Application of Coastal Vulnerability Index (CVI) on the Island of Oahu

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I certify that I have read this thesis and that, in my opinion, it is satisfactory in scope and quality as a thesis for the degree of Bachelor of Science in Global Environmental Science.

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Mahalo!

ABSTRACT

Coastal vulnerability index (CVI) was used to identify and map the vulnerable coastline of Oahu from sea-level rise risks. Vulnerability is the resources at risk from coastal hazards. Sea level rise pose many complications such as loss of land to many coastal communities, especially on islands, such as Oahu. The purpose of this study is to identify the highly vulnerable areas on the island of Oahu, evaluate the vulnerability of Oahu based on the geomorphology without habitats, and provide a reference for adaptation options to overcome sea level rise in coastal management practices for Sunset Beach, HI. The particular CVI method used was Hammar-Klose and Thieler (2001) that the Natural Capital Project's InVEST toolkit (InVEST Coastal Vulnerability version 3.3.2) (InVEST, 2016) software incorporates to analyze the biological and physical environmental inputs of the region to give a spatial mapping of vulnerable areas. Major vulnerable areas are found in the northern shore regions, the western coast, southwest shore, and the southeastern tip. On account of the information for cost benefit analysis at Sunset Beach, we chose this area as a case study. In the Sunset Beach region, factors including high wave exposures, surge potential, geomorphologic features such as sandy beaches, and sea level rise make this area among the most vulnerable. Several adaptation options are available for Sunset Beach, and conducting a cost-benefit analysis can aid to identify the best management practice for decision-makers. This study can contribute toward coastal zone management in areas that have little to no data information that can assist decision-makers in finding vulnerable areas to concentrate on and aid in the best adaptations options for vulnerable areas similar to Sunset Beach.

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1.0 INTRODUCTION

Climatic stressors, including sea level rise, degrade and disrupt coastal communities. Adaptation methods are required to build resilience in order to minimize coastal vulnerability risks. According to the Intergovernmental Panel on Climate Change (IPCC), estimated global averaged mean sea level rise is at 3.2 mm yr^{-1} (3.2×10^{-3} m yr^{-1}) between 1993 and 2010 and will likely increase (IPCC, 2013). The increase in sea level rise and coastal impacts from associated climate change may cause accelerated shoreline erosion, saltwater intrusion, inundation, and a dramatic switch to the natural environment and destruction of human infrastructure in the coastal areas (IPCC, 2007; Nicholls et al., 2007). Altimeter measurements, and tide gauges indicated that sea level has risen approximately 0.054 m from 1993 to 2011 and current mean sea level rise rates are around 3.2 mm yr^{-1} to 3.4 mm yr^{-1} (3.2×10^{-3} m yr^{-1} to 3.4×10^{-3} m yr^{-1}) (Ablain et al., 2009; Nerem et al., 2010; Church & White, 2011; The University of Colorado Sea Level Research Group, 2016). The accelerated sea level rise can be estimated to increase anywhere from 0.3 m to 1.2 m by the year 2100 (NCA, 2014). The local sea level rise may vary from the global mean sea level rise due to land movements, and in Hawaii, the current rise rate is approximately 1.5 mm yr^{-1} (1.5×10^{-3} m yr^{-1}) (NOAA, 2013a; Romine et al., 2013).

Low-lying coastal areas are severely vulnerable to sea level rise, which cause ecological and social impacts such as displacements of the human population (Nicholls & Cazenave, 2010; Wetzel et al., 2012). More specifically, intensified and frequent storm impacts and sea level rise on the islands can cause repercussion to not only the coastal communities, but also on multiple socio-economic activities (e.g. tourism and land usage) (United Nations, 1994; Mimura & Harasawa, 1996; IPCC, 2007; Scott et al., 2012; Hernández-Delgado, 2015). The risks associated with climate change threaten highly populated island infrastructure and economy. In Hawaii, sea level rise can inundate further inland from seasonal waves, storms, increase in flooding, erosion, salt water intrusion, and contribute to storm damages (Vitousek et al., 2008; Vermeer & Rahmstorf, 2009).

In this study, the objective was to create a spatial mapping of vulnerabilities along the coast of Oahu based on a coastal vulnerability index (CVI). Another objective was to provide a cost-benefit analysis of adaptation strategies for the area of Sunset Beach, Hawaii. This thesis will cover the study area of Oahu and its current conditions to sea level rise and geophysical features in Section 2. Next, Section 3 presents the methodology of this research where CVI and a visualization tool were used to calculate and map the relative vulnerability on Oahu. Further explanations for each vulnerability factor and its importance will also be discussed. The model requirement and steps that were taken will also be described in the model database and procedure (GIS) subsection under methodology. The adaptation subsection will discuss the cost-benefit analysis that was used for Sunset Beach. The results and discussion in Section 4 present the finding for each factor that contributes to the coastal vulnerability along with the overall exposure on Sunset Beach, Hawaii. Also within the Results and Discussion section is the cost and benefit tables that present the adaptation options considered for Sunset Beach.

1.1 COASTAL VULNERABILITY INDEX AND ITS APPLICATION ON THE ISLAND OF OAHU

Islands have major challenges to assess coastal vulnerability when there is limited data (e.g. land usage, erosion rates, and geophysical processes) on the coastal zones. Therefore, use of a CVI can fill in missing data by using the geologic and physical processes of the coastline. The CVI is an approach to quantify the degree of coastal vulnerability to sea-level rise at the local and/or regional scale (Thieler & Hammar-Klose, 1999). Numerous indices have been developed or modified to assess vulnerability factors by incorporating more geophysical influences such as wave energy, geomorphology, storm frequency and erosion/accretion rates (Gornitz, 1990; Gornitz et al., 1991, 1993, 1997; Cooper & McLaughlin, 1998; Thieler & Hammar-Klose, 2000; Hammar-Klose & Thieler, 2001; Lizárraga-Arciniega et al., 2001). Natural habitats, human population, and other socio-economic factors were also incorporated into CVIs (Bush et al., 1999; McLaughlin et al., 2002; Boruff et al., 2005; Coelho et al., 2006; Szlafsztein & Sterr, 2007; WRI, 2009; Li & Li, 2011). The combination of CVI with Geographical Information Systems (GIS) to produce vulnerability maps have become widely used across many regions along with a multi-criteria evaluation approach to CVI (McLaughlin et al., 2002; Coelho et al., 2006; Özyurt, 2007; De Pippo et al., 2008; Özyurt & Ergin, 2009, 2010; Bagdanavičiūtė et al., 2015; Satta et al., 2015). Every CVI may require different input variables that may not be present in various regions; therefore with limited data that is already available, a CVI will be advantageous to areas such as Hawaii. A commonly used CVI method that uses six influential factors to coastal vulnerability is from Hammar-Klose and Thieler (2001).

The use of CVI, especially Hammar-Klose and Thieler (2001) methods, can be applied to the area of Oahu to present the relative vulnerability of each coastal segment. Using the combination of various factors that include geomorphology, natural habitats, human population, and geophysical influences along with GIS can provide Oahu with a relative vulnerability map. Using a CVI along with a visualization tool provides a clear identification of coastal vulnerability for decision makers and stakeholders. After identifying areas that are particularly vulnerable, best management adaptation strategies should be examined to help mitigate coastal risks and hazards.

1.2 ADAPTATION THROUGH COST-BENEFIT ANALYSIS

Consideration of adaptation options (e.g. shoreline protection, beach nourishment, and vegetative covers) are necessary to address the rising concerns of risk associated with climate stressors. Deciding whether an adaptation action is needed or to what extent, can avoid unnecessary economic costs and negative impacts on human health or biodiversity of an area. Performing a cost-benefit analysis identifies the cost of the adaptation option and the net benefit of it. The cost-benefit analysis considers the challenges of implementing the adaptation option and societal view on the solution that monetary values cannot capture. Each community and stakeholder may place different values on the adaptation option. Considering the various adaptation options can prevent negative impacts from occurring (e.g. coastal armoring that may decrease property value and cause beach erosion). A quarter of Oahu’s beaches has been narrowed in a span of 70 years due to shoreline armoring (Eversole, 2009). Coastal armoring is one of many adaptation options that can protect property but at the same time will impact nearby beaches or other unprotected properties.

1.3 GAPS AND RESEARCH GOALS

Limited work has been done on the coastal vulnerability of Oahu. Previous studies on Oahu examined coastal erosion, wave height, wave energy, and sea level rise (Jeon, 1995; Kane et al., 2012; Romine & Fletcher, 2013; Kane et al., 2015). Few studies have assessed the coastal communities' perception to sea level rise and climate on Oahu such as Larin (2014). To adequately understand coastal vulnerabilities, communities should be involved to help determine the social values and economic worth of a coastal area. Identifying the locations where areas may be more or less vulnerable to storms and sea level rise is crucial information that can aid decision makers or stakeholders to protect and improve the coastal communities' resilience to coastal risks. Understanding where the vulnerable locations are on Oahu can give an indication of where significant physical changes may occur and the impact on coastal communities.

This research aims to assess the coastal vulnerability and identify the most vulnerable areas on the island of Oahu. By using Hammar-Klose and Thieler (2001) methodology, InVEST (2016), and GIS, this research provides a vulnerability index map as a preliminary identification of high vulnerable areas. This paper will also identify the coastal exposure from each element such as storm surge, sea level rise, and wave exposure. A vulnerability index and visualization of each risk element's contribution to the coastlines can aid decision-makers in the best management practices for high vulnerable areas. This paper will address the adaptation methods by using a cost-benefit analysis approach to a case study area based on its CVI map. Particular areas that are at higher vulnerability, such as the north shore regions, can be negatively impacted by the loss of natural habitats and major changes to the geomorphology of the coastal area.

Understanding the importance of natural habitats and the social and or economic value placed by a coastal community to a coastal zone will help find the best adaptation strategy for a specific area.

2.0 STUDY AREA

Oahu is at considerable risk to climate stressors based on its high population density per square km, socio-economic services, diverse ecosystem, and exposed coastal zones. Oahu is an oceanic island composed mainly of basalt that lies on the northernmost island group in Polynesia (21° 28′N 157 ° 59′W) (See Figure 1). Every year Oahu receives a strong North Pacific Swells that increase wave height, can reach an overall height of 15 Hawaii Scale feet, and alters the sediment transport to a coastal area (Moberly & Chamberlain, 1964; Caldwell, 2005). Recurring significant wave height averages around 7.7 ± 0.28 m and extreme heights during annual swells from the north can reach up to 12.9 ± 0.47 m (Vitousek & Fletcher, 2008). Localized sea level rise rate is around 1.50 ± 0.25 mm yr^{-1} ($1.5\times10^{-3} \pm 2.5\times10^{-4}$ m yr^{-1}) and shoreline change rate is about -0.03 ± 0.03 m yr^{-1} which leaves Oahu beaches eroding at 52% and even higher in the Northern regions at 63% (Romine et al., 2013). These climatic forcing on the islands can disrupt socio-economic activities that are vital to Oahu and damages cultural and human infrastructures (e.g. homes, roads, harbors). Sea level rise is also concerning to Oahu as most of the population and socio-economic industries lies close to the coast. Approximately 27% of major roads, 9% of rail lines, and 72% of ports are built on an elevation at or below 1.22 m. Therefore a storm surge more than 1.22 m can lead to disruptions and damage (Savonis et al., 2008). Sea level rise and other climatic stressors can strain Hawaii's limited freshwater availability by saltwater intrusions to aquifers, stresses and reduce natural habitat, increase flooding and erosion, damage coastal infrastructure, and social or economic services.

In the north shore coastal regions of Oahu, large seasonal winter waves attract many surfers. It is characterized by coarse-grained sandy beaches with isolated rocky outcrops made of basalt or reef-rocks. The area is susceptible to annual high wave energy from the winter swells. The winter swells also causes high erodibility for exposed sandy beaches along Pupukea to Sunset Beach (See Figure 1). In susceptible locations of the island such as Sunset Beach, extreme storm events or large swells can cause severe damages to properties and roads. For example, the large swell event in 2016 caused erosion and water damage to homeowners' properties and inundated part of Kamehameha Highway (Remadna et al., 2016; Hawaii News Now, 2016). Increase in sea level and climatic stressors will worsen conditions and create future problems if no action is taken to reduce and mitigate the coastal risks and hazards. Therefore, it is crucial to identify the coastal vulnerability and the best management adaptation strategies in a coastal area.

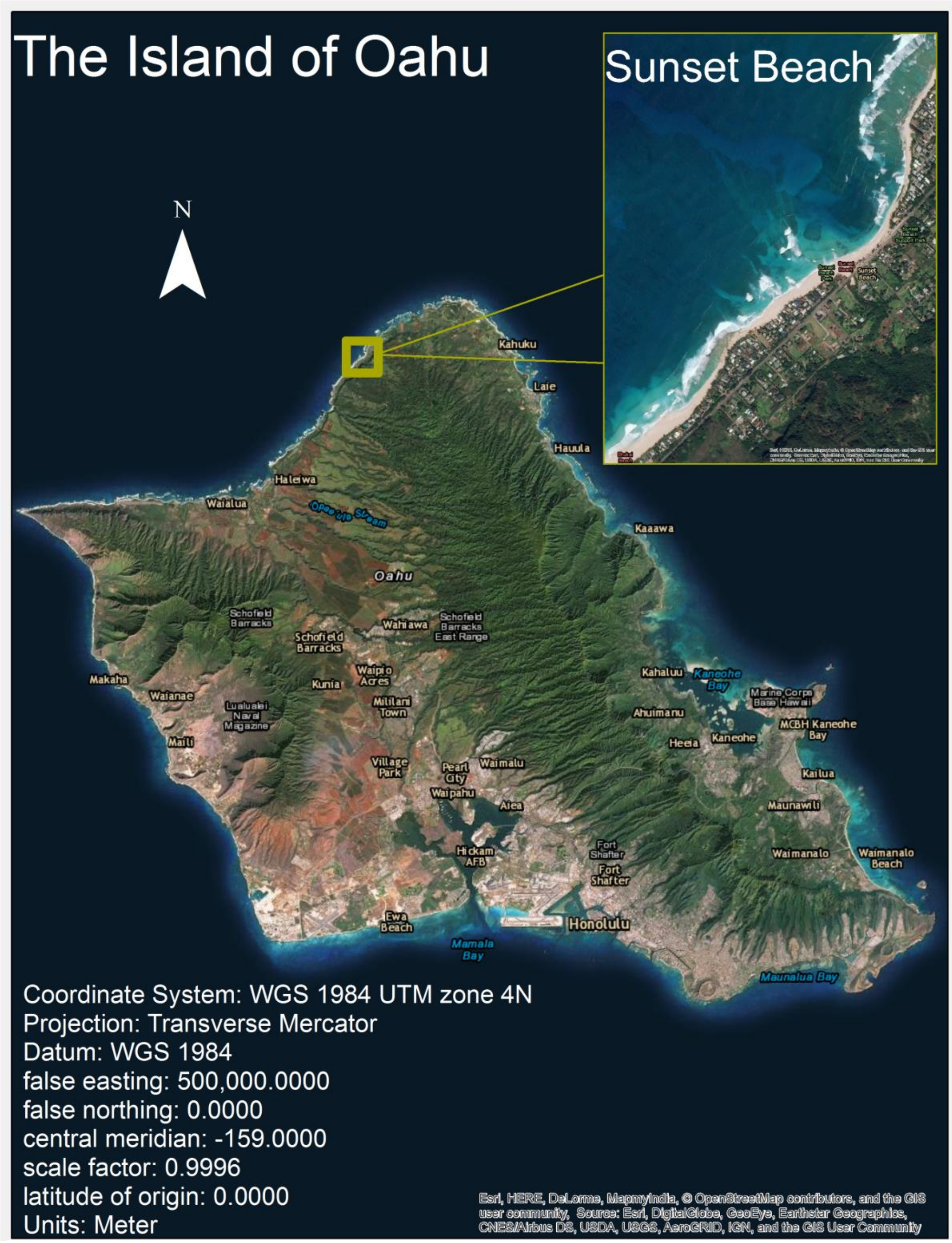


Figure 1: Area of Interest, the Island of Oahu and Sunset Beach (ESRI Basemap).

3.0 METHODS

This section will discuss the CVI, InVEST (2016) model, and GIS tools that were used to calculate and map the relative vulnerability on Oahu. CVI with InVEST (2016) coastal model can generate spatial maps of relative vulnerability as a preliminary identification of highly vulnerable areas. Each factor from the CVI is calculated through InVEST (2016). Each factor is ranked based on the CVI and at the user's discretion. The model requirement and input steps are also described in this section along with a table of sources and modification to the input files. Following the model database and procedure (GIS) subsection, is the adaptation subsection that will provide the steps for a cost-benefit analysis and ranking.

3.1 COASTAL VULNERABILITY

The coastal vulnerability of the human population from exposure to coastal hazards can be measured and evaluated for mitigation and disaster planning. Coastal stresses that drive vulnerabilities such as sea level rise, storm surge, erosion, and frequent flooding threatens the local community and possibly the future condition of the population. Coastal vulnerability assessments help to identify and manage risks.

3.1.1 THEORY OF COASTAL VULNERABILITY INDEX (CVI)

The relative risk of sea level rise from erosion and risk associated with storms can be quantified and assessed using a CVI. Several methodologies assessed coastal vulnerability dependent on geophysical characteristics variables such as relief, geomorphology, landforms, and storm frequency (Gornitz, 1990; Gornitz et al., 1991; Hammar-Klose & Thieler, 2001; Cooper & McLaughlin, 1998). Other CVI methodologies assessed the role of natural habitats, reduction of erosion, and inundation risk within areas (WRI, 2009; Bush et al., 2001). Socio-economic factors such as population have also been included into the CVI (Gornitz et al., 1991; McLaughlin et al., 2002). Using a combination of CVI methodologies, InVEST (2016) modifies several proposed CVI to calculate and rank each parameter (Sharp et al., 2016). The main CVI used was Hammar-Klose and Thielers'. The Hammar-Klose and Thieler (2001) CVI methodology uses geomorphology, shoreline change rate, coastal slope, relative sea level change, mean significant wave height, and mean tidal range that accounts for the physical processes in the area. Multiple organizations, such as the United States Geological Survey, and other CVIs are based off of the Hammar-Klose and Thieler methodology (Pendleton et al., 2004; 2010). Modification can be easily made to incorporate more coastal features and into visualization tools.

By defining the characteristics of a coastal area to include the biological and geophysical will help to give an accurate depiction of the area's hazards, social and environmental conditions, and current risks. These factors can affect the coastline; therefore should receive significant consideration in the CVI. Having a mixture of each CVI methodology can improve ranking and calculating of coastal vulnerabilities for areas with little to no data. The specific CVI model used for this study is InVEST (2016) (See Table 1). Using the model and user defined criteria can create a better suited CVI for the area.

3.2 InVEST (2016) COASTAL VULNERABILITY MODEL

The InVEST (2016) program is an open-source software tool that helps spatially map a broad range of ecosystem services and environments created by the Natural

Capital Project. The version and model used in this study is InVEST (2016) version 3.3.2 x86 Coastal Vulnerability. The InVEST (2016) program creates exposure indices that look at seven biogeophysical variables in the form of GIS shapefiles and rasters. The bio-geophysical coupled with the population raster gives a representation of biological and geomorphic characteristics of a region, the expected sea level rise, and the relative wind and wave forcing related to storms. The biogeophysical variables are geomorphology, relief, natural habitats (biotic and abiotic), net sea level change, wind and wave exposure, and surge potential depth contour.

Geomorphology includes characteristics that will affect the vulnerability of the coast. Based off of Hammar-Kolse and Thieler's (2001) CVI methodology, InVEST (2016) defined a similar classification of geomorphic features and ranked it accordingly for the North American region. Protected or hard features, such as rocky cliffs or sea walls, are less susceptible to erosion and inundation; therefore, a low to moderate ranking can be applied. Other features vulnerable to erosion, such as sandy beaches, deltas, and estuaries, can be given a higher ranking. Other features not listed in InVEST (2016) are at the discretion of the user. Such features include mangroves and non-protective man-made structures. To obtain a befitting geomorphology for Oahu, NOAA's environmental sensitivity index (ESI) for Hawaii helped to define Oahu's coastline (NOAA, 2001). InVEST (2016) coastal vulnerability model requires a polyline shapefile with ranked attributes for each segment on the shoreline. The attribute in this file must have a field titled "RANK" that is a Short Integer containing numeric rank from one to five (Sharp et al., 2016).

The relief variable considers the elevation of mean sea level. Higher elevation will be less susceptible to inundation because it is further away from sea level. InVEST (2016) coastal vulnerability model requires a digital elevation model (DEM) for the area of interest. In this research, the bathymetry and relief can use the same DEM file. This data was obtained from SOEST 50 meter bathymetry and topography grid file for the Hawaiian Islands (SOEST, 2014).

Natural habitats need to be factored into the CVI due to its level of protection from coastal risks. Depending on the habitat of the region, it can reduce the coastal vulnerability from erosion, inundation, and coastal hazards. Different habitats such as corals or vegetation can protect the shoreline by dissipating wave energy (Kobayashi et al., 1993; Ferrario et al., 2014). Other habitats such as coastal dunes can protect against beach erosion (Ruggiero et al., 2001). Natural habitats' variables can be ranked based on the user defined criteria in which habitats provide more protection for the area of interest. The InVEST (2016) program will calculate an exposure rank for each coastline segment based on the user defined radius of the habitat. The model will generate an R vector containing the ranks for all habitats defined as $R_{k,}$ $1 \leq k \leq N$, where N represent the n^{th} habitat. After ranking the habitat, the model calculates an exposure rank for each segment (See InVEST (2016) User Manual for calculations, Sharp et al., 2016). The model requires a polygon shapefile for each habitat and a CSV file accompanying the natural habitats. The CSV file needs to have the name of the habitat shapefiles, ranks, and habitat radii. The CSV includes the name of the shapefile for each habitat along with a number to be able to link the shapefile to the CSV. The rank given to the habitat is based on its protection service to the coast. Habitat radius was found by its range of protection and proximity to the coast.

The net sea level change is accounted for by the sea level rise trends along the coast. To calculate this into the CVI, the model requires a polygon or a point shapefile that contains the attribute “Trend” in millimeters per year of the recorded sea level change.

Wind and wave exposure measures the potential erosion from storm or wind waves. Higher exposure to the open ocean increases the vulnerability compared to sheltered coasts. InVEST (2016) computes the relative exposure in a segment by weighing the maximum average wave energy (E_w) of ocean waves and calculates wind speeds (See InVEST (2016) User Manual for calculations, Sharp et al., 2016). Fetch is the distance traveled by the wind across the ocean. Including fetch, wave height and periods, and wind speed helps differentiate between an exposed or sheltered coastline and the exposure to surges or strong waves. Surge potential can be included by designating the distance to the shoreline in segments. InVEST (2016) provided a default shapefile for wind and wave data from eight years (February 2005 to February 2012) from WAVEWATCH III (WW3, Tolman, 2009) model results.

The social exposure parameter considers the human population to coastal hazards. Depicting the population along each segment allows for a better estimate of people at risk to coastal erosion and storm inundation. The InVEST (2016) Coastal Vulnerability model will take a population value from a raster for the user defined radius from the shoreline. The population raster used in this research was produced by the 2010 U.S Census Bureau (U.S Census Bureau, 2010).

Assessments of the biogeophysical variables are based on the combination of ranked physical and socio-economic parameters along with the use of GIS. The model computes the environmental exposure by ranking the biological and physical variables of the shoreline segment (Table 1). The ranks were calculated based on the proposed methods of Gornitz et al. (1990) and Hammar-Klose and Thieler (2001). The ranks range from one (low exposure) to five (very high exposure). Determining the rank for the area of research can be calculated from the user and model defined criterion. The InVEST (2016) Coastal Vulnerability model calculates the CVI using the exposure index from each shoreline segment in a geometric mean of all variable ranks as:

$$\boldsymbol{EI = (R_{Geomorphology}R_{Relief}R_{Habitats}R_{SLR}R_{WindExposure}R_{WaveExposure}R_{Surge})^{1/7}} \tag{1}$$

Alternatively, in a general form for additional layers with R_i representing the rank of the i^{th} bio-geophysical variable:

$$\boldsymbol{EI = \left(\prod_{i=1}^{n} R_i\right)^{1/n}} \tag{2}$$

The model also computes the erosion index along to mapping the CVI as:

$$\boldsymbol{ErI = \left(R_{Geomorphology}R_{Habitats}R_{WaveExposure}\right)^{1/3}} \tag{3}$$

Table 1: CVI of Bio-Geophysical Variables and Ranking System for the Coastal Ecosystem

Rank	Very Low	Low	Moderate	High	Very High
Variable	**1**	**2**	**3**	**4**	**5**
Geomorphology	Rocky; high cliffs; fjord; fiard, seawalls	Medium cliff; indented coast, bulkheads and small seawalls	Low cliff; glacial drift; alluvial plain, revetments, rip-rap walls	Cobble beach; estuary; lagoon; bluff	Barrier beach; sand beach; mud flat; delta
Relief	0 to 20 Percentile	21 to 40 Percentile	41 to 60 Percentile	61 to 80 Percentile	81 to 100 Percentile
Natural Habitats	Coral reef; mangrove; coastal forest	High dune; marsh	Low dune	Seagrass; kelp	No habitat
Sea Level Change	0 to 20 Percentile	21 to 40 Percentile	41 to 60 Percentile	61 to 80 Percentile	81 to 100 Percentile
Wave Exposure	0 to 20 Percentile	21 to 40 Percentile	41 to 60 Percentile	61 to 80 Percentile	81 to 100 Percentile
Surge Potential	0 to 20 Percentile	21 to 40 Percentile	41 to 60 Percentile	61 to 80 Percentile	81 to 100 Percentile

3.2.1 MODEL REQUIREMENT AND INPUTS

The model used in this study requires the following input parameters as follows: Output area, workspace location, area of interest (AOI), land polygon, bathymetry layer, relief, elevation averaging radius (m), mean sea level datum (m), model resolution (segment size in meters), rays per sector, fetch distance threshold (m), exposures proportions (m), oceanic effect cutoff (m), geomorphology, coastal overlap, natural habitat, natural habitat layers CSV, climatic forcing grid, continental shelf, depth contour level (m), sea level rise, structures, population raster, minimum population in urban centers, coastal neighborhood (radius in m), and if any layer was omitted there is an integer value placeholder as a substitute. The model will also need a spatial resolution that is greater than or equal to 250 meters. See Figure (2).

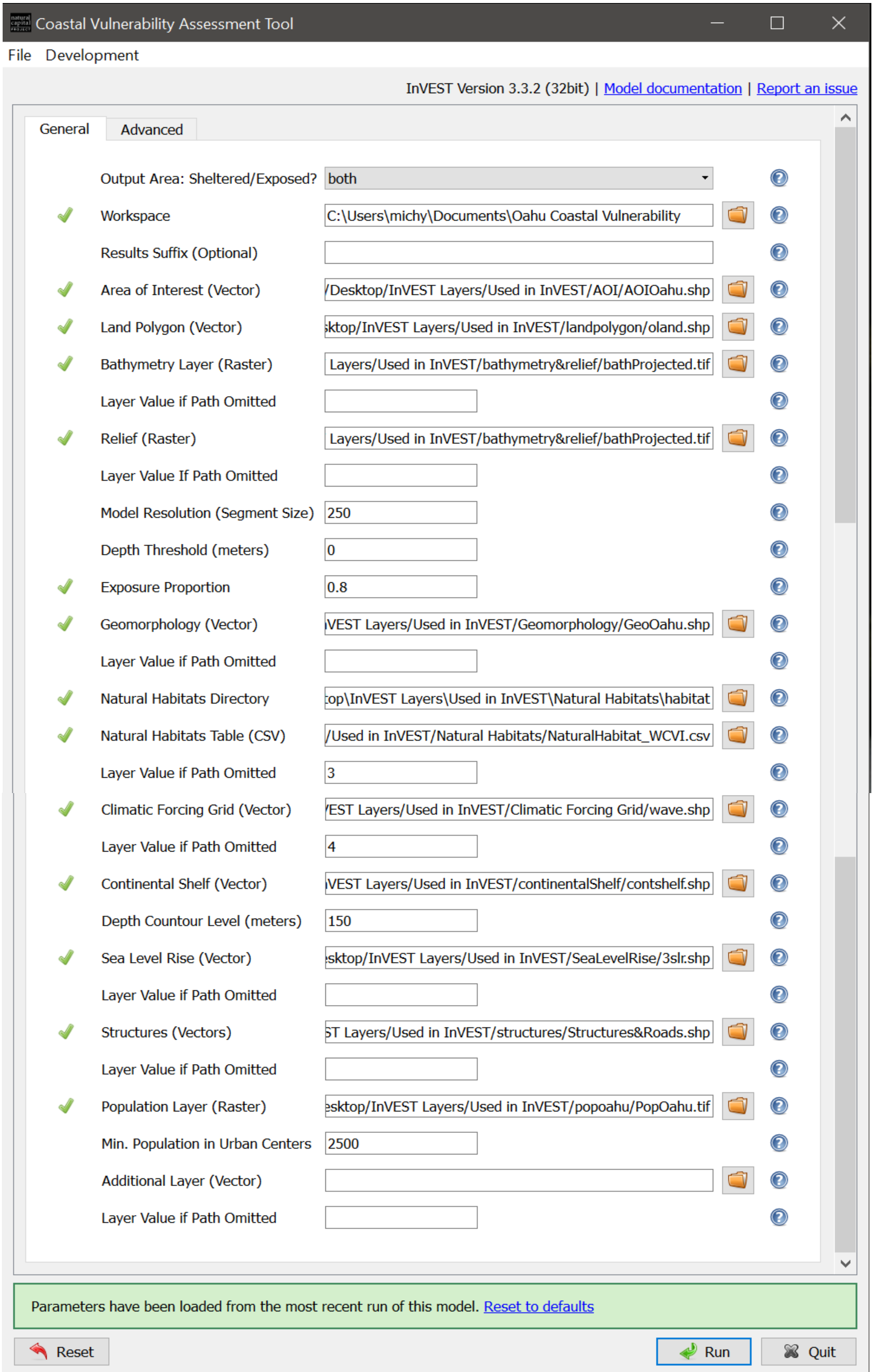


Figure 2: InVEST (2016) 3.3.2 Coastal Vulnerability Assessment Input GUI

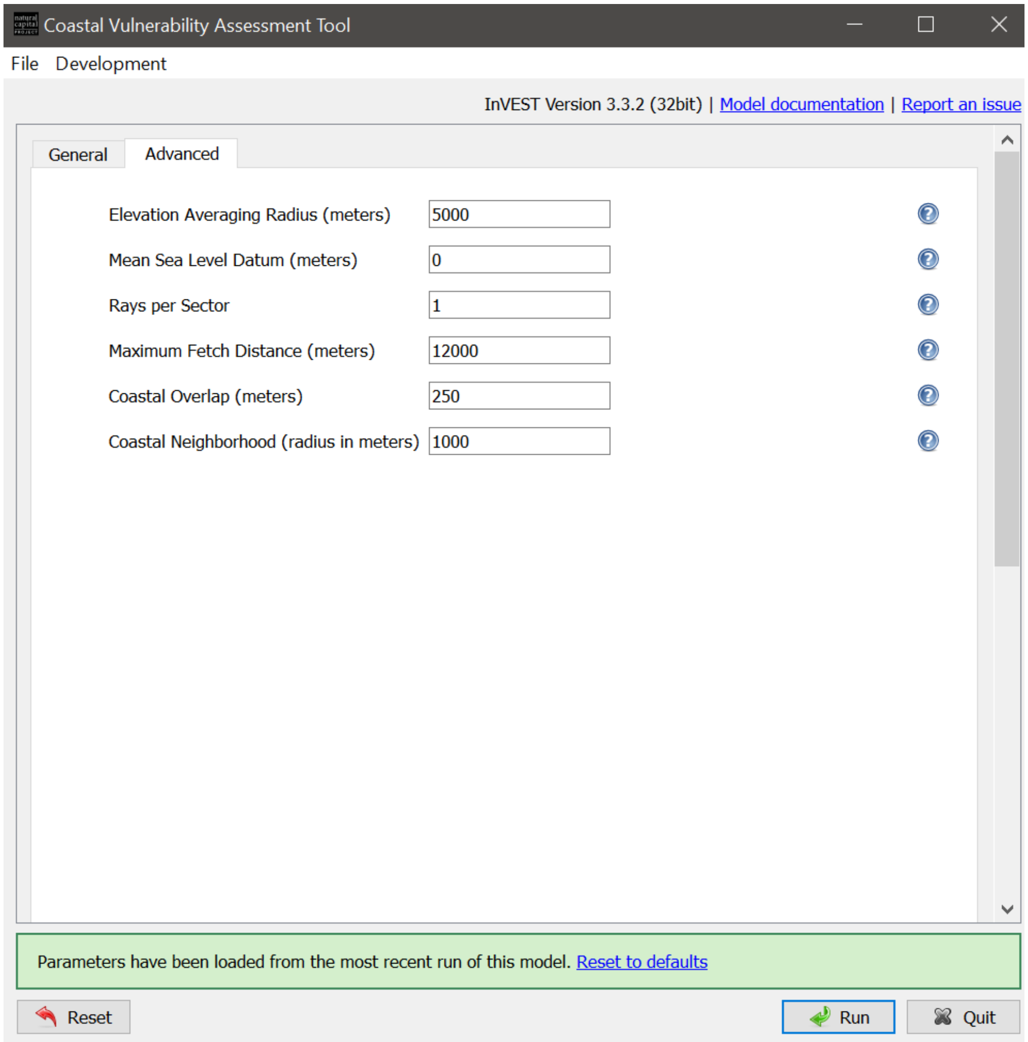
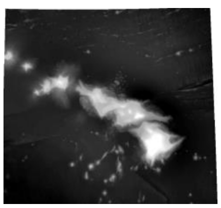


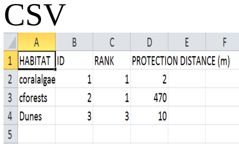
Figure 2: InVEST (2016) 3.3.2 Coastal Vulnerability Assessment Input GUI

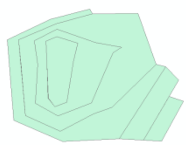
3.3 MODEL DATABASE AND PROCEDURE (GIS)

To create, modify, and define variable ranking, a GIS-based program called ArcGIS was used. ArcGIS is a mapping tool developed by ESRI. The version mainly used in this study is ArcGIS 10.3.1. All files are in the same spatial reference as WGS_1984_UTM_Zone_4N. See Table (2) that provides the file name, form, source, and a description of the file used.

Table 2: Variable Input’s name, type, source(s), and description.

VARIABLE INPUT(S)	FILE(S) NAME	DATA TYPE	SOURCE(S)	DESCRIPTION(S)
Area of Interest (AOI)	AOIOahu.shp	Shape file	Created	Polygon with feature extent at: Max Y (2444673.455 m), Max X (670762.439 m), Min Y (2316614.865 m), and Min X (519596.859 m). Decimals rounded to the thousandths place.
Bathymetry & Relief 	bathProjected.TIF	Raster	http://www.soest.hawaii.edu/HMRG/Multibeam/bathymetry.php 50 Meter Bathymetry and Topography Grids (GMT and Arc) Hillshade Grid (~1.2 GBs) Spatial Reference :GCS_WGS_1984 file (hdr.adf)	Changed raster projection to WGS_1984_UTM_Zone_4N and exported to a new file with Model Resolution (Segment Size) 250.
Continental Shelf 	contshelf.shp	Shape file	InVEST (2016) 3.3.2 input data file Spatial Reference :GCS_WGS_1984 file (continentalShelf.shp)	Changed projection to WGS_1984_UTM_Zone_4N and exported to a new file.
Geomorphology 	GeoOahu.shp	Shape file	http://response.restoration.noaa.gov/maps-and-spatial-data/download-esi-maps-and-gis-data.html Hawaii 2001 Shapefiles/ArcView 3.x project [Zip, 28 MB] Spatial Reference :Old Hawaiian Dominion	Modified file by clipping and joining a created table to the attributes of the file. Created table include descriptions and ranks. Changed projection to WGS_1984_UTM_Zone_4N and exported to a new file.

			file (ESIL.shp)	
Land Polygon 	oland.shp	Shape file	http://pubs.usgs.gov/imap/i2761/oahu.html as a single sipped file for Oahu (2.9 MB) file (oahu_oha.shp)	Modified file by creating polygon from line shape file. Changed projection to WGS_1984_UTM_Zone_4N
Natural Habitats 	coralalgae_1.shp, cforests_2.shp, Dunes_3.shp	Shape file	Coralalgae_1.shp original file from: http://response.restoration.noaa.gov/maps-and-spatial-data/download-esi-maps-and-gis-data.html Hawaii 2001 Shapefiles/ArcView 3.x project [Zip, 28 MB] File (HABITATS.shp) cforests_2.shp & Dunes_3.shp are created	Coralalgae_1.shp: Modified file by clipping polygon. Created table to join the modified attribute that include description. Changed projection to WGS_1984_UTM_Zone_4N cforests_2.shp: Created polygon to match google image on Oahu forest areas and Openstreet. Dunes_3.shp: Created polygon to match google image dune location on Oahu.
Natural Habitats CSV  HABITAT | ID | RANK | PROTECTION DISTANCE (m) coralalgae | 1 | 1 | 2 cforests | 2 | 1 | 470 Dunes | 3 | 3 | 10	NaturalHabitat_WCVI	Excel CSV	Created	Table that links the Natural Habitats to an ID, rank, and protection distance (m).
Climatic Forcing 	wave.shp	Shape file	InVEST (2016) 3.3.2 input data file Spatial Reference :GCS_WGS_1984 file (WaveWatchIII.shp)	Clipped file for area of interest. Changed projection to WGS_1984_UTM_Zone_4N and exported to a new file.
Population	PopOahu.tif	Raster	Original file from Department of Commerce, U.S. Census Bureau, Geography Division	Modified file by clipping area to Oahu. File was then projected to WGS_1984_UTM_Zone_4N. Then ocean,

			TIGER/Line Shapefile, 2010, 2010 state, Hawaii, 2010 Census Block State-based at: https://www.census.gov/geo/maps-data/data/tiger-line.html File: (tabblock2010_15_pophu.shp)	rivers, and lakes polygons census blocks were deleted. Polygon shape file was then transformed into a raster file using the attribute Pop10 with cell size 125 and saved as a TIFF file.
Sea Level Rise 	3slr.shp	Shape file	Created	Created polygons with attributes of sea level trends. Sea level trend information was averaged from NOAA tides and current trends and Romine et al. (2013) in addition to anomalies from LAS AVISO altimetry. Shapes of polygon referenced the shape of the anomalies of LAS AVISO altimetry.
Structures 	Structures&Roads.shp	Shape file	http://planning.hawaii.gov/gis/download-gis-data-expanded/ Roads – C&C of Honolulu File (oah_streets.shp)	Modified polyline shape file to polygon by buffering area to 7.42 meters. Area buffer size was taken by average size of roads to fill line on both ends. Created polygon structures of man-made structures such as buildings. Then merged both files together into one file.

Spatial resolutions of raster files are defined to 250 meters. This model will run on 250 x 250-meter grid to model in highest resolution in InVEST (2016)'s capacity. The exposure proportion was at a default value of 0.8 m. This value is determined by the number of fetch rays and the segment sector. A segment will be classified as a sheltered coast if either the fetch distance is less than 12 km (12,000 m) for more than 80% of the coastal segment or if the average depth of a fetch segment is less than 5 m. Minimum population in urban centers is set to 2,500. This value is defined by the U.S. Census Bureau as the minimum population criteria for an urban area (U.S. Census Bureau, 2010; 2011). The coastal neighborhood input will have the model sum the population within a specified radius, in this case, 1,000 m. Elevation averaging radius, mean sea level datum, rays per sector, and maximum fetch distance are also set to default value. Average elevation for relief is 5,000 m. Mean sea level datum is at 0 m for current sea level relative to the bathymetry layer. Increased mean sea level for this input will mean an increased mean sea level datum above the bathymetry datum. Rays per sector incorporate the ocean depth and land proximity in 16 equiangular fetch sectors. The maximum fetch distance is determined by the current segment that is enclosed by land and average ocean depth of exposed segments; the default value is 12,000 m. For input of coastal overlap if the geomorphology file does not exactly match up to the land polygon where non-overlapping shoreline will match with this input.

Natural habitat requires a CSV to link the habitats to a rank and its protection distance. The model will use the user-defined table to calculate the influence of habitat on each segment. The protection distance considers the coverage of protection for each habitat. The coralalgae.shp habitat consists of coral reefs habitats. The cforest.shp habitat considers the local coastal forest of Oahu. The dunes.shp habitat consists of small and large dunes along the northwest coast of Oahu. See Table (3) for the Island of Oahu inputs.

Table 3: Natural Habitat CSV file input.

	A	B	C	D	E	F
1	HABITAT	ID	RANK	PROTECTION DISTANCE (m)		
2	coralalgae	1	1	2		
3	cforests	2	1	470		
4	Dunes	3	3	10		
5						

3.4 MODEL VISUALIZATION AND LIMITATIONS

The visualization tool of InVEST (2016) used to calculate the CVI considers bio-geophysical and social-economic factors. The multi-variable contributes to understanding the vulnerability of the coast. All of the input files are required to be in the same coordinate system to overlay each other. The specific coordinate system used was the WGS 1984 / UTM zone 4N. This projected coordinate system is suited for areas between 162°W and 156°W which includes Hawaii, where the area of study is located. Instead of the coordinates being measured in decimal degrees, the projected coordinate system is in meters where the point of origin is the intersection of the equator and the zone’s central meridian. Natural habitats and structure shapefiles were created or modified to approximately match the shape or location of the structures or habitat area.

The methods used by InVEST (2016) are similar to other methods such as Özyurt et al. (2008), Satta et al. (2015), and Szlafsztein and Sterr (2007). These CVI methods help to define vulnerable areas more accurately for areas with little to no data. CVI does not require a lot of input and can be applied to a general coastal zone. Similar studies using InVEST (2016) to model various locations have been examined. Guerry et al.

(2012) applied the model to the West Coast of Vancouver Island, British Columbia, Canada. Kumar and Kunte (2012) applied a coastal vulnerability assessment to the Chennai, India with geospatial techniques. Hopper and Meixler (2016) modeled and mapped coastal vulnerability in Jamaica Bay, New York, for the past, present, and future scenarios. The CVI and visualization tools can be widely applied to various regions and can map out the relative vulnerability for a coastal area. Although the CVI approach is suitable for areas with little to no data, there are assumptions on the coastal processes within a segment.

Assumptions that could be inferred may include the tidal or ocean current against the shoreline which remain a constant value. The stability of each physical process can be assumed to not have dynamic changes quickly over time. The CVI is also heavily dependent on geographic and environmental features for an area. Approximation for input layers and features to match actual structures, habitats, population, and climatic input can be a challenge, but in a 250 m resolution the model is not sensitive to minor details. Even though there are general assumptions of processes, this method used was on a regional scale that will, the least, identify where the relative vulnerabilities are located.

3.5 ADAPTATION

Climate adaptation strategies reduce the vulnerability of human and environmental systems from climatic hazards and risks. Adaptation allows a coastal community to better cope with climate changes and improve resilience through protective or accommodating strategies (Camare & Lane, 2015). Each adaptation strategies can provide a beneficial service to reduce risks based on the needs of the environment, community, and policies. Although different adaptation options can provide some benefits to a community, the adaptation also requires some cost at the expense of the environment or community. For that reason, a cost-benefit analysis should be considered when estimating the degree on how the adaptation method will impact the coastal community and environment. Considering how each coastal area and community is unique in the type of hazards, geomorphology, habitats, and social values placed on the area, practical adaptation options can be found through a cost-benefit analysis tailored towards the specific area.

3.6 COST-BENEFIT PROCEDURE

In the final step of the study, a cost-benefit analysis is performed for Sunset Beach, Hawaii. Cost-benefit analysis is an approach to estimate the strengths and weaknesses of alternatives options and helps to identify the best options to be considered. In this case the cost-benefit analysis will be used for coastal adaptation options such as coastal armoring, vegetative cover, beach nourishment, artificial reefs, and elevate or relocate.

The first thing that needs to be identified is the potential benefit of each option, its impact, and cost from estimates of damage and historical damage. This will be considered as the baseline risk. Baseline risk includes the no-action scenario, where no adaptation action will take place. The next step is to review the level of protection of each option and monetize the impacts and the estimated cost for each adaptation action. This includes the investment requirements, funding, health and safety, efficiency, management, and durability of the adaptation.

The final task would be to assess the economic value and the net present value. While some things cannot be monetized such as culture values, it should be considered in the decision-making process whether to implement the adaption or not deteremined by the public and locals. In this step, each action scenario will be assessed, ranked, and calculated to provide the total benefits of each adaptation action. Each action is evaluated in regards to social support of the action if there is improved resilience to the community, the adaptation technical aspects, economic standpoint, and environmental impact. The ranking of each adaptation is from 1 (low) to 5 (high) for the action's benefits and costs. The benefit to cost ratio will determine which action should be given higher priority for consideration. Ratios that are greater than one will be given higher priority, an equal ratio suggests benefits are equal to its costs and are at a lower priority, and ratios that are less than one are at given the lowest priority.

4.0 RESULTS AND DISCUSSION

4.1 COASTAL VULNERABILITY

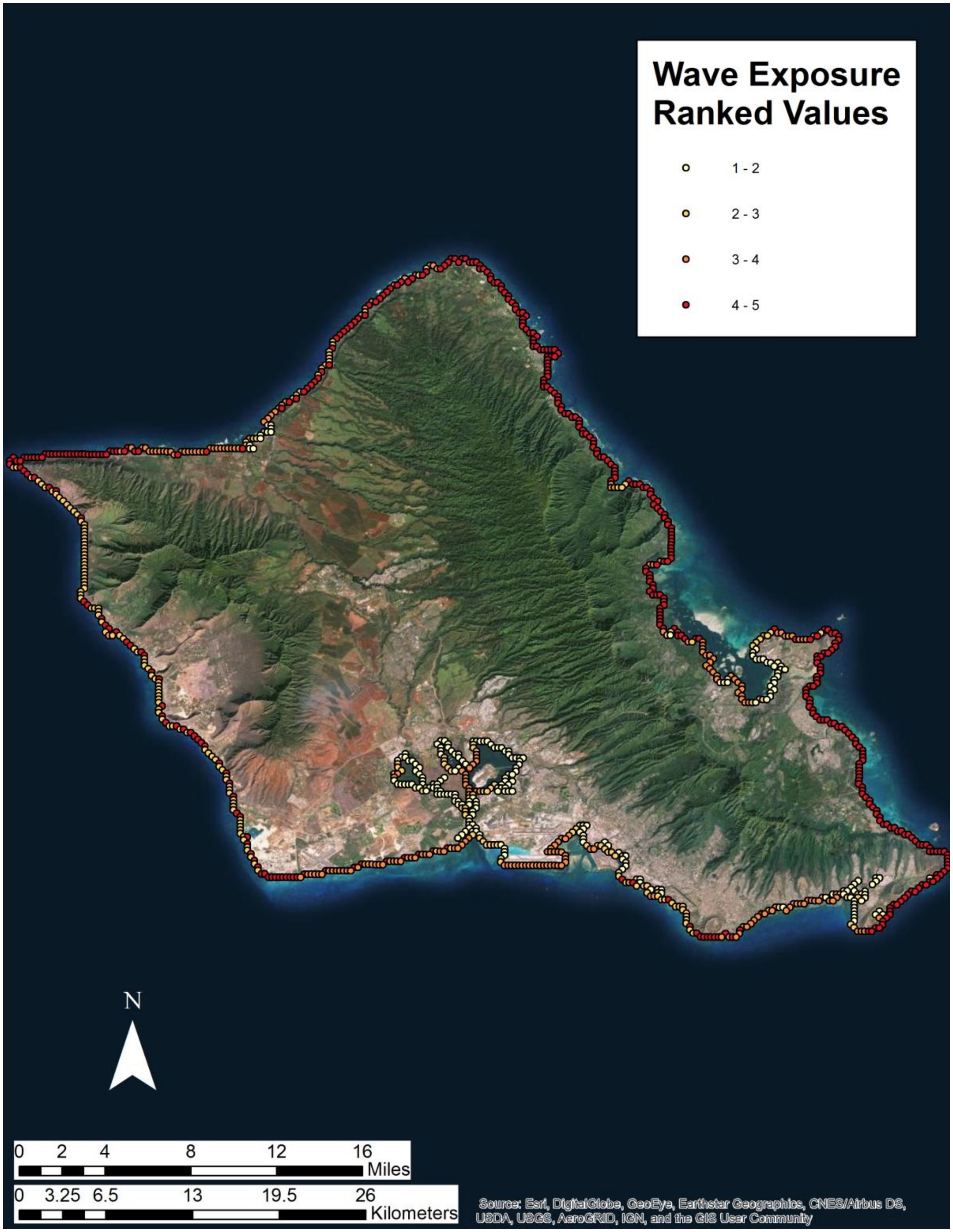


Figure 3: Wave Exposure (Values ranked 1-5)

Figure 4: Distribution of Wave Exposure Layers

Wave exposure contributes to coastal vulnerability from the wave energy, height, and frequency of exposure to the shore. As seen from Figure (3), the northern side of the island has a higher vulnerability compared to the southern areas of Oahu except for sheltered coastal areas. The fact that the north shore regions of Oahu receive large surfs from the North Pacific can be due to the North Pacific Swell and North-East Trade-waves. Several areas that are at lower vulnerability to waves are from its sheltered coast line from the waves. The distribution of the vulnerability rank is spread evenly (mean: 3.002; median: 3) (Figure 4). Surge potential is the rising water levels from the wind and atmospheric pressures changes onto the shore. Surge potential is higher on the northern and western shore (Figure 5). Distribution of potential surge exposure is mostly moderate to high (mean: 2.95; median: 3) (Figure 6). The higher storm surge on the north and western shore could be possibly explained by the longer distance between the coastline and the edge of the continental shelf compared to the south and eastern shores of Oahu.

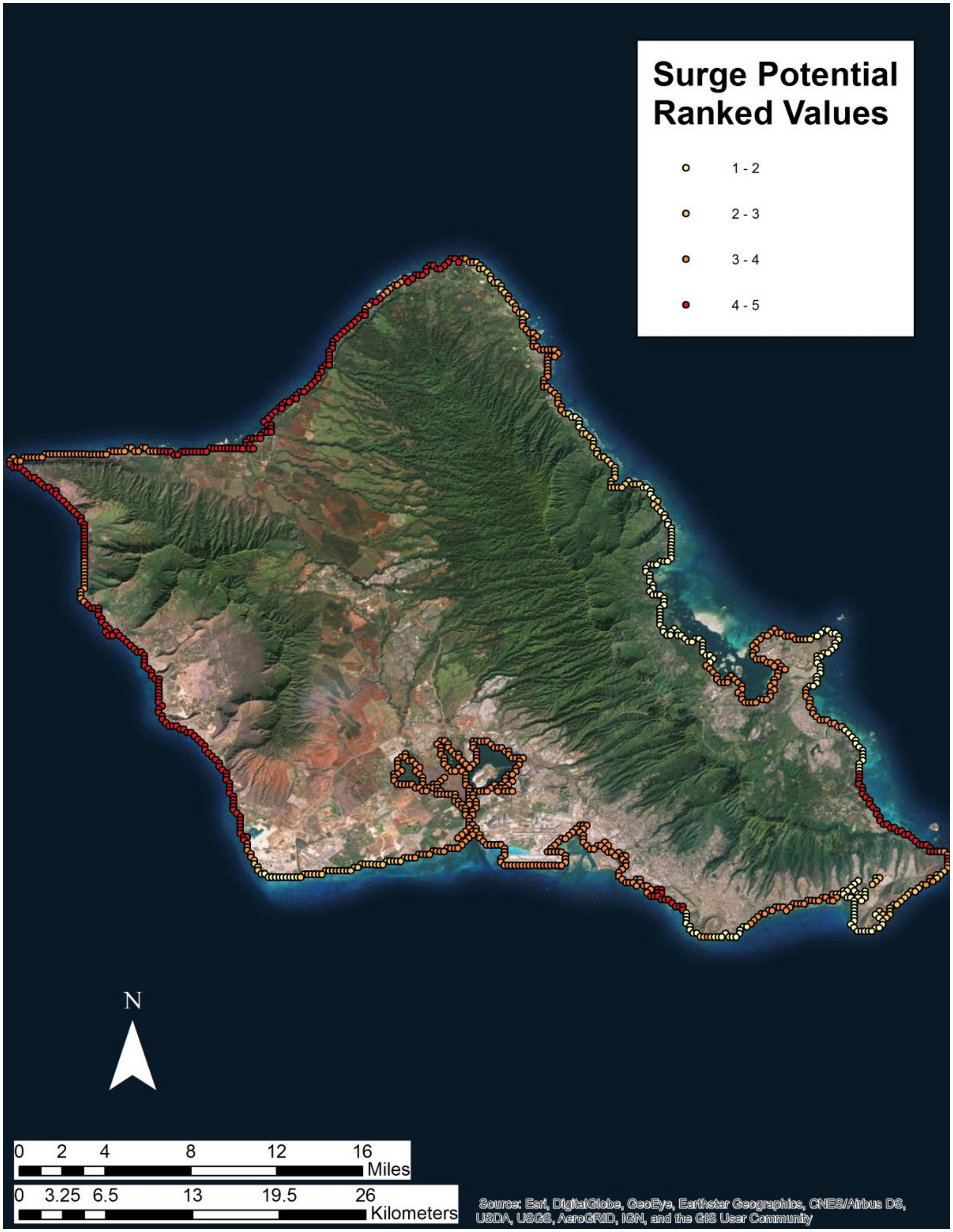


Figure 5: Surge Potential (Values ranked 1-5)

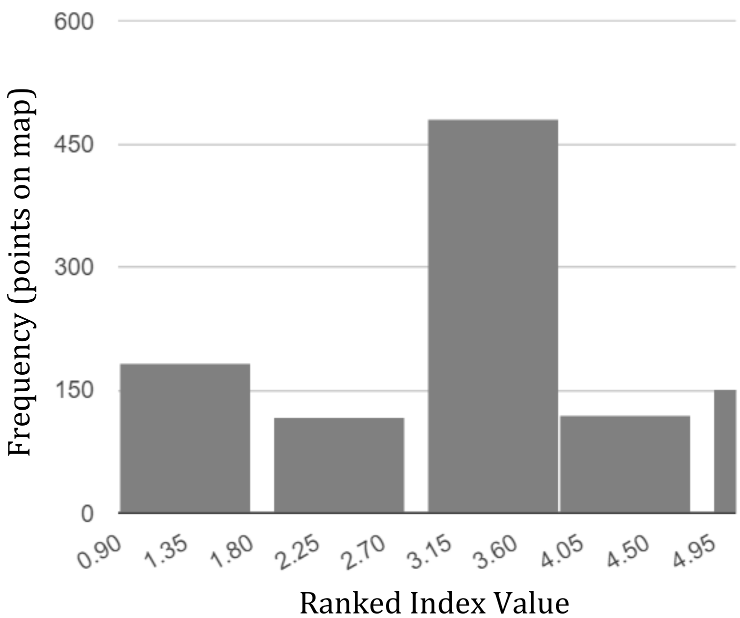


Figure 6: Distribution of Surge Potential Layers

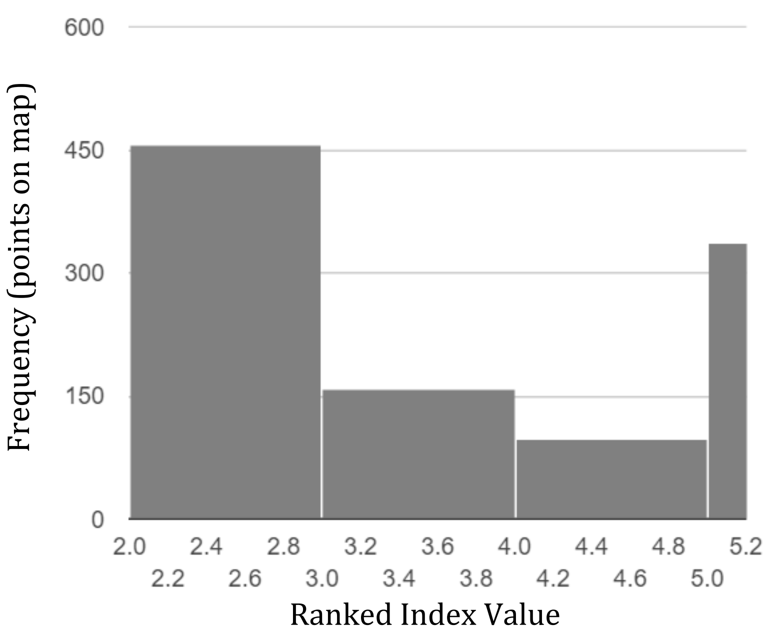


Figure 7: Distribution of Sea Level Rise Layers

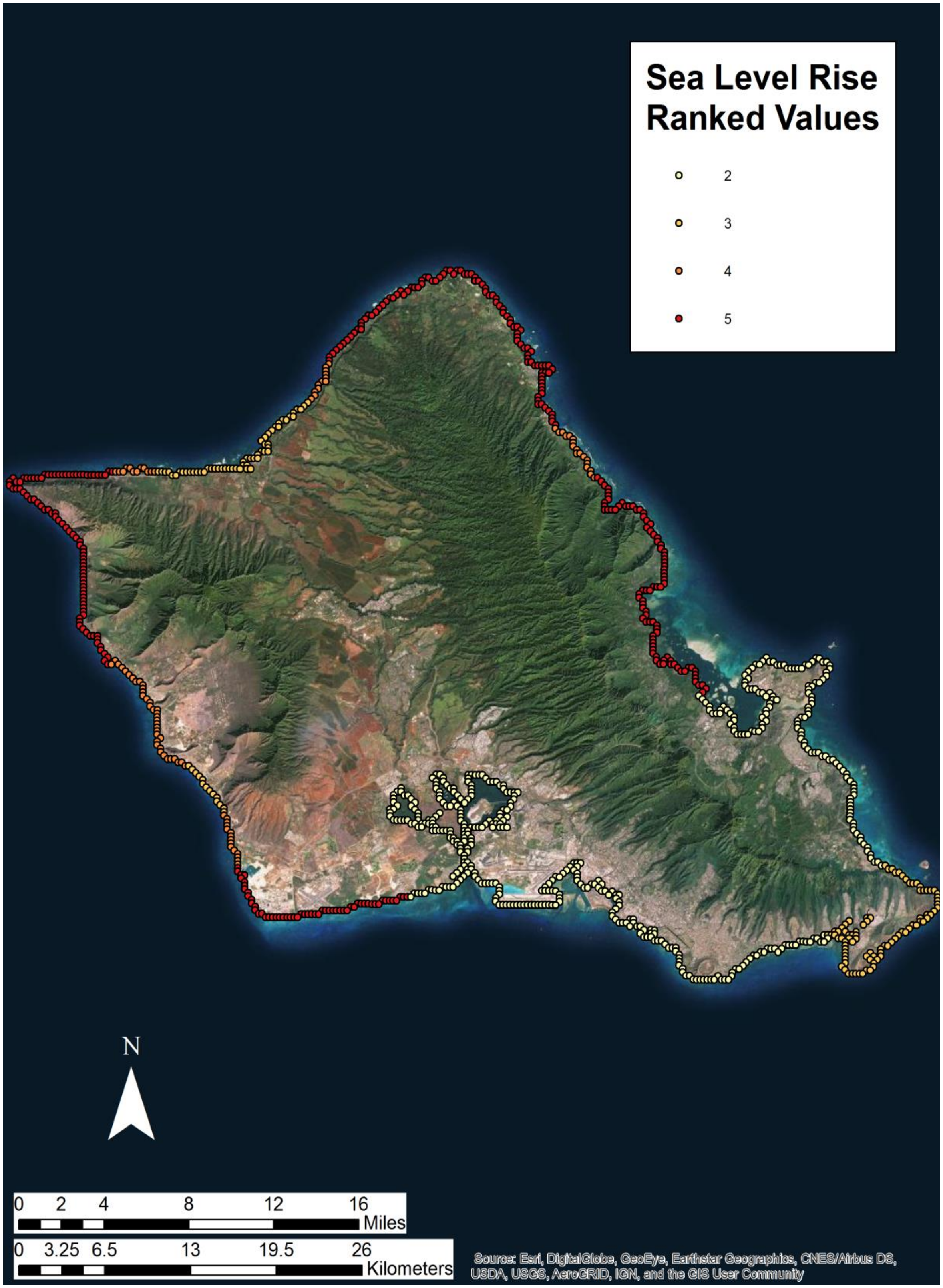


Figure 8: Sea Level Rise (Values ranked 1-5)

Local sea level rise vulnerability values are higher on the northern and western shore as seen in Figure (8). Sea level rise values are predominately low to moderate while exposed areas are at higher vulnerability to sea level rise (mean: 3.298; median: 3) (Figure 7). Although Hawaii sea level rise rate may be lower than global sea level rise, the vulnerability on an island can cause severe damage and flooding. Frequent floods may happen due to the sea encroachment landward and from the poor drainage from below the surface. Low-lying elevation areas will be more susceptible to sea level rise. The Relief variable factors in elevation to vulnerability. The lower the average elevation of the coast is, then the higher the risk of inundation. In Figure (10), the northwestern and northern tips of Oahu and most of the southern parts of the island that are at a lower average elevation have a higher vulnerability. Figure (9) shows evenly distributed relief values of lower and high percentage of low and high elevation (mean: 3.002; median: 3).

Figure 9: Distribution of Relief Layers

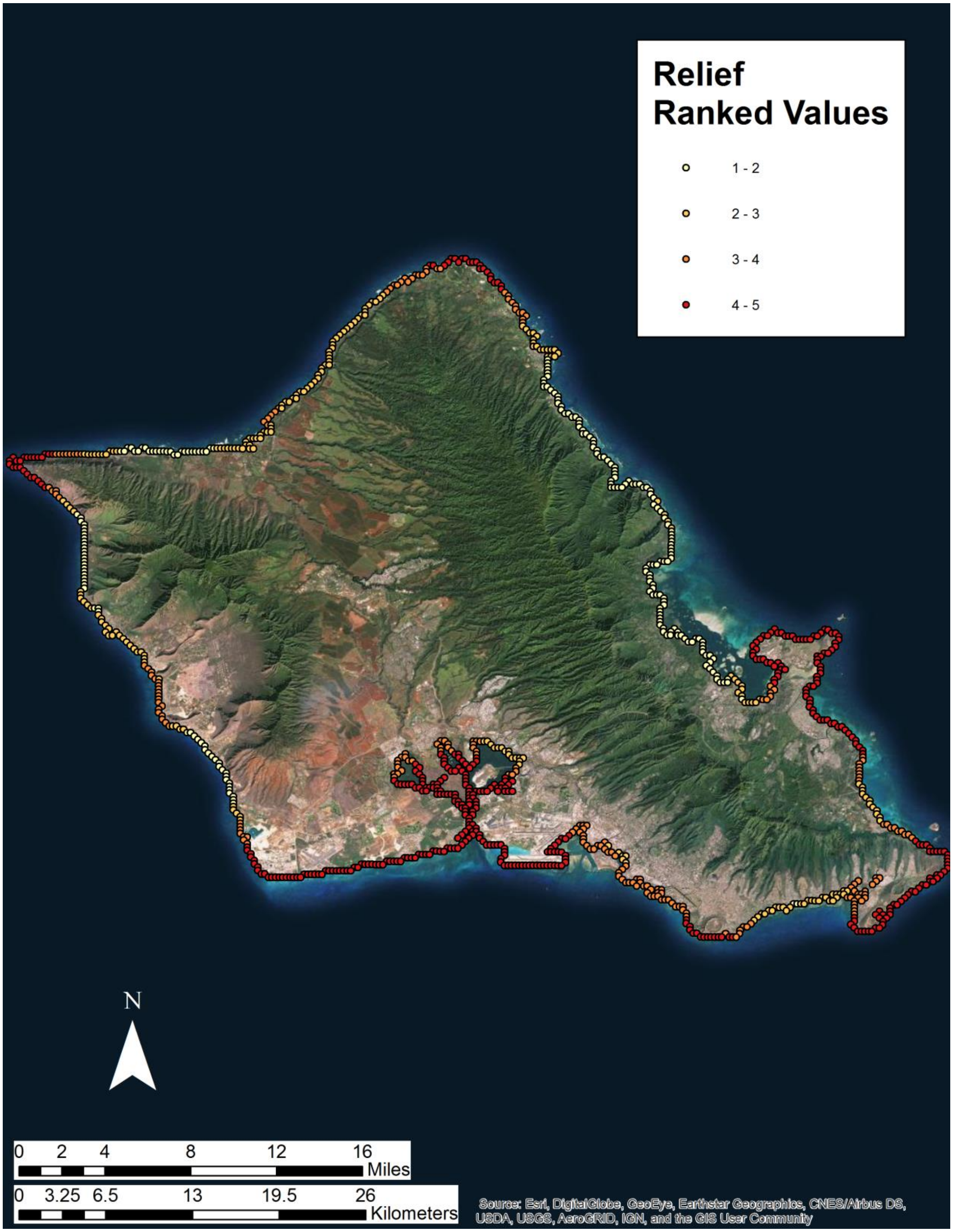


Figure 10: Relief (Values ranked 1-5)

Erosion exposure and erodible shorelines are necessary to consider whether the shore segment is at a higher or lower risk to climatic stressors such as sea level rise. Figure (11) shows erosion exposure with protective structures. The protective structures protect the land from erosion and the lowest erosion ranked values (blue and green points) are areas with structures or is a sheltered area whereas higher erosion values (red and orange points) are in areas with little to no protective structures. Figure (12) shows the erosion without structures. All the areas with structures are removed and the areas that had structures increased in erosion exposure values which can be compared to Figure (11). Figure (12) lowest values (blue points) are the sheltered coastal areas. Factoring geomorphology including the coastal structures, habitats, and wave exposure into the erodible shorelines from equation (3) provides the segments that are at higher vulnerability to erosion from climatic stressors as seen in Figure (11 & 12). Generally, exposed areas with vulnerable geomorphic features such as sandy beaches will likely be highly erodible. When structures that protect the land are factored into the erodible shoreline layer, there will be more areas that are less likely to be at high vulnerability to erosion from climatic stressors.

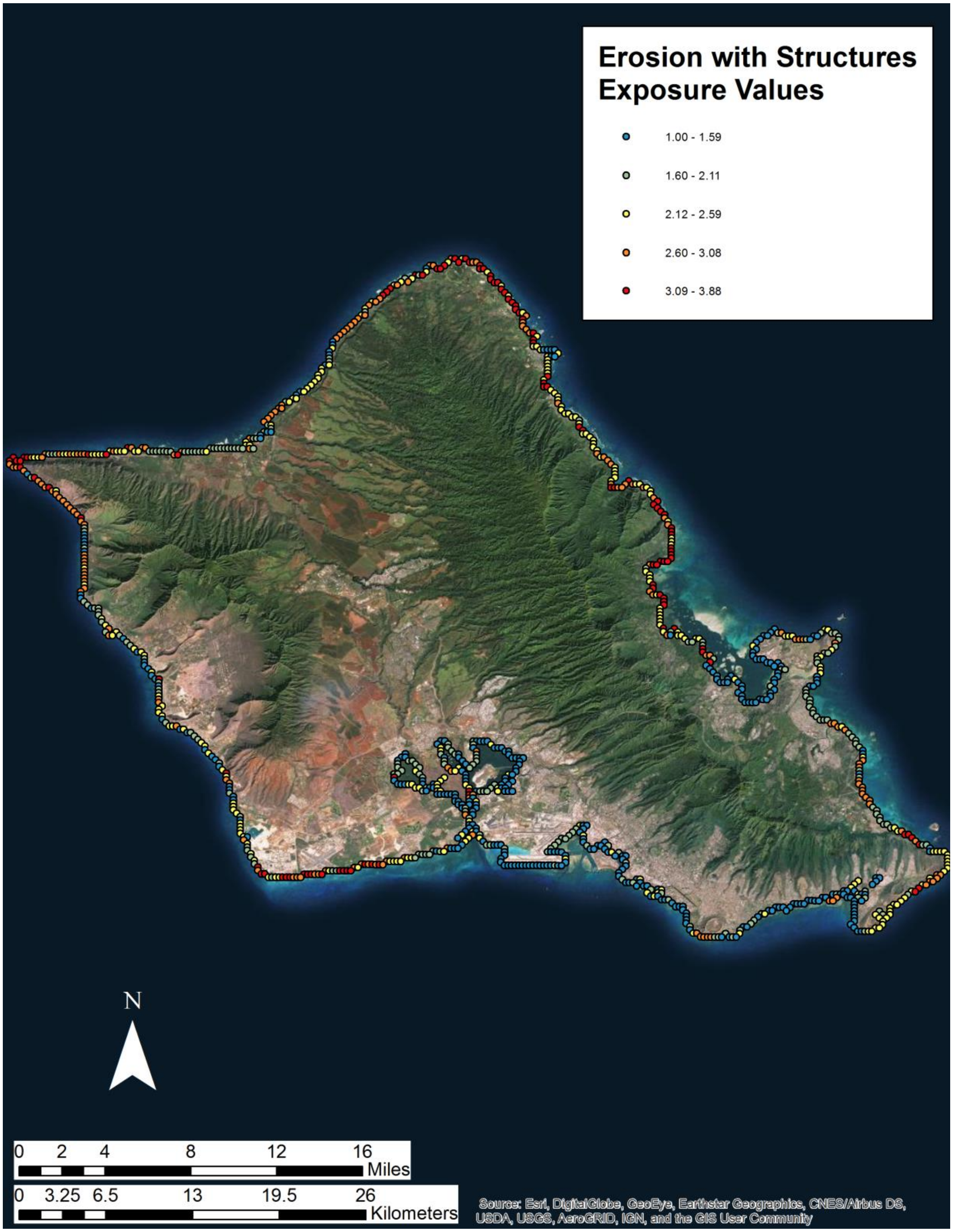


Figure 11: Erosion Exposure with Structures

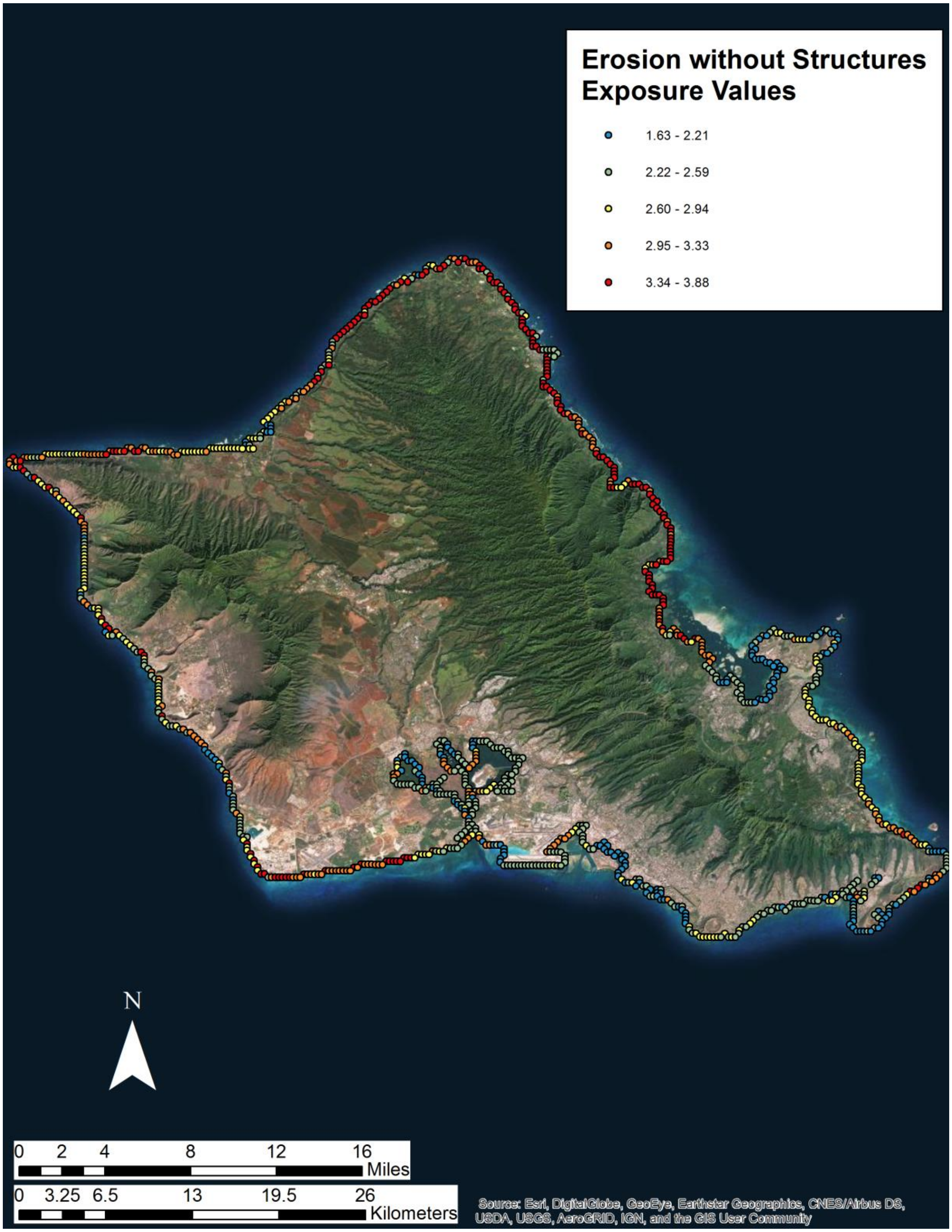


Figure 12: Erosion Exposure without Structures

Human population and geomorphology define the characteristics for a coastal area. The coastal vulnerability is dependent on these variables. The extent of the vulnerability will depend on the features of the coast. In Figure (13), the map displays the human population living within 300 m of the coast. People living in the same elevation will also be affected, but the model shows the population density of the coast. Higher densities are seen from Hawaii Kai to Kahala, Kaneohe, and Pearl City regions. Figure (14) shows the map of geomorphology. The lower value on the map corresponds to the geomorphologic type that is less susceptible to erosion, and higher values correspond to the geomorphologic types that are at higher susceptibility. Many geomorphologic features that have higher susceptibility such as sand beaches and man-made structures are dominant features on Oahu. This indicates that more area on the island will have moderate to high susceptibility with fewer areas that are less susceptible with features such as rocky cliffs or wave-cut bedrocks (mean: 3.328; median: 3) (Figure 15).

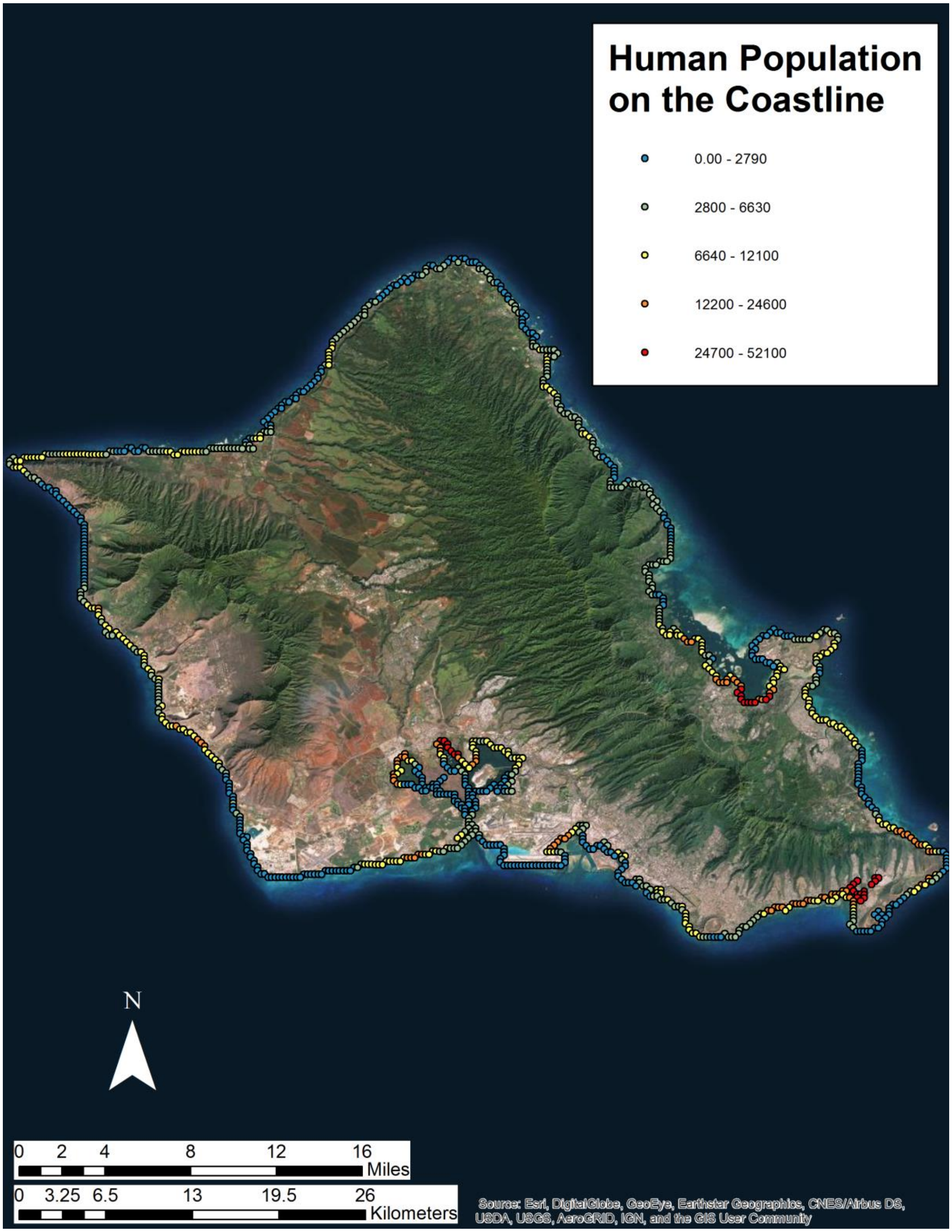


Figure 13: Human Population on the Coastline (Values are population number)

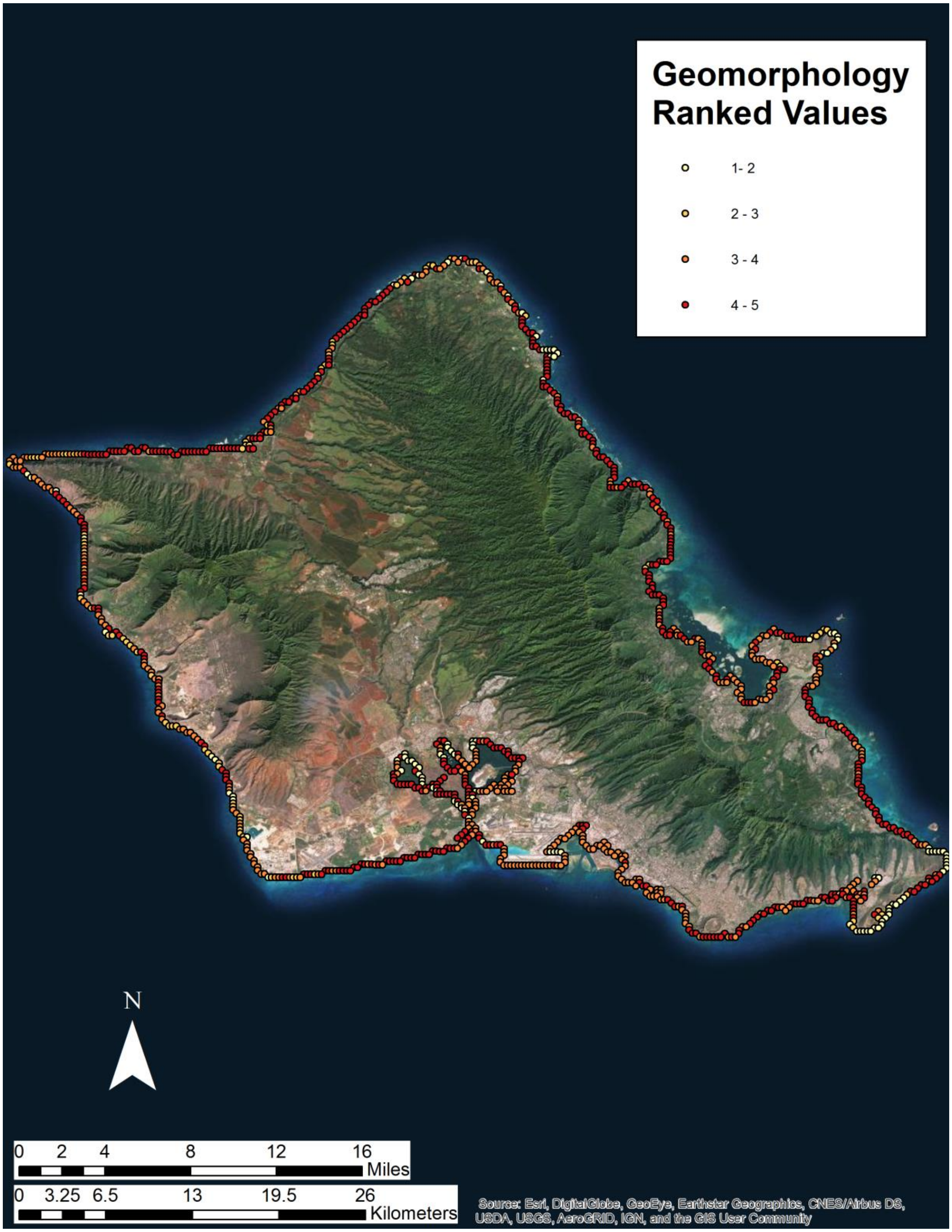


Figure 14: Geomorphology (Values ranked 1-5)

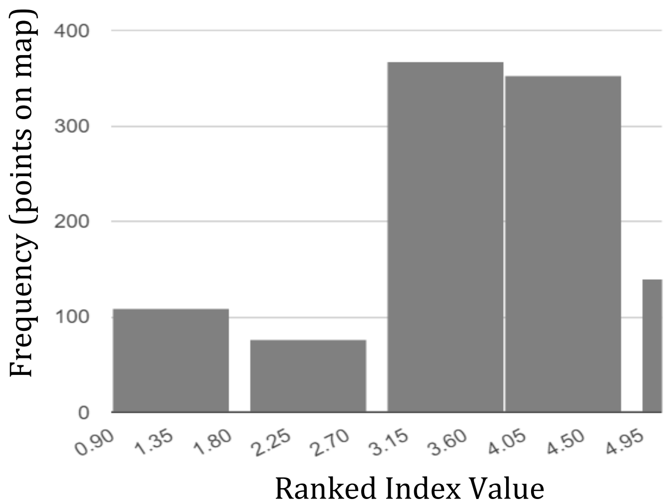


Figure 15: Distribution of Geomorphology Layers

Natural habitat and its role can affect the vulnerability level of the coast by protecting the coast from coastal hazards. Figure (16), shows the natural habitats that are present in the coastal area relative to their protective range that reduces inundation or erosion. The higher ranked values indicate little to low protection from natural habitats. Most of the areas around Oahu have coral reefs habitats that help dissipate large waves, and coastal vegetation/forest can also protect from erosion. Figure (16) and Figure (17) (mean: 2.387; median: 1.8), shows that most of the area around Oahu has some level of protection by natural habitats except for Pearl Harbor regions where this area is predominately man-made structures and little to no reefs in the harbor. In Figure (19), the habitat role is shown as the difference between coastal exposure with and without habitats. Higher increase in vulnerability will be likely where there is a higher difference when habitat is removed. Figure (18) (mean: 0.414; median: 0.469), displays the distribution of habitat role values based on the difference between coastal exposure and exposure without habitats that affects the island. Locations with values at zero indicate places with no habitat present, and there is no difference between exposure with and without habitat.

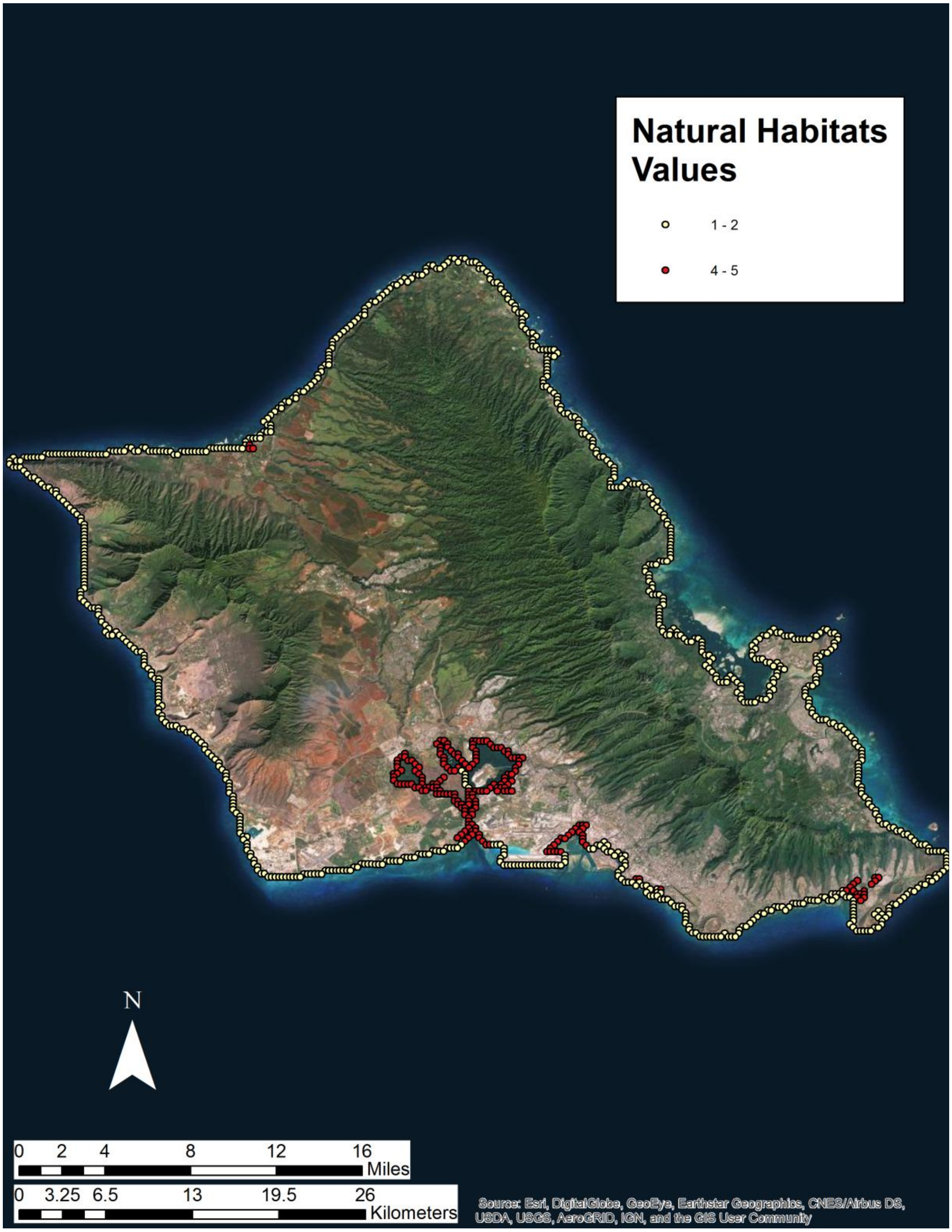


Figure 16: Natural Habitats (Values ranked 1-5)

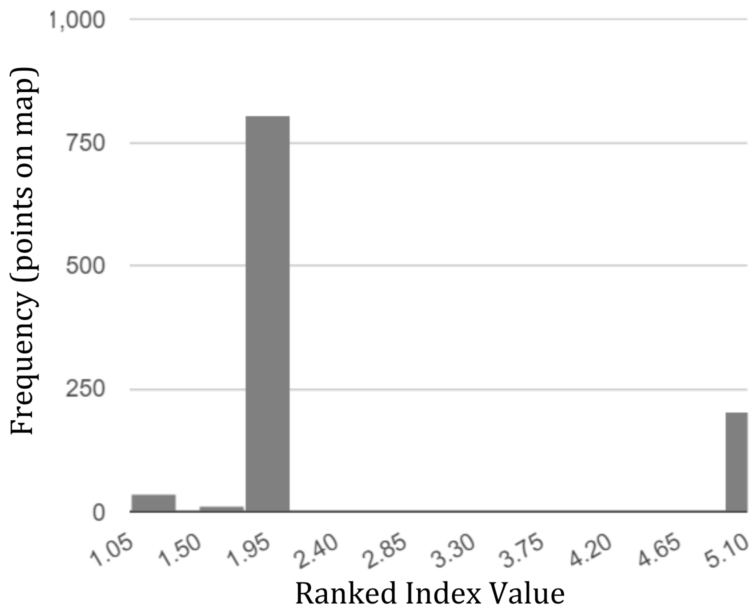


Figure 17: Distribution of Natural Habitats Layers

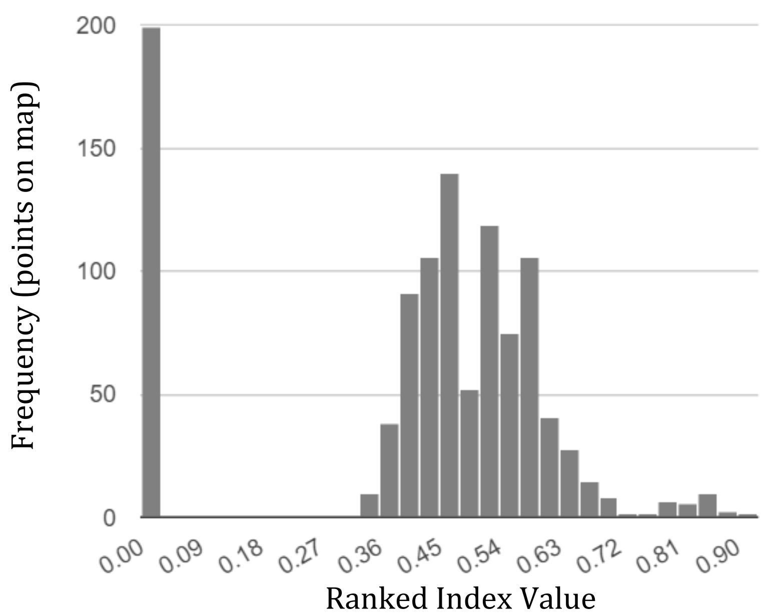


Figure 18: Distribution of Habitat Role Layers

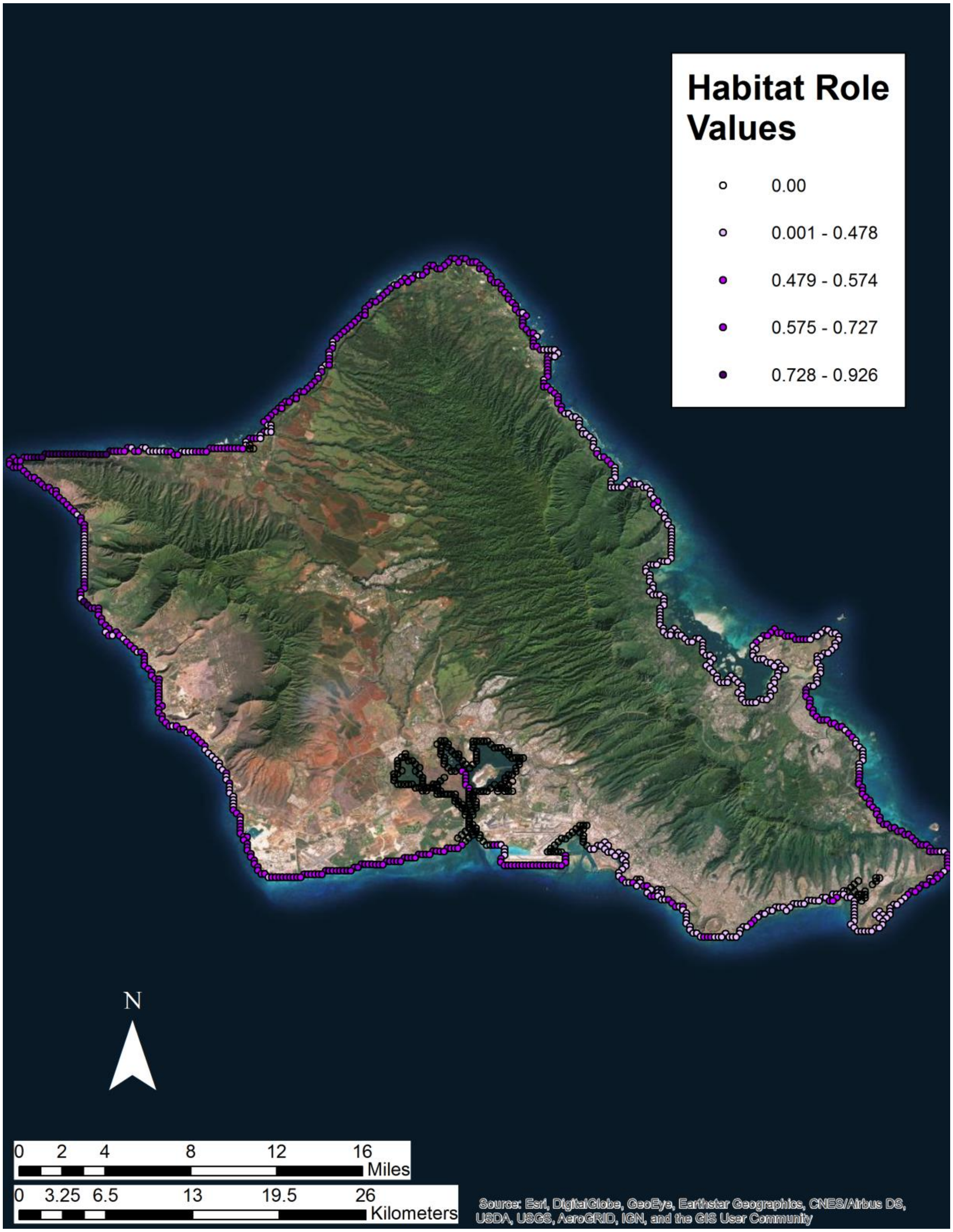


Figure 19: Habitat Role (Values are difference between Coastal Exposure and Coastal Exposure without habitats)

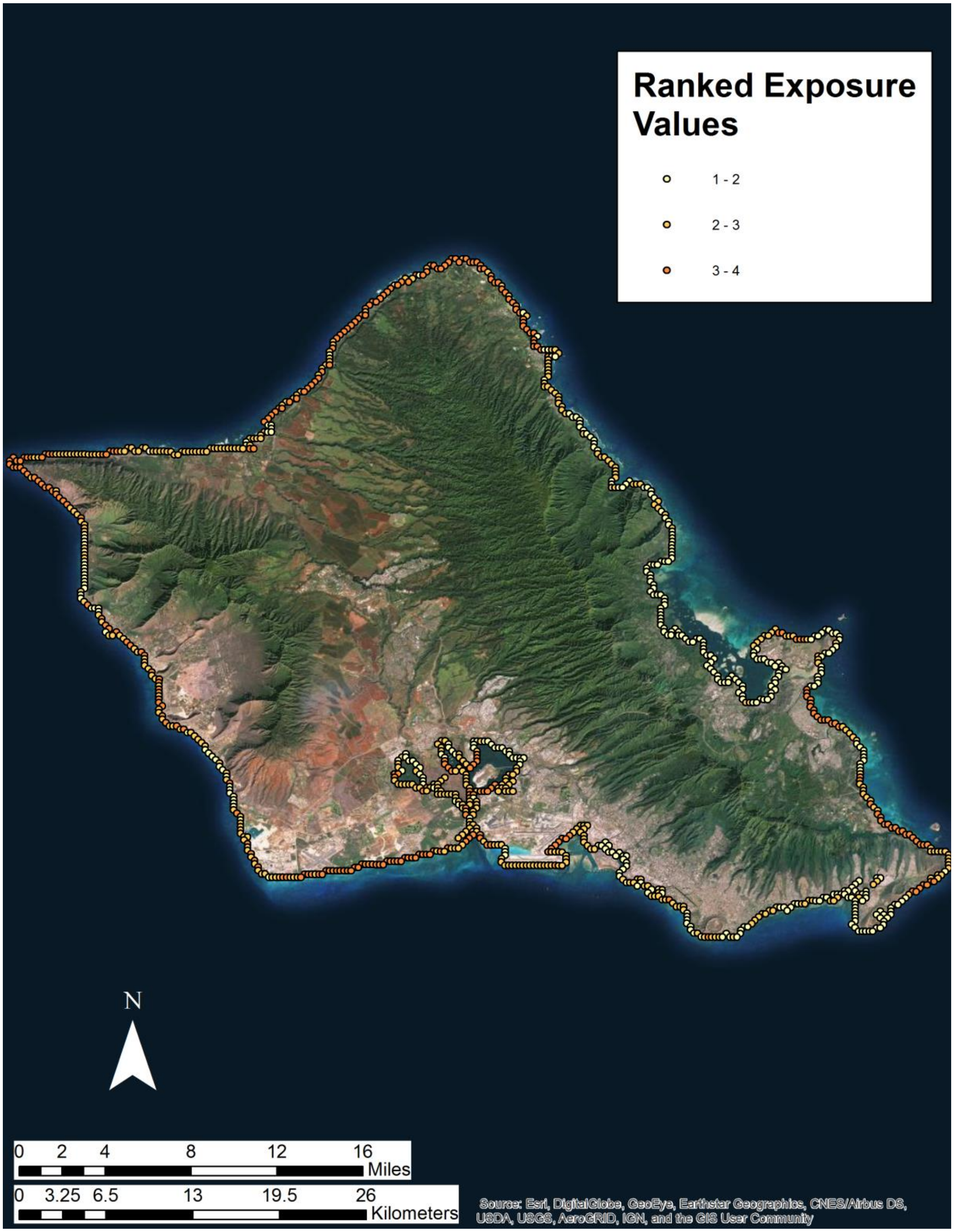


Figure 20: Coastal Exposure (Values ranked 1-5)

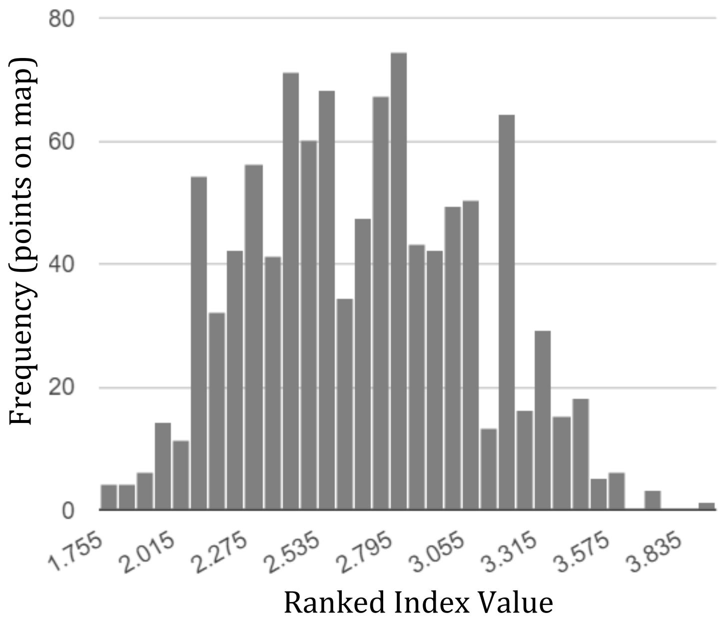


Figure 21: Distribution of Coastal Exposure Layers

Coastal exposure was derived from Eq. (1) that includes all the variables that contributes to the vulnerability for a coastal area. Figure (20) reveal higher exposures to climatic stressors on the northern, northwestern, southwestern, and southeastern shores of Oahu. The distribution of exposure mostly falls in the moderate level of vulnerability (mean: 2.697; median: 2.667) (Figure 21). In Figure (22), coastal exposure without habitats increases vulnerability for highly exposed locations as shown in Figure (20) and little to no change in areas with low exposures. The increase in vulnerability for exposures without habitats will show a shift in distribution having a high level of vulnerability (mean: 3.111; median: 3.047) (Figure 23).

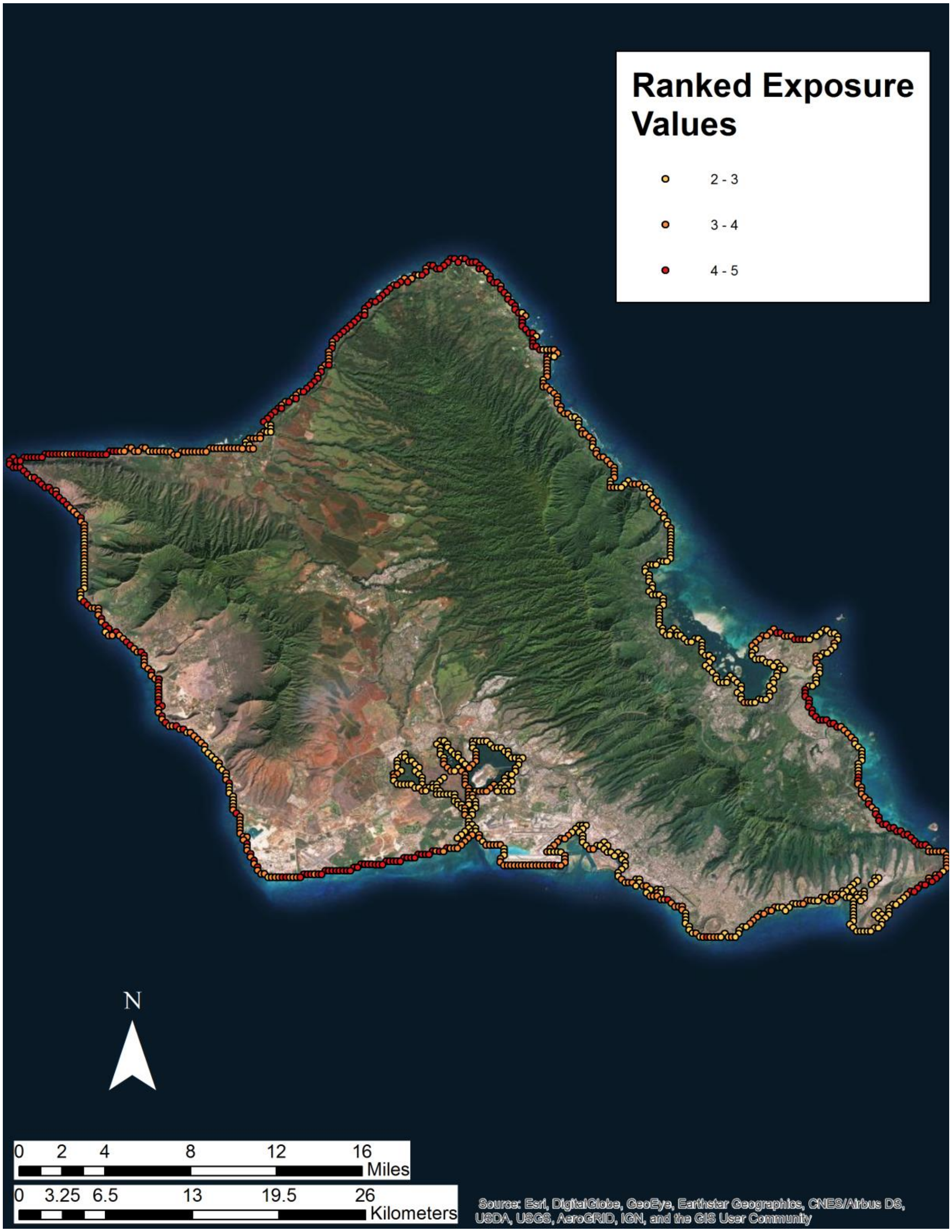


Figure 22: Coastal Exposure No Habitats (Values ranked 1-5)

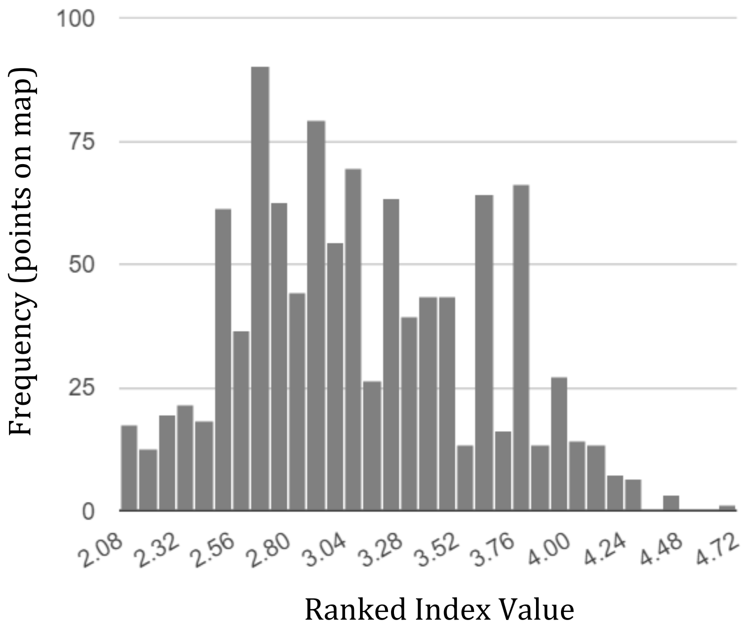


Figure 23: Distribution of Coastal Exposure No Habitats Layers

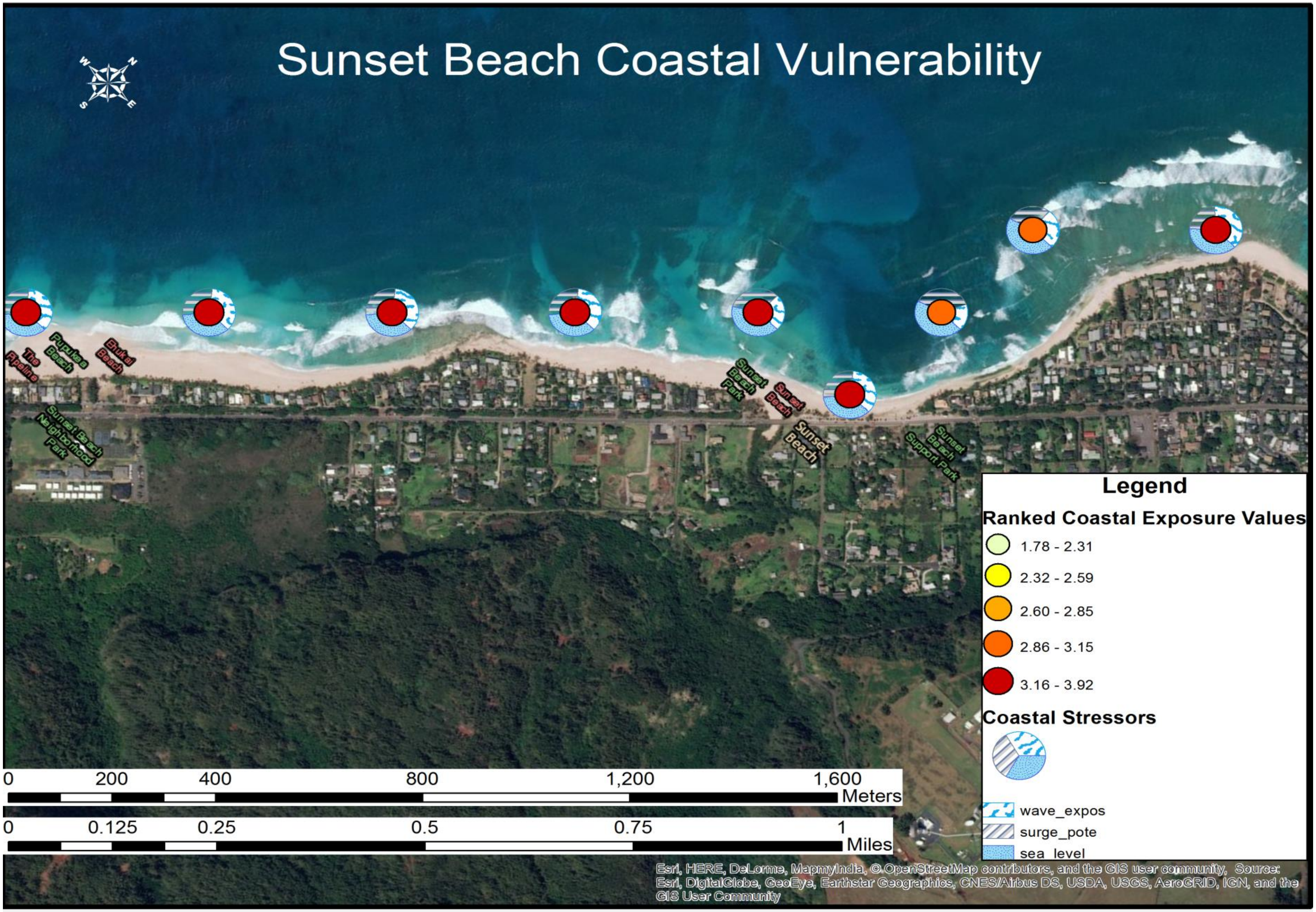


Figure 24: Sunset Beach Coastal Vulnerability

One of the relatively high vulnerable locations is Sunset Beach in the north shore region. This beach segment is characterized by sandy beaches and man-made structures, mostly residential homes. The average significant wave height is around 7.7 ± 0.28 m and 12.9 ± 0.47 m for annual swells (Vitousek & Fletcher, 2008). Sea-level rise in this area is approximately around 1.50 ± 0.25 mm yr^{-1} ($1.5\times10^{-3} \pm 2.5\times10^{-4}$ m yr^{-1}) (Romine et al., 2013). Figure (24), represents the coastal exposure on Sunset Beach with a coastal stressor distribution for each segment. Sunset Beach is strongly impacted by wave exposure, storm surge, and sea level rise. Sunset Beach is predominately within a moderate to high level of vulnerability and has about an equal potential of hazards spread through its region.

4.2 COST-BENEFIT ANALYSIS (SUNSET BEACH)

From large wave heights and accelerated sea level rise, the beach, properties, and socio-economic of the area will be greatly affected. If no action is taken to reduce coastal threats and hazards, there can be a severe erosion of the beach, loss of property to landowners, and loss of tourism to Sunset Beach.

Sea level rise will likely increase and can lead to numerous coastal hazards within communities. The IPCC fifth assessment (IPCC, 2013) provides global sea level rise scenarios for predicting future projections of sea level rise (See Table 4). This helps to assess and prepare for sea level rise risk for coastal communities. If no measures are taken to reduce the climatic stressor then millions of dollars can be lost in the long term and problems can exacerbate hazards.

Table 4: Global mean sea level rise projection (m). Based from 1986 to 2005 projection values for the presented years. Values represent the median and likely range for scenario projections (AR5, IPCC 2013).

Year	SRES A1B	RCP2.6	RCP4.5	RCP6.0	RCP8.5
2007	0.03 [0.02 to 0.04]	0.03 [0.02 to 0.04]	0.03 [0.02 to 0.04]	0.03 [0.02 to 0.04]	0.03 [0.02 to 0.04]
2010	0.04 [0.03 to 0.05]	0.04 [0.03 to 0.05]	0.04 [0.03 to 0.05]	0.04 [0.03 to 0.05]	0.04 [0.03 to 0.05]
2020	0.08 [0.06 to 0.10]	0.08 [0.06 to 0.10]	0.08 [0.06 to 0.10]	0.08 [0.06 to 0.10]	0.08 [0.06 to 0.11]
2030	0.12 [0.09 to 0.16]	0.13 [0.09 to 0.16]	0.13 [0.09 to 0.16]	0.12 [0.09 to 0.16]	0.13 [0.10 to 0.17]
2040	0.17 [0.13 to 0.22]	0.17 [0.13 to 0.22]	0.17 [0.13 to 0.22]	0.17 [0.12 to 0.21]	0.19 [0.14 to 0.24]
2050	0.23 [0.17 to 0.30]	0.22 [0.16 to 0.28]	0.23 [0.17 to 0.29]	0.22 [0.16 to 0.28]	0.25 [0.19 to 0.32]
2060	0.30 [0.21 to 0.38]	0.26 [0.18 to 0.35]	0.28 [0.21 to 0.37]	0.27 [0.19 to 0.35]	0.33 [0.24 to 0.42]
2070	0.37 [0.26 to 0.48]	0.31 [0.21 to 0.41]	0.35 [0.25 to 0.45]	0.33 [0.24 to 0.43]	0.42 [0.31 to 0.54]
2080	0.44 [0.31 to 0.58]	0.35 [0.24 to 0.48]	0.41 [0.28 to 0.54]	0.40 [0.28 to 0.53]	0.51 [0.37 to 0.67]
2090	0.52 [0.36 to 0.69]	0.40 [0.26 to 0.54]	0.47 [0.32 to 0.62]	0.47 [0.33 to 0.63]	0.62 [0.45 to 0.81]
2100	0.60 [0.42 to 0.80]	0.44 [0.28 to 0.61]	0.53 [0.36 to 0.71]	0.55 [0.38 to 0.73]	0.74 [0.53 to 0.98]

Several adaptations are assessed based on social, technical, administrative, economic, and environmental benefits and costs (See Appendix A & C). The use of an Adaptation Assessment Guide (Appendix A) can be a start toward identifying the adaptation option by its function and capacity for support and or knowledge. The guide also helps in understanding how and who is involved in implementing the adaptation, the resource required, level of effort, acceptance from the public, and the urgency to implement the adaptation. Following the assessment guide for Sunset Beach, several options were identified that could be a possible solution (See Appendix B). Adaptation options examined for the area of Sunset Beach were vegetative cover, beach nourishment, shoreline protection, artificial reefs, and elevating structures or moving away. The multi-criteria analysis (See Appendix C) provides questions that can help rank each identified adaptation and which adaptation have higher support or benefit to cost ratio. Multi-criteria analysis was used for the following cost-benefit tables.

Table (5) shows the social benefits and costs for the adaptation option. Citizens may prefer easier, cost effective, and durable solutions. Property owners are likely to want a solution that prevents land loss; surfers do not want to lose the waves on Sunset Beach. Vegetative cover is ranked the highest for a suggested adaptation due to the acceptance level from the public, the existing vegetative cover, and being a quick and easy solution to implement. Beach nourishment is also another option that can be considered to protect the erosion of land and maintain beach conditions with little impact to beach-goers and property owners. Artificial reefs and coastal armoring can reduce erosion, but may alter the waves at Sunset Beach. Elevating structures or relocating can be difficult for property owners due to funding and the challenges of moving.

Table 5: Cost-Benefit for Social Aspects

Adaptation Option	Benefits	Benefits High = 5 Med = 3 Low = 1	Costs	Costs High = 5 Med = 3 Low = 1	Ratio Benefits/ Costs	Rank
Vegetative Cover	Time-saving and reduction in labor requirement.	4	Reduction of costs such as machinery operating expenses, maintenance, and labor cost. Less sandy area for beach-goers.	1	4	1
Beach Nourishment	Reduction in risk of property loss. Restores and widens beach area.	4	Expensive with frequent implementation. Impoundment and closures during nourishment.	3	1.33	2
Artificial Reefs	Can rebuild fish population and increase diving/fishing locations. Can prevent sediment loss depending on design.	4	Varies in cost dependent on materials and site. Reduces wave energy that can affect recreational activities.	5	0.8	3
Coastal Armoring	Reduction in risk of property loss. Can be constructed in small areas.	3	Varies in cost dependent on materials and type. Potential harm to certain recreational activities.	4	0.75	4
Elevation or Relocation	Reduces potential damages to buildings. Stakeholders have ownership over final decision.	3	Varies in cost dependent on structure and size. Relocation is often impractical.	5	0.6	5

Table (6) presents the technical benefit and cost of an adaptation option. Implementing vegetation requires less machinery and labor, and low maintenance is required for the plants. Depending on the species, some coastal plants can withstand high temperature, saltwater intrusion, inundation, unstable ground, and low nutrient conditions. Beach nourishment requires a highly similar grain size and machinery to move the sediments. Beach nourishment is a temporary solution due to the sediments eroding away. Coastal armoring and artificial reefs require a longer term for development. Both shoreline protection and artificial reefs can protect against erosion but can disrupt marine life during implementation. Shoreline protection is highly durable but requires periodic maintenance. Artificial reefs are highly durable to climatic change and requires little to no maintenance. Elevation of an old structure has many challenges and is usually more costly than building a new structure on an empty lot. Relocation is the most viable option for climate stressors such as sea level rise but the cost can be prohibitive.

Table 6: Cost-Benefit for Technical Aspects

Adaptation Option	Benefits	Benefits High = 5 Med = 3 Low = 1	Costs	Costs High = 5 Med = 3 Low = 1	Ratio Benefits/ Costs	Rank
Vegetative Cover	Dissipate wave energy, prevent sediment loss, and reduce run-off. Several coastal species are tolerant to high temperatures, low nutrients, and inundation.	4	Low maintenance for watering and grooming. Cost depends on the plant type and area.	1	4	1
Beach Nourishment	Restores and widens beach area. Preserve beach conditions with minimal impact.	4	Impoundment and closures during nourishment. Temporary.	3	1.33	2
Coastal Armoring	Reduction in risk of property loss. Reduces land loss. Highly durable and long lasting.	4	Varies in cost dependent on materials and type. Costly in construction and maintenance.	4	1	3
Artificial Reefs	Can rebuild fish population, increase diving/fishing locations. Can be designed to dissipate and absorb wave energy.	4	Varies in cost dependent on materials and site. Can disrupt marine life during development.	4	1	3
Elevation or Relocation	Reduces potential damages to buildings.	4	Varies in cost dependent on structure and size. Relocation is often impractical.	5	0.4	4

Table (7) presents the benefits and costs of an adaptation option for a time, finance, and administrative support. Vegetative cover is a cheaper solution compared to other options. Implementing the option requires less labor and can be a one-time implementation. Beach nourishment preserves the beach and produces little disruption. Beach nourishment will likely be a temporary solution for further adaptation options, or when periodic implementation is required which can become costly in the long run. Coastal armoring can be supported by the state and property owner to protect home or property owners land. Shore protection is often expensive. Elevating homes can vary in cost depending on structures and size. Moving away is often not supported except for extreme conditions set by the state or government. Artificial reefs may increase marine life population and provide other economic services, but funding is limited, and the process requires a considerable amount of time.

Table 7: Cost-Benefit for Administrative and Economic Aspects

Adaptation Option	Benefits	Benefits High = 5 Med = 3 Low = 1	Costs	Costs High = 5 Med = 3 Low = 1	Ratio Benefits/ Costs	Rank
Vegetative Cover	Time saving and reduction in labor requirement. Existing use. Easy to implement.	4	Reduction of costs such as machinery operating costs, maintenance, and labor cost. One-time implementation.	1	4	1
Beach Nourishment	State-funding is possible. Minimize use for alternative. Maintain beach area.	4	Impoundment and closures during nourishment. Periodic implementation.	3	1.33	2
Coastal Armoring	Funding or loan is available for stakeholders.	2	Varies in cost dependent on materials and type. Long term process for regulations. Periodic to one-time implementation.	3	0.66	3
Elevation or Relocation	Stakeholders have ownership over final decision.	3	Varies in cost dependent on structure and size. Large amount of funding is needed. Continuous to one-time event.	5	0.6	4
Artificial Reefs	Can rebuild fish population and increase diving/fishing locations. Can prevent sediment loss depending on design.	2	Varies in cost dependent on materials and site. May affect recreational activities. Requires funding. Long term process. One-time implementation with little to no maintenance.	5	0.4	5

Table (8) shows the benefits and costs of an adaptation process to the environment. The vegetative cover provides more plant coverage, reduces sediment erosion and run-off. Machinery operation is nominal which leads to little to no impact on the environment for implanting vegetation. Beach nourishment has little altercation to the beach and may slightly increase resilience temporarily in the environment. During development, beach nourishment will cause disruption to marine life and beach-goers. Artificial reefs can reduce erosion and rebuild fish populations. During development, artificial reefs may cause potential disruption to marine life. Elevation of structures will allow for sand to build up under the structure and prevent further damage to the property but may have temporary disruption during construction. Relocation will have little to no impact on the environment. Coastal armoring may have the least benefit to the environment. Shoreline protection prevents erosion and can disrupt marine life during construction.

Table 8: Cost-Benefit for the Environmental Aspects

Adaptation Option	Benefits	Benefits High = 5 Med = 3 Low = 1	Costs	Costs High = 5 Med = 3 Low = 1	Ratio Benefits/ Costs	Rank
Vegetative Cover	Increase plant cover. Little to no disruption in coastal ecosystem and public.	5	Requires little to no machinery usage. Maintenance and labor cost. Little to no aesthetic disruption.	1	5	1
Beach Nourishment	Temporary increase and maintain beach area.	4	Temporary disruption to beach-goers and marine life.	2	2	2
Artificial Reefs	Can rebuild fish population and increase diving/fishing locations. Can prevent sediment loss depending on design.	5	Temporary disruption and potential hazards to marine life during development.	3	1.66	3
Elevation or Relocation	Reduces potential damages to buildings. Moving away cause little to no negative environmental effects.	4	Temporary disruption during development and process of moving.	3	1.33	4
Coastal Armoring	Prevent land and property loss.	2	Can increase or change wave energy dependent on shore protection type. Temporary disruption to marine life during development and maintenance. Permanent.	3	0.66	5

Table (9) presents the averaged benefits and costs from tables (1- 4) and ranked by the highest benefit to cost ratio for the adaptation options. Vegetative cover is ranked as the highest suggested option. This option is inexpensive per square foot, supported by the public, low-maintenance, and some existing use is in effect at Sunset Beach. Beach nourishment is second. Although beach nourishment can prevent property damages and preserve the beach, the option is temporary and should be done periodically. Artificial reef is an option that can increase fish population and provide other socio-economic services, but it is not preferred if it disrupts waves for surfers and tourist. Coastal armoring would be a good solution for homeowners or property owners to protect their land, but beach-goers and surfers do not prefer this option. Shoreline protection can be costly, but the solution would be more permanent. Elevation of structures is expensive and relocation is often not a viable solution, but the property owner has the final decision except for the conditions that the state or government has set for relocating.

Table 9: Overall Adaptation Cost-Benefit

Adaptation Option	Benefits	Benefits High = 5 Med = 3 Low = 1	Costs	Costs High = 5 Med = 3 Low = 1	Ratio Benefits/ Costs	Rank
Vegetative Cover	Time saving and reduction in labor requirement. Reduces sediment loss. Easy to implement and supported.	4.25	Reduction of costs such as machinery operating costs, maintenance, and labor cost. Less sandy area for beach-goers. One-time implementation with continuous maintenance.	1	4.25	1
Beach Nourishment	Reduction in risk of property loss. Preserve beach conditions with minimal impact.	4	Impoundment and closures during nourishment. Temporary disruption to beach-goers and marine life. Periodic implementation and monitoring.	2.75	1.455	2
Artificial Reefs	Can rebuild fish population and increase diving/fishing locations. Can prevent sediment loss depending on design.	3.75	Varies in cost dependent on materials and site. Reduces wave energy that can affect recreational activities. Temporary disruption and potential hazards to marine life during development. Long term process. One-time implementation with little to no maintenance.	4.25	0.882	3
Coastal Armoring	Reduction in risk of property loss. Can be constructed in small areas. Protect homeowners' properties and other infrastructures.	2.75	Cost dependent on materials and type. Potential harm to recreational activities. Temporary disruption to marine life during development and maintenance. Long term process for regulations. Periodic to one-time implementation and maintenance.	3.5	0.786	4
Elevation or Relocation	Reduces damages to buildings. Moving away cause little to no negative environmental effects. Stakeholders have ownership over final decision.	3.5	Varies in cost dependent on structure and size. Relocation is often impractical. Temporary disruption during development and process of moving. Continuous to one-time event.	4.5	0.778	5

5.0 CONCLUSION

Oahu is a highly populated island in Hawaii, and the dangers from accelerated sea level rise threaten coastal communities. By applying the CVI-based on Hammar-Klose and Thieler methods and using visualization tools the relatively vulnerable areas were able to be identified. High vulnerable areas were dominant on the north shore, western tips and southeastern tips of Oahu. The vulnerability of an area is majorly affected by the geomorphology and natural habitats within the coastal zone. Sandy beaches and man-made structures do not provide suitable protective measures against climatic stressors and are at a higher exposure to risks. The important role of natural habitats such as coral reefs and coastal forest help provides, to a certain extent, protective measures against coastal hazards and risks. Without natural habitats, coastal areas are at a higher vulnerability. Conserving the natural habitat and developing adaptation strategies that best suit the local area can reduce vulnerability and increase resilience in a coastal community without extreme adverse effects.

Sunset Beach is one of many of the highly vulnerable areas on Oahu that experience high erosion rates and high surf close to communities. For this area, a cost-benefit analysis was performed. Many beachgoers value the seasonal surf in this area, and property owners also value their land. Without making extreme sacrifices or altering the wave conditions, the best suitable adaptation option may be vegetative covers because it can create a habitat to reduce exposures. Other solutions can be implemented along with vegetative covers such as beach nourishment to reduce erosion and increase resilience in the community. Although some adaptation option such as beach nourishment may be a viable option, it is also temporary, and in the long run may become costly with the need for frequent implementation as the problem will continue to exist. Small shoreline protection for property owners may significantly reduce erosion and could also be a viable solution, but considerations should be examined further in-depth.

Several limitations of this study are the CVI spatial and temporal resolution, limitations from models, and cost-benefit analysis limitations. Limitations of this model are the simplified representations of actual detailed information on coastal areas and that the data time frame may not overlap each other. Cost-benefit analysis imperfections are the quantification of items and estimations. Measurements of items are usually approximations. The cost-benefit analysis does not go into depth of materials type, location within the area, or implementation design for each adaptation.

The CVI and tools in this study helps to provide a preliminary identification for the relative coastal vulnerability for Oahu. Further research can include cultural or social significance to clearly identify the exposure and risk to a community in detail. Doing so can provide improved adaptation options and greater information that will help decision-makers plan for the future.

APPENDIX A: Adaptation Assessment Guide

Climate Stressor:		Profile:		Asset:			
Part 1 - Identifying Adaptation Options		Part 2 - Assessing Adaptation Options					
Adaptation Option	**Adaptation Type:** Select either A and/or B	**Implementation Mechanism**	**Implementation Party**	**Resources required**	**Level of Effort**	**Acceptance**	**Urgency**
	A) Delivers Adaption Action: * Reduces damage to assets * Reduces service or network disruptions * Exploits opportunities	**What is the primary instrument for implementation?** * Regulations * Legislation * Incentives * Planning processes * Programs	**Who is the primary entity responsible for implementation?** * State government * Local governement * Land owner * Private organization	**What resources might be needed for implementation?** * Staff time * Technical expertise * Funding	**What is the level of effort required?** * Continuous * Periodic * One-time	**To what degree is the public likely to accept the adaptation option?** * Poor * Fair * Good * Excellent	**What is the appropiate timeline for implementation?** * Immendiately * Short term * Long term
	B) Builds Adapative Capacity: * Creates information through research, data collecting and monitoring * Raises awareness through dissemination of information * Supports social structures through orgainizational development, working in partnership, strengthening institutions * Supports governance through regulations, legislation, and guidance	**Are these instruments:** * New * Existing * Existing but modified	**Is this different than who has ownership of asset?** * Yes * No	**Needs can be met with:** * Exisiting resources * Additional resources needed	**How easy is the option to implement?** * Easy * Moderate * Difficult	**To what degree is there political support for this option?** * Poor * Fair * Good * Excellent	**If implementation is delayed, will the cost likely be higher?** * Yes * No

APPENDIX B: Adaptation Assessment for Sunset Beach

Climate Stressor: Sea level rise	Profile: Ecosystem			Asset: Beach			
Part 1 - Identifying Adaptation Options		Part 2 - Assessing Adaptation Options					
Adaptation Option	Adaptation Type: Select either A or B	Implementation Mechanism	Implementation Party	Resources required	Level of Effort	Acceptance	Urgency
Vegetative cover onshore	A) Delivers Adaption Action:	What is the primary instrument for implementation?	Who is the primary entity responsible for implementation?	What resources might be needed for implementation?	What is the level of effort required?	To what degree is the public likely to accept the adaptation option?	What is the appropiate timeline for implementation?
	* Reduces damage to assets	* Regulations * Planning processes	* State government * Local governement * Land owner	* Staff time * Funding * Technical expertise	* Periodic * One-time	* Good	* Immediately
	B) Builds Adapative Capacity:	Are these instruments:	Is this different than who has ownership of asset?	Needs can be met with:	How easy is the option to implement?	To what degree is there political support for this option?	If implementation is delayed, will the cost likely be higher?
	* Creates information through research, data collecting and monitoring * Supports social structures through orgainizational development, working in partnership, strengthening institutions	* Existing	* No	* Exisiting resources	* Easy	* Good	* No
Natural and artificial reefs	A) Delivers Adaption Action:	What is the primary instrument for implementation?	Who is the primary entity responsible for implementation?	What resources might be needed for implementation?	What is the level of effort required?	To what degree is the public likely to accept the adaptation option?	What is the appropiate timeline for implementation?
	* Reduces damage to assets * Exploits opportunities	* Incentives * Planning processes	* State government * Local governement	* Staff time * Technical expertise * Funding	* Periodic * One-time	* Fair	* Long term
	B) Builds Adapative Capacity:	Are these instruments:	Is this different than who has ownership of asset?	Needs can be met with:	How easy is the option to implement?	To what degree is there political support for this option?	If implementation is delayed, will the cost likely be higher?
	* Creates information through research, data collecting and monitoring * Raises awareness through dissemination of information	* New * Existing but modified	* No	* Additional resources needed	* Difficult	* Poor	* No

Beach nourishment & Dunes	A) Delivers Adaption Action:	What is the primary instrument for implementation?	Who is the primary entity responsible for implementation?	What resources might be needed for implementation?	What is the level of effort required?	To what degree is the public likely to accept the adaptation option?	What is the appropiate timeline for implementation?
	* Reduces damage to assets	* Regulations * Legislation * Planning processes	* State government * Local governement * Land owner	* Staff time * Technical expertise * Funding	* Periodic	* Excellent	* Short term
	B) Builds Adapative Capacity:	Are these instruments:	Is this different than who has ownership of asset?	Needs can be met with:	How easy is the option to implement?	To what degree is there political support for this option?	If implementation is delayed, will the cost likely be higher?
	* Creates information through research, data collecting and monitoring * Supports social structures through orgainizational development, working in partnership, strengthening institutions	* Existing	* No	* Additional resources needed	* Moderate	* Good	* Yes
Shore protection	A) Delivers Adaption Action:	What is the primary instrument for implementation?	Who is the primary entity responsible for implementation?	What resources might be needed for implementation?	What is the level of effort required?	To what degree is the public likely to accept the adaptation option?	What is the appropiate timeline for implementation?
	* Reduces damage to assets * Reduces service or network disruptions	* Regulations * Legislation * Planning processes	* State government * Local governement * Land owner	* Staff time * Technical expertise * Funding	* One-time	* Fair	* Long term
	B) Builds Adapative Capacity:	Are these instruments:	Is this different than who has ownership of asset?	Needs can be met with:	How easy is the option to implement?	To what degree is there political support for this option?	If implementation is delayed, will the cost likely be higher?
	* Creates information through research, data collecting and monitoring	* Existing but modified	* No	* Additional resources needed	* Moderate	* Poor	* Yes
Elevate or move away	A) Delivers Adaption Action:	What is the primary instrument for implementation?	Who is the primary entity responsible for implementation?	What resources might be needed for implementation?	What is the level of effort required?	To what degree is the public likely to accept the adaptation option?	What is the appropiate timeline for implementation?
	* Reduces damage to assets * Exploits opportunities	* Regulations * Legislation * Incentives * Planning processes * Programs	* State government * Local governement * Land owner * Private organization	* Staff time * Technical expertise * Funding	* Continuous	* Poor	* Long term
	B) Builds Adapative Capacity:	Are these instruments:	Is this different than who has ownership of asset?	Needs can be met with:	How easy is the option to implement?	To what degree is there political support for this option?	If implementation is delayed, will the cost likely be higher?
	* Raises awareness through dissemination of information * Supports social structures through orgainizational development, working in partnership, strengthening institutions * Supports governance through regulations, legislation, and guidance	* New	* Yes	* Additional resources needed	* Difficult	* Poor	* Yes

APPENDIX C: Multi-Criteria Analysis

Multi-Criteria Analysis Activity

Use the questions below to help you rank each identified section on a scale between 1 and 5, where:
1 = action assigned low value due to low level of support and/or benefit
3 = action assigned medium value due to some level of support and/or benefit
5 = action assigned high value due to high level of support and/or benefits

Social
• Will the citizens be behind this effort?
• Will the action lead to an increase in social resilience?
• Is the action equitable?

Technical
• Can the action be implemented from a technical point of view?
• Can the action handle a range of climate change impacts?

Administrative
• Does your agency/organization have the operational control to implement this action?
• Can this action be implemented in a timely manner?

Political
• Does this action have political support?

Economic
• Is it cost effective? Does the benefit exceed the cost?
• Does funding exist or can it be acquired to finance the action?

Environmental
• Will the action increase the resilience of the natural environment?
• Are there any positive side effects on the environment of the action?

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