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Failure to protect beaches under slowly rising sea level

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Abstract

Coastal land use in the USA is regulated by a chain of integrated federal to local policies that emphasize preservation of open space, public access, and the environment. Are these policies prepared to achieve lawfully stated objectives under accelerating sea level rise? To test the efficacy of these policies during the past century of slowly rising sea level, and thus their potential effectiveness under future accelerated sea level rise, we quantify land use on a section of windward O ahu coast, 1928–2015. Data show a shift from stable/accreting shorelines and wide beaches, to expanding erosion and beach loss concurrent with increasing development and seawall construction; trends at odds with policy objectives. Shoreline hardening increased 63%. Net shoreline change shifted from stable/accreting to erosional on 74% of the coast. More than 45% of this shift was due to flanking (erosion triggered by nearby hardening). Five geomorphic settings were analyzed. Prior to local coastal policy, from 1928 to 1975, headland beaches were mildly erosional with average change rates -0.07 ± 0.1 m/yr. Beaches in all other geomorphic categories accreted. Between 1975 and 2015, following enactment of coastal zone management policy, average change in all geomorphologies shifted to erosional, coastal development and seawall construction expanded, average beach width declined. Today, nearly 20% of beach length has been lost; 55% of beaches have narrowed. Failure to achieve policy goals under slow, historic sea level rise (1.2 to 1.4 mm/yr) implies preserving beaches, open space, and public access will require new policies, or more effective ways for implementing existing policies, in a future characterized by accelerated sea level rise.

Significance

1. Preserving and enhancing beaches, public access, and open space cannot be achieved in a time of rising sea level, if Coastal Zone Management (CMZ) policies allow development, and/or contain exemptions allowing shoreline hardening.
2. Using data-driven analysis of beach conservation in Hawai i, we find a failure to achieve program goals at all levels of the CZM network.
3. CZM policies designed by the State of Hawai‘i under the auspices of the National Coastal Zone Management Act and as implemented by state and county agencies, have proven inadequate to address issues of coastal erosion and thus leave local government ill-prepared to achieve their intended goals in a time characterized by sea level acceleration. This is likely also the case in other US states.

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1 Introduction

Economic growth and development along the shoreline strains coastal ecosystems (Barbier et al. 2011) due to pollution, resource extraction, and hardening of environmental boundaries (Creel 2003; Crosset et al. 2013). Long-term sea level rise (Church and White 2011), and accelerations (Nerem et al. 2018; Chen et al. 2017; Hay et al. 2015), exacerbate this situation.

On eroding coasts, owners will go to extraordinary lengths to protect their investment (Beatley 2009) such as building a seawall or revetment; as a result, 14% of the US tidal shoreline has been hardened (Gittman et al. 2015). This trend is not limited to the US. Studies from Japan (Koike 1996), the Caribbean (Rangel-Buitrago et al. 2015), parts of Europe (Manno et al. 2016), and China (Liu et al. 2018) document that shoreline hardening is a worldwide phenomenon.

Shoreline hardening disrupts natural processes, accelerates erosion on adjacent lands (known as “flanking”), and limits the natural dynamic behavior of the environment (Romine and Fletcher 2012a). Hardening on sandy beaches experiencing chronic erosion, ultimately the result of long-term sea level rise, causes beach narrowing and loss (Fletcher et al. 1997), and flanking triggers more hardening leading to additional beach degradation.

During the last decade, numerous studies document how hardening directly and indirectly impacts a range of ecosystem functions, goods, and services (Dethier et al. 2017). In Hawai‘i, shoreline hardening has caused a total of 21.5 km of beach loss statewide (Fletcher et al. 2012), posing threats to the tourism economy, littoral ecology, federally protected species (e.g., Hawaiian monk seal [*Neomonachus schauinslandi*], and Hawaiian green sea turtle [*Chelonia mydas*]), local culture and (Romine & Fletcher, 2012b), and the general water safety preparation of Hawaiian children who first experience the Pacific Ocean on beaches.

Coastal erosion is a major problem in Hawai i. Data in Fletcher et al. (2012) reveal that 70% of beaches on O ahu, Maui, and Kaua i experience an erosional trend. On O‘ahu’s 115 km coastline, historical seawall and revetment construction caused the narrowing of 17.3 km and total loss of 10.4 km of sandy beach over the period 1928 or 1949 to 1995. Combined, this is 24% of the original sandy shoreline (Fletcher et al. 1997).

In some parts of the world, shoreline hardening as a response to erosion reflects a coastal management model of action-reaction, compounded by the challenge of teasing out the natural causes of erosion (e.g., storms, seasonal waves, sea level rise) from those that are human-induced (e.g., disruptions to sand availability through hardening and dune removal) (Dethier et al. 2017). This is further exacerbated by multiple interests within a coastal management system that exert pressures upon local government officials who try to balance and accommodate competing interests (Nolon 2012). In other parts of the world, coastal management policies are implemented as statutory or as guidance documents (Williams et al. 2018). In the USA, coastal policy is a voluntary partnership between federal government, coastal states, and local jurisdictions. Individual programs vary by state, each under the auspices of the Coastal Zone Management Act (CZMA), but all must fulfill goals of protecting shorelines.

As development increases, and global sea level rise continues to accelerate (Nerem et al. 2018), it is essential to ensure that management policies are effective at preserving and protecting coastal environments including sandy beaches. Studies that evaluate coastal zone management have most typically focused on policies, plans, and organizational issues (Lowry Jr 1980; Hershman et al. 1999). Bernd-Cohen and Gordon (1999) studied US states’ program effectiveness in meeting the goals of shoreline preservation and found programs are generally meeting CZMA objectives. However, this conclusion was based on program indicators and not beach protection outcomes due to limited on-the-ground documentation. A detailed analysis by Good (1994) evaluated the outcomes of shore protection policies within one area of the central Oregon coast, finding policies to protect the beach were ineffective. More recently, Windrope et al. (2016) performed a 35-year evaluation of outcomes of the WA Shoreline Management Act (1977) and find little change in shore hardening despite increased regulation post 1977.

Here we document the efficacy of coastal zone policy in Hawai i over the past century to protect the shoreline, a time characterized by relatively low rates of sea level rise (SLR). During the past century, the historic SLR trend for O ahu (1 to 2 mm/yr) is similar to that of the island of Kaua i but different from Maui (2 to 3 mm/yr) (Romine et al. 2013). In Hawai i, coastal erosion is linked to SLR. However, the relative influence of SLR on shoreline change is understood to be presently minor compared with other driving factors, although this is expected to change with future SLR (Anderson et al. 2015). Coastal erosion is the result of several physical drivers including impacts to sediment supply, wave conditions, sediment transport processes, human derived structures, and geomorphology (Romine et al. 2013).

We use a detailed, data-driven investigation of historical shoreline change and land use patterns on a representative segment of the Hawaiian shoreline to support our analysis of coastal management. Our approach is similar to Manno et al. (2016) and Winthrope et al. (2016) in that we document historical shoreline change to assess the effectiveness of coastal management but we go one step further by linking shoreline erosion to coastal development patterns and hardening.

1.1 Coastal zone management policy

Recognizing rapid growth and the need for better coastal zone management, the US Congress enacted the Coastal Zone Management Act (CZMA) in 1972 (Chasis 1985). The purpose of the CZMA is to “preserve, protect, develop, and where possible, to restore or enhance the resources of the nation’s coastal zone” (16 USC §§ 1451-1466). The CZMA encourages states to create coastal management plans and policies by involving local jurisdictions and communities in the planning and regulatory enterprise, thereby fostering cooperation among federal, state, and local governments (Nolon 2012).

The Hawai i Coastal Zone Management Program (HCZMP) is a typical federal-local partnership under the National CZM Program. Established in 1977 to “provide for the effective management, beneficial use, protection, and development of the coastal zone” (HRS §§ 205A-1 to 49), the HCZMP is a networked system, regulating the coastal zone through the state and local agencies. In fiscal year 2016, for instance, Hawai i allocation for coastal zone management from the National Oceanic and Atmospheric Administration, Office for Coastal Management (NOAA-OCM) totaling $2,269,049 was distributed among local network agencies in support of coastal management activities aligned with federal and state program goals.

Coastal development in Hawai i is regulated through three main policies: 1) Local zoning ordinances that establish approved uses, densities and height limits, 2) Special Management Areas (SMA), and 3) Shoreline Setbacks (Braxton 2003). The SMA designates areas along the shoreline that require special controls on development, while the setback establishes a development prohibition zone defined by a minimum distance from a designated baseline (defined in Hawai i as the highest annual reach of the waves; HRS §§ 205A).

On the capital island of O ahu, the county has adopted an SMA in the local ordinance that mirrors the HCZMP: “to preserve, protect, and where possible, to restore the natural resources of the coastal zone of Hawai i” (ROH § 25-1.2). However, there are a number of exemptions that effectively reduce the scope of the SMA: single-family residences less than 7500 square feet, repair and maintenance of roads and highways, interior alterations to existing structures, structural improvements to existing single family residences including additional dwelling units, and others.

The county setback policy states, “It is the primary policy of the city to protect and preserve the natural shoreline, *especially sandy beaches*; to protect and preserve public pedestrian access laterally along the shoreline and to the sea; and to protect and preserve open space along the shoreline.” (ROH § 23-1.2). The county policy sets distances of 20–60 ft from the shoreline depending on lot size, regardless of the stability of the shoreline and is generally established 40 ft inland. No new development is allowed within the setback unless a “variance” is granted (Cox et al. 1975).

A variance is granted where a hardship exists (ROH § 23-1.8). The hardship standard stipulates that no facilities or improvements may be used to artificially fix the shoreline unless erosion will likely cause a hardship, such as depriving “reasonable use of the land.” It is under this hardship variance that various forms of shoreline hardening, seawalls, and revetments, are routinely permitted, leading to island-wide beach loss.

2 Methods, study area

Our methods follow several earlier publications (Fletcher et al. 2003, 2012; Romine et al. 2009) and are described in Electronic Supplementary Material (ESM). We build geographic information system datasets from a sequence of orthorectified vertical aerial photomosaics across the time period 1928 to 2015. We quantify the history of beach erosion and accretion, coastal hardening, coastal development, flanking, and physical wave and weather events. Our data are binned in terms of the coastal geomorphology, and as time period averages.

The study area is 7.42 km of reef-fronted shoreline (Conger et al. 2009) on the northeast coast of O ahu (Fig. 1). Like most beaches in Hawai i, the sand supply is derived from carbonate sources on nearby reefs and erosion of backshore sand-rich dune systems. Beaches are also exposed to waves year-round (Vitousek & Fletcher, 2008) from varying directions, which serves as the principal driver of sediment transport. Over the period of our analysis, sea level has been rising in the study area, 1.2–1.4 mm/yr (http://tidesandcurrents.noaa.gov). In 1928, the coast consisted of a single continuous

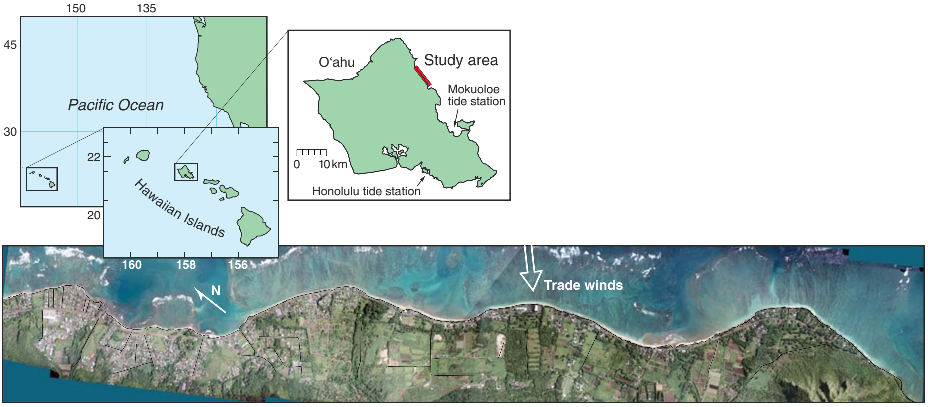

Fig. 1 The study area extends from Hau ula to Makali i Point, northeast O ahu

sandy beach (10- to 30-m wide) composed of late to middle Holocene carbonate sand (Harney et al. 2000), originating from the adjacent fringing reef (Harney and Fletcher 2003).

Following the morphology of the reef, the coastline is characterized by recurrent headland and embayed segments with shorelines that behave in distinct ways (Romine et al. 2016). Thus, we identify patterns of shoreline change and development associated with the following beach morphologies: (1) headland beaches, (2) embayed beaches, (3) transitional beaches between headlands and embayments, (4) shallow reef-fronted beaches, and (5) beaches fronted by sand fields and sand-filled channels.

The area is extensively developed with a coastal highway, homes, and widespread shoreline hardening. The Kamehameha Highway is the main road in the region and is heavily traveled. It was built parallel to the shoreline and acts as a barrier that impedes access to the ocean and pins coastal development on relatively shallow shorefront lots.

3 Results

Analysis of a sequence of aerial photos 1928 to 2015 defines trends in land use and shoreline change (Fig. 2). Four attributes were specifically identified: coastal geomorphology, shoreline change, coastal development, and coastal hardening.

Over the time period, averages of shoreline change rates (Fig. 3, Table SI4) indicate a region-wide switch from stable or accreting beaches to generally eroding, or experiencing reductions in accretion, for all geomorphologies, except headland beaches. Data from headland beaches indicates chronic erosion from the beginning of the study period, which accelerated over the time period.

The average shoreline change rate for the entire coastline reflects a switch from stable/ accreting to erosional. However, the divergence between the distinctly erosional headland beaches and the accretional embayed and transitional beaches early in the time series create large uncertainty in the combined averages of the early data.

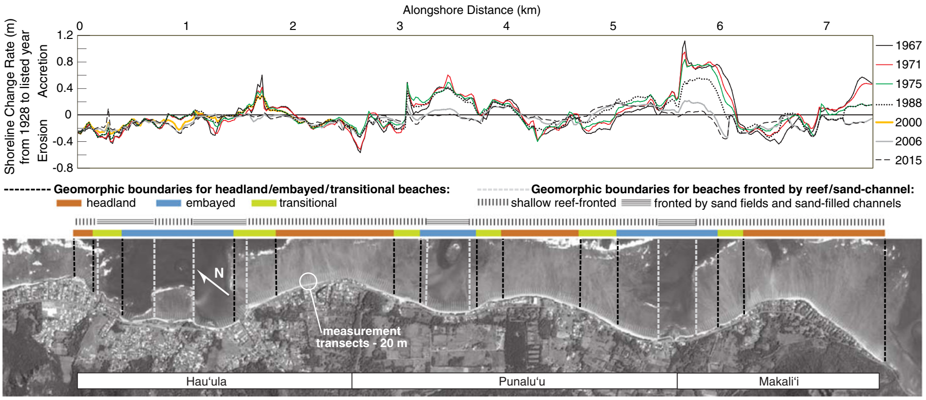

Fig. 2 Rates of shoreline change from 1928 to each successive year were calculated from digitized shoreline positions at transects spaced 20 m along the length of the study area. Data recording historical shoreline behavior were collected from 5 overlapping geomorphic regions: (1) headland beaches, (2) embayed beaches, (3) transitional beaches between headlands and embayments, (4) shallow reef-fronted beaches, and (5) beaches fronted by sand fields and sand-filled channels

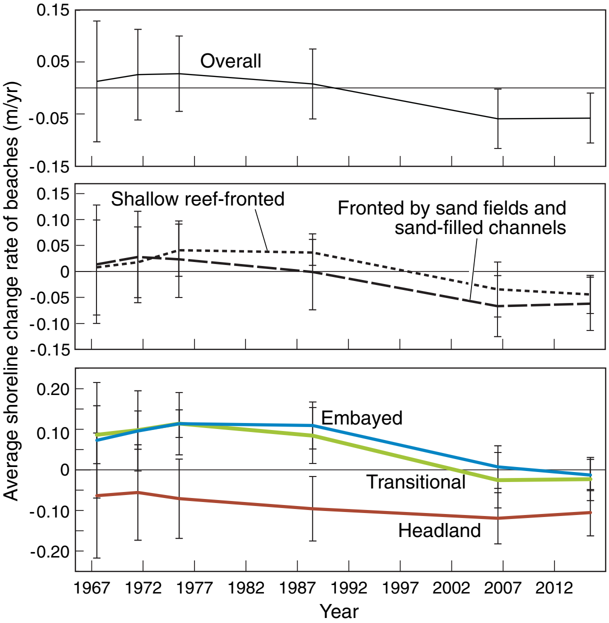

Fig. 3 Over the period of study, the region changed from a generally stable/accreting coast (with the exception of headland beaches) to a coast characterized by chronic erosion. Top: trends in average shoreline change rate (m/yr) including all transects. Middle: average shoreline change rate (m/yr) for shallow reef-fronted beaches and beaches fronted by sand fields and sand-filled channels. Bottom: average shoreline change rate (m/yr) for embayed, transitional, and headland beaches. Whiskers represent the 95% C.I. for the average

Overall, beaches fronted by sand fields and sand-filled channels are less erosional than shallow reef-fronted beaches, and transition and embayed beaches are the least erosional of all morphologies. By 2006, on average, all five morphologies were experiencing chronic erosion. Data document a sandy shoreline that was generally stable or accreting throughout the early and middle twentieth century (with the exception of headland beaches), undergoing a shift to chronically eroding in the present day.

From 1928 to 2015, headland beaches showed significant erosion with an average rate of − 0.11 ± 0.06 m per year, while transition and embayed beaches experienced milder erosion with rates of − 0.02 ± 0.05 m per year, and − 0.01 ± 0.04 m per year, respectively. Shallow reef-fronted beaches, and beaches fronted by sand fields and sand-filled channels eroded from 1928 to 2015 at a rate of − 0.06 ± 0.05 m per year and − 0.04 ± 0.04 m per year, respectively.

Over the study period, the percentage of erosion and the percentage of beach lost to erosion increased (Table SI5). Nineteen percent of the total length of sandy beach was permanently lost to erosion, and 55% narrowed. A total of 74% of the beach was degraded (lost + narrowed) at an average rate of − 0.06 ± 0.05 m per year.

The length of shoreline hardening increased steadily throughout the entire time series rising from a complete absence of seawalls in 1928 to nearly 5 km of hardened shoreline today (Fig. 4).

The use of seawalls and the rise of buildings on beachfront lots are strongly correlated (r-0.97). Records show that in 1928, thirty-nine buildings existed along the shoreline without the need for shoreline hardening (Table SI6). However, the number of buildings along the shoreline increased by more than fourfold, from 39 to 177 between 1928 and 1975 and the length of hardened shoreline increased to 45%.

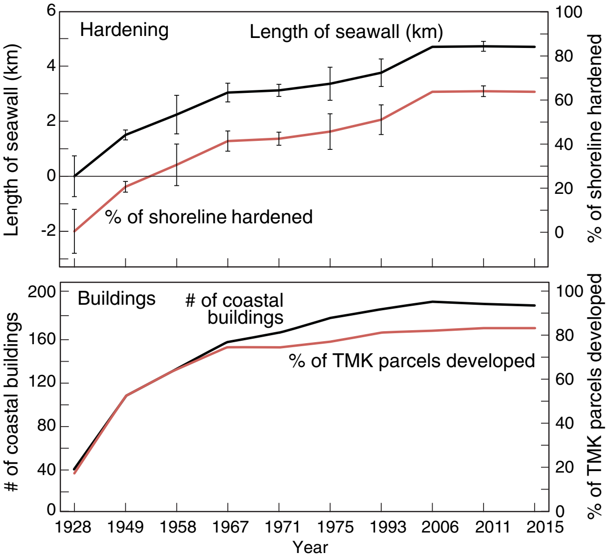

Fig. 4 Top: length of hardened coast (black, km), and percentage of hardened coast (red). Bottom: number of beachfront buildings (black), and percentage of beachfront parcels developed (red)

By 1975, 3.34 km of the shoreline had been hardened. The most recent data for year 2015 shows a total of 189 established coastal buildings fronted by 63% of the shoreline.

The history of beach width is also related to coastal morphology, with embayed and transitional beaches generally having the greatest width, and headland beaches the least (Fig. 5). Over the period of study, beach width for all morphologies displayed significant variability.

On average, headland beaches (combined hardened and unhardened) narrowed by approximately 50% over the period while embayed and transition beaches (combined hardened and unhardened) showed no net trend. The average beach width on hardened shorelines (8.6 m) showed no net trend over the time series but is approximately 42% the width of beaches on unhardened shorelines (14.8 m).

Data was also analyzed to compare the average rate of erosion during the years prior to the adoption of the US and local CZM programs (1928 to 1975) and the years following (1975 to 2015) (Fig. 6).

The data indicate that from 1928 to 1975, embayed and transition beaches accreted (0.11 ± 0.08 and 0.11 ± 0.03 m per year, resp.). However, on headland beaches, the shoreline eroded at an average rate of − 0.07 ± 0.1 m per year. In comparison, following the adoption of CZM policy (1975 to 2015), the shoreline eroded on headland, transition, and embayment beaches at an average rate of − 0.09 ± 0.09 m per year, − 0.18 ± 0.06 m per year, and − 0.18 ± 0.09 m per year, respectively.

From 1928 to 1975, beaches fronted by sand fields and sand-filled channels and shallow reef-fronted beaches accreted 0.02 ± 0.07 m per year and 0.04 ± 0.05 m per year (resp.) (Table SI7). From 1975 to 2015, shorelines became erosive for both types. Shallow reef-fronted beaches experienced erosion of − 0.13 ± 0.05 m per year and beaches fronted by sand fields and sand-filled channels eroded − 0.17 ± 0.07 m per year. Prior to creation of the CZM regime, 0.8% of beaches had been permanently lost. Since creation of CZM policy, 19% of beaches have been lost.

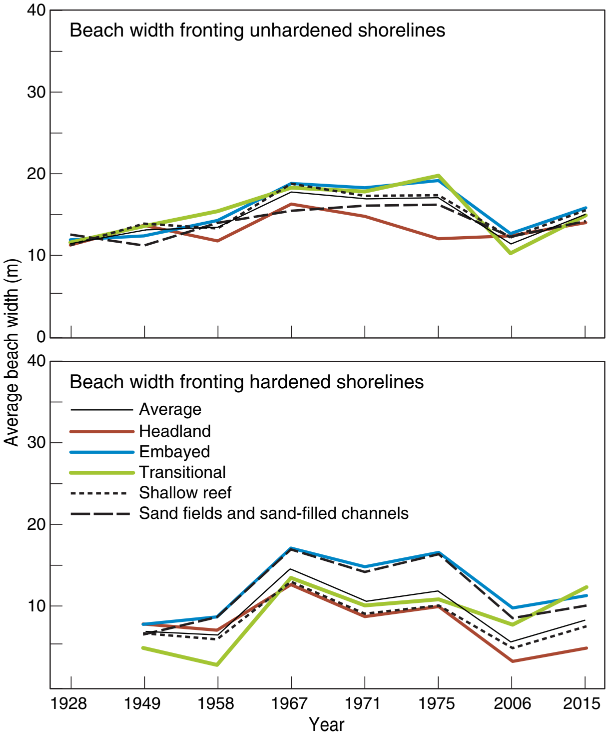

Fig. 5 Top: unhardened beaches are wider than hardened beaches (by 42%) and show no net trend over time. Bottom: width of hardened beaches shows variability and a downward trend from 1967 to present

4 Discussion

By 2015, 62% of buildings were built in headland regions, 27% in transition regions, and 11% in embayed regions. Development activity and beach stability are negatively correlated. The greatest number of buildings was built on the most erosive shoreline, a pattern no doubt aided by lack of data on historical shoreline changes. This unfortunate pattern may be the result of

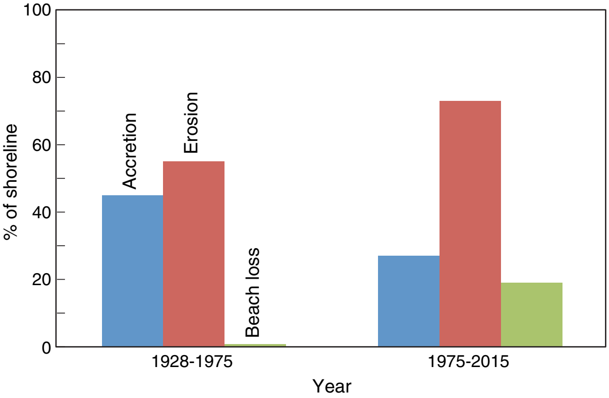

Fig. 6 Percent of measurements eroding, accreting, and beach loss from 1928 to 1975, and from 1975 to 2015

the coastal highway running closer to the ocean where the coast curves landward in an embayment, and being furthest from the ocean in headland regions thus giving more room for development, but simultaneously hemming it in.

4.1 Hardening

Concurrent to the growth in development, coastal hardening increased by 63%, comprising 4.67 km of seawalls and revetments. None of the shoreline was armored in 1928. As development in the study area boomed throughout the 1940's, so did the hardening of coastal lots. Prior to the adoption of the HCZMP in 1975, 45% was armored. From 1975 to 2015, hardening increased by 18%.

An extensive amount of hardening occurred first in headland regions. By 1975, 63% of headland regions were armored, while 42% of transition regions and 22% of embayed regions were armored. Headland regions were subject to coastal hardening before transition and embayed regions for two reasons: (1) the majority of coastal development was concentrated in headland areas, and (2) the geomorphology of headlands and embayments influences sediment transport and deposition. Waves refract at headlands such that their energy is focused on the shoreline. As a result, headlands experience accelerated erosion while embayments tend to be more stable and may even act as depositional locations for sand eroded from an adjacent headland (Romine et al. 2016).

After the 1980s, coastal hardening dramatically increased in transition regions. By 2015, 77% of headland regions and 78% of transition regions were hardened. The increase in the length of seawalls despite the reduced rate of new development after 1975 could be attributed to other variables including the process of "flanking," sea level rise, and an increase in extreme swell events, which may accelerate coastal erosion rates.

A similar trend was observed along 3.14 km of shoreline directly adjacent to the coastal highway. Data show that 46% of the coastal highway was armored by 2015. Although 52% of the coastal highway travels through embayment coasts, areas where the highway ran closer to the ocean in headland regions were armored first.

By 1975, 31% of the coastal highway was fronted by hardening and more than half (53%) of the hardening occurred in headland coasts. However, after the 1980's, coastal hardening to protect the highway had spread to transition regions. By 2015, 46% of the coastal highway was fronted by hardening and of that percentage, 20% occurred in headland and transitional coasts.

4.2 Beach loss

Erosion in the study area increased from 57% in 1967 to 74% in 2015. Prior to 1967, there had been no beach loss aside from localized seasonal loss on 10% of the coast. Seasonal beach loss, followed by recovery, typically occurs with changes in the seasonal wave climate and may be a signal that a beach is severely sand-depleted.

By 2015, 19% of the beach had been permanently lost to erosion (Fig. 7). Beach loss intensified in headland regions compared to embayed regions. Shoreline change rates in headland regions show a steady erosional trend both pre- (1928 to 1975) and post- (1975 to 2015) coastal zone policy. In transition and embayment regions, rates changed significantly

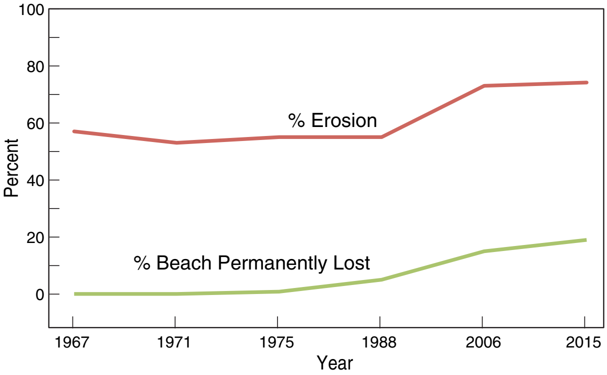

Fig. 7 Erosion in the study area increased from 57% in 1967 to 74% in 2015. By 2015, 19% of the beach had been permanently lost to erosion

from accretion to erosion (Table SI7). Beach loss violates CZM goals of 1) Protecting beaches for public use and recreation, 2) Protecting, preserving, and restoring coastal scenic and open space resources, 3) Protecting valuable coastal ecosystems, 4) Reducing exposure to coastal hazards, and most of the other objectives and policies set forth in Hawai‘i coastal law (HRS205-A).

4.3 Land use

Between 1928 and 1975, the number of buildings in the study area increased from 39 to 177, an annual growth rate of 3.20%. Between 1975 and 2015, the annual growth in new buildings fell to 0.16%. By 1975, for every empty lot, there were seven developed lots. Thus, the slowed rate of individual building construction after 1975 reflects a coastal zone that was largely built out prior to enactment of state and county coastal zone policies.

Since 1975, redevelopment of existing buildings into structures with larger footprints has increased overall density. Expansion of existing single-family homes is allowed under SMA policy (ROH § 25-1.3.2A) and this constitutes a de facto increase in coastal development that continues to present day. Rapid build-out prior to coastal policy, followed by subsequent expansion of these buildings under policy authority, sets the stage for widespread seawall construction against a background of sea level rise.

We calculated average building surface area from digitized coastal buildings shapefiles created in ArcGIS. The average building surface area in the 1970’s was 170 square meters whereas the average building surface area in 2015 was 203 square meters, an increase of 20%.

Photogrammetric analysis reveals that throughout the 1970’s many existing structures along the coastline were either demolished and replaced by larger structures, or they were expanded. The increase in building size combined with the location of the coastal highway directly behind these structures prevented the relocation of threatened buildings in the face of chronic erosion.

CZM policies appear to have done little to prevent a 29% increase in coastal hardening that occurred between 1975 and 2006. Data shows this spike in hardening followed the build-out of 78% of shoreline lots by 1975, and was concurrent with the expansion in average building area that occurred between the 1970’s and 2015.

4.4 Flanking

The shift from a stable beach to an eroding beach may often be attributed to flanking (Romine and Fletcher 2012a) resulting from a long-term pattern of shoreline hardening (Fig. 8) that still continues today.[1]

We tested this phenomenon by calculating shoreline change rates directly north and south of armored locations before and after installation. Data reveal that erosion rates on more than 27% of the study area significantly accelerated due to flanking. In many cases, rates shifted from an accreting trend to an erosional trend following hardening on the adjacent shore. To illustrate, directly adjacent to hardening installed in the 1960's, shorelines became unstable, shifting from an average 0.3 ± 0.06 m per year (accreting) prior to the installation of hardening to -0.4 ± 0.08 m per year (eroding) after the installation of hardening.

Coastal property owners adjacent to seawalls will often harden their own properties in response to flanking. Shoreline history confirms the existence of a "hardening domino effect" in which the first seawall triggers a succession of seawalls by adjacent property owners (Romine and Fletcher 2012a). The domino effect of coastal hardening has been documented in other regions, for example, Manno et al. (2016) traced the decadal evolution of hardening along a portion of the Mediterranean coast and demonstrated protection structures produce a deficiency in sediment while shifting downdrift erosion processes, which are then countered by additional structures.

In our study, by 2015, roughly 45% of the observed hardening was constructed in response to an adjacent seawall or revetment. Contributing to this pattern was the continued construction of beachfront buildings, initially on stable shorelines, but which became vulnerable to erosion due to flanking. Our data reveal that construction of first seawalls along a coastal reach destabilizes adjacent shorelines and promotes subsequent coastal hardening that can sentence an entire region of sandy beach to narrowing and eventual loss.

4.5 Failure to achieve CZM goals

Hawaii's coastal land use management system is complex, but three main laws govern its uses: county zoning ordinances, shoreline setbacks enacted in 1970 that established a minimum 40′ setback from the shoreline,[2] and the Hawai'i Coastal Zone Management Program. There are 10 objectives in the authorizing statute for the HCZMP (HRS §§ 205A), summarized here as protecting and improving natural resources and ecosystems, reducing exposure to hazards, providing for public participation, and affording economic activity in suitable locations. Objective 9 is simply "Beach Protection - Protect beaches for public use and recreation."

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[1] The "Punaluu Beach Homes Shoreline Protection Project" is a 643-ft-long continuous concrete rubble revetment along seven residential lots. A permit application for this project has been evaluated under the authority of CZM policy. The applicant states that "coastal erosion has persisted along this coast for the previous three decades" and concludes that hardening this chronically eroding shoreline will "promote sand accretion." This application has made its way through the HCZMP network, has not been challenged for the deceptive nature of its conclusions, and is currently under construction.

[2] Maui and Kaua i counties adopted erosion rate-based setbacks using a combination of criteria: the rate of historical shoreline change, or the average depth of the lot. On Maui, the setback is calculated as either 50 times the annual rate of erosion plus 25 ft or is based on the average lot depth, whichever gives a greater distance from the shoreline. On Kaua i, the setback is a distance equal to 40 ft plus 70 times the annual coastal erosion rate (for buildings 5000 sq. feet or less) or 40 ft plus 100 times the annual coastal erosion rate (buildings greater than 5000 sq. feet).

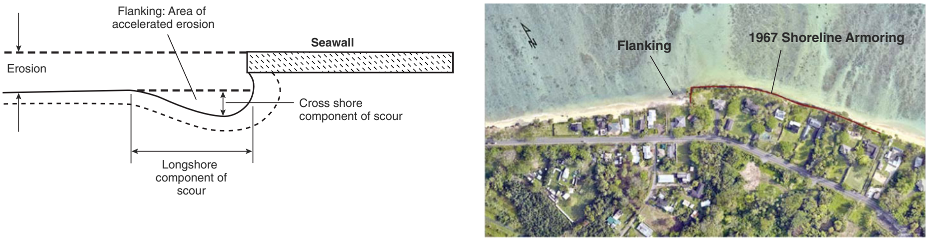

Fig. 8 Left: coastlines adjacent to a seawall or revetment are typically subjected to increased erosion as a result of reductions in sand availability by the presence of the hardened shoreline. This effect, known as "flanking," encourages land owners to harden their own shore in order to protect their newly eroding lands. This, in turn, leads to more flanking and beach loss. Dotted line: future shoreline position. Right: flanking in Makali i as a result of coastal hardening built in the 1960's

Each objective is further expanded with an accompanying policy. Policy 9—Beach Protection, has three elements: (1) locating new structures inland, (2) prohibiting private erosion-protection structures, and (3) minimizing public erosion protection structures.

The HCZMP mandates the establishment of an SMA extending inland "no less than 100 yards from the shoreline." Responsibility for implementing the law rests with county government. Each county established procedures for identifying SMA boundaries and adopted their own permit guidelines (consistent with state law) for new buildings [or substantial renovations] within the SMA.

A challenge to implementing the SMA is county zoning. Land use zoning creates "entitlements" or expectations about how private land owners can use their land. Courts have generally deferred to landowner claims that denial of building permits consistent with underlying zoning would constitute an unconstitutional "taking" of private property. Hence, while the SMA permit provides counties the legal authority to deny permits for building inconsistent with SMA guidelines, few permits are denied for land units. In practice, the SMA permit has been used primarily to impose permit conditions, such as modifications in building site plans to ensure increased shoreline setbacks, requirements for additional public access, and changes in landscaping plans to reduce runoff and similar requirements.

The data-based history of shoreline change rates reported here shows that beaches in the study area experienced either a transition from accretion to erosion, or from light erosion to strong erosion. Shoreline change was observed when comparing rates from 1928–1975 (pre-HCZMP period) to 1975–2015 (enforced HCZMP period) for beaches in all geomorphic settings.

Over the period of our study, the influence of increased coastal development in the study area is evident; continued building and highway construction is eventually threatened by chronic erosion, triggering hardening, beach narrowing, and loss. In addition, widespread shoreline hardening activated the process of flanking, contributing to the shift from stable/accreting to erosional beaches.

This detailed history of shoreline change reveals human-induced factors that likely drove important aspects of the recent erosion trend, a trend that could be partially to blame for Oʻahu losing at least 24% of its sandy beaches to hardening, and possibly more (Fletcher et al. 1997). Other factors that could be driving the erosional trend besides coastal construction, expansion, and hardening include sediment transport processes and SLR. Romine et al. (2013) studied shoreline change across the Hawaiian Islands and found a wide variation in erosion rates across different segments of island shoreline despite a rather homogeneous SLR for the island. This suggests that human impacts and persistent physical transport mechanisms may have a larger influence on historical shoreline change than SLR.

In spite of substantial legal authority to address shoreline erosion, appointed and elected land use officials have frequently:

1. Approved hardship variances allowing seawall construction,
2. Permitted expansion of single family homes within the SMA,
3. Approved building on coastal lots without regard to shoreline stability, and
4. Allowed maintenance and expansion of non-conforming buildings.

These practices have been repeatedly approved over decades since the enactment and enforcement of HCZMP with consequences that fail to meet the goals of the program.

Consequently, our data reveals that despite strategies to mitigate the negative effects of shoreline development and hardening on the beach, the establishment of Hawai i coastal zone management policies did not adequately protect beaches in the study area, public access along the shoreline, nor open space in a meaningful way.

Like other states, local governments in Hawai i are the primary implementers of coastal policies through land use powers and infrastructure improvements (Nolon 2012). Several previous studies show that state mandates for coastal management do not guarantee effective policy implementation at the local level (Blizzard and Mangun 2008; Windrope et al. 2016). There are several reasons why local officials and land use managers might not be using the full weight of HCZM laws. Local governments avoid "taking" claims by either imposing permit conditions on applicants or by issuing variances all together for new development or building expansions.

In Florida, Ruppert (2008) suggests strengthening the state setback law by stipulating that variances only be granted on the condition that a deed restriction is recorded which disallows seawalls and requires the removal of structures at owner's expense if they impact the beach. Local governments can also issue temporary emergency hardening permits. Oftentimes, these emergency provisions, which were meant as temporary, become permanent (Cheong 2011; Ruppert 2008).

Another potential explanation is that local political actors exert significant pressure on officials to obtain permits or to shape local policies all together (Feiock 2004). Coastal properties in Hawai'i hold tremendous value and their owners may translate that wealth into political clout that can be used to obtain a permit (Ruppert 2008). Another complication is disentangling the causal mechanisms of beach loss. Local regulators have had little data to base efforts to strengthen or enforce regulations for restricting structures (Dethier et al. 2017). More longitudinal and place-based studies such as this one are needed to help assess the success or failure of coastal policies and their implementation.

5 Conclusions

Today, Hawai i and the rest of the USA is entering a future characterized by accelerating sea level rise (Sweet et al. 2017; Nerem et al. 2018) and increasing storminess (Murakami et al. 2013). Improving sustainability, resilience, and environmental conservation in the face of these challenges is the obligation of elected officials, policy-makers, and agency professionals.

Coastal land use policies establish a Special Management Area (SMA) and a construction prohibition zone (the setback) with the stated objectives of protecting and enhancing the natural character of the shoreline, public pedestrian access, and open space. We test the success of these policies with a detailed history of shoreline change and coastal development on the coast of O ahu over the span 1928 to 2015, a period characterized by long-term, though slow, sea level rise.

We find a clear failure to achieve policy objectives for six primary reasons:

1. The implementation of a fixed distance setback law allowed building and road construction without regard to coastal erosion patterns, thus ensuring that at least some development will be threatened by erosion before its planned lifetime;
2. The application of SMA rules has allowed expansion of building footprints associated with single-family homes; this ensures that most buildings will have no effective lifetime as they may be continuously renovated, even expanded, further locking in eventual threats by erosion;
3. The setback law contains a loophole called a “hardship variance” allowing all forms of development to be protected by coastal hardening, ensuring the demise of beaches experiencing chronic erosion (a physical certainty in a regime of long-term sea level rise).
4. This sequence of permissive development, hardening, and beach loss is further promoted by the flanking process, whereby a hardened shoreline triggers and accelerates erosion on an adjacent beach.
5. The shoreline is managed parcel by parcel. This promotes short-sighted decision-making without awareness of accumulated impacts, long-term trends, or place-based characteristics.
6. Agency personnel with authority to decide on applications for coastal zone uses are not required to, and traditionally have not had, scientific training in the interpretation of potential impacts. In lieu of this, decisions are made on the basis of statements from consultants hired by the applicant - a situation that is ripe for conflict of interest.

We find that headland beaches were more threatened by erosion than embayed beaches, which led to the majority of seawall construction in these regions. This, in turn, led to accelerated erosion by flanking and a greater percentage of permanent beach loss in headland regions. Embayed and transition beaches, which were accreting prior to CZM policies, experienced accelerated erosion after policies were established. Consequently, the increase in erosion resulted in a spike in the construction of seawalls and revetments despite lawfully enacted objectives against this.

We call attention to the need for substantial revision of coastal zone management in order to protect beaches. Beaches continue to narrow and seawalls and revetments continue to be permitted to protect development sites where the rate of erosion has exceeded the protection afforded by the setback over the lifetime of the building.

Today the world is entering a long and uncertain period characterized by accelerated sea level rise. If Hawai i, the USA, and the world aim to prevent a complete loss of its beaches and associated public access and open viewplanes, it will require a review and revision of the coastal policies and their implementation that have failed to meet lawfully codified objectives.

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