Chapter

Development of an Ocean Hazards Classification Scheme (OHCS) for Projecting Future Scenario Vulnerability Ranking on Coastal Built Infrastructure

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Abstract

From many sources, we develop an ocean hazard classification scheme (OHCS) based on the collection of historical and projected ocean hazards data at 302 locations along Hawaii's state coastal highways. The OHCS identifies ocean hazards impacting coastal built infrastructure, i.e. roadways. In the OHCS, we first rank the vulnerability of: sea level rise; waves; shoreline change; tsunami; and storm surge. Next, using our developed OHCS, provide the vulnerability ranking for all five variables combined. We find the highest OHCS to be on Molokai, the island that has the highest OHCS numbers for most of the island. For the majority of state highway locations in Hawaii, we find the highest vulnerability is from storm surge, with tsunami threat being the second largest contributor. Sea level rise should also be considered a contributor since higher sea levels contribute to more extreme storm surge and tsunami inundation. Although the OHCS is applied towards roads in our study, our method can be applied towards any coastal island-based built infrastructure vulnerability scheme. This is an important tool in planning for future construction projects or identifying which hazards to focus on in more detailed assessments, such a probabilistic risk assessment in a more localized location.

Keywords: ocean hazards, vulnerability ranking, Hawaii statewide highways, sea level change rate, wave height, shoreline change rate, tsunami inundation, storm surge inundation

1. Introduction

Throughout the northern and southern Pacific Oceans, lay many remote islands. These islands are prone to extreme waves, tectonic activity, and climate change which results in storm surges, shoreline change, tsunamis, and sea level rise. The remoteness of these islands, which allows these regions to capture fully-developed seas, and their lack of a continental shelf, puts them at particular risk to ocean hazards. The Hawaiian Islands are among the most remote islands in the world. Seven natural phenomena have been identified as posing significant threat to coastal areas of the Hawaiian Islands which include: coastal erosion, sea level rise, major storms, volcanic and seismic activity, tsunami inundation, coastal stream flooding, and extreme seasonal high wave events [1]. Coastal slope, distance to shoreline and geologic setting are also important factors when considering coastal infrastructure exposure and vulnerability.

We consider ocean hazards on coastal infrastructure, in this case, road infrastructure. Our previous study [2] used ocean hazard values which include: historical sea level rise, historical significant wave height, tides, and historical shoreline change (without sea level rise). A methodology was developed to quantify historical ocean hazards at critical road locations that have particularly large CRESI (Coastal Road Erosion Susceptibility Index) values and where the Department of Transportation is concerned about road collapse. Note, that although tides is an important ocean variable that should correctly be considered around much of the world, we have omitted it now, in this study, since the Hawaiian Islands have a low mean tidal range of about 2 feet [3].

Here, we propose that using projected ocean hazards may give a more accurate representation when planning for future climate change on infrastructure. The ocean hazards we use include historical and projected sea level rise; projected shoreline change with sea level rise; projected storm surge; historical and projected tsunamis, and historical extreme seasonal high wave events. We develop a quantitative Ocean Hazards Classification Scheme (OHCS) based on the Ocean Hazards Database (OHD) [4] of 302 mileposts across coastal state routes in Hawaii (**Figure 1**). These

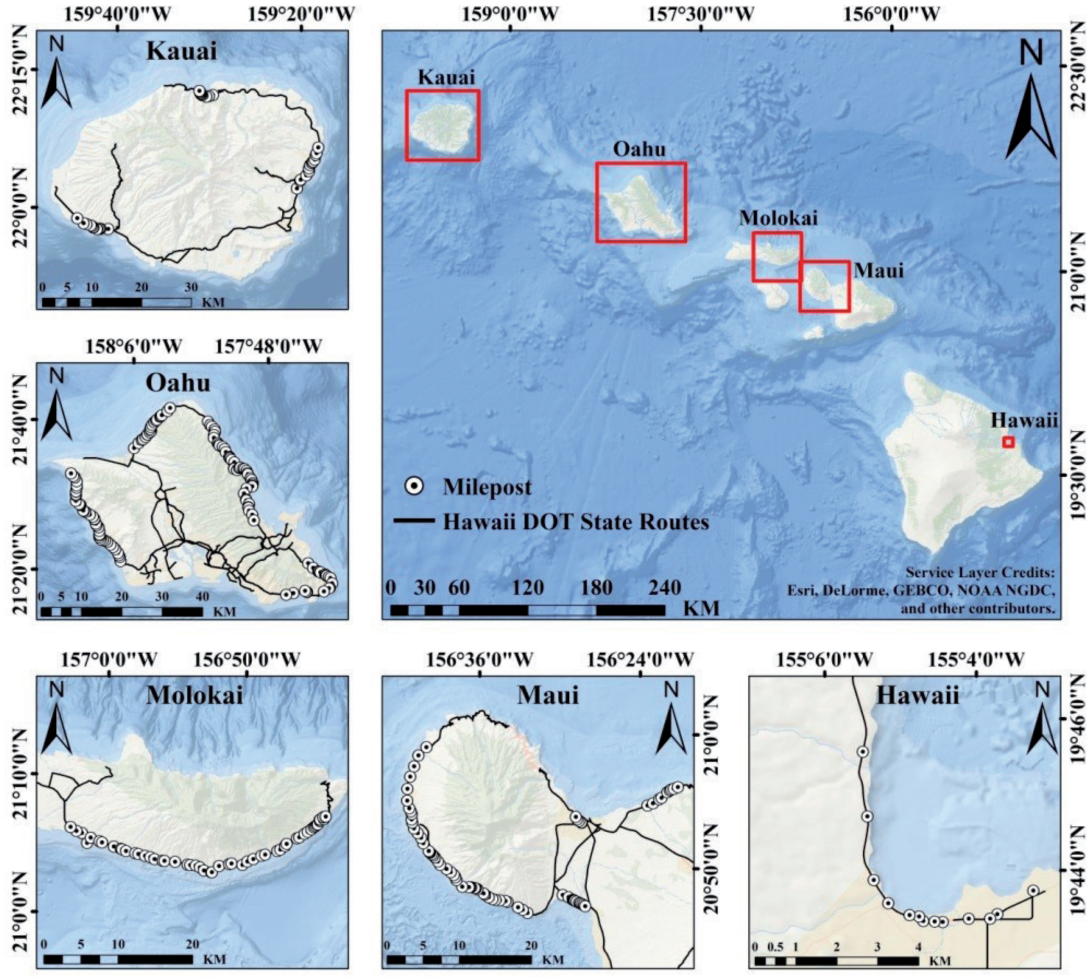

Figure 1.
Study location area, State of Hawaii, USA. The red squares show the location on each island. The white circles (with inner black dots) indicate the milepost (MP) locations where each measurement was taken.

mileposts are identified as vulnerable in [2] due to: road distance to the shoreline, road elevation, and historical road degradation due to coastal processes.

Although probability risks assessments (PRAs) are used widely to give predictions of storminess or shoreline change in a region, it is a time consuming method requiring historical data for twenty years or more, in order to create accurate projections. Also, it is often limited to a localized area due to long computational times.

The aim of this study is to obtain the projected ocean hazards vulnerability rankings using projected rates and projected inundation and the CVI method [5]. The data comes from various governmental and academic sources, which are used and put into the OHCS equation to develop one number, ranging from 0 to 100. With these rankings, we are not only able to produce an overall vulnerability ranking for the five hazards, but we are also able to identify which of the five hazards most affects the coastal road section in a region.

In the next section, we discuss our methodology and the development of the five ocean hazard variables (sea level rise, waves, shoreline change, tsunamis, storm surge) that we use. In Section 3, we give the results by evaluating which of the five ocean hazards most affect vulnerable highway sections in the State of Hawaii and show the overall vulnerability rankings. In the subsequent sections, Sections 4, 5, 6, 7, and 8, we give the conclusions, acknowledgements, references, figures and tables, respectively.

2. Methods and data

2.1 Methodology

The use of historical and projected values is important towards the development of an Ocean Hazards Classification Scheme (OHCS) for projecting future scenario vulnerability ranking on coastal built infrastructure. Our variables we consider: (1) sea level rise rate, (2) wave height, (3) shoreline change rate, (4) tsunami inundation, and (5) storm surge inundation, are described here.

Variable (1), sea level rise, is the sea level rise rate (1905–2050, extreme scenario) (in/yr). Local sea level rise is the result of both global sea level rise and local factors. Global sea level rise is due to warmer ocean temperatures and melting land ice, both caused by climate change. Local factors include land motions and tides, currents, and winds. Local sea levels can rise faster than the average global rate.

Variable (2), maximum annually recurring waves, is the significant wave height (2010–2018) (ft). This includes all forecasted wind-waves from 2010 to 2018, which was modeled in the wind-driven Simulating WAves Nearshore (SWAN) wave model.

Variable (3), shoreline change, is the mean projected shoreline change rate (2008–2100) (ft/yr); and CRESI – armoring ranking (1–5) [6]. Variable 3, shoreline change, determines the seaward encroachment of the beach towards the road and how protected the road is, whether there is existing armoring or not. Shoreline change is seasonal, where erosion and accretion are present during different times of the year. The most significant shoreline change is influenced by wave action, particularly storm surge events, which occur almost annually, transporting much of the coastline away during one event.

Variable (4), tsunamis, considers the historical and hypothetical inundation (ft). Variable 4, tsunamis, are seismic ocean waves causing coastal inundation caused by earthquakes, underwater landslides, volcanic eruptions, or meteorites.

Variable (5), storm surge, is Category 1, 2, 3, and 4 storm inundation (ft). Variable 5, storm surge, is a rapid rise in sea level causing coastal inundation due to low pressure, high winds, and high waves associated with hurricanes.

Using the ranking, from 1 to 5, for each of the five variables, we input these variables into one equation (Eq. (1)), which we call the Ocean Hazard Classification Scheme (OHCS), to obtain a value between 1 to 100, where the higher the values, the more vulnerable the region.

$$OHCS = \sqrt{\frac{(Variable\,1 * Variable\,2 * Variable\,3 * Variable\,4 * Variable\,5)^{1.345}}{5}} \quad (1)$$

where *Variable* 1 is 2050 sea level rise rate ranking (extreme scenario) (1 to 5), *Variable* 2 is significant wave height ranking (1 to 5), *Variable* 3 is mean shoreline change rate ranking (1 to 5), *Variable* 4 is tsunami inundation ranking (1 to 5), and *Variable* 5 is storm surge inundation ranking (1 to 5).

Eq. (1) is taken as the square root of the geometric mean of the ranking variables, with the addition of a power scalar to adjust the range of theoretical OHCS rankings to maximize at a value of 100. Therefore as the number of variables change, so does the scalar power. When considering five input variables, each with a maximum ranked value of 5, a power scalar value of 1.345 results in a potential maximum OHCS value of 100. Our method is similar to that used in Chapter 1 of [2] for calculating Coastal Road Erosion Susceptibility Index (CRESI) values, in [7, 8] who was the first to use the coastal vulnerability index (CVI) for the entire Hawaiian Islands to assess coastal vulnerability, and that described by [5] for finding the coastal vulnerability index (CVI) rankings.

2.2 Sea level rise

Historical rates of sea level rise are estimated from observed data, and future sea level rise rates are estimated from projected data. For both historical and future scenarios, it is essential to take the spatial variation into consideration when determining the rate of sea level rise. For this reason, we divide each island into a certain number of segments and derive the historical and future sea level rise rates for each segment, respectively. Currently, there are two types of data used to estimate the historical sea level rise rate: tide gauge and satellite altimetry data. Tide gauges are usually placed on piers and measure the sea level relative to a nearby geodetic benchmark, known as relative sea level (RSL). Satellite altimetry measures the sea level relative to a reference ellipsoid, known as absolute sea level (ASL). Here, we study how the sea level rise affects the coastal infrastructure (i.e. roads) in the Hawaiian Islands. Therefore, we focus on the trend estimates of RSL. There are six tide gauge stations in operation in the Hawaiian Islands: NAWI is located in Nawiliwili Bay, Kauai Island with data spanning 1955–2016; MOKU is located in Mokuoloe Island, Oahu Island with data spanning 1957–2016; HONO is located in Honolulu, Oahu Island with data spanning 1905–2016; KAHA is located in Kahului Harbor, Maui Island with data spanning 1947–2016; KAWA is located in Kawaihae, Hawaii Island with data spanning 1988–2016; and HIHA is located in Hilo, Hawaii Island with data spanning 1927–2016. The RSL data of the six available stations in the Hawaiian Islands are downloaded from the Permanent Service for Mean Sea Level (PSMSL) [9, 10]. We make use of all available RSL data from the six tide gauge stations to estimate the RSL trends, respectively. Before estimating the RSL trends, the following process is applied. First, the seasonal signal is removed from the RSL time series using the Seasonal Trend Decomposition using Loess (STL) procedure [11]. Second, we remove the common-mode-oceanographic signals from each RSL time series. The common-mode-oceanographic signals can be derived by averaging the monthly detrended and de-seasoned RSL time series of the all six available tide-gauge stations in the Hawaiian Islands. Finally, the linear trends of the RSL are estimated. However, tide gauge stations are sparsely distributed and not all the segments are covered. For those segments not covered by the tide gauge stations, an indirect way is applied to derive the relative sea level rise trend (RSLT). The RSL variation is comprised of two components: ASL variation and vertical land motion (VLM). Eq. (2) indicates the relationship of the three components:

$$ASLT = RSLT + VLMR \tag{2}$$

where *ASLT* represents ASL trend, *RSLT* represents RSL trend, and *VLMR* represents VLM rate. Therefore, the RSLT of the segments without tide gauge stations can be estimated by combining the ASLT and VLMR. In this paper, we use the reprocessed and merged-gridded sea-level-anomaly heights for global areas processed by Ssalto/Duacs [12] to derive the ASLT. The satellite altimetry data spans 1993–2017 and has a resolution of 0.25 arc degrees. If there is more than one satellite altimetry grid point near the study segment, the time series are averaged to derive the ASLT. Before estimating the ASLT, the Dynamic Atmospheric Correction (DAC) is downloaded and added back to the satellite altimetry data to keep in accordance with the tide gauge data which do not use the barometric pressure correction. The DAC data are produced by Collecte Localisation Satellites (CLS) using the Mog2D model from Legos and distributed by Aviso+, with support from CNES (https://www.aviso.altimetry.fr/). The satellite altimetry data is accessible at the Copernicus Marine Environment Monitoring Service (CMEMS) (http://marine.copernicus.eu/). The data of Global Navigation Satellite System (GNSS) which has proven to be a robust tool to monitor VLM [13–15] is used to derive the VLMR. The GNSS data is available at the Nevada Geodetic Laboratory (NGL) (http://geodesy.unr.edu/NGLStationPages/GlobalStationList) [16]. Detailed information for the selected tide gauge, satellite altimetry, and GNSS data of each segment is available in [14].

Several future sea level rise scenario products have been developed to help planning and decision-making stakeholders analyze and understand vulnerabilities and future risks under scientific uncertainty. We use [17, 18] to estimate the future sea level rise rate for each segment. Sea levels under different scenarios of [17, 18] are projected to tide gauge stations and grid points, which have a resolution of 1 arc degree. If a tide gauge station exists in the segment, we use the data projected to the tide gauge station. If no tide gauge station exists in the segment, the projected grid points nearby the segment will be used. If there is more than one grid point nearby a segment, the mean value is derived and used to represent the projected sea level rise of the segment. Detailed information on the projected sea level rise data for each segment is available in [14]. In this paper, we consider the projected sea level rise under extreme scenario for 2050. For segments with tide gauge stations, the tide gauge data are integrated with the projected sea level rise data to obtain the future sea level rise rate. For segments without tide gauge stations, the combined satellite altimetry and GNSS data are integrated with the projected sea level rise data to obtain the future sea level rise rate.

After deriving the historical and future sea level rise rates, we rank them according to the percentile of the observed maximum rates, respectively. If a value falls within the highest 80 to 100th percentile, it is ranked 5 (very high). Similarly, values falling within the 60 to 80th percentile are ranked 4 (high), 40 to 60th percentile are ranked 3 (moderate), 20 to 40th percentile are ranked 2 (low), and 0 to 20th percentile are ranked 1 (very low).

2.3 Maximum annually recurring waves

Due to the sparse distribution of buoy stations in the Hawaiian Islands region, there is not enough coverage to provide wave information at a local level, i.e., for each milepost. Therefore, we use modeled wave output downloaded from Pacific Islands Ocean Observing System (PacIOOS) [19] to understand the wave conditions at each milepost. PacIOOS provides 5-day hourly wave forecasts that are calibrated using local wave buoys for the Hawaiian Islands region. Wave forecasts are simulated using WaveWatch III (WW3), surrounding the main Hawaiian Islands at an approximate resolution of 0.05 degrees, and the SWAN model, surrounding each main island at an approximate resolution of 0.31 mile (500 m) [19]. In this study, we use the wave forecasts simulated by the SWAN model, which has a finer resolution. The time span of wave data for each island varies, i.e., Oahu: 2010–2019, Maui: 2016–2019, Molokai: 2016–2019, Kauai: 2010–2019, Hawaii: 2016–2019. For each milepost, a 'virtual buoy', that is, the closest point offshore and perpendicular to the road at each milepost, is selected to obtain wave data. In this study, significant wave height was used, which is estimated as four times the square root to the zeroth order moment of the wave spectrum [19].

We extract the maximum annually recurring wave information using the method presented in [20, 21]. The process of deriving maximum annually recurring wave information is as follows. First, we identify the local peaks from the time series of significant wave heights with a time interval greater than 24 hours. Second, the peaks are divided into different bins according to incoming directions. Here, we select a 30-degree bin window, which shifts by 15-degree increments. Therefore, a maximum of 24 bins can be obtained, and there are overlaps between bins. Third, we select the three highest significant wave heights from each year and perform the generalized extreme value (GEV) fit for each bin. Then, the maximum annually recurring significant wave height (MARSWH) for each bin are derived. Finally, the wave information triplet with maximum MARSWH among all bins is selected as the annually recurring maximum wave information. We repeat this process to obtain wave information at each milepost.

After deriving the wave information triplet for each milepost, we rank the two index variables, MARSWH and corresponding peak period, according to the percentile of the observed maximum value, respectively. If a value falls within the highest 80 to 100th percentile, it is ranked 5 (very high). Similarly, values falling within the 60 to 80th percentile is ranked 4 (high), 40 to 60th percentile is ranked 3 (moderate), 20 to 40th percentile is ranked 2 (low), and 0 to 20th percentile is ranked 1 (very low).

2.4 Shoreline change

Erosion and weakening shorelines are a direct threat to coastal roads and infrastructure. Through the course of this study, we have observed both damages and an increased failure potential of nearshore state roads induced by coastal erosion.

Seasonal and storm-driven shifts in the directional transportation of sand, as well as the projected effects of sea level rise (SLR), limit the long-term numerical modeling of Hawaiian shoreline evolution. To assess the potential impact of an acceleration of shoreline change in response to rising sea levels, we interpret relative rates of shoreline change from erosion exposure forecasts developed by [20]. In [22], they describe the probabilistic method by which erosion exposure areas are determined. In [22], they use an equation for shoreline change similar to that of [23], while substituting in the geometric sediment transport model for shoreline equilibrium proposed by [24], to forecast the evolution of sandy shores on the islands of Oahu, Maui, and Kauai. Hindcast and study area limits for the model in [20] are identified from historical shorelines produced by [25]. Hindcast timespans vary between islands and study areas. Complete hindcast timespans for each island are: 1910–2007 on Oahu, 1899–2007 on Maui, and 1926–2008 on Kauai [25]. Acceleration of SLR used by [22] are taken from the Intergovernmental Panel on Climate Change (IPCC) 2013 report, AR5 high-end representative concentration pathway (RCP) 8.5 scenario – the "business as usual" scenario [26].

Shoreline change is shown in ArcGIS by digitizing the nearshore vegetation line over different periods [20]. Digitized vegetation lines (polylines), which we refer to as "Shoreline Vegetation Lines (SVLs)", are determined in [20] as the 80th percentile of the probability density function for change due to SLR of the present SVL defined during a 2006–2008 study. Projected shoreline change rates (ft/yr) are determined by dividing the length between the SVLs at the milepost, from the present vegetation line to future projected vegetation lines for SLR of 0.5, 1.1, 2.0, and 3.2 feet, by the number of years within the respective period. We assess the shoreline change at each milepost along a new polyline perpendicular to the road and extending through the SVLs, which we identify as the "measurement axis". Projected occurrence for SLR of 0.5, 1.1, 2.0, and 3.2 feet is identified by [20] using the IPCC 2013 report AR5 RCP 8.5 scenario, for the years 2030, 2050, 2075, and 2100, respectively [26]. We average the rates of shoreline erosion and accretion at each milepost over the four time periods (i.e. 2030, 2050, 2075, 2100).

Rates of interpreted averaged shoreline change are ranked into five classes according to their percentile ranges, from no change and accretion to the maximum observed averaged rate. Erosion values roughly within the highest 80 to100th percentile, are ranked 5 (very high). Similarly, erosion rates falling near the 60 to 80th percentile are ranked 4 (high), the 40 to 60th percentile is ranked 3 (moderate), and the 20 to 40th percentile is ranked 2 (low). Shoreline change values representing accretion or no change, fall roughly within the 0 to 20th percentile of maximum observed values are ranked 1 (very low). Mileposts outside of [20] are ranked based on armoring observations made in CRESI [6]. Mileposts with shoreline change values of N/A and hard armoring, where the CRESI armor ranking is greater than 3, are ranked 2 (low). Mileposts with shoreline change values of N/A and no armoring, where CRESI armor ranking [6] is less than or equal to 3, are ranked 3 (moderate).

2.5 Tsunamis

Tsunami, which is commonly caused by an earthquake in subduction zones, is one of the most devastating coastal hazards. The Hawaiian Islands region, located in the center of the Pacific Ocean, is circled by the 'Ring of Fire', a region of subduction zone volcanism. Therefore, the Hawaiian Islands region is significantly threatened by tsunamis, which result from earthquakes along the 'Ring of Fire' [27, 28]. For this reason, we take into account tsunami hazard in our assessment. We use modeled tsunami flow depth data, provided by [29], to create inundation for each milepost which in turn helps us understand how tsunami hazards affect the coastal roads in the Hawaiian Islands. The term tsunami flow depth refers to the height of tsunami water surface above ground, which can be derived by subtracting ground elevation from tsunami water level. In this study, we use two types of tsunami flow depth data: one is modeled according to historical earthquake events, and the other is based on hypothetical earthquake events. Both types of data were simulated using the model Non-hydrostatic Evolution of Ocean Wave (NEOWAVE), which is a community model developed and maintained at the University of Hawaii [30, 31]. Historical tsunami scenarios are based on the five most destructive far-field or trans-Pacific tsunamis, which were generated by the

1946 Aleutian, the 1952 Kamchatkan, the 1957 Aleutian, the 1960 Chilean, and the 1964 Alaskan earthquakes. NEOWAVE model parameters are calibrated by comparing results with well-documented runup records for those tsunamis on Hawaii shores [32–35]. The NEOWAVE model applied nested grids with increasing resolution, from 2 arcminutes (~2.3 miles) for open ocean to 0.3 arcseconds (~29.53 ft) for coastlines [32–35]. Hypothetical tsunami scenarios are based on two extreme tsunamis which apply the seismic source parameters of two hypothetical great Aleutian earthquakes. Tectonic parameters of the two great Aleutian earthquakes, with moment magnitudes of (Mw) 9.3 and 9.6, are compiled by NOAA Pacific Marine Environmental Laboratory (PMEL) and both hypothetical earthquakes are identified by a seismological study as potential sources of devastating tsunamis to Hawaii [27–29]. The model also applies nested grids with increasing resolution from 2 arcminutes (~2.3 miles) for open ocean to 0.3 arcseconds (~29.53 ft) for coastlines [29].

We use the Geographical Information System (GIS) software ArcGIS to create tsunami inundation and extract tsunami flow depth values for each milepost. Tsunami flow depths are ranked for each milepost as follows. First, mileposts are classified into three categories: Category 1 has values in the historical scenario, Category 2 has no values in the historical scenario, but has values in the hypothetical scenario, and Category 3 has no values in both historical and hypothetical scenarios. For Category 1, if a value falls within the highest 67 to 100th percentile of the observed maximum value in the historical scenario, it is ranked 5 (very high). Similarly, if a value falls within the 33 to 67th percentile, it is ranked 4 (high), and within the 0 to 33rd percentile, it is ranked 3 (moderate). For Category 2, because the tsunami flow depth in the hypothetical scenario for milepost 6 (MP 6) on Route 83, North Shore, Oahu exceeds three standard deviations of the mean, we rank it 2 and remove it from the list when searching the maximum value of Category 2. Therefore, if a value falls within the highest 50 to 100th percentile of the observed maximum value in the hypothetical scenario, it is ranked 2 (low), within the 0 to 50th percentile, it is ranked 1 (very low). All mileposts in Category 3 are ranked 1 (very low).

2.6 Storm surge

Predicting and preparing for hurricanes is a top priority for the residents and city managers of Hawaii. To assess the "worst case scenario" of inundation from storm surge, we utilize the most recent national storm surge hazard maps produced by the Storm Surge Unit (SSU) of the National Hurricane Center (NHC), National Oceanic and Atmospheric Administration (NOAA) [36].

Version 1 of the national storm surge hazard maps are published by [36] and include inundation model results for flooding caused by storm surge along the East and Gulf Coasts of the United States. Version 2, also by [36], became available in November 2018 and includes storm surge inundation estimates for the U.S. Virgin Islands, Hawaii, and Hispaniola. Measures of storm surge inundation height reflect the extents of flooding caused by storm driven uplift of the ocean surface. Estimates of storm surge inundation in this assessment are based on GIS datasets obtained through personal communication with members of the SSU and NOAA affiliates. Internal SSU issues, beyond the control of our team, have prevented a complete handover and description of the Hawaii storm surge data. As a result of the incomplete handover, there are minor errors in the projection of the data, as well as a limited understanding of the model hindcast. However, despite the shortcomings, the data still remains the best and most complete storm surge inundation data for the Hawaiian Islands. Storm surge hazard data presents hypothetical inundations found using a composite deterministic and probabilistic approach with the Sea, Lake and Overland Surges from Hurricanes (SLOSH) numerical model, developed by the National Weather Service (NWS). In the Hawaiian Islands, where steep offshore bathymetry can produce an increase in mean water level due to wave dissipation, or wave setup, the SLOSH model is loosely coupled to the third generation of the SWAN model to account for storm-related increases in mean water levels. SLOSH model forecasts consider historical atmospheric and hurricane track data, to produce a model of the wind field which drives hypothetical storm surge. However, as we mention, internal SSU issues prevents us from describing the time period for the historical atmospheric data, as well as the number and distribution of historical storm tracks.

Hawaii SLOSH model estimates include inundation scenarios for category 1 through 4 hurricanes and a broad range of storm tracks and landfall locations, consisting of hundreds of thousands of hypothetical hurricanes. Assessed storm surge inundation heights are determined as the maximum of the maximum envelops of water (MOMs), relative to a DEM of Hawaii from NOAA Office for Coastal Management (OCM) high-resolution raster elevation datasets. DEMs for each island are reoriented and divided to optimize SLOSH operation, resulting in polar oriented cells of various sizes, as small as roughly 24 ft (9 m), on each side. Within each cell, MOM values are determined in feet as a combination of all simulated inundation scenarios, with the MOM identifying the greatest observed inundation height from all simulations. Milepost assessments of storm surge inundation are sampled from the individual category of storm surge datasets, within a circular buffer centered on the milepost with a radius of 82 ft (25 m). Ranked values of storm surge inundation are determined as the percent coverage-area-weighted mean of the MOM values within the milepost buffer area. Percent coverage for each milepost buffer area is determined by first using the ArcGIS zonal statistics tool to find the buffer area overlapping with the storm surge dataset. Then, the inundation, or overlapping of the buffer area, is divided by the known total buffer area of roughly 21,000 square ft, to determine the percentage of the buffer inundated. Mean inundation height within the milepost buffer areas is also determined using the ArcGIS zonal statistics tool. Ranked values of storm surge inundation are finally calculated as the mean inundation height multiplied by the percent coverage.

Percent coverage-area-weighted mean storm surge inundation heights are ranked based on their observed distribution within the maximum observed value of each category of storm, respectively. Mileposts with inundation heights within the 50 to 100th percentile of Category 1 storm surge are ranked 5 (very high). Inundation heights greater than zero and within the 0 to 50th percentile of Category 1 storm surge, as well as the 50 to 100th percentile of Category 2 storm surge, are ranked 4 (high). If milepost inundation heights for Category 2 storm surge are greater than zero and within the 0 to 50th percentile, or within the 50 to 100th percentile for Category 3 storm surge, they are ranked 3 (moderate). Storm surge inundation heights within the 50 to 100th percentile for Category 4 storm surge, or within the 0 to 50th percentile for Category 3 storm surge are ranked 2 (low). Milepost assessments with no inundation, or with inundation heights in the 0 to 50th percentile for Category 4 storm surge are ranked 1 (very low).

3. Results: projected vulnerability for coastal highways

There are twelve regions in the State of Hawaii where coastal roads, are owned by the State, and selected due to their location to shoreline, elevation and road condition from previous ocean hazards. Of these twelve regions, four are on Oahu, two are on Molokai, three are on Maui, three are on Kauai, and one is on Hawaii. Oahu includes Waianae Coast (WC), North Shore (NS), East Shore (ES), and East Oahu (EO). Molokai includes Molokai West (KW) and Molokai East (KE). Maui includes West Maui (WM), East Maui (EM), and Central Maui (CM). Kauai includes West Kauai (W), North Kauai (N), and East Kauai (E). Hawaii includes Hilo (HILO).

Here, we present our results and how five ocean hazards: sea level rise, waves, shoreline change, tsunami, and storm surge are collectively used to rank the vulnerability of coastal highways in the State of Hawaii. A list of ocean hazards data and their associated references (superscripted) used for the Ocean Hazards Classification Scheme (OHCS) in Eq. (1) is shown in **Table 1**.

Table 2 is the Ocean Hazards Classification Scheme (OHCS) for historical and projected ocean hazards developed from the Ocean Hazards Database (OHD) [4] for state coastal roads in the State of Hawaii. In the first column is the vulnerability rank, 1 to 5, where 1 is low vulnerability and 5 is high vulnerability. The remaining columns are the associated Variables and their resulting rates, heights or depths according to the methodology described in Section 2, using 302 mileposts across the State from [2]. Using **Table 2**, we rank each Variable (1 to 5) and apply it to Eq. (1) to retrieve the OHCS ranking, that is, a combined ranking of vulnerability for sea level rise, significant wave height, shoreline change, tsunami and storm surge. Our results are listed as follows.

Oahu Waianae Coast (WC), **Figures 2-4**: Includes 39 mileposts. The OHCS vulnerability ranking ranges from 1 to 3, with a few higher ranking outliers of 5, 5, and 6 at MPs 19 + 0.55, 16 + 0.41 and 10 + 0.25, respectively. In this region, sea level rise ranges from 1 to 2, significant wave height ranges from 1 to 2, shoreline change ranges from 2 to 3, tsunami ranges from 1 to 4, and storm surge ranges from 1 to 4. The outliers, i.e. the OHCS rankings of 5 and 6 at MP 19 + 0.55, 16 + 0.41 and 10 + 0.25, are a result from the increased tsunami and storm surge rankings, due to proximity and elevation of the road to the shoreline at those particular locations.

Oahu North Shore (NS), **Figure 5**: Includes 19 mileposts. The OHCS vulnerability ranking ranges from 2 to 15. In this region, sea level rise is 2, significant wave height ranges from 1 to 3, shoreline change ranges from 2 to 3, tsunami ranges from 1 to 4, and storm surge is 1 with a three MPs ranked at 4. Although most of the OHCS values range from 7 or below, the three MPs worth noting, i.e. MP 3 + 0.66, 4 + 0.49 and 6, with a ranking of 15, 15, and 10, respectively, are the MPs with a storm surge ranking of 4, compared to the other MPs with a storm surge ranking of 1.

Variable	Classification	Description [units]
1	Sea Level Rise	2050 Sea Level Rise Rate [9, 10, 12, 14, 17, 18] (1905–2050, extreme scenario) [in/yr]
2	Maximum Annually Recurring Waves	Significant Wave Height [19, 20] (2010–2018) [ft]
3	Shoreline Change	Mean Shoreline Change Rate [6, 20] (2008–2100) [ft/yr]
4	Tsunami	Inundation Depth (Historical and Hypothetical) [29, 32–35] [ft]
5	Storm Surge	Category 1–4 Storm Inundation Depth [36] (Hypothetical) [ft]

Table 1.
Historical and projected ocean hazards variables used in the Ocean Hazards Classification Scheme (OHCS) for State coastal roads in the State of Hawaii. For more detailed explanation of each, refer to [4]. 12 inches = 1 foot = 0.3048 meters.

Vunerability Rank	Variable 1	Variable 2	Variable 3	Variable 4	Variable 5
	Sea Level Rise	**Maximum Annually Recurring Waves**	**Shoreline Change**	**Tsunami**	**Storm Surge**
	2050 Sea Level Rise Rate [9, 10, 12, 14, 17, 18] (1905–2050, extreme scenario)	**Significant Wave Height [19, 20] (2010–2018)**	**Mean Shoreline Change Rate [6, 20] (2008–2100)**	**Tsunami Inundation [29, 32–35] (Historical and Hypothetical)**	**Weighted Mean Storm Surge Inundation [36] (Hypothetical)**
1	<0.1 in/yr	<7 ft	<0 ft/yr	No inundation or Hypothetical inundation <16 ft with no Historical Inundation	No Inundation or Category 4 Inundation <4 ft
2	0.1 to 0.2 in/yr	7 to 14 ft	0 to 2 ft/yr & “N/A” with >3 Armoring Ranking	Hypothetical inundation ≥16 ft with no Historical Inundation	Category 3 Inundation <4 ft or Category 4 Inundation of 4 to 8 ft
3	0.2 to 0.3 in/yr	14 to 21 ft	2 to 5 ft/yr & “N/A” with ≤3 Armoring Ranking	Historical inundation <6 ft	Category 3 Inundation of 4 to 7 ft or Category 2 Inundation <1 ft
4	0.3 to 0.4 in/yr	21 to 29 ft	5 to 7 ft/yr	Historical inundation of 6 to 12 ft	Category 2 Inundation of 1 to 6 ft or Category 1 Inundation <1 ft
5	> 0.4 in/yr	> 29 ft	> 7 ft/yr	Historical inundation ≥12 ft	Category 1 Inundation of 1 to 4 ft

Table 2.
Ocean Hazards Classification Scheme (OHCS) for historical and projected ocean hazards developed from [34] for State coastal roads in the State of Hawaii. 12 inches = 1 foot = 0.3048 meters.

Oahu East Shore (ES), **Figures 6-8**: Includes 44 mileposts. The OHCS vulnerability ranking ranges from 1 to 12. In this region, sea level rise is 2, significant wave height ranges from 1 to 2, shoreline change ranges from 1 to 3, tsunami ranges from 1 to 4, and storm surge ranges from 1 to 5. We see particularly high OHCS rankings of 9 to 12 at certain MPs. These regions with OHCS values of 9 to 12, is a result from the increased tsunami and storm surge rankings.

Oahu East Oahu (EO), **Figures 9** and **10**: Includes 20 mileposts. The OHCS vulnerability ranking ranges from 1 to 10. In this region, sea level rise ranges from 1 to 2, significant wave height ranges from 1 to 2, shoreline change ranges from 2 to 3, tsunami ranges from 1 to 4, and storm surge ranges from 1 to 5. High OHCS rankings of 7 to 10, is a result from the increased tsunami and storm surge rankings.

Figure 2.
Ocean Hazards Classification Scheme (OHCS) ranking for Oahu Waianae Coast (WC) MP 13 + 0.1 to 19 + 0.55. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

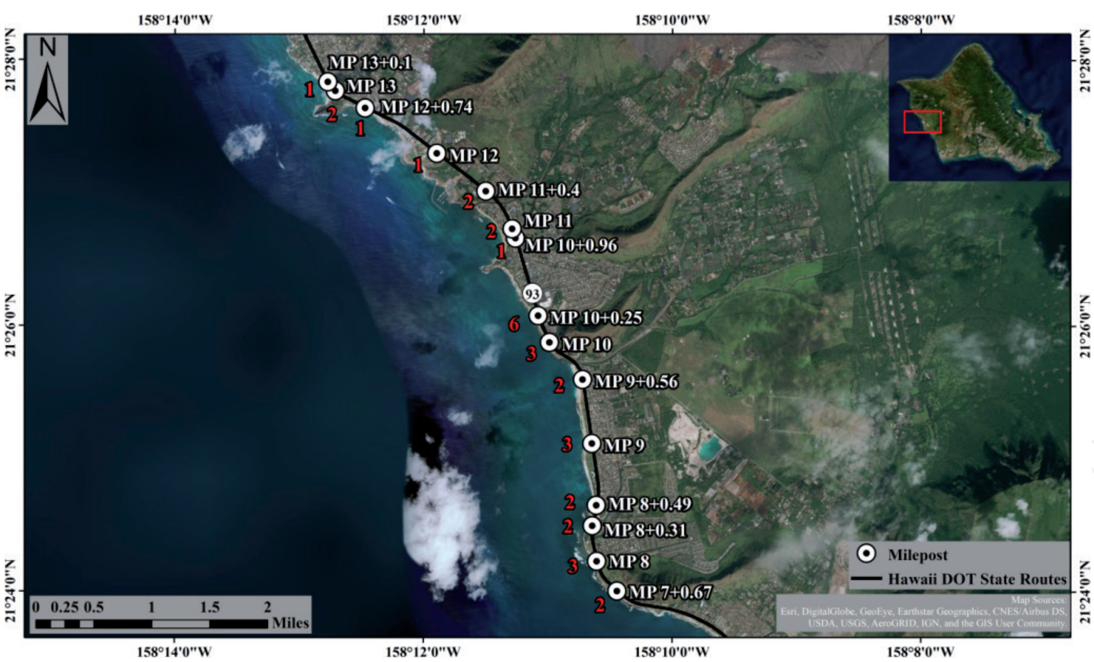

Figure 3.
Ocean Hazards Classification Scheme (OHCS) ranking for Oahu Waianae Coast (WC) MP 7 + 0.67_13 + 0.1. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

Molokai Molokai West (KW), **Figure 11**: Includes 5 mileposts. The OHCS vulnerability ranking ranges from 13 to 17, with a low OHCS ranking outlier of 3 at MP 2. In this region for OHCS rankings of 13 to 17, the sea level rise is 5, significant wave height is 1, shoreline change ranges from 2 to 3, tsunami is 3, and storm surge

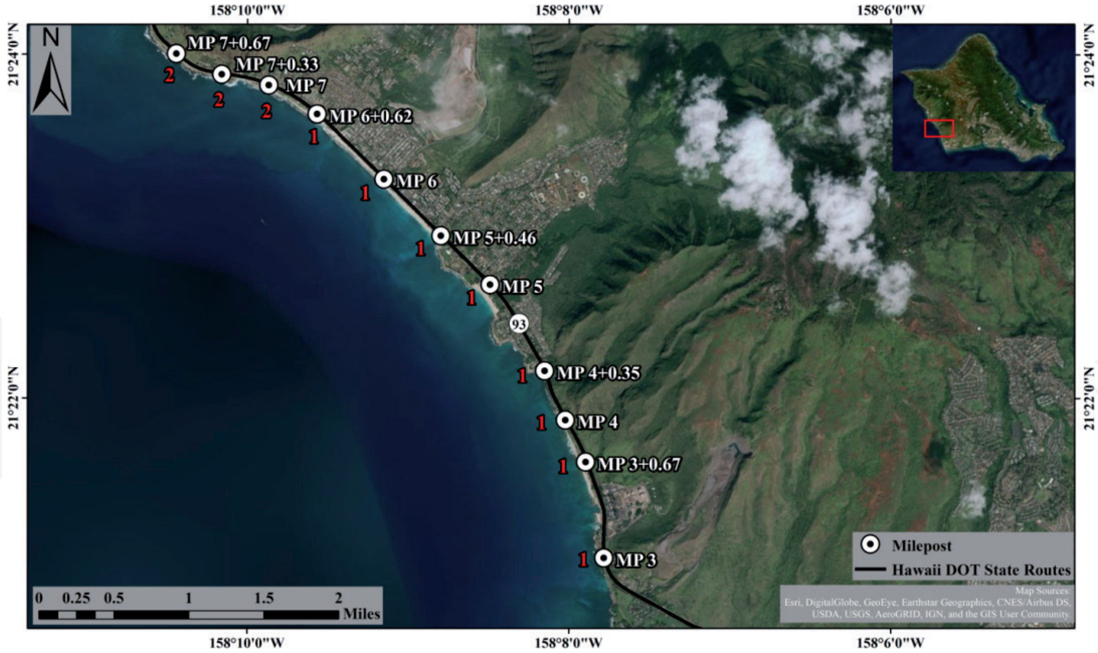

Figure 4.
Ocean Hazards Classification Scheme (OHCS) ranking for Oahu Waianae Coast (WC) MP 3 to 7 + 0.67. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

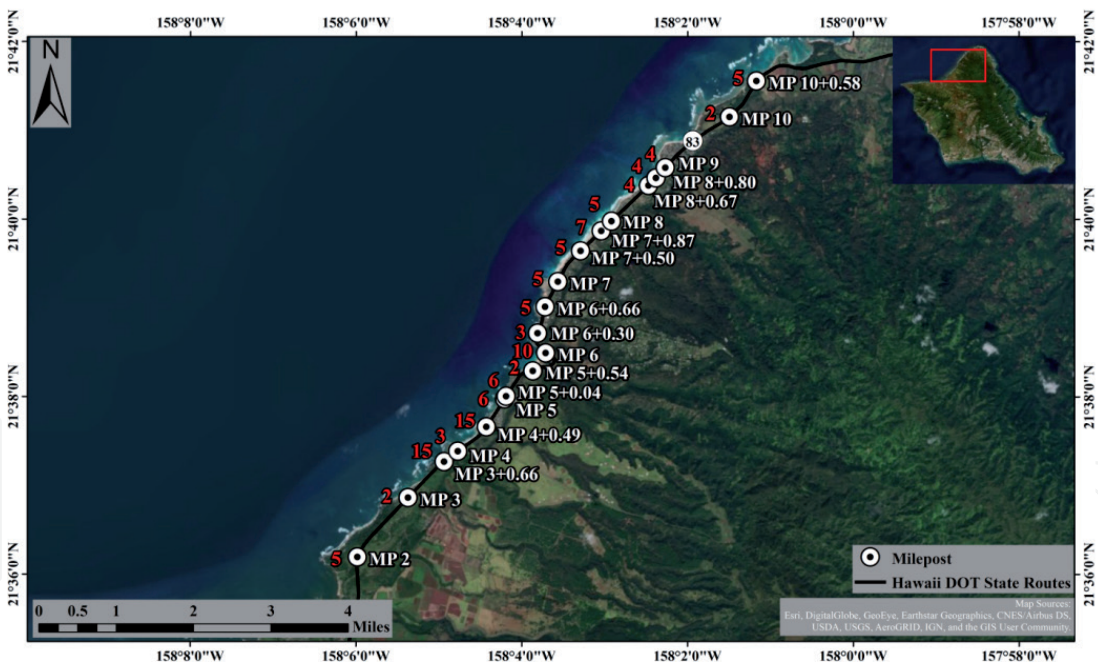

Figure 5.
Ocean Hazards Classification Scheme (OHCS) ranking for Oahu North Shore (NS) MP 2 to 10 + 0.58. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

ranges from 4 to 5. High OHCS rankings of 13 to 17 is a result of higher rankings for sea level rise, storm surge and tsunami inundation in this region.

Molokai Molokai East (KE), **Figures 12-14**: Includes 49 mileposts. The OHCS vulnerability ranking ranges from 3 to 33. In this region, the sea level rise is 5, significant wave height ranges from 1 to 2, shoreline change is 3, tsunami ranges from

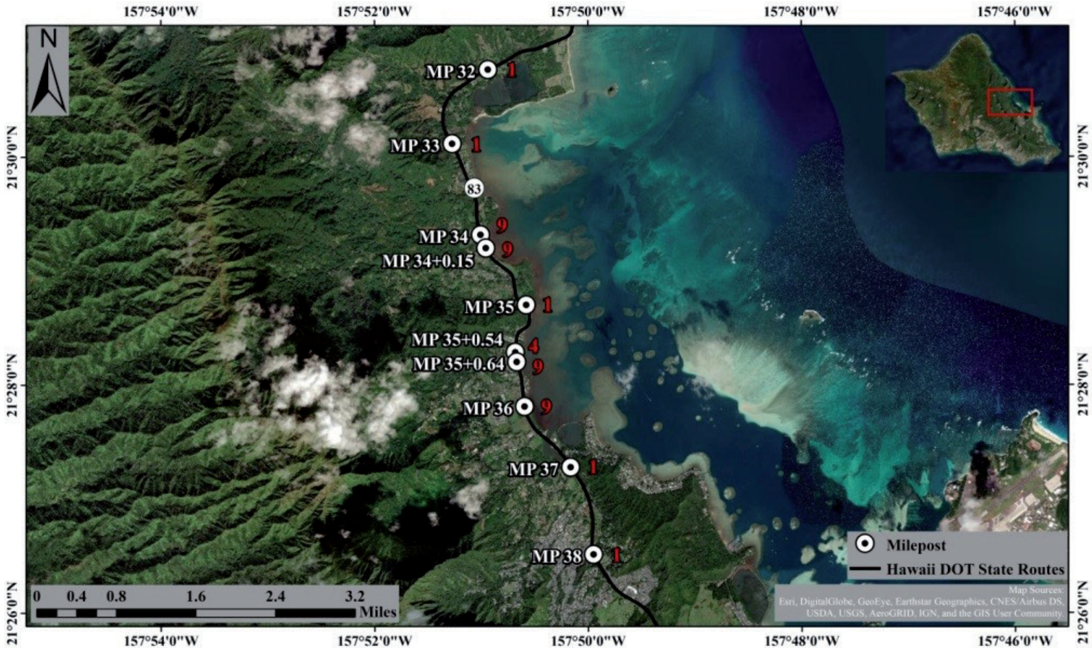

Figure 6.
Ocean Hazards Classification Scheme (OHCS) ranking for Oahu East Shore (ES) MP 32 to 38. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

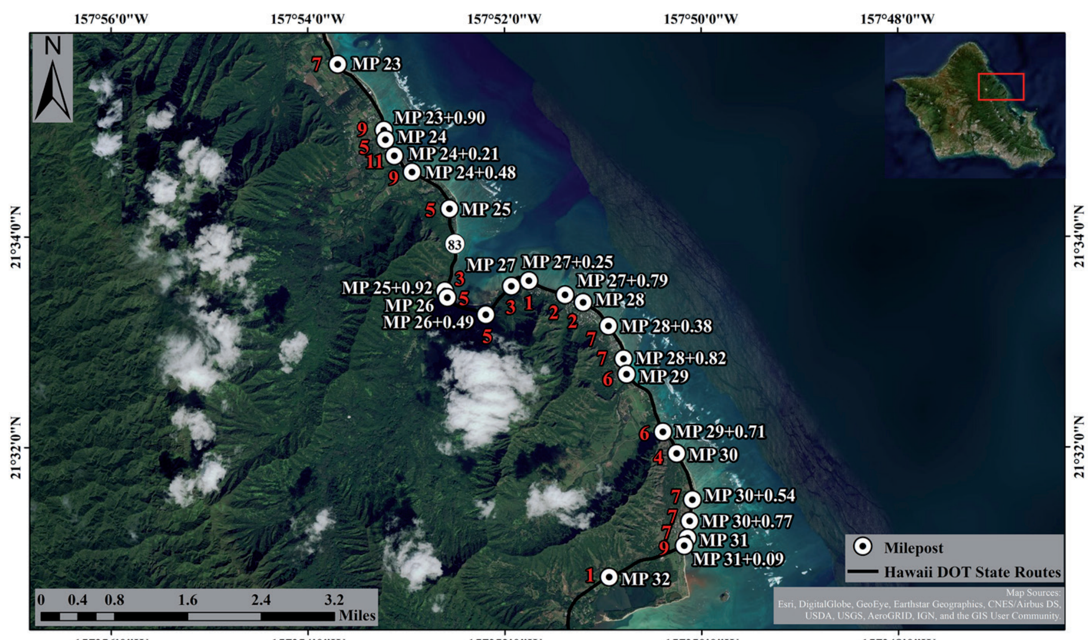

Figure 7.
Ocean Hazards Classification Scheme (OHCS) ranking for Oahu East Shore (ES) MP 23 to 32. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

1 to 5, and storm surge ranges from 1 to 5. High OHCS rankings is a result of high rankings for sea level rise, storm surge and tsunami inundation in this region.

Maui West Maui (WM), **Figures 15-17**: Includes 48 mileposts. The OHCS vulnerability ranking ranges from 1 to 14. In this region, the sea level rise is 2, significant wave height ranges from 1 to 2, shoreline change ranges from 1 to 3, tsunami

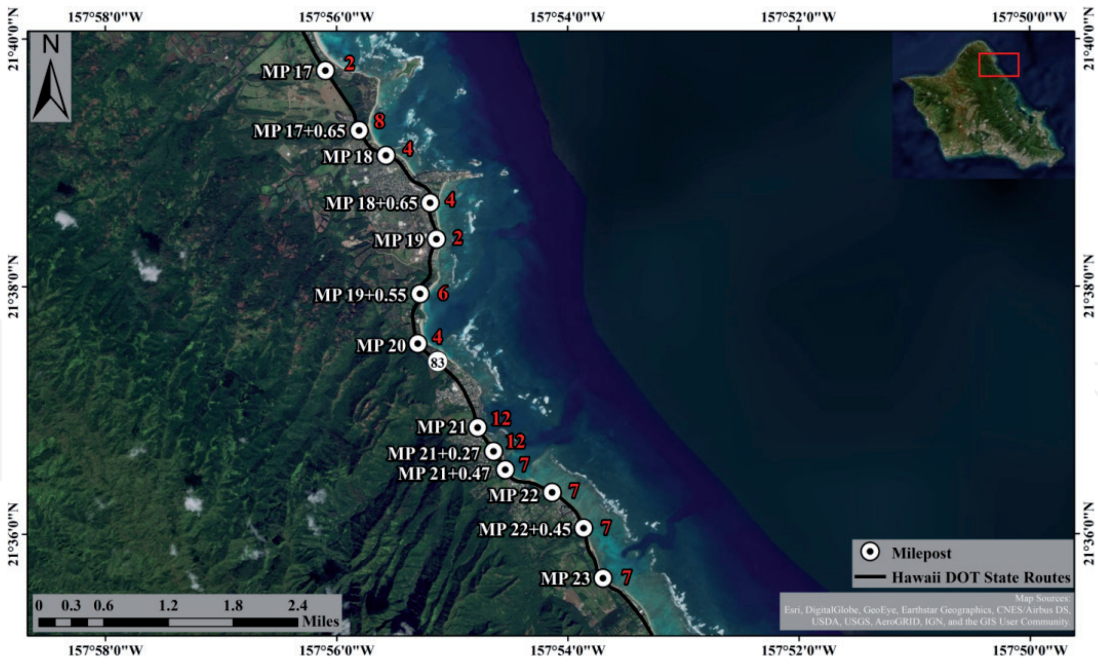

Figure 8.
Ocean Hazards Classification Scheme (OHCS) ranking for Oahu East Shore (ES) MP 17 to 23. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

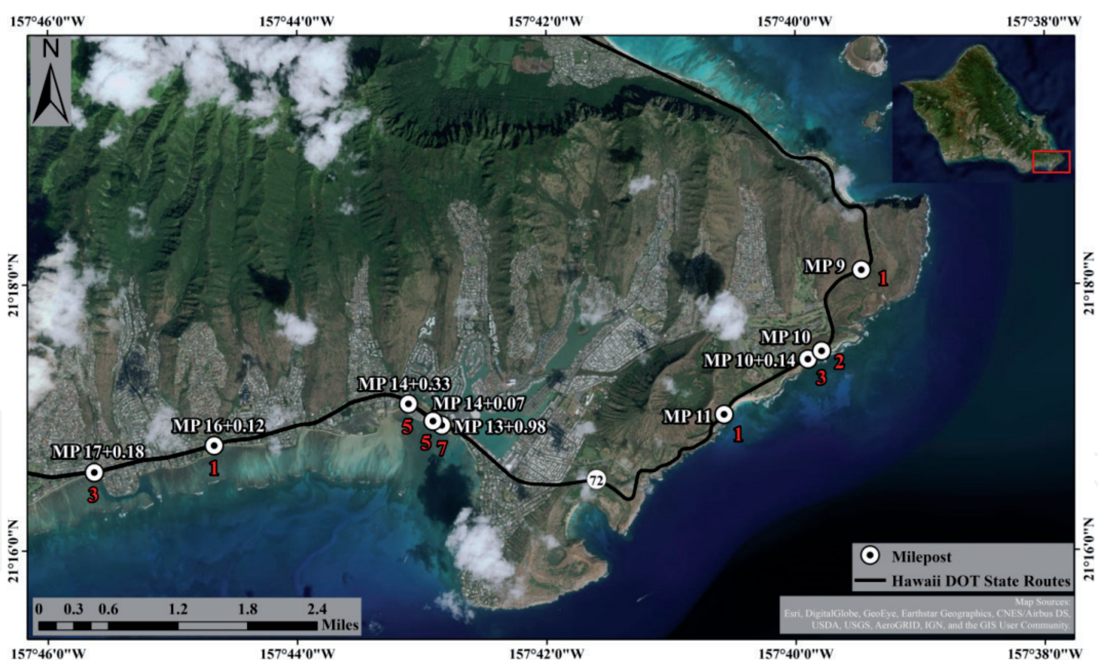

Figure 9.
Ocean Hazards Classification Scheme (OHCS) ranking for Oahu East Oahu (EO) MP 9 to 17 + 0.18. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

ranges from 1 to 5, and storm surge ranges from 1 to 5. High OHCS rankings is a result of high rankings for storm surge and tsunami inundation in this region.

Maui East Maui (EM), **Figure 18**: Includes 11 mileposts. The OHCS vulnerability ranking ranges from 6 to 10. In this region, the sea level rise is 2, significant wave height is 1, shoreline change ranges from 2 to 3, tsunami ranges from 4 to 5, and

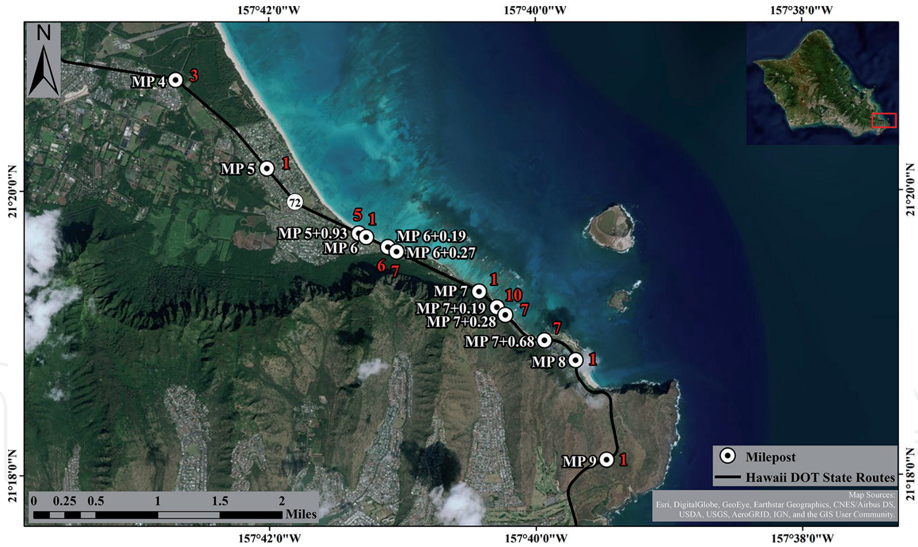

Figure 10.
Ocean Hazards Classification Scheme (OHCS) ranking for Oahu East Oahu (EO) MP 4 to 9. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

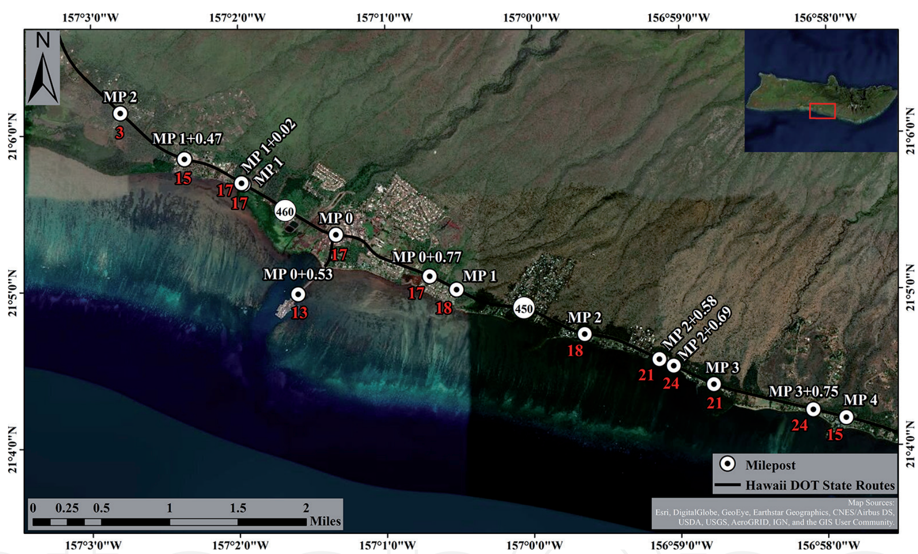

Figure 11.
Ocean Hazards Classification Scheme (OHCS) ranking for Molokai Molokai West (KW) MP 2 to East 4. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

storm surge ranges from 2 to 5. High OHCS rankings is a result of high rankings for storm surge and tsunami inundation in this region.

Maui Central Maui (CM), **Figures 19** and **20**: Includes 13 mileposts. The OHCS vulnerability ranking ranges from 3 to 16. In this region, the sea level rise ranges from 2 to 5, significant wave height ranges from 1 to 5, shoreline change ranges from 2 to 5, tsunami ranges from 1 to 5, and storm surge ranges from 1 to 5. High OHCS rankings is generally a result of high rankings for sea level rise, storm surge and tsunami inundation in this region. However, significant wave height contributes to high OHCS rankings at MPs 8 + 0.42 and 8 + 0.63 and shoreline change at MP 0 + 0.05.

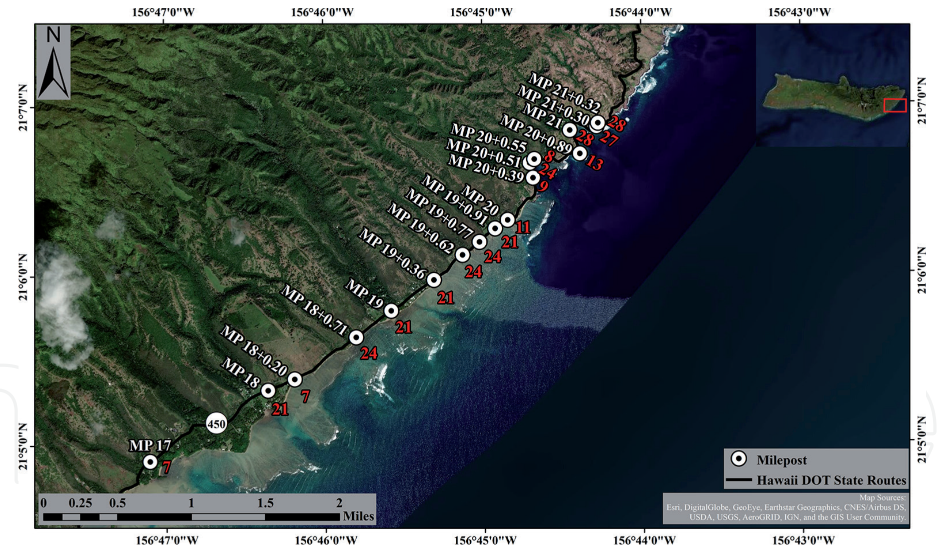

Figure 12.
Ocean Hazards Classification Scheme (OHCS) ranking for Molokai Molokai East (KE) MP 17 to 21 + 0.32. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

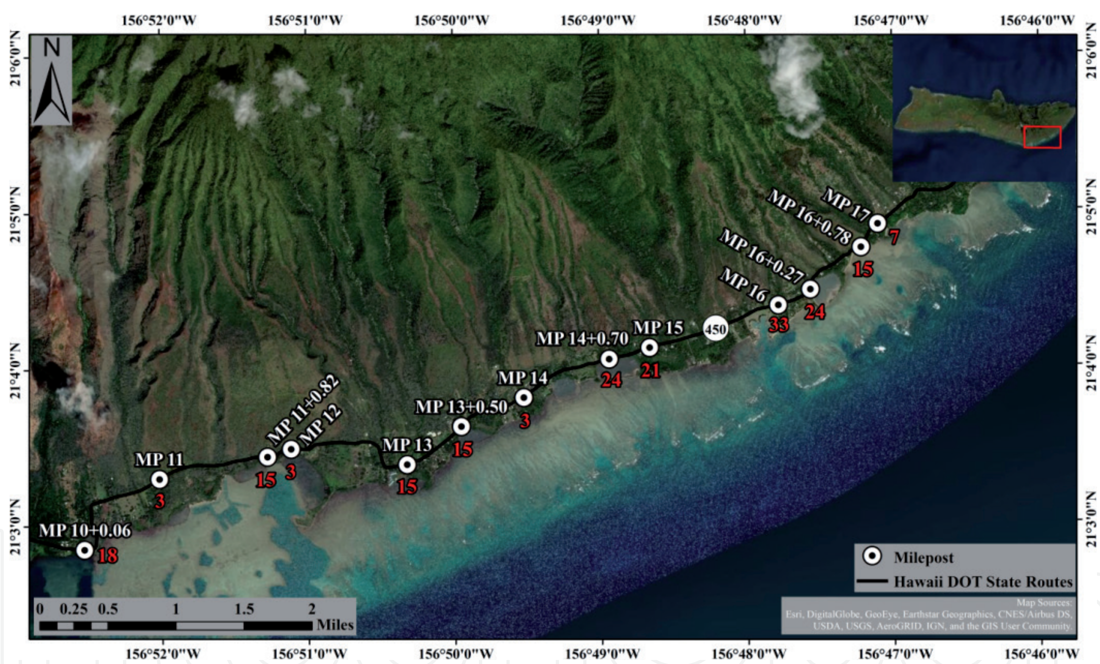

Figure 13.
Ocean Hazards Classification Scheme (OHCS) ranking for Molokai Molokai East (KE) MP 10 + 0.06 to 17. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

Kauai West Kauai (W), **Figure 21**: Includes 11 mileposts. The OHCS vulnerability ranking ranges from 4 to 11, with a low OHCS outlier of 1 at MP 24 + 0.91. In this region, the sea level rise is 2, significant wave height is 1, shoreline change ranges from 1 to 4, tsunami ranges from 3 to 4, and storm surge ranges from 1 to 5. High OHCS rankings is a result of high rankings for storm surge and tsunami inundation in this region.

Kauai North Kauai (N), **Figure 22**: Includes 8 mileposts. The OHCS vulnerability ranking ranges from 3 to 11. In this region, the sea level rise is 2, significant wave

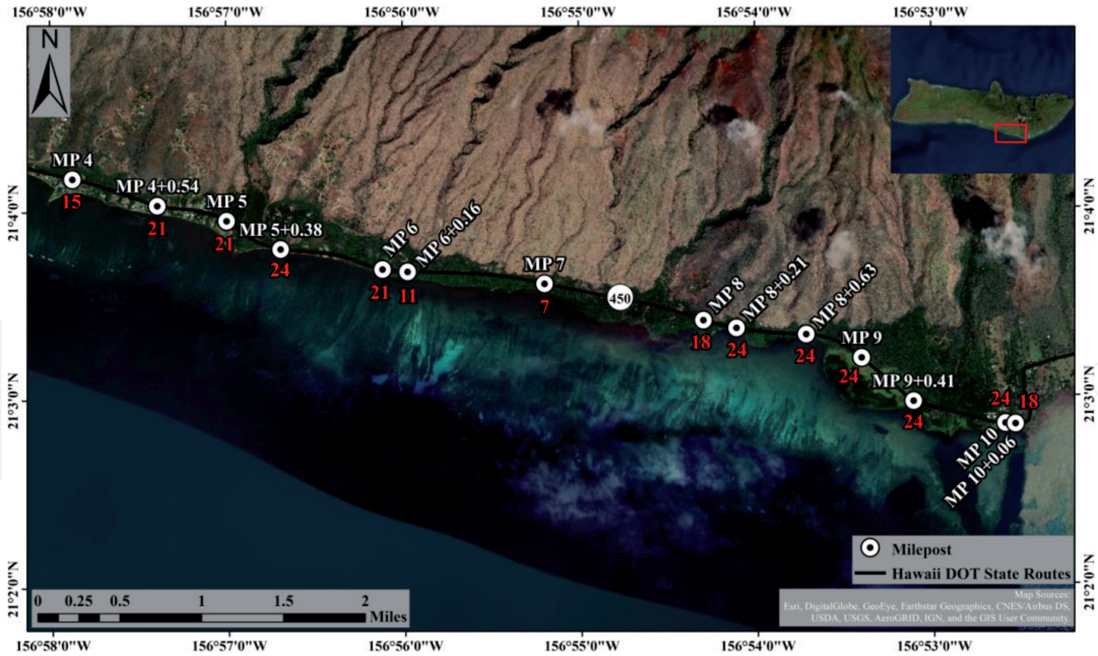

Figure 14.
Ocean Hazards Classification Scheme (OHCS) ranking for Molokai Molokai East (KE) MP 4 to 10 + 0.06. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

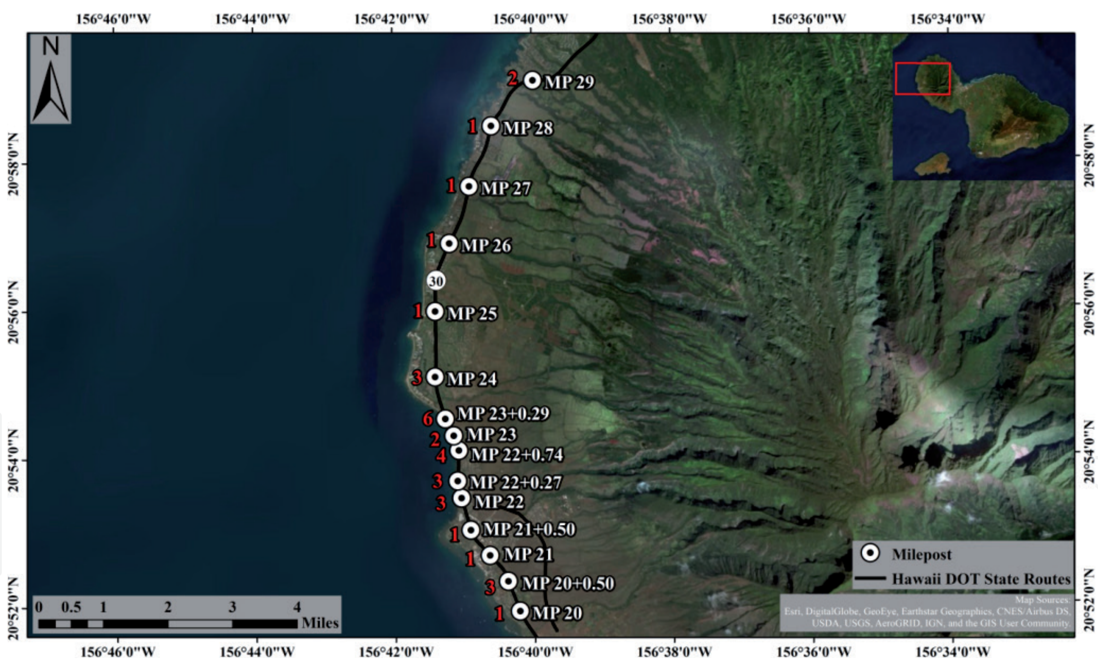

Figure 15.
Ocean Hazards Classification Scheme (OHCS) ranking for Maui West Maui (WM) MP 20 to 29. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

height ranges from 1 to 2, shoreline change ranges from 2 to 5, tsunami ranges from 3 to 4, and storm surge ranges from 1 to 5. High OHCS rankings is a result of higher rankings for storm surge and shoreline change in this region.

Kauai East Kauai (E), **Figure 23**: Includes 13 mileposts. The OHCS vulnerability ranking ranges from 2 to 9. In this region, the sea level rise is 2, significant wave

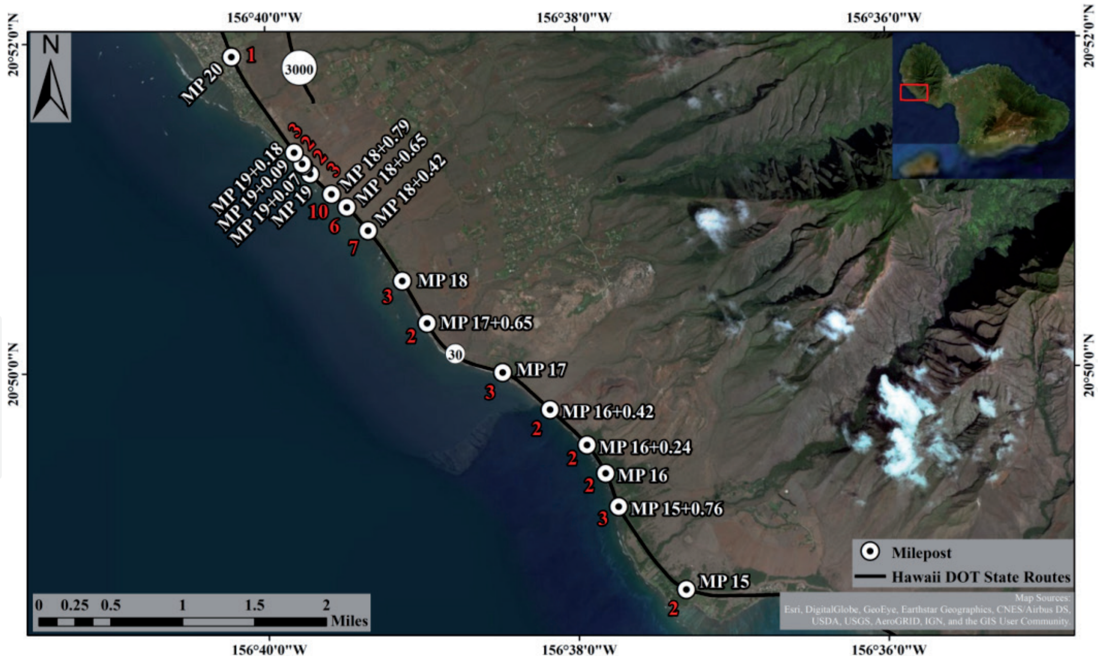

Figure 16.
Ocean Hazards Classification Scheme (OHCS) ranking for Maui West Maui (WM) MP 15 to 20. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

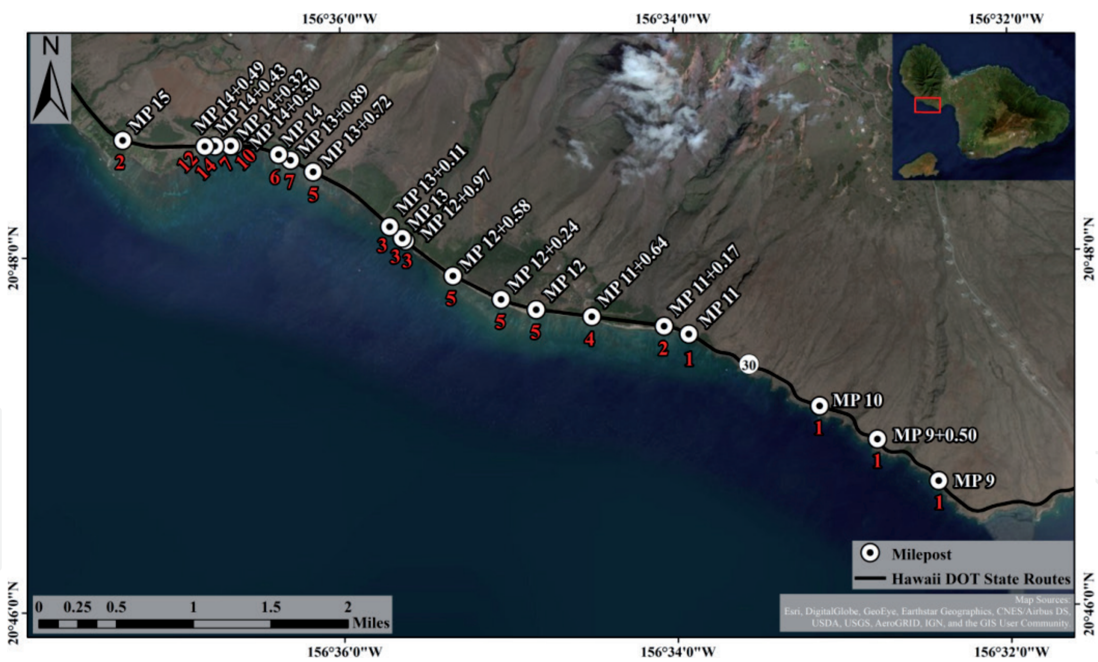

Figure 17.
Ocean Hazards Classification Scheme (OHCS) ranking for Maui West Maui (WM) MP 9 to 15. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

height ranges from 1 to 2, shoreline change ranges from 2 to 3, tsunami ranges from 1 to 4, and storm surge ranges from 1 to 5. High OHCS rankings is a result of higher rankings for shoreline change, tsunami and storm surge in this region.

Hawaii Hilo (HILO), **Figure 24**: Includes 12 mileposts. The OHCS vulnerability ranking ranges from 4 to 18. In this region, the sea level rise is 4, significant

Figure 18.
Ocean Hazards Classification Scheme (OHCS) ranking for Maui East Maui (EM) MP 1 to 3 + 0.14. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

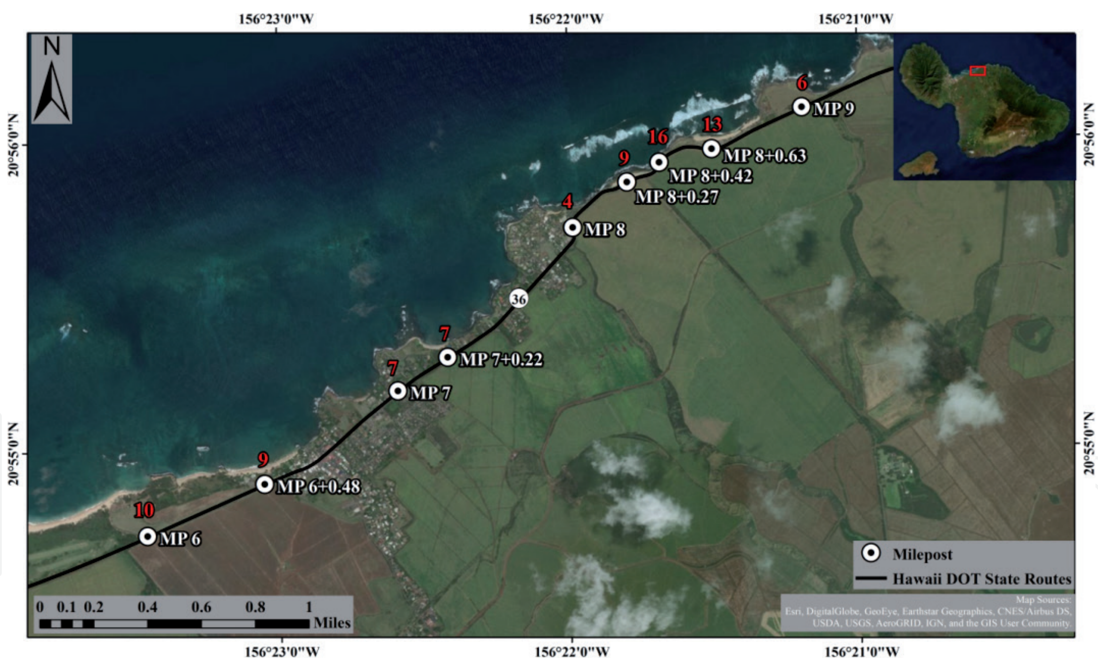

Figure 19.
Ocean Hazards Classification Scheme (OHCS) ranking for Maui Central Maui (CM) MP 6 to 9. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

wave height ranges from 1 to 2, shoreline change ranges from 2 to 3, tsunami ranges from 1 to 5, and storm surge ranges from 1 to 5. High OHCS rankings is a result of higher rankings for sea level rise, tsunami and storm surge in this region.

In summary from our results, sea level rise ranges from 1 to 5, waves ranges from 1 to 5, and the OHCS ranges from 1 to 33. Although the OHCS equation allows

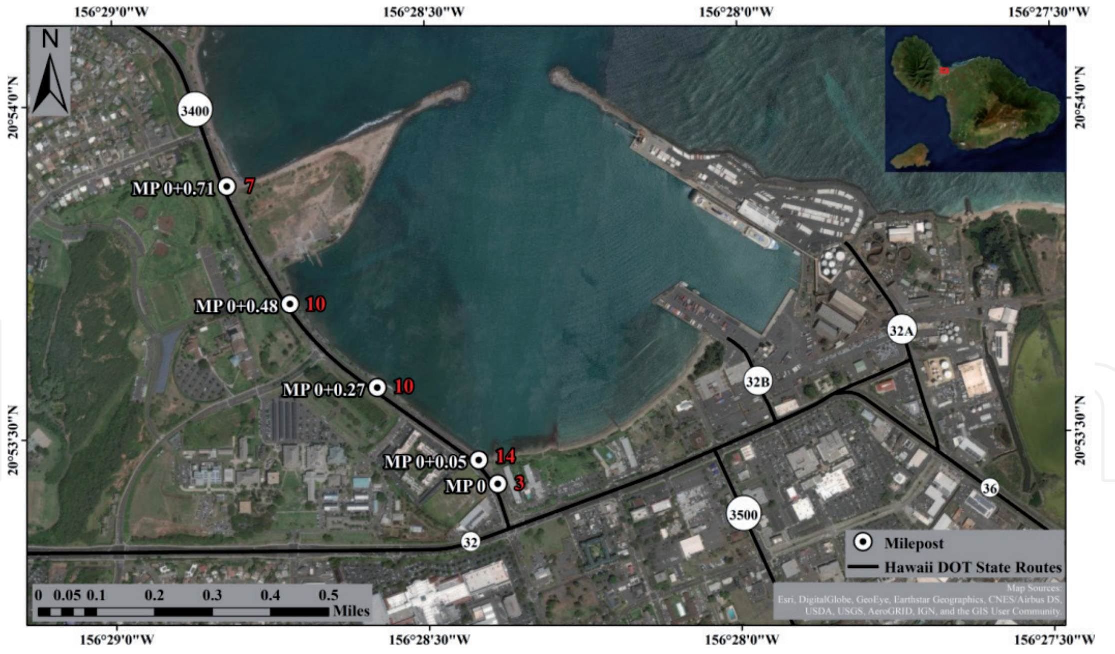

Figure 20.
Ocean Hazards Classification Scheme (OHCS) ranking for Maui Central Maui (CM) MP 0 to 0 + 0.71. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

Figure 21.
Ocean Hazards Classification Scheme (OHCS) ranking for Kauai West Kauai (W) MP 24 to 28. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

a value up to 100, OHCS only went up to 33, showing that no locations have all Variables at high vulnerability (i.e. 5), but rather a one or two Variables may be at rank 5 while the other Variables remain low (i.e. 1 or 2).

Another result shows that the island of Molokai has the highest OHCS overall. The Variables that contribute to the high OHCS includes sea level rise, tsunami and storm surge, all of which were nearly ranked at 5.

Figure 22.
Ocean Hazards Classification Scheme (OHCS) ranking for Kauai North Kauai (N) MP 2 + 0.5 to 4 + 0.51. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

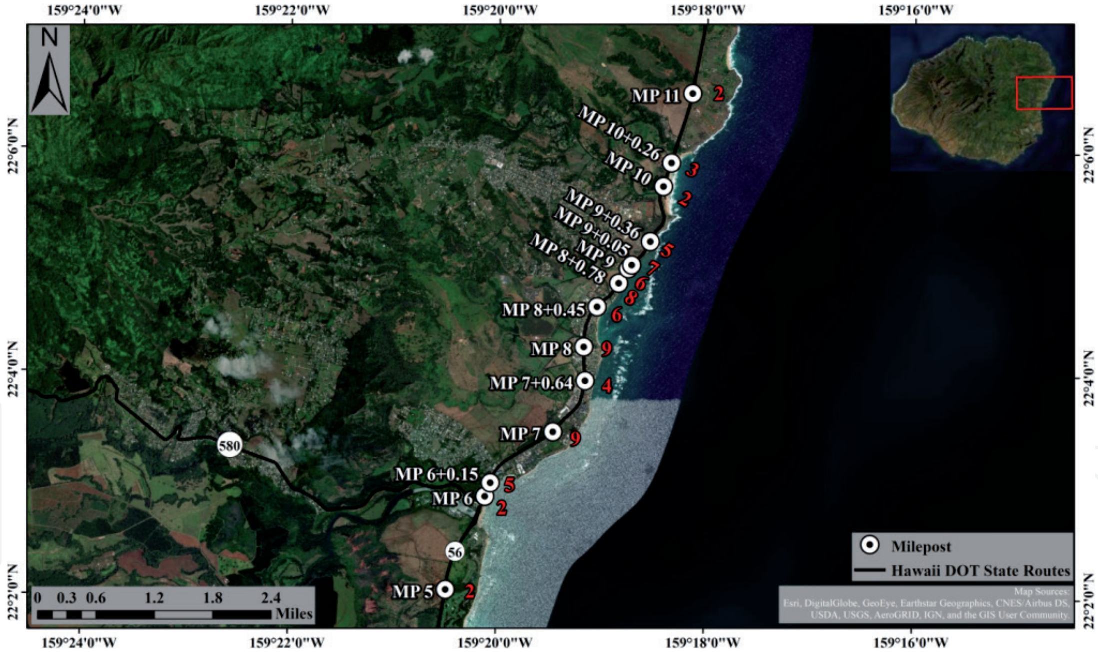

Figure 23.
Ocean Hazards Classification Scheme (OHCS) ranking for Kauai East Kauai (E) MP 5 to 11. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

A third result is that the Variable, storm surge, is consistently the largest contributor in coastal vulnerability on state roads for all islands. This is shown in the ranking of all Variables which largely show a storm surge of rank 5 at most locations, where the other Variables remain at 1 or 2. Tsunamis are the second largest contributor in our results. Although sea level rise was not one of the highest

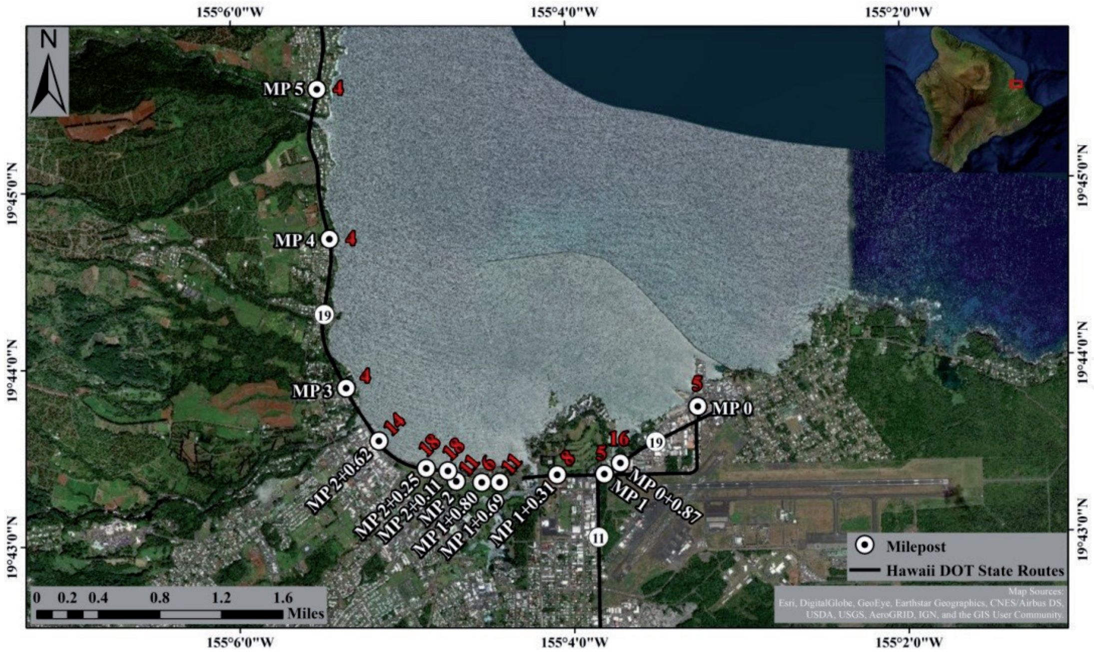

Figure 24.
Ocean Hazards Classification Scheme (OHCS) ranking for Hawaii Hilo (HILO) MP 0 to 5. The OHCS consists of five variables: (i) sea level rise 1905–2050, (ii) maximum annually recurring significant wave height 2010–2018, (iii) shoreline change 2008–2100 and CRESI Armoring, (iv) historical and hypothetical tsunami, and (v) Category 1,2,3,4 hypothetical storm surge. Rankings of ocean hazard increase from 1 to a theoretical maximum of 100.

contributors, it should be considered a main contributor since the sea level rise inundation amplifies storm surge and tsunami inundation.

4. Conclusion

The high rankings of storm surge inundation and tsunami inundation are due to lower road elevation, which puts the road at greater risk. Road relocation inland is recommended, if possible. Where road relocation is not possible, and usually not an option for state roads in Hawaii, elevating the road infrastructure (and therefore other surrounding infrastructure) should be taken into consideration in community planning and development. To reinforce the elevated road, hardening should be included also.

Although our Variables we consider: (1) sea level rise, (2) waves, (3) shoreline change, (4) tsunamis, and (5) storm surge, work for our study region, i.e. the Hawaiian Islands, one should be aware that assessing vulnerability is "location specific". This means that natural hazards affecting an area depend on many factors such as the geology, oceanic, bathymetric, and climate trends in a location. These factors differ region to region. Each coastal region should develop their own vulnerability ranking method to include or not include Variables which most likely affect their region.

While natural hazard exposure to infrastructure is important, other multiple indicators should also be considered. For roadways this may include traffic volume, population served, accessibility, connectivity, reliability, land use, and roadway connection to critical infrastructures, such as hospitals and police stations [37]. However, this type of data changes frequently as land use develops at a rapid pace or additionally roads may be added. Also adding these additional indicators may change the CVI (or OHCS).

Coastal hazard and risk not only comes in the form of the physical processes on the ecosystem or built infrastructure, but also through social perceptions, as well. Perceptions of coastal hazards and risks and community support for engineered adaptation methods are important for implementation among different stakeholder groups (experts, businesses, and community members) [38].

By understanding the vulnerability of a region, we may assign what adaptation method to use in vulnerable coastal regions dealing with climate change, in particular, inundation. These engineered adaptation methods include offshore barriers, coastal armoring, elevated development, floating development, floodable development, living shorelines, and managed retreat [39]. In the future, if we want to continue to live on coast, we must adapt.

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