Sea level rise triggering widespread coastal hardening and environmental destruction on Hawaiian shores

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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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For my friends and family who have supported me through this project.

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Abstract

In Hawai‘i, protecting beach resources reinforces a high quality of life for residents, is critical to its tourism-based economy, and preserves an important ecosystem that is crucial for a number of endangered native species. However, narrowing and loss due to shoreline hardening continues to threaten Hawaiian beaches. Additionally, as sea level rise accelerates erosion, there may also be an acceleration of shoreline hardening across the state. Thus, modeling future beach vulnerability to hardening provides important data for developing resource management plans. We model future erosion for 0, 0.17, 0.32, 0.6, and 0.98 meters of sea level rise on the island of O‘ahu. Results show sea level rise of only 0.32 m triggers a cascade of seawall applications and that after 0.98 m of sea level rise, 49% of the shoreline could potentially harden if widespread hardening is allowed, risking sensitive beach resources. We conclude that current and near-term sea level rise, not future sea level rise, poses the greatest threat to critical habitat. We also conclude that existing coastal management does not effectively protect beaches threatened with hardening, and there is an immediate need for new policy development.

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1.0 Introduction

Beaches in Hawaiʻi possess great significance. Over time, they have served as cultural gathering spots, critical ecosystems, the target of tourists who support the economy, and importantly, an essential element in the lifestyle of residents. The value of beaches is so high, in fact, that they receive special protection under the Hawaiʻi Coastal Zone Management Act (HCZMA), a federally assisted state program that includes local (county) authority through setback and special management area (SMA) policies (HRS §§ 205A). However, the use of seawalls and other styles of shoreline hardening has led to widespread beach loss over the past half-century (Fletcher et al., 2012; Fletcher et al., 1997). While most of the shoreline hardened today was built prior to the early 1990s, and shoreline hardening has greatly decreased in recent years, sea level rise could trigger widespread coastal hardening (Romine et al., 2012).

In this paper, we apply the model of Anderson et al. (2015) to project future erosion threats and shoreline retreat on Oʻahu. To identify beaches that are threatened by hardening, we use policy criteria that trigger emergency applications for erosion mitigation by beachfront homeowners and agencies that manage parks and roads. In our model, shoreline change is simulated under four sea level scenarios defined by RCP8.5 modeling in Assessment Report 5 of the Intergovernmental Panel on Climate Change (IPCC, 2013). These scenarios span the near future to the end of the century.

Our results indicate that beaches on Oʻahu are imminently threatened with hardening, present coastal zone management has not provided effective protections, historically, and if Hawaiʻi authorities seek to protect beaches in a future characterized by accelerated sea level rise, a revised policy and management framework is necessary.

1.1 Cultural Significance

Beaches have been a vital element in the lifestyle and identity of Hawaiians from the first peoples to the modern community. In ancient times and today, Native Hawaiians (and others) utilize beaches as their primary access to the resources of the coastline and ocean for food, medicine and tools (Williams and Racoma, 1997). Recreation and cultural events then, as now, took place on beaches. It is where keiki (children) learn ocean safety, to read the clouds, winds, and waves, and to assimilate and internalize the climate and weather of their homelands.

Today, the coast is still valued by the community, as shown with the perpetuity of the HCZMA in 1977. In the development of HCZMA goals, it was recognized that conservation and enhancement of public access, open space, and the environment were the primary purpose of state and local policies. Having a connection with the ocean and environment is essential to the local and traditional way of life, as well as for the tourism economy. The HCZMA establishes this as a guiding principle.

Beaches underpin a cultural revitalization and rediscovery of Native Hawaiian ways of knowing and doing (Kikiloi, 2010). For example, the restoration of centuries-old fishponds, the practice of traditional wayfinding, traditional stories told in dance and song, resource conservation based on traditional indigenous knowledge, and others have all been re-established at the shoreline after years of abandonment.

1.2 Ecological Significance

As a habitat, beaches support species from microbes to mammals. Native coastal plants that thrive in the salty littoral environment include Scaevola taccada or Naupaka, which act as important groundcover, controlling wind and wave erosion in the subaerial and back beach areas (Rauch et al., 1993). Beach sand hosts several epifauna and infauna such as the detritivores *Ocypode ceratophthalma*, the horned ghost crab, and *Hippa pacifica*, the Pacific mole crab.

Sandy shores are also considered critical habitat for the endemic *Neomonachus schauinslandi,* the Hawaiian monk seal and the indigenous *Chelonia mydas,* the green sea turtle. The Hawaiian monk seal is recognized as endangered in the Endangered Species Act (ESA) (41 FR 51611) and by the International Union for Conservation of Nature (Littnan et al., 2015) and is protected under the Marine Mammal Protection Act (41 FR 30120) and Hawaiʻi State law (HRS §195D-4.5). The green sea turtle is considered threatened in the ESA and is protected under Hawaiʻi State laws (HRS 195D and HAR 13-124).

One of the major threats to both of these species is the loss of its terrestrial habitat, which is critical for resting and pupping or nesting (Sprague et al., 2016) (NMFS, 1998). Shoreline hardening, sea level rise, and the accelerated erosion caused by an interaction of the two, destroys sandy beach habitat (Fletcher et al., 2012). In the Hawaiian Archipelago, the majority (80% and 90% respectively) of Hawaiian monk seal and green sea turtles live in Papahānaumokuākea (Northwestern Hawaiian Islands-NWHI) while the remainder live in the Main Hawaiian Islands (MHI; Carretta et al., 2014). The NWHI consists of low-lying sandy islands on atolls that are especially vulnerable to sea level rise (Reynolds et al., 2012). Since the MHI are high volcanic islands, protecting the sandy beaches as prospective future habitat for a growing population of displaced species would potentially underpin a management plan.

1.3 Economic Significance

Idyllic white sand beaches in Hawaiʻi are sold to the world in the form of marketing campaigns that lure tourists from all points of the globe. Seeking an envisioned slice of paradise, the annual number of visitors has increased from roughly 47,000 in the 1950's, to 8.9 million people in 2016. Visitor spending that year rose just over 4 percent from the previous year, to a record $15.6 billion. Tourism is the largest single contributor to the state's gross domestic product, and in 2016, tourism represented 16.6 percent of Hawaiʻi's GDP and 23.4 percent of collected state taxes (Hawaiʻi DBEDT, 2018). Shoreline-centered goods and services, such as lodging, beach and ocean recreation, surf competitions, meals, shopping, beach-themed products, and many other related expenditures, sum to large amounts of money that flow into every community in the state. Protecting the beaches of Hawaiʻi is, therefore, central to protecting the local economy.

1.4 Coastal Management

On the island of Oʻahu (as elsewhere in Hawaiʻi), beaches are divided into three jurisdictions. The Federal government regulates the ocean, the State under the Conservation District manages submerged areas out to 3 miles and the shoreline, which is considered a public trust (King v. Oʻahu Railway & Land CO., 11 Haw. 711, 1899), and the City and County of Honolulu regulates the land above the shoreline. The shoreline is an administrative and property boundary defined as the annual highest reach of the waves. Its location is typically located by a debris line or other evidence of wave run-up (HCZMA, Haw. Rev. Stat. Ch. 205A).

The shoreline also determines the seaward boundary for private property ownership (In re Ashford, 50 Haw. 314, 440 P.2d 76 (1968)). As identified in the recent opinion of the Attorney General of Hawai'i (Attorney General Opinion 2017-01, 2017), the shoreline also marks the position of state landownership and as the shoreline shifts landward due to erosion and/or sea level rise, state ownership likewise shifts, without the need for private owner compensation.

Landward of the shoreline, the CZMP defines a minimum 20 ft construction prohibition zone, which can be increased by counties. Within this area, no construction is allowed. However, shoreline hardening can be allowed within the setback under a hardship exemption in state and county policies.

1.4.1 State Exemption

Shoreline hardening is any shore-parallel structure built along the coast to prevent beach erosion, excluding offshore structures like breakwalls (Romine et al., 2012). In areas that experience erosion, owners want to protect their land and historically have done so with seawalls. While the State of Hawaiʻi discourages coastal hardening, private owners on Oʻahu can use HAR § 13-5-35 to apply for emergency temporary shoreline protection if their habitable structure is within 20 ft (6.1 m) of the actively eroding shoreline (HAR § 13-5-35). At this point, properties are considered "imminently threatened," and owners are qualified to apply for an emergency permit to protect (including hardening) their shoreline (HAR § 13-5-35). Technically, private owners can apply for a seawall at any time, but in practice the emergency permit is a first step towards hardening or other long-term solutions. HAR § 13-5-35 states that "These actions shall be temporary in nature to the extent that the threat to public health, safety, and welfare, including natural resources, is alleviated (e.g., erosion control, rock fall mitigation)." However, hardened coastal shorelines are hardly removed.

1.4.2 County Exemption

Each county varies with shoreline hardening exemptions. The City and County (C&C) under the Revised Ordinances of Honolulu (ROH) have also committed to protecting and preserving the beaches of Hawaiʻi. Chapter 23 states that C&C prioritizes protecting the natural shoreline as the primary policy, and a secondary policy is reducing hazards (ROH 23-1.2). Both of these actions are achievable by retreating development away from the shoreline. Similar to the state law, development is prohibited within the shoreline setback area unless given a variance (Cox et al., 1975). A variance may be allowed if hardship for the property owner is proven. The hardship clause states, "Private facilities or improvements that may artificially fix the shoreline, but only if hardship is likely to be caused by shoreline erosion and conditions are imposed prohibiting any such structure seaward of the existing shoreline unless it is clearly in the public interest." Shoreline hardening may be granted by C&C through this clause.

1.4.3 Other Exemptions

Other beachfront developments such as transportation, military, and beach park areas have different exemptions and processes that each follow. HRS §13-5-35 states that the state emergency permit rules "shall not be applicable to an agency of the county, state, or federal government, or an independent non-governmental regulated public utility conducting repair, maintenance, or operation for a public purpose use." The agency is only required to report to the department within 30 days of the emergency repair. The Department of Transportation harden shores after requesting emergency waiver proclamations from the governor because of threat to critical infrastructure.

1.5 Shoreline Hardening

Research has shown that hardening a retreating shoreline results in beach narrowing and loss (Fletcher et al., 1997; Romine and Fletcher, 2012). Based on analysis ending between 2005 to 2007, 58 to 60% of O'ahu's sandy shoreline is in a state of chronic erosion. Where the adjacent upland is developed, this length is vulnerable to hardening and beach loss (Fletcher et al., 2012). Romine et al. (2012) found in a study of O'ahu beaches, that over an 80-year period average beach width decreased by 11+/- 4% and nearly all (95%) beach loss was fronting hardened coasts. Among hardened beach sections, they found 72% of beaches were degraded, which included 43% narrowed (28% significantly) and 29% (8.6 km) completely lost to erosion. Beaches fronting coastal hardening narrowed by 36+/-5% or 0.10+/-0.03 m/year, on average. In comparison, beach widths along unhardened coasts were relatively stable with slightly more than half (53%) experiencing any form of degradation. The flanking phenomenon (Komar and

McDougal, 1988), where neighboring shores experience accelerated erosion due to adjacent hardening, was also observed (Romine and Fletcher, 2012). Flanking is the primary reason why the first seawall on a beach eventually leads to a proliferation of seawalls and loss of long sandy segments of shoreline.

Hardening a shoreline not only affects the shape of the beach but also its cultural, ecological, and economical functions. Beach narrowing and loss renders the shoreline hazardous or inaccessible to fisherman and visitors. Beach loss fundamentally changes the substrate, extinguishing the natural ecology, and restricting habitat for native species (Dugan et al., 2008). It also results in decreasing economic value (Pendleton et al., 2012).

1.6 Sea Level Rise

In 2013, the Intergovernmental Panel on Climate Change (IPCC) projected approximately 1 m of global mean sea level rise by 2100 in the most extreme modeling scenario (Church et al., 2013). In their most extreme scenario, the National Oceanic and Atmospheric Administration (NOAA) projected an increase of 2.5 m by the end of the century and 1 m of global mean sea level rise in 2065, 35 years earlier than IPCC projections (Sweet et al., 2017). NOAA also projects that Hawai'i is expected to experience sea level rise that is higher than the global mean (Sweet et al., 2017).

Sea level rise has been shown to be an important factor in historical erosion rates, showing more geographically extensive erosion, and higher average rates of erosion, where the rate of sea level rise is higher (Romine et al. 2013). Romine et al. (2013) compared the shoreline change rates of O‘ahu to Maui, a neighbor island that experiences 65% higher rates of local sea level rise. They found that both the percent of beaches eroding and the average shoreline change rate on Maui were significantly higher than on O‘ahu. It was concluded that for historical shoreline change studies, sea level rise is an important factor.

1.7 Study Area

The study area is O‘ahu (Figure 1), the third largest island in the state of Hawai‘i formed by two shield volcanoes, the Wai‘anae and Ko‘olau mountain range (Macdonald et al., 1983). There are approximately 1.4 million people in the state of Hawai‘i, and O‘ahu holds 69% of that population (DBET, 2017). With the highest population and development occurring on all segments of the shoreline, the coastal pressure on O‘ahu is greater than the other islands, making it a priority study site (Fletcher et al., 2010).

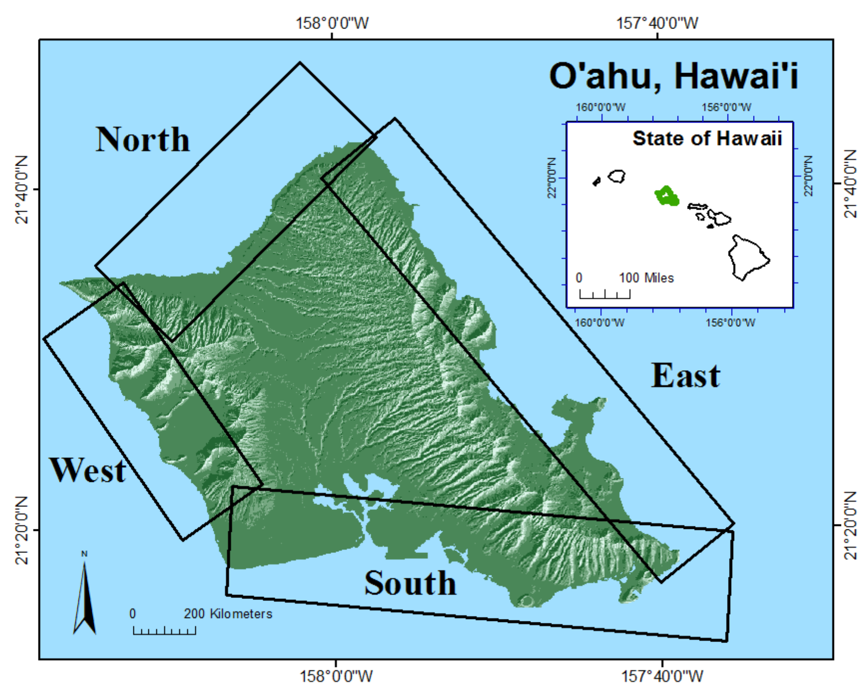

Figure 1. Map of study area and shoreline segments.

The study focuses on the sandy shoreline of O‘ahu utilizing aerial photos and maps as early as 1910. Beach sand consists mainly of calcareous sediment from nearby reefs (Harney et al., 2000) mixed with smaller amounts of volcanoclastic sediments delivered through watersheds. The average grain size is medium sand; however, beaches range from fine to coarse sand (Fletcher et al., 2012). In general beach sand is finer during the summer and coarser during the winter (Fletcher et al., 2012).

The shape of the beach will change seasonally, with extreme events, and with long-term trends of both erosion and accretion (Norcross et al., 2003). Reef morphology, wind, waves and current are the major factors influencing short-term shoreline sediment dynamics (Moberly and Chamberlain, 1964; Grigg, 1998; Norcross et al., 2003). At varying distances offshore, the shallow fringing reef platform, marking the end of the shallow nearshore area (Fletcher et al., 2008).

The shoreline orientation determines the primary wind and wave regime, which affects beach characteristics (Vitousek and Fletcher, 2008). The El Nino Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO; Mantua et al., 1997; Zhang et al., 1997) affect the maximum and minimum extremes of shoreline dynamics (Barnard et al., 2015). Chronic trends are influenced by historical sea level changes and changes in sediment supply. Over the late Holocene, the tropical Pacific experienced sea level fall (Engles et al., 2008; Grossman and Fletcher, 1998) and as the shoreline regressed around O‘ahu, sandy coastal plains were revealed. These sands constitute an important source to beaches retreating today in the face of anthropogenic sea level rise (Romine et al., 2016).

1.8 Data Regimes

O‘ahu is characterized by four principal shoreline orientations (Figure 1). For each orientation, we assembled historical shoreline positions using mosaicked and orthorectified aerial photographs dating from the early 20th century: north (7 shorelines; Figure 2), east (12; Figure 3), south (11; Figure 4), and west (7; Figure 5). The north section includes from west to east Ka‘ena- Mokulē‘ia to Hanaka‘oe-Punalau (Turtle Bay). The east section continues from Hanaka‘oe- Punalau to Makapu‘u. The south section from east to west includes Makapu‘u to ‘Ewa 1, and the west section extends from ‘Ewa 1 to Keawa‘ula (Yokohama).

Each section experiences different wind and wave patterns that uniquely determine beach dynamics. Vitousek and Fletcher (2008) report observed maximum annually recurring significant waves heights for each 30 degree orientation of the compass. The largest swells come from the North Pacific, peaking in winter months (Vitousek and Fletcher, 2008). As a result, north shore beaches narrow and the foreshore increases in height during winter. During the summer, waves are calm and make for wide and flat beaches (Hwang, 1981). The windward side (northeast facing) experiences trade winds, present 75 percent of the year, that occur in any season but are most common in the summer (Vitousek and Fletcher, 2008). These winds are effective at sorting beach sand, building backshore dunes, and thus result in overall finer sand size on the eastern shore. Wave activity increases during times of high trade winds, especially summer, resulting in beaches characterized by coarser and more poorly sorted sand than the median condition (Fletcher et al., 2012). During summer months, south-facing shorelines receive swell generated by distant storms in the Southern Hemisphere. These waves are typically smaller than the winter swell arriving on northern beaches but are nonetheless responsible for significant, though temporary, changes in beach morphology. West-facing shorelines experience refracted waves arriving from the north (winter) and south (summer) at different times of the year.

Much of the O‘ahu shoreline has been developed in some form, including homes, hotels, roads, and beach parks. Consequently, backshore dunes have been largely landscaped, graded and mined out of existence, leaving few natural dune systems in place on the island. Dredging and filling of the shore has created a coast unrecognizable to its natural form in many places such as Honolulu. Groins, breakwaters, and seawalls, built to protect homes, roads, and beach parks, are prolific around the island (Hwang, 1981; Sea Engineering, Inc., 1988). Sand mining, also, has decreased sediment supply at many beaches (Hwang, 1981).

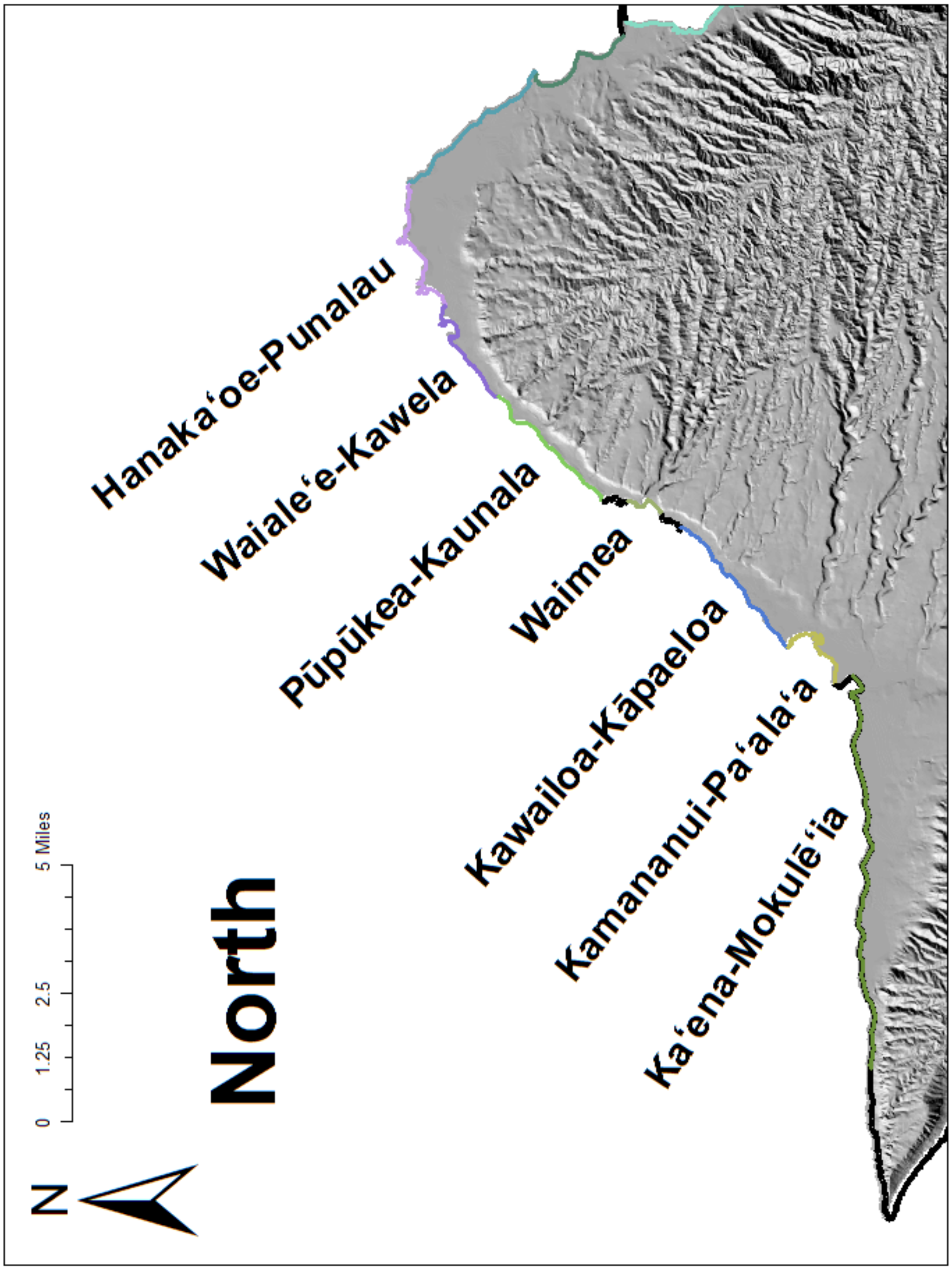

Figure 2. Shorelines in the northern section.

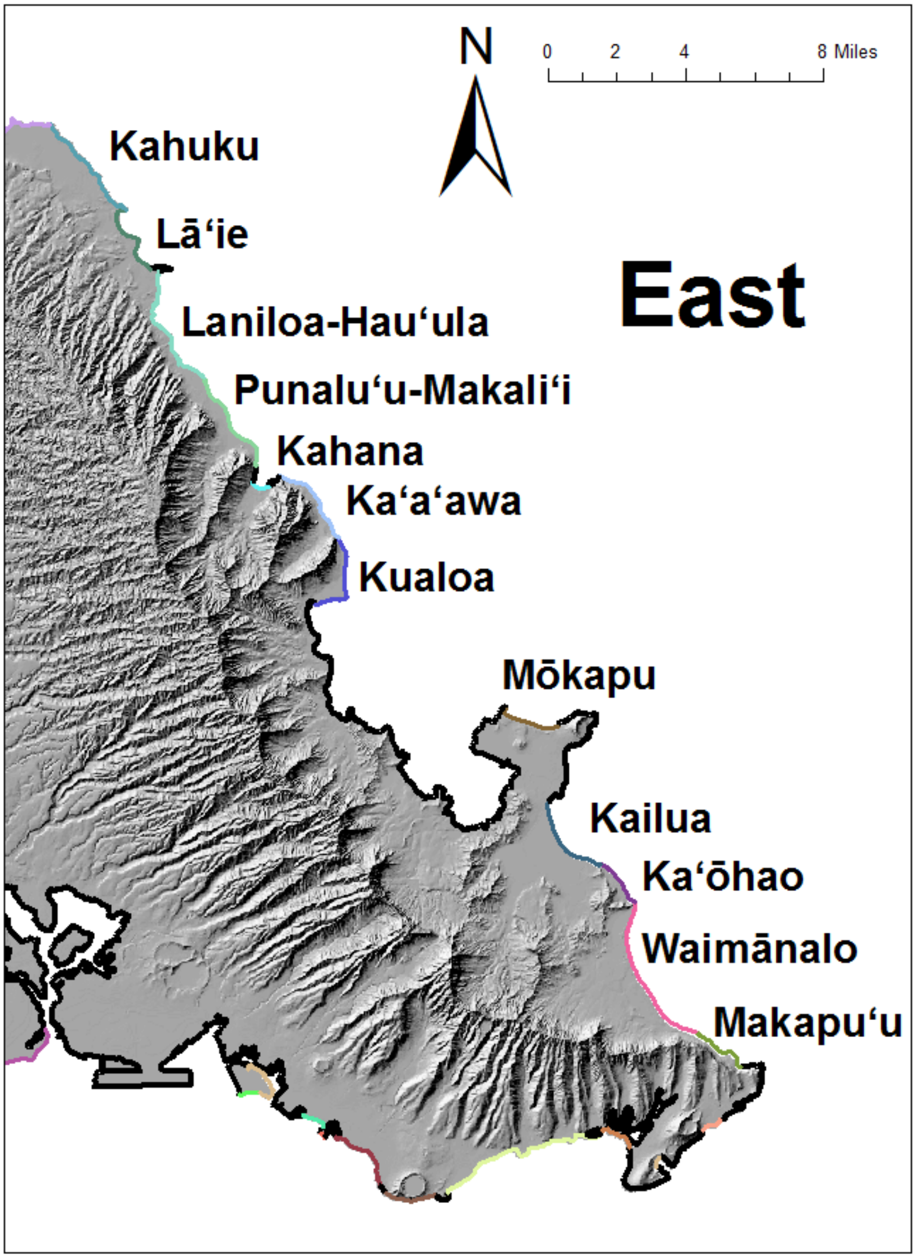

Figure 3. Shorelines in the eastern section.

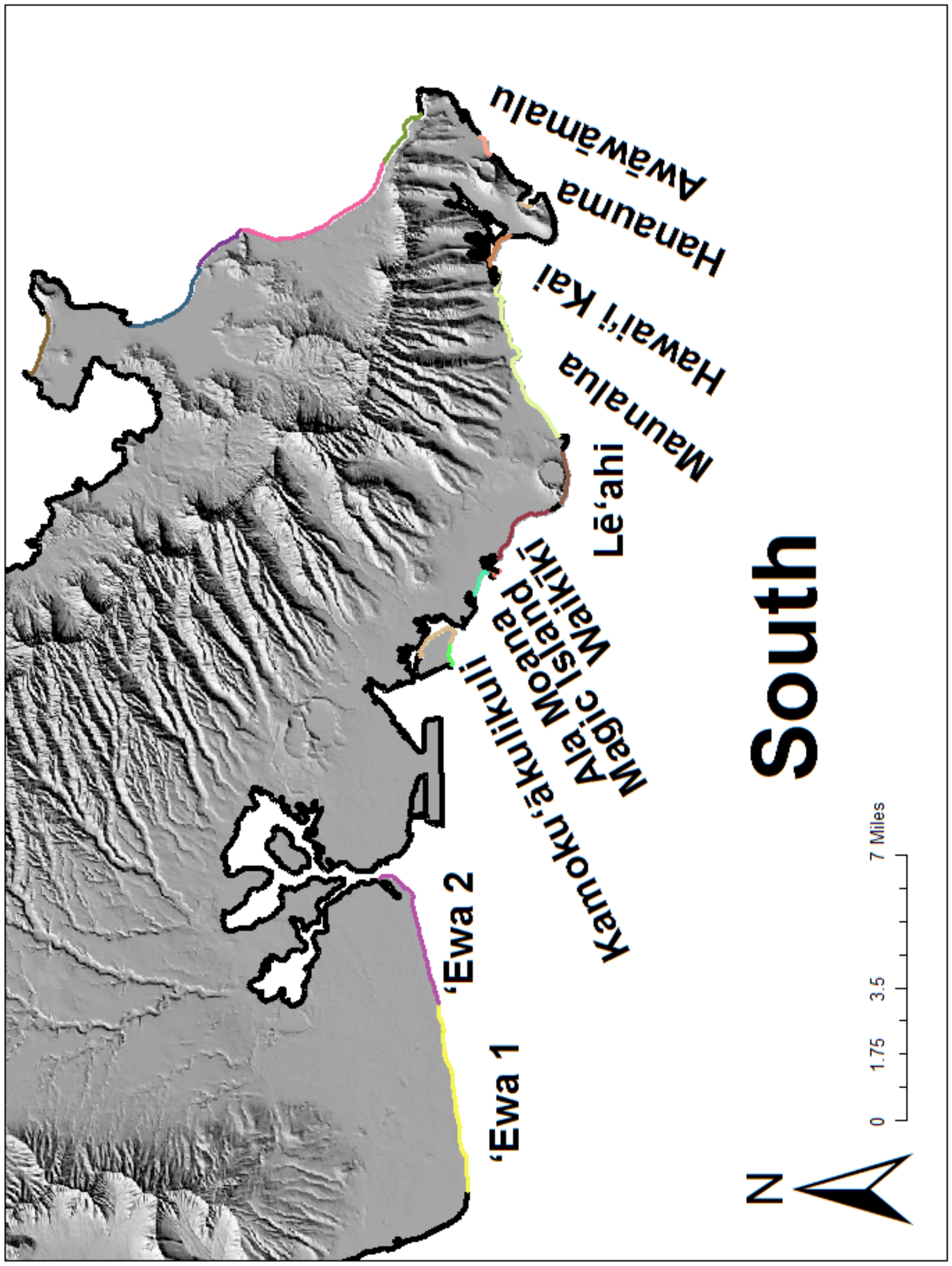

Figure 4. Shorelines in the southern section.

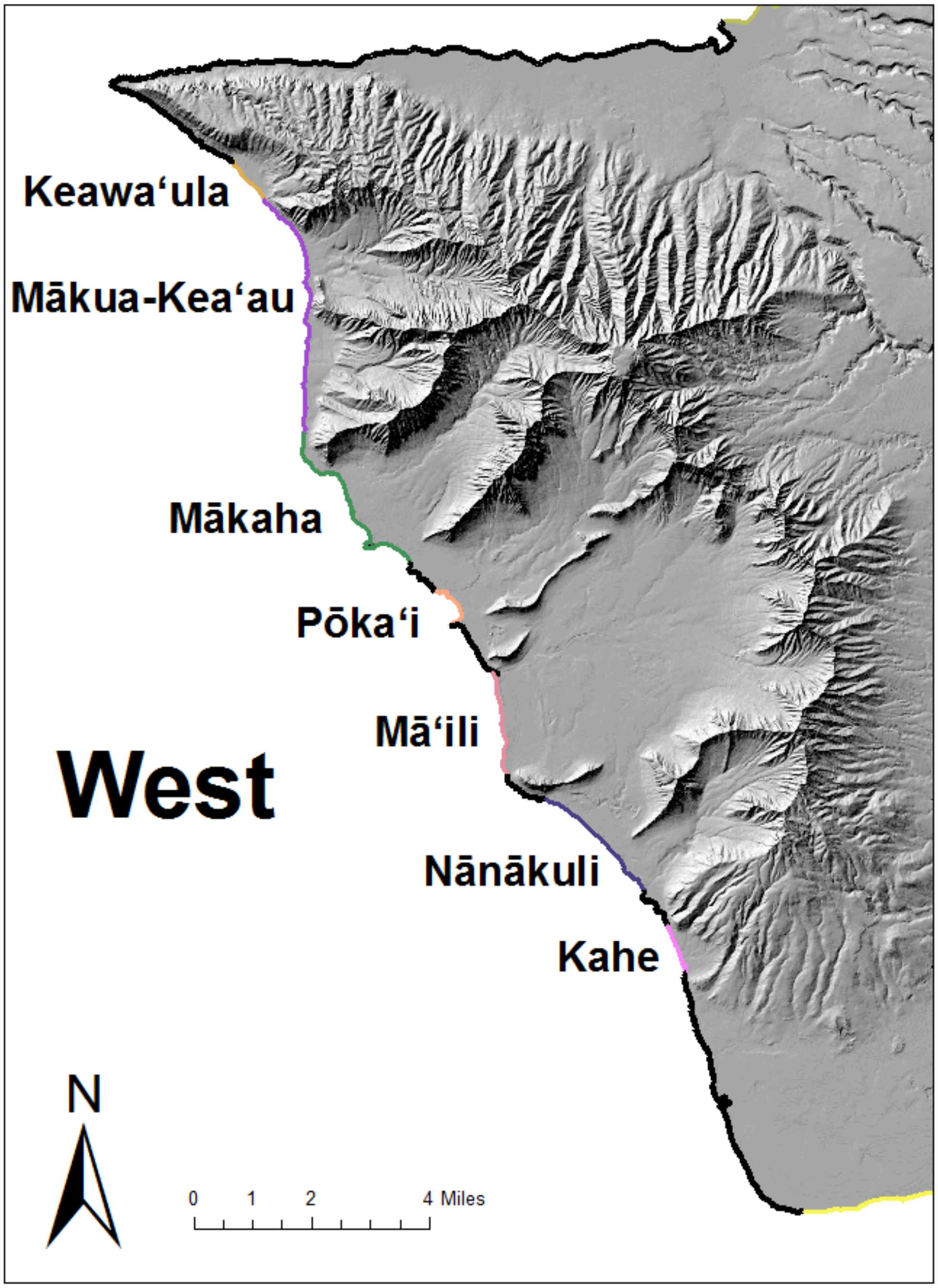

Figure 5. Shorelines in the western section.

2.0 Methodology

To assess the vulnerability of O'ahu shores to hardening in reaction to sea level rise, we updated a historical shoreline database and recalculated historical change rates at 20 m alongshore intervals across all beaches on the island. Using the model of Anderson et al. (2015), we projected future erosion hazard zones and built a spreadsheet of instances where this zone intersected structures, roads, and other types of backshore development (Figure 6). We infer that these locations are vulnerable to future hardening, and thus beach narrowing and loss.

2.1 Historical Shoreline Rates

Historical shoreline change rates were updated using the methodology of Romine et al. (2009). Vertical air photos from 2015 and satellite imagery from 2011-14 were provided by Remote Mapping Hawai'i and WorldView-2 respectively. Mosaics were created from both types of imagery by referencing 2006-7 orthorectified mosaics in the Universal Transverse Mercator (UTM) coordinate system. The air photos were rubber sheeted in PCI Geomatica, and the satellite imagery was adjusted using the affine transformation in ArcMap. Resolution for air photos is 0.2 m, and 0.5 m for satellite imagery. Residual error for mosaics was calculated by the programs. After a ground control point is added, the program measures the adjustment needed to minimize the change based on the other data available. The residual values were kept under 2 m.

The low water mark and the vegetation line were digitized to describe beach width. As has been established by previous workers (Fletcher et al., 2012; Romine et al., 2009; Fletcher et al., 2003; Eversol and Fletcher, 2003; Norcross et al., 2002) a proxy for the low water mark is the beach toe. Per previous workers, the beach toe is chosen because it is a visible feature that represents well the changes in beach volume as it shifts landward and seaward. Other features that have been used by previous workers to track historical shoreline change (i.e., Shalowitz, 1964), such as the mean high-water line, are often difficult to see in aerial photos of Hawaiian beaches because the white calcareous sand tends to obscure the visibility of the feature (Fletcher et al., 2003). Hwang (1981) used the line of vegetation to represent shoreline change, however it is sometimes fixed by hardening or has been artificially landscaped and no longer presents changes in the beach.

Per previous workers (Romine et al., 2009), calculations of beach width were made at transects spaced alongshore every 20 m. The distance between a baseline and the low water mark was subtracted from the difference between the baseline and the vegetation line to calculate the beach width for that year. At each transect a shoreline change rate is computed using weighted least squares regression (Anderson and Frazer, 2013) To calculate the average shoreline change rate, the rates calculated for each transect were averaged for the entire study site as well as each side of the island (Fletcher et al., 2012).

2.2 Sea Level Rise Projections

The model of Anderson et al. (2015) was used to project shoreline vectors under 0.17, 0.32, 0.6, and 0.98 m of sea level rise. Combining the newly calculated historical shoreline change rates and the sea level rise projections of the IPCC Fifth Assessment Report (2013), the model uses the Davidson-Arnott (2005) profile model to project the shorelines into the future. For each sea level scenario, a probability density function of the future shoreline vectors was produced, and the mode was chosen as it is the most likely future shoreline. The 2011-15 shoreline was used as a baseline representing 0 m of sea level rise. Modeled shoreline positions under each scenario were depicted as vectors. Around each vector a buffer zone of 20 ft was depicted as a proxy of the qualifying distance stated in current state policies for an emergency permit application.

2.3 Shoreline Hardening Potential

For each sea level scenario, the number of structures (buildings of various types) and length of properties potentially threatened by erosion, were calculated. Shapefiles were produced including transportation, structures, tax map key parcels (TMK), state and C&C beach parks, and Department of Defense (DOD) properties. These were based on City and County GIS layers provided online (Hawaiʻi State Office of Planning, 2017). TMK parcels were used to calculate alongshore property lengths. Transportation features were digitized on the most shore-parallel seaward edge to calculate the potentially threatened alongshore length. A shapefile of hardened shoreline was used to identify length of shore currently hardened.

To describe coastal development that intersected with the modeled 20 ft buffer, we used four categories: residential, beach parks, DOD, transportation, and undeveloped. Residential areas include any property with structures used for dwelling. Identification of beach parks and DOD-owned lands were provided by the Hawaiʻi Geographic Information Office. Transportation is defined as means of vehicle transportation, including parking lots, highways, and roads that have no seaward development and is near the edge of the vegetation line. Areas that do not fall under any of the previously mentioned categories and have large lengths between the edge of vegetation and the nearest development is noted as undeveloped.

We made certain assumptions for each type of development. If any portion of a residential or transportation property were intersected by the 20 ft buffer, we assumed that the entire length of the property or intersection with the buffer was at risk of hardening. However, when a structure at a beach park or defense parcels intersected with the 20 ft buffer, we only counted the length of the threatened structure.

2.4 Sources of uncertainty

There are several sources of uncertainty in our methodology. The main types have been identified by previous workers (Anderson et al., 2015; Romine et al., 2008, Fletcher, et al., 2003) and include positional and measurement errors. A root mean sum of squares (RMS) is calculated using these and are included in all analysis.

Positional uncertainty is the error caused by changes of shoreline due to seasonal and tidal fluctuations. Measurement error is the uncertainty caused by mapping; such as mosaic resolution, orthorectification, and digitizing. We used original resolution air photo scans (< 0.5 m) to aid in digitizing mosaics. Challenges in the interpretation of air photos included high reflectivity of water bodies, wave position, and turbidity in nearshore waters.

When calculating historical rates of shoreline change, the total position uncertainty is calculated using measurement errors in the low water mark, and tidal and seasonal shifts in the position of the beach toe. Measurement error is calculated using the rectification error, the pixel size of the mosaic, and a standardized digitizing error (Romine et al., 2008, Fletcher, et al., 2003). Measurement error of the vegetation line is calculated using digitizing error as established by Romine et al. (2008).

Anderson et al (2015) uses the RMS error described above, as well as the RMS error associated with each sea level rise scenario, to calculate a joint probability in model results. Other considerations for this model includes the assumption that beach profile does not change during shoreline movement. However, the interaction of the wave energy with the sand is likely to change the slope of the beach profile.

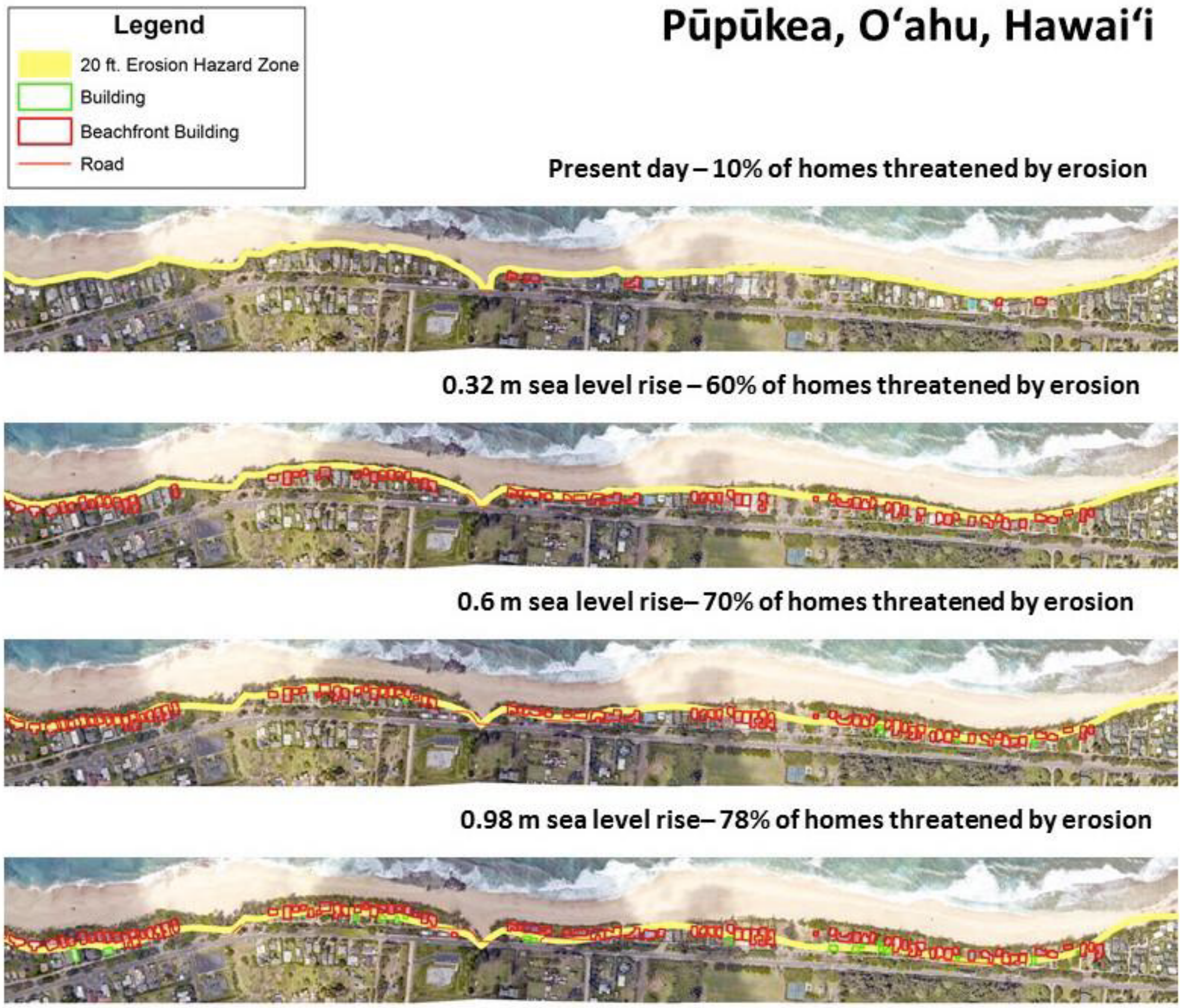

Figure 6. Examples of results on section Pūpūkea.

3.0 Results

3.1 Historical Shoreline Rates

The shoreline on O‘ahu eroded at an average rate of 0.02+0.01 m/yr over the past century (Table 1). The northern, southern, and western sections of O‘ahu displayed an eroding trend, while the eastern section displayed an accreting trend. Analysis revealed that over half of the island is experiencing erosion. Regionally, the western section had the most area experiencing erosion (87%), followed by the northern section (69%), southern section (50%), and eastern section (46%).

Table 1. Historical shoreline change trends for Oahu from the past century.

Section	Number of transects	Average rate (m/yr)	Percent eroding
North	1350	-0.07 $\pm$ 0.01	69
East	2109	0.06 $\pm$ 0.01	46
South	1339	-0.03 $\pm$ 0.004	50
West	628	-0.19 $\pm$ 0.01	87
Oahu	5426	-0.02 $\pm$ 0.01	57

3.2 Current Development

Beachfront development for the island of O‘ahu consists predominantly of beach park (39%) and residential (38%) types (Figure 7). DOD lands constitute 11% of beachfront development, transportation make up 5%, and undeveloped areas is 6%. These development types have unique characteristics on each side of the island.

Beachfront lands on the north shore of O‘ahu consist of mostly beach park (40%) and residential (39%) development types (Figure 8a). There is 18% of undeveloped areas and 3% transportation. Although much of the coast is designated as beach park in official state GIS layers, the public park parcels are mostly fronted by sandy beach adjacent to residential areas. Large coastal properties include Camp Mokulē‘ia, Camp Erdman, and the Turtle Bay Resort. The main highway in this location is Farrington Highway and Kamehameha Highway.

The shoreline in the eastern section consists of residential (41%) and beach park (32%) (Figure 8b). Beach parks include Makapu‘u Beach Park, Kailua Bay Beach Park, Kualoa Regional Park, and the Malaekahana State Recreation Area. DOD make up 14% of development along the shoreline and includes the Kāne‘ohe Marine Corps Air Station and Bellows Air Force Station. James Campbell National Wildlife Refuge, Kahuku Golf course, and Mōli‘i Pond are large coastal properties in this section. Kamehameha Highway and Kalaniana‘ole Highway are the highways of this area and run parallel to the shoreline. There is also 2% of undeveloped coast. Kāne‘ohe Bay is not included in this study.

The south shore is mostly residential (48%) and beach park (26%). DOD constitute about 22% of the development, transportation is 0%, and undeveloped is 4% (Figure 8c). Heavily trafficked beach parks here include Ala Moana Regional Park, Magic Island, and Kapi‘olani Regional Park. DOD areas are Barbers Point Naval Air Station and the Pearl Harbor Naval Station, which also holds the beachfront Pu‘uloa Range training facility and the Pearl Harbor National Wildlife Refuge. Waialae Country club golf course and Waikīkī hotels are included into the residential category.

The beachfront coast of the west side mostly consists of beach parks (87%) (Figure 8d). These include but are not limited to Ka‘ena Point State Park, Mākaha Beach park, Pōka‘i Bay Beach Park, Mā‘ili Beach Park, Ulehawa Beach Park, Nānākuli Beach Park, and Tracks Beach Park. The remaining development is residential (9%) and DOD (4%) (Pililā‘au Army Recreation area at Pōka‘i Bay). An important consideration for this side of the island is the typically short distance from the shore to the roads. However, transportation make up 0% of the beachfront development in the west section. Behind many of the beach parks is Farrington Highway.

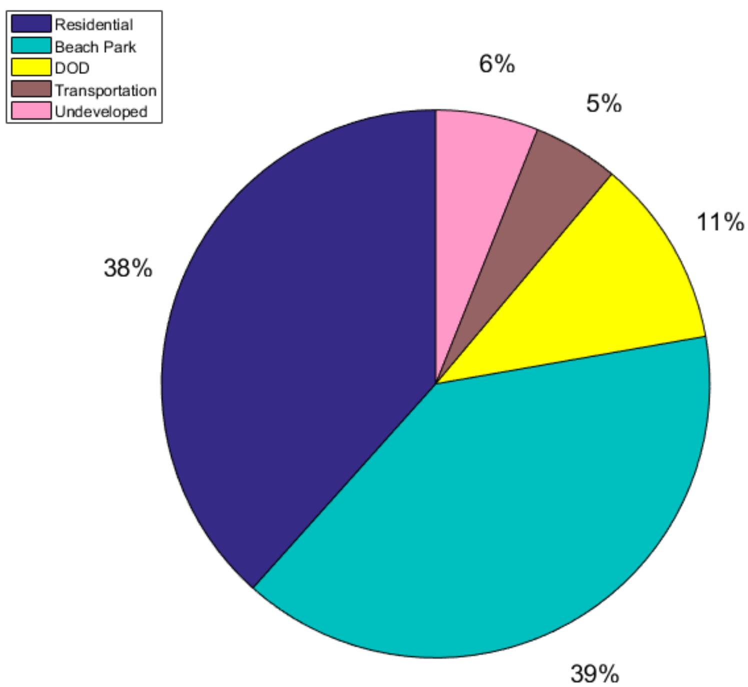

Figure 7. Percent of beachfront development type for Oahu in 2011-15.

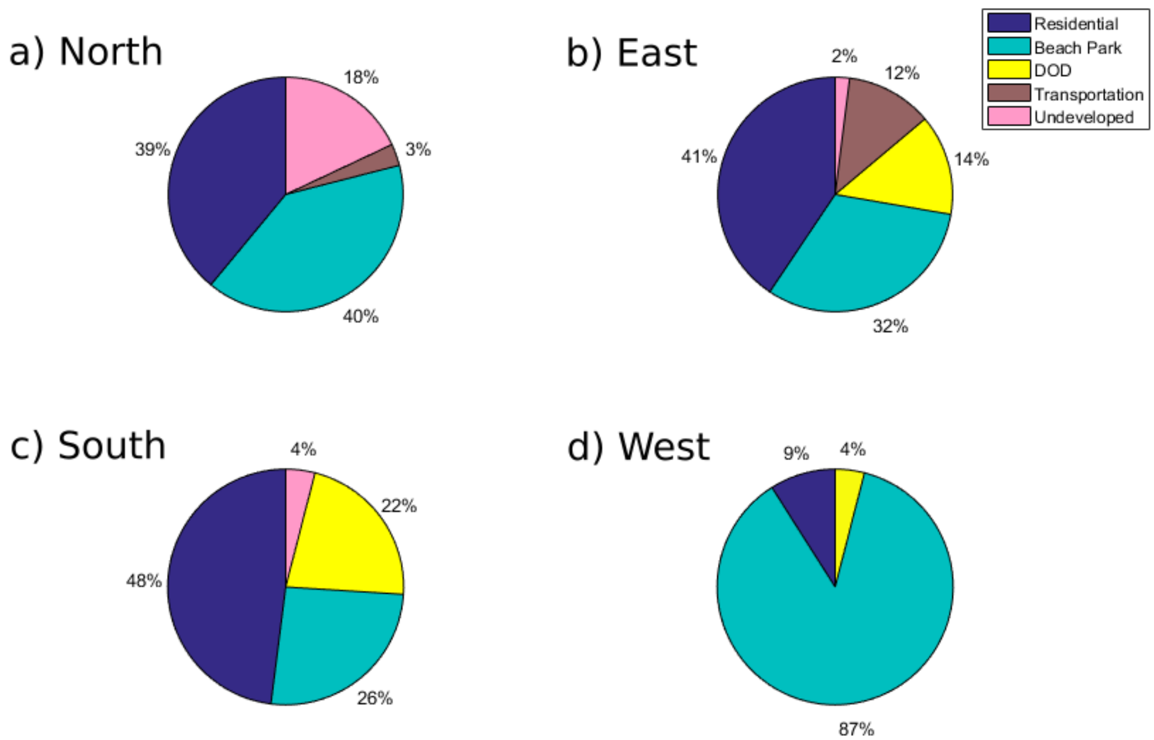

Figure 8. Percent of beachfront development by section: a) north b) east c) south and d) west.

3.3 Threatened Development Type

The number of structures potentially threatened increases as sea level rises. The highest number of impacted structures after 0.98 m of sea level rise are residential followed by DOD and beach park structures. The greatest increase in structures threatened is from 0 m to 0.32 m (393 structures) (Figure 9). This is more than double the number of structures threatened at 0 m of sea level rise (267 structures). Overall, the number of structures increases to a total of 1181 structures at 0.98 m of sea level rise.

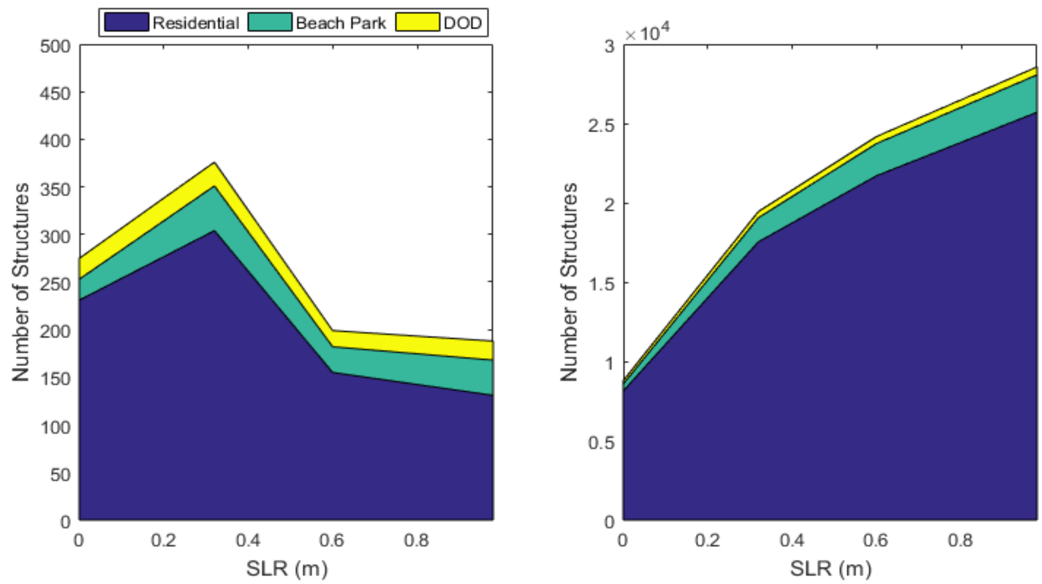

Figure 9. The number and types of structures potentially threatened for each sea level rise scenario. On the left, the increase of structures for each sea level rise scenario. On the right, the total number of structures after each sea level rise scenario.

The development type with the greatest potential risk of new hardened shoreline after 0.98 m of sea level rise is residential areas and roads, approximately 26 km and 17 km respectively (Figure 10). DOD lands and beach parks have a smaller contribution comparatively but is still impacted. The dominant type of transportation property impacted is road (83%) rather than parking (17%). There is also approximately 1.7 km of sidewalk affected.

The main type of development threatened on each side of the island varies, although beach parks and DOD lands contribute significantly less everywhere (Figure 11). The north, east, and south are projected to see more threat to residential areas than areas of transportation (Figure 11a-c). However, the length of transport (7092 m) is almost as much as residential areas (8890 m) for the east after 0.98 m of sea level rise. The north and east peak at 0.32 m while the south peaks at 0.6m. The largest contribution for the west is transportation development followed by residential and peaks at 0.6 m (Figure 11d). Beach parks and DOD lands are both impacted on each side of the island. The north has significantly less DOD lands threatened, and the beach parks there are threatened the least overall.

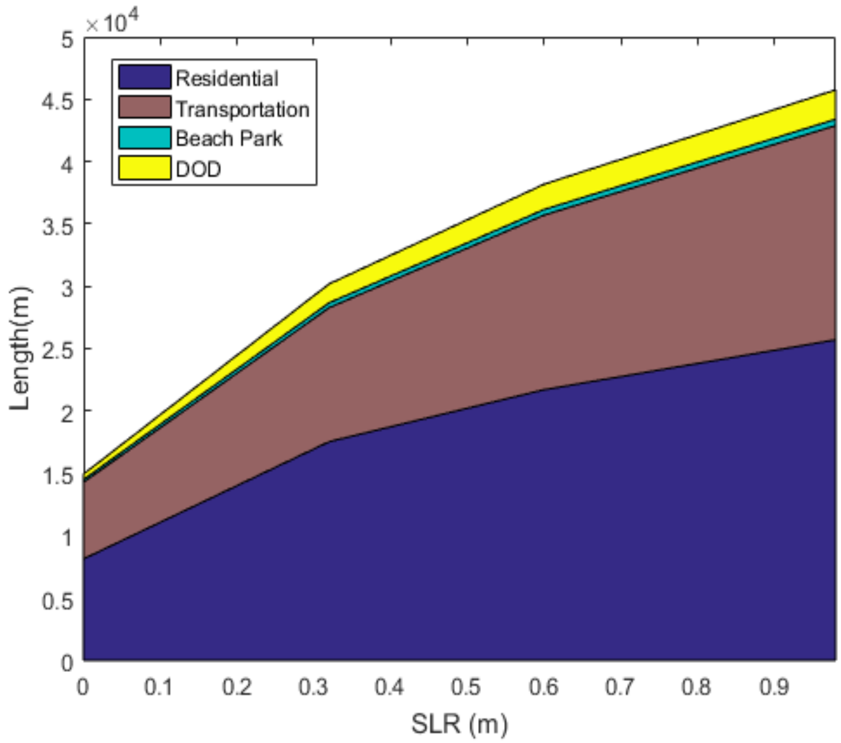

Figure 10. Total length (m) potentially hardened for each sea level rise scenario divided by development type.

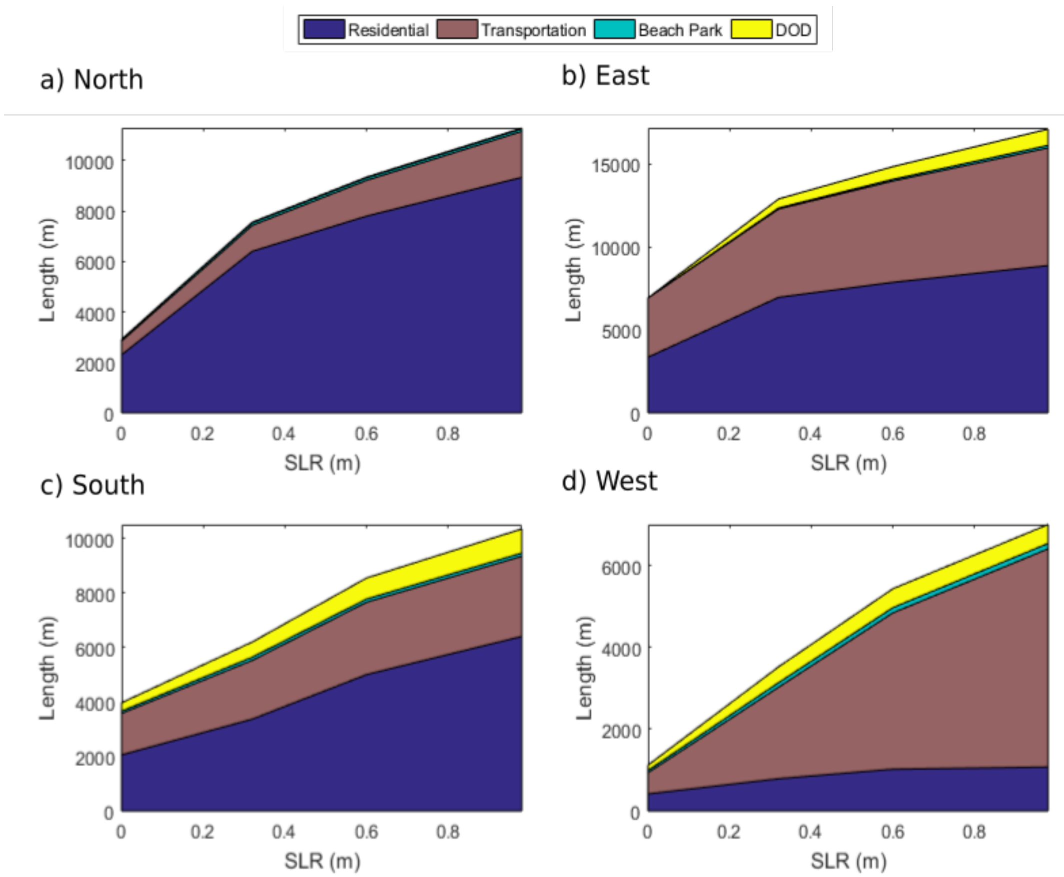

Figure 11. Length of shoreline hardening based on development type for each sea level rise scenario for the a) north b) east c) south and d) west side of the island.

3.4 Current and Potential Hardening

Approximately 27% of the sandy shoreline is hardened today (Figure 12). The most severely hardened is the east section covering 13% of the island (14 km) followed by the south (10% or 10 km), north (3% or 3 km), and the west (1% or 1 km). The percent hardened for each side of the island individually shows that the south side is the most hardened (39%), followed by the east (34%), north (13%), and west (9%) sides (Figure 13).

The eastern and southern section have several beaches with over half of the backshore hardened. These beaches are Ka‘a‘awa (90%), Ka‘ōhao (62%), Punalu‘u-Makali‘i (61%), and Laniloa-Hau‘ula (52%). For the southern section, the heavily hardened beaches are Magic Island (100%), Ala Moana (96%), Waikīkī (94%), and Lē‘ahi (73%). There are no beaches in the northern and western section with half or more of the beach currently hardened.

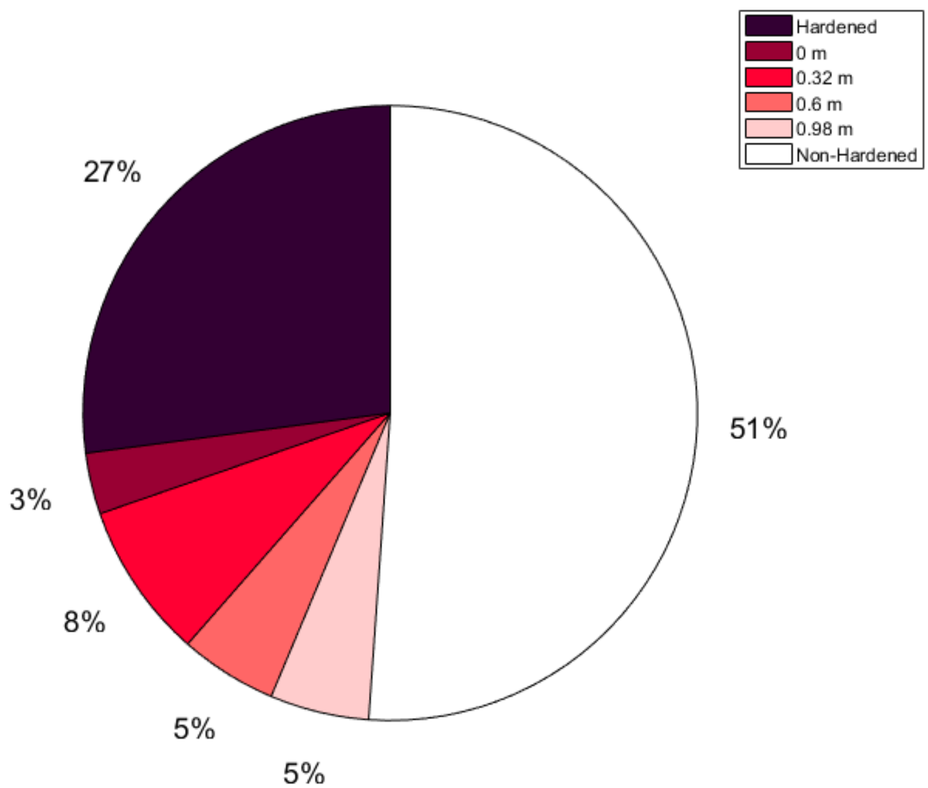

Figure 12. The current and potential to harden on Oahu for each SLR scenario.

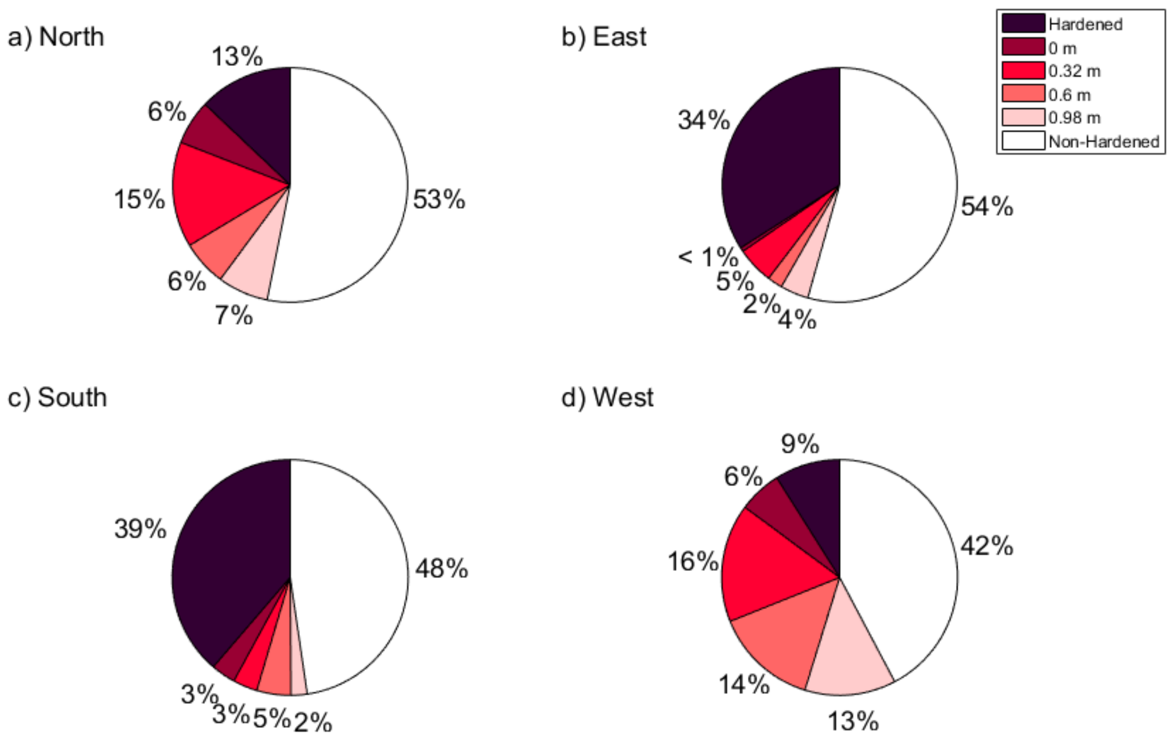

Figure 13. The current and potential to harden in each section for each SLR scenario.

Based on this methodology, 49% of the shoreline within the entire study on O'ahu site will be potentially hardened after 0.98 m of SLR if widespread hardening is permitted. The increase of potential new shoreline hardening is greatest between 0 m and 0.32 m of SLR. The length of shoreline threatened doubles from 13% to a total of 27% (14% increase) at 0.32 m of SLR. At 0.6 and 0.98 m of sea level rise, it is projected that the threat will increase by approximately 7% each.

Each side of the island contributes a certain portion of potential hardening after 0.98m of SLR. The east has the largest length at 17 km followed by the north (11.1 km), south (10.5 km), and west (7 km). Regionally, the western section has the largest potential for hardening at 55%. The northern section follows at 43%, followed by the eastern and southern section, which are both projected to be 39% (Figure 9). These values do not include shores currently hardened.

The overlap of currently hardened areas and potentially threatened areas were calculated to determine the length or shoreline that is hardened but does not qualify for hardening based on our methodology. The southern section has the longest length that did not overlap (3.5 km), followed by the eastern section (2.8 km), northern section (1 km) and western section (0.2 km). In terms of individual sections, the southern section had the largest percent of currently hardened shoreline that did not overlap (13%) followed by the eastern section (7%). The northern and western section have lower percent of non-overlapping areas at 4% and 2% respectively.

Once the currently and potentially hardened coasts were combined, the total potential for shoreline hardening after 0.98 m of SLR is 49% of the entire length of sandy beach on the island of O‘ahu (Figure 12). In terms of greatest length, the order is east (18 km), south (14 km), north (12 km), and west (7 km). Nearly half or more of every side of the island is projected to be threatened by 0.98 m of SLR. The section projected to be the most hardened if widespread hardening is allowed is the western section (58%), followed by the south (52%), north (47%) and east (46%).

3.5 Priority Beaches

The projections for each shoreline within the four sections differ. Some beaches projected to be potentially hardened are currently hardened while others are not. Below we present the beaches experiencing the most change for each side of the island.

Of the nine shorelines in the northern section, three have 50% or over projected threat of potential future hardening after 0.98 m of SLR. They are Kawailoa-Kāpaeloa (90%), Pūpūkea-Kaunala (70%), and Kamananui-Pa‘ala‘a (54%). Accounting for the currently hardened shoreline, beaches with the most change in potential future hardening are Pūpūkea-Kaunala (62% increase) and Kawailoa-Kāpaeloa (50% increase). Pūpūkea-Kaunala includes the beach from Ke Iki to Velzyland and is approximately 5.1 km long. Kawailoa-Kāpaeloa stretches from Papailoa beach to Leftovers Surf Break and is approximately 2.6 km long. Kawailoa-Kāpaeloa has the higher potential threat modeled than Pūpūkea-Kaunala; however, because of the presence of seawalls, the percent change is less than Pūpūkea-Kaunala.

There are 12 shorelines in the eastern section, and there are five beaches with a percent overall threat 50% or higher. The beaches are Ka‘a‘awa (99%), Ka‘ōhao (93%), Punalu‘u- Makali‘i (85%), Kualoa (50%), and Laniloa-Hau‘ula (63%). Including the currently hardened areas, the beaches projected to have the most change are Makapu‘u and Ka‘ōhao. Makapu‘u shoreline is from Makapu‘u beach to Kaiona Beach Park and is approximately 1.5 km long. One end of Ka‘ōhao is Beach and the other is Wailea Point. This beach is approximately 2.3 long. Makapu‘u is projected to see a 37% increase of shoreline threatened after 0.98 m of SLR. The change projected for Ka‘ōhao is 31%.

There are 11 shorelines in the southern section. There are six shorelines with 50% or higher projected threat at 0.98 m of SLR. They are Magic Island (100%), Ala Moana (96%), Waikīkī (94%), Lēʻahi (78%), Awāwāmalu (78%), and Maunalua (55%). These areas are also almost or totally hardened already. The beach projected to have the most change is Awāwāmalu (78%) followed by ʻEwa 2 (21%) and ʻEwa 1 (20%). Awāwāmalu includes the beach commonly known as Sandy Beach Park and is 0.5 km long. ʻEwa 1 begins at Barbers Point and continues to Oneula Beach. This shoreline is approximately 5.6 km long. ʻEwa 2 continues from the eastern end of ʻEwa 1 until the ʻEwa 2 lagoons. ʻEwa 2 is approximately 5 km long.

Nearly all of the seven shorelines in the western section are projected to have over half of the shoreline threatened at 0.98 m of SLR. The order is Kahe (83%), Mākaha (74%), Nānākuli (66%), Keawaʻula (65%), Māʻili (63%), and Pōkaʻi (59%). Mākua-Keaʻau has less than half of the beach with a 13% projection. The shorelines projected to see the most change is Kahe (83%) and Nānākuli (66%). These are adjacent shorelines. Nānākuli begins at Ulehawa Beach Park and ends at Zablan beach. Kahe is the shoreline that fronts the Hawaiian Electric Kahe Power Plant.

4.0 Discussion

4.1 Potential Threat of Sea Level Rise

Our results show that sea level rise will increase the number of structures and length of property threatened, making sea level rise a major concern and hazard for shoreline development. The greatest increase in potentially impacted development is expected to come with 0.32 m of sea level rise for O‘ahu, while 0.6 m and 0.98 m will be less of relative increase. This emphasizes that a more dramatic change will happen sooner rather than later, making it essential that policies are adjusted in a timely matter in order to manage the impacts projected by the model. By the end of our study, 49% of the 57% area chronically eroding is considered potentially threatened. If the local sea level rises beyond 0.98 m, a likely scenario, there is still room for more of the shoreline to be threatened (approximately 8%). Of course, this depends on the development type in the path of the eroding shoreline.

The impacts of large lengths of shoreline hardened is significant socially, ecologically, and economically. An increase of hardened shoreline would increase the length of beach loss, decreasing resource availability to users for the following reasons. Socially, there would be less areas for communities to gather and to practice cultural traditions and recreational activities. Human visitation at certain beaches may increase, intensifying impacts relating to overcrowded beaches. The loss of connection to a place also threatens identity for people who have used an area for many years or have generational connection to a place. Ecologically, native and endangered species that depend on the beach environment would have to migrate. Interaction between marine animals and humans would increase at remaining beaches. Also, if a species is unable to migrate, it would be endangered of local extinction. In an economic sense, losing beaches may lose the appeal of the tourist community, decreasing visitor spending. Beaches and dune systems also act as buffers to storm events and can protect coastal development. Thus, beach loss is an economic and public safety challenge because of an increase in vulnerability to high waves and storms.

4.2 Policy Failure

The length of shoreline currently hardened compared to the length that could potentially be hardened in our 0 m (present-day) scenario reflects the past failures of the regulatory programs and policies in place. The length of present hardened coastlines is larger than those exposed in our model at 0 m of sea level rise for every section, except the western section where the lengths are approximately the same. In other words, extensive areas have been hardened historically that don't meet the State's criteria for imminently threatened. The south side of the island has the largest length (3.5 km or 13% of the shoreline) currently hardened that is not included in our modeling.

This could be due to the limits of our methodology. There are other factors allowing existing shoreline protection projects that we did not consider. These include the exceptions for properties with seawalls present before the adoption of the CZM in 1967 and permits for temporary structures. There also exist homes currently qualified to apply for an emergency permit but have not been given permits by the state to build seawalls. Perhaps because no official application was submitted or is currently in process. For example, many properties on the north shore are permitted instead to practice temporary remedial measures such as sand pushing and using geotextile cloth. Future work could be to identify the areas that would qualify for these cases that may have exceptions in order to understand the weight of these situations in terms of current shoreline hardening.

4.3 Priority Users

Knowing the extent of threat for each user (local residents, county, state, federal) involved will help to determine the order that those working on improving policies and management plans should work. Consequently, development type of an area determines the type of development threatened. Much of O‘ahu is developed as residential, which is also the most threatened. This pattern is reflected in the north, east, and south shore. Thus, those working on policies and management plans should begin their focus with local residents, and perhaps in those areas.

Beach parks constitute a significant amount of the shoreline development, yet the length of park threatened to hardening is relatively insignificant compared to residential. Beach parks are important buffers between the beach and development, which are often parking structures and highways developed just inland. Thus, the threat to beach parks may be better reflected in the length of road threatened. If means of transportation are hardened, the beach and beach park may narrow. This highlights the importance of recognizing the Department of Transportation (DOT) as an important user that may affect beach and beach park loss.

Major beach and beach park lost because of transportation hardening by DOT happened in the north-eastern section. This section should be a priority managed retreat area for DOT. The entire shoreline could be hardened within a few decades if hardening continues as it has been by DOT. In terms of potential future hardening, the west side would be a DOT priority section, particularly the Nānākuli shoreline. As a coastline almost entirely developed by beach parks, it is most vulnerable to transportation. With means of transportation threatened nearly as much as residential, it is important to clearly address the state and county process to properly manage hardening for this type of development. This does not currently exist in the state policies.

DOD is not a priority user because the threat is projected to be significantly less than residential and transportation. Because of our methodology, the projection is most likely an underestimate of the true potential to harden. While DOD may not be subject to State and County rules related to shoreline hardening, DOD should still practice best shoreline management.

4.4 Priority Mitigation Areas

As SLR and coastal development is threatened, plans of mitigation are necessary to ensure communities protect the areas they value. This could be through shoreline hardening or managed retreat. Priority areas for mitigation management plans should be eroding shorelines since only areas of erosion may qualify for permits. Coastal erosion is the dominant historical shoreline change trend on O‘ahu. Since more than half of the beaches is in a state of erosion, then more than half of the island is vulnerable to shoreline hardening. Based on the amount of annual erosion, the west side of the island would be of most concern. However, average rates based on island sides may not be the best approach for choosing priority areas. For example, the east is the most hardened side, yet is, on average, accreting. The rate being predominantly accreting is most likely because of a few areas such as Kailua with high rates of accretion. Other areas on this shore experience predominant erosion. This shows that local shoreline change is more indicative of areas that would be most threatened. Therefore, a more accurate way to identify priority areas would be to look at erosional rates of shoreline stretches between headlands, something not presented in this paper.

Choosing focus areas should be based on the combination of current and potential hardening. For the entire study area, if we looked only at the total potential to harden for each section, we would consider the order of priority to be the east, followed by the north, south, and west. Once we combine current and projected hardened shores, the order changes to east, south, north, and west. In terms of regional percent threat after 0.98 m of SLR, the order is the west, followed by the south, north, and east. Priority should be given in either of these previous two orders since each are more accurate for including the present-day situation.

Examining the amount of change happening to each section individually is important to consider because changes within a community will have significant implications. If, for example, half of the beaches on one side of the island disappeared, the local access to beaches in that section would significantly decrease. The west and north would have highest priority, if priority is based on largest change overall. These areas experience a 49% and 34% change after 0.98 m of sea level rise respectively. At 0.32 m both are also over double and triple the percent change projected for the other sides of the island. The west would have higher priority over the north since the rate of change for the following scenarios continues to have high values, while the north decreases.

Communities may want to move towards no shoreline hardening or a completely hardened shoreline. For this paper, we highlight beaches with over half of the shoreline projected to be hardened as a way of identifying most threatened beaches. However, any percent of shoreline hardened or potentially hardened can be considered threatened. Of the 39 shorelines, only five (Kamokuʻākulikuli, Hanauma, Mōkapu, Kahana, Kahuku) have no projected threat. Only two (Kailua and Lāʻie) are less than 10%. The rest are 10% or higher.

Pūpūkea-Kaunala, Kawailoa-Kāpaeloa, and Kaʻōhao have the highest percent of shoreline change projected for shorelines whose change is predominantly due to residential development. Kawailoa-Kāpaeloa and Kaʻōhao already have 40% and 62% of the shoreline hardened. Pūpūkea-Kaunala only has 8% and should be given higher priority for mitigation plans, while the other beaches are better candidates for a combination of mitigation and restoration plans.

Kahe, Nānākuli, and Keawaʻula would be the top beaches in terms of transportation. Farrington highway is very close to the shoreline at all three of these beaches. The dunes at Nānākuli are also currently infringed upon with beach retaining walls. Awāwāmalu technically has the third largest change. However, the parking lot at Awāwāmalu is not officially counted as a hardened shoreline, so the projected change for Awāwāmalu is an overestimate. Thus, Awāwāmalu was not included in the top priority beaches.

4.5 Priority Managed Retreat Areas

Shoreline restoration is another important consideration. Coastal hardening could be removed in areas after development retreat. This would lessen the length vulnerable to beach loss. The sections that have the highest need for shoreline hardening restoration based on the length is the east (14 km) and the south (10 km). These two areas could be the main focus in restoration efforts if priority is based on longest length hardened. Kawailoa-Kāpaeloa and Ka‘ōhao are also potentially good candidates for managed retreat because these beaches have the largest percent of its shoreline hardened.

4.6 Other Considerations

An important consideration for this study is the methods used to measure the potential threat for beach parks, defense lands, and larger than average properties. They may not be well described in this study. We showed that beach parks and DOD development types have significantly less potential threat than residential and transportation types. When there are structures on large properties in the aforementioned development types, we assume that only the length of the structure is hardened. If, instead, threatened structures triggered the hardening of the entire length of a property in these categories, the potential for shoreline hardening would be greater than our projections. We assume that these structures are given the same consideration as a habitable structure. This assumption would affect the length actually hardened in practice, and that could be longer or shorter. The trigger may also not necessarily be the 20 ft buffer used, so the beach parks lengths could shift SLR scenarios in practice. There is the matter of areas without dwellings that may want to protect the property through hardening. Other types of development that may be in this situation include golf courses, firing ranges, and wildlife refuges. Hardening beach parks, empty properties, and other beachfront amenities are possible as there are examples of existing hardening at these types of locations around the island and may be possible because of a lack of guidance.

We also assume that the development will not change. However, no change is unlikely. The results could increase but would more likely decrease because shoreline hardening is hardly allowed, and many homeowners have left or are trying to leave their properties. Many beachfront homes are currently vacation rentals that would be good candidates for coastal development retreat from the shoreline.

Flanking is also not factored into our methodologies but would likely increase the rate of erosion on neighboring shores and, thus, the length of shore potentially hardened. A study done on the Punaluʻu-Makaliʻi and Laniloa-Hauʻula shore in the eastern section found that flanking accelerated erosion significantly on 27% of the shoreline over an 87 year period (Summers et al., 2017). After an increase of 0.32 m, the number of threatened beachfront residential homes more than doubles compared to the 0 m scenario. Thus, the amount of pressure from beachfront development is projected to increase. This could introduce new areas to flanking, increase local erosion rates, and, thus increase the rate at which shoreline is at risk of hardening.

4.7 Future Work

Addressing the assumptions made in our methodology should be considered in future work. We assume that the vegetation line is the shoreline. However, the debris line is used more often and is typically landward of the vegetation. Local shoreline studies would benefit from a more accurate depiction of the shoreline defined by the state.

We also only include potential hardening using state policies. However, as we mentioned before, there are other ways such as the C&C variance to harden a shoreline.

Addressing other processes of hardening would give a more accurate projection of potential hardening.

Another major component not included in this study are seasonal variability and storm events. We based shoreline hardening on historical erosion rates. However, extreme events, such as strong winter swells in the north of O‘ahu, may also trigger the construction of hardening the shore. Including other layers such as flooding hazards may increase the accuracy of the future potential threat.

5.0 Conclusion

We show that sea level rise will greatly increase the risk of hardening on Oʻahu. The bulk of the potential threat of shoreline hardening is projected to be sooner rather than later and nearly half of the island could potentially harden if allowed after 0.98 m of SLR. To ensure that beaches can be sustained, current policies for shoreline hardening must be reevaluated. It is important to develop a system that upholds beaches as a public trust resource. Our findings suggest that place based management is most appropriate because of the unique character of each section of shore. There are multiple stakeholders, showing the importance of interagency collaboration and public-private partnerships. Because there are over one thousand beachfront residents on Oʻahu, there is an immediate need for options to transition away from the shore in areas where the island wants to conserve beaches. Currently no formal system exists for preserving sandy beaches with rising sea level.

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