Coastal Vulnerability Assessment of Kaloko-Honokohau National Historical Park to Sea-Level Rise

By Elizabeth A. Pendleton, E. Robert Thieler, and S. Jeffress Williams

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Rebecca Beavers
National Park Service
Natural Resource Program Center
Geologic Resources Division
P.O. Box 25287
Denver, CO 80225-0287
Rebecca_Beavers@nps.gov
Telephone: 303-987-6945

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Contents

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Abstract

A coastal vulnerability index (CVI) was used to map the relative vulnerability of the coast to future sea-level rise within Kaloko-Honokohau National Historical Park in Hawaii. The CVI ranks the following in terms of their physical contribution to sea-level rise-related coastal change: geomorphology, regional coastal slope, rate of relative sea-level rise, historical shoreline change rates, mean tidal range and mean significant wave height. The rankings for each input variable were combined, and an index value calculated for 500-meter grid cells covering the park. The CVI highlights those regions where the physical effects of sea-level rise might be the greatest. This approach combines the coastal system's susceptibility to change with its natural ability to adapt to changing environmental conditions, yielding a quantitative, although relative, measure of the park's natural vulnerability to the effects of sea-level rise. The CVI provides an objective technique for evaluation and long-term planning by scientists and park managers. Kaloko-Honokohau National Historical Park consists of carbonate sand beaches, coral rubble, rocky shoreline, and mangrove wetland areas. The areas within Kaloko-Honokohau National Historical Park that are likely to be most vulnerable to sea-level rise based on this analysis are areas of unconsolidated sediment and highest wave energy.

Introduction

The National Park Service (NPS) is responsible for managing nearly 12,000 km (7,500 miles) of shoreline along oceans and lakes. In 2001, the U.S. Geological Survey (USGS), in partnership with the NPS Geologic Resources Division, began conducting hazard assessments of future sea-level change by creating maps to assist NPS in managing its valuable coastal resources. This report presents the results of a vulnerability assessment for Kaloko-Honokohau National Historical Park, highlighting areas that are likely to be most affected by future sea-level rise.

Global sea level has risen approximately 18 centimeters (7.1 inches) in the past century (Douglas, 1997). Climate models predict an additional rise of 48 cm (18.9 in) by 2100 (IPCC, 2002), which is more than double the rate of rise for the 20th century. Potential coastal impacts of sea-level rise include shoreline erosion, saltwater intrusion into groundwater aquifers, inundation of wetlands and estuaries, and threats to cultural and historic resources as well as infrastructure. Predicted accelerated global sea-level rise has generated a need to determine the likely response of a coastline to sea-level rise for planning and management purposes. However, an accurate and quantitative approach to predicting coastal change is difficult to establish. Even the types of data necessary to predict shoreline response are the subject of scientific debate. A number of predictive approaches have been proposed (National Research Council, 1990 and 1995), including:

1. extrapolation of historical data (e.g., coastal erosion rates),
2. static inundation modeling,
3. application of a simple geometric model (e.g., the Bruun Rule),
4. application of a sediment dynamics/budget model, or
5. Monte Carlo (probabilistic) simulation based on parameterized physical forcing variables.

However, each of these approaches has inadequacies or can be invalid for certain applications (National Research Council, 1990). Additionally, coastal response to sea-level change is further complicated by human modification of the natural coast such as beach nourishment projects, and engineered structures such as seawalls, revetments, groins, and jetties. Understanding how natural or modified coasts will respond to sea-level change is essential to preserving vulnerable coastal resources.

The primary challenge in predicting shoreline response to sea-level rise is quantifying the important variables that contribute to coastal evolution in a given area. In order to address the multi-faceted task of predicting sea-level rise impact, the USGS has implemented a methodology to identify areas that may be most vulnerable to future sea-level rise (see Hammar-Klose and Thieler, 2001). This technique uses different ranges of vulnerability (low to very high) to describe a coast's susceptibility to physical change as sea level rises. The vulnerability index determined here focuses on six variables that strongly influence coastal evolution:

1. Geomorphology
2. Historical shoreline change rate
3. Regional coastal slope
4. Relative sea-level change
5. Mean significant wave height
6. Mean tidal range

These variables can be divided into two groups: 1) geologic variables and 2) physical process variables. The geologic variables are geomorphology, historic shoreline change rate, and coastal slope; they account for a shoreline's relative resistance to erosion, long-term erosion/accretion trend, and its susceptibility to flooding, respectively. The physical process variables include significant wave height, tidal range, and sea-level change, all of which contribute to the inundation hazards of a particular section of coastline over time scales from hours to centuries. A relatively simple vulnerability ranking system (table 1) allows the six variables to be incorporated into an equation that produces a coastal vulnerability index (CVI). The CVI can be used by scientists and park managers to evaluate the likelihood that physical change may occur along a shoreline as sea level continues to rise. Additionally, NPS staff will be able to incorporate information provided by this vulnerability assessment technique into general management plans. However, It should be noted that the methodology used in this analysis is best suited for larger parks (greater than 20 km of shoreline) where the geologic and physical process variables differ spatially along the coastline. Because Kaloko-Honokohau NHP is relatively small compared to other parks where this methodology has been applied, readers may want to supplement data from this report with higher resolution studies where variables, such as shoreline change, wave energy, and geomorphology have been better resolved and therefore may contribute to the vulnerability of that section of coast more than is apparent in this study.

Data Ranking

Table 1 shows the six variables described in the Introduction, which include both quantitative and qualitative information. The five quantitative variables are assigned a vulnerability ranking based on their actual values, whereas the non-numerical geomorphology variable is ranked qualitatively according to the relative resistance of a given landform or lithology to erosion. Shorelines with erosion/accretion rates between -1.0 and +1.0 m/yr are ranked as being of moderate vulnerability in terms of that particular variable. Increasingly higher erosion or accretion rates are ranked as correspondingly higher or lower vulnerability. Regional coastal slopes range from very high vulnerability, <4.59 percent, to very low vulnerability at values >14.7 percent. The rate of relative sea-level change is ranked using the modern rate of eustatic rise (1.8 mm/yr) as very low vulnerability. Since this is a global or "background" rate common to all shorelines, the sea-level rise ranking reflects primarily local to regional isostatic or tectonic adjustment. Mean wave height contributions to vulnerability range from very low (<1.1 m) to very high (>2.6 m). Tidal range is ranked such that microtidal (<1 m) coasts are very high vulnerability, and macrotidal (>6 m) coasts are very low vulnerability.

The Kaloko-Honokohau National Historical Park

Kaloko-Honokohau National Historical Park (NHP) lies on Hawaii, the largest of the Hawaiian Islands, in an area just north of the Kailua-Kona coast (fig. 1). The oldest Hawaiian Island, Kauai, began forming about 5 million years ago and the youngest island, Hawaii, continues to grow today (Hazlett and Hyndman, 1996). For more information and links to Hawaii geology see http://geology.wr.usgs.gov/stateinfo/HI.html. The coastal areas in Kaloko-Honokohau NHP consist mostly of large, dry, rugged lava flows some of which are just over a thousand years old (Wolfe and Morris, 1996). The shoreline is primarily rocky basalt with storm beach deposits (60%) which are locally interrupted by sections of intertidal beach or fishponds (Hapke and others, 2005). Most of the coast is paralleled by shallow fringing reefs, which are vulnerable to not only expected sea-level rise, but also to storm damage, increased water temperatures, and land runoff and sedimentation (for more information on coral reefs in the Hawaiian Islands see: USGS Pacific Coral Reefs and Hawaii Coral Reef Network). Because coral reef systems need light to grow, sea-level rise could result in death to ecosystems at the depth limit of light penetration (Hoegh-Guldberg, 1999). Some scientists would argue that sea-level rise alone could result in increased coral growth by providing more 'headroom' for ecosystems that have reached their limit of vertical growth. Although this is a possible scenario, sea-level rise is likely to be accompanied by increased water temperatures and changes in salinity, which could further damage or stress coral ecosystems. Further, slow growing corals may not be able to keep pace with potential increases in the rate of sea-level rise (Hoegh-Guldberg 1999; Graus, 1998). In addition to the many natural and biologic resources along the Kona coast, there are also significant cultural resources within the park such as a historical Hawaiian settlement with fishponds, petroglyphs, and religious sites (heiau).

Methodology

In order to develop a database for park-wide assessment of coastal vulnerability, data for each of the six variables mentioned above were gathered from state and federal agencies (table 2).

The database is based on that used by Thieler and Hammar-Klose (1999) and loosely follows an earlier database developed by Gornitz and White (1992). A comparable assessment of the sensitivity of the Canadian coast to sea-level rise is presented by Shaw and others (1998).

The database was constructed using a 1:24,000-scale shoreline for Kaloko-Honokohau obtained from the Hawaii Statewide GIS Program. Data for each of the six variables (geomorphology, shoreline change, coastal slope, relative sea-level rise, significant wave height, and tidal range) were added to the shoreline attribute table using a 500-meter grid (fig. 2). Next each variable in each grid cell was assigned a vulnerability value from 1-5 (1; very low vulnerability, 5; very high vulnerability) based on the potential magnitude of its contribution to physical changes on the coast as sea level rises (table 1).

Geologic Variables

The **geomorphology** variable expresses the relative erodibility of different landform types (table 1). These data were derived from 2000 vertical aerial photography provided by NOAA's Center for Coastal Monitoring and Assessment's Benthic Habitat Mapping of the Main Hawaiian Islands (table 2) (Coyne and others, 2003). In addition, field visits were made within accessible locations of the park to verify the geomorphologic classification (fig. 3 and fig. 4 A-C). The coastal geomorphology of Kaloko-Honokohau NHP includes moderate vulnerability rocky coastline backed by carbonate storm beaches, high vulnerability coral rubble areas, and very high vulnerability mangrove and sand beaches ((fig. 3 and fig. 4 A-C).

Shoreline erosion and accretion rates for Kaloko-Honokohau NHP were available from USGS at 50 m intervals (transects) along the coast (table 2) (Hapke written communication, 2005). The change rates for each transect within a 500-meter grid cell were averaged to determine the shoreline change value used here, with positive numbers indicating accretion and negative numbers indicating erosion. Shoreline change rates in Kaloko-Honokohau all fell within +1 to -1 m/yr (moderate vulnerability) (fig. 5). For higher resolution shoreline change data (not averaged over a 500-meter section of coast) see Hapke and others (2005).

Regional coastal slope is an indication of the relative vulnerability to inundation and the potential rapidity of shoreline retreat because low-sloping coastal regions should retreat faster than steeper regions (Pilkey and Davis, 1987). The regional slope of the park was calculated from a grid of topographic and bathymetric elevations extending 5 km landward and seaward of the shoreline. Elevation data were obtained from the National Geophysical Data Center (NGDC) as gridded topographic and bathymetric elevations at 0.1-meter vertical resolution for 90-meter (table 2) cells. Regional coastal slopes for Kaloko-Honokohau National Historical Park fall within the very low vulnerability category (> 14.7%) (fig. 6).

Physical Process Variables

The **relative sea-level change** variable is derived from the change in annual mean water elevation over time as measured at tide gauge stations along the coast. The rate of sea-level rise for Kaloko-Honokohau is 3.36 +/- 0.21 mm/yr based on 73 years of data at Hilo, Hawaii (table 2) (Zervas, 2001). This variable inherently includes both eustatic sea-level rise as well as regional sea-level rise due to isostatic and tectonic adjustments of the land surface. Relative sea-level change data are a historical record, and thus portray only the recent sea-level trend (< 150 years). Relative sea-level rise for the big island of Hawaii falls in the very high vulnerability category based on water elevation data at Hilo (fig. 7).

Mean significant wave height is used here as a proxy for wave energy which drives coastal sediment transport. Wave energy is directly related to wave height

$$E = 1/8\,\rho\, gH^2$$

where E is energy density, H is wave height, ρ is water density and g is acceleration due to gravity. Thus, the ability to mobilize and transport coastal sediments is a function of wave height squared. In this report, we use historical mean significant wave height data for the period 1984-2001 obtained from the National Data Buoy Center (table 2) (NDBC). Buoy station 51002 located 215 nautical miles south-southwest of Hilo, HI was used for the mean significant wave heights for Kaloko-Honokohau. The Atlas of Natural Hazards in the Hawaiian Coastal Zone (Fletcher and others, 2002) was also used to verify wave heights within the park. The open coast is at high vulnerability with respect to wave heights, however, inside Honokohau Harbor mean significant wave height is low to very low vulnerability (fig. 8).

Tidal range is linked to both permanent and episodic inundation hazards. Tide range data were obtained from a NOAA/NOS published benchmark in Kawaihae, Hawaii and from a USGS Circulation study within the park (table 2) (Storlazzi and Presto, 2005). Mean tidal range here is 0.446 m; therefore Kaloko-Honokohau National Historical Park is classified as very high vulnerability (< 1meter) with respect to tidal range (fig. 9).

Calculating the Vulnerability Index

The coastal vulnerability index presented here is the same as that used in Thieler and Hammar-Klose (1999) and is similar to that used in Gornitz and others (1994), as well as to the sensitivity index employed by Shaw and others (1998). The CVI allows the six variables to be related in a quantifiable manner that expresses the relative vulnerability of the coast to physical changes due to future sea-level rise. This method yields numerical data that cannot be equated directly with particular physical effects. It does, however, highlight areas where the various effects of sea-level rise may be the greatest. Once each section of coastline is assigned a vulnerability value for each specific data variable, the coastal vulnerability index is calculated as the square root of the product of the ranked variables divided by the total number of variables:

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

where, a = geomorphology, b = shoreline erosion/accretion rate, c = coastal slope, d =relative sea-level rise rate, e = mean significant wave height, and f = mean tide range. The calculated CVI value is then divided into quartile ranges to highlight different vulnerabilities within the park. The numeric CVI values that correspond to a specific vulnerability index (low - very high) are unique to Kaloko-Honokohau NHP, and are not comparable to CVI ranges in other parks where the CVI has been employed (i.e., very high vulnerability means the same among parks; it's the numeric values that differ, such that a numeric value that equals very high vulnerability in one park may equal moderate vulnerability in another). To compare vulnerability among coastal parks, the national-scale studies should be used (Thieler and Hammar-Klose, 1999, 2000a, and 2000b). This approach best describes and highlights the vulnerability specific to each park.

Results

The CVI values calculated for Kaloko-Honokohau range from 7.91 to 15.81. The mean CVI value is 12.4; the mode and the median are 12.25. The standard deviation is 2.4. The 25th, 50th, and 75th percentiles are 11.0, 13.0 and 15.0, respectively.

Figure 10 shows a map of the coastal vulnerability index for Kaloko-Honokohau National Historical Park. The CVI scores are divided into low, moderate, high, and very high-vulnerability categories based on the quartile ranges and visual inspection of the data. CVI values below 11.0 are assigned to the low vulnerability category. Values from 11.0 to 13.0 are considered moderate vulnerability. High-vulnerability values lie between 13.01 and 15.0. CVI values above15.0 are classified as very high vulnerability. Figure 11 shows the percentage of Kaloko-Honokohau NHP shoreline in each vulnerability category. Eight kilometers of shoreline along Kaloko-Honokohau NHP were evaluated in this assessment. Of this, nineteen percent of the mapped shoreline is classified as being at very high vulnerability due to future sea-level rise. Twenty-five percent is classified as high vulnerability, thirty-one percent as moderate vulnerability, and twenty-five percent as low vulnerability. The methodology for CVI analysis is best suited for parks with larger shoreline extents and greater geologic and physical process variability than Kaloko-Honokohau NHP. Results presented here should be used in conjunction with higher resolution studies for park management planning.

Discussion

Kaloko-Honokohau NHP is a small park; therefore most of the variables that determine the coastal vulnerability index vary little within the park boundary. The value of the relative sea-level rise variable is constant at very high vulnerability for the entire study area. The tidal range is very high vulnerability (< 1 m) for all of Kaloko-Honokohau NHP. Vulnerability assessment based on shoreline change is moderate vulnerability. Regional coastal slope is very low for all of Kaloko-Honokohau NHP.

Mean significant wave height (very low to high vulnerability) and geomorphology are the only variables that vary spatially within the park. Geomorphology includes very high vulnerability sandy beach shoreline, high vulnerability coral rubble and rock and sand beaches, and moderate vulnerability rock shoreline with storm deposits (fig. 3 and fig. 4 A-C).

The most influential variables in the CVI are geomorphology and mean significant wave height; therefore they may be considered the dominant factors controlling how this park will evolve as sea level rises. The methodology for this coastal vulnerability assessment is best suited for parks larger than Kaloko-Honokohau NHP, however the results presented here are useful for park planning purposes in conjunction with higher resolution studies.

Conclusions

The coastal vulnerability index (CVI) provides insight into the relative potential of coastal change due to future sea-level rise. The maps and data presented here can be viewed in at least two ways:

1. as an indication of where physical changes are most likely to occur as sea level continues to rise; and

2. as a planning tool for Kaloko-Honokohau National Historical Park in conjunction with other park research.

As ranked in this study, geomorphology and mean significant wave height are the most important variables in determining the spatial variability of the CVI for Kaloko-Honokohau NHP. Tidal range, relative sea-level rise, historic shoreline change, and regional coastal slope, as measured in this study, do not contribute to the spatial variability in the coastal vulnerability index.

Kaloko-Honokohau National Historical Park preserves a dynamic natural environment, which must be understood in order to be managed properly. The CVI is one way that park managers can assess objectively the natural factors that contribute to the evolution of the coastal zone, and thus how the park may evolve in the future.

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Figures

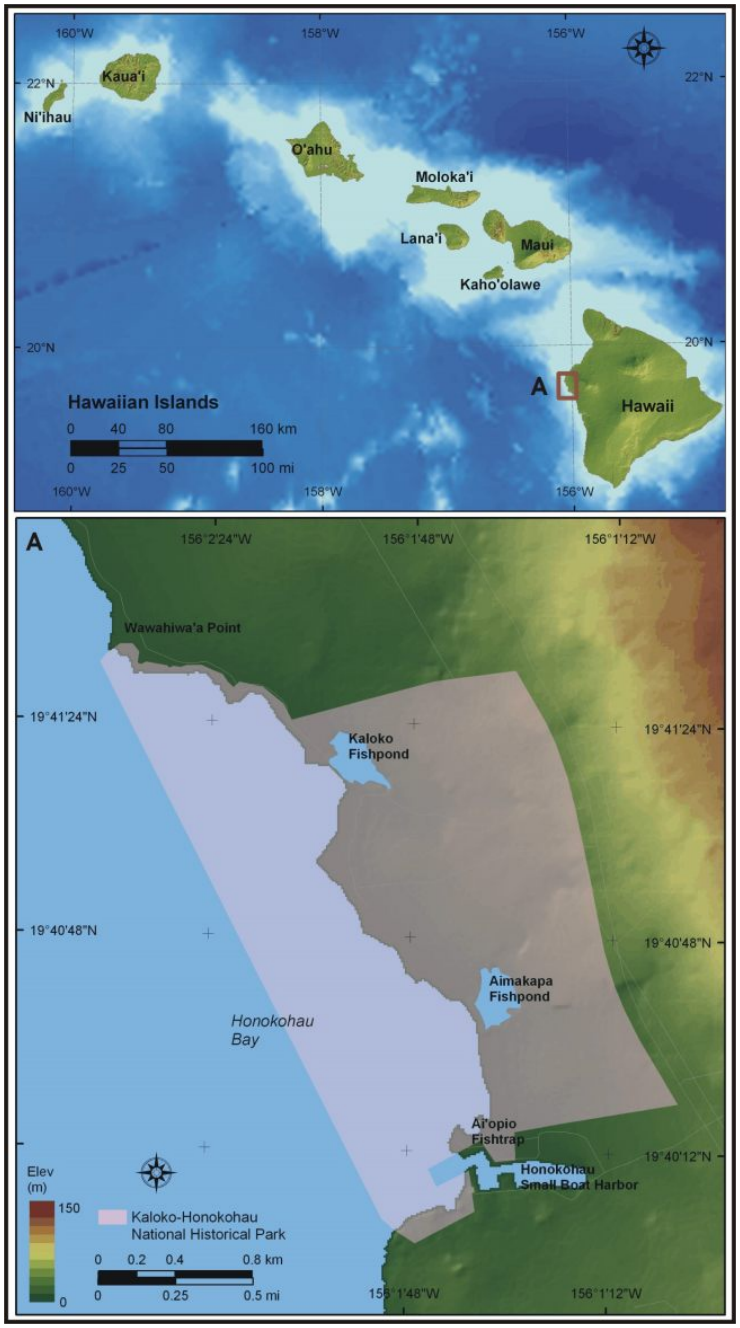

Figure 1. Location of Kaloko-Honokohau National Historical Park, Hawaii.

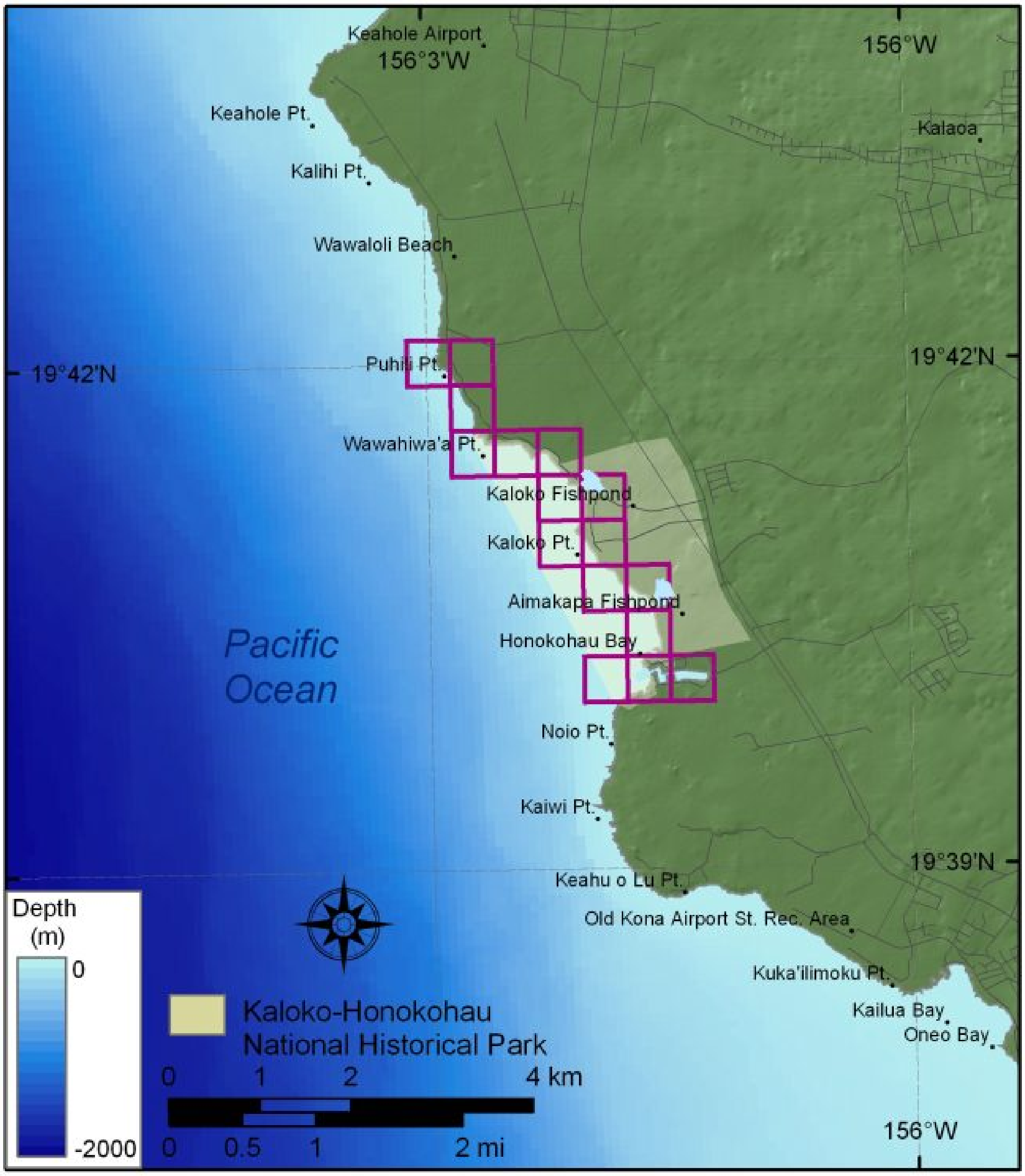

Figure 2. Shoreline grid for Kaloko-Honokohau NHP. Each cell is approximately 500 meters of shoreline and represents a shoreline segment for which each variable is defined.

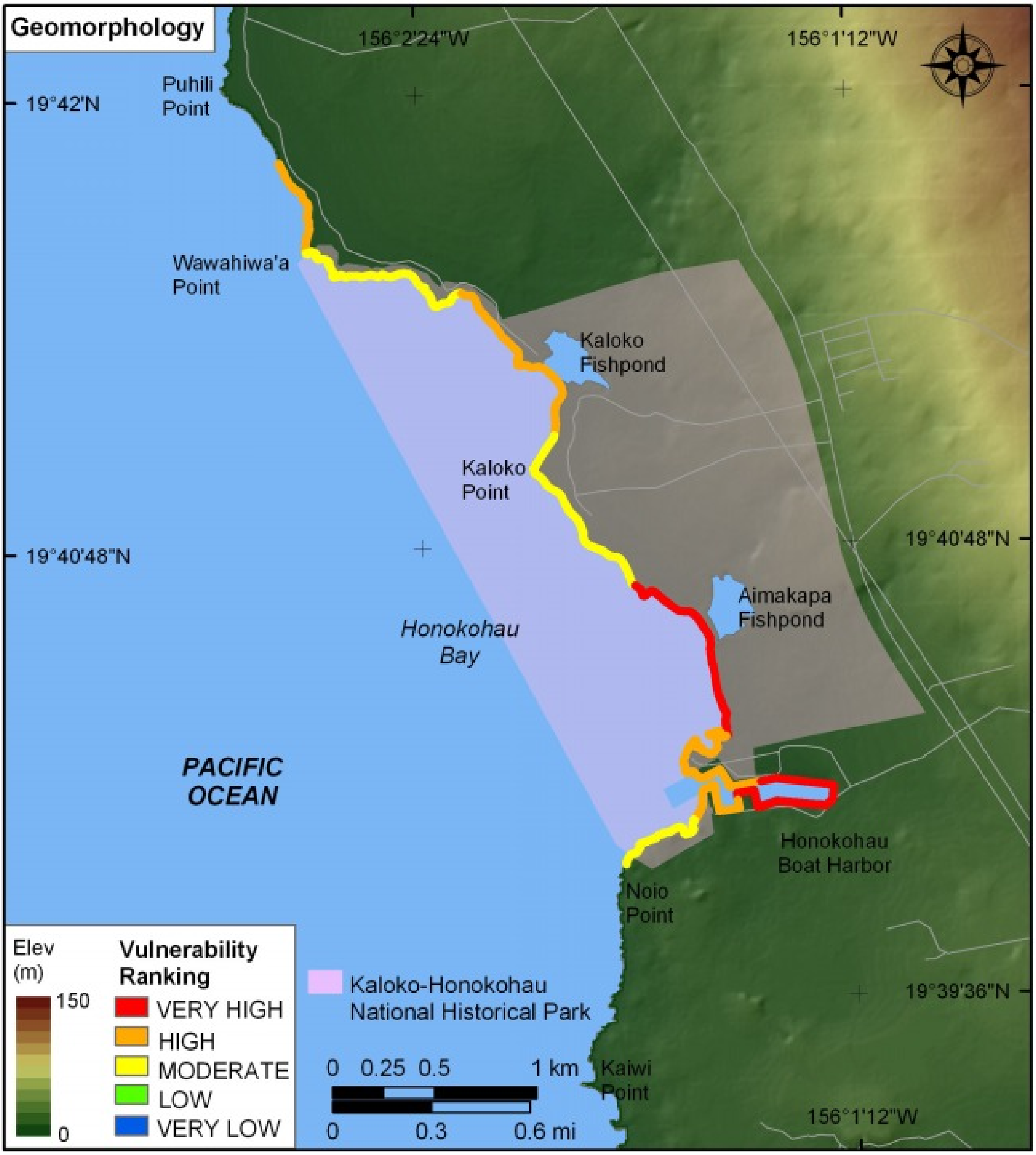

Figure 3. Coastal Geomorphology for Kaloko-Honokohau National Historical Park. The colored shoreline represents the variations in coastal geomorphology within the park. The very high vulnerability geomorphology is mostly sand beaches or mangrove areas. High vulnerability geomorphology includes gravel or coral rubble beaches with basalt platforms outcropping. Moderate vulnerability geomorphology consists of primarily rocky platforms with thin layers of storm deposits.

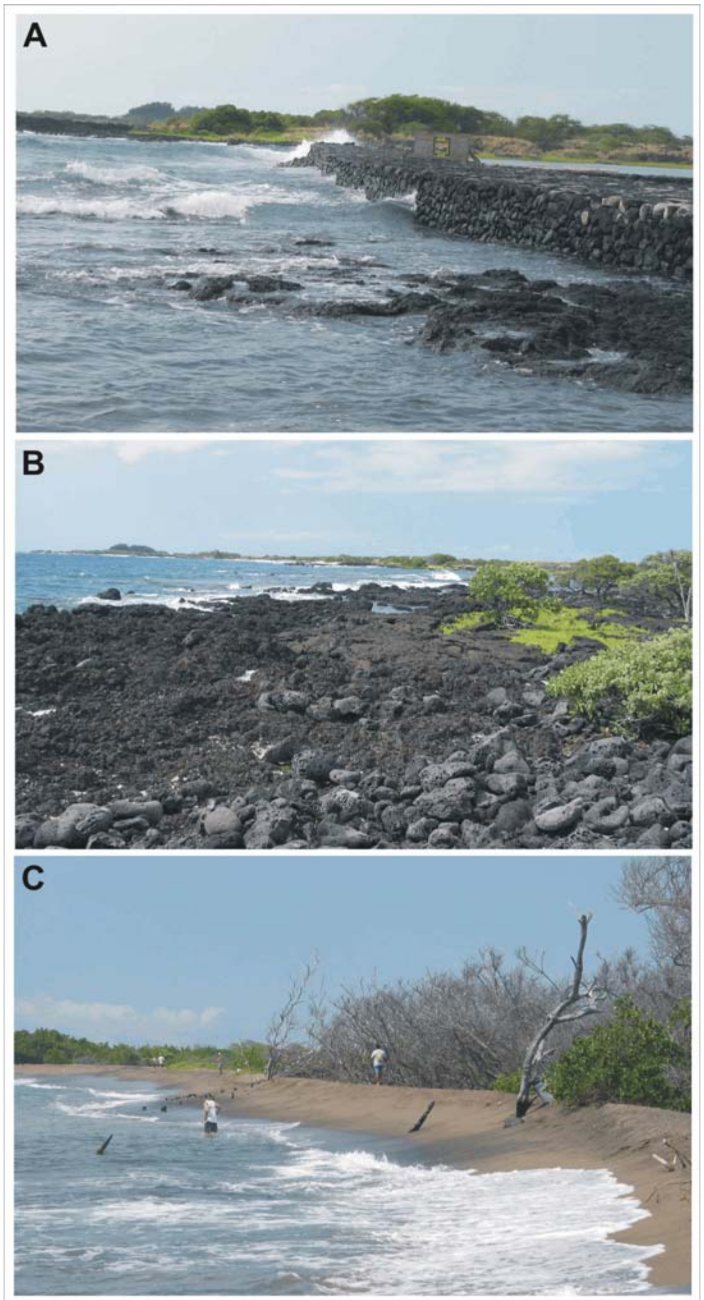

Figure 4. Photos of different geomorphologic settings within Kaloko-Honokohau National Historical Park. A) A view looking north from the Kaloko Fishpond, this area is ranked as high vulnerability with respect to geomorphology due to manmade structures and rubble beaches. B) The rocky shoreline at Kaloko Point is ranked as moderate vulnerability. C) The beach fronting the Aimakapa Fishpond is ranked as very high vulnerability with respect to geomorphology.

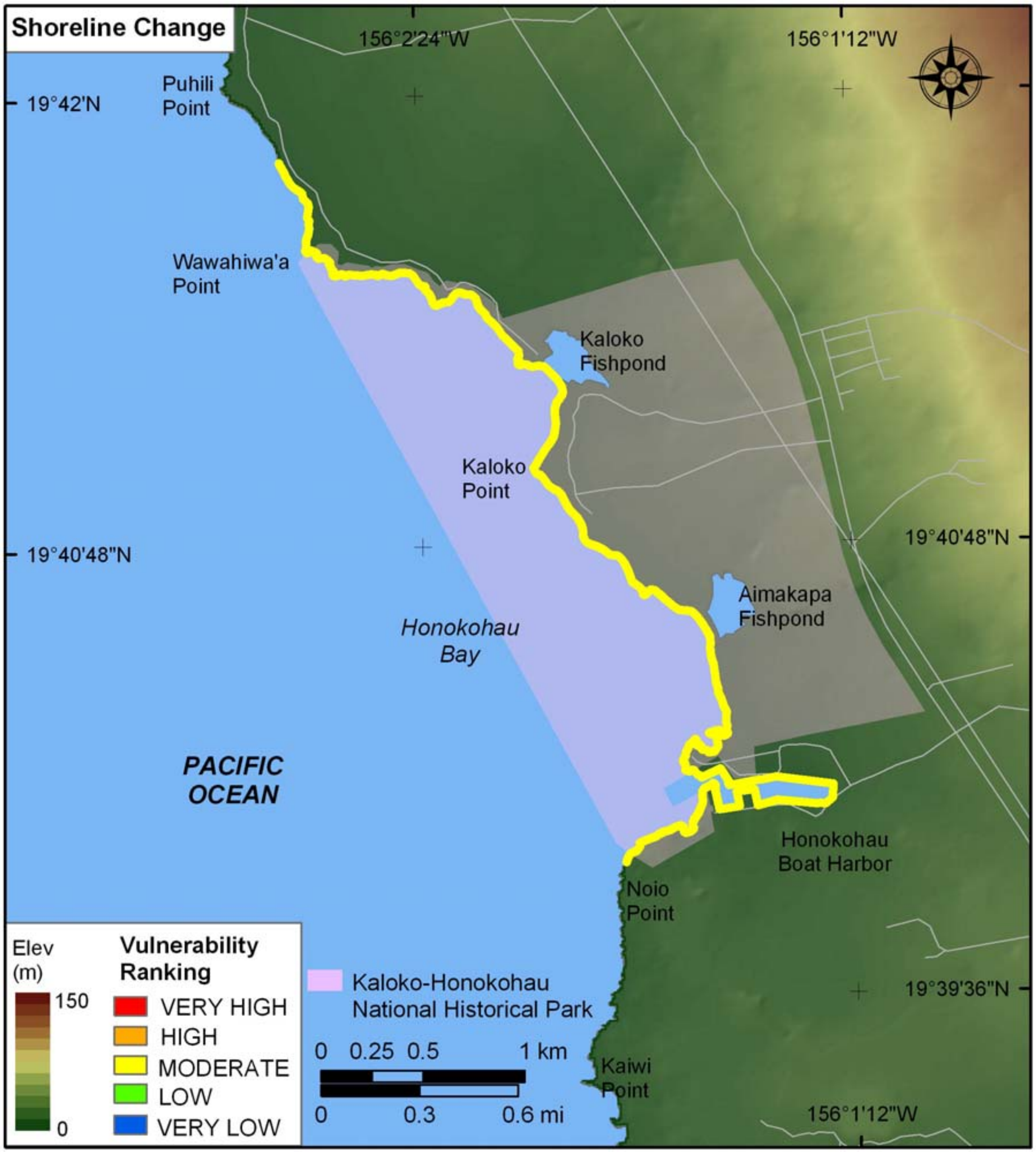

Figure 5. Shoreline change rates for Kaloko-Honokohau National Historical Park. The colored shoreline represents the rate of shoreline erosion or accretion. All of Kaloko-Honokohau National Historical Park is moderate vulnerability (-1m/yr - +1m/yr).

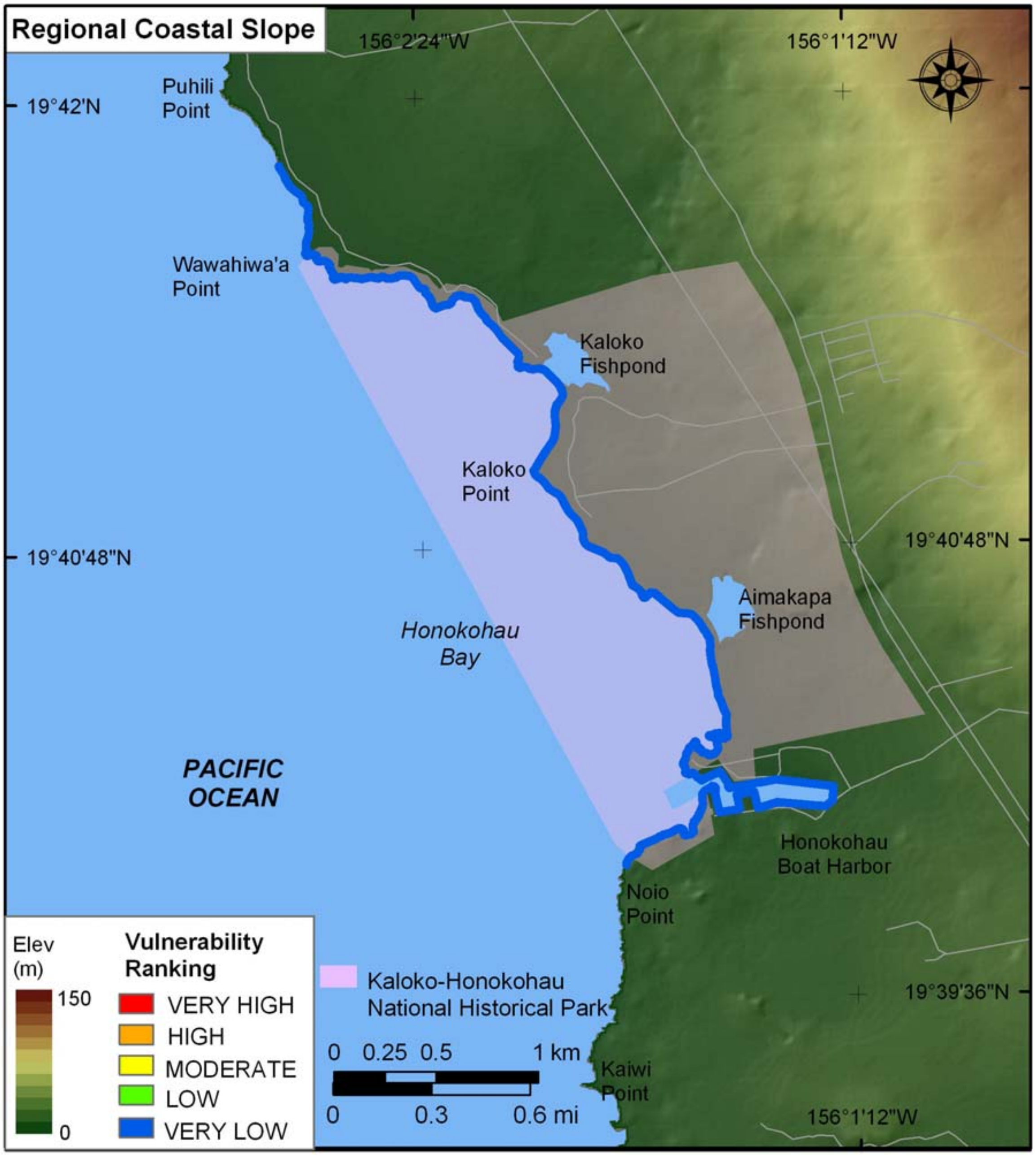

Figure 6. Regional coastal slope for Kaloko-Honokohau National Historical Park. The colored shoreline represents the regional slope of the land, 5 km landward and seaward of the shoreline. All of Kaloko-Honokohau is classified as very low vulnerability with respect to coastal slope.

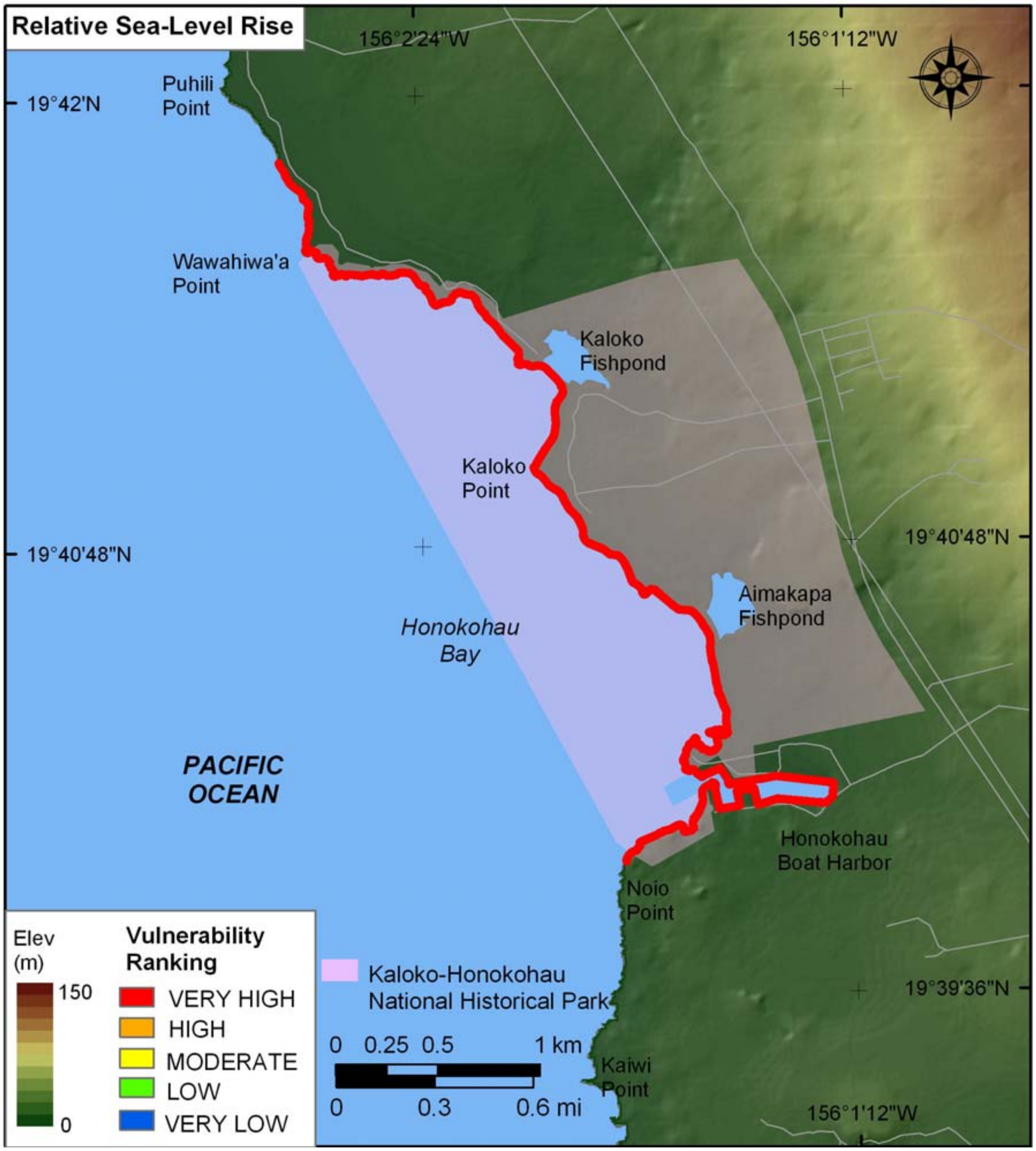

Figure 7. Rate of relative sea-level rise for Kaloko-Honokohau National Historical Park. The colored shoreline represents the ranked rate of rise at Hilo, HI. All of Kaloko-Honokohau National Historical Park is ranked as very high vulnerability with respect to relative sea-level rise.

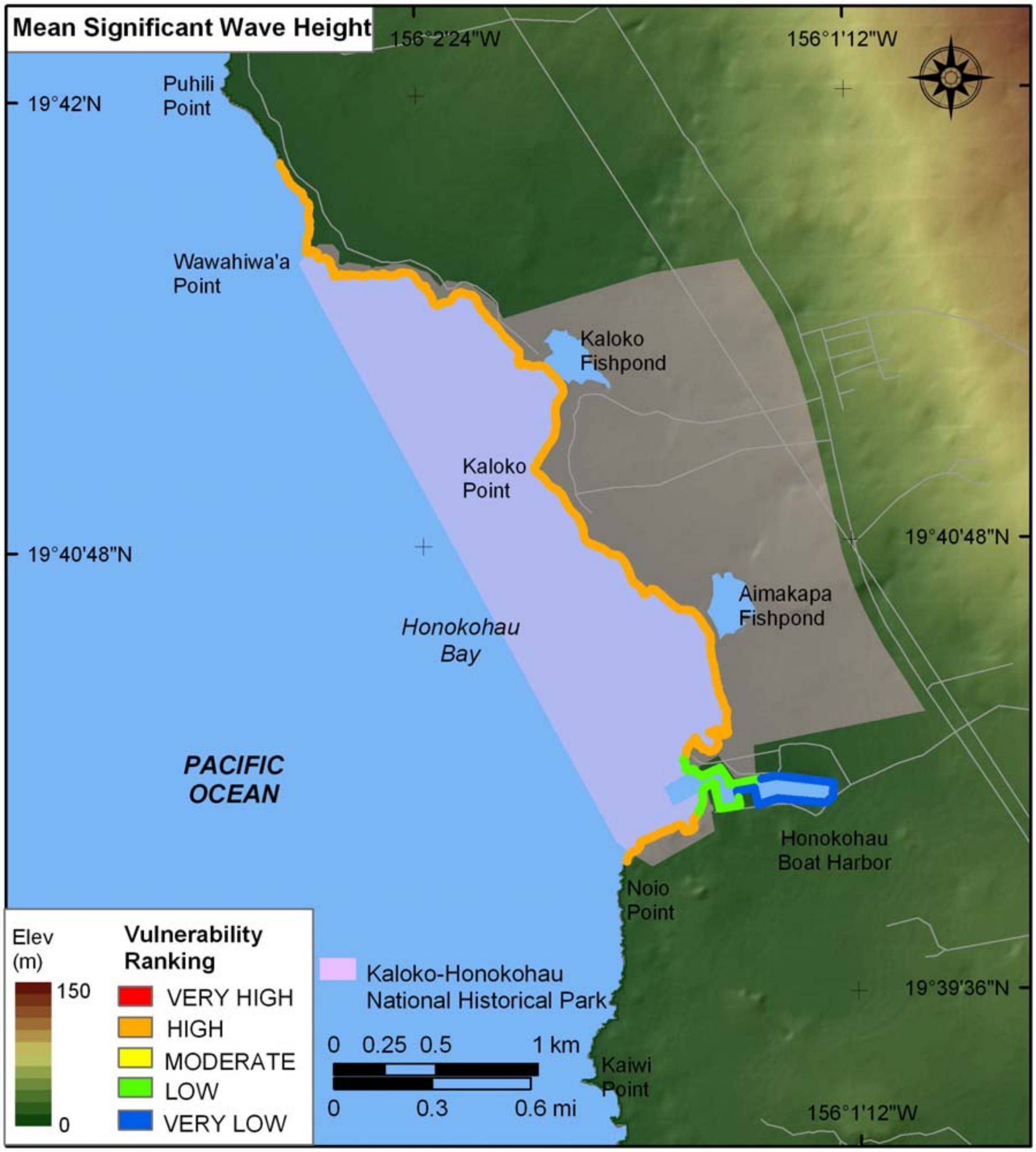

Figure 8. Mean significant wave heights for Kaloko-Honokohau National Historical Park based on NDBC data. The colored shoreline represents the mean significant wave heights within the park. The open coast is high vulnerability with respect to significant wave height; the lower vulnerability areas are within the sheltered Honokohau Harbor.

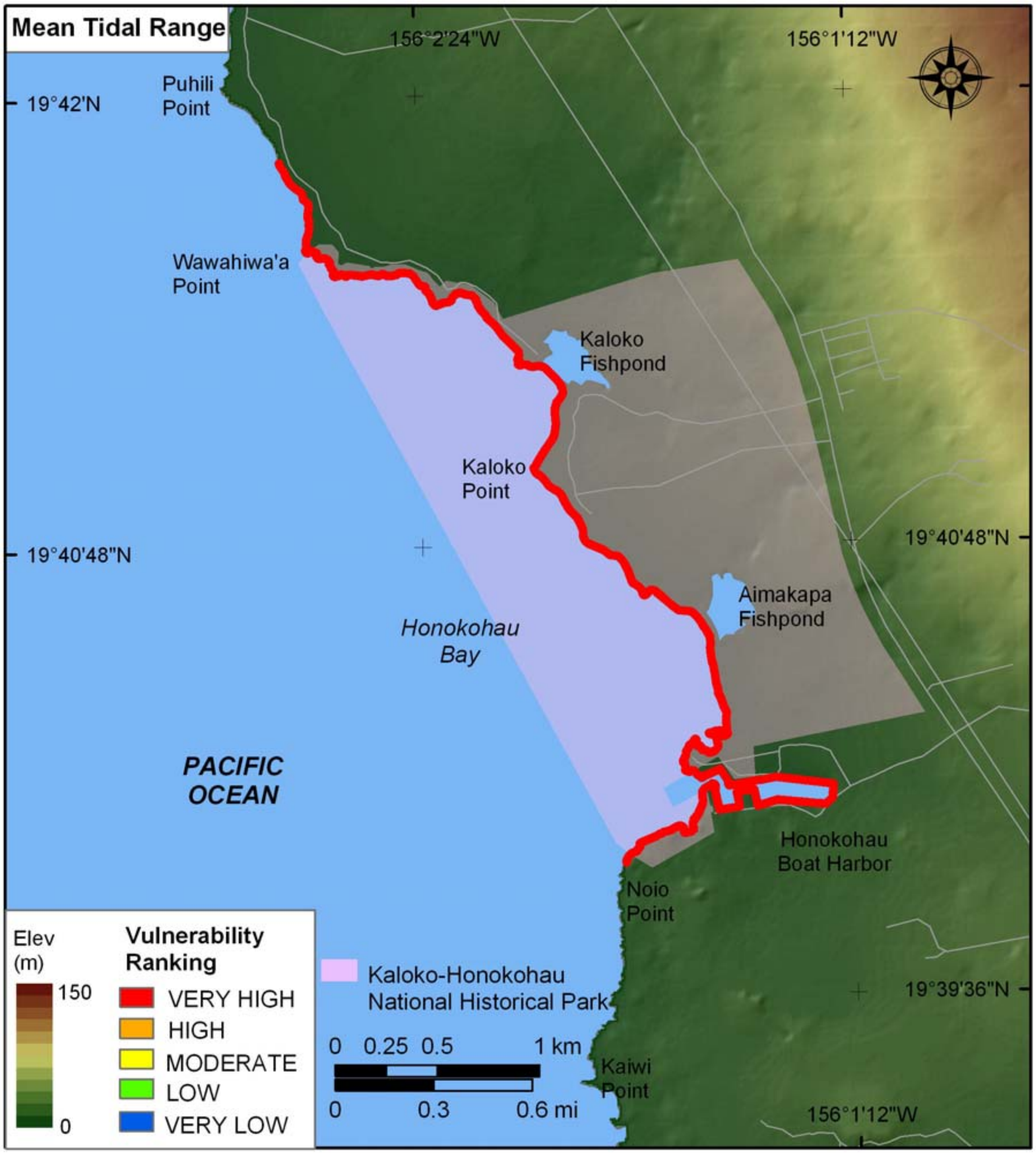

Figure 9. Mean Tidal Range for Kaloko-Honokohau National Historical Park. The colored shoreline represents the ranked mean tidal range for Kawaihae, HI. All of Kaloko-Honokohau National Historical Park is ranked as very high vulnerability with respect to tidal range.

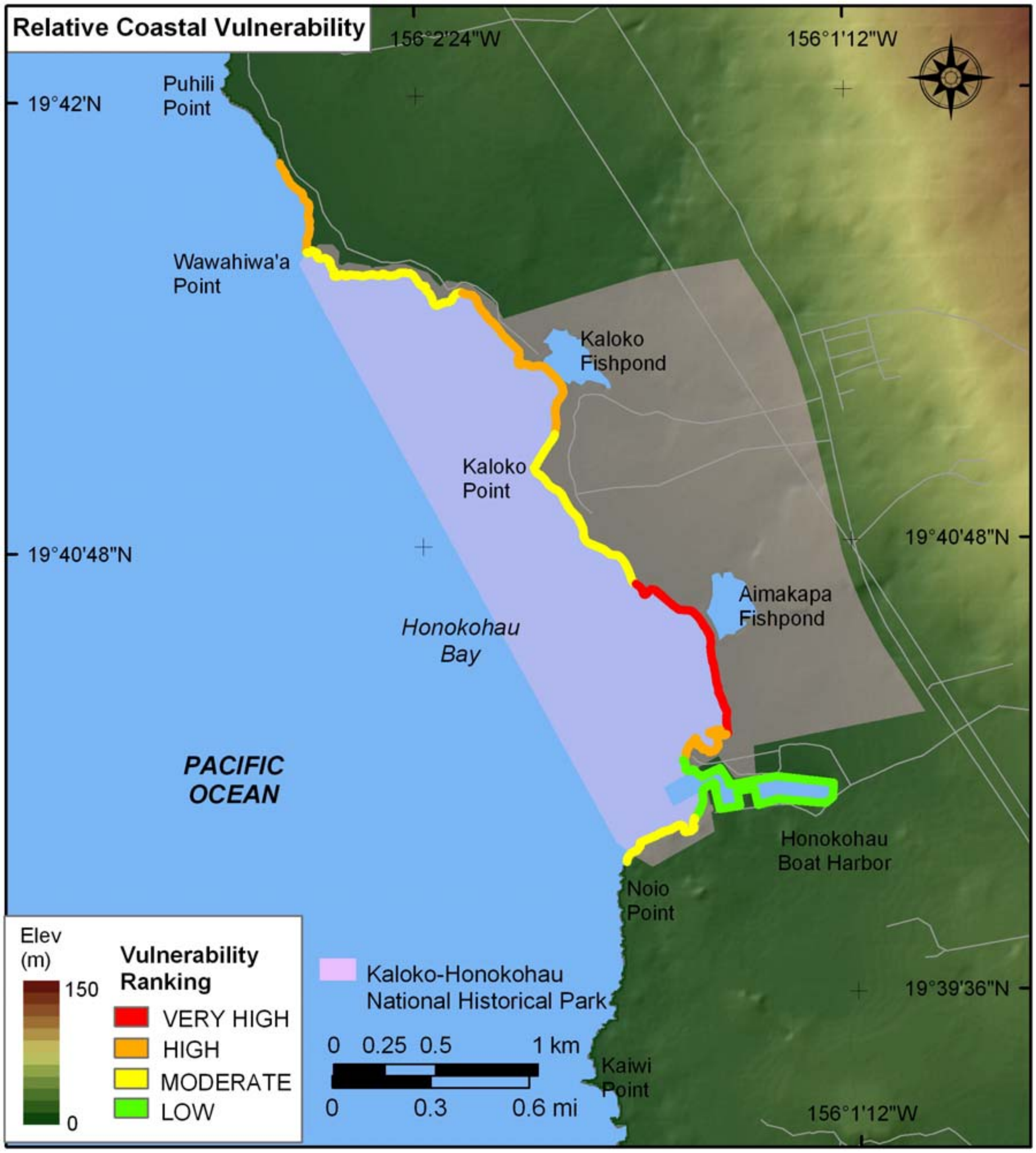

Figure 10. Relative Coastal Vulnerability for Kaloko-Honokohau National Historical Park. The colored shoreline represents the relative coastal vulnerability index (CVI) determined from the six variables. The very high vulnerability shoreline is located along sand beach fronting Aimakapa Fishpond. The low vulnerability shoreline lies within the protected area of Honokohau Harbor.

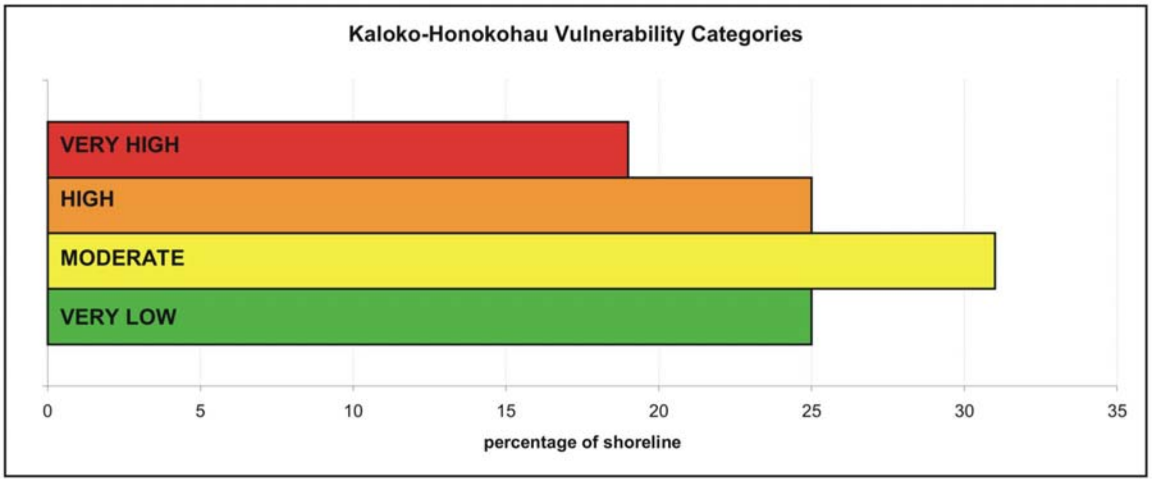

Figure 11. Percentage of Kaloko-Honokohau shoreline in each CVI category.

Tables

Table 1. Ranges for Vulnerability Ranking of Variables on the U.S. Pacific Coast.

Variable	Very Low 1	Low 2	Moderate 3	High 4	Very High 5
SHORELINE EROSION/ ACCRETION (m/yr)	> 2.0	1.0 to 2.0	-1.0 to 1.0	-2.0 to -1.0	< -2.0
COASTAL SLOPE (%)	> 14.7	10.9 - 14.65	7.75 - 10.85	4.6 - 7.7	< 4.56
RELATIVE SEA-LEVEL CHANGE (mm/yr)	< 1.8	1.8 - 2.5	2.5 - 3.0	3.0 - 3.4	> 3.4
MEAN WAVE HEIGHT (m)	< 1.1	1.1 - 1.9	2.0 - 2.24	2.25 - 2.6	> 2.6
MEAN TIDE RANGE (m)	> 6.0	4.0 - 6.0	2.0 - 4.0	1.0 - 2.0	< 1.0
SHORELINE EROSION/ ACCRETION (m/yr)	> 2.0	1.0 to 2.0	-1.0 to 1.0	-2.0 to -1.0	< -2.0

Table 2. Sources of Data

Variables	Source	URL (Not all sources are downloadable)
GEOMORPHOLOGY	1. 2000 Mosaiced aerial photography from Benthic Habitats of the Main Hawaiian Islands. U.S. National Oceanic and Atmospheric Administration. National Ocean Service, National Centers for Coastal Ocean Science, Biogeography Program. (Coyne and others, 2003)	http://biogeo.nos.noaa.gov/products/hawaii_cd/htm/data.htm
SHORELINE CHANGE RATES (m/yr)	2. Coastal Change Rates and Patterns; Kaloko-Honokohau NHP, Kona Coast, Hawai'I (Hapke, and others, 2005)	http://pubs.usgs.gov/of/2005/1069/
REGIONAL COASTAL SLOPE (%)	3. NGDC Coastal Relief Model Vol. 10	http://www.ngdc.noaa.gov/mgg/coastal/coastal.html
RELATIVE SEA-LEVEL CHANGE (mm/yr)	4. Sea level variations of the United States 1854-1999 (Zervas, 2001)	http://www.co-ops.nos.noaa.gov/publications/techrpt36doc.pdf
MEAN WAVE HEIGHT (m)	5. NOAA National Data Buoy Center 6. The Atlas of Natural Hazards in the Hawaiian Coastal Zone (Fletcher and others, 2002) 7. Coastal Circulation and Water Column Properties along Kaloko-Honokohau NHP, Hawaii (Storlazzi and Presto, 2005)	http://seaboard.ndbc.noaa.gov/ http://pubs.usgs.gov/imap/i2761/ http://pubs.usgs.gov/of/2005/1161/
MEAN TIDE RANGE (m)	8. NOAA/NOS CO-OPS Historical Water Level Station Index 9. Coastal Circulation and Water Column Properties along Kaloko-Honokohau NHP, Hawaii (Storlazzi and Presto, 2005)	http://tidesonline.nos.noaa.gov/ http://pubs.usgs.gov/of/2005/1161/