Chapter 10
Armoring on Eroding Coasts Leads to Beach Narrowing and Loss on Oahu, Hawaii

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Abstract Coastal armoring (defined as any structure designed to prevent shoreline retreat that interacts with wave run-up at some point of the year) has, historically, been a typical response to managing the problem of beach erosion on the island of Oahu, Hawaii. By limiting the ability of an eroding shoreline to migrate landward, coastal armoring on Oahu has contributed to narrowing and complete loss of many kilometers of beach. In this paper, changes in beach width are analyzed along all armored and unarmored beaches on the island using historical shoreline positions mapped from orthorectified aerial photographs from as early as the late 1920s. Over the period of study, average beach width decreased by 11% ± 4% and nearly all (95%) documented beach loss was fronting armored coasts. Among armored beach sections, 72% of beaches are degraded, which includes 43% narrowed (28% significantly) and 29% (8.6 km) completely lost to erosion. Beaches fronting coastal armoring narrowed by −36% ± 5% or −0.10 ± 0.03 m/year, on average. In comparison, beach widths along unarmored coasts were relatively stable with slightly more than half (53%) of beaches experiencing any form of degradation. East and south Oahu have the highest proportion of armored coast (35% and 39%, respectively) and experienced the greatest percent of complete beach loss (14% and 12%, respectively). West and north coasts, with relatively little armoring (10% and 12% armored, respectively), experienced little complete beach loss (2% and 6%, respectively). However, beaches are still significantly narrowed compared to historical patterns on west and north coasts (61% and 70%, respectively). We find at these sites that cultivation of coastal vegetation may be a factor in beach narrowing on Oahu, along with beach erosion. Increased 'flanking' erosion (accelerated

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shoreline retreat adjacent to armored sections) is documented at several beaches, often requiring extension of armoring structures to protect abutting coastal properties, a process that leads to alongshore seawall proliferation.

10.1 Introduction

A recent study finds that erosion dominates shoreline change on the beaches of Kauai, Oahu, and Maui. Since a strand plain of unconsolidated carbonate sand backs large segments of the Hawaii shoreline (Sherrod et al. 2007; Fletcher et al. 2011), one may assume there is adequate sediment on the backshore for an eroding beach migrating landward to develop a profile in equilibrium with nearshore conditions and underlying geology. However, on many Hawaii beaches, the response to beach erosion has been to armor the backshore to protect coastal properties, and thus impound this sand resource (Hwang 1981; Sea Engineering Inc 1988; Fletcher et al. 1997; Fletcher 1992; Makai Ocean Engineering and Sea Engineering 1991). In such cases, the water line continues to migrate landward while the backshore remains fixed – resulting in narrowing and eventually complete loss of the beach. Sediment that would otherwise be available to the littoral system is impounded behind seawalls, revetments, sand bags, and other designs; thereby depriving adjacent beaches and leading to a trend of increased erosion within the littoral cell. The narrowing effects of armoring on beach width are also documented in studies from other regions (e.g., Carter et al. 1986; Hall and Pilkey 1991; Komar and McDougal 1988; Kraus and McDougal 1996; McDonald and Patterson 1984; Tait and Griggs 1990).

'Healthy' Hawaii beaches are important to the local lifestyle and a vital attraction for the tourism-based economy. Fletcher et al. (1997) found that coastal armoring led to narrowing or complete loss along ~24% of beaches on the island of Oahu, Hawaii.

Seawalls and other armoring styles are often attributed with causing coastal erosion, yet in Hawaii we find that shoreline armoring is typically a response to pre-existing coastal erosion. Because of this, it is appropriate to ask two sets of questions. One, does armoring accelerate pre-existing erosion and does it initiate and or accelerate erosion on adjacent properties? Two, does armoring lead to other negative impacts such as beach loss or beach narrowing, which, although caused by erosion, we define as separate from erosion? Here, we primarily explore the latter through analysis of beach narrowing fronting coastal armoring. Evidence is also provided for 'flanking' erosion on beaches adjacent to coastal armoring.

10.2 Physical Setting

The Hawaiian Islands are comprised of eight high volcanic islands in the upper tropics of the north Pacific. Oahu, located between 21 and 22° north latitude, is the most populated of the main islands. The island is fringed by a Pleistocene

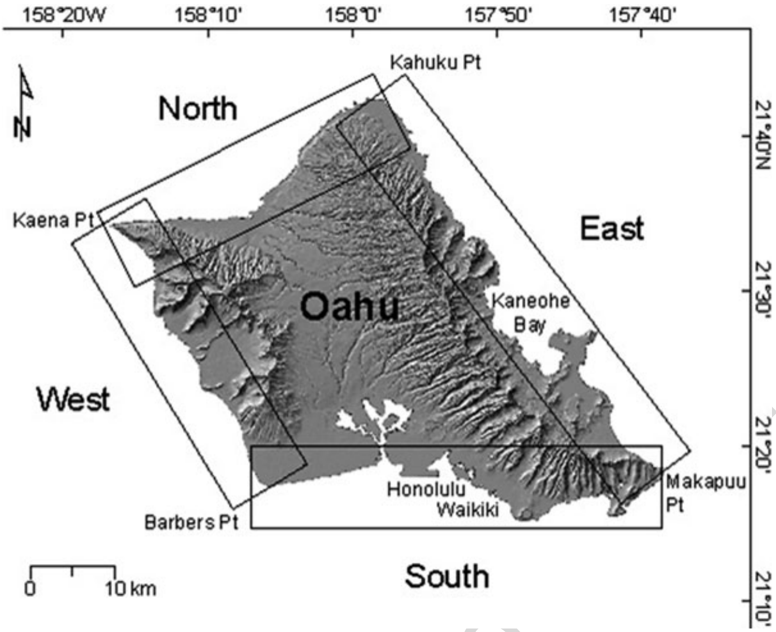

Fig. 10.1 Four regions of Oahu

reef platform cut by relict erosional features (e.g., channels, karst depressions) formed during periods of lower sea level (Fletcher et al. 2008). Hawaiian beaches are comprised primarily of calcareous sands. This sediment originated on the fringing reef platform through either direct organic precipitation in the reef ecosystem or through bioerosion of skeletal limestone. Sands may be stored in offshore channels and depressions, on low-lying coastal plains stranded by late-Holocene sea level fall (Fletcher and Jones 1996), or in the modern beach and dune system (Harney et al. 2000; Harney and Fletcher 2003). Hawaii beaches, like most carbonate beaches, are typically narrower than continental beaches due to limited sediment supply.

Located in the middle of the Pacific in a microtidal zone, wave energy is the predominant driver of shoreline processes in Hawaii. Large waves from North Pacific storms are common in winter months, typically affecting north and west - exposed shores. South-exposed shorelines are affected by smaller long-period swell from southern oceans in summer. Easterly trade winds and the waves they produce are common on leeward shores year-round but most frequent in summer months (Vitousek and Fletcher 2008).

The island is divided into four regions for analysis: east, south, west, and north (Fig. 10.1). East Oahu, from Kahuku Point in the north to Makapuu Point in the south, is moderately developed with single-family homes and a coastal highway lining most beaches. The east Oahu shoreline faces directly into the predominant easterly trade winds and is occasionally affected by large refracted northerly swells in winter. Beaches in the northeast (north of Kaneohe Bay) are typically narrow and fringed by a wide (~0.5 km), shallow reef platform. Many homes and the coastal highway were constructed too close to eroding beaches in the past century resulting in extensive coastal armoring along northeast shores. Beaches in the southeast (south of Kaneohe Bay) are wider, relative to the northeast, with a deeper fringing reef.

South Oahu, from Makapuu Point in the east to Barbers Point in the west, is the most densely populated and urbanized region of Oahu and includes the highly engineered shores of Honolulu and Waikiki. The south shore is fringed by a wide shallow reef and is affected by southerly swells in summer and refracted tradewind waves year-round.

West Oahu, from Barbers Point in the south to Kaena Point in the north, is the least developed of the four island regions. Single-family homes, beach parks, and undeveloped property line most beaches. Western, leeward shores receive refracted northerly waves in winter and refracted southerly waves in summer – leading to large seasonal changes in alongshore transport and beach width.

Development along north Oahu, between Kaena Point in the west and Kahuku Point in the east, is similar to east Oahu with single-family homes lining most beaches. Northern shores are impacted by large northerly waves in winter causing temporary seasonal erosion on many beaches. Relatively small, refracted tradewind waves are typical in summer.

10.3 Data and Methods

For our analysis, we use historical shoreline positions mapped from high-resolution (0.5 m pixel) orthorectified aerial photo mosaics following Fletcher et al. (2003, 2011), and Romine et al. (2009). Two shoreline proxies are utilized for beach width analysis: the Low Water Mark (LWM) and the vegetation line. The LWM or beach toe is the base of the foreshore and marks the seaward edge of the subaerial beach. The vegetation line marks the landward edge of the beach and is located at the seaward extent of interannual vegetation growth (vegetation that survives annual high run-up of waves) or at the base of armoring structures (e.g., sea wall). Beach width is defined as the distance between the LWM and vegetation line (or armoring) (Fig. 10.2).

We use survey-quality vertical aerial photographs with sufficient spatial resolution (<0.5 m) and tonal contrast to identify shoreline features. New imagery was acquired for the Oahu shoreline in 2005–2008 including synchronous position and orientation (POS) navigation data from an on-board aircraft global positioning system and inertial and mobilization unit (IMU). The POS data is used with a high-resolution digital elevation model (DEM; 5 m horizontal, sub-meter vertical) to rectify and mosaic the imagery. Typically, one historical air photo set meeting minimum quality standards is available for each decade going back to the late 1920s or late 1940s. Historical air photos are orthorectified and mosaicked using ground control points collected from more recent ortho imagery. The orthorectification process typically produces mosaics with root mean square (RMS) positional errors <2 m.

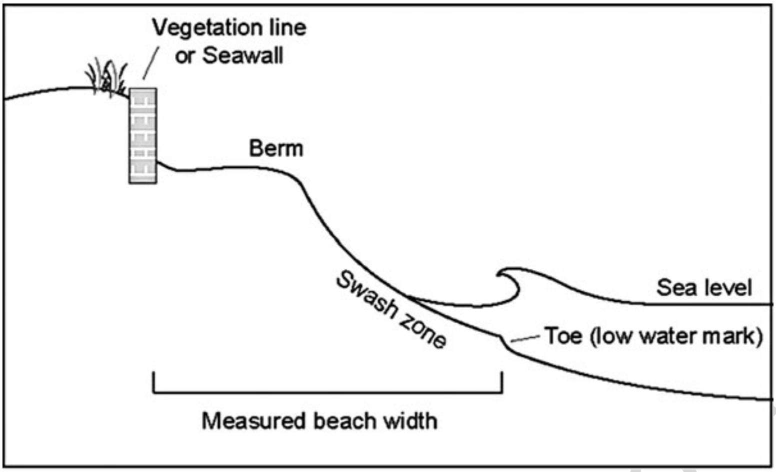

Fig. 10.2 Beach width is the distance between the beach toe (*low water mark*) and vegetation line (or armoring) (Modified from Fletcher et al. (1997))

Due to limited availability of historical air photos, we attempt to locate and utilize all available imagery. We do not remove historical shorelines from a time series based on records of large storms or waves. Rather, we account for fluctuations in shoreline position due to waves and storms in our uncertainty analysis (see: Uncertainties). However, historical shorelines may be removed from the time series in special cases. Some Oahu beaches have been artificially altered to the extent that the physics of the beach system have been permanently changed. Examples include removal of beach sand by mining operations, artificial beach fills, and construction of coastal engineering structures such as groins or sea walls. In these cases, shorelines prior to such alterations are removed from the time series and beach changes are analyzed only for the recent configuration of the beach. LWM and vegetation line positions are measured at regularly-spaced (roughly 20 m) shore-normal transects cast from an arbitrary offshore baseline.

For this study we define coastal armoring as any structure coming in contact with wave run-up and thereby interfering with natural coastal processes at any point of the year. Typically, these are designed to prevent coastal recession and retain sand. This includes rubble or stone revetments (with or without mortar); cement, brick, or stone walls; and wood or metal bulkheads. We also include landscaping or retaining walls that have transitioned into shoreline armoring on receding coasts. Armoring structures typically have little or no intra-annual vegetation growth (e.g., tall shrubs or trees) on the seaward side indicating the wall is impacted by wave run-up.

Coastal armoring is mapped using the most-recent (2005–2008) orthophoto mosaics. Locations are verified with high-resolution (~10 cm resolution) original air photo images and site visits. For this study we map only shore-parallel armoring structures on beaches or former locations of beach (i.e., where the beach was lost in the time span of analysis). Armoring on rocky shoreline or along engineered shorelines that never had beach in the time span of this study are not included in this study.

10.3.1 Beach Width Uncertainties

LWM shoreline positions are highly variable due to tides, storms, and waves resulting in positional uncertainties with shorelines mapped from aerial photographs. Additional uncertainties for LWMs and vegetation lines also arise from the mapping process including RMS error of the orthorectification process and on-screen identification and digitization of shoreline features. Following Fletcher et al. (2003), Romine et al. (2009), and Fletcher et al. (2011), five positional errors are calculated for LWMs: rectification error (*Er,* RMS error of ortho process), digitization error (*Ed,* identification and digitization of LWM), pixel error (*Ep*, spatial resolution,) tidal fluctuation error (*Etd,* horizontal shifts due to tides) and seasonal error (*Es,* waves and tides,); combined as a root sum of squares to arrive at a total positional error, *Etp*. In similar fashion, the total positional error of a vegetation line (*Eveg*) is the root sum of squares of *Er*, *Ep*, and digitization error for vegetation lines (*Evid*, estimated at 2 m). The vegetation line is assumed to mark the annual high wash of waves and is, therefore, not prone to shorter-term (intra-annual) fluctuations. Thus, *Es* and *Etd* are not included when calculating positional uncertainties for vegetation lines.

Beach width is the difference between vegetation line distance and LWM distance along a transect. However, calculating the uncertainty of the beach width as the root sum of squares of *Etp* and *Eveg* overestimates the error. We may omit the rectification errors (*Er*) for both the LWM and vegetation line because we are no longer concerned with geographic position; only the net distance between the vegetation line and LWM. Any errors due to rectification between the shoreline features are assumed to be negligible at those distances (<100 m). Therefore, a more accurate estimate of the beach width error, $Ev - t$, is:

$$(Ed^2 + 2^*Ep^2 + Etd^2 + Es^2 + Evid^2)^{0.5}$$

10.3.2 Calculating Beach Width Changes

Beach width change rates and net beach width change are calculated at each transect using weighted least squares (WLS) linear regression to fit a trend line to the time series of measured beach widths. Beach width uncertainties are applied as weights ($1/Ev - t^2$). Thus, beach widths with higher uncertainty values have less influence on the trend line. This method is similar to recent studies (Romine et al. 2009; Hapke et al. 2010; Fletcher et al. 2011) – only, beach width data is used instead of shoreline positions. The annual rate of beach width change (m/year) is the slope of the trend line (Fig. 10.3). The net change in beach width is the difference between the estimated beach width values at the end points of the WLS trend line (at the earliest and most recent shoreline times). Uncertainties of estimated

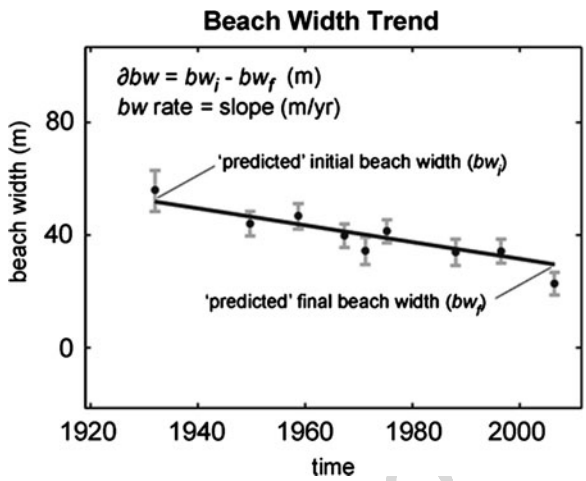

Fig. 10.3 Calculating beach width change with weighted least squares (WLS)

beach widths from the regression line are calculated at 1-sigma (standard deviation) to be consistent with 1-sigma positional uncertainties calculated for measured beach widths. Uncertainty of the net change in beach width is the root sum of squares of the uncertainties of the initial and final beach widths.

Regional average beach widths, average beach width changes, and average beach width rates are the average of values from all transects in a beach section. Following equation 9 of Hapke et al. (2010), the uncertainty of regional averages are estimated using an effective number of independent uncertainty observations (n*), calculated using a spatially-lagged (along-shore) autocorrelation of the uncertainty values.

A beach width trend (narrowing or widening) is considered significant if the net change is greater than the uncertainty (@ 1-sigma). A section of beach is considered completely lost to erosion if no beach remains (beach width $= 0$ m) at the most recent shoreline time(s) and beach was present at the earliest shoreline time(s). The total percent of 'degraded' beach is the sum of percents of beach lost and beach narrowed. To avoid reporting some beach width rate uncertainties as ±0.0 m/year, we report rates and uncertainties to the nearest cm/year (±0.00 m/year) even though our measurements at individual transects may not provide this high level of precision.

Shoreline change rates are calculated at select locations to compare rates before and after installation of coastal armoring. For this, we use historical shoreline positions (LWMs) and the method of single-transect WLS rate calculation from Fletcher et al. (2011).

10.4 Results

Beach width changes are measured at 5,332 shore-normal transects spaced roughly 20 m along 107 km of Oahu beaches from 1928 or 1949 to near-present (2005–2008) (Table 10.1). Approximately 29 km or 27% of the total extent of

Table 10.1 Length and percent of armored and unarmored beach on Oahu (measured from recent air photos and ground surveys)

	Beach studied, total		Armored beach			Unarmored beach		
Region	Transects	(km)	Transects	(km)	(%)	Transects	(km)	(%)
East	2,101	42.0	734	14.7	35	1,367	27.3	65
South	1,316	26.3	512	10.2	39	804	16.1	61
West	628	12.6	61	1.2	10	567	11.3	90
North	1,287	25.7	157	3.1	12	1,130	22.6	88
Total	5,332	106.6	1,464	29.3	27	3,868	77.4	73

Table 10.2 Beach width trends for Oahu (all beaches, armored beaches, and unarmored beaches; 1928 or 1949 to near present)

All beaches (armored and unarmored)							
	Lost		Narrowed (%)		Degraded (%)[b]	Widened (%)	
Region	(km)	(%)	Total (%)	Significant (%)[a]	Total (%)	Total (%)	Significant (%)[a]
East	5.7	14	42	17	55	45	18
South	3.1	12	38	22	49	50	25
West	0	0	60	41	61	39	23
North	0.2	1	69	46	70	30	12
Total	9.1	8	49	28	58	42	19
Armored beaches							
	Lost		Narrowed (%)		Degraded (%)[b]	Widened(%)	
Region	(km)	(%)	Total (%)	Significant (%)[a]	Total (%)	Total (%)	Significant (%)[a]
East	5.6	38	36	20	74	26	10
South	2.8	27	40	27	67	33	17
West	0	2	80	59	82	18	2
North	0.2	6	70	54	76	24	11
Total	8.6	29	43	28	72	28	12
Unarmored beaches							
	Lost		Narrowed (%)		Degraded (%)[b]	Widened (%)	
Region	(km)	(%)	Total (%)	Significant (%)[a]	Total (%)	Total (%)	Significant (%)[a]
East	0.1	0	45	15	45	55	23
South	0.4	2	36	18	38	61	29
West	0	0	58	40	58	42	25
North	0	0	69	45	69	31	12
Total	0.5	1	52	29	53	47	21

[a]Percent of transects where narrowing or widening is greater than 1-sigma uncertainty
[b]Degraded total equals percent lost plus total percent narrowed

Oahu beaches (or locations of former beaches) are armored. Over 9 km or 8% of Oahu beach was completely lost to erosion in the time span of analysis – nearly all of it (95%) fronting artificial coastal armoring (Table 10.2). A majority or 58% of Oahu beaches are degraded (narrowed or lost) including 49% narrowed (28% significantly) and 8% completely lost. Of the 49% of narrowed beaches, roughly

Table 10.3 Average beach width changes for Oahu (all beaches, armored beaches, and unarmored beaches)

Region	Initial average beach width (m)[a]	Final average beach width (m)[a]	Average beach width change (m)[a]	Average beach width change (%)[a]	Average beach width change rate (m/year)[b]
All beaches (armored and unarmored)					
East	19.4 ± 1.0	18.4 ± 0.8	−1.0 ± 1.4	−5% ± 7	−0.02 ± 0.05
South	18.2 ± 0.7	16.4 ± 0.4	−1.8 ± 0.7	−10% ± 4	−0.02 ± 0.02
West	35.5 ± 2.3	32.3 ± 1.6	−3.1 ± 2.8	−9% ± 8	−0.03 ± 0.12
North	33.2 ± 1.4	27.5 ± 1.2	−5.7 ± 1.9	−17% ± 6	−0.07 ± 0.07
Total	24.3 ± 0.7	21.8 ± 0.6	−2.6 ± 0.9	−11% ± 4	−0.03 ± 0.03
Armored Beaches					
East	15.3 ± 1.1	8.7 ± 1.0	−6.6 ± 1.5	−43% ± 10	−0.09 ± 0.07
South	21.3 ± 1.0	14.5 ± 0.3	−6.9 ± 1.1	−32% ± 5	−0.09 ± 0.03
West	39.3 ± 1.8	24.9 ± 1.2	−14.4 ± 2.1	−37% ± 5	−0.18 ± 0.08
North	29.3 ± 1.2	20.6 ± 1.0	−8.7 ± 1.5	−30% ± 5	−0.11 ± 0.05
Total	19.9 ± 0.7	12.7 ± 0.6	−7.2 ± 0.9	−36% ± 5	−0.10 ± 0.03
Unarmored Beaches					
East	21.7 ± 1.0	23.6 ± 0.6	1.9 ± 1.2	9% ± 6	0.02 ± 0.03
South	16.2 ± 0.6	17.7 ± 0.7	1.5 ± 0.9	9% ± 5	0.02 ± 0.03
West	35.1 ± 2.4	33.1 ± 1.7	−1.9 ± 2.8	−6% ± 8	−0.01 ± 0.12
North	33.7 ± 1.5	28.5 ± 1.2	−5.3 ± 1.9	−16% ± 6	−0.07 ± 0.07
Total	26.0 ± 0.8	25.2 ± 0.7	−0.8 ± 1.1	−3% ± 4	−0.01 ± 0.03

[a] ±1-sigma uncertainly, calculated using effective number of independent observations (n*), see text

[b] ±95%Cl, calculated using effective number of independent observations (n*), see text

one-quarter (24%) is attributed to armoring. Island-wide, average beach width decreased by 11% ± 4% (2.6 ± 0.9 m) at a rate of −0.03 ± 0.03 m/year (Table 10.3). Forty-two percent of beaches widened (19% significantly), overall, with most of the widening (82%) occurring along unarmored beaches.

Looking at beach width changes on armored and unarmored beaches separately, we find the majority, or 72%, of armored beaches are degraded, including 43% narrowed (28% significantly) and 29% completely lost to erosion. The average width of beaches fronting coastal armoring decreased by 36% ± 5% (7.2 ± 0.9 m) at a rate of −0.10 ± 0.03 m/year.

Beach widths along unarmored coasts were roughly stable, overall, with 52% of unarmored beaches narrowed (28% significantly) and 47% widened (21% significantly). Complete beach loss was documented at only 1% of unarmored beaches where sandy shoreline was replaced by natural rock shoreline. Average beach width on unarmored beaches remained approximately the same at 26.0 ± 0.8 m at the beginning of historical data and 25.2 ± 0.7 m near the present (−3% ± 4%).

10.5 Discussion

Coastal armoring on eroding beaches of Oahu has resulted in beach narrowing and loss as beaches that are prevented from migrating upland are unable to access coastal plain sands that are trapped behind structures. In addition, increased erosion due to ‘flanking’ is observed adjacent to several armored sections on Oahu, often resulting in further construction of armoring to protect abutting property, a process that leads to alongshore proliferation of seawalls. Here we provide analysis on a regional scale and present several case studies documenting the effects of coastal armoring on Oahu beaches.

10.5.1 East Oahu

Of the four island regions, the relatively narrow (average ~ 18 m) beaches of east Oahu suffered the most damage from beach erosion and coastal armoring (Fig. 10.4). Roughly 35% or 14.7 km of east Oahu beaches are armored. The average beach width fronting coastal armoring decreased from 15.3 ± 1.1 m to 8.7 ± 1.0 m (−43% ± 10%), suggesting that many of the remaining narrowed beaches fronting armoring likely become unusable at high tide. Nearly 6 km or 14% of east Oahu beaches were completely lost to erosion; nearly all of it (98%) fronting coastal armoring. Seventy-four percent of armored beaches on the east side are degraded including 38% lost and 36% narrowed (20% significantly). Forty-five percent of east Oahu beaches widened (18% significantly), of which 80% occurred on unarmored coasts.

While erosion and narrowing is a problem on many east Oahu beaches, the region also has some of the longest extents of accreting beaches in Hawaii (Fletcher et al. 2011) As a result, widths of east Oahu beaches remained approximately stable, as a whole, with an average change of −5% ± 7%. Beach widths on unarmored beaches on east Oahu increased by 9% ± 6% or roughly 2 m. However, it is interesting to note that Kailua Beach, which is accreting along most of its length, actually narrowed as seaward growth of vegetation outpaced the prograding beach.

The highest proportion of armoring, narrowing, and beach loss on any segment of the Oahu shoreline is found between Laie and Kaaawa on the northeast coast. Flanking erosion north of armoring at Makalii Point has resulted in shoreline recession of over 40 m since 1967, loss of beachfront property, and is threatening to undermine beach front homes (Figs. 10.5 and 10.6).

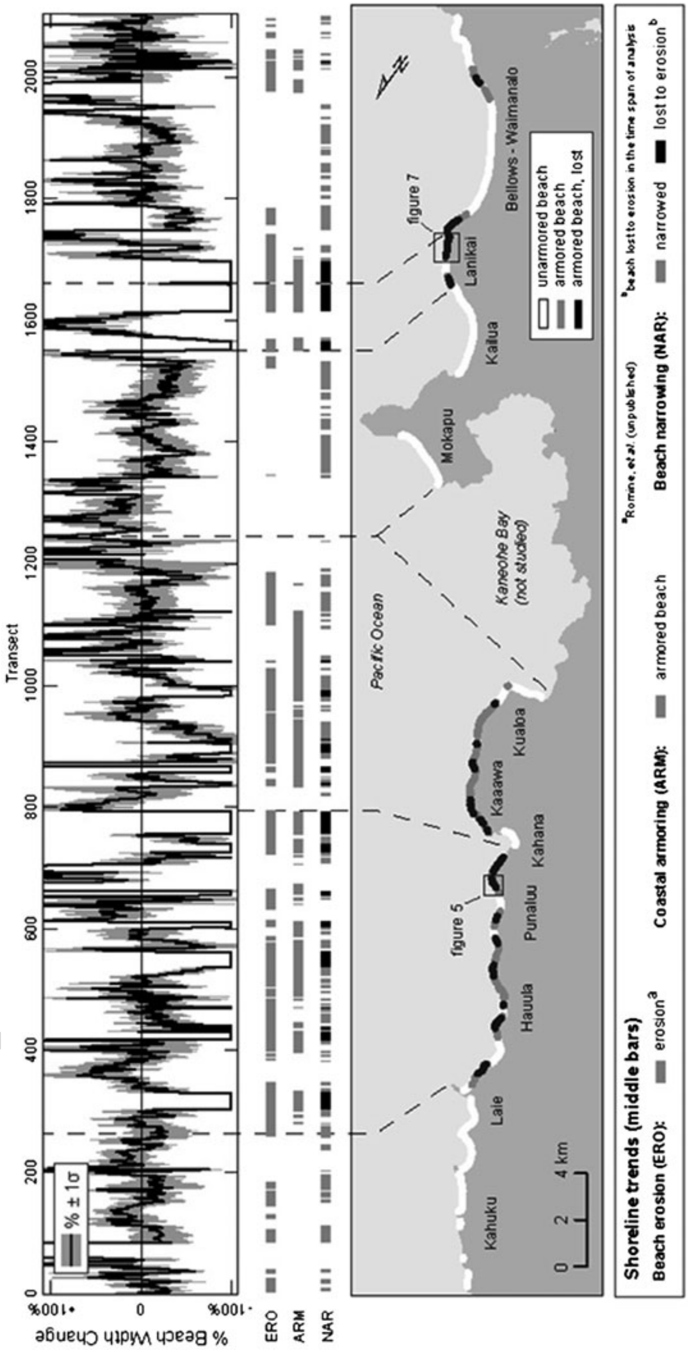

Fig. 10.4 East Oahu beach width percent changes (plot, 1928 or 1949 to near present), shoreline trends (*middle bars*), and coastal armoring (map)

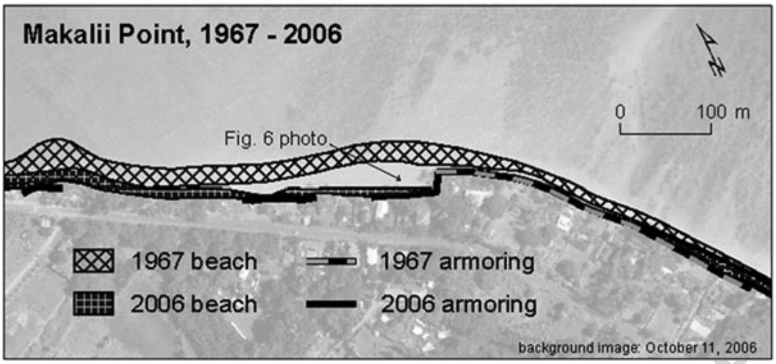

Fig. 10.5 Beach loss and flanking erosion at Makalii Point, east Oahu (1967–2006, location shown in Fig. 10.4). The unmarked area between the 1967 and 2005 beach was vegetated sand, which has since been lost to erosion

Fig. 10.6 Flanking erosion at Makalii Point (Photo location shown in Fig. 10.5; photo date, March 15, 2011)

There is strong evidence that coastal armoring has contributed to accelerated flanking erosion at Makalii Point following installation of armoring in the 1960s. Shoreline change rates calculated for the beach immediately north of armoring installed by 1967 show statistically significant increases in erosion rates (at the 95% confidence interval) when comparing rates from 1928 to 1967 and 1967 to 2005. As an example, directly adjacent to the armoring (within Fig. 10.6 photo) the rate changed from 0.5 + 0.4 m/year (accretion) to -1.0 ± 0.5 m/year (erosion) following installation of armoring. Erosion also increased fronting the northern half of the 1967 armoring, though not to the degree measured on the flanking unarmored beach. Low rubble revetments were recently (2000s) installed to protect homes on the north side of the point.

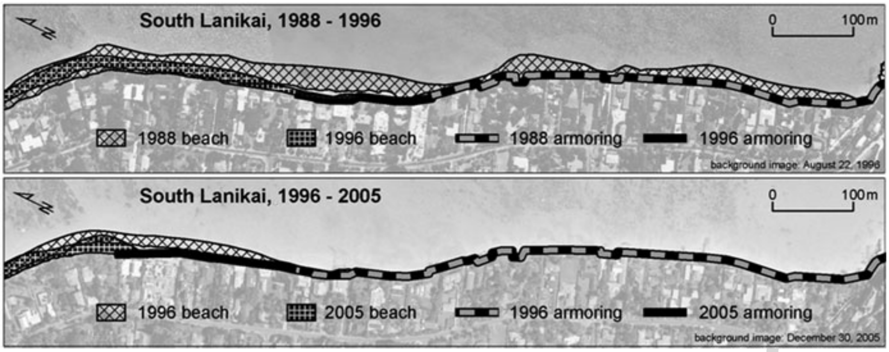

Fig. 10.7 Beach loss and flanking erosion at south Lanikai (1988–2005, location shown in Fig. 10.4)

At south Lanikai beach a trend of accretion reversed in the late 1970s. In the late 1980s, in response to the erosion, seawalls were constructed along much of the southern end of the beach to protect coastal properties (Fig. 10.7). By the mid-1990s the beach at the southern end of Lanikai had been completely lost to erosion and armoring proliferated to the north ~ 150 m in response to the northward-moving beach loss. By 2005 the beach had completely disappeared along the southern half of Lanikai. Recent beach surveys at south Lanikai indicate that flanking erosion continues to move north.

Comparisons of shoreline change rates at south Lanikai indicate that accelerated erosion due to the flanking process followed installation of the first armoring in the 1980s. Shoreline change rates are compared for the periods 1975–1988 (from the beginning of the erosion trend at south Lanikai to the first installation of coastal armoring) and 1988–2005 (after the first installation of coastal armoring). Rates along roughly 700 m of the beach flanking the north end of the armoring became more erosional and in most cases switched from accretion to erosion following installation of the armoring. However, none of the rate changes are statistically significant due largely to the limited number of historical shorelines available for the two measurement periods (three shorelines, each).

10.5.2 South Oahu

Along south Oahu (Fig. 10.8), analysis of beach width changes and its relation to shore-parallel coastal armoring is complicated by extensive use of other types of coastal engineering including groins, breakwalls, dredging, and fill – especially along beaches of Hawaii Kai to Kahala and Waikiki. As mentioned previously, beach changes are calculated for the modern configuration of the shoreline following major engineering efforts.

Thirty-nine percent (10.2 km) of beaches along south Oahu are armored; the highest percent of the four Oahu regions. Looking at south Oahu beaches as a

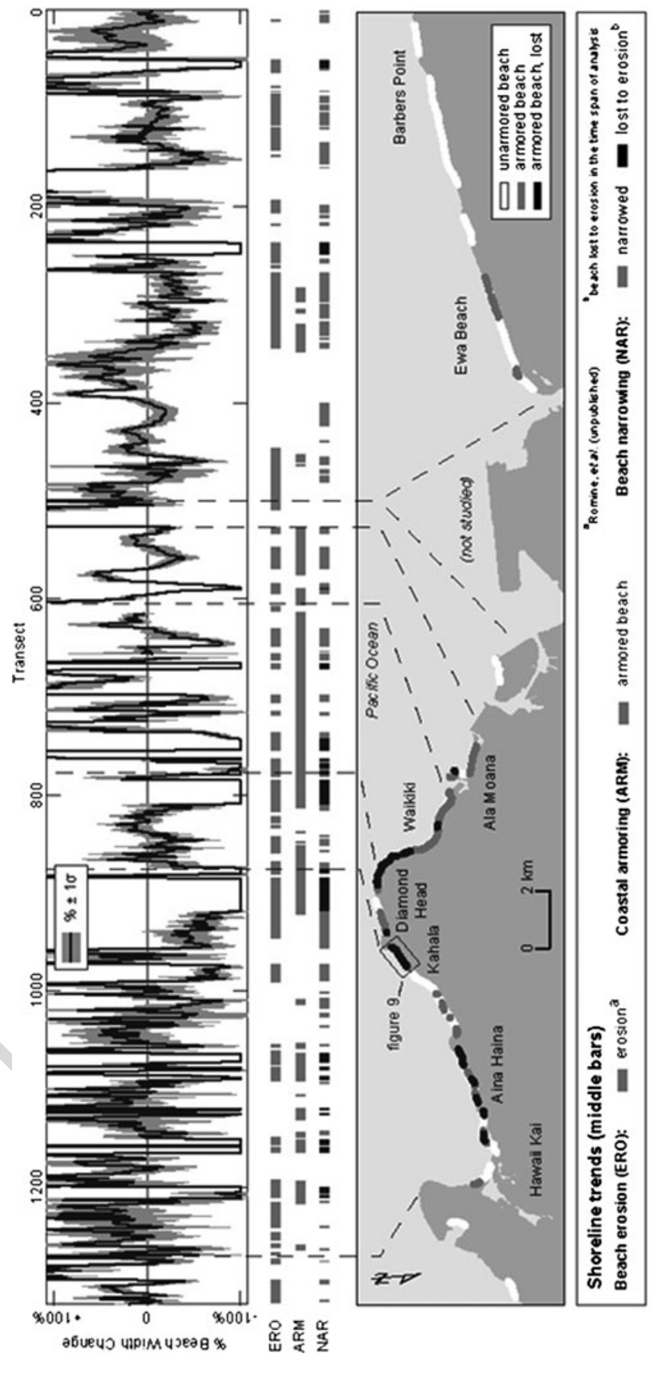

Fig. 10.8 South Oahu beach width percent changes (plot, 1928 or 1949 to near present), shoreline trends (*middle bars*), and coastal armoring (map)

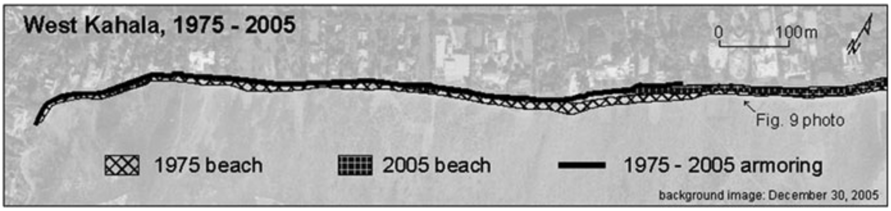

Fig. 10.9 Beach loss at Kahala, south Oahu (1975–2005, location shown in Fig. 10.8)

whole, roughly half of the beaches are degraded (22% significantly) and half widened. Twelve percent (3.1 km) of south Oahu beaches were completely lost to erosion. Average beach width along south Oahu decreased by 10% ± 4% or 1.8 ± 0.7 m.

Comparing armored and unarmored beaches we find that the majority (67%) of armored beaches along south Oahu are degraded with 40% narrowed (27% significantly) and 27% lost, while the majority, or 61%, of unarmored beaches have widened over the period (29% significantly). Beach width decreased by 32% ± 5% (6.9 ± 1.1 m) on armored beaches and beach widths increased by 9% ± 5% (1.5 ± 0.9 m) on unarmored beaches.

Areas of significant narrowing fronting coastal armoring include the Kahala shoreline where the beach has been completely lost to erosion. Beach width changes for the rest of Maunalua Bay (Hawaii Kai – Kahala) and Waikiki are highly variable alongshore. This is likely related to numerous groins and other shore-perpendicular structures that interrupt alongshore sediment transport leading to updrift impoundment and downdrift erosion. Nearly the entire length of the Waikiki and Ala Moana shoreline is armored. The greatest extent of beach loss in this section is at the eastern end of Waikiki adjacent to Diamond Head.

At the west end of Kahala Beach, roughly 900 m of beach was completely lost to erosion fronting coastal armoring (Fig. 10.9). Historical changes in the extent of armoring along west Kahala are difficult to discern from air photos due to dense cultivated vegetation along seaward property lines. It appears that most or all of the armoring was constructed prior to 1975 with extensions along a few adjacent properties in recent years in response to flanking erosion (Fig. 10.10). Analysis of changes in erosion rates on flanking beaches is not provided for this region due to the difficulty in mapping armored locations from historical air photos and limited shoreline data following the installation of armoring.

10.5.3 West Oahu

The west Oahu coast (Fig. 10.11) is the least armored of the four Oahu regions with armoring along only 1.2 km or 10% of beaches. However, the beaches are highly

Fig. 10.10 Flanking erosion and temporary armoring (*sand bags*), west Kahala Beach (location shown in Fig. 10.9; photo date, March 21, 2011)

erosional (Fletcher et al. 2011) and coastal armoring has contributed to beach narrowing. As a whole, 61% of west Oahu beaches are degraded, including 41% significantly narrowed; while 39% of beaches widened (23% significantly). Complete beach loss was noted at only a handful of transects. West Oahu has the widest initial and final average beach widths, though beaches narrowed by 9% ± 8% (3.1 ± 2.8 m).

Of the 10% of beaches armored along west Oahu, 82% are degraded with 80% narrowed (59% significantly) and only 2% completely lost. The average beach width fronting coastal armoring decreased by 37% ± 5% (14.4 ± 2.1 m). The majority or 58% of unarmored beach also narrowed (40% significantly), while 42% widened (25% significantly). The average change in beach width was not significant along unarmored beaches at −6% ± 8% (−1.9 ± 2.8 m).

The shoreline at the north end of Maili has retreated over 100 m due to chronic erosion and removal of sand by mining operations in the mid-1900s (Hwang 1981) (Fig. 10.12). In spite of the shoreline recession, substantial beach still remains at north Maili. Coastal armoring has only been constructed along a short section (~ 50 m) to protect a public restroom. The beach is preserved as the vegetation line is allowed to erode into a lightly-developed beach park, which has acted as a buffer between the receding beach and the coastal highway.

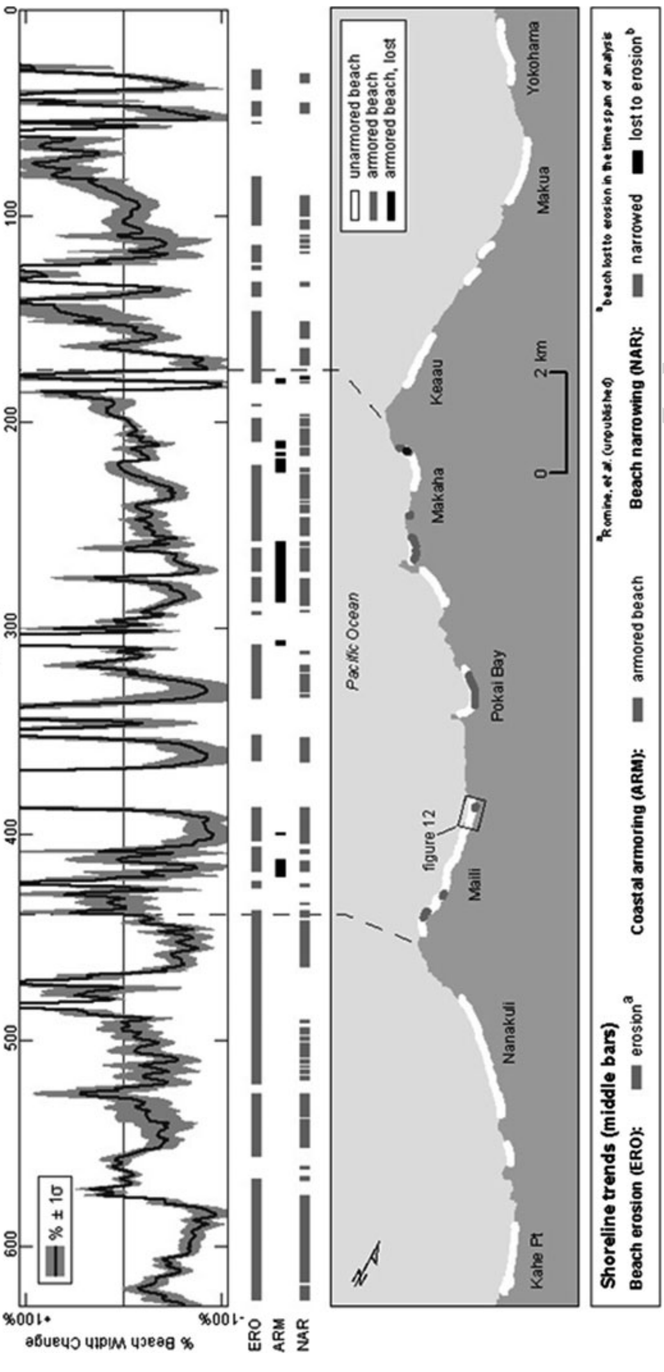

Fig. 10.11 West Oahu beach width percent changes (plot, 1928 or 1949 to near present), shoreline trends (*middle bars*), and coastal armoring (map)

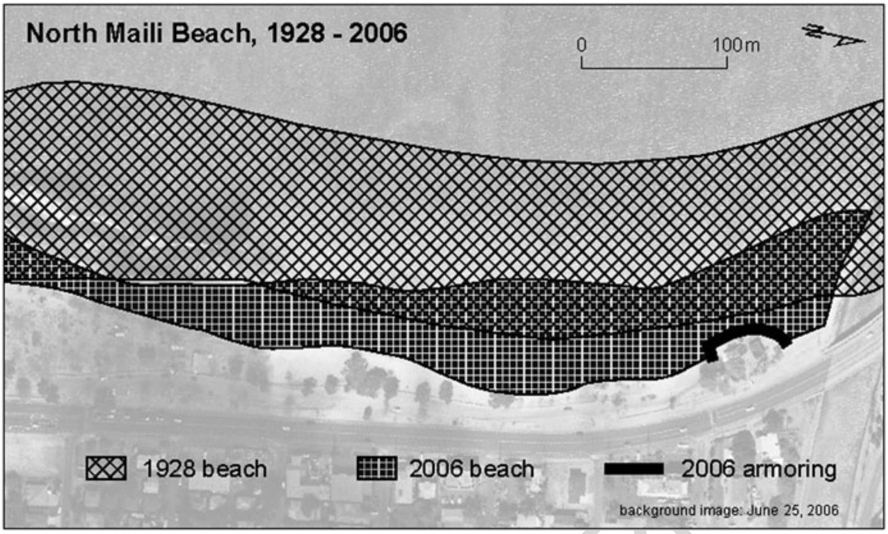

Fig. 10.12 In spite of shoreline recession of over 100 m, substantial beach remains along the (mostly) unarmored northern end of Maili Beach (1928–2006, location shown in Fig. 10.11)

10.5.4 North Oahu

Over 3 km or 12% of north Oahu beaches are armored (Fig. 10.13). Only about 200 m (1%) of north Oahu beaches was completely lost to erosion – all of which was at the northern end of Haleiwa fronting sea walls. As a whole, narrowing is the dominant trend of beach width change along north Oahu beaches, with 69% narrowed (46% significantly) and 30% widened (12% significantly) – the lowest percentage widened of the four Oahu regions. On average, north shore beaches narrowed by 17% ± 6% or 5.7 ± 1.9 m – the highest percent and net decrease of the four Oahu regions.

Significant narrowing is found on both armored and unarmored north Oahu beaches; though, narrowing was greater on armored beaches. Seventy-six percent of armored beaches are degraded including 70% narrowed (54% significantly) and 6% lost. Beach widths decreased by 30% ± 5% or 8.7 ± 1.5 m along armored beaches. The majority or 69% of unarmored beaches also narrowed, though the amount of narrowing was less than along armored sections with average decrease in beach width of 16% ± 6% or 5.3 ± 1.9 m – the most narrowing on unarmored beaches of the four regions.

Beaches are narrowed along most of a continuous beach between Mokuleia and Waialua, including armored and unarmored sections. Near-complete beach loss is observed in 2006 air photos of a small embayment at Mokuleia (Fig. 10.14). Armoring, constructed in the early 1970s, was extended in the 1980s and more recently to protect coastal properties threatened by flanking erosion. Continued narrowing has resulted in complete beach loss fronting armoring in the middle of the bay as observed in a site visit in March of 2011 (Fig. 10.15).

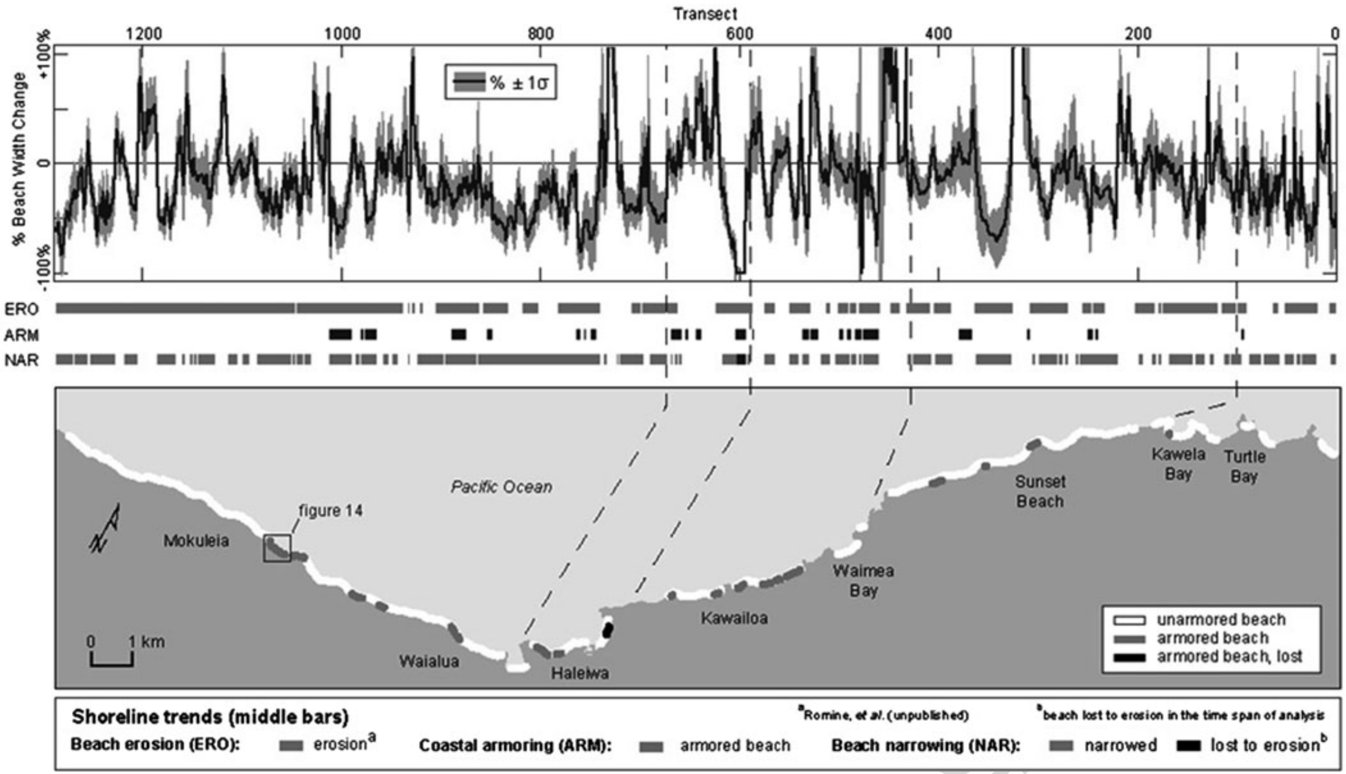

Fig. 10.13 North Oahu beach width percent changes (plot, 1928 or 1949 to near present), shoreline trends (*middle bars*), and coastal armoring (map)

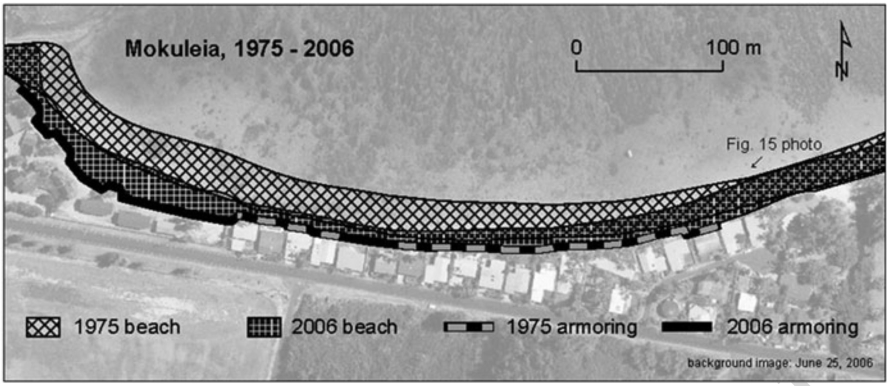

Fig. 10.14 Beach narrowing and flanking erosion at Mokuleia, north Oahu, as of June, 2006 (1975–2006, location shown in Fig. 10.13)

Fig. 10.15 Beach loss at Mokuleia, north Oahu (location shown in Fig. 10.14; photo date March 22, 2011)

Unlike Makalii Point and Lanikai, beach erosion rates flanking the north side of the 1975 armoring at Mokuleia appear to have slowed following installation of the armoring. Rates fronting the armoring and along roughly 100 m of the southern flanking beach suggest accelerating erosion following installation of the armoring. As with Lanikai, none of the rate changes are statistically significant.

10.5.5 Island-Wide

Over the period of study, average beach width decreased by 11% ± 4% and nearly all (95%) documented beach loss was fronting armored coasts. Among armored beach sections, 72% of beaches are degraded, which includes 43% narrowed (28% significantly) and 29% (8.6 km) completely lost to erosion. Beaches fronting coastal armoring narrowed by −36% ± 5% or −0.10 ± 0.03 m/year, on average. In comparison, beach widths along unarmored coasts were relatively stable with slightly more than half (53%) of beaches experiencing any form of degradation.

As mentioned in the introduction, we examine two questions regarding the effects of coastal armoring on eroding coasts on Oahu. One, does armoring accelerate pre-existing erosion and does it initiate and or accelerate erosion on adjacent properties? Two, does armoring lead to other negative impacts such as beach loss or beach narrowing, which we define as separate from erosion? Analysis of shoreline change rates preceding and following installation of armoring suggests accelerated erosion on flanking beaches at several locations on Oahu after installation of armoring. However, the statistical significance of some of these rate changes is questionable due largely to limited shoreline data. Also, the argument could be made that the evidence is somewhat circumstantial. It is not possible through our analysis to conclude what proportion of the documented rate accelerations are due to the influence of coastal armoring or unrelated coastal dynamics. In response to question two, our analysis has clearly shown that armoring beaches in response to preexisting erosion leads to increased beach narrowing and loss by fixing the landward edge of the beach (vegetation line) and preventing it from receding with the seaward edge (beach toe).

These results support the findings of Fletcher et al. (1997) that construction of coastal armoring on eroding beaches of Oahu has contributed to beach narrowing and loss. However, the cause of narrowing along the majority of unarmored coasts of west and north Oahu (58% and 69%, respectively) is not clear. The north and west shores are dominated by beach erosion (Fletcher et al. 2011) so some narrowing is expected. However, the relatively high percentage of narrowing on unarmored beaches suggests that movement or stabilization of vegetation lines by means other than coastal armoring may be a factor. Cultivation of vegetation along the seaward edge of coastal properties is common practice and in some cases may be an attempt at 'soft armoring' to protect property from seasonal or chronic erosion – perhaps contributing to narrowing along these coasts. Therefore, the vegetation line does not necessarily denote the stable landward edge of the beach on all coasts and may be governed by more than erosion and accretion.

Another possible cause of narrowing is that interannual run-up interaction with a seawall, which would not be identified by our methodology, is responsible for a trend of narrowing. An example of this might include non-recovered sand loss related to wave reflection off seawalls during particularly high swell events such as in 1969 and 1998. Such intermittent losses, if significant, could contribute to decreased sand availability and, thus, beach narrowing.

Historical shoreline studies are typically hindered due to limed data (often <10 shorelines). By utilizing all available beach data with WLS regression, rather than an end-point analysis (only two data points), our analysis provides a more statistically defensible analysis of beach width change for highly variable coastal regions like Hawaii.

Sea level rise is likely to accelerate in coming decades (Vermeer and Rahmstorf 2009) and is almost certain to increase erosion and beach loss along Hawaii shores. With this study we have documented the negative effects of armoring eroding beaches and identified 'hotspots' of beach erosion and narrowing – data that may assist coastal resource managers in protecting beaches for future generations through improved management practices.

10.6 Conclusions

Coastal armoring has been a typical response to beach erosion on Oahu, Hawaii. To better understand the effects of armoring on eroding beaches, changes in beach width are compared among armored and unarmored beaches using historical shorelines mapped from aerial photographs. The results from this study show that armoring has contributed to beach narrowing and loss as receding beaches are prevented from migrating upland and sediment is trapped behind structures. Evidence is also provided for increased 'flanking erosion' on select beaches adjacent to coastal armoring by increased shoreline erosion rates following installation of armoring.

Over 27% of Oahu beaches (or former locations of beach) are armored and the majority, or 72%, of armored beaches are degraded (including 43% narrowed and 29% completely lost to erosion). Virtually all beach loss documented in this study (95%) occurred fronting coastal armoring. The remaining beaches fronting coastal armoring narrowed by 36% ± 5%. In contrast, beach widths along unarmored sections were much more stable with percents of degraded and widened beaches roughly even (53% vs. 47%), little or no change in average beach width change (−3% ± 4%), and little beach loss (1%).

The most armored regions of Oahu, the east and south sides (35% and 39% armored, respectively), suffered the greatest percents of beach loss (14% and 12% lost, respectively). Many of the remaining beaches along armored sections of east Oahu are narrowed to the extent that they likely become unusable at high tide (average beach width 8.7 ± 1.0 m). In comparison, the relatively unarmored west and north regions (10% and 12% armored, respectively) experienced little beach loss (0% and 1% lost, respectively). Like south and east Oahu, beaches along armored sections of the west and north shores are highly degraded (82% and 76%, respectively). In all four coastal regions of Oahu the majority of the beach fronting armoring was degraded (between 67% and 82%). Along south and east

Oahu the majority of unarmored beaches widened (55% and 61%, respectively). Sixty-nine percent of unarmored beaches on north Oahu narrowed (45% significantly) indicating that the common practice of stabilizing seaward property lines by cultivating vegetation may be contributing to narrowing.

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