Coastal Vulnerability Assessment for Archaeological Sites on San Clemente Island and San Nicolas Island, California

by

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To my parents, whose constant support is always my driving factor.

Table of Contents

List of Figures

List of Tables

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List of Abbreviations

CRVI	Cultural Resource Vulnerability Index
CVI	Coastal Vulnerability Index
GIS	Geographic Information System
NAVFAC	Naval Facilities Engineering Command
SCI	San Clemente Island
SNI	San Nicolas Island

Abstract

Archaeology allows us to see our human past and who we are as a people. This is a global narrative that spans the entirety of human existence. Many archaeological sites are delicate and are often unknowingly destroyed by human development. Because of this, pristine and protected islands offer a complete wealth of archaeological information. Stewardship programs and regulations set in place for protecting these cultural resources have been set into place on federally owned lands. San Nicolas Island and San Clemente Island, two of the Channel Islands owned by the United States Navy, are among the most well-documented and protected locations for archaeological sites in the United States. However, many of these sites are currently at risk from inundation and erosion. Global sea level rise not only potentially inundate the coastal zones but also accelerate geological erosion processes.

To help the U.S. Navy understand and protect against the threats from these natural processes, this study aims to identify the at-risk archaeological sites on San Clemente Island and San Nicolas Island. A spatial-explicit Coastal Vulnerability Index (CVI) was developed from the ranked vulnerability score of environmental variables, including slope, inundation, generalized rock type, and vegetation, using a Geographic Information Systems (GIS). Based on the CVI, a Cultural Resource Vulnerability Index (CRVI) was developed to rank the coastal vulnerability of the archaeological sites on the two islands

The results of the CRVI showed that 3.6% of the archaeological sites on San Nicolas Island and 19.2% of the archaeological sites on San Clemente Island fall within the Highly Vulnerable to Very Highly Vulnerable categories. The CRVI informs the land managers in the U.S. Navy an earlier response time to save these at-risk sites that may be completely destroyed in the next 100 years. With the result from the CRVI, further actions can be taken to mitigate and/or

excavate these at-risk sites to preserve the rich cultural resources of San Nicolas Island and San Clemente Island.

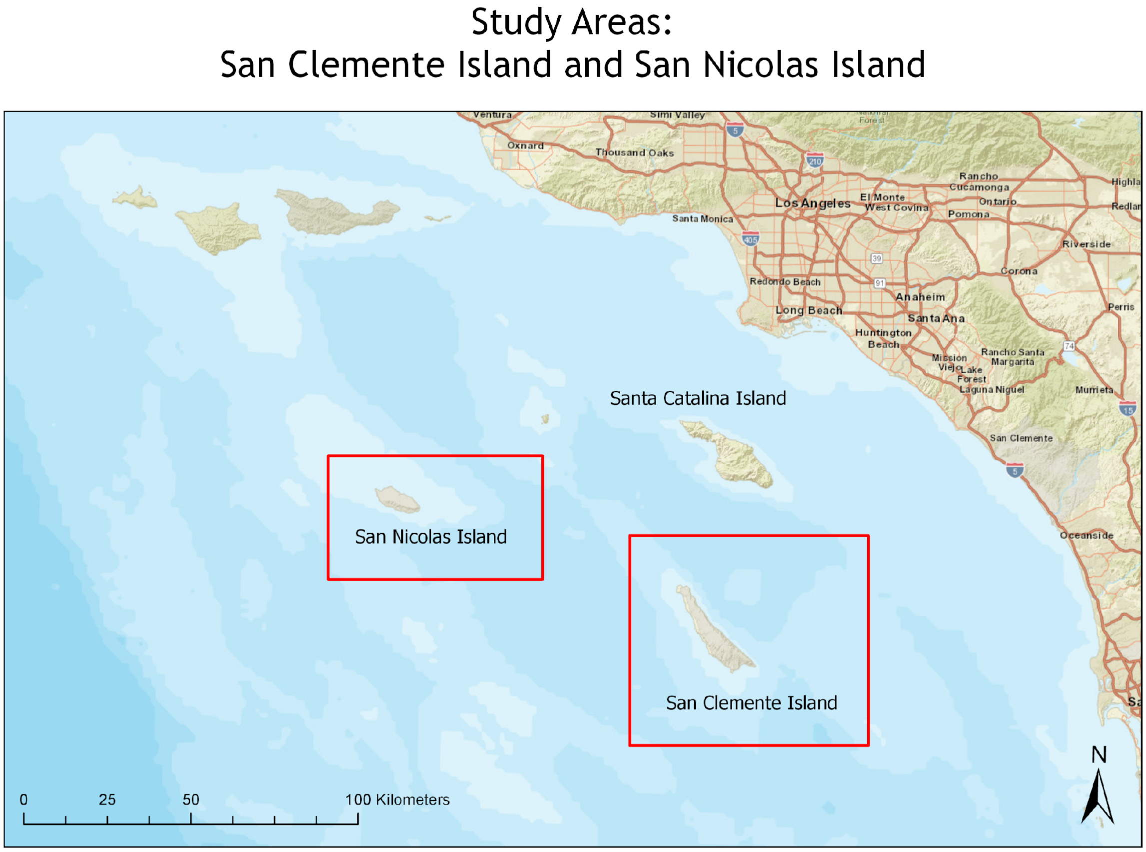
Chapter 1 Introduction

Archaeological sites are an important part of our collective human history. These fragile resources provide a wealth of knowledge that not only affect our understanding of the past, but also allow us to understand the trajectory of where our human story is headed (Reeder, Rick, and Erlandson 2012). Archaeology allows us as humans to find the source of who we are as a people. This is a global narrative that spans the entirety of human existence.

The study of material culture pushes past the written historic literature that focuses on the world's great individuals and societies, and allows for researchers to understand the everyday lives of all cultures, even if their unique histories were thought to be lost. Similar to modern day living, evidence of ancient cultures is often found in coastal areas due to the bountiful resources and pleasant climate. However, many of these sites are at risk because continuous erosion and wave action effectively tear apart these sites and destroy the resources found within. While archaeological sites might survive under water, the wave actions are incredibly damaging to the sites and erosion processes (Jones 2017). With global sea level projected to rise as high as two meters by 2100, sea level rise is expected to further exacerbate these factors and weaken coastal zone stability within the next 100 years (Gornitz, Beaty, and Daniels 1997; Lindsey 2017; NOAA 2010).

This study started with the request by the U.S. Navy to identify at-risk archaeological sites due to the potential sea level rise on the Navy-owned San Nicolas and San Clemente Islands. San Clemente Island and San Nicolas Island off the coast of Southern California are one of the most well-documented areas in the United States (Chiles 2015) (Figure 1). These islands are owned and protected by the United States Navy from typical human threats such as looting and coastal development. Through archaeological surveys conducted by the Naval Facilities

Engineering Command (NAVFAC) Southwest Division, 5,058 archaeological sites have been found on San Clemente Island and 535 archaeological sites have been found on San Nicolas Island. With sites dating back to approximately 8,000 to 9,000 years ago on the two islands, a wealth of cultural knowledge can be studied from early years to today (Jazwa and Perry 2013).



Study Areas:
San Clemente Island and San Nicolas Island

Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, © OpenStreetMap contributors, and the GIS User Community

Figure 1 - Study area including surrounding areas.

1.1. Channel Islands Archaeology

The archaeology of the Channel Islands is unique due to the islands' relative isolation, lack of development, and generally arid climate (Braje 2010). Due to these variables, the rich archaeological history of these islands provides a wealth of knowledge to archaeologists. Archaeological evidence has provided researchers with an abundance of data that will influence the ways we see how Native Americans lived and even arrived in the Americas. In fact, the Channel Islands are at the center of a debate on the Americas' early settlement.

Because of the early dates of archaeological sites on these islands and the ancient human remains that we now call Arlington Springs Man, it is now believed that the earliest human ancestors to reach the Americas probably followed the coastline down from Alaska to Central and South America while also spreading eastward instead of the initial theory that these ancestors migrated between glaciers following game animals through Canada (Chiles 2015; Rick et al. 2005; Erlandson et al. 2007). Among the sites found that contribute to the new North American migration theory, Arlington Springs Man (found on Santa Rosa Island with bones carbon dated to around 13,000 years ago, making the remains one of the oldest in North America) and numerous sites showing evidence of early mastery of seafaring (shown in very early fishing technology and shell mounds dating back to over 10,000 years ago) are perhaps the most notable (Erlandson et al. 2007). However, even before these sites were found, archaeologists and other researchers were drawn to these islands.

The archaeology of the Channel Islands has been a source of intrigue for scientists since the 1870s when the first researchers searched the island for artifacts to fill museum shelves (Yatsko 2000). It was not until the 1950s that professional research and archaeological excavation was established across San Nicolas, San Clemente, Anacapa, Santa Catalina, and Santa Barbara Islands through University of California at Los Angeles' (UCLA) Archaeological Survey (Yatsko 2000). These surveys focused less on collecting from cemetery sites and more on shell refuse piles (commonly known as shell "middens") to gain a better understanding of the native peoples' day-to-day life (Yatsko 2000).

With the focus less on collecting and more on understanding, archaeology has created a research boom on these islands to understand many aspects of ancient life that include human impact on island ecosystems, subsistence strategies, Holocene settlement, marine adaptations, trade systems, and the emergence of cultural complexity (Rick et al. 2005). Today, the entirety of San Nicolas Island has been surveyed and most of San Clemente Island has been surveyed with results that include a vast variety of sites that can contain burials, housing depressions, quarries, middens, tool production sites, and many more (Rick et al. 2005). More information about the history of these islands can be seen in Appendix A.

1.2. Motivation

With the concerns of sea level rise, the United States Navy is in pursuit of saving many archaeological sites through their NAVFAC Cultural Resources Program. Through a partnership with the program, this study attempts to understand which of the archaeological sites are most at risk on Navy-controlled San Clemente Island and San Nicolas Island. Although these islands have been well surveyed, a study of this kind has yet to be accomplished for the two islands. This study uses geographic information systems (GIS) to examine the sites by exploring spatial-explicit assessment methods such as the Coastal Vulnerability Index (CVI). Through these assessment methods, a multitude of factors that could endanger archaeological sites, such as water inundations and coastal erosion are considered (Anderson et al 2017; Reeder, Rick and Erlandson 2012).

Although NOAA has conducted many studies on sea level change, their simulation models have not covered to the spatial extents of San Nicolas Island and San Clemente Island.

As seen in Figure 2, NOAA's sea level rise estimator does not cover the two islands (NOAA, n.d.). These two islands are exempt from the simulation perhaps due to their close connection with the Navy and how the Navy has protected these islands and the data attached to them.

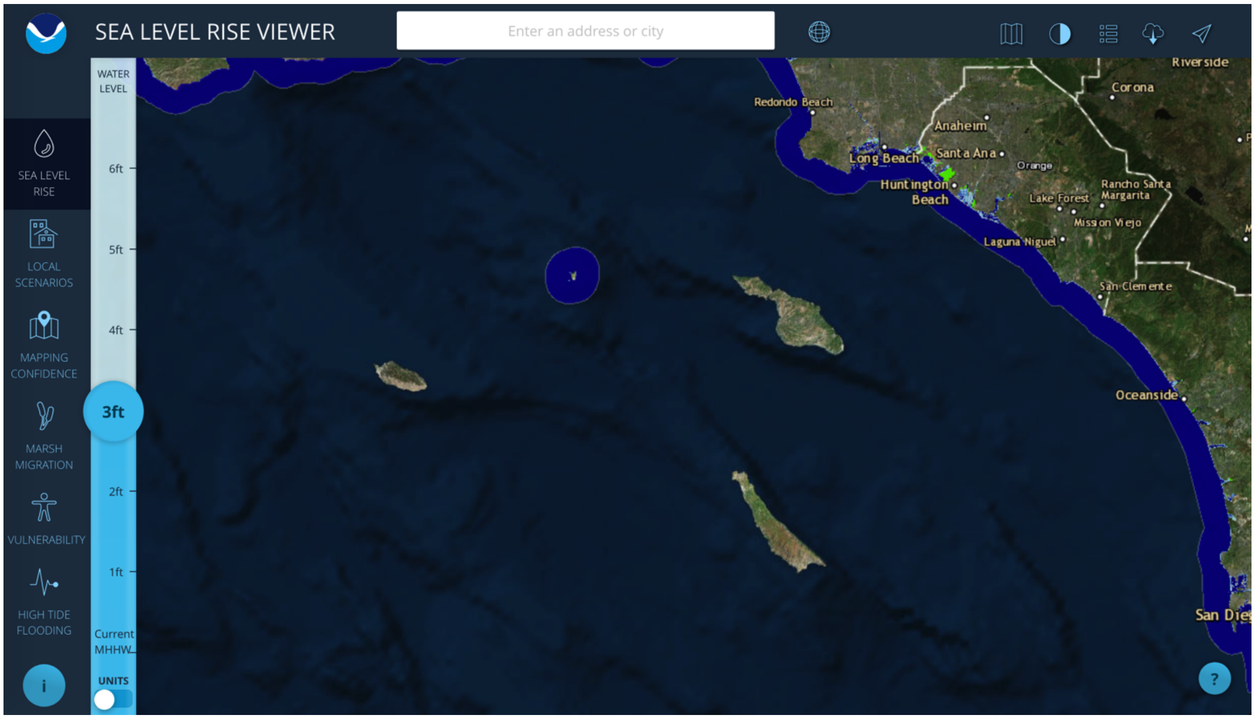


Figure 2 - Sea Level Rise Viewer from NOAA's Office of Coastal Management with view of the southern Channel Islands including San Nicolas and San Clemente Islands.

1.3. Research Objectives

San Clemente Island and San Nicolas Island are unique because of their deep ties to Navy stewardship and possession. In order to continue their pursuit of stewardship, the NAVFAC Cultural Resources team needs a viable source of data to protect the archaeological sites at risk from rising sea levels. Viable data for the Navy's use is the primary goal of this study. The goal of this study is to understand which archaeological sites are most at risk and to understand which portions of the coastline are most vulnerable on San Nicolas Island and San Clemente Island. The study is aimed to recognize at-risk archaeological sites on the two islands, not only due to sea level rise threats but more broadly on overall coastal vulnerability.

1.4. Thesis Layout

The following chapters will outline previous works done in the field, the methods used to complete this study, the results of this work, and a conclusion to the works created in this study. Chapter 2 will examine how previous researchers have designed and understood coastal vulnerability through assessment processes and how these assessment processes have been adapted for use in the archaeological field. The methods used in this study are examined in Chapter 3 and include the introduction of data editing, the Coastal Vulnerability Index (CVI) creation and use, and the final creation of the Cultural Resource Vulnerability Index (CRVI). Once methods are established, Chapter 4 describes the results of this study. Finally, Chapter 5 takes a critical look at the results and concludes with the successes and changes that can be made in future renditions of this study.

Chapter 2 Related Work

Coastal assessment is an important step towards future coastal mitigation. Researchers have attempted to understand how coasts change and what can be done to prevent coastal devastation for many years. This chapter reviews past studies of coastal vulnerability assessments to bridge what has been done in the past and what this study accomplishes. It starts with an overview of the environmental characteristics that contribute to coastal vulnerability (Section 2.1), moves on to describe the coastal vulnerability assessments (Section 2.2), and finishes with the assessment methods for cultural resources along the coast (Section 2.3).

2.1. Coastal Vulnerability

Sea level rise and coastal erosion are two major threats to communities and existing archaeological sites near coastlines. Sea level rise, while gradual, has received much attention for research in recent years due to its linkage to global climate change. On the other hand, near-coast areas also experience the danger from eroding by dynamic ocean processes. The causes and projections of sea level rise are reported in Section 2.1.1, and the environmental characteristics affecting coastal erosion are presented in Section 2.1.2.

2.1.1. Sea Level Rise

Oceanography research has been attempting to understand the potential sea level rise. Water expansion from warmed ocean waters and ice/glacier melt are two major contributors to sea level change (Williams and Gutierrez 2009), and have increased the volume of ocean waters significantly over the past 200 years (NOAA 2010). While this global sea level change has been seen during the natural warming and cooling cycles for the last 400,000 years (Figure 3) (NOAA

2010), the pattern of sea level change in recent century was found greatly punctuated by the periods of ice and glacial melt (Church et al. 2008).

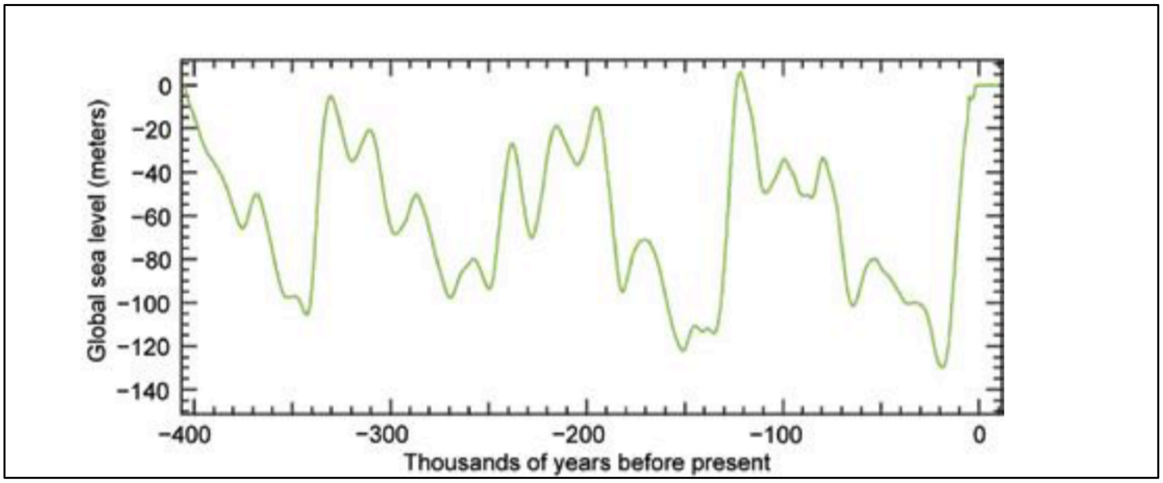


Figure 3 - Global sea level change from 400,000 years ago to present (NOAA 2010)

The most notable sea level rise projections can be attributed to the National Oceanic and Atmospheric Administration (NOAA) and the Intergovernmental Panel on Climate Change (IPCC) (NOAA 2010 and IPCC 2013). The two agencies have shown slightly differing sea level projections in the next 100 years. NOAA uses tidal gauges located all over the world and satellite laser altimeters to measure sea level height and change for over 100 years. Combined with these past records with temperature data (to factor thermal expansion in), the global mean sea level is projected to have a very high confidence (greater than 90% chance) to rise between 0.2 meters and 2.0 meters by 2100 (Lindsey 2017).

On the other hand, the IPCC's Fifth Assessment Report (AR5) estimates sea level rise using three different scenarios of global carbon dioxide (CO_2) emission. If globally high CO_2 emissions continue, sea levels are projected to rise between 52 cm to 98 cm by Year 2100. If there are aggressive emission reductions instated globally, the sea level rise could be reduced to 28 cm – 61cm by the same year. The best scenario estimated, as of 2014, is a 44cm rise by 2100 (IPCC 2013).

The affects of sea level rise can be seen in heightened water levels flooding previously dry shorelines. Moreover, sea level rise enhances storm intensity, shoreline retreat, rates of erosion, tidal ranges, and coastal flooding. These environmental changes result in further change of the physical terrain on coastlines (Reeder, Rick, and Erlandson 2012; Rowland 1992; Westley et al 2011; Erlandson 2012).

2.1.2. Coastal Erosion

Compared to sea level rise, coastal erosion is innate to all coastal areas. For naturally caused erosion in coastlines, both water erosion and wind erosion can be involved, but water is known as the major force. The processes, including wave actions, high tide and storm surge, result in soil material loss and displacement. An example of this destructive force can be seen in Figure 4 below. As seen in the Figure, storm surges can easily undercut previously secure embankments, causing significant damage.

Figure 4 - Coastal erosion from January 2-24, 2010 from storm surges in San Francisco (https://www.usgs.gov/media/images/coastal-erosion-san-francisco-0)

Erosion can impact various types of coastal geomorphology, but it is especially prominent in sandy beach environments (Feagin, Sherman, and Grant 2005). In sandy beach environments, wave directions, wave intensity, and availability of barriers from wave actions are variables highly correlated to erosion’s effect on coastal vulnerability. On the other hand, for cliffed, rocky coastal areas, coastal erosion is controlled by other sets of variables including the hardness of rocks, structural weakness, coastal configuration, strength of stone compaction, cliff height, and wave intensity (Feagin, Sherman, and Grant 2005; Shepard and Grant 1947). The diversity of these variables makes it difficult to pinpoint the exact cause of major erosion events.

Many of the variables mentioned can be attributed to broader variables including slope, soil, and geology. Vegetation can also strengthen coastlines against erosion. The severity of erosion, therefore, not only depends on water force from the ocean. Site variables such as slope, soil, geology, and vegetation inhibit or advance erosion processes. These site variables have been studied spatially through geographic information systems (GIS) for better understanding of the complex nature erosion prevention (Gornitz et al 1994; Özyurt and Ergin 2010; Aboudha and Woodroffe 2010; Thieler and Hammar-Klose 2000).

2.2. Coastal Vulnerability Assessment Methods

One of the oldest methods to understand how coastal areas are affected by sea level rise is the Bruun Rule. Based entirely on an erosion equation to calculate the probability of shoreline retreat and erosion caused by sea level rise, Bruun (1962)'s study sparked more coastal assessment studies that continue to evolve today. More recent studies have examined erosion, much like Bruun, but most have included variables such as slope, geology, tide, and significant wave height, among many more. These methods include the DINAS-Coast Dynamic Interactive Vulnerability Assessment (DIVA), Coastal Zone Simulation Model (COSMO), and the Coastal Vulnerability Index (CVI) (Kay and Travers 2008; McFadden, Vafeidis, and Nicholls 2003; Kotinas et al, n.d.).

To understand how sea level rise will affect coastal regions, Vafeidis et al (2008) attempted an assessment by instating the Dynamic Interactive Vulnerability Assessment (DIVA) modeling tool through the DINAS-COAST project. This tool is a part of a global coastal database that is intended to form a reliable, consistent basis for coastal vulnerability evaluations. It uses a graphical user interface (GUI) that produces scenarios regarding climate change and socio-economics to understand all aspects of vulnerability to sea level rise. The DIVA tool allows for the database to be used in a practical way by modeling coastline segments in relation to parameters provided by the database (Vafeidis et al 2008; DINAS-COAST 2006). DIVA, unfortunately, is now unavailable due to high running costs.

The Coastal Zone Simulation Model (COSMO) is another modeling tool created to improve coastal management. Created in Holland, the interactive tool explores the impact of development for environmental and coastal protection. The data processed from this method enables developers as a decision support tool. However, any data created from this process would need to be further studied to ensure accurate results (Kay and Travers 2008).

The Coastal Vulnerability Index (CVI) was first introduced by Gornitz *et al.* (1990) as an efficient way to spatially analyze the variables that influence coastline susceptibility. A CVI is a spatial index of coastal vulnerability created by classifying environmental risk variables from least to most susceptible using a GIS system. The index ranks variables from least to most vulnerable and then uses layered spatial data to understand areas of least and most vulnerability. The classification of the variables is in 5 categories: 1 – very low risk, 2 - low risk, 3 – moderate risk, 4 - high risk, 5 – very high risk, shown in Table 1. The environmental risk variables include elevation, lithology, subsidence, tropical storm probability, susceptibility to erosion, and storm surge, but many variables can be added or subtracted based on coastline type and need.

Table 1 - Gornitz *et al*'s coastal risk classification scheme (1994)

Variable	Very Low (1)	Low (2)	Moderate (3)	High (4)	Very High (5)

Elevation (m)	≥ 30.0	20.1 – 30.0	10.1 – 20.0	5.1 – 10.0	0 – 5.0
Geology (relative resistance to erosion)	Plutonic Volcanic (lava) High-medium grade metamorphics	Low-grade metamorphics Sandstone and conglomerate (well-cemented)	Most sedimentary rocks	Coarse and/or poorly sorted unconsolidated sediments	Fine unconsolidated sediment Volcanic ask
Landform (geomorphology)	Rocky, cliffed coasts Fiords Fiards	Medium cliffs Indented coasts	Low cliffs Glacial drift Salt marsh Coral reefs Mangrove	Beaches (pebbles) Estuary Lagoon Alluvial plains	Barrier beaches Beaches (sand) Mud flats Deltas
Rising sea level change (mm/year)	< - 1.0 Land rising	-1.0 – 0.99	1.0 – 2.0 Within range of eustatic rise	2.1 – 4.0 Land sinking	> 4.0
Shoreline erosion/ Accretion (m/year)	> 2.0 Accretion	1.0 – 2.0	- 1.0 - +1.0 Stable	- 1.1 - -2.0	< -2.0 Erosion
Mean tide range (m)	< 1.0 Microtidal	1.0 – 1.9	2.0 – 4.0 Mesotidal	4.1 – 6.0	> 6.0 Macrotidal
Maximum wave height (m)	0 – 0.29	3.0 – 4.9	5.0 – 5.9	6.0 – 6.9	> 6.9

The classified environmental risk variables, represented in spatial layers in the GIS, were next used to calculate a numeric value indicating coastal vulnerability for each unit of analysis, typically a gridded cell along the coastline, as seen in Figure 5. There have been a variation of the CVI equations used to calculate this index, many of which were recommended by Gornitz, Beaty, and Daniels (1997) and Thieler and Hammar-Klose (1999). See Table 2 for the list of CVI equations recommended by Gornitz, Beaty, and Daniels (1997). All equations involve the multiplication or addition of all classified coastal risk values.

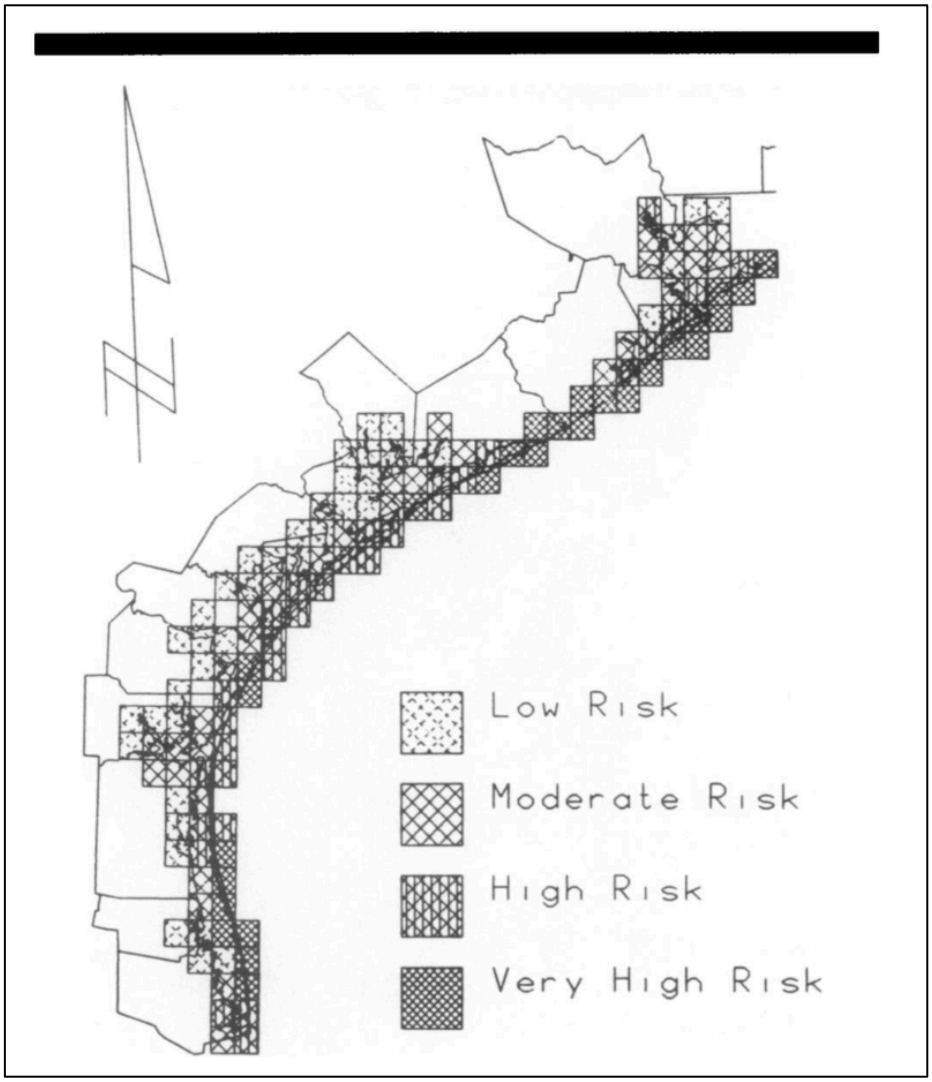


Figure 5 - The distribution of Texas coastal risk using CVI in 30-m resolution (Source: Gornitz *et al* 1994)

Table 2 - CVI Equations from Gornitz, Beaty, and Daniels (1997)

Modifications of CVI Equations (Gornitz, Beaty, and Daniels 1997)	
Product mean	$CVI = \frac{(x_1 * x_2 * x_3 * \dots x_n)}{n}$
Square root of product mean	$CVI = \sqrt{\frac{(x_1 * x_2 * x_3 * \dots x_n)}{n}}$
Modified product mean	

	$CVI = \frac{[x_1 * x_2 * \frac{1}{2}(x_3 * x_4) * x_5 * \frac{1}{2}(x_6 * x_7)]}{n-2}$
Average sum of squares	$CVI = \frac{({x^2}_1 * {x^2}_2 * {x^2}_3 * {x^2}_4 \dots {x^2}_n)}{n}$
Modified product mean (2)	$CVI = \frac{(x_1 * x_2 * x_3 * x_4 \dots x_n)}{5^{(n-4)}}$
Sum of products	$CVI = 4x_1 + 4x_2 + 2(x_3 + x_4) + 4x_5 + 2(x_6 + x_7)$
Where: n = variables present x_1 = mean elevation x_2 = local subsidence trend x_3 = geology x_4 = geomorphology x_5 = mean shoreline displacement x_6 = maximum wave height x_7 = mean tidal range	

The main difference between these CVI equations is their sensitivity to data change (Kotinas et al, n.d.). The mean value for the product of all the classified environmental risk values (product mean) is highly sensitive to small changes in the vulnerability ranking of variables while the square root of the product mean allows for a more consistent ranking system (Kotinas et al, n.d.). As the result, the equation used in this study is the square root of product mean introduced by Thieler and Hammar-Klose's (1999) study:

$$CVI = \sqrt{\frac{a * b * c * d * e * f}{6}}$$

where *a* was geomorphology, *b* was coastal slope, *c* was relative sea-level rise rate, *d* was shoreline erosion rate, *e* was mean tide range, and *f* was mean wave height.

While the DIVA and COSMO systems have been successful in their own right, the CVI continues to be the most popular method to inform coastal vulnerability. Since Gornitz *et al* (1990), the CVI approach has been used for coastal vulnerability assessments not only in the United States (e.g. Atlantic Coast, Pacific Coast, and the Gulf of Mexico), but broadly around the world (e.g. Turkey, Israel, Newfoundland, Australia, India, and Sicily) (Özyurt and Ergin 2010; Lichter and Felsenstein 2012; Westley et al 2011; Abuodha and Woodroffe 2010; Nageswara Rao et al 2008; Anfuso and Del Pozo 2009).

While Gornitz *et al* (1994)'s and Thieler and Hammar-Klose (1999)'s CVI allow for large variations of environmental risk variables, some recent studies believe that weighted variables create a stronger study. Nageswara Rao *et al* (2008) created a weighted CVI on the Andhra Pradesh coast of India. Instead of the original CVI's un-weighted variables, the authors placed higher weights on the coast's largest stressors (geomorphology, slope, and shoreline change) in the threat of sea level rise. This allowed for a higher variation of variables, but enabled the most important variables (geomorphology, slope, and shoreline change) to have a stronger influence on the study. I chose not to use a weighted equation due to inconsistent levels of data resolution.

2.3. Tools Adapted for Archaeology and Cultural Resource Management

In the past several years, CVI has also been adapted for use in studying the effect of coastal vulnerability to archaeology sites. Reeder, Rick, and Erlandson (2012) studied on the vulnerability of coastal archaeological sites for the northern Santa Barbara Channel region of California, including the northern Channel Islands and the mainland coast ranging from Santa Barbara to Point Conception, by extending CVI to a Cultural Resource Vulnerability Index (CRVI). Based on Thieler and Hammar-Klose (1999)'s CVI (the square root of the product mean), Reeder, Rick, and Erlandson (2012) further used GIS to measure an archaeological site's risk to coastal vulnerability by a weighted average approach:

$$CRVI = \frac{4d + 3v + 2u}{3}$$

where d is the distance of the archaeological site to shoreline, v is the CVI of the shoreline the site is the closest to, and u is the threat of urban development. Similar to CVI, these variables were firstly classified, with a numeric value from one (least vulnerable) to five (most vulnerable) before inserting to the equation for the final CRVI (Reeder, Rick, and Erlandson 2012). The final product of this study can be seen in Figure 6 below.

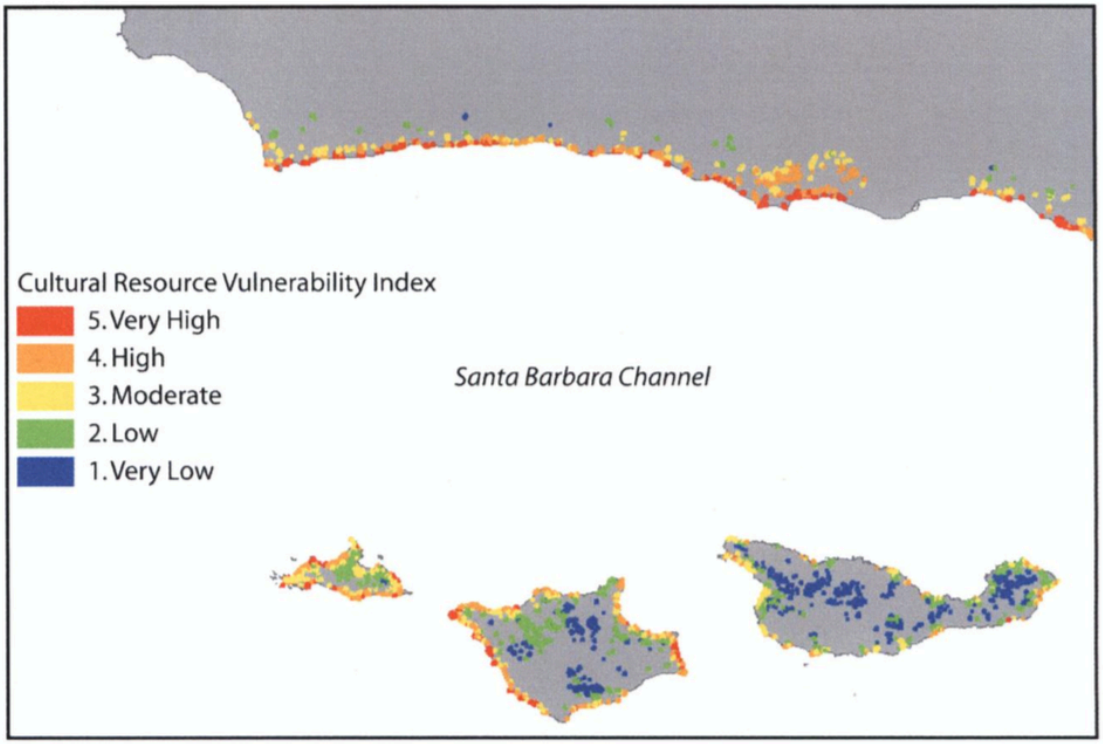


Figure 6 - Archaeological sites ranked according to CRVI (Reeder, Rick, and Erlandson 2012)

Chapter 3 Methods

This chapter describes data sources, data preparation, and analysis approaches used in this study. This chapter starts with the data source and preparation (Section 3.1). The section thereafter discusses the calculation of the Coastal Vulnerability Index (CVI) (Section 3.2) and the subsequent Cultural Resources Vulnerability Index (CRVI) (Section 3.3).

3.1. Data Acquisition and Preparation

The data for this study was compiled from various sources, both within organizations' ArcGIS Online databases and own hosted websites. The list of data information and their sources can be found in Table 3.

Table 3 - Data Sources

Source Data:	Year:	Data Type:	Data Available:	Additional Information:	Source:
Cultural Resource Datums	N/A	Points	San Clemente Island	Gathered and corrected using digitized reports and site maps	Navy NAVFAC
SNI_ Archaeological _Sites_2002	2002	Polygon	San Nicolas Island		Navy NAVFAC
USGS NED	2013	Raster	Southern Channel Islands and Small Portion of Mainland Coast	1/3 arc second (~10 meter) Imported as three DEM rasters.	USGS (https://viewer.nationalmap.gov/basic/#productSearch)
Geologic Map of California	2010	Polygon	California	Source media from hardcopy paper. 1:750,000 scale.	Department of Conservation (https://maps.conservation.ca.gov/cgs/gmc/)

Vegetation – San Nicolas Island [ds1501]	2013	Polygon	San Nicolas Island	Created using National Vegetation Classification Standards (NVCS) for Naval Base Ventura County (NBVC)	HDR, Inc. (https://tiles.arcgis.com/tiles/Uq9r85Potqm3MfRV/arcgis/rest/services/biosds1501_cpu/MapServer)
SCI_ Vegetation Map20180430	2018	Polygon	San Clemente Island	Created for Navy use. Created from 4-band, digital multispectral image dataset with spatial resolution of 0.15m. Tested accuracy of 77% using fuzzy methods.	Department of Geography, San Diego State University (https://services1.arcgis.com/SIYkiqjmENweC50g/arcgis/rest/services/draftMap20180618/FeatureServer)
Medium Resolution Shoreline	1994	Vector Line	Contiguous United States	1:80,000	NOAA (https://idpgis.ncep.noaa.gov/arcgis/rest/services/NOAA/NOAA_Medium_Resolution_Shoreline/MapServer)

Through careful research of the coastal assessment methods descried in Chapter 2, the methods used in this chapter were mainly adapted from Reeder-Myers (2015) and Aboudha and Woodroffe (2010). The variables investigated in this study included vegetation, generalized rock type, slope, and inundation levels. Due to the government-protected nature of these islands, very little high-resolution data was available for use through traditional online public GIS sites.

Therefore, data such as geomorphology, sea level change, mean tide range, shoreline erosion/accretion, and wave height are not used.

The overall workflow of data preparations is presented in Figure 7. Specific processes of data preparation for individual variables are detailed in the following subsections. Unless noted, the preparation and analysis were conducted in Esri ArcGIS Pro 2.1. All data was projected into the Universal Transverse Mercator (UTM) Projection Zone 11N with a North American Datum of 1983 (NAD 83) prior to analysis.

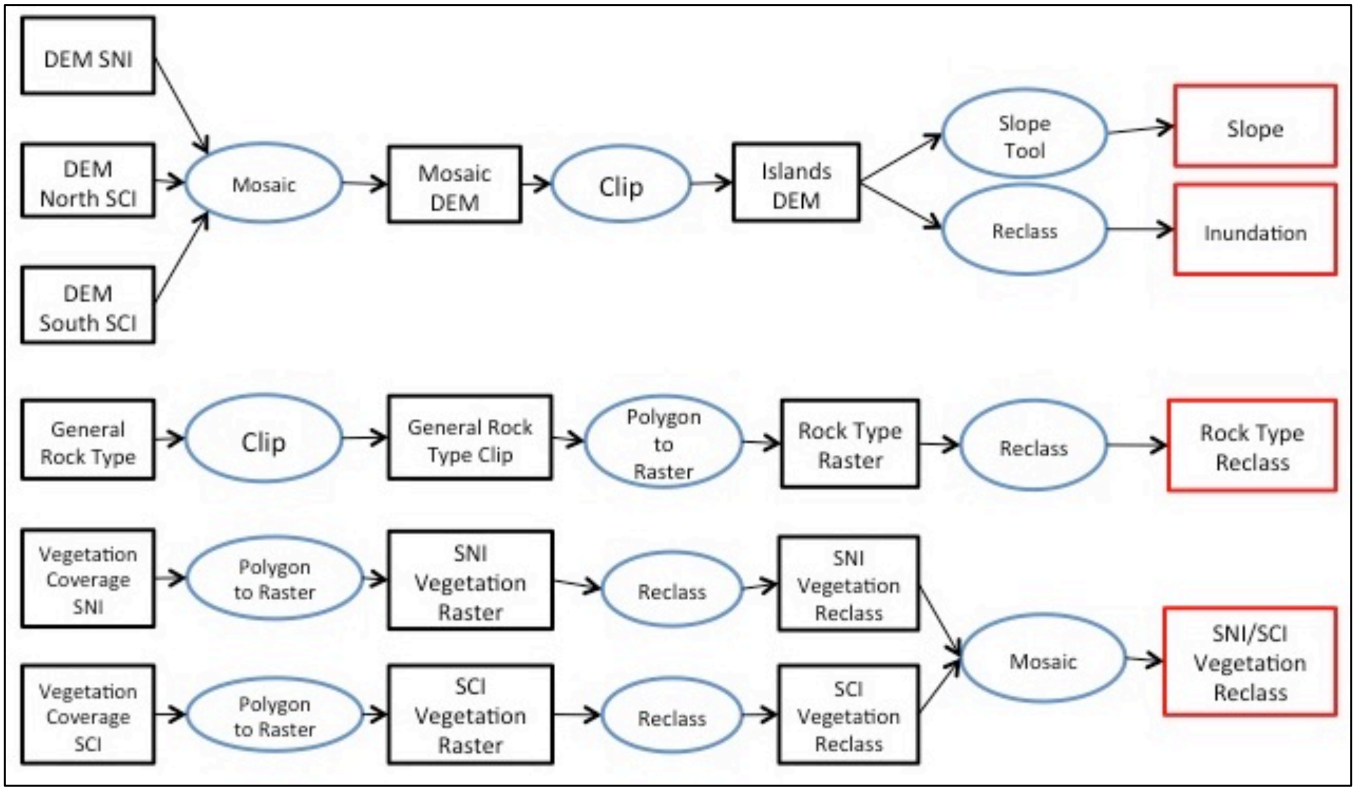


Figure 7 - The workflow of spatial data preparation for the calculation of CVI

3.1.1. Archaeological Site Data

Archaeological site data was provided by the NAVFAC team. The spatial data for the archaeological sites for the two islands were collected for different archaeological research purposes, which resulted in different data types (Rich Bark, personal communication). The SCI archaeological site data was a point shapefile collected from several previous studies. The site data on SNI, on the other hand, was surveyed as polygons documenting the boundaries of the sites. The data of the archaeological sites for both islands was ready to use as-is with the exceptions of projection transformation (to UTM zone 11N) and reclassification (as described in the CRVI section below).

3.1.2. Elevation

The elevation data comprised of 1/3 arc-second Digital Elevation Model (DEM) rasters downloaded from the U. S. Geological Survey website. Three raster grids covered the entire extent of the study area was mosaicked together using the "Mosaic to New Raster" tool in ArcGIS Pro. An island boundary shapefile was used to only focus on the two islands. This was done by creating a 200-meter buffer around the island shapefile and merging the buffer to the polygon. Then, the DEM was clipped to this buffered polygon to account for any possible land area not accounted for in the coastline polygon. This elevation gridded data was then used to create slope and inundation zone variable data, described in the subsections below.

3.1.3. Slope

A slope raster was created by the DEM created in the last section for the study area using the Slope tool (Figure 8). The same resolution as the DEM layer (10 m) was used for the slope raster. In order to create a CVI, the slope raster was reclassified into five categories ranked from one (most vulnerable) to five (least vulnerable) in terms of coastal vulnerability: 1 - Cliffed slope (> 45 degrees), 2 - steep slopes (20.1 – 45 degrees), 3 - moderate slopes (10.1 – 20.0 degrees), 4 - gentle slopes (6.1 – 10 degrees) and 5 - low plains (0 – 6.0 degrees).

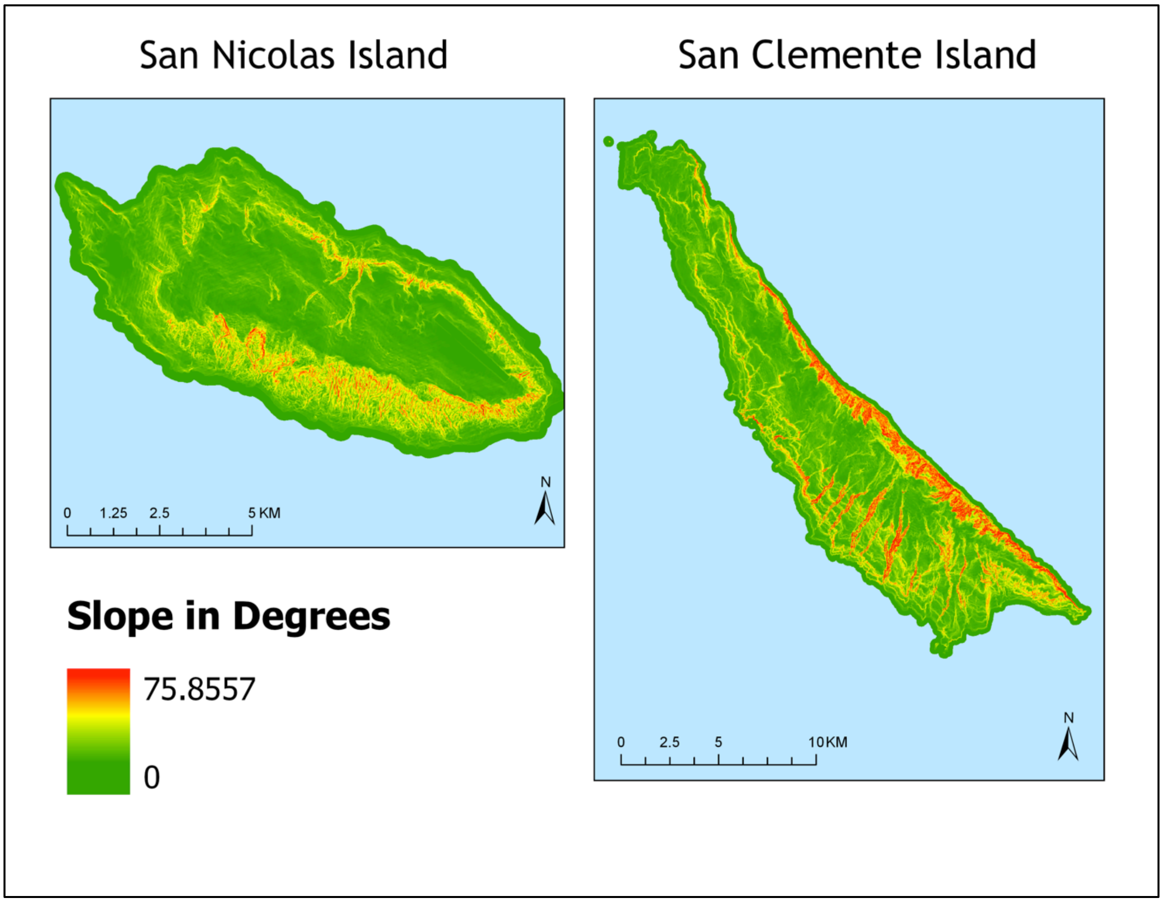


Figure 8 - Slope in degrees for San Nicolas Island and San Clemente Island

3.1.4. Inundation

Inundation zone layer was the second dataset produced from the DEM. Inundation indicates the area extent potentially underwater with various levels of sea level rise projected by NOAA (2010) and IPCC (2013). In order to create inundation, the DEM raster was reclassified into five categories using the "Reclassify" tool in ArcGIS Pro. The classification of the inundation zones layer took into account both the sea level rise projection from the two trustworthy sources (NOAA and IPCC) and the accuracy of the source data (USGS 10-meter DEM). The classification of the inundation zones can be seen in Table 4.

Table 4 - Reclassification of Inundation Levels

DEM Range (m)	Classification Description	Vulnerability Ranking
0* - 0.3	Any land area less than 0.3 m; the value was rounded from both NOAA projection (0.272 m) and the lowest end of IPCC's aggressive emission reduction projection (0.28m)	Very High (5)
0.3 – 0.6	From IPCC's aggressive emission reduction projection range (0.28 to 0.61m) and also encompasses IPCC's best estimate (0.44m) and NOAA's best estimate (0.272m)	High (4)
0.6 – 1.0	From the high end of IPCC's estimates (0.52 to 0.98m rounded up to 0.6 – 1.0m)	Moderate (3)
1.0 – 2.0	From highest IPCC estimate (0.98 rounded to 1m) to highest NOAA projection (2m)	Low (2)
> 2.0	Above highest NOAA estimate (2m)	Very Low (1)
*Including any DEM reported lower than zero (0)		

Any land area less than 0.3 m in elevation, rounded from both NOAA's best-scenario projection (0.272 m) and the lowest end of IPCC's aggressive emission reduction projection (0.28m), was most likely to be inundated; the area was reclassified into the value of five (5) as "most vulnerable". Areas with elevation equal or higher than 0.3 m but lower than 0.6 m were reclassified to the value of four (4) as moderately high vulnerable; the range of values were rounded up from IPCC AR5's aggressive emission reduction projection range (0.28 to 0.61m). Based on the high end of IPCC's estimates (0.52 to 0.98m), the inundation zone for the areas with elevation between 0.6 m to 1.0 m was reclassified to the value of three (3). Similarly, the "Less Vulnerable" area of inundation was reclassified to the value of (2), with the range from 1.0 m (rounded up from the highest IPCC estimate (0.98 m) to 2.0 m (the highest NOAA projection). Any areas with elevation equal to or greater than 2.0 m were reclassified as the value of one (1).

3.1.5. Generalized Rock Types

Generalized rock types show areas of rock difference on the two islands. Different rock types erode at unique rates and this data shows the areas where the rock is most susceptible to erosion. This dataset gives insight to areas that are more vulnerable than others across the two islands. The generalized rock type data used in this study comes from the 1977 California Geological Survey conducted by the California Department of Conservation and digitally updated in 2010. The dataset was digitized from hardcopy maps with an inherent potential error in the creation of the map for legibility at the 1:750,000 scale.

The data file for this variable included all of California and was clipped to include only SCI and SNI. A new layer was created from this clip. Once this was done, the vector data was transformed into a raster for use in the CVI equation using the Polygon to Raster tool in ArcGIS Pro. Once the raster was created, the generalized rock type variable was reclassified much like the inundation layer. Table 5 below shows the created rankings.

Table 5 - Generalized Rock Type reclassification rankings

Rock Type	**Abbreviation**	**Gornitz *et al* (1994) Relation**	**Vulnerability Ranking**
Tertiary volcanic rocks	Tv	Plutonic, volcanic, High-medium grade metamorphics	Very Low (1)
Eocene marine sedimentary rocks	E	Low grade metamorphics, Sandstone and Conglomerates	Low (2)
Miocene marine sedimentary rocks	M	Most sedimentary rocks	Moderate (3)
Pleistocene marine and non-marine sedimentary rocks	Qoa	Coarse, poorly sorted unconsolidated sediments	High (4)

Pleistocene-Holocene marine and non-marine sedimentary rocks	Q	Fine unconsolidated sediments, volcanic ash	Very High (5)
NODATA			NODATA

3.1.6. Vegetation

Vegetation data for these islands can only be found for each individual island. Vegetation for SNI was created for regulatory purposes on Naval Base Ventura County (NBVC) San Nicolas Island by the company HDR while the vegetation data for SCI was created by a team at San Diego State University for Navy use which followed California Native Plant Society protocol (Uyeda et al 2018). The vegetation data used in this study was a strong addition because the data was created by two respected institutions hired by the Navy to be conducted for each island. The two vegetation datasets used allowed for a significantly better understanding of how each island differed and how erosion is naturally prevented. I would feel confident using this data in future research.

Both datasets give the proper Latin names of each vegetation type, and while there are slightly different vegetation types for each island, the general types of vegetation are comparable. The Latin names of these plants and the common names can be seen below in Table 6 for SCI and Table 7 for SNI as well as the generalized vegetation type and the reclassification CVI vulnerability ranking.

Table 6 - Vegetation ranking for San Clemente Island

Metadata Name	Common Name	Vegetation Type	Vulnerability Ranking
Ambrosia chamissonis – Ambronia maritima	Silver burr ragweed, Red sand verbena	Scrub, Shrub	Very Low (1)
Artemisia	California	Shrub	Very Low (1)

californica	sagebrush		
Baccharis pilularis	Coyote brush	Shrub	Very Low (1)
Bare	-	Bare	Very High (5)
California Cliff, Scree, Rock Vegetation Group	-	Bare	Very High (5)
Coastal Unvegetated	-	Bare	Very High (5)
Cylindropuntia prolifera Association	Coastal Cholla	Cactus	Moderate (3)
Developed	-	Developed	NODATA
Distichlis spicata	Desert saltgrass	Grass	Moderate (3)
Grassland semi-natural stands	-	Grass	Moderate (3)
Iceplant	-	Iceplant	Moderate (3)
Lycium californicum	California boxthorn	Shrub	Very Low (1)
Lyonothamnus floribundus (individual)	Catalina ironwood	Tree	Very Low (1)
Optunia littoralis	Coastal prickly pear	Cactus	Moderate (3)
Prunis ilicifolia ssp. lyonii	Catalina cherry	Tree	Very Low (1)
Quercus tomentella (individual)	Channel Islands oak	Tree	Very Low (1)
Rhus integrifolia (individual)	Lemonade berry	Shrub	Very Low (1)
Salicornia pacifica (alliance)	Pickleweed	Succulent	Moderate (3)
Salsola sp. provisional	Saltwort	Succulent	Moderate (3)

Table 7 - Vegetation ranking for San Nicolas Island

Metadata Name	**Common Name**	**Vegetation Type**	**Ranking Number**
Ambrosia chamissonis – Ambronia maritima – Cakile maritima	Silver burr ragweed, Red sand verbena, European searocket	Scrub	Very Low (1)
Ammophila arenaria	Marram grass	Grass	Moderate (3)
Artemisia nesiotica	Island sagebrush	Shrub	Very Low (1)
Baccharis pilularis/Annual grass-herb	Coyote brush	Shrub	Very Low (1)
Barren		Barren	Very High (5)

Cakile maritima – Ambrosia chamissonis – Carpobrotus edulis	European searocket, Silver burr ragweed, Iceplant	Succulent	Moderate (3)
Carpobrotus edulis (or other iceplant)	Iceplant	Iceplant	Moderate (3)
Coreopsis gigantea	Giant coreopsis (Daisy)	Bush	Very Low (1)
Deinandra clementia	Island tarplant	Bush	Very Low (1)
Distichlis spicata	Desert saltgrass	Grass	Moderate (3)
Frankenia salina	Alkali heath	Shrub	Very Low (1)
Frankenia salina/Distichlis spicata	Alkali heath, Desert saltgrass	Shrub	Very Low (1)
Isocoma menziesii	Coastal goldenbush	Shrub	Very Low (1)
Lupinus albifrons	Silver lupine	Shrub	Very Low (1)
Marine	-	Marine	Very High (5)
Mediterranean California Naturalized Annual & Perennial Grassland	-	Grass	Moderate (3)
Optunia littoralis – Mixed coastal sage scrub	Coastal prickly pear	Cactus	Moderate (3)
Saxlis lasiolepis	Arroyo willow	Tree	Very Low (1)
Urban	-	Urban	NODATA

These vegetation layers were created as vector layers. Since this study needs raster data for the CVI equation, the data was first transformed into rasters by using the Polygon to Raster tool in ArcGIS Pro. Once the vegetation layers for both islands were transformed into rasters, the vegetation types were reclassified into the three rankings shown in Tables 6 and 7 and the two islands were join together for use in the CVI equation described in Section 3.2.

3.1.7. Coastline

While coastline data was not a part of the CVI equation, it was still an important part of this study due to its use in creating a clipped DEM. This coastline data was created by the USGS to assess shoreline change and is a fairly good resolution for encompassing all of the contiguous United States.

3.2. Coastal Vulnerability Index (CVI)

In this study, Thieler and Hammar-Klose (2000)’s equation was used due to its minimizing effect on extreme variables that might be outliers:

$$CVI = \sqrt{\frac{a * b * c * d}{4}}$$

In this equation, *a* is Slope in Degrees, *b* is Inundation in Meters, *c* is Generalized Rock Type, and *d* is Vegetation Type. All data used in these equations are discussed in the previous sections and have been edited and reclassified for use within these equations. A summary of these classifications can be seen in Table 8 below. Using the equation mentioned above, the “Raster Calculator” tool was used to input all variables as designated. The result of this calculation allows for a better understanding of vulnerability around the islands, and will be used for the CRVI analysis in the following section.

Table 8 - Coastal Vulnerability Index ranking

I.D.	**Variable**	**Very Low (1)**	**Low (2)**	**Moderate (3)**	**High (4)**	**Very High (5)**
a	**Slope** **(in Degrees)**	Cliffed Slopes (> 45)	Steep Slopes (20.1 – 45)	Moderate Slopes (10.1 – 20.0)	Gentle Slopes (6.1 – 10.0)	Low Plains (0.0 – 6.0)
b	**Inundation (in Meters)**	> 2.0	2.0 – 1.0	1.0 – 0.6	0.6 – 0.3	< 0.3
c	**Generalized Rock Type**	Tertiary volcanic rocks	Eocene marine sedimentary	Miocene marine sedimentary	Pleistocene marine and non-marine	Pleistocene-Holocene marine and

		(Tv)	rocks (E)	rocks (M)	sedimentary rocks (Qoa)	non-marine sedimentary rocks (Q)
d	**Vegetation Coverage**	Ground Cover, Shrubs, Trees	-	Grasses, Cactus, Ice plant	-	Barren, Bare, Unvegetated, Marine

3.3. Cultural Resource Vulnerability Index (CRVI)

The final analysis for this study was to create the Cultural Resource Vulnerability Index (CRVI) to recognize the most at-risk archaeological sites based on CVI. The steps for this task are outlined below in Figure 9. This was done by creating a cell index around the coastline of the islands that include the index numbers of the cells calculated from the CVI.

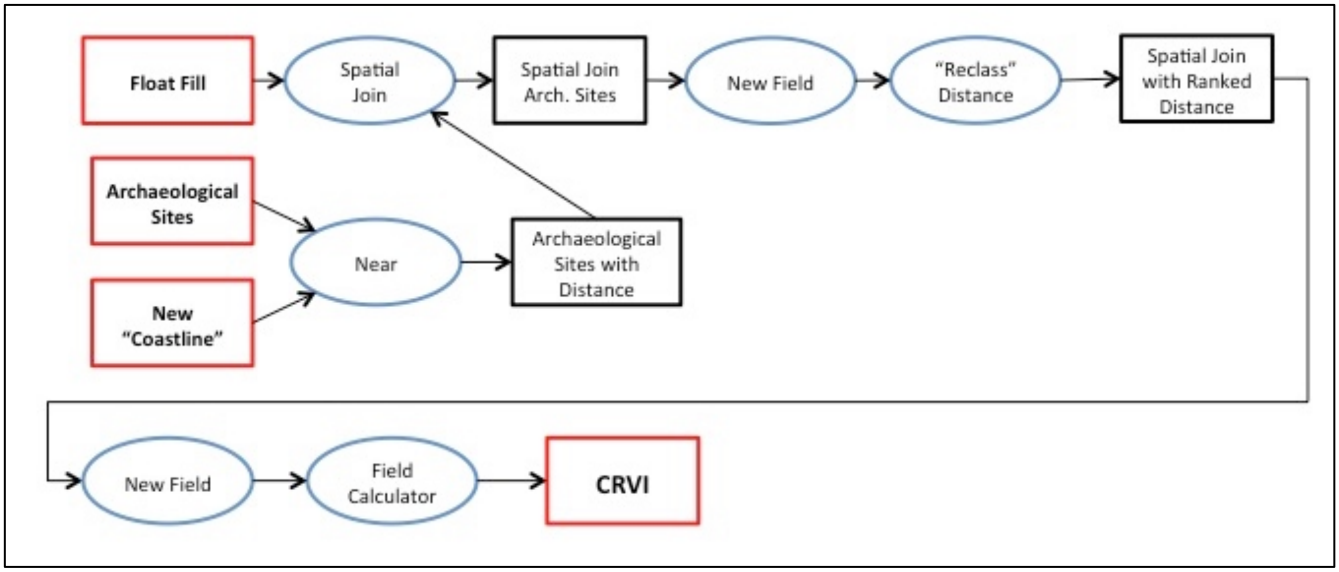


Figure 9 - CRVI workflow

Variables used in CVI had inconsistent coastline polygon boundaries due to the source data. A new coastline was created from the CVI to ensure uniformity. CVI was converted from a floating data type into an integer data type raster using the Raster Calculator tool to remove decimals in the CVI by multiplying the raster by a multiple of 10. For the CVI in this study, the raster needed to only be multiplied by 10 to convert to an integer. Once this was completed, I used the "Int" tool to convert the CVI raster into a new Integer Raster. This was done to create the new coastline for use in the CRVI for distance and for a coastline-specific CVI.

3.3.1. Coastline CVI

An index grid along the coastline was necessary for use in the CRVI equation. Using the newly established coastline, 10-meter squares were placed along the coast. The coastline polygon squares created allowed for the Zonal Statistic tool to be used. The Zonal Statistic tool was used to attribute the CVI value to the newly created squares along the coastline. The output from this tool was used in the Join, which ultimately creates the CRVI.

3.3.2. Archaeological Site Distance From Coast

Before using the Add Join function to create the CRVI, the distance of the archaeological sites to the coastline was calculated by using the Near tool. The resulting distance was seen in the archaeological sites' attribute table and was used to ascribe a vulnerability ranking for use in the CRVI equation.

For use in the CRVI, distances needed to be reclassified into ranks in order for the CRVI equation to be successful. This was done by manually reclassifying the distance ranges into five ranks in the archaeological sites' attribute tables. The distance ranks can be seen below in Table 9.

Table 9 - Distance from coastline ranking for archaeological sites.

Distance to Coastline	**Vulnerability Rank**
< 50 meters	Very High (5)
50 – 100 meters	High (4)

100 – 500 meters	Moderate (3)
500 – 1000 meters	Low (2)
> 1000 meters	Very Low (1)

Once these rankings were completed, the Add Join tool was used to join the data in the archaeological sites' attribute tables to the CVI coastline data. Once this tool was run, all data necessary for the CRVI equation was located in the archaeological sites' attribute table and a new layer was created showing the CVI along the coast.

3.3.3. CRVI Equation

Finally, after completing all steps mentioned above, the CRVI equation was used to calculate the vulnerability of each archaeological site. This was done by opening the newly produced CVI coastline layer (created from the Add Join step above) and creating a new attribute table field. This new field was created to use the Field Calculator tool to calculate the CRVI. In this study's case, the equation was:

$$CRVI = \frac{(a \ast b)}{2}$$

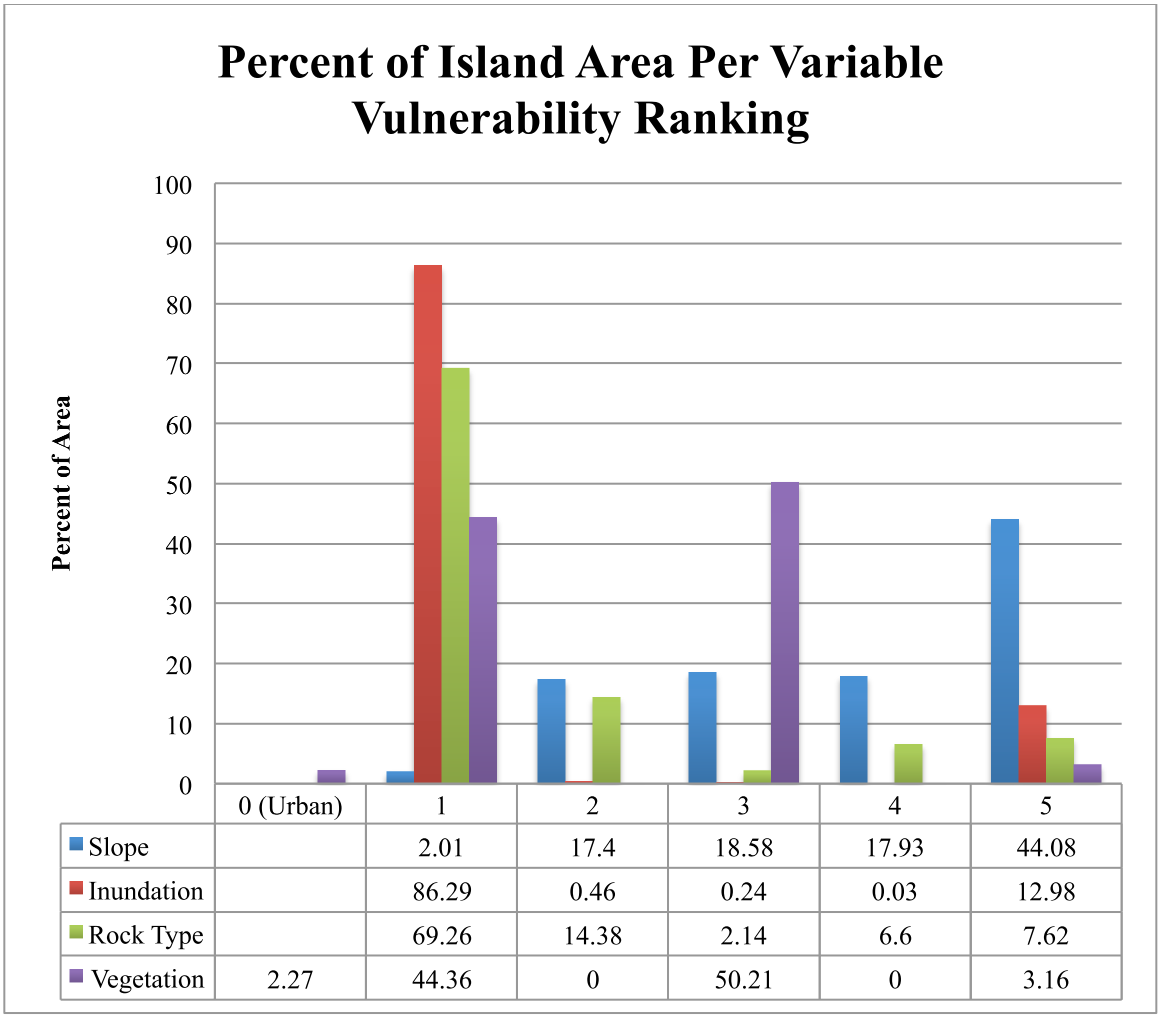
where *a* was the newly reclassified distance variable and *b* was the CVI ranking created from the Join step mentioned in the previous section. All new numeric results from this CRVI equation could be seen in the CRVI field in the islands' attribute tables. This new data was visualized and the result of this visualization can be seen in the next chapter.

Chapter 4 Results and Discussion

The analysis results of the coastal vulnerability and the at-risk archaeological sites for San Nicolas Island and San Clemente Island are reported in three parts in this chapter. First, the vulnerability ranking results for the relevant variables are presented in Section 4.1, followed by the results of the CVI and the CRVI in Section 4.2 and Section 4.3, respectively. Discussions about the results and their implications are also included at the end of individual sections.

4.1. Vulnerability Rankings for Environmental Variables

This section presents the classification results for the four variables that affect coastal vulnerability. Upon examining the vulnerability rankings for slope, inundation, generalized rock type, and vegetation, it can be seen that a large percentage of area (44.08%) had a high vulnerability ranking (or 5) for slope (Figure 10). In contrast, inundation, vegetation, and rock type had the high percentage of areas with very low vulnerability rankings (1). The percentage of area for all rankings of individual variables (1-5) are described in each subsection below.



	0 (Urban)	1	2	3	4	5
🟦 Slope		2.01	17.4	18.58	17.93	44.08
🟥 Inundation		86.29	0.46	0.24	0.03	12.98
🟩 Rock Type		69.26	14.38	2.14	6.6	7.62
🟪 Vegetation	2.27	44.36	0	50.21	0	3.16

Figure 10 - The area percentage of vulnerability ranking for the CVI variables in the study area

4.1.1. Slope

Figure 11 below shows the slope vulnerability rating for San Nicolas Island and San Clemente Island. More than half of the island areas were relatively flat, either at low plains (0 – 6°) (44.08%) or with a gentle slope (6-10°) degrees slope (17.93%). The areas with gentle slopes along the coastline were considered vulnerable due to the ease of water inundation. On San Nicolas Island, the low elevation areas near the coastline with gentle slopes were at northern and northwestern parts of the island. On San Clemente Island, however, these plains areas are located on the northern and northwestern regions.

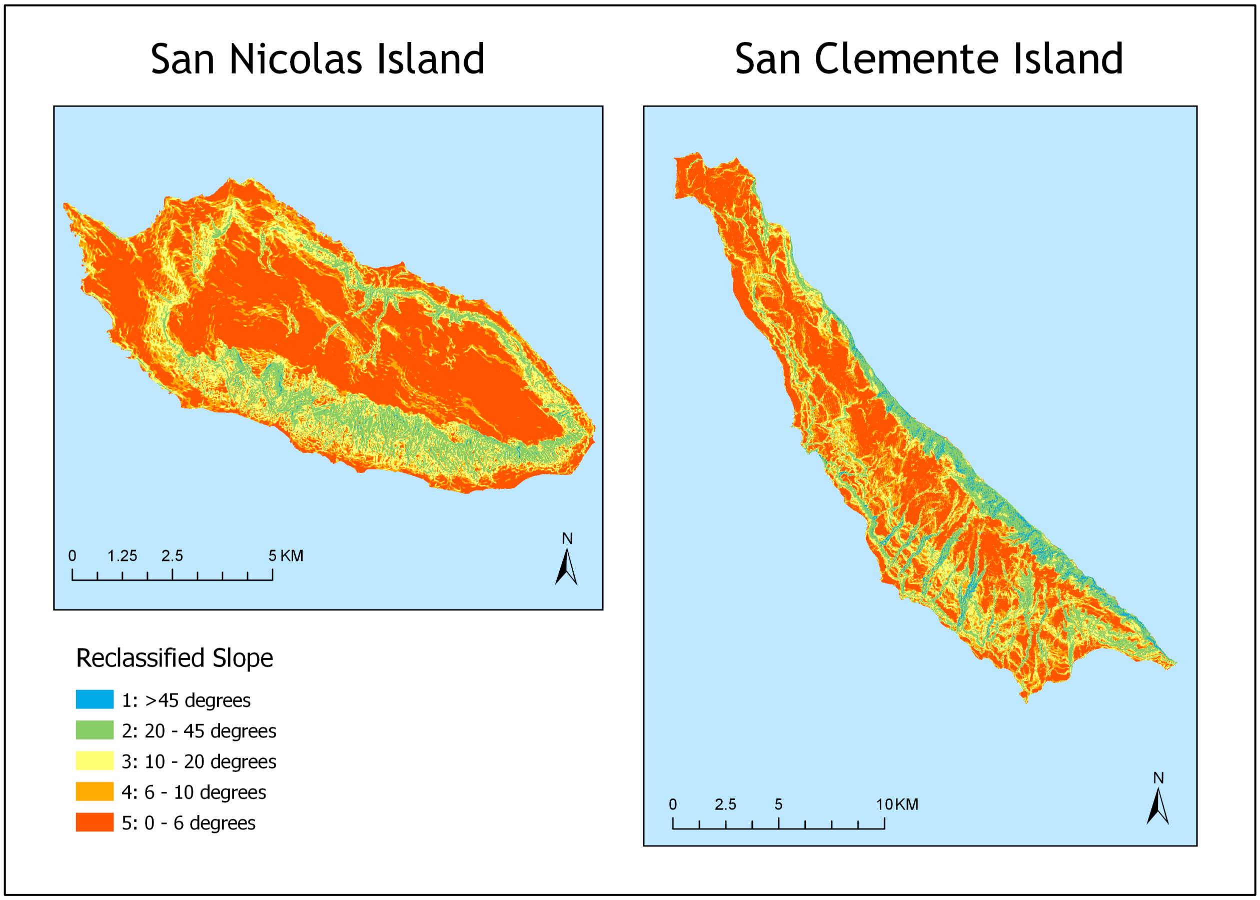


Figure 11 - The classification of slope from least vulnerable (1) to sea level rise to most vulnerable (5).

While one could argue that gentle slopes are less vulnerable in regards to erosion, it is important to state that this study focuses on the coastal risk created from sea level rise. Because of the bedrock formation on cliffed slope (greater than 45°), the areas with cliffed slopes are more resistant to erosion as well as permanent water inundation from sea level rise. These cliffed slopes are less susceptible to erosion than gentle slopes (less than 10 degrees) (Westley et al. 2011 and Aboudha and Woodroffe 2010). With very little elevation change, flooding from storm surges and inundation from sea level rise are a threat (Gesch, Gutierrez, and Gill 2010 and Reeder-Myers 2015). Gentle slopes along the coast are also typically indicators of sandy beaches, which are vulnerable due to frequent erosion and shoreline retreat (Church et al. 2008).

Steep slope (20.1 – 45° slope) and cliffed slope (>45° slope) areas, ranked low and very low in coastal vulnerability, respectively, were seen primarily on the northeastern shoreline and some narrow ridges in the center of San Clemente Island. The same vulnerability settings (on steep slope or cliffs) were seen inland around the entire San Nicolas Island. The cliffed slope was only seen on 2.01% of the two islands, but is indicative of immediate change between the coastline and inland. The steep slopes, on the other hand, had the highest area percentage of the overall rankings, amassed 17.40% of the entire study area. Moderate slopes (10 – 20°), comprising 18.58% of the islands, were found near low to very low vulnerability ranking areas, as expected.

4.1.2. Inundation

Inundation zones, as expected, were in general consistent around the shorelines of the two islands. It is, however, important to note that a buffer was created around the islands to ensure all low-lying land areas were accounted for, as no consistency of shoreline boundaries were found from source data as the baseline extent. Therefore, some portions of the low-lying areas might include the oceans; there were about 13.0% of the area ranked most vulnerable in the inundation classification (< 0.3 meters above sea level) around all of the two islands. Perhaps the better indicator of vulnerability in coastal inundation is the classification of areas at 0.3 – 0.6 m above mean sea level ('High' vulnerability with a ranking score of '4'). However, these high vulnerability areas of inundation were seen primarily along San Clemente Island's northern coast and consisted of less than 1% (0.03%) of the islands' total area. Both moderate vulnerability areas of inundation (0.6 – 1 m above mean sea level) and low vulnerable areas of inundation (1.0 – 2m above mean sea level) also comprised less than 1% (0.24% and 0.46%, respectively) of the two islands. The moderate vulnerability area of inundation were along the northwestern portion of San Nicolas Island and the southern and northern points of San Clemente Island, and the low vulnerability area of inundation were primarily seen on the northern tip of San Clemente Island and southeastern quadrant of San Nicolas Island.

Most areas (86.3%) of the two islands, in the use of our vulnerability classification based on the sea level rise concern, were higher than 2 meters above mean sea level on San Nicolas and San Clemente Islands. The maps for the vulnerability classification of inundation can be seen in Figure 12 below.

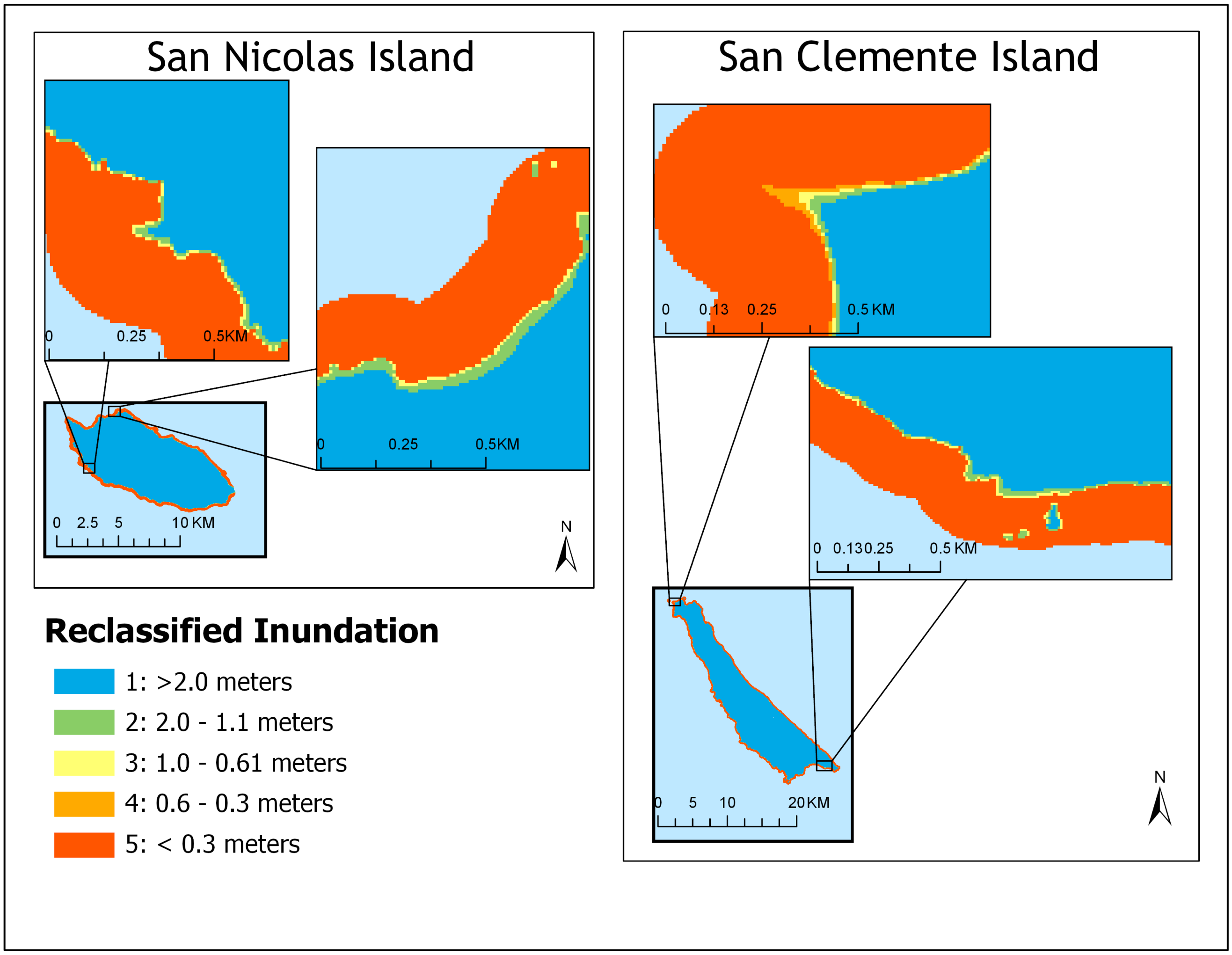


Figure 12 - The classification of water inundation zones based on the predicted sea level rise, ranked from most vulnerable (5, in red) to least vulnerable (1, in blue).

With NOAA and IPCC sea level rise projections estimating a 2-meter sea level increase by 2100, approximately 13.71% of land area on San Nicolas and San Clemente Islands were susceptible to inundation (Lindsey 2017). Inundation can be devastating to archaeological sites. Inundation also exacerbates shoreline retreat. In fact, 70% of the world's shorelines have been experiencing retreating due to erosion caused by inundation (Maio et al. 2012 and Church et al. 2008).

4.1.3. Generalized Rock Type

Figure 13 shows the vulnerability classification of the generalized rock types. A total of five generalized rock types were seen on the two islands. The most vulnerable rock type, "Q", covered 7.6% of total area across the two islands, and the second most vulnerable rock type, "Qoa", covers 6.6% of total land area across the two islands.

Over the entire study area, 14.2% of the areas consisted of very highly and highly vulnerable rock types ("Q" and "Qoa", respectively). These two rock types were only seen on San Nicolas Island. The most vulnerable rock type "Q" was located along the northwestern portion of the island while the "Qoa" rock type was seen directly south and east of "Q." The moderate rock type (with a ranking score of 3), "M", covered only 2.14% of the total islands' land mass and was located in small portions across San Clemente Island. Finally, the second lowest vulnerability (with a ranking score of 2) can be seen across 14.38% of the landmass. This "E" rock type was located in many areas across San Nicolas Island, specifically along the island's southern quadrant and along portions of the island's northern coastline.

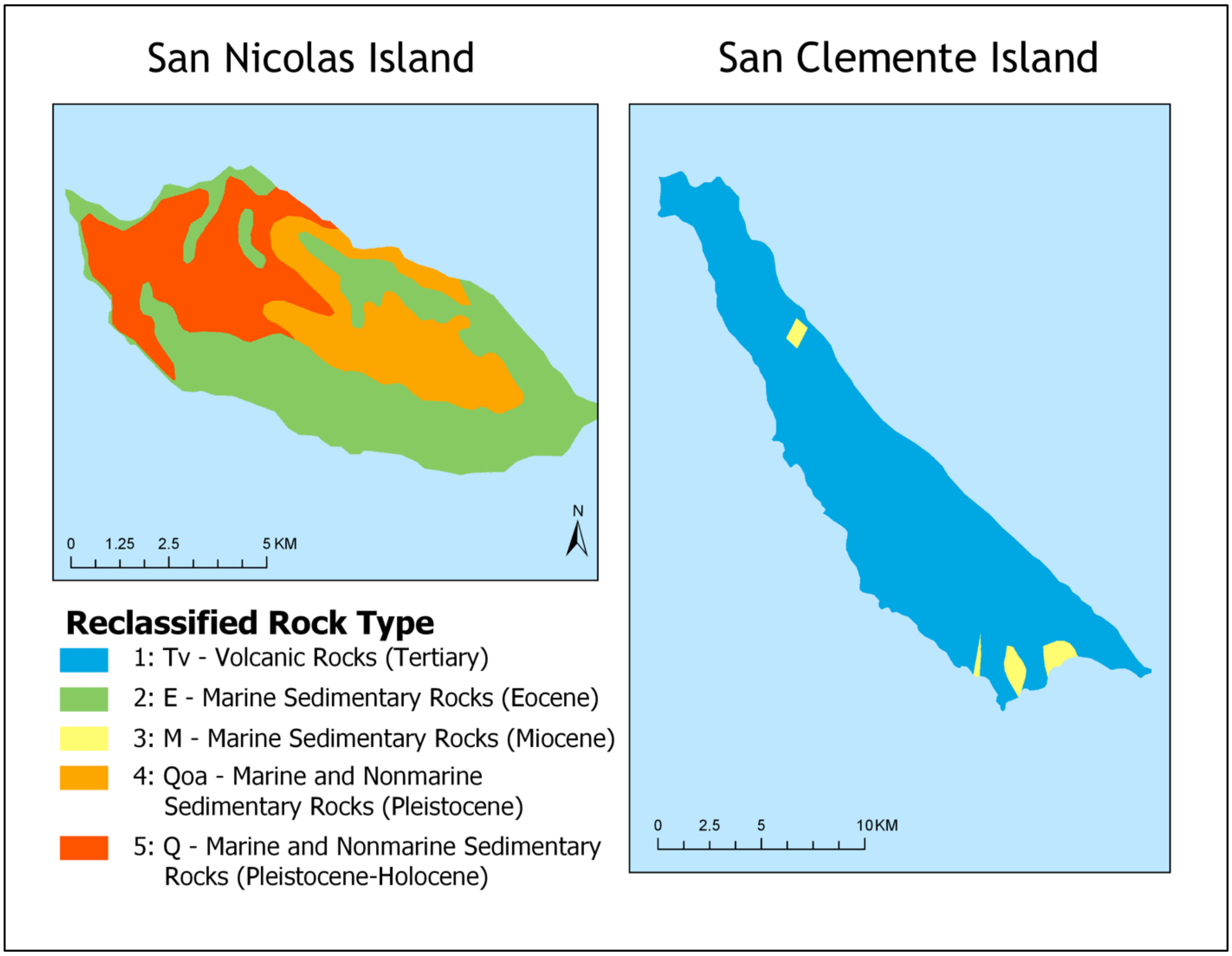


Figure 13 - The vulnerability classification of generalized rock type.

4.1.4. Vegetation

Existing vegetation plays an important role to prevent the islands from both water and wind erosion as it creates erosion-inhibiting root systems and wind barriers. This type of erosion control, with shrubs, trees, and groundcover, were seen across San Nicolas Island and San Clemente Island. Groundcover, shrubs, and trees covered 44.4% of the two islands (Figure 14). Most of San Nicolas Island was in this very low vulnerability class, but only seen along the northeastern and western coastal areas of San Clemente Island. Some of this vegetation class was also found in the small canyons on San Clemente Island's southern quadrant.

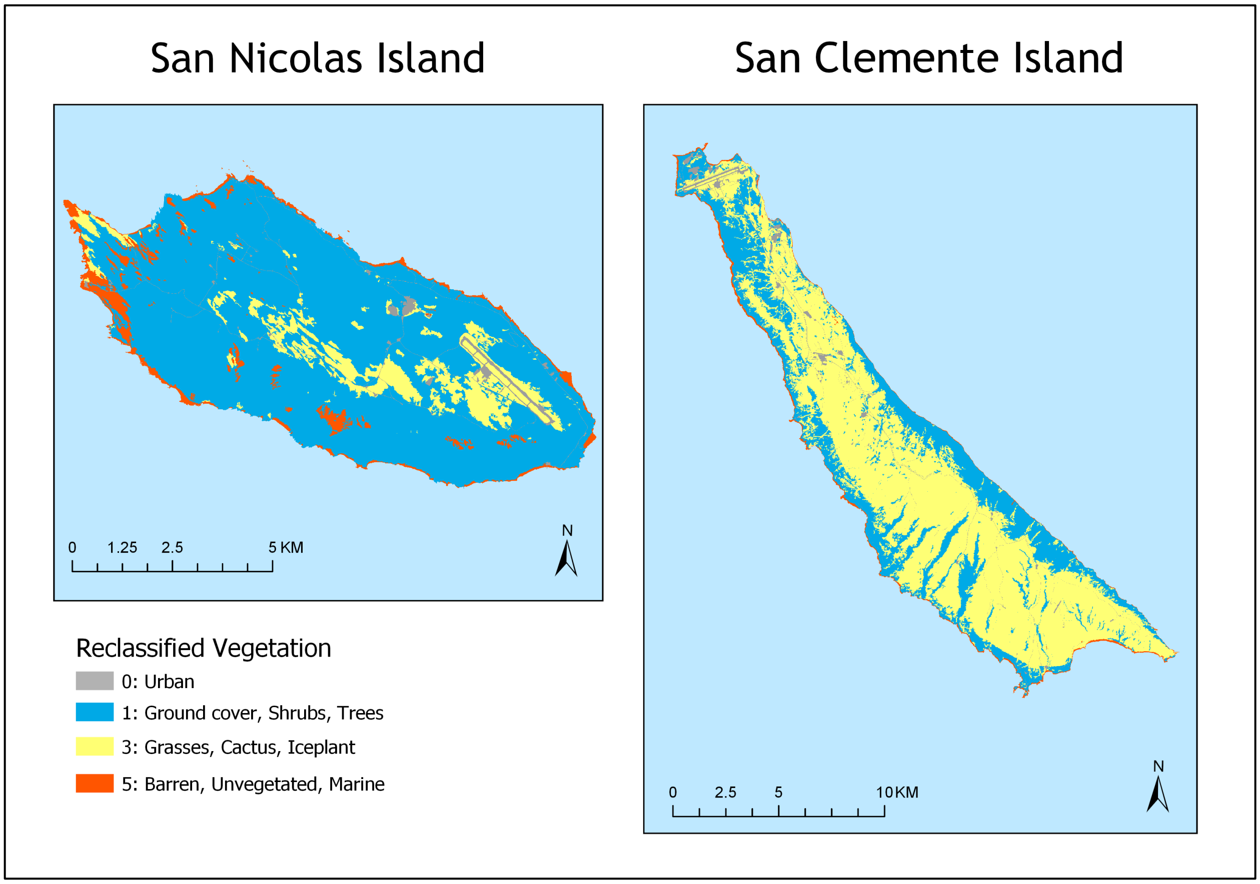


Figure 14 - The vulnerability classification of vegetation.

Grasses, cactus, and ice plants were prolific across the two islands. 50.2% of the islands total area was in this moderately vulnerable classification of vegetation (Figure 14). Most of San Clemente Island, especially inland, was covered by grasses, cactus and ice plants. The type of vegetation was spread sporadically across the middle of San Nicolas Island and the island's northern point. Only 3.2% of the total study area was there a lack of vegetation ("barren, unvegetated, and marine") and ranked the most vulnerable due to its lack of vegetation erosion control. Specifically, these areas were seen along most coastlines. 2.3% of the islands was classified as urban development and was given a score of '0' in this classification.

4.2. Coastal Vulnerability Index

The Coastal Vulnerability Index (CVI) combined all classified variables, to rank areas along the coastline from least vulnerable to most vulnerable. In the following sections, the results of CVI for San Nicolas and San Clemente Island are described in detail.

4.2.1. CVI for Entire Study Area

The CVI for the entire island of San Clemente Island is presented in Figure 15. The most vulnerable areas, as expected, were located along the coastline as thin strips. Overall, San Clemente Island was less vulnerable with the exception of four very highly vulnerable zones on the southern coast and on the mid portions on the northern half of the island. These vulnerable zones are displayed in red in Figure 15. The areas were categorized as “very high” in coastal vulnerability due to the weaker of the two rock types on the island (Miocene sedimentary rocks, “M”). While the rock type “M” was classified as moderately vulnerable to erosion, it can be seen that the areas that are within the boundary of this rock type are significantly more vulnerable on San Clemente Island. Apart from these four areas, the coastline of San Clemente Island was the most vulnerable portion (“Very High”) of the island – specifically the northeastern portion of the coastline and the northern most tip of the island. Recall that Figure 14 and Figure 12 showed some areas of the island with no vegetation and low elevation; these areas were susceptible to sea level rise impacts. The most vulnerable areas of the San Clemente Island were the southern-most coast where the rock type was the weakest and the elevations was close to sea level and would allow excessive water inundation.

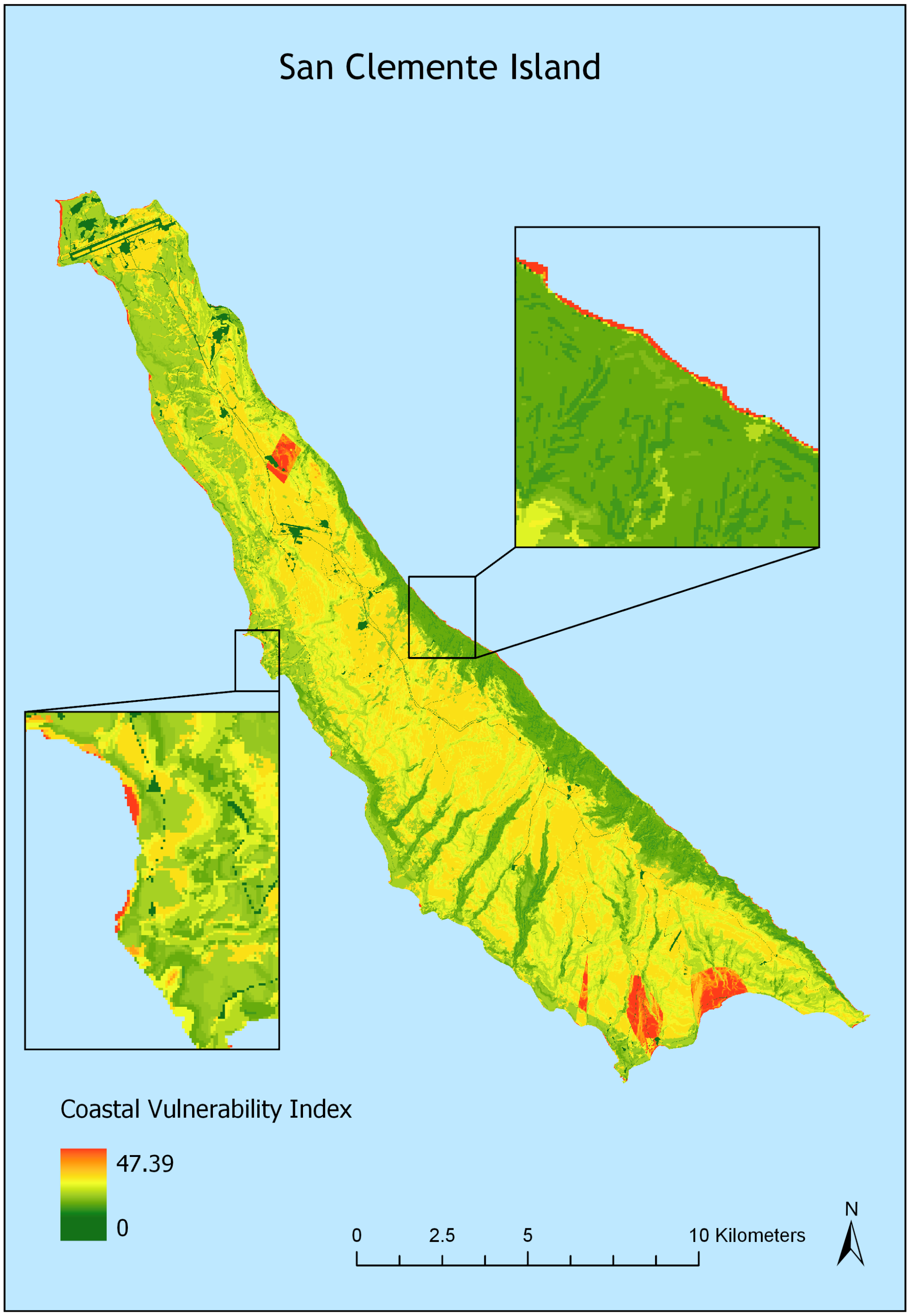


Figure 15 - The Coastal Vulnerability Index for the entire San Clemente Island

Fortunately, most of the San Clemente Island was ranked low in coastal vulnerability. This was directly related to two risk variables: rock type and slope. Because San Clemente Island was primarily covered by the “Tv” (Tertiary volcanic) rock type, most of the island was fairly resistant to erosion. Moreover, since most of the island’s northern side had steep slopes, the vulnerability was ranked low, and the potential damage caused by inundation in the next 100 years would be low.

On the other hand, many of the areas in San Nicolas Island contained the most vulnerable ratings of various variables and resulted in more vulnerablility (Figure 16). Specifically, the island is most vulnerable due to its flat slope, “Q” (Pleistocene-Holocene marine and nonmarine sedimentary rocks) and “Qoa” (Pleistocene marine and nonmarine sedimentary rocks) rock types, and larger portions of barren areas without vegetation. The rock types are highly susceptible to erosion due to its unconsolidated to semi-consolidated states. The slope on San Nicolas Island was also gentler allowing for more water inundation along the coastlines. This was seen across most of the island, specifically across the entire northern tip of the island. In low-plain areas that were near the sea level, the barren landscape is commonly seen across the island; these areas would be highly vulnerable to inundation.

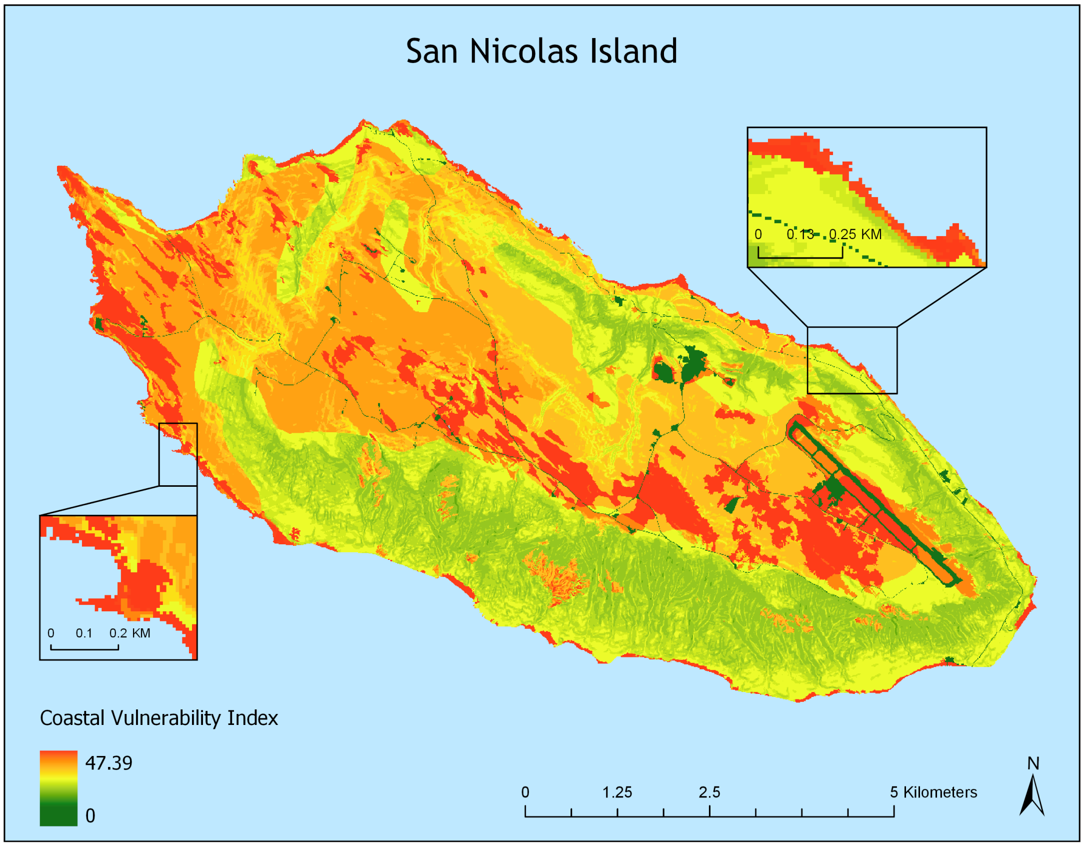


Figure 16 - The Coastal Vulnerability Index for the entire San Nicolas Island

Aside from the urban areas that were rated most vulnerable (in dark green in Figure 16), the second to most vulnerable areas (in light green in Figure 16) were across the islands. These areas consisted of the rock type “E” (Eocene marine sedimentary rocks) and had steep slopes. The combination of these two variables resulted in the areas less vulnerable to sea level rise and other coastal threats.

4.2.2. Coastline CVI

Based on the results in Section 4.2.1, it is clear that coastlines are not the only vulnerable areas for inundation and erosion on these two islands. However, CVI near the coastline was further inspected for the archaeological sites vulnerability. The coastline CVI layer was created for San Clemente Island and San Nicolas Island. Figure 17 shows coastal areas in the northwest quadrant of San Nicolas Island are the most vulnerable compared to other parts of the coastline on the same island. For San Clemente Island, the coastal CVI indicated the most vulnerable coastal areas were on the southern coast and farthest northern point of the island (Figure 18).

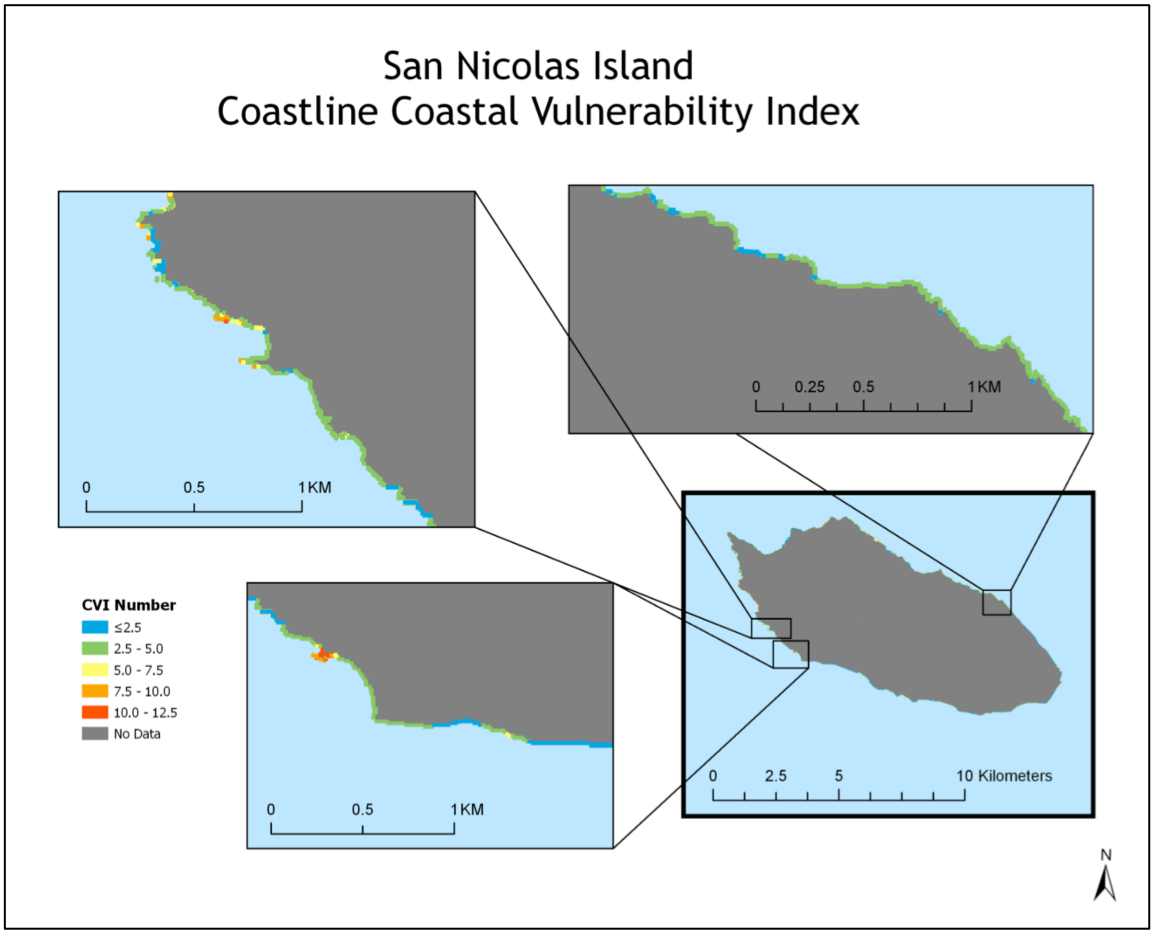


Figure 17 - Coastline CVI for San Nicolas Island

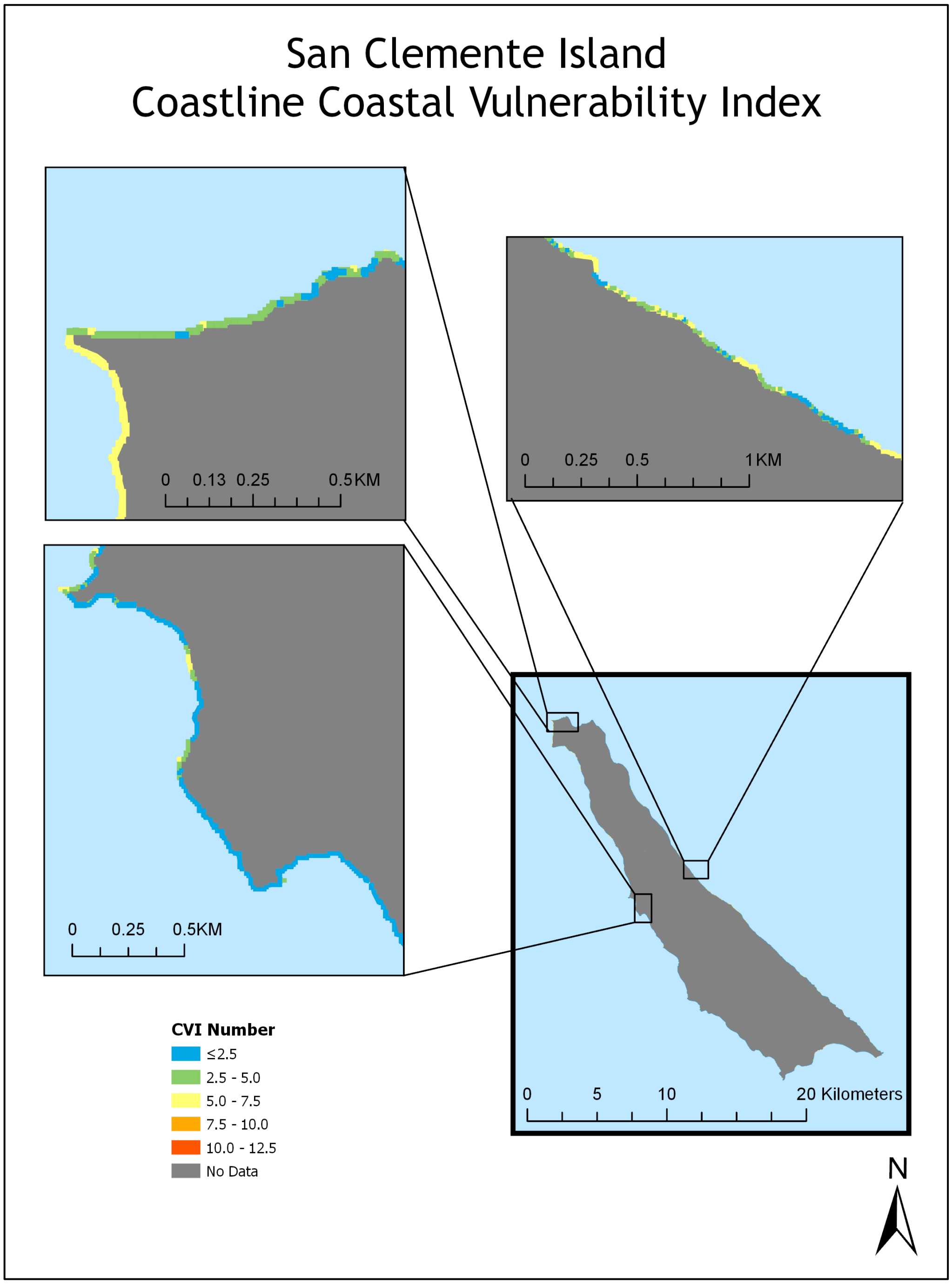


Figure 18 - Coastline CVI for San Clemente Island

Only 0.3% of the coastline on the two islands was considered most vulnerable. These areas were scattered throughout the islands, but were primarily seen on San Nicolas Island's southwestern coast. The second to most vulnerable class of CVI consisted of 1.7% of coastline grids on the two islands. Next, moderate vulnerability was found to encompass a higher percentage (9.4%) of coastal areas, primarily along the northern point of San Clemente Island and scattered along San Nicolas Island's northwestern side. The low and very low vulnerability areas covered 33.2% and 55.3% coastal area, respectively, mainly located on the southwestern side of San Clemente Island and the northeastern side of San Nicolas Island.

The purpose of generating the coastline CVI layer was to calculate the CRVI, but areas of "No Data" exist due to missing raster points in the original variable layers. Upon the coastline CVI being conducted, a small amount of "No Data" area could be seen. A fix was conducted by using the Zonal Statistic tool to fill any areas of no data with the mean of the points and merging the Zonal Fill with priority set on Zonal Fill. Since the fix, very few errors occurred.

4.3. Cultural Resource Vulnerability Index (CRVI)

Based on the nearest coastal cell's CVI and its distance to the archaeological site, CRVI ranked the coastal vulnerability for archaeological sites. The CRVI for each island is presented in the following sections.

4.3.1. San Nicolas Island

As seen in Table 10, most archaeological sites (75.7%) were more than 100 meters away from the coastline. These sites (ranked 1-3) were less at risk due to their distance from the ocean and higher elevation (so less susceptible to water inundation by sea level rise). There were 31 (5.79%) of these sites within 50 – 100 meters from the coast (a ranking of 4) and 99 (18.51%) archaeological sites were less than 50 meters from the shore (a ranking of 5). These sites would be most at risk due to their close proximity to rising sea levels and the effects related to this sea level change. However, upon calculating the coastline CVI for these sites, it can be seen that 5 archaeological sites (0.93%) are close to 7.5 – 10.0 CVI rankings ("4") and only 4 sites (0.75%)

are close to the most at risk CVI ("5"). Moderately vulnerable CVI rankings ("3") make up 7.29% of archaeological sites' coastline CVI. The second least vulnerable CVI ranking value ("2") can be seen with 263 sites (49.16%) and the least vulnerable ranking value ("1") can be seen with 224 sites (41.87%).

Table 10 - Ranking of CRVI variables on San Nicolas Island where *n* is the number of archaeological sites found for each ranking.

Classification	Cultural Resources Vulnerability – San Nicolas Island				
Parameters	Very Low (1)	Low (2)	Moderate (3)	High (4)	Very High (5)
No. of Samples in Distance from Coast	(> 1000 m)	(500 - 1000 m)	(100 -500 m)	(50 - 100 m)	(0 - 50 m)
	191	81	133	31	99
No. of Samples in Coastal CVI*	(0 - 2.6)	(2.6 - 5.0)	(5.0 - 7.5)	(7.5 - 10.0)	(> 10.0)
	224	263	39	5	4
No. of Samples in CRVI**	(0 - 4.0)	(4.0 - 8.2)	(8.2 - 12.2)	(12.2 - 16.3)	(> 16.3)
	344 (64.3%)	126 (23.6%)	46 (8.6%)	16 (3.0%)	3 (0.5%)

*Coastal Vulnerability Index
**Cultural Resources Vulnerability Index

The final map of CRVI for San Nicolas Island can be seen in Figure 19. The CRVI ranking for San Nicolas Island shows 3 archaeological sites (0.56%) that are most vulnerable ("5" ranking). These sites are small in area and are located on the northeastern coastline and the southwestern coastline of the island. More archaeological sites (2.99%) are ranked highly ("4") by the CRVI. These 16 sites are fairly scattered across the island's coastline, but can be seen on the southwestern coast, northern coast, and southeastern coast. Specifically, these sites are found in areas of very low slope, slope that was ranked "5" and "4" for the CVI. These areas also include barren vegetation. Moderately ranked archaeological sites ("3") can be seen on the northern coast, the southeastern coast, and the northwestern coast and make up 8.60% of the island's sites. The least vulnerable archaeological sites in regard to sea level rise make up 23.55% for "2" ranking and 64.30% for "1" ranking. These sites are primarily seen on the inland of the island.

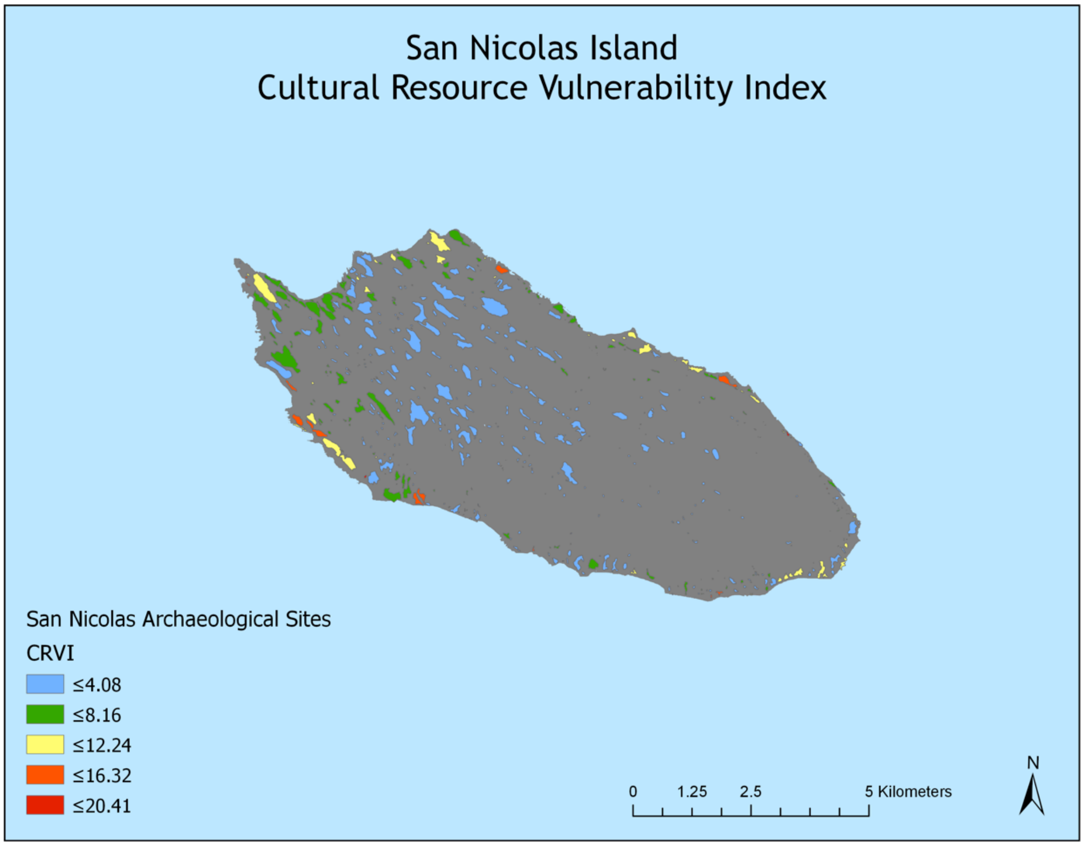


Figure 19 - CRVI for San Nicolas Island with archaeological site rankings.

4.3.2. San Clemente Island

San Clemente Island is a unique study due to the sheer volume of archaeological sites across the island. Similar to San Nicolas Island, most archaeological sites (84.80%) are at least 100 meters away from the shoreline, but 769 sites (15.20% of the total sites) still remain within 100 meters from the coast. These sites could still be at risk for its close proximity to the coast, but only 4 sites were within the “high” to “very high” vulnerability in terms of their CVI on-site. Moderately vulnerable ranking of the CVI (5.0 – 7.5) was dominant of all archaeological sites (7.89% of the total sites). The second least vulnerable CVI (a ranking score of 2) was seen in 23.1% of the sites across the island. A majority (64.6%) of the archaeological sites has the least vulnerable CVI ranking (1). A small percentage (4.3%) of the sites received a “0” for its CVI ranking. This error issue is discussed toward the end of this chapter.

While using CVI, the results showed the majority of the archaeological sites were rated low to very low vulnerability, the CRVI ranked a larger number of “high” to “very high” vulnerability for archaeological sites on San Clemente Island, because of the calculation used the distance and correlating coastline CVI (Table 11). A total of 408 archaeological sites (8%) were ranked most vulnerable (“very high”, with a ranking of 5). These sites can be seen in red in Figure 20. Primarily, these most vulnerable sites were located along San Clemente Island’s northwestern coastline with some scattered along the southwestern and northern tips.

Table 11 - Ranking of CRVI variables on San Clemente Island where *n* is the number of archaeological sites found for each ranking.

Classification Parameters	Cultural Resources Vulnerability – San Clemente Island					
	Zeros	Very Low (1)	Low (2)	Moderate (3)	High (4)	Very High (5)
No. of Samples in Distance from Coast	N/A	(> 1000 m)	(500 - 1000 m)	(100 -500 m)	(50 - 100 m)	(0 - 50 m)
	N/A	1636	1196	1457	300	469
No. of Samples in Coastal CVI*	= 0	(0 - 2.6)	(2.6 - 5.0)	(5.0 - 7.5)	(7.5 - 10.0)	(> 10.0)
	216	3269	1170	399	4	0
No. of Samples in CRVI**	= 0	(0 – 1.3)	(1.3 – 2.6)	(2.6 – 4.2)	(4.2 – 7.2)	(> 7.2)
	216 (4.3%)	1641 (32.4%)	1427 (28.2%)	801 (15.8%)	565 (11.2%)	408 (8%)

*Coastal Vulnerability Index
**Cultural Resources Vulnerability Index

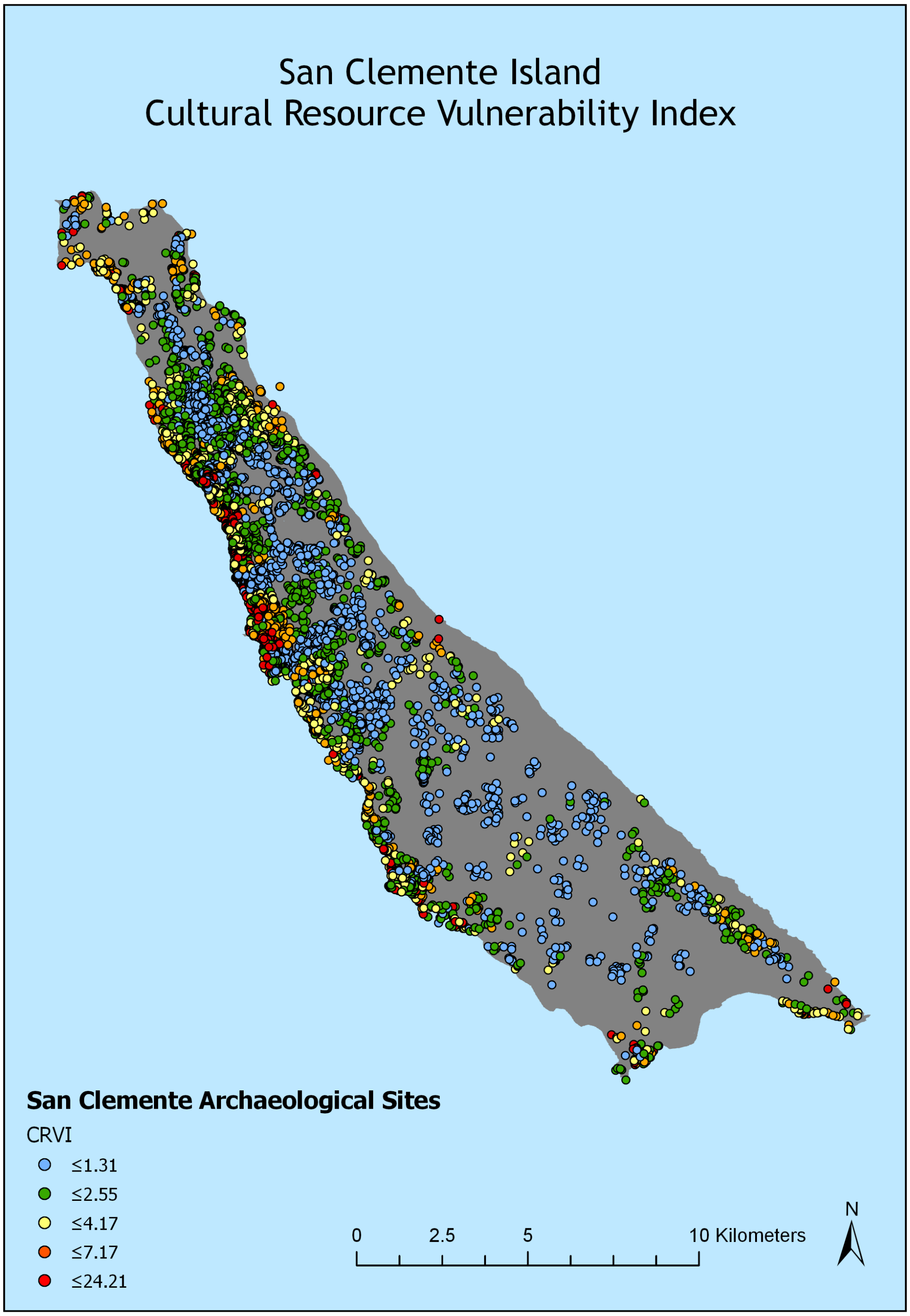


Figure 20 - The CRVI for archaeological sites on San Clemente Island; higher values indicates higher coastal vulnerability.

The second highest ranked CRVI, with a vulnerability ranking of “4”, consisted of 565 sites (11.2% of the total sites) throughout the island. These highly vulnerable sites appeared to be near those sites that had “very high” vulnerability, and were mostly found on the island’s northern-most tip. Overall, the “very high” (5) and “high”(4) rankings were in areas with a combination of gentle slopes, inundation zones (low elevation), and less or lack of vegetation. Moderately ranked (3) archaeological sites (15.8% of total sites) were located mostly along the western coast and on the northern tip of the island. The second lowest vulnerability (2) are given to 28.2% of the archaeological sites and were located inland. The least vulnerable (1) archaeological sites, consisted of 32.4% of the total archeological sites, were located further inland.

Collectively across the two islands, 411 archaeological sites were most at risk (“very high” vulnerability) to coastal instability and inundation. With this in mind, archaeologists can conduct research more focused on these very highly vulnerable sites before they are to lost to coastal inundation and erosion. It is also important to keep in mind that 585 of these sites are also “high” vulnerability

4.3% of archaeological sites on San Clemente Island received a value of zero (0) for the coastline CVI (the CVI of the closest coastline gridded cell). At this point, it was still unclear where this error was generated. Possibly, the Add Join function used in linking the archaeological site data and the nearest coastal cell created areas of No Data when attaching value to these archaeological sites. It would be possible to recalculate the coastal CVI values for these sites, but a new method of calculating CRVI in ArcGIS would have to be used.

Chapter 5 Conclusions

As this study concludes, it is important to evaluate whether this study was successful and in what ways it can be improved. This study has found success in understanding which archaeological sites are most at risk across San Nicolas Island and San Clemente Island off the coast of Southern California. Using the CVI and CRVI methods, 19 archaeological sites on San Nicolas Island were found highly or very highly vulnerable due to coastal instability and potential inundation. In contrast, 973 archaeological sites on San Clemente Island were identified to be highly or very highly vulnerable.

The second achievement of this study is a better understanding of the spatial locations that are most vulnerable to inundation and coastal erosion. By creating the spatial layer of CVI using four environmental variables – slope, inundation, generalized rock type, and vegetation, a total of 2.07% of the coastline was ranked highly or very highly vulnerable.

5.1. Limitations

This study faced its own set of challenges throughout. The most obvious limitation is data unavailability to the study area, particularly due to its location and the protected status by the U.S. Navy. Compared to the CVI variables used in Abuodha and Woodroffe (2010) and the CRVI variables in Reeder, Rick, and Erlandson (2012), only four variables (slope, inundation, generalized tock type and vegetation) were used in the study. Several other relevant environmental variables such as geomorphology and shoreline change were not available for use at the time of analysis. While the Navy ownership and stewardship of the two islands allows for research, most of the data from these studies remain unpublished or unavailable for public use.

The data used in this study was secondary. Although the data came from seemingly reliable sources, it is possible that the data was not accurate in some areas across the two islands.

Secondary data are sources collected from studies not conducted by the author. Because the data is not created by the author, accuracy testing data can only be obtained from metadata when available. In this study, it is assumed that the generalized rock type data is accurate due to its creation by the California Department of Conservation. The source layers of vegetation on both islands were created using California Native Plant Society protocol for the Navy.

Data fitness for use was also a concern during this study. The best available data for geology was generalized rock type, but it was over generalized for the large spatial scale used in this study, and very little variation between and within the two islands could be seen. Among the variety of CVI equations developed, only one equation was adapted for use in this study. It would be beneficial to test this CVI against the other equations.

Sea level rise data was only referenced globally. Because of the small areas of these islands, there was very little sea level rise variation across the two islands. The regional sea level rise projection was not available or could not be found at the time of this study. However, for better accuracy, sea level rise estimates for the Channel Islands region should be reviewed in future studies much like this.

Vegetation data was ranked into only three vulnerability classes. This type of ranking could have caused a skewed weight for the CVI. A better understanding of the complexities of vegetation erosion control would be beneficial to this type of study in order to rank the vegetation types into the five classes instead of three.

Finally, there were several cells with the value of zero (0) created from the joining of archaeological sites to the coastline CVI. These errors came from variables with incomplete raster coverage where “No Data” was allocated to the raster cells. These 0s might have created accuracy issues for the resulting archaeological site vulnerability.

5.2. Future Research

As missing CVI and CRVI variables limit the result of the study, future research should consider incorporating these missing variables (e.g. barrier type, shoreline exposure, shoreline change, mean wave height, and mean tide range) into CVI and CRVI calculations when they become available and handy. Specifically, king tide and detailed geomorphology data would need to be added to future renditions of this study. King tide that shows the highest point of the tide cycle would inform where water will be seen in the future. A more detailed geologic data that shows variations of rock types among the two islands will remedy the resolution issues. A more detailed geologic data map was found for San Clemente Island via the USGS National Geologic Map Database, created in 1958. This geologic data was not used because it did not include San Nicolas Island. Future studies of this type should use the more detailed geologic data.

The indices used for this study can be applied to various fields of studies related to sea level rise and erosion vulnerability in coastal regions. These fields, such as real estate, ecology, and endangered animal and plant protection, can adapt the Cultural Resource Vulnerability Index to suit assessment needs. An example in the real estate field would be to understand which residential communities and houses would be affected by sea level rise. A recent study projected that 1.9 million homes would be underwater by the year 2100 if the sea level rises six feet (Bretz 2017); a similar index like CRVI used for archaeological sites can be applied to understand which sites need to protect from the coming sea level rise.

5.3. Final Take Away

With the global sea level rise, coastal vulnerability might affect most areas of everyday life in the next 100 years. This study took steps towards understanding the danger of the potential sea level rise and coastal instability for a practical reason – protecting archaeological sites.

This study developed the CVI and CRVI layers for San Clemente Island and San Nicolas Island and will provide the archaeologists in the U.S. Navy a guideline for prioritizing the study of archaeological sites and mitigating the risks of losing the at-risk archaeological sites.

The CVI and CRVI conducted in this study allow us to quantify and visualize how the world around us is changing every day. With sea levels continuing to rise, researchers and scientists continue to work on understanding the threat and creating methods to adapt or mitigate the inevitable environmental change. It is my hope that this study would be a small stepping-stone for helping these coastal researchers in the right direction.

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Appendix A – A Short History of San Clemente Island and San Nicolas Island

San Nicolas and San Clemente Islands have long histories spanning thousands of years. From archaeological data, researchers believe San Nicolas Island was first settled 8,000 years ago and San Clemente Island was settled around 9,000 years ago, if not earlier (Yatsko 2000). With many similarities in technology and evidence of abundant trade between the two islands, archaeologists have attempted to find familiar relationships between the two island populations. However, because the languages of the native people on two islands were not the same, the genetic relationships of these islands could not be confirmed. The histories of these cultures may seem remarkably similar on the surface, the trajectory of the islands and their inhabitants deviate in the years just before contact (Chiles 2015).

San Clemente Island

With the general isolation of San Clemente Island, the native peoples of the island were believed to be excellent sea voyagers. Evidence of this can be seen in the Clementeños deep archaeological record that spans from the Early Holocene to Spanish contact in the mid-sixteenth century. While the pre-contact history of this island parallels the story of San Nicolas Island, San Clemente Island's initial contact with outside forces occurred much earlier than their San Nicolas neighbors (Chiles 2015).

Juan Rodríguez Cabrillo first spotted San Clemente Island in 1542, but contact with the islanders was not initiated until 1796 when the Franciscans and Russian-American otter hunters sought out the island for its people and the resources it held. Following a similar history as the Nicoleños after contact, by 1803, the approximately 250 Clementeños were reduced to only eleven. The last of these islanders departed for the mainland around 1829 for Mission San Gabriel (Chiles 2015).

In 1850, the United States government officially owned the title for San Clemente Island when California was granted statehood. In the years to follow, the island was used as a safe harbor for whalers, fishermen, hunters, ranchers, and even scientists. Unfortunately, as with San Nicolas, sheep herding dramatically changed the vegetation of the island. By 1934, leasing of the land ended and administration of the island was given to the Navy (Chiles 2015).

San Nicolas Island

The Nicoleños of San Nicolas Island were successful traders, sea mammal hunters, and fishermen. With numbers reaching 200 to 300 individuals, the Nicoleños were successful on the small island. San Nicolas Island was the only island to evade notice of the Spanish, Mexicans, and missionaries for more than two centuries. However, by the nineteenth century, Russian-American otter hunters found the island and made first contact with the native peoples. After this contact, Franciscan missionaries heard of native peoples on this island and enticed many of the Nicoleños to come to the missions in Los Angeles and San Gabriel. The earthquake of 1812 convinced many of the native peoples to go to the mainland with the missionaries, but most of them died due to diseases and poor living conditions. By the end of the second decade of the nineteenth century, fewer than two-dozen Nicoleño people remained. By 1835, the Franciscans sent for the remaining Nicoleños and all but one woman left for the mainland. The one woman, whose picture can be seen in Figure 20, who remained on the island sparked the legend of "The Lone Woman of San Nicolas" which inspired the classic novel "The Island of the Blue Dolphins" by Scott O'Dell. While only a legend for eighteen years, the Lone Woman was finally found in 1853. Her finding sparked scientific interest of the island with archaeologists (Chiles 2015).

Figure 21 - A photograph of a woman believed to be the Lone Woman of San Nicolas Island, 1853 (Source: Chiles 2015)

By 1858, the first modern settlers came to the island that was now under federal government control. These settlers brought sheep herding to the island, and by the 1870's, the vegetation of the island had changed dramatically from the herds. Since 1934, the United States Navy took over the administration of the island. To this day, San Nicolas Island is a designated auxiliary air station and training ground for the U.S. Navy (Chiles 2015).