

# Beach Loss Along Armored Shorelines on Oahu, Hawaiian Islands

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## ABSTRACT

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An analysis of an aerial photographic time series of Oahu's shoreline reveals that historical seawall and revetment construction (coastal armoring) to protect eroding lands has caused the narrowing of  $17.3 \pm 1.5$  km and loss of  $10.4 \pm 0.9$  km of sandy beach over the period 1928 or 1949 to 1995. This is  $\sim 24\%$  of the  $115.6 \pm 9.8$  km of originally sandy shoreline of Oahu. All narrowed and lost beaches occur in front of coastal armoring structures that fix the position of the shoreline. In addition, nearly all narrowed and lost beaches show a history of recent (5% of narrowed and lost beaches) or long-term (92% of narrowed and lost beaches) retreat. We conclude from this study that using a wall or revetment to fix the position of a shoreline undergoing retreat will cause the narrowing and eventual loss of the adjoining beach.

**Additional Index Words:** *Hawaii, shoreline armoring, seawalls, coastal erosion, beach erosion, beach loss, coastal management.*

## INTRODUCTION

At Honolulu, a long-term (83 yr) tide-gauge record indicates a local relative sea-level rise of 1.55 mm/yr (HICKS and HICKMAN, 1988). Studies show that if local relative sea level is rising or if beaches are deficient in sediment, such that the shoreline is undergoing long-term retreat, beach narrowing and loss are more likely to occur at armored beaches<sup>1</sup> than at non-armored beaches (McDONALD and PATTERSON, 1984; CARTER *et al.*, 1986; KRAUS, 1988; PILKEY and WRIGHT, 1988; TAIT and GRIGGS, 1990; HALL and PILKEY, 1991). In the Hawaiian Islands, a history of ad hoc shoreline armoring characterizes attempts by coastal zone authorities and landowners to mitigate a regional trend of coastal land loss due to shoreline retreat (HWANG, 1981; SEA ENGINEERING, 1988; FLETCHER, 1992; MAKAI OCEAN ENGINEERING and SEA ENGINEERING, 1992)<sup>2</sup>.

While this approach has proven successful in preserving valuable coastal lands, there exists no assessment of the environmental state of Hawaiian beaches, hence there has been no scientific basis for evaluating current land management practices. We report here that armoring the shoreline of Oahu, Hawaii's most populous island and home of the capital

city of Honolulu, an important international destination, has resulted in significant negative impacts to adjoining sandy beaches.

## MEASUREMENTS

We measure beach width and length using aerial photogrammetric analysis over the period 1928 or 1949 to present. Four coastal segments (Figure 1) are detailed here that exemplify the trend of beach loss and narrowing as determined by our measurements on Oahu. These are: Mokuleia (north shore) which has  $2.1 \pm 0.2$  km of narrowed beach and  $0.2 \pm 0.0$  km of lost beach; Kaaawa Headland (windward coast) which has  $3.2 \pm 0.3$  km of narrowed beach and  $0.8 \pm 0.1$  km of lost beach; Kailua/Waimanalo (windward coast) which has  $0.9 \pm 0.1$  km of narrowed beach and  $1.6 \pm 0.1$  km of lost beach; and Maili-Makaha (leeward coast) which has  $1.3 \pm 0.1$  km of narrowed beach and  $0.2 \pm 0.0$  km of lost beach (Table 1).

These four segments, representing geographically distinct areas, are subject to diverse oceanographic conditions and developmental pressures. In this paper, we briefly 1) examine shoreline movement rates as indicated by the historical changes of the vegetation line, 2) quantify beach loss and beach narrowing as determined by the history of beach length and width changes, and 3) examine the type and management of coastal development.

We measured the shore-parallel distance of the most seaward line of stable beach vegetation, a proxy for beach length, as revealed in historical vertical aerial photographs of Oahu

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<sup>1</sup> We use the term armoring to indicate the presence of seawalls, revetments and other solid structures designed to fix the position of the shoreline.

<sup>2</sup> Shoreline retreat was determined in these studies by photogrammetric measurement of the movement history of the first line of stable beach vegetation.

# Oahu

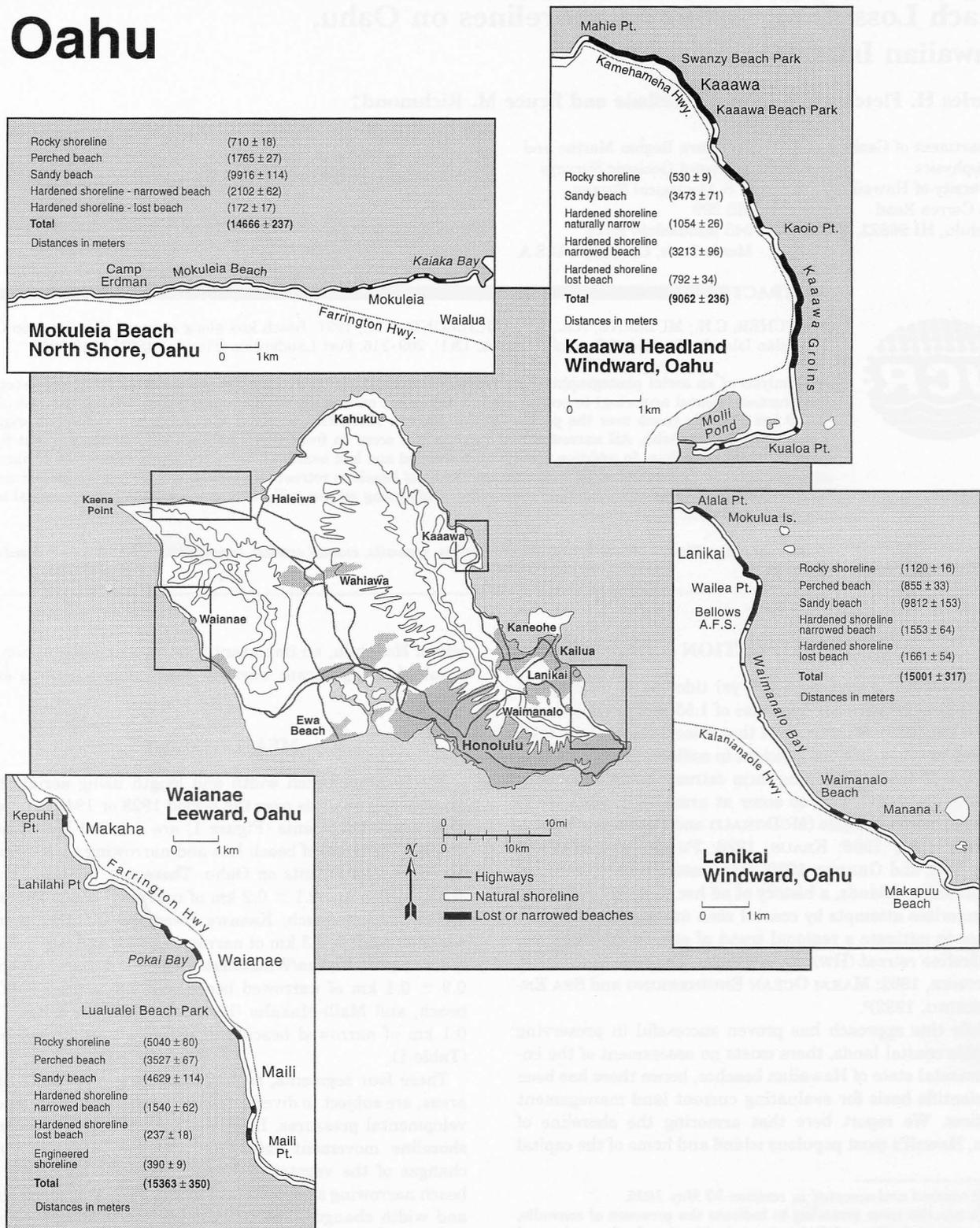


Figure 1. Map of Oahu, Hawaiian Islands. Four study areas detailed in the text are shown with shoreline classification measurements.

Table 1. Beach trends on Oahu.

	Mokuleia	Kaaawa-Kualoa	Kailua-Waimanalo	Maili-Makaha	Island-Wide
A. Originally sandy (km)	12.2 ± 1.0	7.5 ± 0.6	15.5 ± 1.3	6.0 ± 0.5	115.6 ± 9.8
B. Narrowed beach (km)	2.1 ± 0.2	3.2 ± 0.3	0.9 ± 0.1	1.3 ± 0.1	17.3 ± 1.5
C. Lost beach (km)	0.2 ± 0.0	0.8 ± 0.1	1.6 ± 0.1	0.2 ± 0.0	10.4 ± 0.9
D. Degraded beach	18.7%	53.6%	16.3%	24.9%	23.9%
E. Short-term shoreline change rate (m/yr)	-5.1 to 7.7	-5.8 to 14.0	-6.4 to 5.1	-2.2 to 4.0	n/m
F. Net shoreline change rate (m/yr)	-0.2 to 0.3	-1.7 to 1.8	-0.9 to 0.6	-0.4 to 0.6	n/m
G. Non-armored MSBW	26.8 m*	13.2 mψ	22.4 mψ	43.7 m*	n/m
H. Armored MSBW	12.8 m*	8.9 mψ	7.1 mψ	24.5 m*	n/m
I. Mean long-term shoreline change rate for degraded transects (m/yr)	-0.2	-0.3	-0.6	-0.5	n/m
J. Range of shoreline change rates for degraded transects (m/yr)	-0.1 to -0.3	0.0 to -1.7	0.2 to -1.8	-0.2 to -1.0	n/m
K. Mean photographic interval	19 yr	34 yr	23 yr	30 yr	n/m

97.4% of transects on degraded beaches underwent retreat prior to or during the period of narrowing.

92.1% of transects on degraded beaches underwent long-term (>12 yr) retreat prior to or during the period of narrowing.

Island-wide, all beaches classified as degraded are on armored shorelines.

A. Includes beaches presently classified as sandy, narrowed and lost.

D. (B+C)/A expressed as a percentage of originally sandy beach length.

E. Shoreline change rates were measured on shore-normal transects spaced alongshore at approximately 300 m intervals. Short-term refers to rates determined between sequential photographic surveys. Net refers to the 1928–1993 or 1949–1993 end-point calculation of change. The range provided is maximum retreat rate (–) and maximum advance rate.

G,H.MSBW = mean sandy beach width, the shore normal distance from the beach toe (a distinct total change at the base of the foreshore) to the shoreline indicator (vegetation line or seaward base of a shoreline structure).

ψ From 1995 field measurements.

\* From 1993 NOS aerial photographic set.

n/m Not measured.

K. The mean photographic interval that was used to determine the long-term shoreline change rate on degraded transects.

dated 1928, 1949, 1967, 1971, 1975, 1979, 1988, and 1993. Additional photographs were available for selected areas dated 1950, 1957–1959, 1961–1963, 1965, 1972, 1978, 1980, 1982, 1989, and 1991. Shoreline retreat rates were determined using historical shifts in the vegetation line relative to ground control points (GCP's). Beach width is measured from the vegetation line, or base of a seawall or revetment, to the base of the foreshore (Figure 2). The base of the foreshore is identified by a topographic feature, known as the beach step (BAUER and ALLEN, 1995), that displays a distinct tonal change in the water column visible in both color and

black and white vertical aerial photographs. The step experiences little cross-shore displacement (approx. <1 m) due to tidal effects or short-term wave regime shifts. This measurement of beach width includes intertidal portions of the foreshore plus the subaerial beach. Hence, our reported beach widths are generally greater than the more commonly measured subaerial beach width (e.g., DOLAN *et al.*, 1980; CROWELL *et al.*, 1991; HALL and PILKEY, 1991).

Photographic scale was assessed using GCP's extant throughout the time series and on stable-base U.S. Geological Survey 1:24,000 orthophotoquads (OPQ). For each aerial photograph, the scale between several GCP pairs was computed and those photos with internal scale variations exceeding 10% were excluded from the database.

A distance measurement on either an OPQ or an aerial photograph involves two read errors (each estimated to be ±0.2 mm). Because read errors are assumed to be independent and randomly distributed, an estimate of the total error associated with each measurement is  $[(\pm 0.2 \text{ mm})^2 + (\pm 0.2 \text{ mm})^2]^{0.5} = \pm 0.28 \text{ mm}$ . Scale uncertainty is a function of measurement errors of both OPQs and photographs and, for our photographic database, ranged from ±2.6% for large-scale (1:3,000) photographs to ±7.5% for smaller-scale (1:8,500) photographs. Shoreline classification measurements were made on 1993 natural color vertical aerial photographs, confirmed by field checks, with scales between 1:8,000 and 1:9,000. The total uncertainty is based on a scale of 1:8,500. Additionally, instrumental error was introduced by inherent inaccuracies

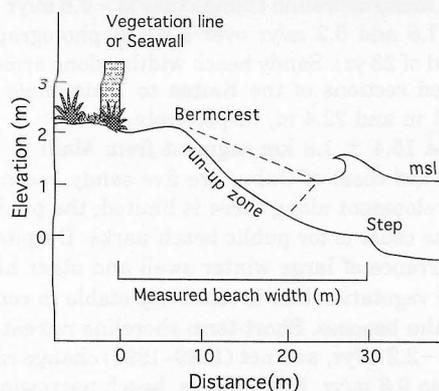


Figure 2. Definition sketch of our term "beach width."

in the determination of shoreline segment lengths, which resulted in a total uncertainty of  $\pm 8.5\%$ . This error comprises our reported uncertainty in measured beach segment lengths. Beach width and vegetation line measurements are subject to similar uncertainties.

### COASTAL SEGMENT HISTORIES

Mokuleia is a  $12.9 \pm 1.1$  km segment on the western end of Oahu's north shore. The majority of development at Mokuleia is along the eastern half of the segment. Mokuleia is subject to large (2–6 m heights, 10–20 sec periods) winter surf (GERRITSEN, 1978) and infrequent tsunamis and tropical cyclones. Vastly different seasonal wave conditions lead to a strong seasonal change in beach width, and coastal erosion tends to be sporadic, occurring during high wave events. Short-term fluctuations in shoreline position frequently exceed  $\pm 1.0$  m/yr, while net (1949–1993) change rates vary from  $-0.2$  to  $0.3$  m/yr. Vegetation retreat is more pronounced along the sparsely developed western half of Mokuleia. Vegetation line stability or advancement is typical of eastern transects, but this is due to a greater abundance of shoreline armoring, which stabilizes the upland and promotes plant growth on or immediately behind the tops of walls and revetments. This vegetation is also frequently landscaped and maintained by property owners because it is the frequently used *proxy* of the "... upper reaches of the wash of the waves ..." as the legal shoreline is designated in Hawaii. The shoreline is the baseline for determinations of the coastal construction set-back zone that controls property use according to Hawaii State and County Administrative Rules (FLETCHER and HWANG, 1994).

Seawalls, and other armoring structures have successfully curtailed upland retreat, but have led to beach narrowing and loss. Of Mokuleia's originally sandy shoreline,  $18.7\%$  ( $2.3 \pm 0.2$  km of  $12.2 \pm 1.0$  km) has experienced beach narrowing or loss, all of which is along the eastern half of the segment. Where beach loss or narrowing has occurred, the mean shoreline change rate is  $-0.2$  m/yr (varying between  $-0.3$  and  $-0.1$  m/yr over a mean photographic coverage period of 19 yr). Sandy beach width in front of armored sections of Mokuleia averages 12.8 m, as opposed to 26.8 m along non-armored segments. Greater building setbacks for coastal lots would have reduced the need for shoreline structures and prevented beach narrowing and loss in eastern Mokuleia.

Kaaawa, a  $9.1 \pm 0.8$  km segment on the windward coast of Oahu, is densely settled, mostly with single-family residences, except for Kualoa Beach Park on the southern end. An offshore reef attenuates incoming wave energy (nearshore breaking wave heights rarely exceed 1 m) but strong south-directed alongshore currents persist. Several groins were constructed ca. 1900 and have altered littoral processes along the entire segment. The groins interrupt the predominantly southward alongshore sediment transport. Although widening—even creating—beaches immediately updrift of each, the groins have starved downdrift sections and accelerated coastal retreat and beach erosion. The most dramatic impact of the groins is the rapid (up to  $-5.8$  m/yr short-term and up to  $-1.7$  m/yr net) down-drift shoreline change at sediment-

starved Kualoa Beach Park, a cusped foreland where shoreline stability is dependent upon alongshore sand delivery.

Building setbacks along the Kaaawa headland rarely exceeded the 40 ft ( $\sim 12.2$  m) minimum required by Hawaii state law, and with sediment starvation downdrift of the groins, have led to the widespread construction of seawalls, revetments, and breakwaters. Updrift accreted lands have been claimed for development and, in some cases, subdivided. Hence, even along accreting sections, no undeveloped parcels provide coastal erosion buffer zones. Currently,  $59.3\%$  of this segment is armored, and  $53.6\%$  ( $4.0 \pm 0.4$  km of  $7.5 \pm 0.6$  km) of the originally sandy shoreline is narrowed or lost. Where beach narrowing or loss has occurred, the mean shoreline change rate is  $-0.3$  m/yr (varying between  $-1.7$  and  $0.0$  m/yr over a mean photographic coverage period of 34 yr). The mean sandy beach width along armored sections of Kaaawa is 8.9 m, as opposed to 13.2 m along non-armored segments.

A  $17.0 \pm 1.4$  km segment along the southern windward coast includes three popular beaches: Kailua, Lanikai, and Waimanalo. Except for Kailua, Bellows, and Waimanalo Beach Parks, most beachfront lots have been developed with coastal houses and cottages. The shoreline histories vary: Kailua has experienced net seaward advancement of the vegetation line; Lanikai is subject to episodic shoreline movement; and Waimanalo has experienced long-term retreat. Changes in shoreline position are related to fluctuations in alongshore sand transport and sediment budget deficiencies, rather than event-based erosion because a wide fringing reef platform diminishes incoming wave energy (typical breaking wave heights are less than 0.5 m). Net (1949–1993) shoreline change rates vary from  $-0.9$  to  $0.6$  m/yr, but short term change rates as high as  $-6.4$  m/yr are observed.

Insufficient building setbacks along areas prone to episodic or chronic coastal retreat (Lanikai and Waimanalo) have led to a proliferation of seawalls and revetments (Figure 3). Such armoring diminishes upland erosion along these segments, but removes upland sand deposits from the littoral sediment budget. This has contributed to beach loss in front of most armored areas and has accelerated erosion along downdrift, non-armored sections. Beach narrowing and loss, which has occurred along  $16.3\%$  ( $2.5 \pm 0.2$  km of  $15.5 \pm 1.3$  km) of the sandy segments, is especially apparent in south Lanikai and north Waimanalo. Where beach narrowing and loss has occurred, the mean shoreline change rate is  $-0.6$  m/yr (varying between  $-1.8$  and  $0.2$  m/yr over a mean photographic coverage period of 23 yr). Sandy beach widths along armored and non-armored sections of the Kailua to Waimanalo segment average 7.1 m and 22.4 m, respectively.

Along the  $15.4 \pm 1.3$  km segment from Maili to Makaha, on the leeward coast of Oahu, are five sandy beaches. Residential development along these is limited; the predominant usage of the coast is for public beach parks. Despite the frequent occurrence of large winter swell and other high wave events, the vegetation line is relatively stable in comparison to other Oahu beaches. Short-term shoreline retreat rates do not exceed  $-2.2$  m/yr, and net (1949–1993) change rates vary from  $-0.4$  to  $0.6$  m/yr. Nonetheless, beach narrowing or loss has occurred along  $24.9\%$  ( $1.5 \pm 0.1$  km of  $6.0 \pm 0.5$  km) of the sandy shoreline. Where beach narrowing or loss has oc-



Figure 3. Southeast Lanikai (HWANG and FLETCHER, 1992). (A) Prior to 1971 this shoreline was characterized by a wide, accreting beach. Accreted lands were claimed as private property under state law and residential development advanced to the limit of the legally permitted 40 foot setback. The accretion trend reversed in the late 1970's and shoreline retreat necessitated armoring the coast in order to protect houses and claimed private lands. Continued retreat of the beach against the fixed position of the shoreline led to 820 m of beach loss. The 1990 photo is taken in the late afternoon. Trees cast their shadows in the water. (B, next page) The public access path adjacent to Lanipo Drive (see above). Lateral access along the shoreline is now impossible and the former economic, protective, cultural, and environmental value of the beach is lost.



Figure 3. Continued.

curred, the mean shoreline change rate is  $-0.5$  m/yr (varying between  $-1.0$  and  $-0.2$  m/yr over a mean photographic coverage period of 30 yr). Narrowing is more common than loss ( $1.3 \pm 0.1$  km versus  $0.2 \pm 0.0$  km), in part because of locally abundant sources of sand. Still, there is a significant difference in mean sandy beach widths of armored (24.5 m) and non-armored (43.7 m) beach segments.

### ISLANDWIDE

Islandwide, our data indicate that beach narrowing and loss occur in front of active<sup>3</sup> armoring where the shoreline has a history of either recent (5% of narrowed and lost beaches) or long-term<sup>4</sup> (92% of narrowed and lost beaches) retreat. We measure a mean shoreline change rate of  $-0.4$  m/yr over a mean photographic interval of 27 yr at the four coastal segments highlighted in this report. Islandwide, the total length of impacted beaches due to armoring consists of  $17.3 \pm 1.5$  km of narrowed and  $10.4 \pm 0.9$  km of lost beach. This is  $\sim 24\%$  of the  $115.6 \pm 9.8$  km of originally sandy shoreline of Oahu.

### DISCUSSION

We make a distinction between coastal erosion and beach erosion. Coastal erosion is the natural shoreline response to a rising sea level by landward displacement of coastal environments causing erosion of the upland. In Hawaii, the coastal upland is often comprised of sand stored in dunes, former

marine terraces, and beach accretion plains (e.g., the Kapapa Stand terrace found on both Kauai and Oahu; CALHOUN and FLETCHER, 1996; FLETCHER and JONES, 1996). Erosional scarp retreat releases these sand stores and they constitute an important component of the beach sediment budget. Beach erosion, a volumetric loss of sediment from the beach, occurs when the sand supply is decreased and/or when erosion is refocused away from the upland and onto the adjoining beach. Hence, artificially fixing the shoreline with seawalls and revetments removes upland sand from the sediment budget, and reduces sand supplies to the beach (PILKEY and WRIGHT, 1988; KRAUS, 1988). Sea-level rise on a sediment-deficient, armored shoreline undergoing retreat will result in beach loss (KRAUS, 1988; TAIT and GRIGGS, 1990; HALL and PILKEY, 1991). Furthermore, active seawalls and revetments may enhance scouring in front of and flanking such structures during an erosive event (KOMAR and McDOUGAL, 1988; MORTON, 1988; LIPP, 1995) and, on a sand-starved beach, will compromise the ability of a beach to recover after an erosive event (MORTON, 1988).

### CONCLUSIONS

The reliance upon shoreline armoring to mitigate coastal erosion on Oahu has, instead, produced widespread beach erosion resulting in beach narrowing and loss. Beach narrowing and loss occurs on retreating shorelines that have been armored. Our analysis yields no evidence of interannual periodicity to loss and recovery, and we infer that presently degraded beach segments are unlikely to experience natural recovery.

Beach erosion is a pressing environmental phenomenon be-

<sup>3</sup> We use the term *active* armoring to describe seawalls and revetments that interact with waves and/or wave run-up.

<sup>4</sup> We define long-term as exceeding 12 yr duration.

cause the beaches of the Hawaiian Islands are an important economic and cultural resource. Specific impacts of beach narrowing and loss include reduced public access for ocean-related recreation, commerce, subsistence, and the performance by modern and indigenous Hawaiian cultures of social and religious customs that are beach-dependent. Another consequence is habitat loss for marine species with beach-dependent life-stages, and for ~25% of indigenous, non-endemic Hawaiian plant species (SOHMER and GUSTAFSON, 1987). A sandy beach provides partial mitigation of the effects of damaging coastal processes such as large wave impacts, storm surge, and tsunami flooding. Additionally, beaches form the basis for a thriving visitor industry that supplies one third of all jobs in the state, and exceeds, by a factor of three, all other industries combined as ranked by direct income to the State of Hawaii.

Because Hawaiian beaches possess intrinsic cultural and economic value, our findings of beach loss indicate that present coastal management practices in Hawaii are having a detrimental impact on the culture and economy of the state. We recommend that efforts to mitigate coastal land loss in Hawaii focus on techniques emphasizing management of the littoral sediment budget and remediation of the impacts of coastal erosion by strategic withdrawal from erosional hotspots. Although the cost of individually sponsored beach nourishment is high (NATIONAL RESEARCH COUNCIL, 1995), the political and economic resources of an entire neighborhood, and associated levels of government, could be pooled in the establishment of a coastal management district (HWANG and FLETCHER, 1992). Where conditions warrant, beach nourishment can be used to buy time while development and redevelopment undergo a managed withdrawal from erosion sites to provide long-term mitigation of the problem. As the major tourist destination in the Pacific, Oahu and Hawaii have the opportunity to provide regional leadership in developing proactive beach management techniques for insular administrative authorities who must cope with the implications of continued, possibly accelerated, sea-level rise.

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