RATE OF BEACH LOSS GREATEST WITH NEAR-TERM SEA LEVEL RISE

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ABSTRACT

Shoreline hardening threatens beaches globally and is a problem that is expected to accelerate with sea level rise (SLR). Modeling risk of hardening for future beaches provides important data for resource managers, communities, and other stakeholders. However, few comprehensive studies of this issue exist. For all sandy beaches on Oʻahu, Hawaiʻi, we model modern (2015) and future (0.25, 0.46, 0.74 m of SLR) erosion hazard zones. We identify the relationships between coastal land use patterns and erosion hazard zones to define areas at risk of hardening. Our results show half of the beachfront shoreline will be at risk of hardening at 0.74 m of SLR. Shorelines become increasingly at risk of hardening throughout all SLR scenarios, with the largest increase (+7.4% island-wide) occurring between modern-day and 0.25 m of SLR. Modern-day and near-term hardening under 0.25 m of SLR pose maximum risk of beach loss because of heavy development on some shoreline segments. Coastal communities in other settings may be facing significant modern-day and near-term threats to beach resources that have not been identified. Adaptation to SLR should be considered an immediate need and not solely a future issue.

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LIST OF ABBREVIATIONS

IPCC AR5	Intergovernmental Panel on Climate Change Fifth Assesment Report
NCZMP	National Coastal Zone Management Program
PDF	probability density function
SLR	sea level rise

INTRODUCTION

Beaches are critical ecosystems, an essential cultural setting, storm buffers, and an attraction for tourists. In the U.S., partnerships between federal, state and local governments establish management of coastal resources through the National Coastal Zone Management Program (NCZMP) under the National Oceanic and Atmospheric Administration. Based on NCZMP criteria, states design their own programs and set their own objectives. For example, in Hawai'i, the national and local partnership is based on Hawai'i Revised Statutes §§ 205A[1], the state Coastal Zone Management law, which declares protection of view planes, public access to and along the shoreline, and conservation of coastal ecosystems, especially beaches, as the primary purpose of beach management efforts. Summers et al.[2] established that despite this robust legal and planning framework, there has been a failure to achieve stated goals, especially due to poor management permitting shoreline hardening.

Around the world, beaches are threatened by shoreline hardening, the construction of hard structures such as seawalls (**Figure 1**). Hardening the shoreline prevents property erosion and protects backshore development from erosional hazards. However, it causes beach narrowing and eventual loss on chronically retreating shorelines, an inevitability with sea level rise (SLR)[2–4]. Shoreline erosion is projected to occur along more of the shoreline as well as accelerate the rates of erosion due to SLR[5–7], increasing the length of shoreline at risk of hardening and beach loss if poor management practices continue.

To provide coastal managers and stakeholders with an improved understanding of the impacts of shoreline hardening related to accelerated SLR, we use shoreline change projections under three SLR scenarios modeled by Anderson et al.[5] In
combination with an analysis of backshore land use to identify parcels at risk of hardening, and by extension beach loss, we establish a chronology of threatened beach resources.

Many models used to project shoreline change resulting from SLR[8–10] fail to assimilate historical data and, therefore, do not provide results reflecting site specific parameters. Also problematic are models that use simplified projections of historical change without taking into account the accelerating nature of global mean SLR.[11] Anderson et al.[5] provides a model that accommodates both of these needs by assimilating historical patterns of beach change and SLR scenarios based on SLR projections from the Intergovernmental Panel on Climate Change Fifth

Figure 1. Hardening to protect backshore assets has resulted in widespread beach loss in Hawai‘i. Photo of Ko‘olauloa shoreline in March 2020 by Kammie Tavares.

Assessment Report (IPCC AR5)[12]. Because the shoreline of O‘ahu (**Figure 2**) has been carefully mapped for historical rates of change[13], the Anderson et al.[5] model offers an ideal opportunity to analyze the relationship between projections of future shoreline change due to SLR and backshore land use.

We apply the shoreline change model to project future erosion and shoreline retreat on all sandy shorelines of O‘ahu, Hawai’i. We create erosion hazard zones for modern and future shorelines based on current management practices to identify shorelines at risk of hardening to improve our understanding of challenges related to beach conservation. We use O‘ahu as a living laboratory of land use decisions, and, by extension, these results are indicative of beach conservation stresses in similar situations around the world. For purposes of management, the State of Hawai’i defines an administrative shoreline, as the highest wash of the waves at high tide during the time of the year when the waves are highest[1]. The state uses this shoreline to identify cases under its jurisdiction where homeowners may apply for emergency permits to harden the shoreline. The criteria under which an emergency permit may be submitted is when evidence of active erosion occurs within 20 ft (6.1 m) of a habitable structure, major structures and public facilities[14]. We use this 20 ft buffer in a GIS analysis as a proxy for future risk of hardening by landowners under three SLR scenarios on the beaches of Oʻahu.

Located in the North-Central Pacific, Oʻahu is exposed to a highly variable and diverse wind-wave climate[15]. As a result, shoreline orientation is a fundamental parameter affecting beach characteristics. Oʻahu can be characterized by four principal orientations (north, east, south, and west). The north shore of Oʻahu experiences large winter swells generated by low pressure centers in the North Pacific. The west shore is characterized by both refracted winter and summer swells. The south shore of Oʻahu, exposed to summer swell and oblique trade wind waves, is the most heavily developed coastline on the island. The east side of the island experiences trade wind waves and, at its northernmost and southernmost ends, seasonally refracted swell. We characterize projected shoreline changes island-wide as well as for each of these directional segments.

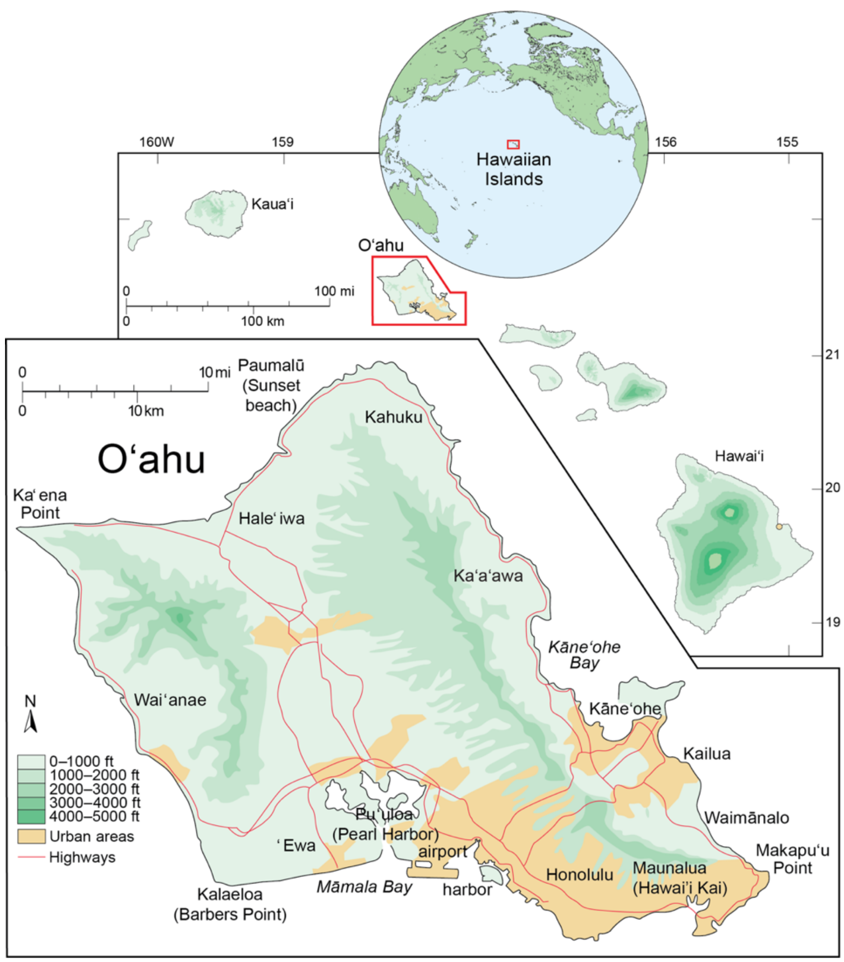


Figure 2. The island of Oʻahu, Hawaiʻi, has four fundamental shoreline orientations, north, northeast, south and southwest.

METHODOLOGY

The greatest threat to beach conservation under conditions of accelerating SLR is shoreline hardening. To provide managers with improved understanding of this problem, we use a three-step process: 1) projecting the position and rate of change of future shorelines under three SLR scenarios per Anderson et al.[5], 2) defining land use categories that have historically been most likely to be hardened, 3) identifying backshore parcels and their development pattern where an administrative trigger (20 ft from the shoreline) for hardening is crossed (**Figure 3**).

FUTURE SHORELINE PROJECTION

We project future shoreline positions under three scenarios of SLR (0.25, 0.46, and 0.74 m) using the method described in Anderson et al.[5] The SLR scenarios refer to the mode probability values in the IPCC AR5 report[12], which correspond to the years 2050, 2075, and 2100 respectively for Representative Concentration Pathway (RCP) 8.5. The RCP 8.5 "business as usual" greenhouse gas concentration pathway was used in this study as results are intended to inform the development of land use policies in a low risk tolerance framework.

The shoreline change model of Anderson et al.[5] combines historical shoreline patterns of change with the conceptual geometric model by Davidson-Arnott[16] of beach profile adjustment to SLR to project future shoreline positions and rates of change under each scenario. The projected amount of net shoreline change is characterized by a joint probability density function (pdf) that includes uncertainties arising from the historical shoreline methodology[13], the geometric model[16], and the IPCC AR5 sea level projections[12]. From this pdf, the shoreline change that corresponds to the median (or maximum probability density) is used to represent the most likely amount of projected net shoreline change in each scenario.

We use the current vegetation line to represent the present-day administrative shoreline, as it is a reasonable approximation of the state's shoreline definition, which describes the highest wash of the waves at high tide during the time of the year when the waves are highest[1]. This proxy shoreline also represents the landward edge of the beach, as well as the seaward boundary of backshore land use. We project the modeled net future shoreline change inland from the modern vegetation line under each scenario and refer to this as a projected shoreline.

SHORELINE HARDENING POTENTIAL

Using GIS layers available online through the Hawaiʻi Office of Planning's GIS Program[17], all backshore land use on the island of Oʻahu was classified into five major categories: residential, transportation-related, beach parks, other types of government-controlled lands, and undeveloped (unclassified areas where the shoreline was more than 20 ft from any type of development). In addition, the locations of existing shoreline hardening were digitized. Land use categories and hardened shorelines were identified to the parcel level and overlain with the projected shorelines (including the 20 ft buffer).

We identify the 20 ft buffer extending inland from each projected shoreline and note where it intersects habitable structures, transportation infrastructure and public facilities. These three assets have historically been the frequent target of hardening[2]. A database was developed of alongshore length of at-risk parcels, land use category, and presence or absence of modern hardening. The length of shoreline was measured using transects perpendicular to the shoreline every 20 m.

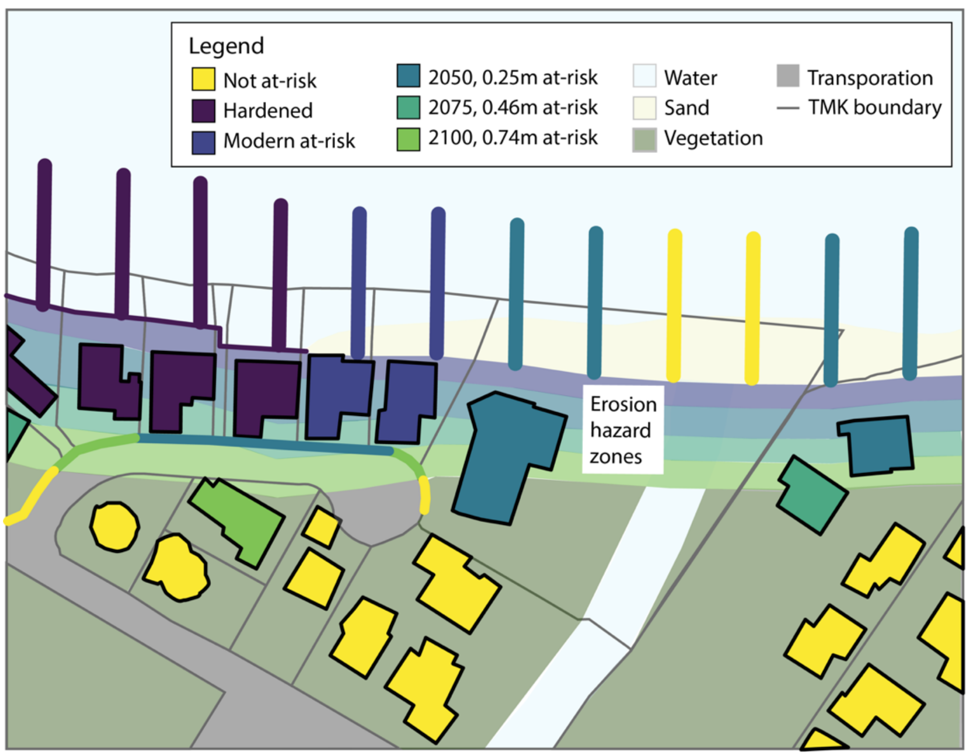


Figure 3. Conceptual diagram of shoreline development and structures hardened and at risk of hardening in modern and future erosion hazard zones (0.25, 0.46, and 0.74 m of sea level rise or 2050, 2075, and 2100 respectively). Transects perpendicular to the shore.

RESULTS

Our results reveal patterns of modern-day backshore land use on the sandy shorelines on O‘ahu (**Figure 4**). Of the 108 km of sandy shoreline analyzed, modern-day backshore land use is predominantly residential (44%) and government-owned beach parks (34%). The east, north, and south shore are mostly residential, while the west shore is mostly beach park (**Figure 5**). The remaining categories (other government lands, transportation-related, and undeveloped areas) together constitute the remaining 22% of backshore land use. We also find that 28% of all O‘ahu sandy shoreline is presently hardened, mainly adjacent to residential parcels and on the east and south shore (**Figure 6**).

In addition to the 28% of sandy shoreline that is currently hardened, another 3.6% are currently at-risk of hardening, especially beaches on the north and south shore, when considering the 20 ft. criteria for triggering an emergency permit (**Figure 7**). At greatest risk are residential lands (1.4%), followed by transportation-related backshore lands (1%), while beach parks (0.7%) and other government-controlled land (0.6%) each constitute less than 1% of backshore land use at risk of new hardening. No undeveloped lands were identified as being currently at risk of hardening.

Model results indicate that in addition to the sandy shoreline that is already hardened or at-risk in the modern-day scenario, an additional 7.4% of shoreline will be at risk of hardening under the 0.25 m SLR scenario (very likely by the year 2050[18]). This increase between modern-day and 0.25 m of SLR scenario constitutes the largest increase of hardening risk between any of the consecutive SLR increments in our analysis. At this scenario, there is a total of 39% of shoreline hardened or at risk of new hardening. Most of this at-risk area is associated with residential lands (3.8%) and beach parks (2.6%). Most of the residential lands at risk are in the north, and most of the beach parks at risk are in the west.

Between 0.25 and 0.46 m SLR (very likely by the year 2075[18]), beach parks, residential lands, and other governmental lands continue to grow risk of hardening in that order throughout the island. Notably, while the amount of at-risk shorefront residential lands will continue to increase between 0.25 and 0.46 m of SLR, the increase is less (2.6% newly at-risk residential land) compared with the increase between the modern-day and 0.25 m SLR scenarios (3.8% newly at-risk residential land). In this scenario, beach parks have a larger increase than residential lands (2.8% newly at-risk beach park land). Virtually all backshore lands related to transportation are hardened or projected to be at-risk.

Results indicate that with 0.74 m SLR (very likely by the year 2100[18]), approximately 50% of all sandy shorelines on O‘ahu will be hardened or at risk of hardening. This constitutes an 80% increase compared to the amount of presently hardened shorelines. For the length at risk of hardening, the total risk of hardening in this SLR scenario (24%) is a 515% increase compared to the current at-risk shoreline (3.9%). By this scenario, all transportation-related land is at risk of hardening. Newly identified (between 0.46 and 0.74 m SLR) at-risk residential lands (2.0%) and other government lands (0.5%) indicate a decrease in the rate of new risk compared to lower SLR intervals, while beach parks continue their pattern of consistently growing risk with each higher SLR scenario.

We also considered average shoreline change rates for the island by region (**Table 1**). Today, over half of the shoreline is eroding (defined by negative shoreline-change rates). The average shoreline change rate for the entire island is -0.03 $\pm$ 0.01 m/yr. The eastern shoreline is the only region that has a positive average rate, indicating accretion, largely due to well-documented accretion at one beach (Kailua Beach) that comprises a large portion of east Hawai‘i Beach length. However, by the 0.25 m SLR scenario, every side of the island will establish a pattern of chronic erosion with the percent of eroding shoreline increasing, and the average rate of shoreline change becoming greater. Island-wide, under the highest SLR scenario of 0.74 m SLR by 2100, 89% of the sandy shoreline will be eroding. The most erosive segments of the island are on the west and north-facing shores, where nearly all portions of these two regions are currently experiencing chronic erosion with average rates of -0.44 $\pm$ 0.04 m/yr and -0.30 $\pm$ 0.08 m/yr, respectively. Consistent with the island-wide results, residential backshore land use is exposed to the greatest risk on the north shore, while beach parks have the greatest risk exposure in the west region.

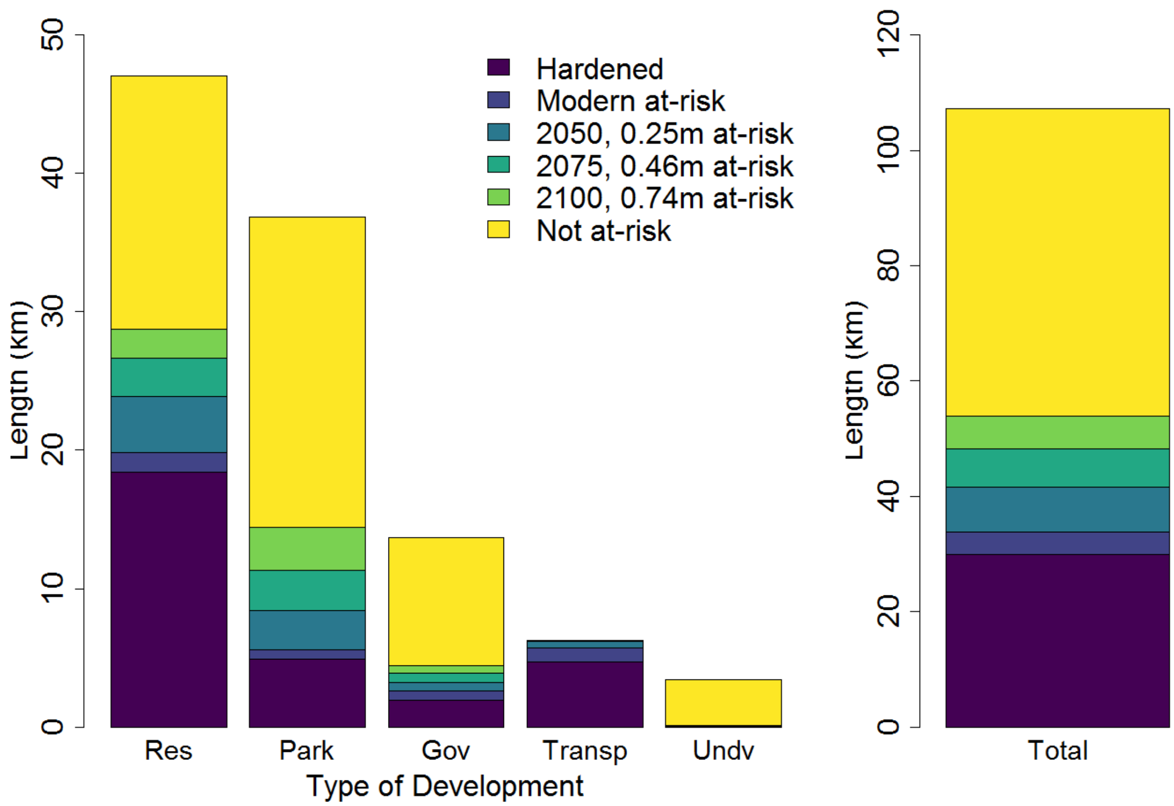


Figure 4. Patterns of coastal development. Length (km) of total sandy shoreline related to modern backshore land use (residential (Res), beach park (Park), other government lands (Gov), transportation related (Transp), and undeveloped (Undv)); modern-day hardened shoreline; projected risk of hardening under modern-day and future SLR scenarios: 2050 by 0.25 m, 2075 by 0.46 m, 2100 by 0.74 m, and totals.

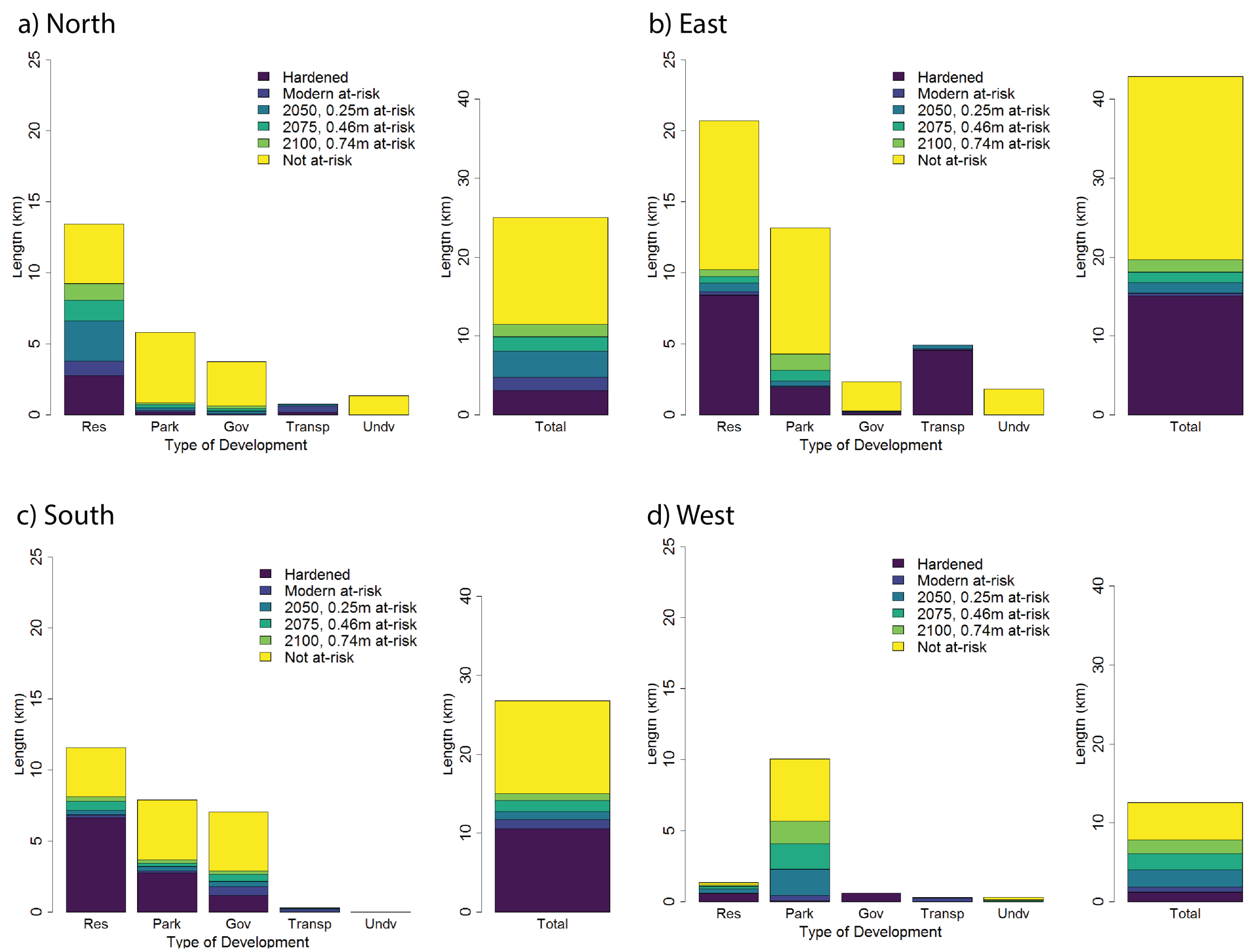
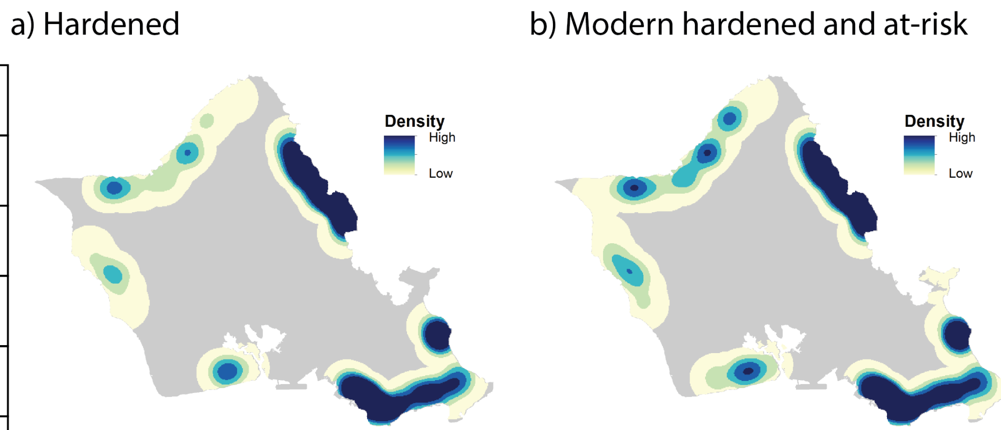


Figure 5. Patterns of coastal development for each shoreline orientation: a) North, b) East, c) South, and d) West. Length (km) of total sandy shoreline related to modern backshore land use (residential (Res), beach park (Park), other government lands (Gov), transportation-related (Transp), and undeveloped (Undv)); modern-day hardened shoreline; projected risk of hardening under modern-day and future SLR scenarios: 2050 by 0.25 m, 2075 by 0.46 m, 2100 by 0.74 m, and totals.

Cumulative Increase

Scenario	Length (km)	Percent
a)	30	28
b)	34	31
c)	42	39
d)	48	45
e)	54	50



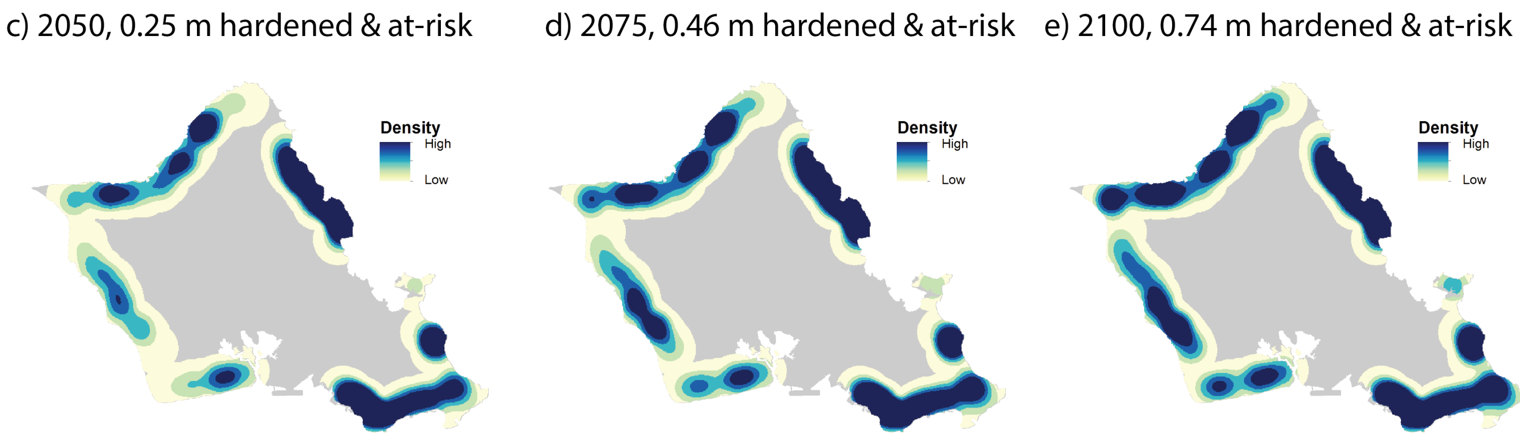
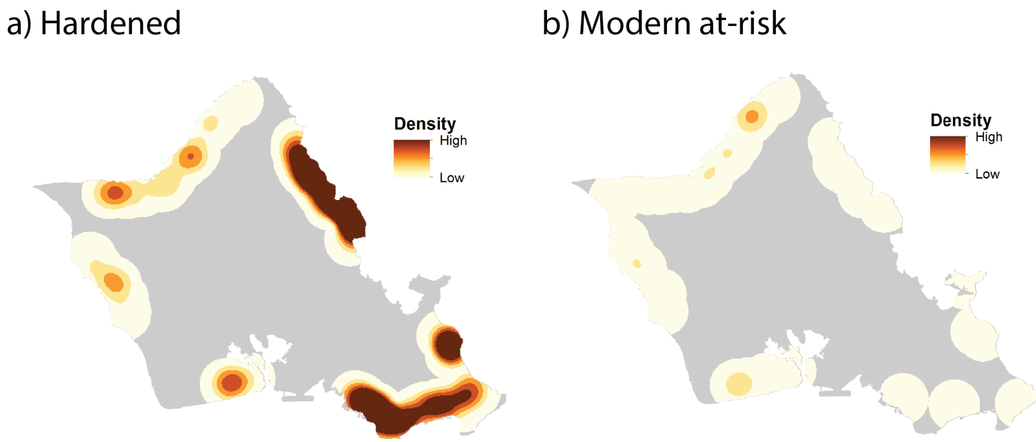


Figure 6. Density map of cumulative increase for each scenario (a) hardened and at risk of hardening under b) modern and future SLR scenarios: c) 0.25 m by 2050, d) 0.46 m by 2075, and e) 0.74 m by 2100).

Individual Increase

Scenario	Length (km)	Percent
a)	30	28
b)	3.9	3.6
c)	7.9	7.4
d)	6.5	6.1
e)	5.8	5.4



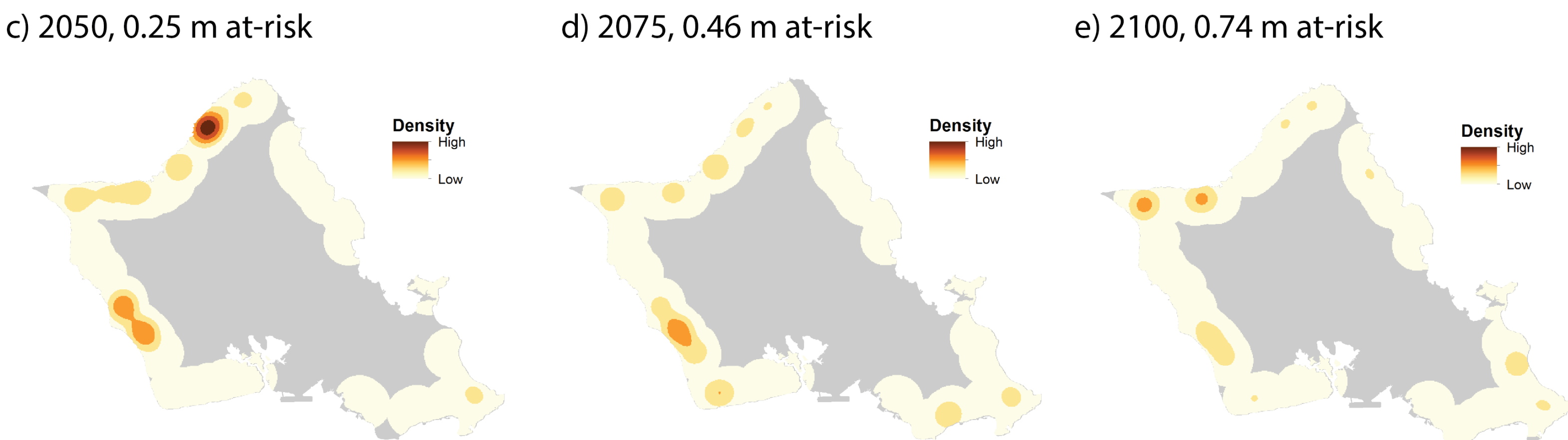


Figure 7. Density map of individual increase for each scenario (a) hardened and at risk of hardening under b) modern and future SLR scenarios: c) 0.25 m by 2050, d) 0.46 m by 2075, and e) 0.74 m by 2100).

Table 1. Patterns of shoreline change rates for the island and by each region for the modern shoreline and SLR scenarios (0.25 m, 0.46 m, 0.74 m).

Region	SLR Scenario	Shoreline change rate (m/yr)	Percent eroding (%)	Percent accreting (%)
North	Modern	-0.07 ± 0.03	72	28
	0.25 m	-0.20 ± 0.05	92	8
	0.46 m	-0.25 ± 0.06	95	5
	0.74 m	-0.30 ± 0.08	97	3
East	Modern	0.04 ± 0.03	51	49
	0.25 m	-0.09 ± 0.03	72	28
	0.46 m	-0.14 ± 0.05	78	22
	0.74 m	-0.18 ± 0.07	82	18
South	Modern	-0.03 ± 0.01	52	48
	0.25 m	-0.14 ± 0.03	75	25
	0.46 m	-0.19 ± 0.05	81	19
	0.74 m	-0.23 ± 0.07	86	14
West	Modern	-0.20 ± 0.04	89	11
	0.25 m	-0.33 ± 0.04	97	3
	0.46 m	-0.39 ± 0.04	98	2
	0.74 m	-0.44 ± 0.04	98	2
All	Modern	-0.03 ± 0.01	61	39
	0.25 m	-0.16 ± 0.01	80	20
	0.46 m	-0.21 ± 0.01	85	15
	0.74 m	-0.25 ± 0.02	89	12

DISCUSSION

Under three SLR scenarios (0.25, 0.46, 0.74 m), we are able to project future shoreline position and rate of change. Applying the 20 ft buffer rule currently in use by shoreline managers, we identify five backshore land use categories that have historically been protected by hardening as a policy choice and which qualify for emergency permitting under each scenario, as a proxy for risk of hardening. We show that SLR will likely increase shoreline erosion and, after 0.74 m of SLR, put a total of 50% of the beaches on the island at risk of hardening because of the nature of backshore land use. Consequently, we expect more shoreline to become vulnerable to beach loss, decreasing the beach resources available for social, ecological, and economical uses. Unless proactive, collaborative and conservation-oriented governance is developed, shoreline hardening and beach loss will continue to characterize coasts where backshore land use is developed.

When considering: 1) the amount of already hardened shoreline; 2) the current shoreline at risk of hardening because of assets located within 20 ft of active erosion; and 3) our model projections for hardening risk under 0.25 m of SLR, nearly 40% of beaches on Oʻahu face near-term critical management decisions that will determine their fate. The primary land use category driving risk of beach loss in all cases (currently hardened, currently at-risk, and at-risk under 0.25 m of SLR) is residential. Ironically, the second most frequently hardened shoreline today is beach parks. Transportation-related land use and other government lands are significantly hardened today and face continued risk of hardening under 0.25 m of SLR. According to Sweet et al.[18], relative to the year 2000, global mean sea level is very likely (90-100% probability) to rise 15 to 38 cm by 2050. Consequently, management decisions regarding beach conservation made today and in the next two decades will determine the continued existence of a significant portion of the beaches on Oʻahu and other coastlines in the world with similar SLR and development patterns.

Whereas there are public amenities at beach parks, these only constitute a small portion of the alongshore length at risk of hardening of this land use category. Along much of the shoreline, beach parks are adjacent to inland transportation, which is the main trigger for beach parks being at risk of hardening. Thus, beach parks act as a buffer between the retreating coast and inland transportation assets. The length of transportation assets at risk is high today and increases across the first SLR scenario (0.25 m). Thereafter, in the last two SLR scenarios, risk of hardening at transportation assets is near zero. We infer from this that by 0.46 m of SLR almost all coastal transportation assets will have experienced erosion threats. In fact, the peak in increased risk related to SLR for residential, transportation and other government lands occurs in the earlier stages of SLR (0.25 m). Undeveloped lands, stretches of unclassified land that have no development 20 ft from the shoreline, continue to show zero or near zero risk of hardening throughout all scenarios. Beach parks experience a consistently growing risk across all scenarios. This result suggests, again, that the critical time for beach conservation decisions is now and in the immediate future.

Our results confirm that shoreline hardening has been used as the primary policy tool in response to chronic erosion[2]. We find that 28% of all present-day backshore land use already hardened, with another 3.6% currently at risk. Our data reveal that with only another 0.25 m of SLR, over 10% of shoreline are at risk of being hardened. Our results identify the north and west shores as experiencing the greatest rates of shoreline change, percentage of eroding coast as well as risk of hardening under all SLR scenarios, while the south and east shore have considerable shoreline hardening and beach loss from over-development and inappropriate road placement. It is critically important that adaptation, mitigation and retreat options are developed for beachfront landowners and resource managers to avoid additional shoreline hardening. Interagency collaborations and public-private partnerships have not been deeply explored as avenues of beach conservation on Oʻahu or statewide. As identified by Summers et al.[2] shoreline management is largely a reactive, parcel by parcel, system of choices in Hawaiʻi that diminishes the role of proactive and place-based decisions. Poor shoreline hardening management practices have threatened beaches around the world historically and today and will continue into the future if not changed. Our data indicate that the critical time for resolving this problem is now.

CONCLUSION

- Future shoreline projections under SLR scenarios, when analyzed in terms of backshore land use, provide a globally relevant warning to resource managers and stakeholders that modern-day and immediate near-term decisions strongly impact beach conservation.
- Modeling reveals that the maximum risk of shoreline hardening, and, by extension beach loss, peaks before mid-century.
- Residential lands, beach parks, other government lands, and transportation assets (respectively) are in critical need of new management options focused on beach conservation.
- The reactive and piecemeal approach to beach management has failed under historic policies. A new regime of decision-making that emphasizes proactive, place-based and collaborative partnerships is urgently needed if beaches are to be conserved for future generations, cultural practices, critical ecosystems, and state economies.

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