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Improving Adaptation Planning for Future Sea-Level Rise: Understanding Uncertainty and Risks Using a Probability-Based Shoreline Model

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Abstract

Sea-level rise (SLR) presents risks to communities and ecosystems because of hazards like coastal erosion. In order to adapt, planners and the public seek estimates of shoreline change with high confidence and accuracy. The complexity of shorelines produces considerable uncertainty in the timing, location and magnitude of change. We present and discuss a probabilistic shoreline model for SLR planning. Using the coast of Maui as an illustrative case, we compare this model to a common deterministic model. We discuss the advantages of a probability-based model for SLR adaptation, including for prioritizing actions, phasing, visualizing risk and uncertainty, and improving adaptive management.

Keywords

climate change adaptation, sea-level rise, probability models, shoreline change

Introduction

Sea-level rise (SLR) presents significant risks to coastal settlements, infrastructure, cultural resources, and sensitive species habitats. Increasingly, planners, resource managers and policy-makers must identify how, where, and when to adapt to changes resulting from SLR, while minimizing the impact to human populations, natural systems, or both. Incorporating future hazards associated with SLR, such as coastal erosion and beach loss, into land use planning is vital to land use policy. This article presents a probabilistic model of coastal hazards associated with SLR that makes explicit use of scientific uncertainty and discusses its application to land use planning for the next 50–100 years, using the example of a Hawai`i coastal community.

Coastal managers, planners, and engaged communities in adaptation planning seek projections of SLR impacts and want to examine what specifically is at risk, what the magnitude of the impact might be, and how long they have to prepare. Historical data or geometric models are commonly used to forecast hazards. Yet, the dynamic nature of open coast environments is difficult to model accurately for every specific place. Consequentially, there have been recent calls for the use of probabilistic forecasts of future shoreline change and associated hazards as a basis for coastal adaptation with the explicit incorporation of uncertainty (Cowell et al. 2006; Moser, Williams, and Boesch 2012). This article addresses how coastal planners can use best-estimate models of the future, and the associated uncertainties, to prioritize adaptation strategies and develop long-term plans. We argue that an adaptive risk management approach with probabilistic methods can improve the scientific basis for coastal land use policies and support community participation in adaptation planning.

The goals of this article are: (1) to present a case of how a probability-based model can be used to estimate, manage, and adapt to long-term SLR; and (2) to discuss the benefits to local governments and communities of linking scientifically based SLR predictions and their uncertainty to SLR adaptation planning, planning processes, and land use policies. This can improve land use planning in the face of SLR, including the ability to prioritize areas for adaptation while accounting for variability in coastal change, managing uncertainty, and incorporating flexibility into future decision making.

The first part of this article discusses the need for, and use of, a probability-based model of shoreline change,

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which incorporates future SLR, and how this tool can be used to plan for SLR adaptation. The second part uses the Ka`anapali coast of Maui as an example, where we develop probability-based erosion hazard maps and compare the outcomes with a deterministic model for estimating future hazards. We estimate the likelihood of loss of assets, properties, and infrastructure 50–100 years in the future, and show how a community can visualize risk and develop a place-specific decision matrix of priority adaptation actions. The third part of this article discusses the benefits of the model in a community land-use planning context, including the ability to describe the spatial and temporal extent of impacts, and examine the risks in light of uncertainty. Through this example, we accentuate opportunities for communities to shape land use plans through strategies that respond to local conditions by explicitly mapping uncertainty and incorporating adaptive management that emphasize flexibility and learning.

The Need to Plan for and Adapt to Sea-Level Rise

One of the anticipated impacts of climate change is SLR threatening low-lying areas around the globe (IPCC 2014). The implications to coastal systems are significant, including the physical impacts from submergence, flood damage, saltwater intrusion, rising water tables, wetland loss, and accelerated coastal erosion (Nicholls and Cazenave 2010). Future accelerated SLR is particularly worrisome for many of the world's sandy beaches that already experience chronic erosion and are expected to experience more land loss. A recent study estimates 6,000 to 17,000 km^2 of coastal lands will be lost globally during the twenty-first century due to SLR-induced erosion and between 1.6 and 5.3 million people may be forced to migrate (Hinkel et al. 2013). As most of the world's population lives within 60 km of the coastline, community infrastructure and support services are also at risk. Critical habitat for many sensitive species in the shoreline are currently under threat because of degradation and loss of coastal lands; additional loss of marshes, dunes, and beaches due to the "coastal squeeze" could spell disaster for many of the world's shorebirds, sea turtles, and seals (Defeo et al. 2009; Pontee 2013). For example, sea level rise might further reduce shoreline habitat for Hawaiian monk seals to rest, pup, nurse, and mate (National Marine Fisheries Service 2016).

Beach loss due to SLR is the consequence of more than just the inundation of coastal lands. As sea levels rise, beaches and dunes transform as a consequence of climate-induced oceanographic processes (e.g., storms, waves, and currents), sediment supply and transport dynamics, and human activities that alter sediment movement (Nicholls 2010; Williams 2013).

Coastal managers and planners look for credible scientific information to facilitate coastal adaptation, the management of resources, and the implementation of strategies over time (Tribbia and Moser 2008). However, the dynamics of a coastline make it difficult to predict future SLR-induced erosion with a high degree of confidence and place-based accuracy. SLR, in particular, presents several challenges for land use planning and coastal management. SLR is a long-term problem that is mostly "invisible" from daily problems because it progresses relatively slowly (Moser 2005). Thus, it may not be obvious that there is a direct causal link between the slow, creeping process of SLR and the acute impacts of storms, flooding, and erosion, which, in turn, makes it difficult to isolate SLR from other coastal processes. Another challenge is the considerable uncertainty in understanding the geographic patterns, timing, and magnitude of future impacts of SLR, especially (1) uncertainties associated with future global emissions scenarios that affect the future rate of SLR, and (2) uncertainties associated with the relationship between SLR and shoreline change. This article is primarily concerned with the latter as it influences local efforts to plan and adapt to a shifting coastline.

Traditional decision-making frameworks that rely on single "best estimates," fixed spatial hazard lines, and cost–benefit analyses (Dittrich, Wreford, and Moran 2016; Bell et al. 2014) face considerable challenges when applied to climate adaptation. O'Brien et al. (2012) review the psychological and economic barriers shaping how people make decisions under uncertainty. Individuals and groups often underestimate low-probability and high-risk events. Where there are high upfront costs associated with adaptation, the focus will often be on short-term goals rather than long-term benefits of alternative options. For example, a focus on short-term interests that respond to extreme events will preclude long-term adaptation strategies, and long-term erosion problems will be omitted from local solutions (Donner and Webber 2014). The result can lead to lock-in legacy infrastructure, such as protective sea-walls. Under conditions of uncertainty, different views emerge on the nature of risks associated with future hazards. Conflicts arise over preferred response options (e.g., sea-wall vs. managed retreat) due to contested understandings of causal relationships between SLR, erosional exposures, and impacts (Moser, Williams, and Boesch 2012). Further, and perhaps more consequential to planners, different groups respond to risks according to their own values, leading to divergent interpretation over whether risks are acceptable, tolerable, and potentially leading to mistrust in outcomes (Van Asselt and Renn 2011). Experience shows that meaningful interaction and dialogue around scientific uncertainty is paramount for building trust in the adaptation process and confidence in policy outcomes (Dietz 2013; Bell et al. 2014; Kettle and Dow 2014).

Uncertainty can also lead to inherent skepticism in model predictions particularly among groups that voice opposition to planning for SLR (Great American Adaptation Road Trip 2013). This can delay adaptation efforts, leading some groups to support a reactive, "wait to plan" approach until there is more certainty in model outputs. Yet, the disaster and hazards community has recognized the need to shift from an ad hoc reactive system to a proactive, mitigative focus (Burby et al. 2000; Godschalk 2003; Beatley 2009). Integrating hazards into land use planning involves technical analysis of hazards *and* community participation within a long-term, anticipatory, and comprehensive planning and risk management framework (Godschalk, Brody, and Burby 2003). Community engagement is essential to ensure citizen interest in natural hazards and to obtain broad support for the implementation of plans and policies. Recommendations for climate change adaptation agree that risk-based management approaches are more effective (Lim et al. 2004; NRC 2010). Better decisions can be made if they are place-based and contain a sequential adaptive management approach. Moser, Williams, and Boesch (2012) assert that this proactive approach involves six components: (1) careful risk identification; (2) vulnerability assessment and evaluation; (3) systematic development and assessment of adaptation strategies; (4) iterative decision making combined with deliberate learning; (5) decisions with long time horizons that maximize flexibility, enhance robustness, and ensure durability; and (6) a portfolio of approaches rather than single technological fixes or market mechanisms.

The risk characterization process for hazards is more than a scientific effort or summarizing activity, it is decision-driven from the outset, recognizes all significant concerns, reflects both analysis and deliberation, and is designed to be appropriate to the decision (NRC 1996). Thus, there is growing acceptance that adaptation efforts should take place at the community level, with an assessment process closely involving local stakeholders (van Aalst, Cannon, and Burton 2008; Berke and Lyles 2013). Characterizing the risks requires information and data on the local impacts of SLR on shorelines with sufficient detail to quantify the risks[1] associated with future SLR. Risk is defined as the product of the probability or likelihood of an event and its consequence (NRC 1996). The consequence (or set of consequences) is associated with the exposure to future hazard(s). Uncertainty is inherently a part of identifying risks as uncertainty can affect the probability and consequences of risk. Taken together, a risk-based approach to coastal adaptation implies the use of a place-based model that can approximate the impacts of SLR and its uncertainties over the next fifty to hundred years.

Models Predicting Coastal Impacts of SLR

Models can estimate the impacts and risks of SLR both quantitatively and qualitatively. Simple quantitative approaches include the "bathtub" model, where, under a given SLR scenario, land lower than a particular sea level is presumed inundated. The bathtub approach has been used widely for modeling impacts, particularly with the advent of high-resolution digital elevation data. However, this assumes static SLR and ignores the dynamics of the coastal environment and geomorphic feedbacks, in particular the physical reorganization of sediment material leading to shoreline migration. Another quantitative approach is to extrapolate trends of historical shorelines to project future shoreline change. Yet, this is problematic because extrapolation does not account for future SLR and, oftentimes, past records to determine rates are incomplete (Pilkey and Cooper 2004). An alternative approach commonly used is the "Bruun Rule," a simple mathematical model that relates SLR to shoreline retreat based on the conservation of beach volume. Using two variables, SLR and beach slope, the model essentially predicts that, as sea-level rises, sediment erodes from the upper part of the beach and is deposited on the nearshore bottom while maintaining the original slope of the beach (see model details in Appendix A).

The Bruun rule has been criticized for its limiting assumptions of the physical setting. For example, it assumes no sediment sources or sinks and ignores the effects of surrounding geology, man-made constraints, and sediment availability. It also runs the risk of being applied incorrectly as a "one model fits all," with SLR as the only important factor always causing shoreline retreat (Pilkey and Cooper 2004; Bell et al. 2014). There are variations of the Bruun Rule, such as the R-DA method, which alter the underlying assumptions of the model and incorporate more accurate sediment transport processes (Davidson-Arnott 2005). Yet, because these models are derived from the Bruun Rule, they suffer from similar inaccuracies. These deterministic approaches have advantages for being easily understood and updated as new data are collected. However, they do not account for spatial or temporal variability in coastal processes or for the fact that erosion can be episodic.

Pilkey and Cooper (2004) argue that Bruun-type models are inherently inaccurate due to the dynamic nature of coasts. They propose the use of a more qualitative approach that combines historical trends with an "expert eye" that considers local geological constraints, local sand sources, and man-made structures (present and future). As an alternative, process models can describe beach evolution with more detail than the above-referenced models. However, one problem with process models is that they require intense computation and field data collection of waves and water levels at high temporal and spatial resolutions, which makes them functionally impractical over large geographic areas (Hanson et al. 2003).

By comparison, probabilistic forecasts can provide a more transparent basis than deterministic predictions for management decisions by communicating the inherent uncertainty in future coastal hazards (Cowell et al. 2006). For this reason, there have been calls for the incorporation of probabilistic methods to account for both uncertainty in model outputs and the complexity in coastal change (Cowell et al. 2006; Moser, Williams, and Boesch 2012). Probabilistic approaches to inform SLR impacts have been developed in several planning domains, most commonly in order to assess the probability of coastal flooding. Kirshen, Knee, and Ruth (2008) used bootstrapping of historic SLR and Monte Carlo simulation of projected sea levels and coastal inundation of the Metro Boston harbor. Lin et al. (2013) estimated probabilities of annual exceedance of specific inundation levels at future time points to examine change in exposure across the Southeast Australian coast. Recently, probabilistic methods have gained momentum in the beach management sphere to incorporate the temporal-spatial variability of shoreline change (Callaghan, Roshanka, and Andrew 2009; Ranasinghe, Callaghan, and Stive 2011). Baron et al. (2014) incorporates the uncertainty associated with both SLR and changing beach dynamics using a probabilistic approach to map shoreline change hazards with varying confidence levels. Lentz et al. (2015) used a Bayesian network to assign probabilities to sea-level rise, elevation, and land cover that take into account a static response (inundation) and a dynamic response to SLR (e.g., sediment transport dynamics and ecosystem migration). To our knowledge, probabilistic approaches have not been adopted and applied in a community land-use decision-making context for adaptation planning.

Methods

Probability-Based Model of Shoreline Change in Hawai`i

We use a hybrid geometric-historical model to estimate shoreline change under SLR in Hawai`i. This model is similar to the Bruun rule in its beach response to SLR; however, it adjusts the morphology of the beach with data on changes in the local sediment budget. This model was constructed to take advantage of a probabilistic approach to define bounds of uncertainty and represent future shoreline with likelihood estimates. It is intended to provide an assessment of erosion exposure over a large coastal area while taking into account SLR and local long-term sediment behavior. The details of this model are explained elsewhere (Anderson et al. 2015). For the purposes of this article, we present a brief overview of the model variables and how they estimate present and future rates of shoreline change.

In this model, the rate of change in shoreline position is approximated using three critical variables: future SLR, a coastal beach profile, and historical shoreline positions. Figure 1 graphically depicts the model with arrows to show the relationship between model variables. "Future SLR in excess of historical SLR" is estimated based on the IPCC AR5 high-end "business as usual" climate scenario (RCP 8.5) for SLR. This scenario was selected based on State planning agency preference for the most cautious predictions of SLR for long range planning purposes. Future SLR is calculated by subtracting local absolute SLR (from Honolulu tide gauge data) from the IPCC AR5 global mean sea-level estimate. "Coastal beach profile" is constructed from beach survey transects of cross-shore elevations—previously conducted for years 1994–1999 on the islands of O`ahu and Maui, and 2006–2008 for shorelines on O`ahu and Kaua`i (Fletcher et al. 2012). Each beach profile is geomorphically adjusted for future SLR. Shoreline change is approximated using historical shoreline position data from high-resolution aerial photographs and NOAA Topographic charts as part of the USGS National Assessment of Shoreline Change (Fletcher et al. 2012). Using a model of a coast with a fringing reef that responds to future SLR, shoreline change rate is predicted combining historical shoreline position data with coastal beach profiles that are adjusted for projected SLR (Anderson et al. 2015). We provide the model equation and methodological details in Appendix A.

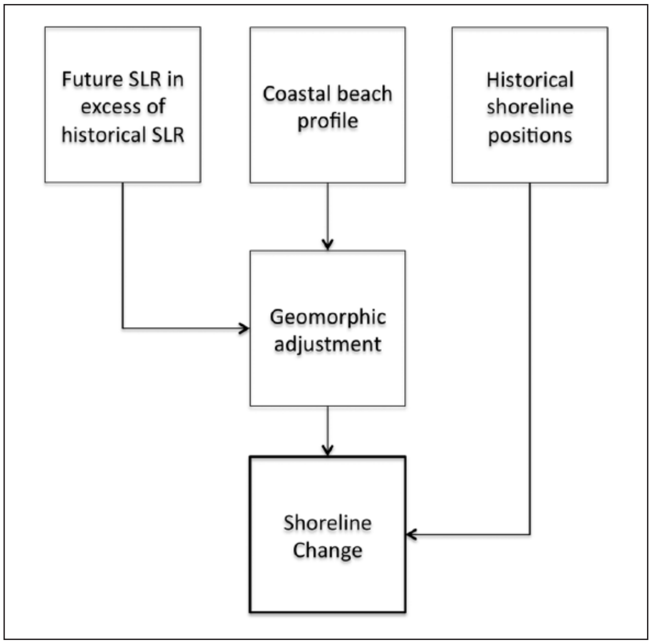

Figure 1. Graphical depiction of probability-based model with input variables to predict shoreline change.

By 2100, Hawai`i shorelines are forecasted to retreat 2.5 times farther inland than historical shoreline trends (Anderson et al. 2015). On average, Hawai`i beaches are expected to retreat 11.3 meters by 2050 and 31.2 meters by 2100 (Anderson et al. 2015). However, there is considerable variability in erosion estimates both across and within coastal areas. The Ka`anapali coast of Maui (Figure 3, inset) exemplifies the variability in shoreline change and the challenges in predicting future erosion. Although shoreline retreat is expected to dominate, the area will alternate in shoreline recession and accretion. Additionally, the coastline experiences substantial seasonal fluctuations. Because of its west-facing aspect, episodic seasonal swells can have a sudden and dramatic impact on the beaches. These episodic yet significant events can get lost in the historical data and therefore are difficult to incorporate into model parameters. Additional sources of uncertainty are also generated because of errors in the construction of beach profiles and in areas with shorter time series of historical data.

A unique feature of the model is its treatment of uncertainty. Individual probability density functions (pdf) at each beach transect is produced combining probability distributions of (1) future SLR, (2) coastal beach profile and dune data, and (3) historical shoreline change rate. A final pdf is produced to determine the mean, median, and various percentiles using the cumulative distribution function of the pdf for the projected shoreline (Figure A1 in Appendix A.). Using these pdfs, we define a series of probability-based shoreline change hazard zones for planning periods of interest.

Shoreline Change Hazard Zones

Similar to Baron et al. (2014), we define shoreline change hazard zones by exploiting the confidence bands surrounding the future shoreline position. At periods of interest, shoreline hazard zones are defined by the probability that the shoreline will be further landward than an existing position. For example, the 20th percentile of the pdf (see Figure 2) is the location where there is a 20% probability that the shoreline will retreat, at least, to this location. Figure 2 graphically illustrates hazard zones that depict probabilities of shoreline change exceedances. These zones provide coastal planners and decision makers with the ability to select probabilities that best match the local community risk tolerance. For example, members of the Hawaiian community may have a low-risk tolerance for the loss of iwi kupuna (burials) and therefore will use the most conservative zone, 20–49 percent probability of exceedance. By contrast, planners may use a moderate zone of 80–90 percent probability because they have a higher risk tolerance for the erosion of the beach. The development of these hazard zones facilitates (1) a risk and vulnerability assessment and (2) the explicit incorporation of uncertainty into community planning and decision making for SLR adaptation.

Application of Model for Adaptation Planning in Ka`anapali, Maui

Maui is a useful illustrative case to explore the application of this probability approach because the island experiences some of the highest rates of erosion among Hawai`i beaches and has an established policy framework for integrating hazards into shoreline planning. Historical data show 85 percent of Maui beaches are currently eroding and 11 percent are completely lost (Fletcher et al. 2012). As a result, Maui's local resources, physical structures, infrastructure, and tourism developments face substantial risk and, in turn, can influence the use of protective measures such as seawalls and shoreline hardening. It is well documented that—unfortunately, and perhaps ironically—while these structures are intended to prevent erosion, they actually often have spillover effects, intensifying beach erosion in adjacent areas by interrupting the natural flow of sand, leading to further narrowing of beaches (NRC 2007; Norcross-Nu'u et al. 2008).

Maui integrates hazards planning into land use decisions under the regulatory authority of the Hawai`i Coastal Zone Management (CZM) Program. The county is also actively engaged in adaptation efforts (Owens et al. 2012). Hawai`i established a shoreline setback policy under Chapter 205A, Hawai`i Revised Statutes of the Hawai`i CZM law, that restricts the use of land within a defined distance from the upper reaches of the wash of the wave. Permanent structures are prohibited in shoreline areas defined by the setback and land uses are restricted to minor activities (Codiga, Hwang, and Delaunay 2011). In 2003, Maui County adopted a science-based approach to determine the setback by incorporating erosion-based data (Norcross-Nu'u et al. 2008). The law requires a 50-year erosion multiplier, plus a 25-foot buffer. The 25-foot buffer is established as a safety margin to reflect current and future erosional trends; however, given the expected acceleration of SLR, this safety margin may underestimate future rates.

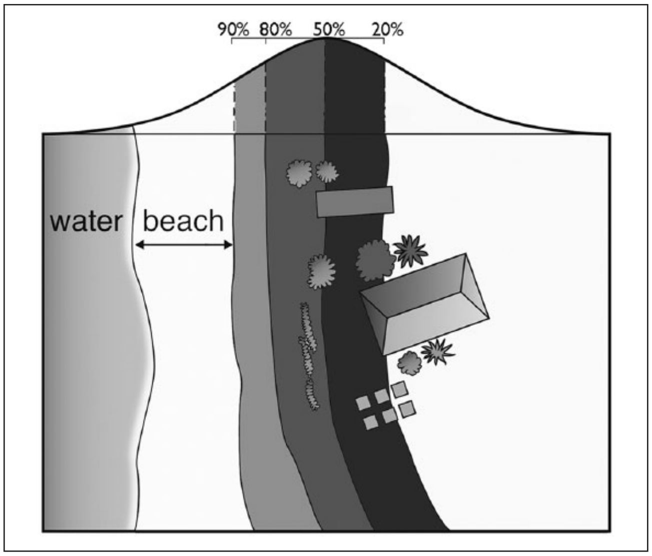

Figure 2. Conceptual representation of hazard zones using probabilities that the shoreline will be landward of the current position. Hazard zones range from >90 percent (very likely) to >20 percent (less likely) the shoreline will be further landward than the current shoreline.

During the early 1960s, Maui shifted from an agricultural-based economy to tourism and Ka`anapali became the first master-planned resort in Hawai`i. Ka`anapali, on the West Coast of Maui, hosts many large hotels and resorts, and the visitor industry provides a significant source of jobs and economic activities. Historically, Ka`anapali has lost 0.10 meters of beach every year (Anderson et al. 2015). By 2050, this rate is expected to more than double (0.3 meters/year) and nearly quadruple by 2100. Yet, there is considerable uncertainty in the rates due to high seasonal fluctuations and large variability in the beach slope (Anderson et al. 2015).

We apply the probability-based model to examine the spatial and temporal variability of risk in Ka`anapali for 2030, 2050, and 2100. We compare the outcomes of the probability approach with the commonly used Bruun Rule for estimating future hazard exposure due to SLR. We focus on the hazard aspect of risk by providing an assessment of exposure to future erosion; but not the extent of the impact, which would involve a fuller vulnerability assessment of resources of value.

Framework for Prioritizing Adaptation Needs

We develop a framework for prioritizing adaptation needs based on the risk and onset of impacts to coastal resources, structures, and infrastructure in erosion hazards zones for three time frames: 2030 (near-term), 2050 (mid-term), and 2100 (long-term). We evaluate risk based on the probability of erosion and time frames—assigning “less likely” to 20–49 percent; “more likely than not” to 50–79 percent; and “likely/very likely” to 80–100 percent—which draws on best practices for qualitatively characterizing and reporting uncertainty (CCSP 2009). We modify decision matrices, originally developed by the California Emergency Management Agency and the California Natural Resource Agency for the Cal-Adapt program (cal-adapt.org), to help local jurisdictions prioritize and identify adaptation strategies (Boswell, Greve, and Seale 2012).

Table 1 shows the decision matrix where the risk/uncertainty according to probabilities is presented in the columns, and the time frames of expected onset are in the rows. The assessment and prioritization of adaptation needs and strategies can be determined based on the intersection of the estimated time frame and likelihood of onset. We assign a ranking of “high,” “medium,” or “low” based on equal weights for level of risk and time frame.

Another approach, which would be a joint decision by the community and adaptation team, might be to base a heavier weight on uncertainty, so even if the uncertainty is high (less likely) in the near-term, the priority for adaptation might remain “high.” This might take into account important cultural resources, natural systems, and other assets ranked as a high priority, and would trigger a need for adaptation immediately, whereas assets ranked as medium priority would require further assessment and evaluation, and assets ranked as low priority would be monitored.

Future Shoreline Hazard Zones

We perform an impact assessment of the Ka`anapali coastline to SLR-induced erosion, using GIS (ArcGIS version 10.2.2), within erosion hazard zones at given probabilities for near-term (2030) medium-term (2050) and long-term (2100). For comparison, we also estimate exposure to future erosion due to SLR determined by the Bruun Rule. We create hazard polygons using the most recent low water mark as the seaward boundary, whereas 90th, 80th, 50th, and 20th percentiles of the cumulative pdfs were used as the landward boundaries of each zone. We assign qualitative characterizations to their respective probability field, as discussed above. Because the percentiles of the cumulative pdf represent the given probability that the future shoreline will be landward of the particular line, the erosion zones equate the minimum amount of eroded land at a given probability.

We project the probable erosion hazard zones for 2030, 2050, and 2100 (Figure 3). We estimate structural and land use impacts by extracting data on land cover types, parcel areas, building footprints, building and land values, and major roadways within each hazard zone. Ancillary parcel and infrastructure data were obtained from the Maui County GIS databases, and 2010 land cover was extracted from NOAA’s Coastal Change Analysis Program (C-CAP). We calculated the percentage of land cover within each erosion zone by dividing the total area of land cover type by the total area in each erosion zone.

To estimate the impacts to structures and lands, we assume that once erosion reaches a structure, it either becomes unusable or must be protected. Any structure within the hazard zone, either partially or completely, is considered an “affected” structure. Similarly, because the value of a building cannot necessarily be divided, we count the cumulative value of entire structures. To gauge the absolute structural impact, we calculate the square footage of building footprints within each erosion zone. We determine land impacts by identifying parcels within each erosion zone and summarizing total acreage. Since erosion may affect only portions of land parcels, we estimate land value based on the proportion of the parcel value within each erosion zone.

Results

The outputs from the two models are graphically represented in Figure 3. This map depicts four probability hazard zones that qualify shoreline change from “less likely” to “most likely” for 2030, 2050, and 2100. We overlay the projected future shoreline from the Bruun Rule (dashed line). There are three zones that are noteworthy to visually compare. The first is the beach in the northern portion of the North Ka`anapali Coast, an area just south of Kekaa Point and located in front of the Sheraton Maui (Figure 3). This area has shown a steady trend of net accretion over the last 80 years (Fletcher et al. 2012). However, because of seasonal differences in wave exposure, the beach width varies noticeably between winter- and summertime (Anderson et al. 2015; Eversole and Fletcher 2003). Here, the Bruun Rule is likely to overpredict the future erosion hazard because it does not account for the steady net gain in sediment. The second noteworthy zone is the shoreline in front of the Ka`anapali Alii hotel (central portion of Figure 3). Similar to the first zone, this portion of the beach experiences large changes in sediment transport because of oscillating directions of incoming seasonal swells (Eversole and Fletcher 2003). For example, during the summer of 2003, an extreme erosional event from a south swell in conjunction with a high water level caused the loss of more than 200 feet of beach, as well as inland flooding, which prompted the installation of steel road plates to protect the sidewalk from eroding (Owens et al. 2012). As the summer swell subsided, and the winter swell season began, more than 100 feet of beach was reestablished in front of the hotel. These episodic events in both of these locations produce hazard zones marked by bands of high uncertainty (20–49 percent “less likely”) and moderate uncertainty (50–79 percent “more likely than not”). Conversely, the Bruun Rule results only indicate one predicted location (relatively near the current vegetation line)

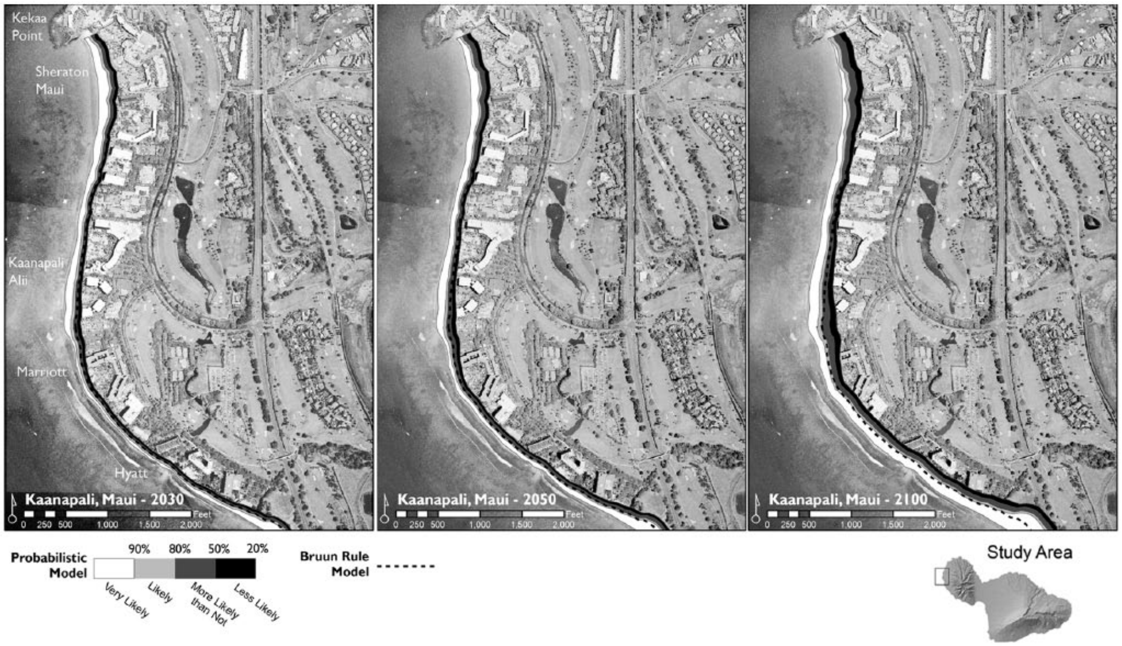

Figure 3. Ka`anapali Coast depicting four probabilistic hazards zones from "less likely" to "very likely" for three time periods, 2030, 2050, and 2100. The dashed line is the future erosion hazard line determined by the Bruun Rule.

Table 1. Framework for Prioritizing Adaptation Needs.

Impact/onset (time frame)	Risk/Uncertainty		
	Likely/Very Likely	More Likely Than Not	Less Likely
Near-term (2030)	High	High	Medium
Medium-term (2050)	High	Medium	Low
Long-term (2100)	Medium	Low	Low

that does not give any indication of the short-term (seasonal) events that are known to cause severe episodic erosion in this area. The third noteworthy area is in front of the Marriott and Hyatt Regency properties (Figure 3). This area is less dynamic than the first two. It experiences less gross sediment transport, yet suffers from both episodic erosion and long-term chronic erosion (Fletcher et al. 2012). As a result, the Bruun Rule likely underpredicts future shoreline change because it does not account for the chronic loss of sediment.

We calculate the total predicted land area exposed to future erosion using the Bruun Rule and the probability model for 2030, 2050, and 2100 (Table 2). The Bruun Rule estimates 18.4, 19.6, and 24.5 acres at risk for the three time periods, respectively. By comparison, the probability model generates the ranges: 10.8–26.8 (2030), 12.5–30.8 (2050), and 19.2–45.8 (2100) acres. Overall, the output from the Bruun Rule has a smaller footprint (in total land area) than all probability model zones combined, but according to independent studies and as illustrated here, the Bruun Rule likely overpredicts in some areas and underpredicts in other areas.

We calculate the proportion of each land cover type exposed to future erosion according to the probability-based model for years 2050 and 2100 (Figure 4). The pie charts (Figure 4A) represent the estimated percentage of each land cover type in the hazard zones at risk by 2050 and 2100. The bar graphs (Figure 4B) show the distribution of the likelihoods associated with each exposure estimate. For example, by 2050, the probability model estimates that up to 30.8 acres of land are at risk of erosion (Table 2). Of this total land area, 21 percent is categorized as "unconsolidated shore." The bar graph indicates that by 2050, more than 70 percent of this unconsolidated shore is "very likely" to be lost to erosion.

Most of the certainty in the probability model results is associated with the projected "unconsolidated shore" land at risk in 2050 and 2100—nearly 90 percent of the beach area at risk is "likely" or "very likely" to be exposed. By contrast, there is significantly more uncertainty associated with the exposure of developed lands. Nearly 50 percent of the built environment (classified as impervious surfaces) projected as exposed to erosion in 2050 is "less likely," which signifies

Table 2. Total Land Area (in Acreage) Calculated from Satellite-Derived Land Cover Estimated at Risk Using the Bruun Rule and the Hybrid Probability Model.

	Bruun Rule	Very Likely (≥90%)	Likely$^+$ (≥80%)	More Likely Than Not $^+$ (≥50%)	Less Likely$^+$ (≥20%)
Near-term (2030)	18.4	10.8	14.1	20.5	26.8
Midterm (2050)	19.6	12.5	16.4	23.6	30.8
Long-term (2100)	24.5	19.2	24.8	35.2	45.8

Note: The superscript plus sign indicates cumulative probability zones (e.g., "Likely$^+$" = "Very likely" + "Likely").

that our confidence in these estimates varies widely. Similarly, the amount of open space (which accounts for the largest at-risk land cover type) that is "less likely" to be exposed is high, nearly 40 percent in 2050. However, this likelihood estimate decreases to almost 25 percent in 2100, signaling that our confidence increases the further we project into the future.

Table 3 reports total private property acreage, length of roads, number of structures, and property values (calculated and estimated as discussed above) within each probability erosion zone for 2030, 2050, and 2100. In the near term, 4.1 acres of coastal land are likely or very likely to be affected by erosion, which represents $7.3 million in property value. By comparison, in the near term, more than double that amount of land (8.8 acres) is more likely than not eroding, signaling a potential loss of nearly $19 million. Although there is less likelihood, an additional 6 acres of coastal land are at risk of exposure in the near term, which is valued at approximately $16 million. Projecting into the future, we estimate that nearly 7 acres (almost double the 2030 acreage) are likely to be affected by 2050, and more than twice that amount (over 15 acres) by 2100.

Building structures do not appear urgently at risk in the near-term, yet between two and four buildings might be at risk. Given that these buildings represent upward of $1 billion in investment, further assessment and evaluation is warranted. By 2100, it is likely that three buildings will be affected by erosion, and there is a chance that somewhere between five and fifteen buildings could also be at risk, with values potentially running as high as $1.4 billion.

In the near-term, roads do not appear directly at risk. Although less certain, portions of an arterial road and a major highway may be at risk (between 322 and 615 feet). Projecting further into the future, the likelihood of road exposure increases. By 2050, 368 feet of road will likely be at risk and by 2100, more than 1,000 feet of road will likely be at risk.

Discussion

We estimate exposure and map risks for the Ka`anapali coast of Maui, a shoreline with tremendous value to the local culture, population, and tourism industry. It is also a location that will likely experience accelerated rates of erosion due to SLR, threatening the future of the beach. Further, the development pattern of the coastline, which is primarily composed of static resort amenities, buildings, and infrastructures, prevents shoreline migration, producing the proverbial "coastal squeeze." We compared the outcomes of two models that estimate future erosion hazards zones, one that adopts the Bruun Rule, a widely used deterministic approach to predict future erosion, and another that is a hybrid model that takes advantage of likelihood estimates to produce probable hazards zones. We discuss the four principal benefits of a probability-based model for adaptive coastal risk management: (1) as a tool for prioritizing adaptation actions, (2) the phasing of adaptation strategies and investments with long lead times, (3) to visualize risk and associated uncertainty, and (4) for adaptive management.

Prioritizing Adaptation Actions

Outputs from probability-based models are useful for prioritizing climate adaptation efforts. In our illustration, areas that fall within the 50–80 percent probability hazards zones are at risk in the next fifteen to thirty-five years and require immediate attention by the local planning agency and community. Local efforts may want to engage stakeholders in identifying sensitive social, ecological, and cultural systems that are vulnerable to near-term erosion, as well as appraising adaptation strategies. Care must be taken not to interpret these risks as short-term. The erosional pattern may be part of a long-term trend, which, if viewed through too narrow a lens, can influence shortsighted measures that prove maladaptive or detrimental. For instance, protective responses such as shoreline hardening, which has already made its imprint on more than 70 percent of Maui's shoreline (Norcross-Nu'u et al. 2008), aimed at reducing acute losses and thus increasing land or resource value, may eventually fail because of the long-term trend of SLR. Moreover, such strategies may produce negative externalities and spatial spillover effects by increasing the local rate of erosion downshore (Fletcher et al. 2012). There is general agreement that when current climate risks are large, such as chronic and accelerated rates of erosion under SLR, addressing these risks in combination with more distant risks may be the most effective and efficient adaptation strategy, leading to desirable outcomes, as discussed below (Füssel 2007).

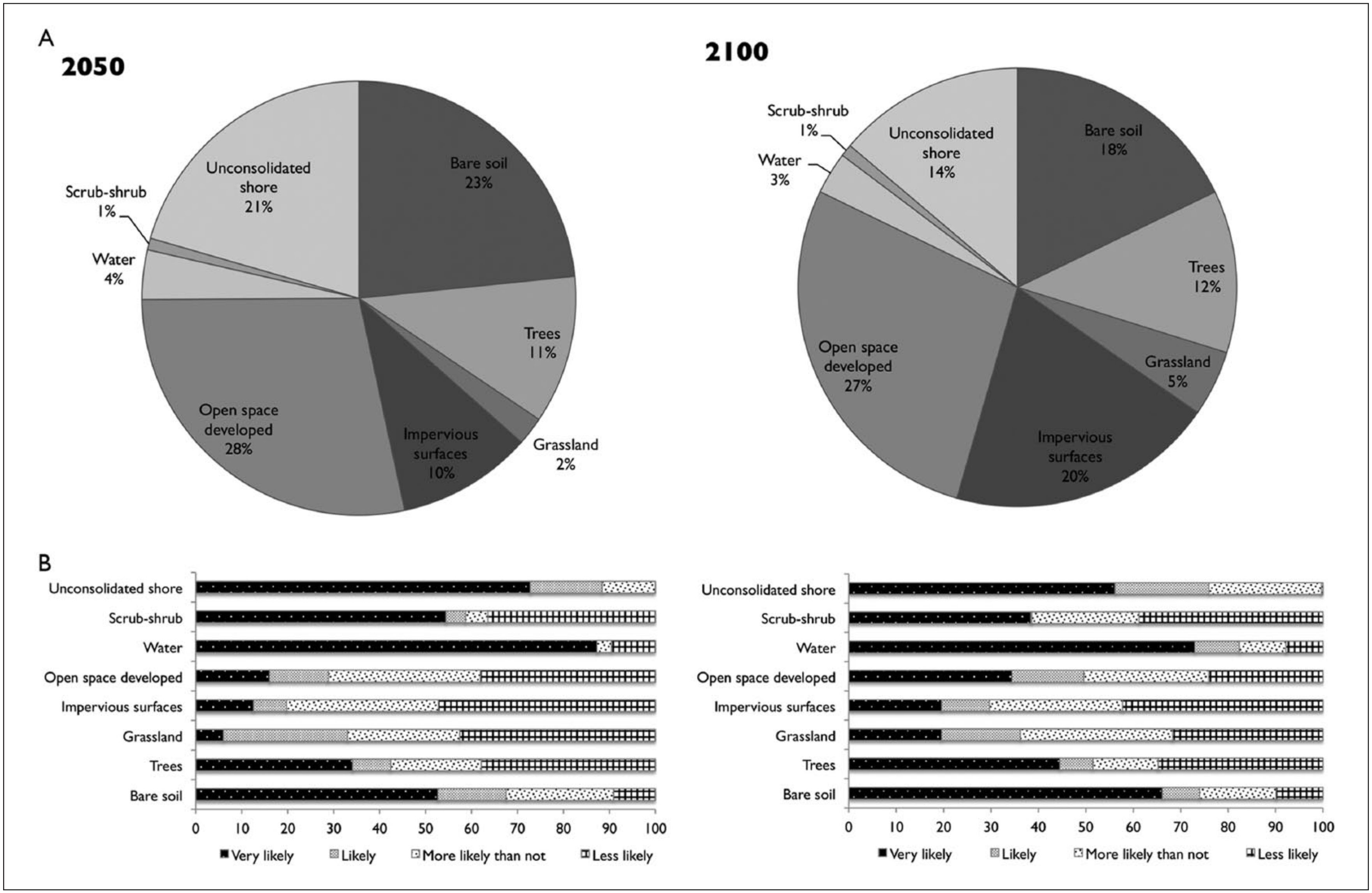

Figure 4. (A) Pie charts show the percentage of total land cover at risk for the time periods of 2050 and 2100. The exposure estimates are derived from the probability-based model. (B) The bar graphs show the likelihood estimates associated with each land cover type expected to be at risk by 2050 and 2100.

Table 3. Exposure Estimates of Properties, Structures and Roads in the Study Area of the Kana`apali Coast.

	Likely/Very Likely (≥80%)	More Likely Than Not (≥50%)	Less Likely (≥20)
Parcel area in acres			
Near-term (2030)	4.1	8.8	15
Midterm (2050)	6.7	12	19
Long-term (2100)	15.2	23	34
Number of structures affected			
Near-term (2030)		2	4
Midterm (2050)		2	6
Long-term (2100)	3	5	15
Land value in millions of dollars			
Near-term (2030)	7.3	18.8	34.8
Midterm (2050)	11.5	24.7	42.9
Long-term (2100)	27	48.4	74.7
Building exposure in millions of dollars			
Near-term (2030)		666	1,106
Midterm (2050)		666	1,845
Long-term (2100)	666	1,106	1,462
Length (ft) of road affected			
Near-term (2030)		322	615
Midterm (2050)	368	651	893
Long-term (2100)	1,083	1,425	1,565

Phasing of Adaptation Strategies

A more reasonable solution than short-term mitigation strategies would be to pair probability-based hazards zones with near-, mid-, and long-term time frames to examine the timing of projected hazards and associated losses, as we did. This can help local planning efforts strategize investments and land use policy decisions more efficiently. For instance, building "anticipatory planned adaptation," such as managed retreat schemes, involves staged planning and a schedule of implementation. Amending comprehensive plans by designating special "retreat zones," enforced by regulations and incentives that encourage land owners to relocate upland, may require a lead time of at least several decades (Grannis 2011; Burkett and Davidson 2013).

Visualizing Risk and Uncertainty

We map levels of risk associated with erosion hazards as a form of risk communication. There are three main benefits of risk maps that explicitly incorporate uncertainty. First, because one of the central goals of risk communication is to raise awareness of risks so that individuals do not underestimate low-probability risks (CCSP 2009), the type and method of communication is important; specifically, incorporating estimates of uncertainty gives more legitimacy to the risk assessment process and the outcomes are deemed fairer (CCSP 2009; Moser, Williams, and Boesch 2012). Second, uncertainty in climate impact predictions allows coastal planners and managers to make more informed decisions (Tribbia and Moser 2008). Although uncertainty in SLR and erosion is one of the most cited reasons why adaptation efforts are impeded at the local level (Bierbaum et al. 2012; Moser 2005), planners are very familiar with the challenge of making decisions with high levels of uncertainty and over long time frames (Abbott 2005). What seems critical is how the science and information is produced and presented. Tribbia and Moser (2008) found that California coastal managers sought uncertainty ranges around climate change impact projections, well-founded distinctions between more and less likely impacts, a better scientific basis for uncertainty buffers, and a basic understanding of the reasons for the uncertainty. These and other authors suggest explicitly incorporating uncertainty into the framing of risk and the risk scoping process can facilitate better land use decisions at the local level (Mills et al. 2015). Third, the ability to visualize risks, even though their reliability may be questioned, enables decision makers to analyze and discuss acceptable exposure and calculate the risk of doing nothing. If potential exposure is deemed serious—and this raises sociopolitical considerations as to individual judgments—then a more comprehensive probabilistic assessment may be justified, providing an opportunity for disparate groups to contribute their expertise on areas and features of importance. This is critical in Hawai`i because future shoreline erosion could threaten cultural artifacts and other features along the coast that will require unique adaptation strategies because they are nonrenewable (Kane et al. 2012). Community involvement in risk assessments not only engages communities, it also establishes normative goals and fosters trust among parties, essential ingredients in "wicked" post-normal situations characterized by long time horizons, uncertainty over outcomes, multiple interests, and high stakes (Moser, Williams, and Boesch 2012; Preston, Yuen, and Westaway 2011; van Aalst, Cannon, and Burton 2008).

Adaptive Management

Adaptive management provides a blueprint for incorporating new data and to re-assess adaptation strategies. Probability-based predictions, such as those discussed in this article, are likelihood estimates, where the outcome depends on the input data and assumptions. As the data and information improves or is updated, the results correspondingly improve. Thus, models and outputs need to be reevaluated and data monitored for continuous improvement. Such an adaptive management approach presumes necessary technical, financial, and other important resources to support local planners and the community's capacity to adapt. We do not expect local jurisdictions to build their own shoreline model and project future erosion hazards zones. The construction of the probability-based shoreline model presented here involved significant technical and scientific resources built off years of data collection and research at the University of Hawai`i with input from coastal managers. In Maui, there has been a long-time collaboration among local planners, the State, University of Hawai`i researchers, and the Sea Grant College Program, and successful adaptation may hinge on such a network (Berke and Lyles 2013; Keys et al. 2013).

The Role of Governance

A significant obstacle to the use of the model is less about the model itself and more about governance. Prioritizing climate adaptation and placing the importance of high-quality adaptation plans on local government agendas remains a deficiency. Learning from past disasters, local governments lack motivations to prepare and implement strong hazards mitigation plans because of few external incentives and an indifferent public, a phenomenon that Raymond Burby calls the "local government paradox" (Burby 2006). This is of great concern because, as we have seen, $1.4 billion in real estate alone is at risk from future erosion in Ka`anapali, Maui. Berke and Lyles (2013) argue that there is a need for more acceptance of shared responsibility for addressing public risks. While new governance structures are no doubt necessary for truly transformative climate change adaptation (Berke and Lyles 2013; Moser, Williams, and Boesch 2012), we believe an important first step involves empowering planners and communities with a better capacity to understand and communicate public risks.

Conclusion

In this article, we present an illustrative case using a probability-based model of shoreline change to SLR for adaptation planning. We propose five recommendations for planning researchers and coastal managers working on climate adaptation for SLR in using shoreline change models for land use planning: (1) acknowledge and communicate uncertainty in existing spatial data and modeling, and, if possible, develop quantitative estimates of uncertainty, otherwise use qualitative estimates, but be explicit about how those estimates were derived; (2) use a probabilistic-based approach to map hazards zones at local scales to visualize risks and educate stakeholders; (3) identify time frames and link them to probabilistic projections for longer term planning; (4) adopt community-level risk mapping and other participatory methods to engage a wide spectrum of stakeholders in the risk assessment and risk management process; and (5) establish a robust adaptive risk management framework using a probabilistic method to monitor risks, revisit strategies, and revise goals and assessments in light of changing information.

This study only assessed the exposure of buildings, lands, structures, and land use using readily available county GIS data. A more thorough assessment would need to identify and assess the exposure of other assets, resources, and sensitive ecosystems. The probability model only considered one climate change scenario (RCP 8.5 Business as Usual). Depending on the planning objective, it would be instructive to develop another series of probability hazards zones based on a less conservative SLR scenario or worse-case scenario (e.g. Greenland ice caps collapse). In addition, a full vulnerability assessment would consider multiple hazards associated with SLR, such as coastal erosion with inundation or storm surge. A natural next step would be to combine these hazards zones with other assets (particularly cultural features and sensitive species habitats) that may be critical for adaptation planning.

Appendix A

Bruun Rule Equation

The Bruun Rule is expressed as:

$$\Delta y = (S_f - S_0) / \tan\beta \tag{1}$$

where

- Δy is the net change ($-\Delta y$ is retreat) in mean shoreline position;
- $S_f - S_0$ is the rise in sea level between future sea level S_f and initial sea level S_0; and
- $\tan\beta$ is the slope of the beach profile, up to the berm.

Probability-Based Model of Shoreline Change

The equation for the hybrid geometric-historical model is:

$$\Delta y = r(t_f - t_o) - (S_f - S_{hist}) / \tan\beta \tag{2}$$

where

- Δy is the net change ($-\mathbf{\Delta y}$ is retreat) in mean shoreline position between initial time t_o and future time t_f;
- r is the historical shoreline change rate;
- $(S_f - S_{hist})$ is the difference between the IPCC projected sea level and Hawaii extrapolated sea level at time t_f; and
- $\tan\beta$ is the average slope of the submerged portion of the beach profile.

A probability density function (pdf) is produced for Δy, the net change in shoreline by combining pdfs of the three variables depicted in equation 2. Figure A1 shows the historical extrapolation and projected shoreline change for years 2005–2100 at one location in West Maui. The beach at this location is historically eroding (negative values indicate a landward retreat). Figure A1a shows the model mean, and the 80 and 90 percent confidence intervals of the projected shoreline change in 2050. Figure A1b shows for the same location 20th, 80th, and 90th percentiles, the positions at which there is a 20, 80, and 90 percent probability, respectively, the future shoreline will be landward of the contour line.

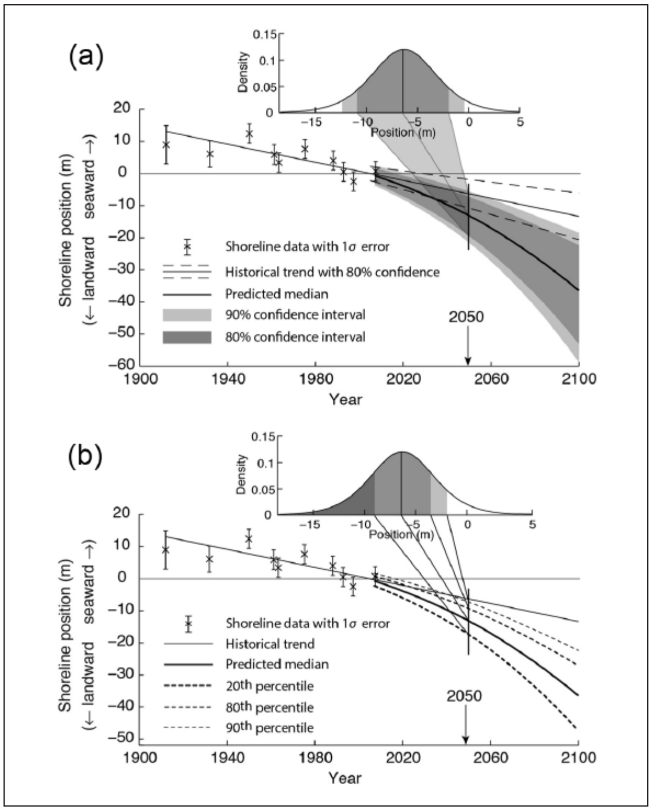

Figure A1. Historical shoreline data from one transect in the historically eroding South Ka`anapali beach of West Maui. The top panel (A1a) displays the median with the 80 and 90 percent confidence bands around the median projected shoreline position in 2050. The bottom panel (A1b) shows the predicted median, 20th, 80th, 90th percentiles the shoreline will be further landward than the contour line in 2050.

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Note

1. Herein, we draw primarily upon the "frequentist" definition of risk while acknowledging that there are alternative interpretations, namely, the "subjectivist" or "Bayesian" view, in which a statement of risk includes a person's belief in the likelihood of an event given all available information (CCSP 2009).

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