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Just beach

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ABSTRACT

Sandy beaches are being squeezed out of existence due to a combination of erosion, coastal development, poor management practices, and sea level rise. This study offers a beach-scale analysis of the cost of managed retreat for the island of Kaua'i through the end of the century, prompted by state laws to preserve sandy beaches and County efforts to implement proactive planning solutions. We estimate the cost of property acquisition, deconstruction, and infrastructural realignment across forty beaches under future projections of coastal erosion and sea level rise – a total of $3.1 billion ($2025). Half of the total costs through 2100 is for immediate (2025) needs ($1.7 billion), 94% of which is road infrastructure and the water supply pipes underneath. Infrastructure dominates the total cost of adaptation ($2.0 billion). While residential development represents the largest land use type impacted by coastal erosion, residential parcels account for the second greatest share of adaptation costs ($0.6 billion). Meanwhile, hotel and resort areas affect fewer beaches yet with substantial costs ($0.5 billion). Our results show that historical coastal planning decisions have created development lock-in patterns that make beach-centered adaptation costly. Furthermore, as achieving justice within adaptation relies on information at multiple spatial and temporal scales, this study can be used to inform broader deliberations for sea level rise adaptation.

1. Introduction

The combination of coastal development practices, poor beach management, coastal erosion and sea level rise are resulting in the narrowing of beaches across the globe – increasingly referred to as "coastal squeeze" (Defeo et al., 2009; Jackson et al., 2012; Lansu et al., 2024; Masucci & Reimer, 2019; Pontee, 2013; Romine & Fletcher, 2012). Coastal hardening in response to accelerated erosion due to sea level rise may protect land but can accelerate sand loss, impacting beach ecosystems and communities who rely on beaches (Klöck et al., 2022; Mentaschi et al., 2018; Nunn et al., 2021; Schlacher et al., 2008). Beach erosion models suggest that 21–50 % of sandy beaches globally may be extinct or near extinction by the end of the century (Lansu et al., 2024; Nawarat et al., 2024; Vousdoukas et al., 2020).

Beaches are important social-ecological systems because they function as critical habitats and places for socializing, subsistence, and recreation, as well as possessing spiritual, cultural, historical, and economic significance (Bremer et al., 2022; Defeo et al., 2021).

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Beach nourishment is a common adaptation strategy used for beach preservation, and, while viable for some areas, it is a more short-term management activity that can pose ecological harm and may become unviable under sea level rise (Mikkelsen et al., 2022; Parkinson & Ogurcak, 2018; Wooldridge et al., 2016). "Managed retreat" is to purposefully intervene through policy and management decisions to proactively remove or relocate development away from vulnerable areas (Ajibade & Siders, 2021; Haasnoot et al., 2021; O'Donnell, 2022). This adaptation strategy has been controversial to implement because it often involves the displacement of residents from their homes, which has social, financial and political implications (Gibbs, 2016; Hanna et al., 2019; Hino et al., 2017; Lawrence et al., 2020; Noy, 2020). However, managed retreat is an increasingly discussed adaptation option for the purpose of preserving beach ecosystems and the diverse values that they provide (Coffman et al., 2025; Nunn et al., 2021; Setter et al., 2023).

Financial resources are commonly identified as the primary driver of adaptation choices (Griggs & Reguero, 2021; Hashida & Dundas, 2024; Hinkel et al., 2018; Moser et al., 2019), and there is a growing literature on the cost of managed retreat (Porro et al., 2020; Revell et al., 2021; Setter et al., 2023). Setter et al. (2023) estimate \$89.4 million (\$2021) to retreat the at-risk development at Paumalū, Oʻahu, a beachfront residential area with single-family homes. Porro et al. (2020) look at coastal erosion for Waikīkī, Oʻahu's main tourist district, and find \$129 million (~\$2019) in retreat costs, largely from demolition. Revell et al. (2021) estimate \$184 million (\$2014) in retreat costs for Imperial Beach, California, which they describe as a residential, military and coastal ecotourism area and accounts for demolition and private asset loss. This study contributes to this body of literature by assessing the cost of managed retreat for 40 beaches on the island of Kauaʻi. We estimate the cost of property acquisition (by zoning type), deconstruction, and infrastructural realignment under future projections of coastal erosion and sea level rise, reaching approximately one meter higher by 2100.

As beaches are complex social-ecological systems, we conduct a multi-scalar analysis based on beach dynamics and political processes (Anderies et al., 2004; Berkes et al., 1998; Ostrom, 2009). Applying a beach-focused approach connects managed retreat costs to broader equity considerations, including intergenerational access to beaches and their function as ecological systems for many

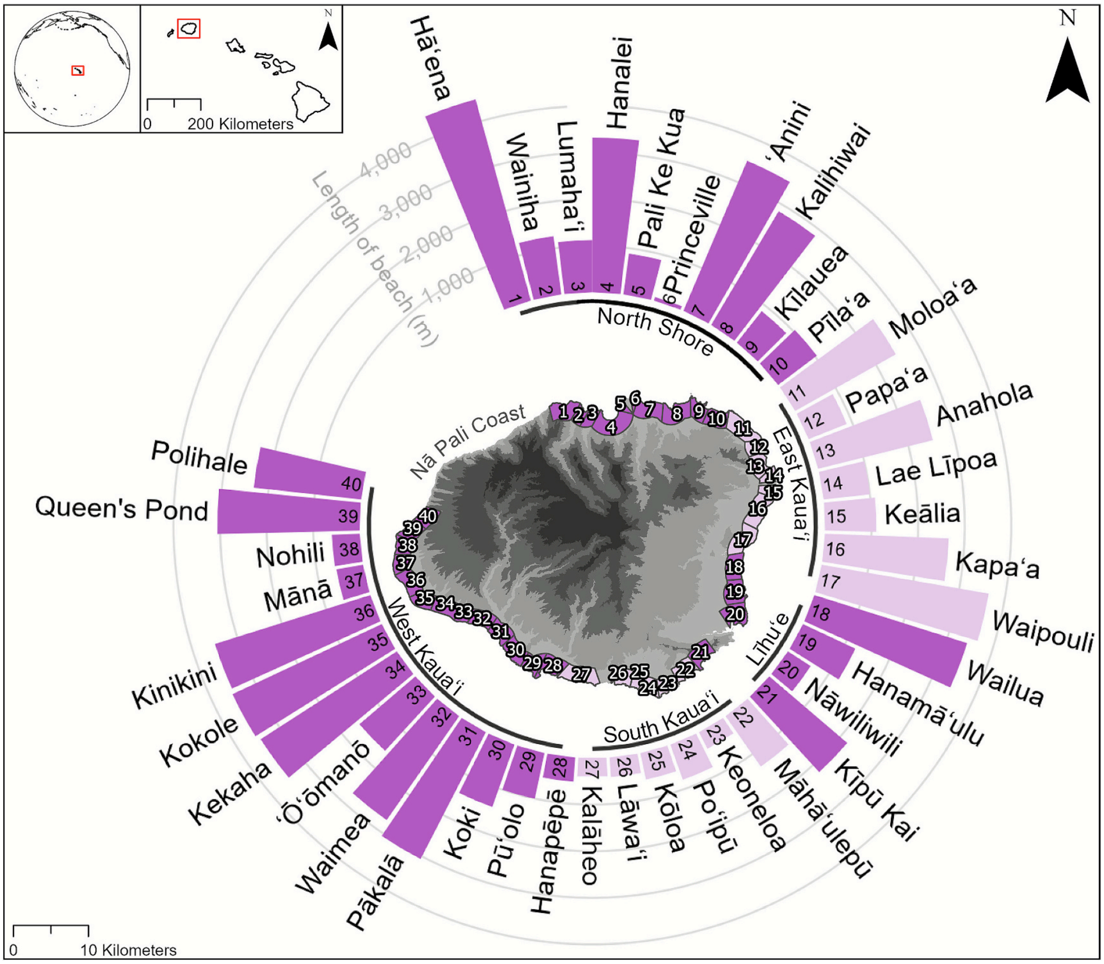

Fig. 1. Overview of the location of Kauaʻi, Hawaiʻi with names shown along the coast for each of the 40 beaches. The color groupings show community planning areas (North Shore, East Kauaʻi, Līhuʻe, South Kauaʻi and West Kauaʻi), the length of the bar chart represents beach length (m), and every beach is given an identification number (Beach ID) for quick reference in future figures.

species (Teodoro et al., 2023; Weston, 2012). Adaptation decisions are often made at the parcel-level between property owners and the government (Summers et al., 2018). However, this ignores beach biogeophysical patterns, which most often run adjacent to or through to multiple properties (Lloyd et al., 2013; McGlashan & Duck, 2010). Whole segments of beaches can disappear due to the flanking effect, which is a process of accelerated erosion that occurs on properties adjacent to hardened shorelines. This commonly initiates a chain reaction, where neighboring landowners install their own shoreline hardening in response to increased eroding lands (Romine & Fletcher, 2012; Summers et al., 2018). Additionally, we apply a regional analysis, which is important for considering larger scales of community connections such as the distribution of government funds and connections through road infrastructure (Anderies et al., 2004; Cooper & McKenna, 2008).

Equitable adaptation requires clear and transparent programmatic goals (Ajibade et al., 2022; Mach et al., 2019; Siders, 2019) and, as such, decision-makers (e.g. community members, county planners, infrastructure planners) must understand the different values and trade-offs that can occur. The purpose of this study is to help decision-makers evaluate the public and private funding needs of managed retreat at a beach and regional scale over the next 75 years.

2. Background and approach

2.1. Kauaʻi's beaches and sea level rise adaptation

Kauaʻi, ancestral home to Kanaka ʻŌiwi (Native Hawaiians), is the northernmost populated island in the archipelago of Hawaiʻi with a current resident population of 74,000 (Department of Business and Tourism, 2025). Additionally, there are on average 29,000 visitors on the island on any given day (Department of Business and Tourism, 2023). Due to the geography of this high volcanic island, the majority of development occurs near the coastline. A rural highway runs along the southern portion of the island from the southwest to the northeast, much of which is near and parallel to the shoreline.

There are 72 km (km) of beaches across Kauaʻi (Fig. 1), used for a range of recreational, subsistence and cultural activities. Based on littoral cell estimations (Anderson et al., 2015), there are 40 distinct beaches ranging from 80 to 4,480 m in length (excluding the Nā Pali Coast, which is conservation land with no road access). The types of beaches range from pocket beaches, embayments, and fringing reef systems that are composed of a mix of calcareous and terrigenous sediment (Fletcher et al., 2012). The entire sandy shoreline on average is eroding at -0.2 ± 0.2 m/yr (Coastal Research Collaborative, 2021). The highest erosion rate is -1.3 ± 0.5 m/yr at ʻŌʻōmanō (Beach ID 33), and the highest accretion rate is 1.8 ± 0.6 m/yr at Waimea (Beach ID 32; Coastal Research Collaborative, 2021).

An important principle for organizing land use in Hawaiʻi is the moku system (County of Kauaʻi Planning Department, 2025a; Winter et al., 2018), which has several social-ecological communities that run from ocean to inland (ahupuaʻa) and social-ecological zones that run parallel to the coast (such as wao and kai). Beaches are a critical social-ecological zone and an integral part of the whole system. Beach dunes are the resting place for many iwi kūpuna (ancestral bones) of Kanaka ʻŌiwi (Kane et al., 2012). Residents commonly use the beach for swimming, fishing, gathering other marine resources, camping, diving, boating, and surfing (Bremer et al., 2022; Takeuchi, 1975; Vaughan & Ardoin, 2014; Vaughan & Vitousek, 2013). Beaches also are an important habitat for native flora like naupaka, pōhuehue, and ʻakiʻaki and native fauna like monk seals, sea turtles, shore birds, and sand crabs (Ziegler, 2002).

The preservation of sandy beaches is called for in multiple layers of state and county laws. Beaches are constitutionally protected within the Public Trust Doctrine (Haw. Const. Art. XI § 1, 1978; Sproat, 2015), and within the State's Coastal Zone Management (CZM) Act (Haw. Rev. Stat. § 205a, 2021). The 1975 CZM sets the public shoreline as the annual high wash of the waves (Haw. Rev. Stat. § 205a, 2021). Other tools to manage coastal development include the shoreline certification (which is usually the debris line, sometimes the vegetation line), development setback (which is a variable rate on Kauaʻi based on annual erosion of the transect plus a set distance depending on lot depth; (County of Kauaʻi, Haw., Ord. § 8-27.3, 2021)) and the Special Management Area permit (which is a discretionary county permit required for any major development in the coastal area).

Prior to the CZM program many shorelines were already hardened with seawalls or sandbags, resulting in about 8 % of Kauaʻi's beaches lost by 2012 (Fletcher et al., 2012). Despite efforts to protect sandy beaches, the path dependency created by legacy hardening results in the persistence of poor coastal management practices and maladaptive actions towards further hardening (Summers et al., 2018). Sea level rise further exacerbates this issue as the rate and extent of coastal erosion increases (Anderson et al., 2015; Moskvichev et al., 2025; Tavares et al., 2020). Most recently, to put an end to the domino effect of seawalls along Hawaiʻi's coast, the legislature in 2020 passed a law that prohibits all shoreline hardening for private purposes, allowing no variances by state or county entities (Haw. Rev. Stat. § 205a, 2021). However, hardening is still allowed for public purposes like infrastructure; and the law does not apply retroactively to previously legally hardened shorelines. Because this law was not supplemented with alternative adaptation strategies, the state created a reactive retreat program for private lands (Setter et al., 2023), where state action is taken only after a built asset falls into the public beach. There are now several instances of houses collapsing, at great risk to human safety and environmental contamination (Burgos, 2024; Cocke, 2022; Shikina & Hurley, 2014).

Government officials are exploring managed retreat as an adaptation strategy (County of Kauaʻi Planning Department, 2025a; Office of Planning and Sustainable Development, 2025). The County of Kauaʻi Planning Department has created planning documents like the Climate Adaptation and Action Plan to guide the integration of climate adaptation into local decision-making, including strategies to create a managed retreat program (County of Kauaʻi Planning Department, 2025a). In this process, the County has also conducted workshops and polls with each community planning district (Fig. 1) to gather perspectives on adaptation approaches. Polling results from across the island broadly found that participants somewhat support managed retreat (County of Kauaʻi Planning Department, 2023b). However, participants at in-person workshops showed more variation in their responses. Participants from

Kauaʻi's North Shore mostly supported a retreat strategy while participants from West Kauaʻi mostly did not (County of Kauaʻi Planning Department, 2023a). To further advance these community conversations and support informed decision-making, this study was done at the request of the County of Kauaʻi Planning Department.

2.2. Methods

This study takes a beach-scale approach to assess the cost of retreat for properties and roads, including water utility infrastructure underneath, adjacent to Kauaʻi's sandy beaches. We do so by building upon two prior studies. Anderson et al. (2015) defines Kauaʻi's beach boundaries based on littoral zones (Fig. 1), and projects the impact of approximately one meter of sea level rise on coastal erosion patterns through 2100 (based on RCP 8.5; IPCC, 2014). We apply the methods established in Setter et al. (2023), which is a case study for Oʻahu's North Shore, and adapt it to Kauaʻi's conditions. Setter et al. (2023) presents the concept of "threshold-based" retreat – which is akin to a "trigger" within an adaptation pathways approach (Griggs & Reguero, 2021; Revell et al., 2021). The threshold for retreat of a built asset is when the coastal erosion line (projected vegetation line and proxy for the public shoreline) is within 6.1 m. This is based on existing permitting law in Hawaiʻi that considers an asset "imminently threatened" when the shoreline reaches this point (Haw. Admin. R. § 13-5-2, 2011). Once a built asset is identified as threatened by the future coastal erosion line, which we timestamp in 2030, 2050, 2075, and 2100 (representing 0.17, 0.32, 0.60, and 0.98 m of sea level rise), a cost for adaptive action is attributed. The latest coastal erosion line coupled with the assumption of a 6.1 m "trigger" to the built asset serves as our baseline in 2025. We additionally conduct a sensitivity analysis to evaluate how the trigger distance to erosion hazard as well as the discount rate used may affect the total cost to retreat – under 1.5 and 3.0 m distance as the "trigger" and with a 1 % and 5 % discount rate.

We estimate the cost of acquiring building and land, building and parcel infrastructure removal, the loss in property tax revenues, and the cost of acquiring new inland parcels and rebuilding shared infrastructure. Because our inquiry is to support proactive retreat, all costs are borne publicly. We calculate costs of building acquisition at the full building assessed value. We assume that the coastal erosion line sets new property boundaries and, therefore, land acquisition costs are proportional to the parcel's current assessed land value and removes the land area lost from the projected coastal erosion line – as this is not a retreat cost but rather an underlying private value loss from coastal erosion as the shoreline migrates landward. We account for building demolition (single level and multi-level buildings, including foundations), shoreline hardening removal (e.g. seawall deconstruction), and wastewater (sewer connected and on-site) systems removal. We organize parcels by their tax classes to estimate county property tax losses: Residential, Hotel and Resort, Commercial, Agricultural, Conservation, and Industrial. Residential includes Owner-Occupied, Non-Owner-Occupied Residential, Owner-Occupied Mixed Use, and Vacation Rental. For Condominium Property Regime (CPR) units, we assume that all units follow the predominant zoning use (based on TMK8). This is most applicable to mixed resort and apartment areas. For road infrastructure, we assume that highways are relocated while non-highways (local roads) are demolished– except in the case that local roads are the only access to communities– ʻAnini (Beach ID 7) and Poʻipū (Beach ID 24). For roads that are relocated, we identify the average cost of parcels near to the road segment, but outside of the future hazard area, to estimate the cost of eminent domain for a new road alignment. This property acquisition cost is incorporated into the overall cost of building a new road.

All cost data used for this study are summarized in Tables 1 and 2 for private and public assets, respectively. Spatial data were provided by the State Office of Planning GIS Portal (coastal erosion hazard zones) and the County of Kauaʻi Planning Department (building data, wastewater systems, roads, and seawalls), and analyzed in ArcGIS Pro. Building and land value data, which are used as a proxy for acquisition costs, were provided by the County of Kauaʻi and represent their 2025 assessor's data for tax purposes. This set of methods is designed to illustrate the potential magnitude of managed retreat costs over time, acknowledging the inherent uncertainty in cost parameters and sea level rise impact estimates.

Table 1
Costs and sources related to private properties.

Category	Cost Type	Cost($2025)/ Unit	Source and Notes
Acquisition	Property value	Variable	Land value is proportionally reduced based on coastal erosion coverage. Cost is from the County of Kauaʻi Planning Department.
Demolition	Non-multi-level building	$15,450/ building	The building is assumed to be 149 square meters. Cost is from RSmeans with local multiplier (RSMeans Data, 2025; Uno, 2016).
	Multi-level building	$7/sqm	The building is assumed to be 15 m tall which is the maximum building height allowed (County of Kauaʻi, Haw., Ord. § 8-6.3, 2012). Cost is from RSmeans with local multiplier (RSMeans Data, 2025; Uno, 2016).
	Apartment building	$8,640/CPR unit	The unit is assumed to be 204 cubic meters. Cost is from RSmeans with local multiplier (RSMeans Data, 2025; Uno, 2016).
	Apartment foundation	$2/sqm	Cost is from RSmeans with local multiplier (RSMeans Data, 2025; Uno, 2016).
	Water and wastewater lateral connections	$1,210/ property	Cost is from RSmeans with local multiplier (RSMeans Data, 2025; Uno, 2016).
	On-site sewage disposal	$2,430/ property	Updated to $2025 from Setter et al. (2023); (Babcock et al., 2019).
	Shoreline hardening	$14,120/m	Personal communications with local engineering and construction companies.

Table 2
Costs and sources related to public infrastructure.

Category	Cost Type	Cost($2025) /Unit	Source and Notes
Demolition	Non-critical road	$40/m	Updated to $2025 from Setter et al. (2023); (Hometown Demolition, 2022).
Temporary Adapt-in-place	Bridge	$77,380/m	Updated to $2025 from Setter et al. (2023); estimated based on existing bridge retrofitting projects (County of Maui, 2020).
	Critical road	$39,890/m	Updated to $2025 from Setter et al. (2023); (Francis et al., 2019).
Realignment	Eminent domain	Variable	Cost is determined by the property value (from County of Kaua'i Planning Department) of inland properties of the erosion hazard projections for the size of a two-laned highway.
	Bridge	$363,680/m	Updated to $2025 from Setter et al. (2023); estimated based on existing bridge realignment projects (Department of Transportation Highways, 2019, 2021).
	Critical roads	$279,210/m	Updated to $2025 from Setter et al. (2023); (Francis et al., 2019).
	Shoreline hardening	$14,120/m	Personal communications with local engineering and construction companies.
	Water mains	$6,030/m	Updated to $2025 from Setter et al. (2023); estimated based on Teague (2017) and confirmed through personal communication with a Board of Water Supply official.

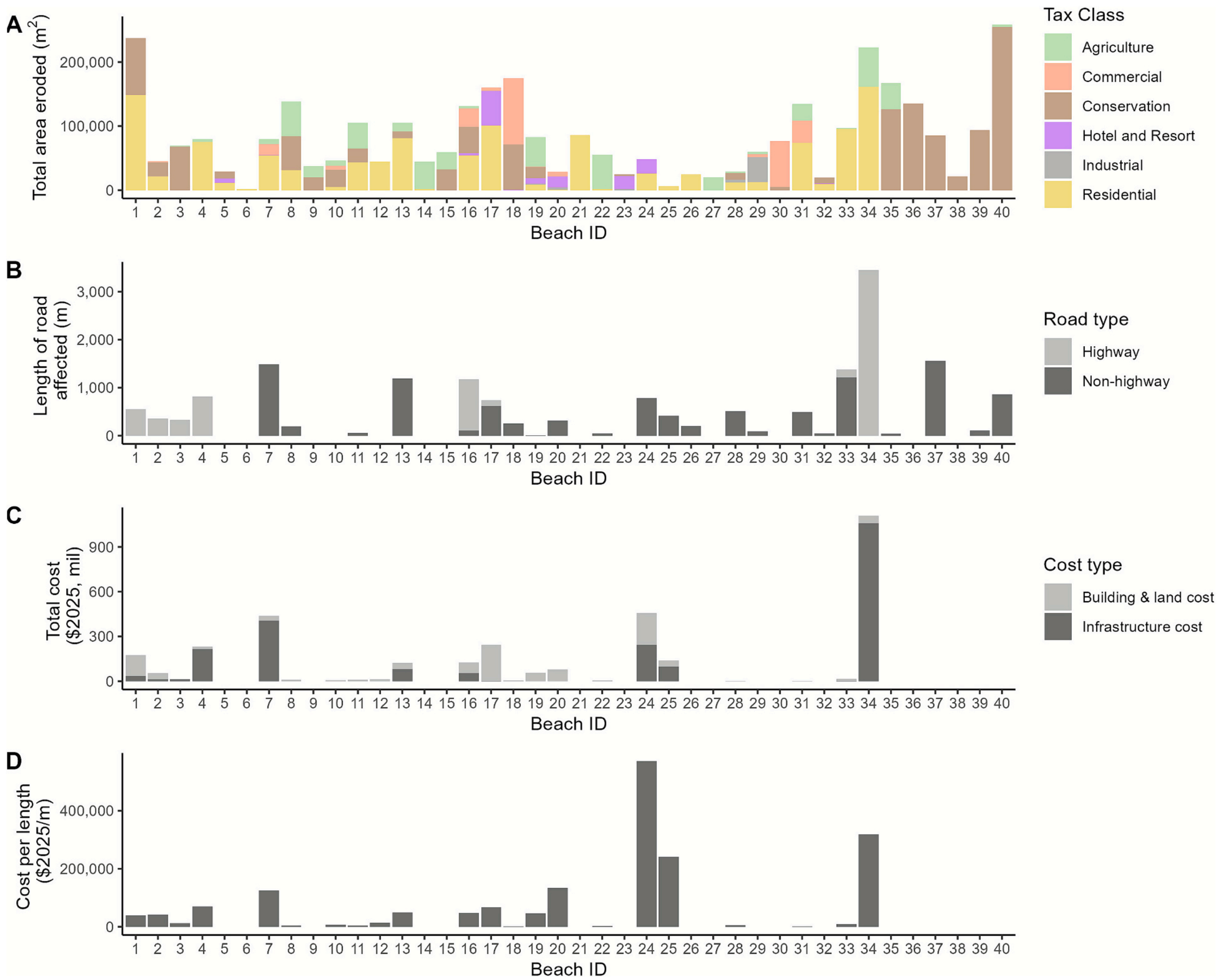

Fig. 2. Bar graphs show (A) total area eroded (m^2) by 2100 per tax class, (B) length of road affected (m), (C) total cost ($2025, mil) by cost type, and (D) cost per length of beach ($2025/m) for each beach on Kaua'i. Beach identification numbers correspond to the beaches shown in Fig. 1.

3. Results

3.1. Impacts and costs by beach

Fig. 2 shows estimated impacts to Kaua‘i’s 40 beaches, including total area eroded, length of affected roads, the total cost of managed retreat by beach, and the total cost normalized by a meter of beach. The future coastal erosion line is projected to impact development along 30 of Kaua‘i’s 40 beaches. There are 2,245 land parcels impacted by accelerated coastal erosion due to sea level rise by 2100. There are 3,400,000 m^2 of expected beach loss from accelerated coastal erosion through 2100 (Fig. 2A), where the largest impacts are to residential areas. There are 28 beaches with adjacent residential lands experiencing coastal erosion. On an area basis, the next largest impacted area is on conservation zoned lands. There are 6.9 km of impacted major roads (classified as highway) and 10 km of local roads (Fig. 2B), across 27 beaches. By far the largest impacted major road is in Kekaha (Beach ID 34).

In Figs. 2C and 2D we show the total cost of retreat per beach and cost per meter of beach, respectively. There are 10 beaches (25 % of total island-wide beach length) that have a total cost of retreat between $1–50 million each. There are 11 beaches (34 % of total beach length) that cost between $50–500 million, and an outlier (Kekaha, Beach ID 34) at over $1 billion (5 % of total beach length). There are also eight beaches (24 % of total beach length) that have little to no cost to preserve through retreat, at less than $1 million in retreat costs. In terms of cost per length, the majority (22) of the beaches are less than $50 thousand per meter, while the remaining eight are between $50–350 thousand per meter.

3.2. Community spotlights

The cost of retreat by beach varies based on several key factors: value of properties, number of impacted properties, and realignment of roads. Fig. 3 illustrates the role of the value of property acquisition in relation to the number of impacted properties,

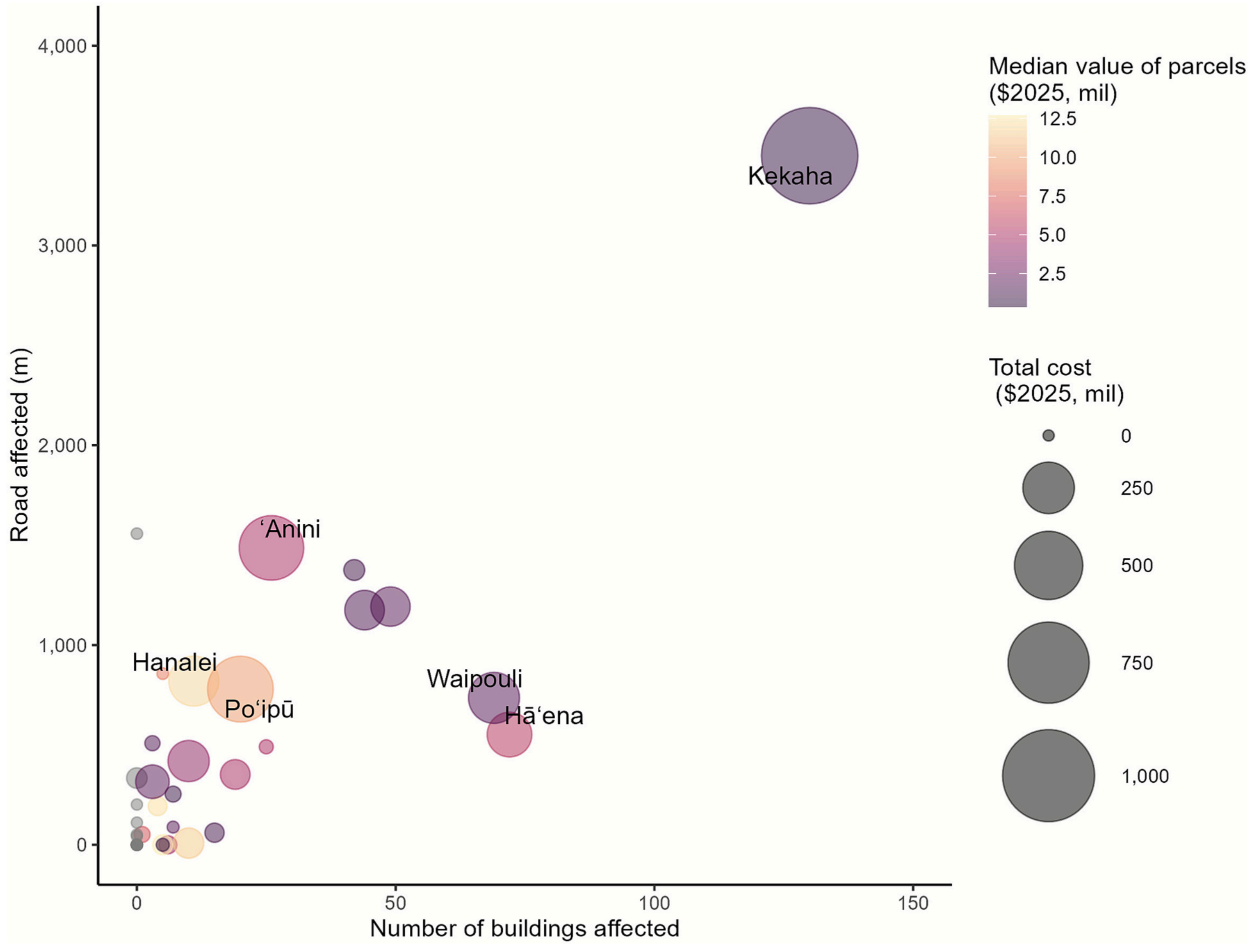

Fig. 3. Relationship between length of road affected and the number of buildings affected by projected coastal erosion in 2100 for each beach. Circle size indicates the total cost, and the color represents the median property value. Gray circles indicate beaches where only infrastructure is affected but no buildings are impacted. Selected beaches that are discussed in the text are labeled.

and the need to realign existing roads. Fig. 4 provides a spatial view of the communities named in Fig. 3, and spotlights their community-specific adaptation considerations.

3.2.1. *Highest total cost (Kekaha, beach ID 34)*

Kekaha has the highest total cost at $1.1 billion ($2025) to retreat because its beach is fronted by a highway, with 3.4 km of impacted road (Figs. 3 and 4A). Much of Kekaha's beachfront immediately falls into the trigger for retreat, within 6.1 m from the coastal erosion line. As the most western residential community, the road accesses other sandy beaches, agricultural land, and military facilities to the northwest. In this area, beach loss is already occurring and shoreline hardening has been the response to historical coastal erosion. Half of the upfront cost for retreat on the island is due to the removal and realignment of infrastructure at this beach. Notably, Kekaha also has the highest number of impacted residential buildings (80 homes inclusive of 111 structures), and additional agricultural structures (29 buildings). This area also provides relatively affordable housing for residents of Kauaʻi, with median property values at $800,000 ($2025) – which is just under the median island-wide residential property value, $840,000.

3.2.2. *Highest cost per length (Poʻipū, beach ID 24)*

The highest cost per length of beach is for Poʻipū at $345,000/m ($2025), due mainly to impacts to hotels and residences. Poʻipū is a smaller beach (800 m in length; Fig. 4B) with 195 m of roads impacted. The total cost is $276 million – most is due to costs to acquire and demolish several hotel and resort and residential properties ($214 million), which have a median value of $10 million (Fig. 3). The remaining cost is to realign road infrastructure ($62 million).

3.2.3. *Highest residential property value (Hāʻena, beach ID 1)*

Hāʻena has the largest cost to retreat for residential areas at $139 million (Figs. 3 and 4C). The total cost of retreat within Hāʻena is $174 million. There are 55 impacted single-family homes with a median value of $5 million (Fig. 3). Notably, Hāʻena has one of the higher concentrations of Vacation Rentals on the island (County of Kauaʻi Planning Department, 2025b).

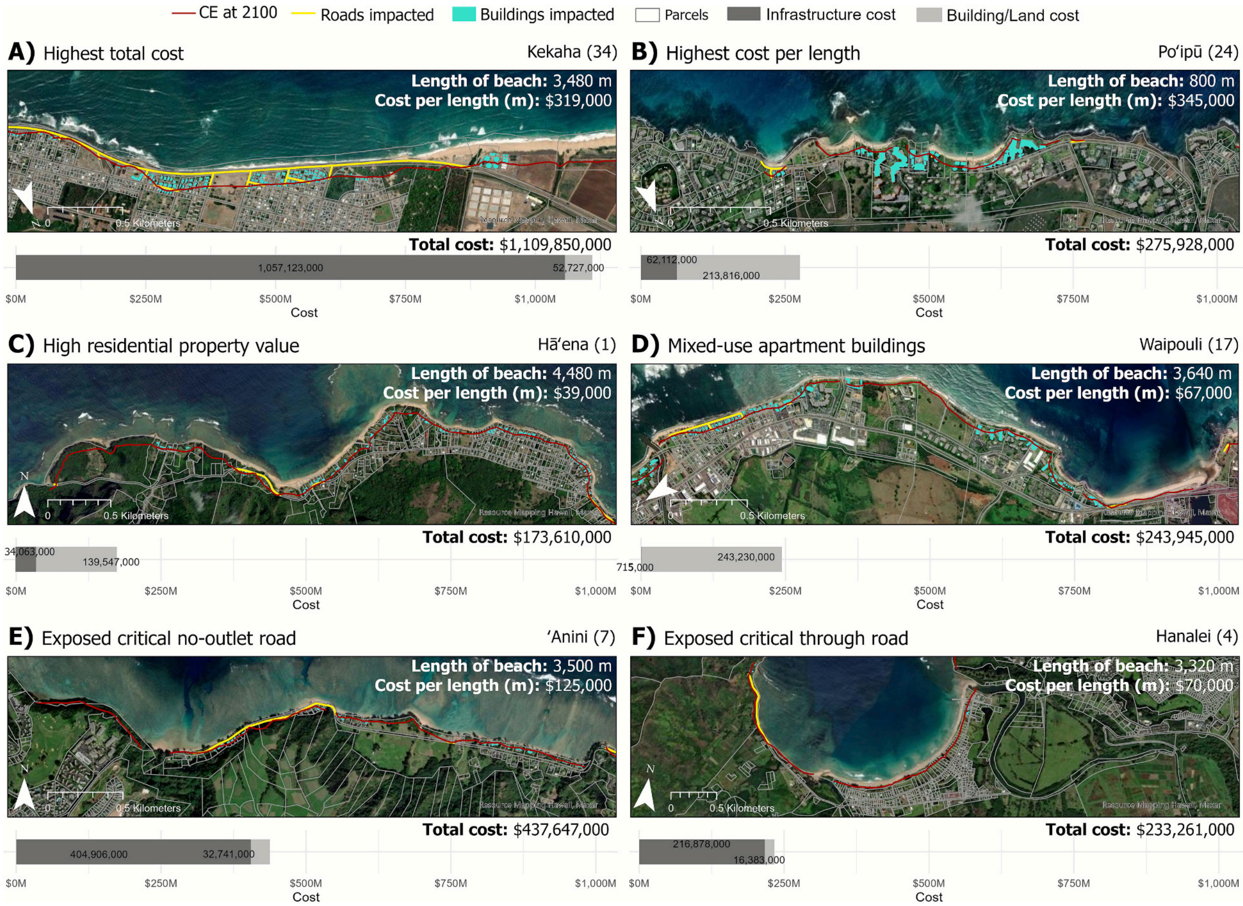

Fig. 4. Summary of data and aerial images overlaid with GIS data for selected beaches. Spotlight examples include (A) highest total cost, (B) highest cost per length, (C) high residential property value, (D) mixed-use apartment buildings, and (E) a no-outlet road and (F) a through road with exposed critical infrastructure.

3.2.4. *Mixed-use apartment buildings (Waipouli, beach ID 17)*

In Waipouli, coastal erosion impacts a mix of hotel, commercial, and residential properties. However, most (50 %) of the cost to retreat this beach is attributed to retreating residential properties at approximately $123 million, followed by hotel and resort at $120 million (Figs. 3 and 4D). While Waipouli doesn't have the highest number of buildings impacted, it does have the largest number of residential units impacted (240) because of the relative density of apartment units in the area (11 apartment buildings). Despite the high number of residential units impacted, the costs are relatively low because the median property value of impacted properties in Waipoli is $900,000.

3.2.5. *Exposed critical no-outlet road (ʻAnini, beach ID 7)*

After Kekaha, the next beach with high infrastructure costs is ʻAnini at $405 million to retreat 1.5 km of road (Figs. 3 and 4E). This road is notable for having no-outlet and being the only access road to this community, which is mainly a residential area. Besides the road, there are also 26 residential buildings projected to be impacted by coastal erosion, costing $33 million to retreat. The median value of impacted properties in this area is $5 million.

3.2.6. *Exposed critical through road (Hanalei, beach ID 4)*

Hanalei has 11 impacted residential buildings and 800 m of impacted road, some of which already has shoreline hardening due to existing issues with coastal erosion (Figs. 3 and 4F). While the median parcel value is one of highest at $12 million ($2025), the cost to retreat the road makes up 93 % of the total cost ($233 million). This section of road is notable because it is a critical through road to the rest of the north shore community.

3.3. *Total costs of retreat*

The threshold-based retreat strategy is estimated to have an island-wide cost of approximately $3.1 billion (in net present value, $2025, for the baseline; Fig. 5). Because beach erosion is already occurring in Kauaʻi, $1.6 billion is triggered as an immediate adaptation expenditure – almost entirely in road removal and relocation, including utilities beneath the road (Fig. 5). The average annual cost thereafter is substantially lower, at an average of $18 million per year ($2025) (Fig. 5). The average annual cost within the residential and hotel and resort sectors increases over time both at an average of $6 million per year ($2025). Infrastructure remains the highest total cost (65 %). Loss in property tax revenues to the county are minimal compared to other costs of adaptation; we estimate a loss of $158 million ($2025) over the study time horizon, with the largest tax losses coming from residential ($74 million) and hotel and resort ($67 million; See Supplementary Table 1).

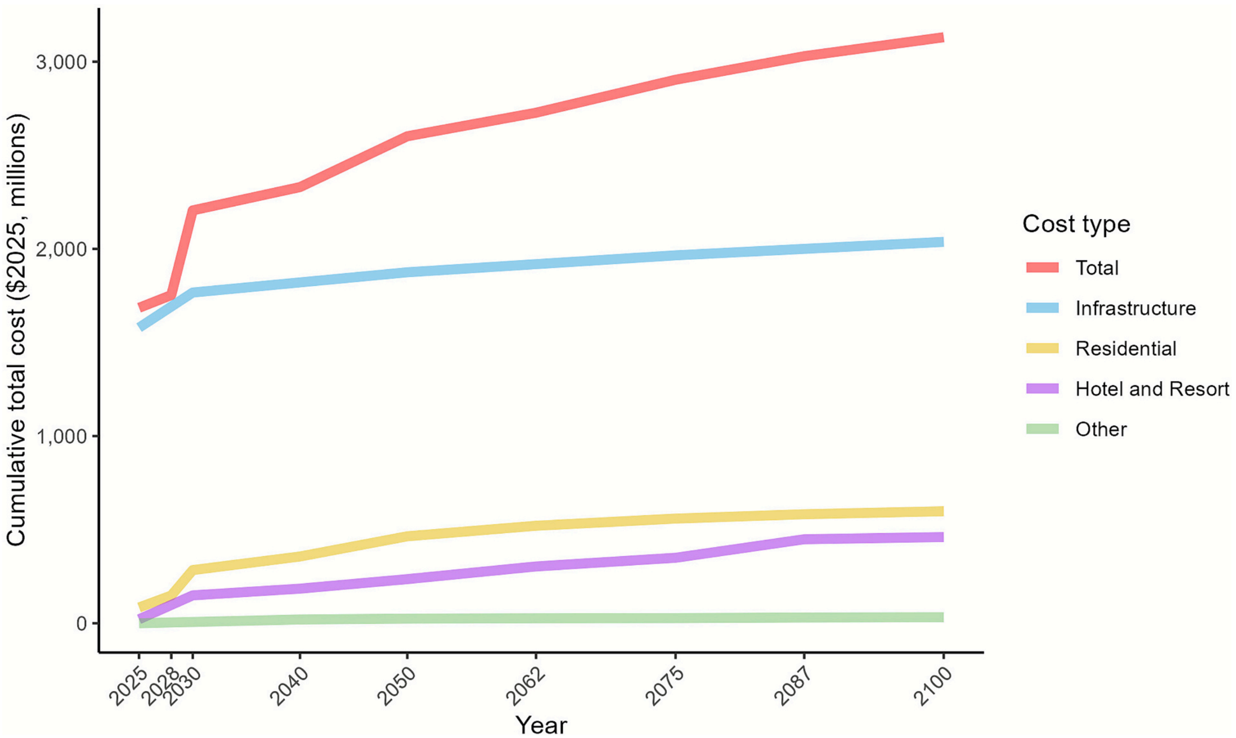

Fig. 5. The cumulative cost to retreat over time by activity: Infrastructure, Residential, Hotel and Resort, and Other (Agriculture, Commercial, and Conservation). Industrial properties have no buildings affected by the future coastal erosion line and, therefore, never trigger retreat.

There are few impacted assets that meet the criteria for threshold-based retreat within conservation, agricultural and commercial areas. Conservation land has the largest area impacted by the future coastal erosion line (36 % of all impacted lands in 2100 are zoned conservation; Fig. 2), though with only $4 million to retreat impacted assets (see Supplementary Table 1). Agricultural areas have a much smaller impacted area, at 14 %, and with $17 million to retreat impacted assets that include agricultural buildings and local roads. Though commercially zoned areas comprise 8 % of all impacted land in the future coastal erosion land, the cost of their threshold-based retreat is relatively low at $13 million. This is because the impacted commercial land holdings are not predominantly in commercial activity (like malls) but rather commercially zoned government lands and a few commercially zoned areas that actually have housing.

3.4. Sensitivity analysis

Lastly, we present the results of our sensitivity analysis for both the rate of time preference through 2100 and the distance from the built asset to the coastal erosion line (i.e. the “trigger” for retreat). Whereas the baseline assumes a standard 3 % rate, the sensitivity analyses estimate results under 1 % and 5 % rates. In addition, the baseline assumes a 6.1 m threshold from the coastal erosion line to the built asset as the adaptation action trigger, based on the current permitting statute (Haw. Admin. R. § 13-5-2, 2011). As this could clearly change based on updates to adaptation planning and policy approaches in the state and county, we look at more conservative, closer distances (1.5 m and 3 m). Table 3 shows the total cost of retreat for the island of Kauaʻi under these varying assumptions and in comparison to our baseline.

Decreasing the trigger distance decreases the financial cost of retreat because it delays actions in time. However, it should be emphasized that delaying retreat increases the risk to the public and the environment. Our retreat costs assume that proactive acquisition and removal of structures occurs before breaking up into the nearshore. If there is inadequate time to take such action, financial and environmental costs would both increase substantially (Setter et al., 2023). In addition, the higher the rate of time preference, the lower the cost of future action and, therefore, the lower the cost of delayed retreat. Though a 5 % rate of time preference is relatively standard, lower rates should be applied in the case of intergenerational environmental goods (Stern, 2008). Between the two variables, changing the rate of time preference had a greater effect on the total cost than the trigger distances chosen.

4. Discussion and conclusion

While cost analyses are only a piece of the broader adaptation discussion, the influential role finances play in the outcome of adaptation warrants this investigation. We create a method that calculates the cost of managed retreat as sea level rises based on an adaptation trigger where assets are deemed “imminently threatened” within a regulatory planning framework. Additionally, we study costs at both the beach and regional scale where the beach-scale keeps intact beaches as ecological systems, and the regional-scale addresses community connectivity. This method can be generalized for other coastal communities who have a moving shoreline designation, such as a rolling easement, and similar estimates for the positioning of a future shoreline under sea level rise. We find that multiple layers of government play a significant role in retreat, most particularly due to the need of public funds to address the high cost of adaptation and for their role in the management of road infrastructure.

By the end of the century, the total cost of managed retreat across Kauaʻi’s beaches is $3.1 billion ($2025), and over half of the cost of retreat in immediately needed expenditures for road removal and realignment. We estimate that by the end of the century there are 6.9 km of threatened major roads. The urgency and magnitude of these findings prompt discussion as to funding adaptation pathways, as action towards managed retreat can take years to decades to implement (Freudenberg et al., 2016; Lawrence et al., 2020; Siders, 2019). The high cost of retreating road infrastructure makes typical means for road maintenance or adaptation (e.g. the gasoline tax or post-emergency federal funds) inadequate (County of Kauaʻi Planning Department, 2023a). Thus, additional federal highway funding or the creation of new funding sources will be required. Most recently the State passed legislation for a “green fee” that can be used for resiliency projects including road realignment; but there will be tremendous competition for the approximately $100 million annual allocation (Honoré, 2025; S.B., 1396;). If sufficient funds are not found, the high costs to retreat Kauaʻi’s infrastructure threatens to create a path dependency towards hard protection measures (Hanger-Kopp et al., 2022; Klöck et al., 2022). Furthermore, the potential to lock-in into in-situ adaptation is reinforced by current laws, which allow hardening of shorelines to protect public assets. The engineering elements and thereby costs of adapting current shoreline roads to withstand sea level rise are likely substantial; moreover, it would lead to the almost certain squeeze of 10 % of Kauaʻi’s beaches.

We find that the cost to acquire and deconstruct private properties by the end of the century is $0.6 million for residential areas and $0.5 million for hotel and resort areas. Though their costs of managed retreat are similar, residential areas cover far more beaches (28 of 40). Where involuntary acquisition is used, just compensation to landowners is required to avoid constitutional takings claims. For voluntary programs, landowners are only likely to participate if market value compensation is given. As such, proactive retreat for Kauaʻi will require new sources of public funds to move buildings before they enter the shoreline. If a proactive retreat program is created, there would be a major shift of financial cost burden from the private to the public, which is highly controversial and would need to be addressed by planners and decision-makers. Such a program does not currently exist and instead the status quo, supported by law, is reactive retreat – where property owners are not allowed to harden the shoreline and thereby buildings fall into the public beach with coastal erosion. Buildings are required to be removed at this point and at the expense of the owner (Haw. Rev. Stat. § 205a, 2021). The cost of demolition and removal could be much greater than what we estimate herein if the buildings have broken up or crumbled into the nearshore environment (Setter et al., 2023). The non-financial costs of reactive retreat include impacts to public safety (e.g. from exposed rebar and concrete), limited beach access, and the introduction of additional environmental pollution

Table 3
Total cost of retreat: sensitivity analysis.

	1 %	**3 % (Baseline)**	5 %
1.5 m	$4,276,000,000	$2,932,000,000	$2,418,000,000
3.0 m	$4,394,000,000	$2,975,000,000	$2,444,000,000
6.1 m (Baseline)	$4,548,000,000	**$3,128,000,000**	$2,583,000,000

without remediation solutions (e.g. asbestos and lead). While non-financial costs are outside of the scope of this study, this is an important area for future inquiry. If shoreline laws to preserve beaches go unenforced, proactively or reactively, the cost will be the broad devastation of beach ecosystems.

If funds are not available to retreat development at all 40 beaches, there will need to be a systematic way to prioritize the distribution of funding that incorporates just decision-making processes that considers the needs and interests of impacted beach communities and the regional area (Ajibade et al., 2022; Mach et al., 2019; Siders, 2019). Prioritizing funding for beachfront critical roads, like those in Kekaha, ʻAnini, and Hanalei, will be challenged not only by high costs but also by accessibility and mobility needs, which varies by beach (Sun et al., 2021). For residential properties, planners in Kauaʻi will have to consider how to distribute funding amongst communities like Waipouli, where the cost to retreat 240 residential properties is $124 million whereas Hāʻena, a high-value area with many Vacation Rentals, is $159 million for only 55 residential properties. Equity considerations related to need lead to questions such as if and how to retreat high property value areas. Studies have shown higher income communities typically have more access to resources that can enhance resilience to hazards (Chen & Lee, 2022; Lindersson et al., 2023). There may also be issues related to relocation to consider, such as identifying receiving communities and additional costs that may be incurred during the relocation process. Retreat programs must address how to protect beaches while providing safety nets to households in need of adaptation assistance.

Beaches in Hawaiʻi play an important role in cultural, social, economic and ecological systems, and coastal management decisions must be put in context of past and future generations of land stewardship (Teodoro et al., 2023; Weston, 2012). If not done carefully, government decisions on adaptation may result in the perpetuation of harm in marginalized communities (Jessee, 2022; Phillips et al., 2022; Siders et al., 2021; Woodruff et al., 2018). Thus, essential to this discussion are the voices of people who steward these beaches, some of whom will face the landward consequences of adaptation action (Coffman et al., 2024; Hino et al., 2017). It is critical that these communities are recognized throughout the decision-making process, and that their engagement is reflected in outcomes. Our hope is that the results of this study can further inform community discussions and assist in avoiding maladaptation of beach social-ecological systems.

Code availability

All code can be found at https://github.com/UHawaii-ISR/KauaiRetreat.

CRediT authorship contribution statement

Kammie-Dominique Tavares: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Data curation, Conceptualization. **Renee O. Setter:** Writing – review & editing, Visualization, Software, Methodology, Data curation, Conceptualization. **Tanya Dreizin:** Writing – review & editing, Writing – original draft, Conceptualization. **Alan Clinton:** Writing – review & editing, Resources, Conceptualization. **Alisha Summers:** Writing – review & editing, Conceptualization. **Makena Coffman:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2026.100790.

Data availability

Data will be made available on request.

The sources of all data used in this analysis are cited in the Methods section of this paper.

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