest suitability value, which was 0 since all of the parameters from the hard criteria class had a suitability score of 0. The resulting feature showed all areas within the study area that were completely off-limits for the implementation of tidal energy technology. To isolate areas that were excluded from the hard criteria classification, the study area raster was clipped using the new hard criteria raster, resulting in an area that did not include restricted cells.

3.5.2. Analysis

The next part of the analysis used the soft criteria to perform a weighted overlay analysis on the remaining study area that was identified by removing the hard criteria area. Using the weighted overlay tool, the soft criteria parameters were given varying weights. The input rasters used in the weighted overlay analysis were the classified bathymetry raster, classified tidal range raster, the state park raster, and the shipping lanes raster (Table 5). The tidal range raster was given a weight of 50%, and the scale was set so that classifications of '1', '2', '3', '4', and '5' were set to 1, 1, 3, 5, and 5, respectively. These numbers were chosen so that the highest two classes of tidal range were given a higher suitability score while the lowest classes of tidal range values were given low suitability scores. A 50% weight was chosen because tidal range directly impacts the flow of water generated, which is what powers tidal turbines. This factor will have the most impact on how successful tidal energy technology would be if it was implemented. The bathymetry raster was given a weight of 25%, and the scale was set so that a classification of '0' was restricted and the classification of '1' was set at 5. This scale was set with the intention of restricting non-ideal ranges of ocean depth, and the weight was chosen based on previous research for this project that indicated bathymetry was less important to tidal energy technology compared to the tidal range and was therefore given a lower weight. The state park raster was given a weight of 15%, and the classification value of '3' was set to 3. This weight was chosen because the restrictions regarding state parks are somewhat unknown, so their impact on tidal energy technology implementation is smaller. Lastly, the shipping lane raster was given a weight of 10%, and the classification of '2' was set to 2. Shipping lanes were given the smallest weight because they impact a very small area of the study area, and generally do not affect tidal energy technology on larger scales. For both the parks and shipping lane parameters, the classification value of 0 was given a scale value of 5. Values of 0 represented cells in each raster that were not identified as either a park or shipping lane, meaning they had no restrictions regarding tidal energy implementation. For that reason, they were given a high scale value of 5. Once the weighted overlay analysis was run, a raster was generated showing how suitable each cell within the study area was for the siting of tidal energy technology based upon the soft criteria parameters described above. This exact process was completed two times, the first time using the IDW interpolated tidal range raster and then a second time using the RBF interpolated tidal range raster.

Table 5. Scales and weights used for the weighted overlay analysis.

	Weight	**Classification**	**Scale**
Tidal Range	50%	1	1
		2	1
		3	3
		4	5
		5	5
Bathymetry	25%	0	Restricted
		1	5
State Parks	15%	0	5
		3	3
Shipping Lanes	10%	0	5
		2	2

3.6. Fuzzy Membership

In order to perform the Fuzzy Overlay Analysis, the rasters used in the analysis must be first classified using the fuzzy membership technique. Fuzzy membership uses a 0 to 1 scale that indicates the possibility of a cell being a member of a specified set. To classify each raster into the 0 to 1 scale, the fuzzification process was followed. To apply fuzzy logic to both the IDW and RBF tidal range rasters, the fuzzy membership tool in ArcGIS Pro was used with a specified membership type ‘large’ and an auto-generated midpoint of 1.16. The large membership type was chosen because the largest tidal range values are ideal, so the fuzzy membership process will allocate a higher value to the larger tidal range values. A similar logic was used for the bathymetry raster. The raster was run through the fuzzy membership tool used with a membership type of ‘Near’, a midpoint of -30 and a spread of 0.01. The Near membership type was chosen because the ideal bathymetry range is specific, represented by a midpoint of -30, which translates to a 30 m depth, so the fuzzy membership prioritizes bathymetry values near the midpoint and then reduces the outlying values towards 0.

For the remaining soft criteria parameters, state parks and shipping lanes, the fuzzy membership tool was applied using the large type. This allowed for areas not identified to be a state park or shipping lane to be considered higher suitability. The auto generated midpoint was used

3.7. Fuzzy Overlay Analysis

Similar to the weighted overlay analysis, the fuzzy overlay analysis was performed on the study area that excluded the areas that were restricted by the hard criteria in Section 3.3.2. The analysis was based on the tidal range, bathymetry, state parks, and shipping lane rasters that had been classified using the fuzzy membership principle described in Section 3.4 as inputs. The ‘and’ operator was used in the analysis and the snap raster and extent were set to match the new study area raster that excluded the hard criteria areas to ensure the correct spatial extent and a perfect overlay. The resulting raster generated values between 0 and 1 indicating how suitable each cell is for implementing tidal energy technology based on the input data. Values closer to 1 represent higher likelihood of suitability while values of 0 represented no suitability. This process was repeated two times, first using the IDW interpolated tidal range raster and then a second time using the RBF tidal range raster.

3.8. Distance to Energy Facilities

Once both the weighted and fuzzy overlay analyses had been completed, it was important to calculate the distance to energy facilities for the most suitable areas. Since there is no specific literature on the ideal distance between tidal energy installations and energy facilities, three different distances were analyzed. Three buffers were created around the selected energy facilities as described in Section 3.1.4 with a radius of 15, 10, and 5 km. Then the extract by mask tool was used on both the weighted and fuzzy overlay rasters. This produced a result showing all of the suitable areas for tidal energy technology identified in the previous analyses that were within 15, 10, and 5 km to an energy facility.

3.9. Summary

The methodology of this study followed a simple workflow, relying heavily on the initial data manipulation and methods used in Williams (2018). After reviewing and editing all of the data from each source, the datasets were classified based on ideal values. These classifications were then used in both a weighted and fuzzy overlay analysis, and finally connected with neighboring energy facilities based on the distance thresholds.

Chapter 4 Results

A weighted and fuzzy overlay analysis were conducted using ArcGIS Pro to search for suitable areas in southern California to implement tidal energy technology. The results from these analyses are examined in detail below, highlighting the results from both approaches as well as the proximity to renewable energy power plants.

4.1. Interpolation

The foundation for both the weighted overlay and fuzzy overlay analysis was built on the success of interpolating the tidal range data. The IDW interpolation method was performed first (Figure 6) and the RBF interpolation was performed second (Figure 7). While the two different interpolation methods produced similar results with regard to estimated tidal range values, they differ in their spatial extents. For that reason, both of the interpolation types were used in the following overlay analyses, and their effect on the results is examined and discussed later in this chapter.

Figure 6. Results of the IDW interpolation, showing the estimated average tidal ranges within the study area.

Figure 7. Results of the RBF interpolation, showing the estimated average tidal ranges within the study area.

When comparing the tidal range data produced by the two different interpolation methods, it is noticeable that the IDW method produces more of a clustered result with similar values of tidal range being seen over more condensed areas. The RBF method shows a larger spatial range of where similar tidal range values are clustered. Both interpolation methods showed the largest tidal range values in San Diego, which is consistent with the raw data before interpolation.

4.2. Weighted Overlay Analysis

The weighted overlay analyses were performed in two phases. The first phase took the hard criteria that were established in section 3.2 to identify areas within the study area that were completely unsuitable for tidal energy technology based on physical, government, and commercial limitations. These areas were then removed from the study area. The second phase of the weighted overlay analysis used the soft criteria that were established in section 3.2 to perform the weighted overlay analysis on the new and smaller study area that excluded the areas disqualified with hard criteria.

4.2.1. Eliminating Hard Criteria

After creating a raster data set that included all of the hard criteria, including MPAs, ASBS, Military Use Zones, Oil Pipelines, Submarine Cables and Marinas, a new study area was created. The new study area ensured that the weighted overlay could be applied to areas that were free of complete restrictions to tidal energy technology implementation. Figure 8 shows the new study area after removing all of the areas disqualified with the hard criteria. This new area, represented in red, is potentially suitable for the siting of tidal energy technology.

Figure 8. The new study area, represented in red, created after elimination of the areas disqualified with the hard criteria.

The new study area now had many areas that are excluded. Cells disqualified using the hard criteria accounted for approximately 25.4% of the study area. Figures 9 and 10 show the new study area, represented in red, that excludes the hard criteria in the Long Beach and San Diego areas. This new study area is potentially suitable for the siting of tidal energy technology.

Figure 9. The new study area, represented in red, that excludes the areas disqualified with the hard criteria in and near Long Beach, CA.

Figure 10. The new study area that excludes the areas disqualified with hard criteria in and near San Diego, CA.

4.2.2. Weighted Overlay Analysis

The weighted overlay analysis was first performed using the IDW interpolation method and the soft criteria on the new study area that was created by excluding the hard criteria. The results from this analysis show that areas near Long Beach and San Diego have higher numbers of cells that scored in the suitable range compared to other areas. This can be attributed to these areas having larger tidal ranges, which are more beneficial to tidal energy technology. For this analysis, scores of 0 indicated low suitability while scores of 5 indicated the highest suitability. Figure 11 shows the results of the weighted overlay analysis.

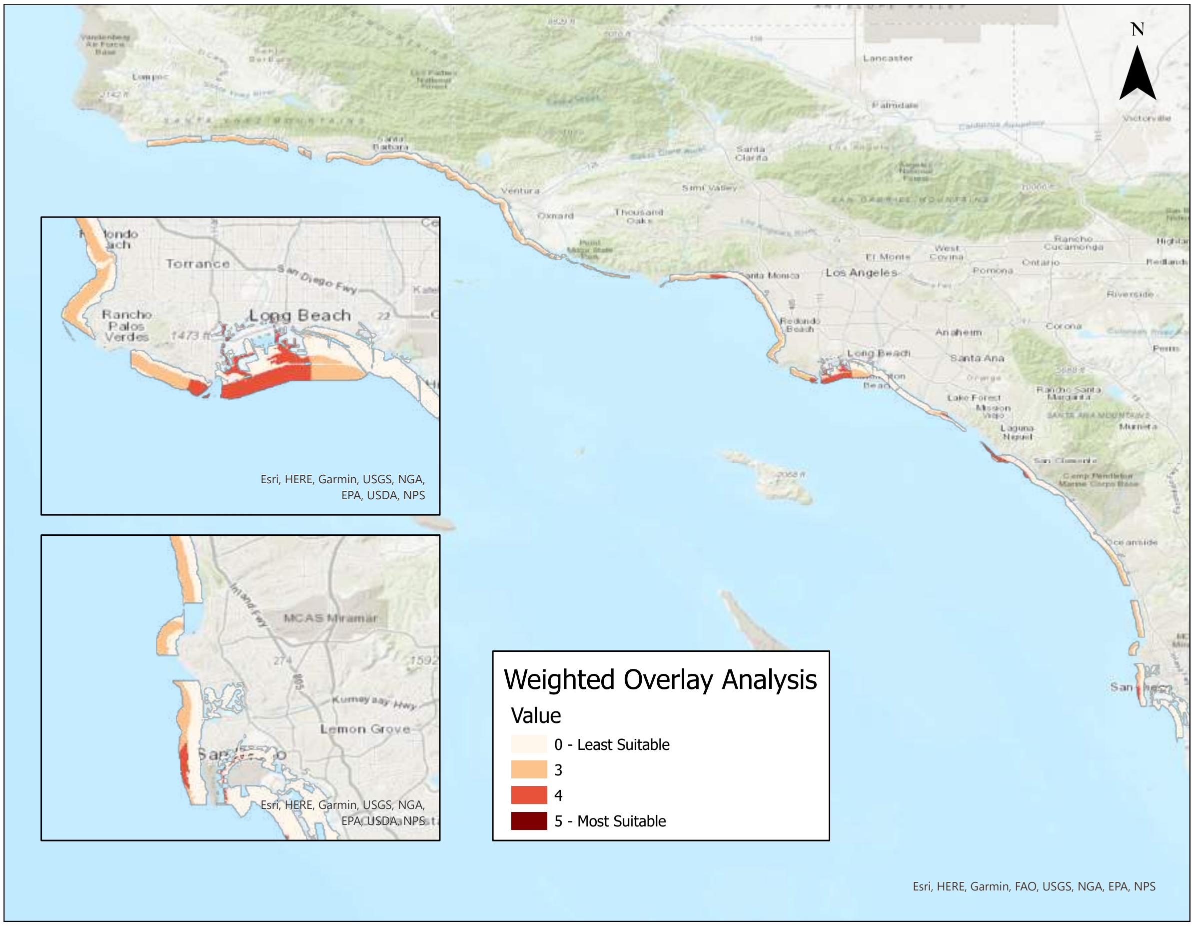


Figure 11. Weighted overlay analysis results using the IDW interpolation method. Top inset image shows Long Beach, CA. Bottom inset image shows San Diego, CA.

From this analysis, no cells received a score of 1 or 2. The majority of cells (60.04%) had a suitability score of 0. The most suitable cells, with suitability scores of 4 and 5, accounted for 12.62% of cells. Table 6 shows the breakdown of cells by suitability score.

Table 6. Breakdown of cells from the weighted overlay analysis using the IDW interpolation method.

Value	Count	Percent
0	50,435	60.04
1	0	0
2	0	0
3	22,976	27.35
4	10,550	12.56
5	48	0.05
Totals	84,009	100

A second weighted overlay analysis was performed using the RBF interpolation method, with results seen in Figure 12. These areas showed the highest number of cells scoring in the suitable range. This analysis used the RBF interpolated tidal ranges to locate suitable areas for implementing tidal energy technology based on the soft criteria. The resulting cells were given scores that reflected the inputs and how suitable they were for tidal energy technology. A score of 0 indicated no suitability while a score of 5 represented the most suitable cells. In this analysis no cells received a score of 1 or 2. The results are similar to the IDW results, especially when looking at the breakdown of how many cells were scored in which category. Table 7 shows the number of cells scored for each category using the RBF method. The RBF method identified approximately 5.8% fewer cells in the suitable categories compared to the IDW method.

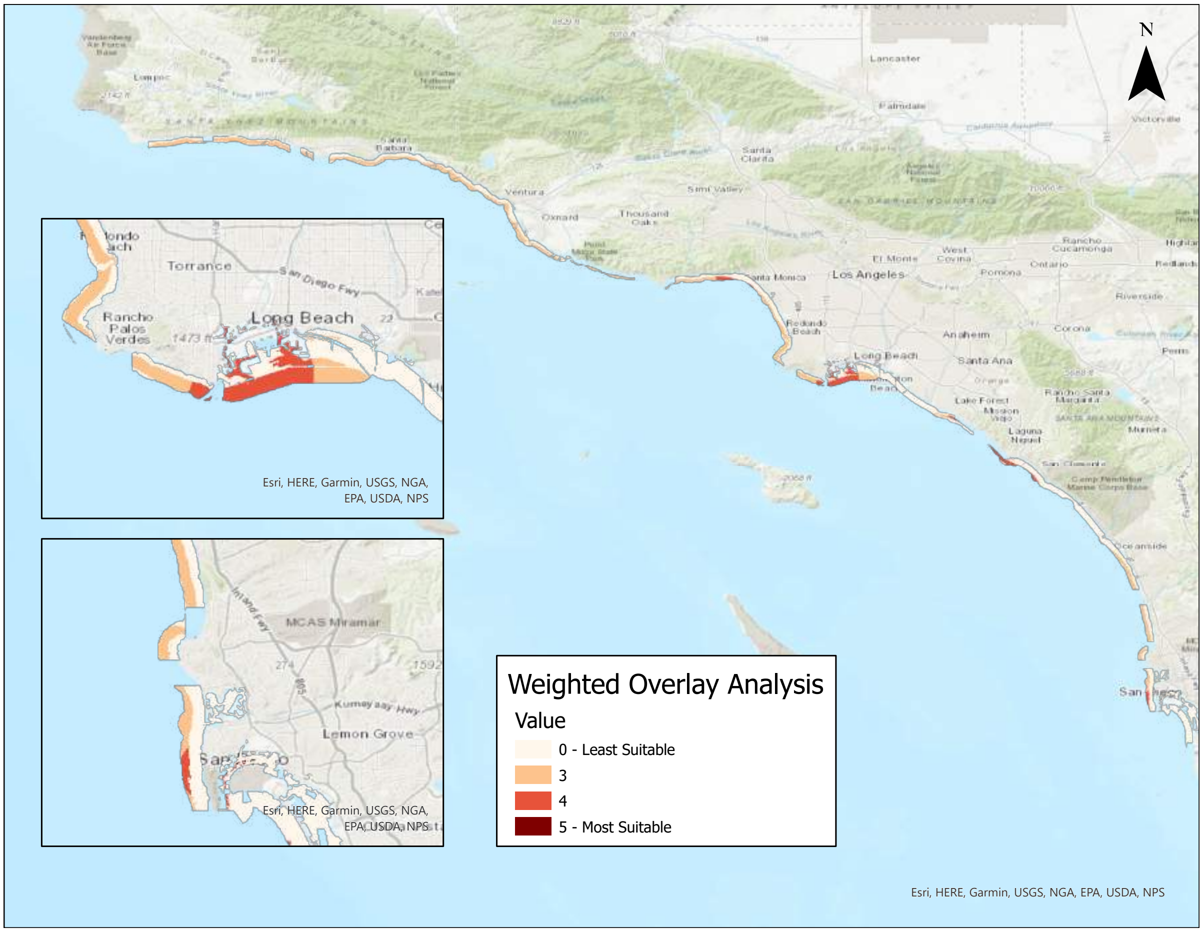


Figure 12. Weighted overlay analysis results using the RBF interpolation method. Top inset image shows Long Beach, CA. Bottom inset image shows San Diego, CA.

Table 7. Breakdown of cells from the weighted overlay analysis using the RBF interpolation method.

Value	Count	Percent
0	50,435	60.04
1	0	0
2	0	0
3	27,912	33.22
4	56,19	6.69
5	43	0.05
Totals	84,009	100

To compare the differences between the IDW and RBF interpolation methods when performing the weighted overlay analysis, a map was created showing the suitable areas identified by both interpolation methods. Suitable cells were considered to be any cell that scored either a 4 or 5 in the weighted overlay analysis. Figure 13 shows cells identified by the IDW method, RBF method, and both methods. Table 8 shows the breakdown of those classifications with 50.74% of suitable cells identified with the IDW interpolation method, 7.8% with the RBF method, and 36.4% of cells with both methods. This indicates that most of the cells identified by the RBF method were also identified by the IDW method, showing that the suitable results from the IDW method have a larger spatial extent.

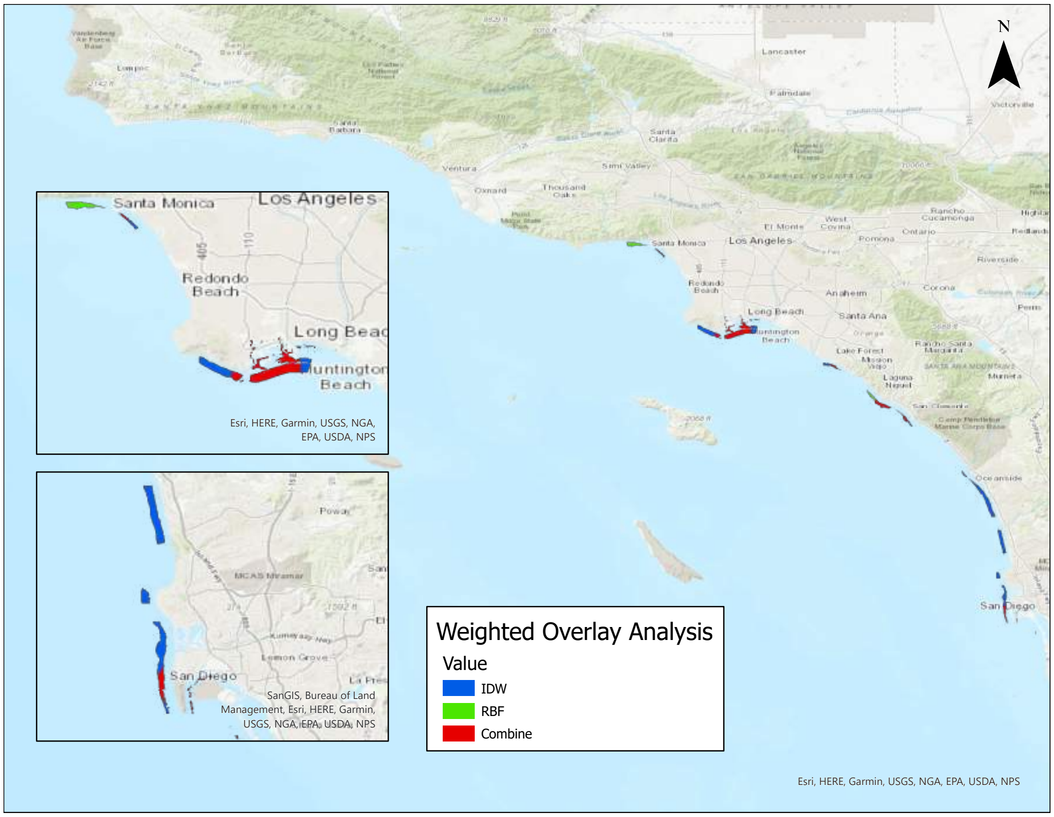


Figure 13. Results of the weighted overlay analysis comparing suitable cells identified by each interpolation method. Top inset image shows Long Beach, CA. Bottom inset image shows San Diego, CA.

Table 8. Breakdown of suitable cells that were identified in the weighted overlay analysis using each interpolation method.

Weighted Overlay	Count	Percent
IDW	5,834	50.75
RBF	898	7.81
Both	4,764	41.4
Totals	11,496	100

4.3. Fuzzy Overlay Analysis

The second analysis type used to look at suitable areas for tidal energy technology was the fuzzy overlay analysis. Similar to the weighted overlay analysis, the fuzzy overlay analysis was performed on the new study area that was created after eliminating the areas disqualified with the hard criteria as described in Chapter 3. Using the same study area as the weighted overlay analysis ensured accurate results in the fuzzy overlay analysis that could then be compared with the weighted overlay results.

The fuzzy overlay analysis was first performed with the IDW interpolation method using the soft criteria which included tidal range, bathymetry, state parks, and shipping lanes. The analysis resulted in each cell having a score on a 0 to 1 scale, with higher values representing a better likelihood of those cells being suitable based on the input parameters. Figure 14 shows the results of the fuzzy overlay analysis using the IDW method. Darker colors indicate cells with higher suitability scores while lighter colored cells indicate lower suitability.

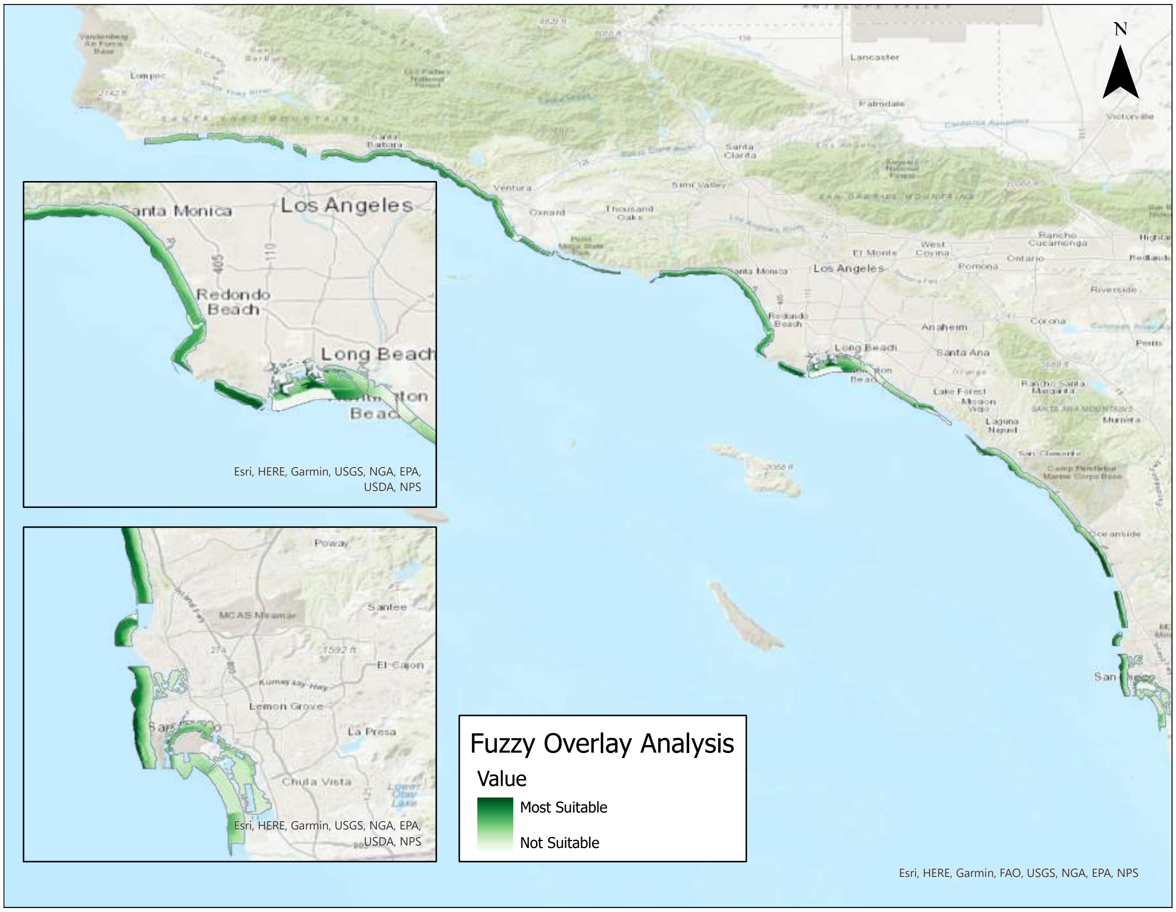


Figure 14. Fuzzy overlay analysis results using the IDW interpolation method. Top inset image shows Long Beach, CA. Bottom inset image shows San Diego, CA.

Compared to the weighted overlay analysis, the fuzzy overlay analysis has a much larger spatial range. Whereas the weighted overlay did not identify many suitable cells north of the Los Angeles metropolitan area, the suitable cells identified with the fuzzy overlay extended as far north as the Santa Barbara area. The fuzzy overlay analysis identified 34.45% of cells as suitable while the majority of cells were considered unsuitable. Suitable cells were determined to be any cell that scored in the top 50% of the fuzzy value range. Table 9 shows the breakdown of cells from the fuzzy overlay analysis using the IDW method.

Table 9. Breakdown of cells from the fuzzy overlay analysis using the IDW method.

Value	**Count**	**Percent**
Not Ideal	55,070	65.55
Ideal	28,939	34.45
Totals	84,009	100

The fuzzy overlay analysis was performed a second time using the RBF interpolated tidal range data. The results have a similar spatial distribution to the IDW method, again with a larger spatial range compared to the weighted overlay analysis. Figure 15 shows the results of the fuzzy overlay analysis using the RBF interpolation method. From this analysis, only 36.6% of cells were considered suitable. This was an increase (2.16%) compared to the IDW method. Table 10 shows the breakdown of cells from the fuzzy overlay analysis using the RBF interpolation method.

The results for both interpolation method analyses and the fuzzy overlay were compared against each other to characterize the spatial variation in suitable cells. Table 11 shows the distribution of cells showing that the majority, approximately 85.2% of cells, was identified as suitable using interpolation methods. Only a small percentage of suitable cells, 4.6% were solely identified by the IDW method, meaning that this method had a much smaller spatial extent compared to the RBF method, which identified 10.2% of the cells as suitable. Table 11 summarizes suitable cells identified by the different interpolation methods. The spatial distribution of suitable cells identified by each interpolation type is shown in Figure 16.

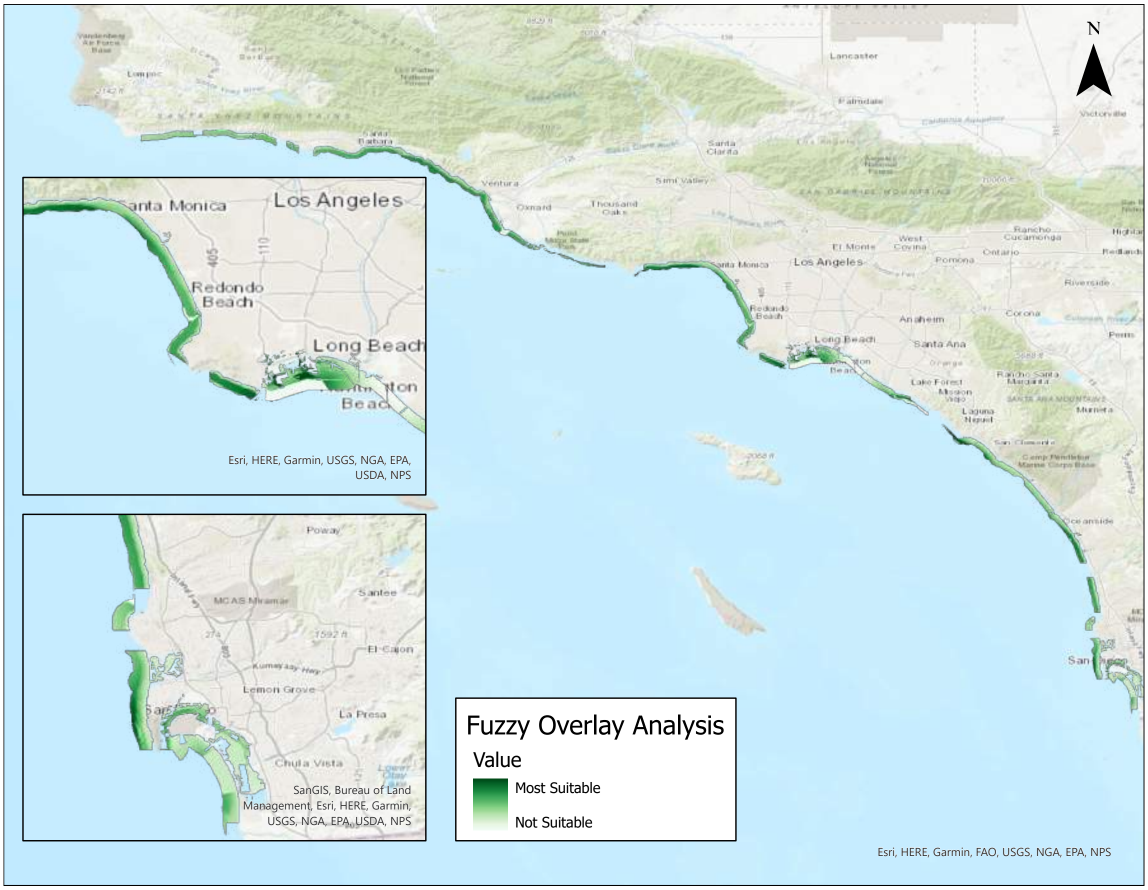


Figure 15. Fuzzy overlay analysis results using the RBF interpolation method. Top inset image shows Long Beach, CA. Bottom inset image shows San Diego, CA.

Table 10. Breakdown of cells from the fuzzy overlay analysis using the RBF interpolation method.

Value	**Count**	**Percent**
Not Ideal	53,253	63.39
Idea	30,756	36.61
Totals	84,009	100

Table 11. Breakdown of suitable cells identified by each interpolation method.

Fuzzy Overlay	**Count**	**Percent**
IDW	1,476	4.58
RBF	3,293	10.22
Both	27,463	85.20
Totals	32,232	100

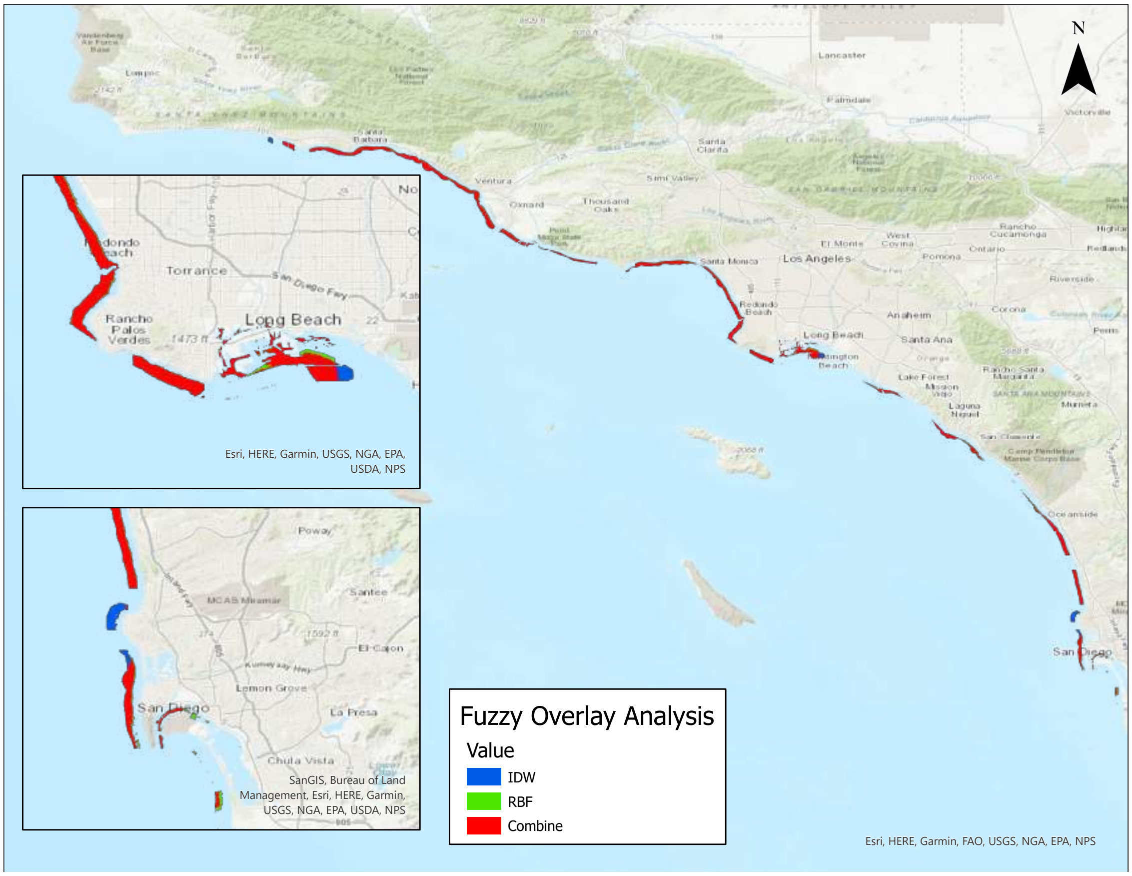


Figure 16. Results of the fuzzy overlay analysis comparing each interpolation method. Top inset image shows Long Beach, CA. Bottom inset image shows San Diego, CA.

4.4. Breakdown by County

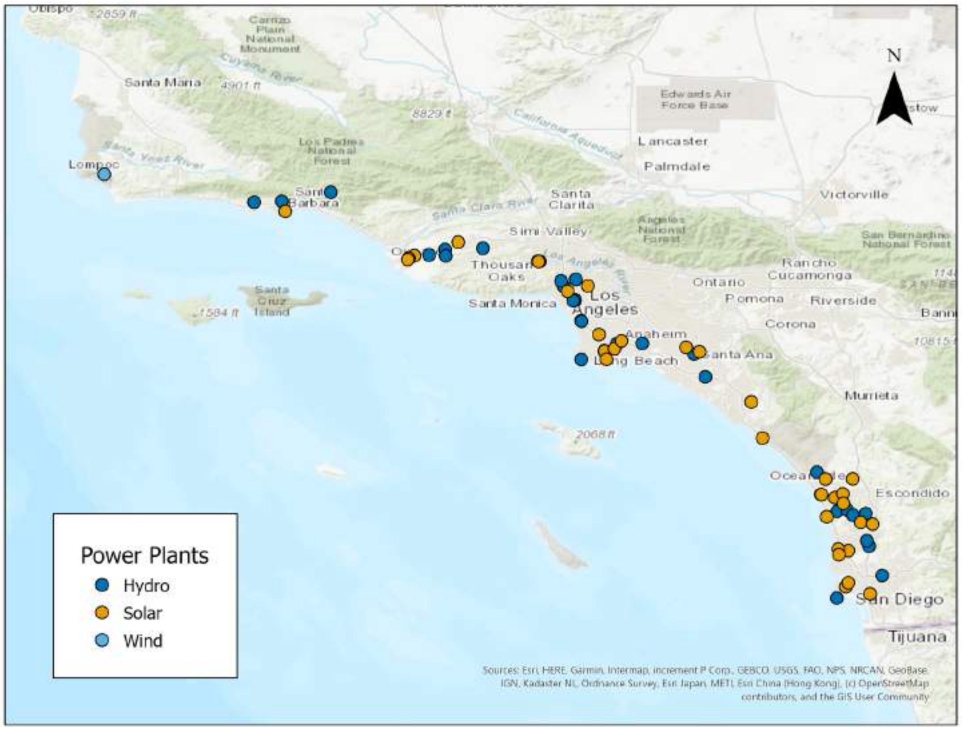
Of the cells identified as suitable in the weighted overlay analyses, the majority (46.7%) were located in Los Angeles County. These numbers were calculated using the total number of suitable cells and all interpolation methods. Ventura and Santa Barbara Counties had no suitable cells. Orange and San Diego Counties had 15.1% and 38.18%, respectively. The fuzzy overlay analysis also identified the majority of suitable cells in Los Angeles County with 33.5%. This was a decrease of 13% compared to the suitable cells identified by the weighted overlay analysis. Comparatively, the fuzzy overlay analysis identified suitable cells in both Ventura and Santa Barbara Counties whereas the weighted overlay analysis did not. Orange and San Diego Counties had relatively low numbers of suitable cells which were 7.05% and 8.54% less than that for the weighted overlay, respectively. These results show that the weighted overly approach identified more suitable cells in San Diego, Los Angeles, and Orange Counties while the fuzzy overlay approach identified more suitable cells in Santa Barbara and Ventura Counties. Table 12 shows the breakdown of the analysis results by county.

Table 12. Breakdown of suitable cells by county comparing the weighed overlay analysis and fuzzy overlay analysis.

	San Diego	**Orange**	**LA**	**Ventura**	**Santa Barbara**	**Total**
Weighted Count	4,389	1,736	5,371	0	0	11,496
%	38.18	15.10	46.72	0	0	100
Fuzzy Count	6,838	2,595	10,796	6,862	5,141	32,232
%	21.22	8.05	33.49	21.29	15.95	100

4.5. Distance to Energy Facilities

The last portion of the analysis completed for this study examined the distance to energy facilities. Energy facilities in southern California that processed wind, solar, and hydro energy types were selected from a California Power Plants database and then clipped to the study area. A 15, 10, and 5 km buffer was applied to the data points to analyze how many suitable cells were within these varying ranges. Figure 17 shows a map of renewable power plant locations relative to the study area.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 17. Renewable power plants located near the study area.

The results vary greatly between analysis types as seen in Table 13. When looking at cells identified as suitable by both interpolation methods, the weighted overlay analysis identified more cells than the fuzzy overlay analysis at each distance. For the 15 km distance, each analysis type had a majority of its cells fall within the range. The weighted overlay had 95.6% of cells fall within this 15 km distance, which was 16.0% more than the fuzzy overlay. For the shortest distance, 5 km, 24% of the weighted overlay cells fell within the range while the fuzzy overlay only had 21.5%. California has an abundance of energy facilities, especially along the coast, so it is not surprising to see the variation of suitable cells that fall within the different distance ranges of these facilities.

Table 13. Breakdown showing the percent of cells that were within the specified distances to energy facilities for each different interpolation method and analysis type.

	15 km	**10 km**	**5 km**
Weighted Combined Count	10,988	9,763	2,797
%	95.58	84.92	24.33
Fuzzy Combined Count	25,656	21,093	69,27
%	79.59	65.44	21.49

Chapter 5 Discussion

The results of this study are discussed in detail in this chapter, starting with a review of the data procedures and the two different interpolation methods. The results of the weighted and fuzzy overlay analyses are then analyzed with a focus on areas determined to be the most suitable for the potential siting of tidal energy technology. The discussion of the results is also broken down by county, as well as including a review of nearby potential energy facilities. Given the results of the weighted and fuzzy overlay analyses, areas within Los Angeles County were found to be the most suitable for implementing tidal energy technology.

5.1. Data

The foundation for all of the results from both types of analyses was from the data. Each data set that was used as an input for the different overlay analyses was originally defined on vastly different scales and projections and represented spatial areas much larger than what was needed for this study. The process of manipulating the data so that everything was cohesive was an extensive process but resulted in a workflow that could be applied to each parameter. Each dataset had to first be converted to the correct datum (NAD 1983) and projection (UTM Zone 11), and then trimmed to the correct extent for this study. While doing this, it was important to use a carefully selected snap raster and extent parameter in which to align the data correctly. The same snap raster was used for each dataset resulting in a perfect alignment between raster datasets. It was also important to resample each dataset to the same spatial scale. Each parameter was set to a 100 m cell size. Having each dataset on the same spatial scale and with perfect alignment set up the remainder of the analysis for success.

5.2. Differences in interpolation methods

There were two different types of interpolation methods used to create the raster dataset containing tidal range values. In order for the weighted overlay and fuzzy overlay analyses to work, the tidal range data needed to be a continuous surface that had the same spatial scale and extent as the remainder of the datasets. The first interpolation method used was the IDW method. This method uses the proximity of surrounding values to predict a new location's value while still using the original data points, making it an exact interpolator. It works on the assumption that nearby values contribute more to the estimation than farther values. Because of this, the IDW method is prone to clustering. Areas with a low density of data points exert an influence in all directions that diminishes evenly which results in concentrated patterns of estimated values. This can be seen in Figure 18 in the tidal range data that was estimated using the IDW method. Where the original data points are more spread out there is less variance in estimated value, while in areas such as San Diego where there is a concentration of data points the values are much more diverse. It could be assumed that if more sample points containing tidal data were included in the interpolation, there would be greater variability in the resulting raster which could help to refine the overall results of this study.

The second interpolation method used for estimating the tidal range values was the RBF method. The multi-quadratic function was used in this study. RBFs are used to produce smooth surfaces from a large number of data points. The functions produce good results for gently varying surfaces and pass through the original data points making it an exact interpolator, similar to the IDW method. RBFs can predict values that are larger or smaller than the minima and maxima of the original data, which allows them to produce smoother surfaces. Figure 19 shows the RBF interpolation compared to the original data points.

Esri, HERE, Garmin, FAO, USGS, NGA, EPA, NPS

Figure 18. Estimated tidal range values using the IDW interpolation method overlaid with original tidal range data points.

Esri, HERE, Garmin, FAO, USGS, NGA, EPA, NPS

Figure 19. Estimated tidal range values using the RBF interpolation method overlaid with original tidal range data points.

Figures 20 and 21 show the comparison of estimated values from the IDW and RBF interpolations in the San Diego region. The maps show how the different interpolation methods affect the spatial distribution of estimated values. The RBF method shows a wider spatial range of similar values and a more spatially diverse series of estimates compared the IDW method. These differences can be attributed to the mathematical models each interpolation type uses and could be one of the causes of varying results produced by the weighted and fuzzy overlay analyses.

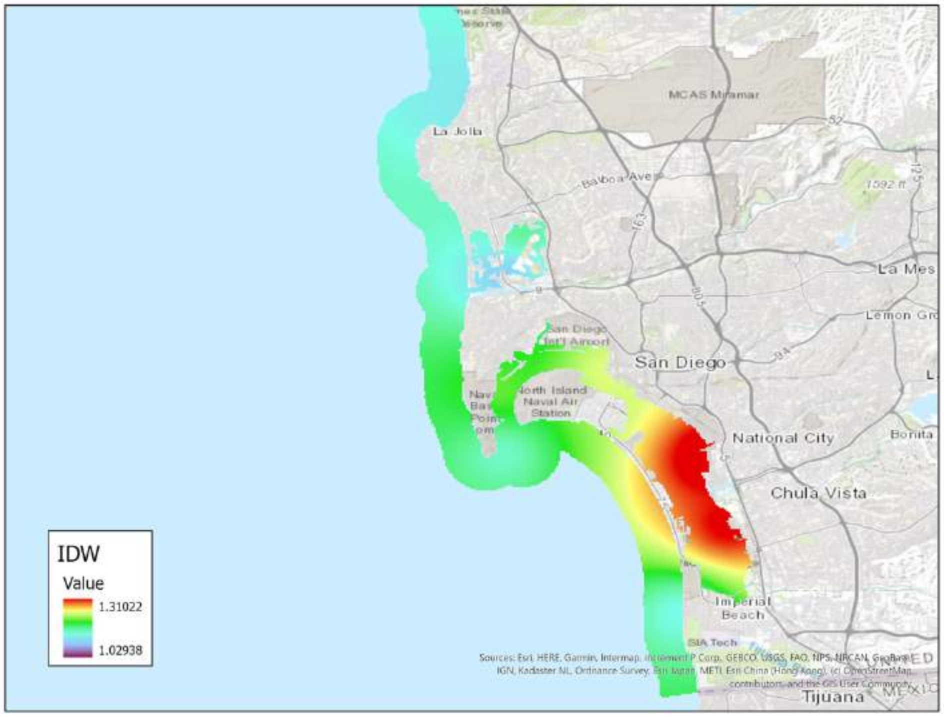
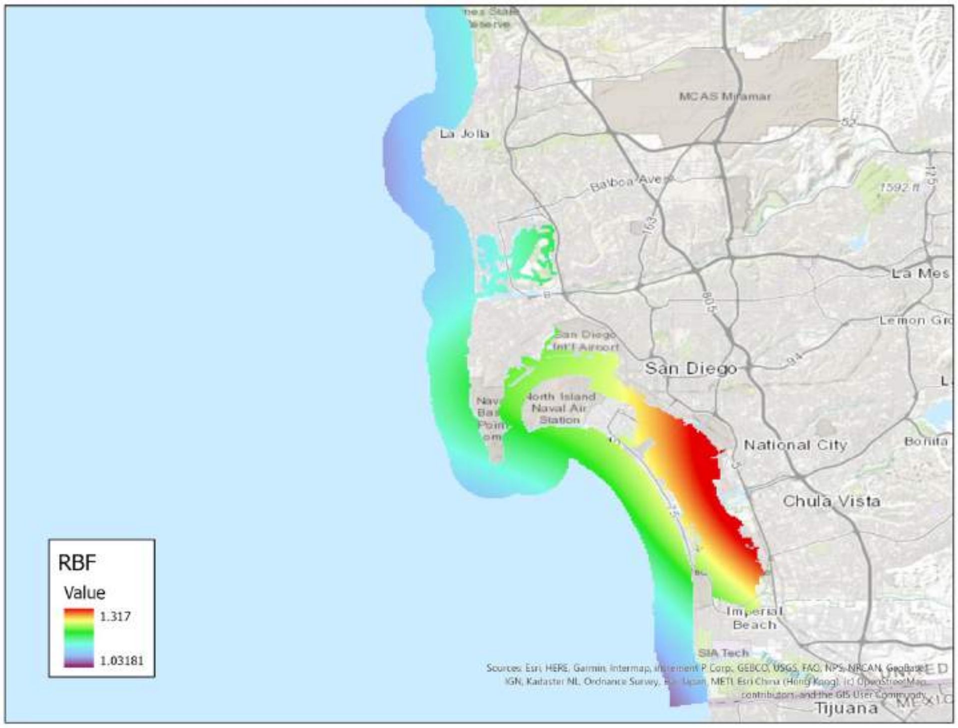


Figure 20. IDW interpolated tidal range values in San Diego County, CA. The values represent the average tidal range.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 21. RBF interpolated tidal range values in San Diego County, CA. The values represent the average tidal range.

After performing both the weighted overlay and fuzzy overlay analyses, differences in the interpolation method used are quite large. In the weighted overlay analysis, 50.75% of suitable cells were identified by the IDW method compared to 7.8% identified by the RBF method. The remaining cells were identified by both methods (41.4%). The large difference shows how the IDW method could be favored by the weighted overlay because of the clustering of similar cell values produced by the IDW interpolation. Comparatively, the fuzzy overlay analysis found more suitable cells from the RBF interpolation method (10.2%) compared to the IDW method (4.6%). The majority of suitable cells in the fuzzy overlay (85.2%) were identified by both interpolation methods. This indicates that the fuzzy overlay favored the RBF interpolation method which provided greater spatial variability of tidal ranges. It is important to note that the tidal ranges created by interpolation are not the only factor in determining suitable cells, and that other restrictions did influence the results of the overlay analyses.

5.3. Weighted Overlay

Looking at the general trends from the results of the weighted overlay analysis it can be seen that there are many more suitable cells located in the southern half of the study area, in Los Angeles, Orange, and San Diego Counties. This could be attributed to the spatial variance of tidal ranges in southern California. The initial tidal range data used in this study showed that average tidal ranges were larger in the southern regions. Los Angeles acted as a midpoint in which lower tidal ranges were seen north of Los Angeles up to Conception Point, and larger tidal ranges were seen south of Los Angeles down to the California-Mexico border. Because the weighted overlay analysis placed a large weight on the tidal range values, the results predicted more suitable cells in the southern half of the study area where tidal ranges are larger.

This factor drove the conclusion that tidal energy technology would be most suitable off of the coast of Los Angeles County. This area contained 46.8% of cells that were identified as suitable from the weighted overlay analysis. This result was generated using the total number of suitable cells predicted with both interpolation methods. Figure 22 highlights the suitable cells in Los Angeles County from the weighted overlay analysis.

While tidal range plays a large role in determining where are the most suitable areas for tidal energy technology, it is not the only factor. As seen in the initial tidal range data, the largest average tidal ranges within the study area occur in San Diego County. Even though this area had the highest tidal ranges, it only contained 38.2% of the predicted suitable cells, a difference of 8.5% compared to Los Angeles County. This indicates that there were likely more restrictions in the San Diego region that limit the identification of suitable cells. Specifically, San Diego

County has many Military Use Zones as well as protected areas and government regulation areas. These limiting factors contributed greatly to the results produced by the weighted overlay analysis and the differences seen between Los Angeles and San Diego Counties.

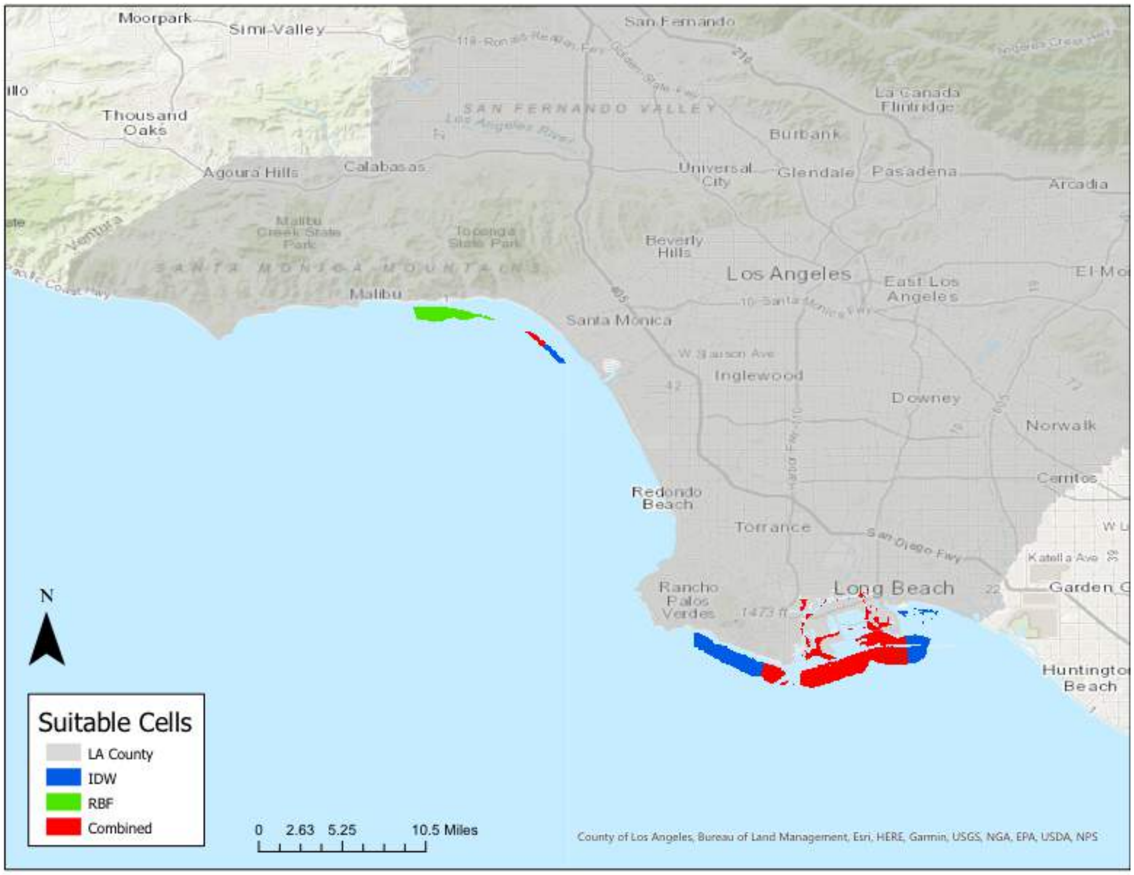


Figure 22. Weighted overlay analysis results in Los Angeles County, CA.

5.4. Fuzzy Overlay

The results of the fuzzy overlay analysis show that Los Angeles County again had the highest number of suitable cells (33.5%). This is a smaller percentage compared to the weighted overlay analysis (46.7%). This can be attributed to the spatial variation in cells produced by the fuzzy overlay analysis. Analyzing the results from the fuzzy overlay analysis shows that there were more cells overall that were identified as suitable compared to the weighted overlay analysis, although these results show a larger spatial variability compared to the weighted overlay analysis, most notably in the northern half of the study area. While the weighted overlay analysis found no suitable cells in both Ventura and Santa Barbara Counties, the fuzzy overlay analysis found 21.3% and 15.9% of the cells were suitable in those areas, respectively. The larger spatial variation can be attributed to the method by which the cells were classified, as the fuzzy method implements all parameters using a 0 to 1 scale. This allowed for a more fluid classification compared to the crisp logic used by the weighted overlay method. A more fluid classification would allow for more cells to be considered suitable, which is seen in the results of the fuzzy overlay analysis in Los Angeles County (Figure 23).

Figure 23. Results of the fuzzy overlay analysis in Los Angeles County, CA.

5.5. Energy Facilities

Energy facilities within close proximity to tidal energy technology sites are important so that once tidal energy is eventually harnessed it can be added into the energy grid and used efficiently. In the results of the weighted overlay analysis, almost every suitable cell (95.6%) was located within 15 km of an appropriate energy facility. This is an excellent statistic indicating that once tidal energy technology is implemented it can almost always be connected to the grid even if it is at a greater distance. Almost a quarter of all suitable cells (24.3 %) were located within 5 km of an appropriate energy facility, which would allow for even greater efficiency in adding usable energy to the grid.

The fuzzy overlay analysis found slightly fewer cells located within similar distances to energy facilities: 79.6% of suitable cells were located within 15 km and 21.5% of suitable cells were located within 5 km of an energy facility. While slightly less than the results from the weighted overlay, the statistics still indicate that a connection to the energy grid from tidal energy technology sites would be possible and efficient. The differences between the results of the different overlay methods can be attributed to the spatial variability of suitable cells produced by each method.

Chapter 6 Conclusions

The results of this study show that tidal energy technology is suitable and can be implemented in southern California. The coastal areas in Los Angeles County are the most suitable areas for the implementation of tidal energy technology based upon a weighed overlay and fuzzy overlay analysis. The implementation of tidal energy technology in southern California could have a positive impact in reducing the population's carbon footprint as well as mitigating some of the effects of climate change. A study conducted by the National Renewable Energy Laboratory found that renewable energy generation from today's and a few emerging technologies could adequately supply 80% of the U.S.'s energy needs by the year 2050 (NREL 2017). This would reduce greenhouse gas emissions from electricity by almost 81%, which would help to reduce harmful emissions. The potential for implementing tidal energy is immense; hence, the importance of continued exploration into the development and use of this technology.

The areas around Los Angeles and San Diego Counties were identified as the most suitable for tidal energy technology in both the weighted overlay and the fuzzy overlay analyses (Figure 24). The city of Los Angeles has an action plan to achieve 100% renewably generated electricity by 2045 (City of Los Angeles, 2020). Based on the results of this study, tidal energy technology development could potentially help the city of Los Angeles reach the renewable energy goals, with more in-depth research, planning and commitment on the part of vested interests. Other cities in California also have their own renewable energy goals, such as the city of San Diego, which has a Climate Action Plan that includes a goal of 100% renewable energy citywide by 2035 (City of San Diego 2019). Implementing tidal energy technology in areas identified by this analysis could potentially help cities reach their emissions goals.

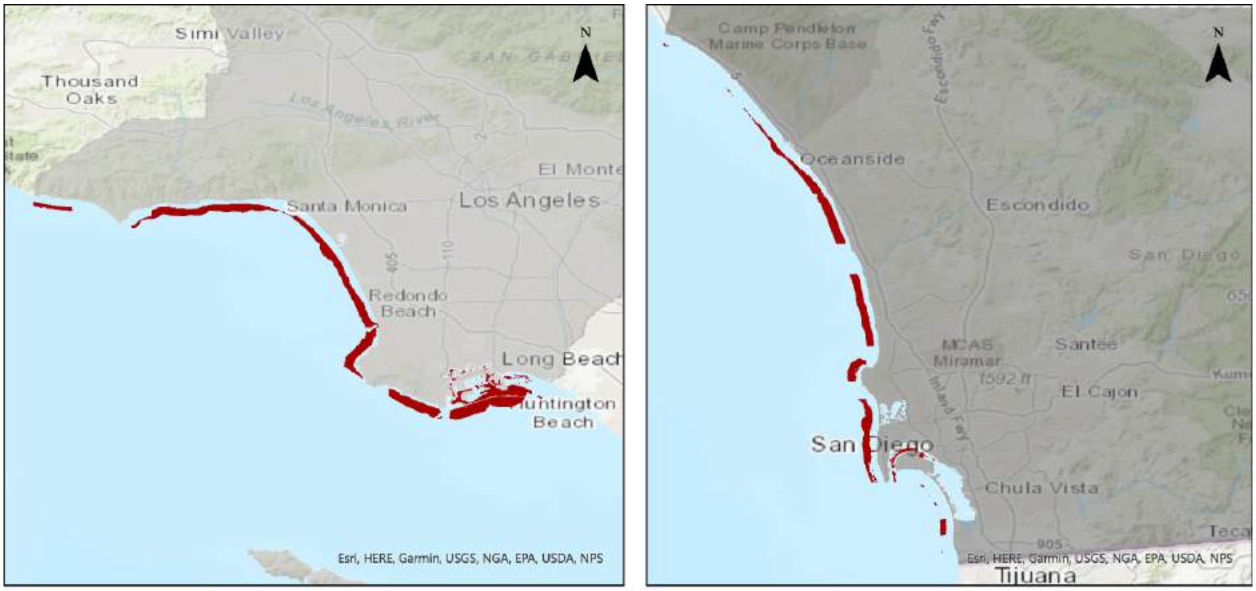


Figure 24. Suitable cells, represented in red, from both the weighted overlay and fuzzy overlay analyses. The left map shows Los Angeles County and the right map shows San Diego County.

6.1. Project Expansion

One major drawback in this study, and in southern California in general, is that the southern west coast of the United States does not have a large tidal range compared to other parts of the country. The average tidal range in the study area was approximately 1.2 m, whereas the east coast of the United States can see tidal ranges up to 2.5 m and Alaska experiences tidal ranges up to 9 m (U.S. Department of Commerce, 2008). Having a larger tidal range would be more beneficial in the long run when trying to produce tidal energy because a larger volume of water being moved through the converters results in higher rates of energy conversion. It is important to consider the fact that southern California does not have large tidal ranges when looking at the suitability of implementing tidal energy technology. While areas of southern California were found to be suitable based upon the analysis conducted in this study, California may not be the most suitable location in general for implementing this type of renewable energy. An examination of the cost efficiency between different types of renewable energy compared to tidal energy technology, could be used to identify the best solution for California. Additionally, a larger study that utilizes more areas throughout the United States could be of use to find the most suitable areas for tidal energy technology.

By applying the methodology used in this analysis of tidal energy technology to other parts of the United States, a larger database can be created of suitable locations for tidal energy technology installation. This could be useful for interested developers as well as local and federal governments that may have an interest in this type of renewable energy. There are many initiatives across the country with important renewable energy goals, and tidal energy technology could help in reaching those milestones.

6.2. Spatial Analysis

The use of spatial analysis within this study proved to be successful in identifying suitable areas for the implementation of tidal energy technology. The use of two interpolation methods for estimating tidal range values across the study area was also very successful. The IDW and RBF interpolation methods both provided strong predictions and had a wide spatial range of values. The results of these interpolations as well as the pre-processing of data also resulted in the creation of valuable spatial databases that store important information related to tidal energy in the state of California.

Spatial analysis has been used to study tidal and wave energy technologies in the past (Defne et al. 2011; Work et al. 2012; Vasileiou et al., 2017; Williams 2018) with great success. These studies utilized overlay analysis techniques with the application of spatial data. These principles were built upon successfully in this study of tidal energy technology by utilizing spatial data processing techniques and spatial data analysis. Spatial sciences proved very useful for identifying suitable sites for renewable energy development and should be applied further to advance the use of GIS techniques in the renewable energy industry.

6.3. The Future of Tidal Energy

Tidal energy technology is still relatively new and in the early stages of development. Many forward strides within the industry will come within the next few years, which will help to expand the number of areas that can host these kinds of technologies. The world's first subsea offshore tidal array, known as the Paimpol-Bréhat Tidal Array, has been deployed 16 km off-shore at a depth of 35 m with a second unit about to be deployed (REW 2019). Once completed, the Paimpol-Bréhat Tidal Array is expected to produce of 1 MW of power. Another company, Magallanes Renovables, is looking to design tidal turbines that attach to the underside of floating platforms (Givetash 2019). This idea would potentially reduce the costs of installation and maintenance compared to other types of tidal turbines. Companies like these represent the future development of tidal energy technology, proving that big gains are being made that will make tidal technology more efficient and cost-effective.

With newer developments in tidal energy technology, it is important to look at what will need to change in order to host these new technologies. This study was conducted using current tidal turbine technologies as a reference, and the results therefore do not reflect newer developments. Continuing this suitability study of tidal energy technology will be important moving forward, especially as the technology becomes more advanced.

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