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A Summary of Historical Shoreline Changes on Beaches of Kauai, Oahu, and Maui, Hawaii

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ABSTRACT

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Shoreline change was measured along the beaches of Kauai, Oahu, and Maui (Hawaii) using historical shorelines digitized from aerial photographs and survey charts for the U.S. Geological Survey's National Assessment of Shoreline Change. To our knowledge, this is the most comprehensive report on shoreline change throughout Hawaii and supplements the limited data on beach changes in carbonate reef–dominated systems. Trends in long-term (early 1900s–present) and short-term (mid-1940s–present) shoreline change were calculated at regular intervals (20 m) along the shore using weighted linear regression. Erosion dominated the shoreline change in Hawaii, with 70% of beaches being erosional (long-term), including 9% (21 km) that was completely lost to erosion (*e.g.,* seawalls), and an average shoreline change rate of -0.11 ± 0.01 m/y. Short-term results were somewhat less erosional (63% erosional, average change rate of -0.06 ± 0.01 m/y). Maui, Hawaii, beaches were the most erosional of the three islands with 85% of the beaches erosional, including 11% lost, and an average change rate of -0.17 ± 0.01 m/y. Seventy-one percent of Kauai, Hawaii, beaches were erosional, including 8% lost, with an average change rate of -0.11 ± 0.01 m/y. Most (60%) of the Oahu, Hawaii, beaches were erosional, including 8% lost, with an average change rate of -0.06 ± 0.01 m/y. Short-term results for Maui, Hawaii, and Oahu, Hawaii, were roughly the same as those found in the long term. Short-term analysis for Kauai, Hawaii, was less conclusive with an accretional average rate, but most of the beaches were erosional. Spatially, shoreline change is highly variable along the Hawaii beaches (length scales of hundreds of meters). Areas of chronic erosion were identified on all sides of the islands.

ADDITIONAL INDEX WORDS: *Coastal erosion, shoreline recession, Pacific islands, National Assessment of Shoreline Change, DSAS.*

INTRODUCTION

The University of Hawaii Coastal Geology Group, in conjunction with the U.S. Geological Survey (USGS), recently completed an analysis of historical shoreline change along the beaches of Kauai, Oahu, and Maui, Hawaii, as part of the USGS National Assessment of Shoreline Change Project (Fletcher *et al.,* 2012; Romine *et al.,* 2012; USGS, 2012). To our knowledge, this work is the first to report on shoreline changes throughout the Hawaii archipelago at high spatial and temporal resolution. This study provides important data on shoreline changes to U.S. coasts and on carbonate beach systems throughout the world. In an era of accelerating sea level rise (Merrifield, Merrifield, and Mitchum, 2009), it is vital that the scientific community closely monitor shoreline changes because there is limited understanding about how shorelines will respond.

Chronic coastal erosion is a problem along most of the U.S. coast, including the carbonate beaches of Hawaii (*e.g.,* Crowell and Letherman, 1999; Fletcher *et al.,* 2004; Hapke *et al.,* 2006; Hapke *et al.,* 2010; Morton and Miller, 2005; Morton, Miller, and Moore, 2004). Coastal resource managers benefit from site-specific knowledge of historical shoreline change, assuming that historical changes have a relationship to future vulnerability to erosion. In the absence of a widely accepted physical model, historical shoreline positions can be used to characterize shoreline variability (National Academy of Sciences, 1990). Here, we report on our measurement of "chronic" shoreline change (decadal–century) on the three most populated Hawaiian Islands: Kauai, Oahu, and Maui, using historical shorelines mapped from air photos and survey charts. Shoreline changes were measured over two periods: long term (all available data, early 1900s–present) and short term (mid-1940s–present) as a rudimentary investigation into whether shoreline change rates have changed over time.

Geologic Setting

The Hawaii island chain comprises eight major volcanic islands in the tropics of the central North Pacific (Figure 1). The islands increase in age to the northwest with distance from actively growing Hawaii Island. The islands are built of one or

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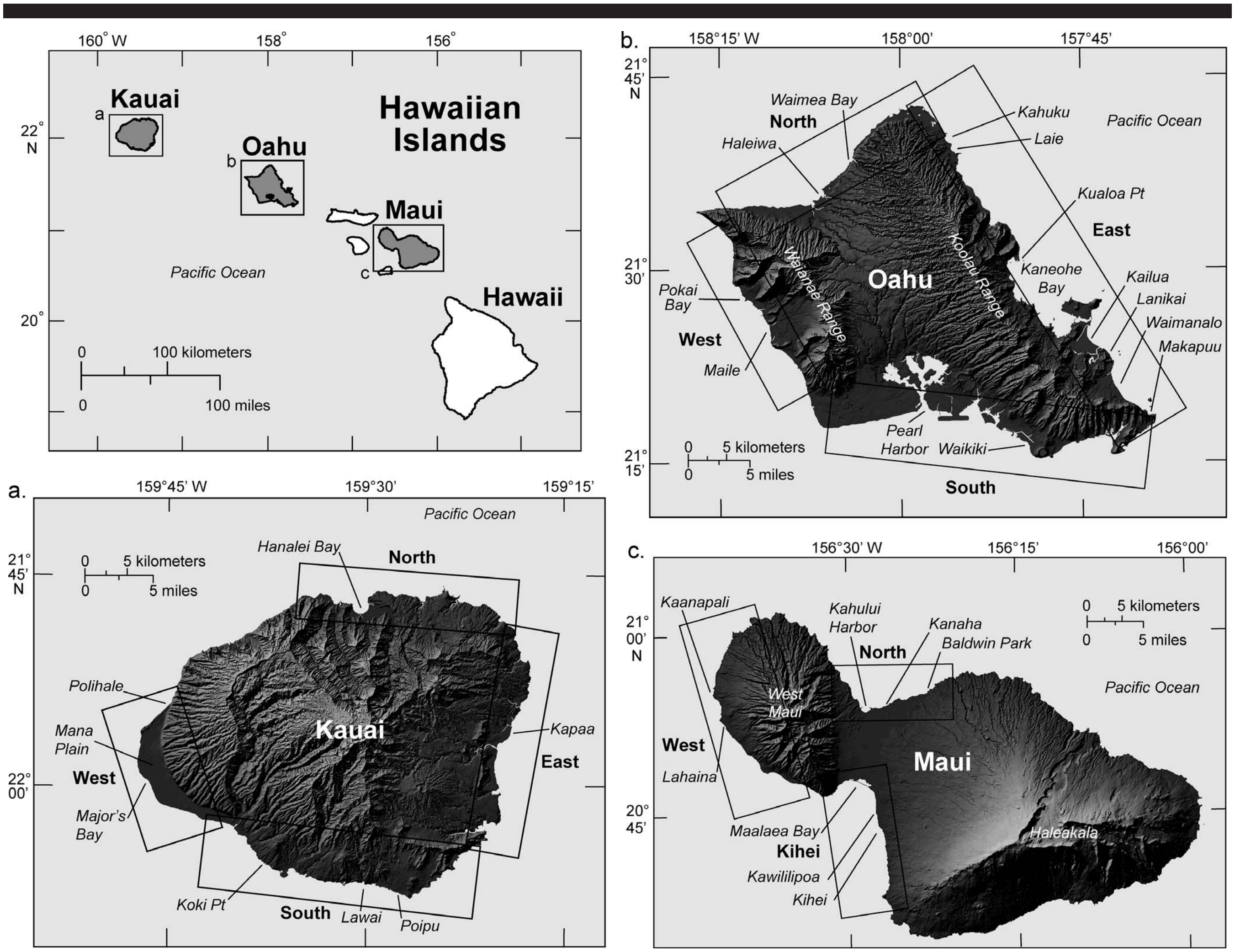

Figure 1. Shoreline study regions of Kauai, Oahu, and Maui; Hawaii (map scale varies).

more basaltic shield volcanoes, intrusive dike complexes, and tephra deposits. Rejuvenated volcanism may add new land to island coasts hundreds of thousands to millions of years following the end of the main shield building stage. The geology of Hawaiian coasts is typically characterized by volcanic bedrock, alluvial deposits from the volcanic interior, and carbonate deposits. Carbonate eolianite (Fletcher *et al.,* 2005), exposed reef formations (Muhs and Szabo, 1994; Szabo *et al.,* 1994), and beachrock (Meyers, 1987) are found on many Hawaii beaches and form headlands and nearshore islets (Fletcher and Jones, 1996) on some coasts, especially Oahu, Hawaii.

All but the youngest portions of the islands are fringed by a complex reef platform formed by a mosaic of reef accretion during the late-Pleistocene high sea-level stands. Modern reef growth is typically limited to a thin veneer in wave-exposed regions (Grigg, 1998) with most reef accretion occurring in wave-protected settings with sufficient accommodation space and on the reef-front below the effects of damaging waves (Fletcher *et al.,* 2008). Hawaiian fringing reefs are incised by relict erosional features (stream channels, karst depressions) formed during periods of lowered sea level and provide important reservoirs for sediment supply and storage (Bochicchio *et al.,* 2009; Conger *et al.,* 2009).

Hawaii's "white" sand beaches are derived primarily from reworked calcareous debris eroded from the insular reef shelf and, to a lesser degree, alluvial volcanic sediment deposited by streams and eroded from headlands (Harney and Fletcher, 2003) (Figure 2). Because of the relatively limited sediment supply, Hawaii beaches are typically narrower than continental beaches. Sediment can be lost from a littoral system by seaward transport beyond the reef crest and through paleo stream channels.

Hawaii is in a microtidal zone with a maximum spring range of about 1 m. Astronomic high tides typically represent the highest water levels. However, other temporary conditions produce sea level variations of tens of centimeters, including atmospheric pressure, wind setup, El Niño–Southern Oscillation cycles, and oceanic disturbances (such as mesoscale eddies (Firing and Merrifield, 2004). Rates of relative sea level rise

Figure 2. Photographs representing typical Hawaii beach types: (a) "pocket" beach at Makapuu, east Oahu, Hawaii; (b) partially embayed and deeply embayed beaches at Lanikai (foreground) and Kailua (background), east Oahu, Hawaii; (c) coastal strand plain and dunes on the Mana coastal plain, west Kauai, Hawaii; (d) highly urbanized and engineered beaches at Waikiki, south Oahu, Hawaii (Photographs b and d by Andrew D. Short, University of Sydney).

vary with distance from Hawaii Island because of differences in lithospheric flexure from the weight of actively growing volcanoes (Moore, 1987). Maui, Hawaii, closest of the three islands in this study to the Hawaii Island, has the greatest rate of relative sea level rise at 2.32 ± 0.53 mm/y (NOAA, 2012). Sea level rise is roughly 65% slower around Kauai and Oahu, Hawaii, at 1.53 ± 0.59 mm/y and 1.50 ± 0.25 m/y, respectively. Accelerated sea level rise seen in global records has not been detected in the Hawaii tide-gauge records (Church and White, 2006; Merrifield, Merrifield, and Mitchum, 2009).

Ocean waves arrive from four dominant regimes in Hawaii (Moberly and Chamberlain, 1964; Vitousek and Fletcher, 2008). In the northern hemisphere, during winter, powerful North Pacific swells affect the north- and west-exposed coasts, and occasionally, large N to NE swells affect the eastern shores. In summer, smaller, long-period South Pacific swells affect south- and west-exposed coasts. Persistent easterly trade winds and the short-period waves they create are common year-round but are strongest and most frequent in the summer. High trade-wind events may cause extensive erosion to windward beaches. Occasional winter "Kona" storms, with southerly winds and waves, can cause temporary erosion to south- and west-exposed beaches. Infrequent hurricanes can affect any coast, with the most recent example, Hurricane Iniki in 1992, causing extensive damage on the coasts of Kauai, Oahu, and Maui, Hawaii.

Data and Methods

We adhered closely to the methods of Fletcher *et al.* (2004) and Romine *et al.* (2009) for mapping historical shoreline positions and calculating positional uncertainties. We provide a summary of those methods here and refer the reader to those publications and to Fletcher *et al.* (2012) for more detail.

Historical shoreline positions were mapped from orthorectified, aerial photo mosaics and topographic survey charts (T-sheets). Typically, one historical shoreline is available approximately every decade going back to the early 1900s. We digitize a low water mark (LWM) or beach "toe" position as the shoreline proxy using geographic information system (GIS) software.

Only survey-quality, high-resolution (≤0.5 m pixel), vertical aerial photographs with sufficient tonal quality and contrast to resolve shoreline features were used for mapping historical shorelines. New aerial photographs were acquired for Kauai, Oahu, and southwest Maui, Hawaii, coasts between 2005 and 2008 and were rectified and mosaicked in photogrammetric software. The orthorectification process employs synchronous positional and orientation system data from the aircraft global positioning system, the inertial mobilization unit, and a high-resolution digital elevation model (DEM; 5 m horizontal, submeter vertical). Recent (1997 and 2002) aerial photographs for north and west Maui, Hawaii, were orthorectified using ground control points (GCPs) collected in a differential global positioning system survey and a 10-m, horizontal-resolution DEM. Older aerial photographs were sourced from local vendors, libraries, and archives and were georeferenced in photogrammetric software using GCPs collected from a more-recent orthophoto mosaic with a 5-m DEM. The orthorectification process typically produced mosaics with a root mean square (RMS) error less than 2 m.

Georeferenced T-sheets as early as 1927 for Kauai, Hawaii; 1910 for Oahu, Hawaii; and 1899 for Maui, Hawaii, were obtained from the National Oceanographic and Atmospheric Administration (NOAA) National Ocean Service. Rectification of T-sheets was verified by overlaying them on a modern orthorectified aerial photograph in a GIS to compare fit with unchanged coastal features (*e.g.,* rocky headlands). If necessary, the georeference of the T-sheets was improved using polynomial rectification models in the photogrammetric software, typically achieving RMS errors less than 4 m. The original surveyors working on T-sheets typically mapped a high waterline (HWL) as the shoreline proxy. To include a T-sheet shoreline with LWM shorelines from aerial photos in our study, a T-sheet HWL was migrated to a LWM using an offset calculated from data collected in biannual beach-profile measurements (Gibbs *et al.,* 2001) (C.H. Fletcher, B.M. Romine, T.R. Anderson, and M. Dyer, unpublished data) from the study beach or a nearby beach with similar littoral characteristics. The HWL–LWM migration distance was equal to the median of the measured distances between the HWL and the LWM from the profile surveys.

Because historical shoreline data sets are typically sparse and noisy, we attempted to use all available historical shorelines from air photos and T-sheets that met minimum quality standards and did not attempt to remove shorelines from the data set based on records of storms or large waves. We account for variability due to waves and storms in our uncertainty calculations. An exception was the historical shoreline for Kauai, Hawaii, from 1992, following the destructive *Hurricane Iniki,* which was not included. Shorelines were also removed from the data set in the following special situations. We attempted to reduce temporal bias on the shoreline trends by removing historical shorelines that fell within 2 years of another shoreline (the shoreline with the lower positional uncertainty was retained). Some beaches had been altered by human activity (engineering), such as the construction of coastal armoring, artificial beach fill, and sand mining, to an extent that the physics of the beach had been permanently altered. In those cases, we calculated the shoreline change rates using only shorelines that followed the major engineering efforts in an attempt to capture the present dynamics of the beach. Where the beach had been completely lost to erosion (*e.g.,* replaced by a seawall), we calculated a rate using the historical shoreline up to and including the first shoreline indicating no beach.

Table 1. *Sources and ranges of positional errors for historical shorelines in Hawaii (Fletcher et al., 2012).*

Source of Error	Magnitude Range (m)		
	Maui	Oahu	Kauai
Seasonal error (E_s)	±1.2–7.1	±3.6–6.2	±2.5–19.9
Tidal error (E_{td})	±1.4	±2.5–3.4	±2–6
T-sheet conversion error (E_c)	±1.9–7.5	±3.4–5.7	±1.0–13.8
Digitizing error (E_d)	±0.8–5.1	±0.5–5.7	±0.8–9.7
Pixel error (E_p)	±0.5	±0.5	±0.5–3.41
Rectification error (E_r)	±0.1–6.1	±0.6–3.0	±0.0–7.3
T-sheet plotting error (E_{ts})	±5.1	±5.1	±5.1

Historical shoreline positions derived from aerial photographs depict the shoreline at a single instant but represent the shoreline location for a decade or more in a historical shoreline data set. Therefore, it is important to rigorously identify and calculate positional uncertainties resulting from short-term (hourly to interannual) variability and the mapping process. We calculated up to seven sources of uncertainty for each historical shoreline: (1) the RMS error of the image rectification process (±0.1–7.3 m), (2) the on-screen identification and digitization of shoreline position (±0.5–9.7 m), (3) the image pixel size (resolution: 0.5 m for air photos, 1 to 3 m for T-sheets), (4) the seasonal shoreline fluctuations due to waves (±1.2–19.9 m), (5) the horizontal variability due to tides (±1.4–6.0 m), (6) the original field survey and plotting of T-sheet shorelines (applied to T-sheet shorelines only; ±5.1 m) (Shalowitz, 1964), and (7) the conversion of T-sheet HWM to LWM shoreline positions (±1.0–13.8 m) (Table 1). The individual uncertainties were combined as a root sum of squares to arrive at a total positional uncertainty, U_t, for each historical shoreline.

Changes in shoreline position were measured, and annual shoreline change rates were calculated in ArcGIS version 9.3 using the Digital Shoreline Analysis System version 4.2 (DSAS, Thieler *et al.,* 2009). Changes in shoreline position were measured at regularly spaced (roughly 20 m), shore-perpendicular transects cast from an arbitrary offshore baseline (Figure 3). We report the shoreline change rates calculated independently at each transect using weighted least squares (WLS) regression, which applied the individual shoreline uncertainties as a weight ($1/U_t^2$), so that shorelines with higher positional uncertainty (typically older shorelines) had less influence on the trend line. The uncertainty in the annual shoreline change rates (m/y) are reported at the 95% confidence interval (95% CI). Rates were calculated for long-term (all available shorelines) and short-term (1940s to near present) data to provide verification of chronic trends and insight into whether rates may have changed with time (Table 2).

We report regional, average shoreline-change rates as the mean of shoreline-change rates from all transects in a region. The uncertainty of a regional average rate is the root sum of the squares of the rate uncertainties from all transects. That calculation often leads to uncertainties on the order of a few centimeters *per* year. To avoid reporting some average rates as

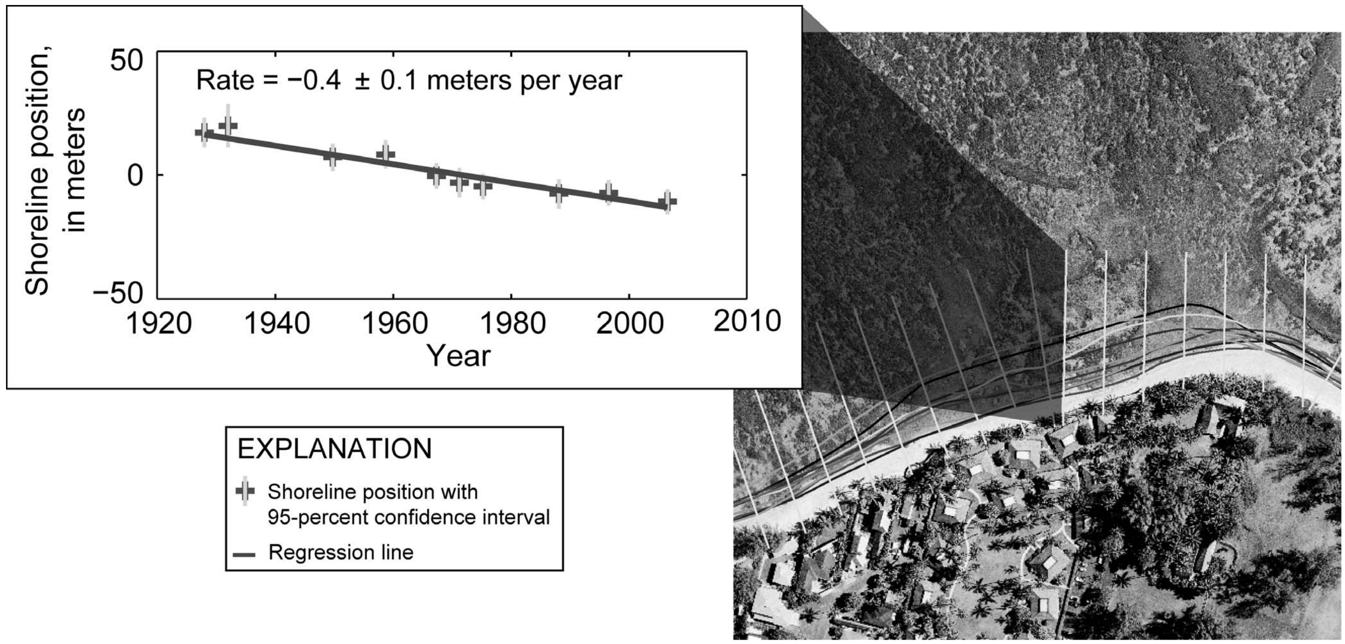

Figure 3. Historical shorelines (shore-parallel lines) are measured at regularly spaced transects (shore-perpendicular lines, ~20 m spacing). Shoreline change rates are calculated using weighted least squares (WLS) linear regression (Fletcher *et al.*, 2012).

having no uncertainty because of rounding (0.0 m/y), we report uncertainties at a higher precision (cm/y, 0.00 m/y) than the rates from individual transects (dm/y, 0.0 m/y), even though our measurement errors may not support that high degree of precision. The percentage of the eroding or accreting beach is the percentage of the transects that indicate an erosional or accretional trend in a particular region. A beach was considered completely lost to erosion (beach loss) in the time span of the analysis if it appeared in the earliest aerial photos and no beach was present in the most recent aerial photos.

RESULTS

Historical shoreline changes were measured along 244 km of beaches at 12498 transects (20-m spacing) of Kauai, Oahu, and Maui, Hawaii. Erosion was the dominant trend of shoreline change on the islands, with 70% of the beaches indicating an erosional trend and an overall average shoreline change rate of −0.11 ± 0.01 m/y (Table 3) during the long term. Only 28% of beaches indicated an accretional trend during the long term.

Table 2. *Number and range in years of historical shorelines for long- and short-term shoreline change analysis on Kauai, Oahu, and Maui, Hawaii (Fletcher et al., 2012).*

	Long Term		Short Term	
	No. of Shorelines[1]	Range (y)[1]	No. of Shorelines[1]	Range (y)[1]
Kauai	3–11	1926–2008	3–10	1950–2008
Oahu	3–12	1910–2007	3–10	1949–2007
Maui	3–10	1899–2007	3–8	1949–2007

[1] Actual number of shorelines and range varies for each beach.

Shoreline change had high spatial variability in Hawaii, with cells of erosion and accretion typically separated by hundreds of meters on continuous beaches or by short headlands that divide the coast into many small embayments. More than 21 km or 9% of the total length of the beaches studied was completely lost to erosion within the period of analysis. In nearly all cases, the beaches lost were replaced by seawalls or other coastal armoring. Short-term analysis also indicated an overall erosional trend, although the rate and extent of beach erosion appears to have slowed somewhat, with an overall average rate of −0.06 ± 0.01 m/y and 63% of beaches that were erosional. Thirty-four percent of the beaches were accretional in the short term.

Maui, Hawaii, beaches were the most erosional of the three islands, with an average long-term rate of −0.17 ± 0.01 m/y and 85% of the beaches that were erosional. Nearly 7 km (11%) of the Maui, Hawaii, beaches were completely lost to erosion during the span of analysis. Short-term results were similar to long-term trends, with an average rate −0.15 ± 0.01 m/y and 76% of beaches eroding. Only 14% and 18% of beaches were accretional in the long and short term, respectively.

The three Maui coastal regions (north, Kihei, and west) had dominant erosion trends in both the long and short term (Figure 4). North Maui, Hawaii, was the most erosional region of the three islands, with an average rate of −0.26 ± 0.02 m/y and 87% of the beach erosional in the long term and an average rate of −0.22 ± 0.03 m/y and 74% of beaches erosional in the short term. Areas of extensive erosion on north Maui, Hawaii included the beaches adjacent and to the east of Kahului Harbor; Kanaha, Hawaii, among a series of groins; and at Baldwin Park. Kihei and west Maui, Hawaii, had similar

Table 3. *Shoreline change trends for Kauai, Oahu, and Maui, Hawaii (Fletcher et al., 2012).*

Region	No. of Transects	Beach Loss (km)	Beach Loss (%)	Average Rate (m/y) Long Term (LT)	Average Rate (m/y) Short Term (ST)	% Eroding LT	% Eroding ST	% Accreting LT	% Accreting ST
Kauai									
North	1104	1.7	8	−0.11 ± 0.02	−0.06 ± 0.02	76	60	23	38
East	867	1.0	6	−0.15 ± 0.02	−0.06 ± 0.02	78	63	19	33
South	790	1.9	14	−0.01 ± 0.02	0.05 ± 0.04	63	57	34	39
West	962	1.5	7	−0.13 ± 0.04	0.16 ± 0.08	64	48	33	49
Total	3723	6.0	8	−0.11 ± 0.01	0.02 ± 0.02	71	57	27	40
Oahu									
North	1287	0.2	1	−0.11 ± 0.01	−0.07 ± 0.01	73	68	25	30
East	2108	5.5	13	0.01 ± 0.01	−0.01 ± 0.01	50	54	47	44
South	1319	3.0	11	−0.04 ± 0.01	−0.03 ± 0.02	50	47	48	50
West	628	0.0	0	−0.25 ± 0.01	−0.13 ± 0.02	83	71	16	27
Total	5342	8.7	8	−0.06 ± 0.01	−0.05 ± 0.01	60	58	38	40
Maui									
North	903	0.9	6	−0.26 ± 0.02	−0.22 ± 0.03	87	74	12	16
Kihei	1011	2.1	11	−0.13 ± 0.01	−0.12 ± 0.02	83	77	16	20
West	1519	3.8	14	−0.15 ± 0.01	−0.13 ± 0.01	85	77	14	18
Total	3433	6.8	11	−0.17 ± 0.01	−0.15 ± 0.01	85	76	14	18
Hawaii (all beaches studied)									
Total	12498	21.5	9	−0.11 ± 0.01	−0.06 ± 0.01	70	63	28	34

overall trends toward erosion with average rates between −0.12 and −0.15 m/y and more than 80% of beaches erosional in the long term and more than 70% erosional in the short term. Although the Kihei, Hawaii, and west regions were less erosional than was the north region, they are highly erosional compared with most regions of Kauai and Oahu, Hawaii. Substantial erosion and beach loss were found along the beaches fronting Kihei (town), Hawaii, and adjacent to Maalaea Harbor. The beaches fronting Lahaina, Hawaii, in west Maui, were largely replaced by seawalls (beach lost). The beach fronting the resort area of Kaanapali, Hawaii, was experiencing chronic erosion and was subject to large seasonal changes in beach width (Eversole and Fletcher, 2003).

The highest erosion rates on Maui, Hawaii (long term, −1.5 ± 1.1 m/y and short term −2.2 ± 1.1 m/y; Table 4) were found at Baldwin Park, in north Maui, Hawaii, where sand-mining operations in the mid-1900s contributed to the shoreline retreat of more than 100 m. Partially submerged beachrock stranded offshore marks a former shoreline position before sand mining. The maximum long-term accretion rate (1.6 ± 0.4 m/y) was found at Kawililipoa (Kihei region), Hawaii, at an accretional cusp between the remains of two fish ponds (low breakwall enclosures). The maximum short-term accretion rate (2.1 ± 0.2 m/y) was found between two rock groins at Kanaha Beach Park on the north Maui, Hawaii, coast.

Kauai and Oahu, Hawaii, beaches had less erosion than did Maui, Hawaii; although the islands all had an overall trend of shoreline retreat. Kauai, Hawaii, beaches were erosional in the long term with an overall average rate of −0.11 ± 0.01 m/y, and 71% of beaches were erosional. Kauai, Hawaii beaches lost 6 km or 8% of their total extent to erosion during the period of analysis. Results were less conclusive for Kauai, Hawaii, beaches in the short term with an average rate 0.02 ± 0.02 m/y, which suggest stable or accreting beaches overall, but localized trends varied widely. In contrast, most (57%) of the Kauai, Hawaii, beaches were erosional in the short term, suggesting an overall erosional trend. The difference between long- and short-term trends on Kauai, Hawaii, was due largely to the increased accretion along west Kauai, Hawaii, in the short term, although rates also slowed considerably for north and east Kauai, Hawaii, in the short term.

East Kauai, Hawaii, was the most erosional region of the island in the long and short term, based on average rates of −0.15 ± 0.02 m/y in the long term and −0.06 ± 0.02 m/y in the short term, and the percentages of eroding transects (78% long term and 63% short term). North Kauai, Hawaii, was also erosional in the long and short term, with average rates of −0.11 ± 0.02 m/y in the long term and −0.06 ± 0.02 m/y in the short term, and results for most of the beaches indicated an erosional trend (76% long term, 60% short term). A notable exception to the dominant trend of erosion along north Kauai, Hawaii, was found at Hanalei Bay, Hawaii, where the beach was accreting at an average rate of 0.11 ± 0.03 m/y (long term). Results for south Kauai, Hawaii, were less conclusive, with average rates that suggest roughly stable or accreting beaches, overall (long term, −0.01 ± 0.02 m/y; short term, 0.05 ± 0.04 m/y), but the percentages of eroding transects suggested an overall trend of erosion (63% long term; 57% short term). Fourteen percent (1.9 km) of south Kauai, Hawaii, beaches were completely lost to erosion—the most of the four Kauai, Hawaii, regions. Beach loss along south Kauai was concentrated around Poipu and Pakala, Hawaii. Results for west Kauai were also inconclusive, with an erosional average rate in the long term (−0.13 ± 0.04 m/y) and an accretional average rate in the short term (0.16 ± 0.08 m/y). Sixty-four percent of west Kauai beaches were erosional in the long term, and 48% were erosional in the short term. As shown in Figure 4, short-term rates for west Kauai, Hawaii, varied widely, with the

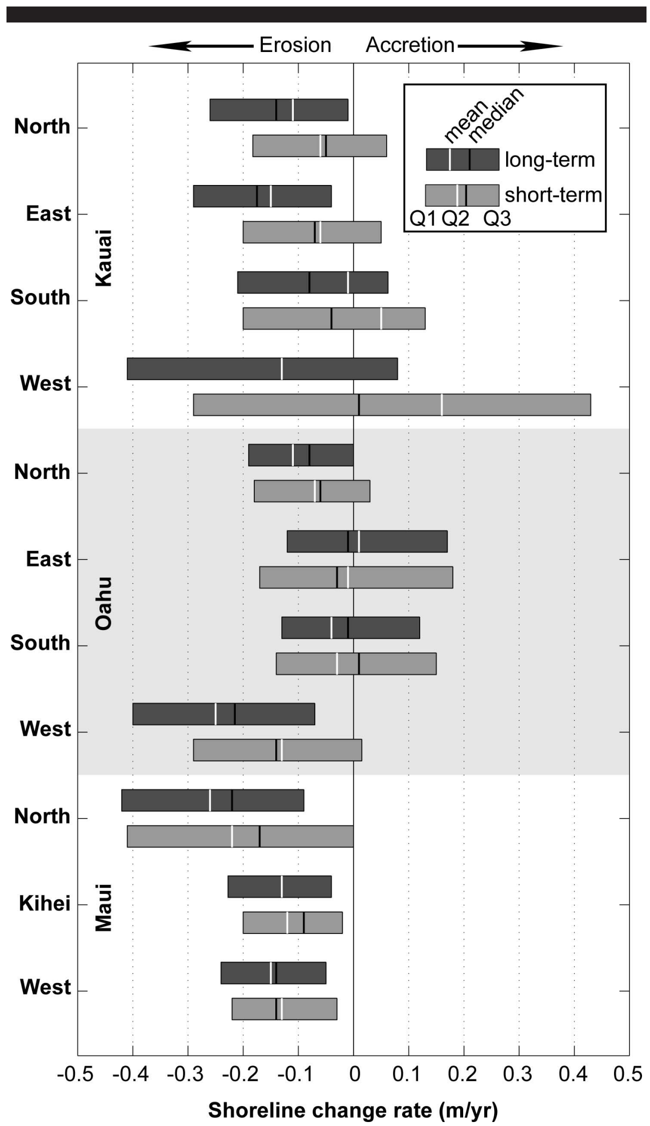

Figure 4. Box plot of long- and short-term shoreline change rates for coastal regions of Kauai, Oahu, and Maui, Hawaii. The width of a box depicts the upper and lower quartiles (Q1 and Q3) of the distribution of shoreline change rates for a region (*i.e.,* the middle 50% of the data). Results outside Q1 and Q3 are not shown.

distribution skewed toward accretion. Much of the increasing, short-term accretion was found at the north end of the region (Polihale, Hawaii) and along the central portion of the Mana Plain.

The maximum erosion rates on Kauai were found in the south region at Koki Point, Hawaii (-1.5 ± 0.4 m/y long term), and Lawai Bay, Hawaii (-1.7 ± 9.9 m/y short term), where the south end of the beach was lost to erosion. The high rate of uncertainty at Lawai Bay, Hawaii, was a result of calculating a rate with only three shorelines leading up to loss of the beach. The maximum long-term accretion rate, 1.6 ± 1.8 m/y, was found at Major's Bay on west Kauai, Hawaii, where the shoreline position was highly variable, with alternating predominant seasonal wave directions (reflected in the high rate uncertainty). The maximum short-term accretion rate, 2.8 $\pm$ 6.2 m/y, was found at the north end of Polihale Beach, Hawaii, where the beach also varied widely with the season.

Oahu, Hawaii, beaches were erosional overall, indicating trends similar in the long and short term, with an average long-term rate of -0.06 ± 0.01 m/y and an average short-term rate of -0.05 ± 0.01 m/y. Most (60%) of Oahu, Hawaii, beaches were erosional in the long term, and 58% of beaches were erosional in the short term. Nearly 9 km or 8% of the total extent of the Oahu, Hawaii, beaches were completely lost to erosion. Thirty-eight percent of the beaches were accretional in the long term, and 40% were accretional in the short term.

The west region was the most erosional side of Oahu, Hawaii, with an average long-term rate of -0.25 ± 0.01 m/y and a short-term average of -0.13 ± 0.02 m/y. Eighty-three percent of the west Oahu, Hawaii, beaches were erosional in the long term, and 71% were erosional in the short term. Less than 1% of west Oahu, Hawaii, beaches were completely lost to erosion because, in part, of the limited seawall construction on this coast (Romine and Fletcher, 2012). North Oahu, Hawaii, also has a dominant overall trend of erosion based on average rates (-0.11 ± 0.01 m/y long term; -0.07 ± 0.01 m/y short term) and percentages of eroding beach (73% long term; 68% short term). Shoreline position was seasonally variable along north Oahu, Hawaii, especially along the eastern half of the region. Temporary erosion from large winter waves was a major hazard to beachfront development. Results for east Oahu, Hawaii, were somewhat inconclusive, with average rates that suggest roughly stable beaches overall (0.01 ± 0.01 m/y long term; -0.01 ± 0.01 m/y short term) and results on approximately half of the beaches indicating a trend toward erosion (50% long term; 54% short term). Beach accretion on east Oahu, Hawaii (47% long term; 44% short term) was most prevalent in several deep bays including Laie, Kailua, and Waimanalo, Hawaii. The north half of east Oahu, Hawaii, was characterized by alternating cells of erosion and extensive beach loss fronting coastal armoring along low-lying headlands. Results for the highly urbanized south shore suggest a slight overall prevalence of erosion with average rates of -0.04 ± 0.01 m/y in the long term and -0.03 ± 0.02 m/y in the short term. Percentages of eroding and accreting transects in the south were roughly equal. Results for the largely engineered shoreline at Waikiki, Hawaii, were variable alongshore, with accretion typical on updrift sides of groins and erosion and beach loss common on downdrift sides.

The maximum erosion rates on Oahu, Hawaii, were found at Kualoa Point on the east side of the island at the southern terminus of a low-lying coastal strand plain. The sandy headland was eroded at -1.8 ± 0.3 m/y in the long term and -1.9 ± 0.9 m/y in the short term. Sand from the eroded headland was transported into Kaneohe Bay and was forming an accretional cusp at similar rates. The highest accretion rate, 1.7 ± 0.6 m/y (same in the long and short term), was found at Pokai Bay, west Oahu, Hawaii, where sand was accumulating on the updrift side of a harbor breakwall.

DISCUSSION

Shoreline change in Hawaii was dominated by an overall trend of erosion. However, shoreline change was highly

Table 4. *Maximum shoreline change rates for Kauai, Oahu, and Maui, Hawaii (adapted from Fletcher* et al., *2012).*

Region	Long-Term Rate (m/y)	Location[1]	Short-Term Rate (m/y)	Location[1]
Kauai				
Maximum erosion	−1.5 ± 0.4	Pocket beach near Koki Point	−1.7 ± 9.9	Lawai Bay; east end, beach lost
Maximum accretion	1.6 ± 1.8	Major's Bay, seasonal variability	2.8 ± 6.2	Polihale, seasonal variability[2]
Oahu				
Maximum erosion	−1.8 ± 0.3	Kualoa Point[2]	−1.9 ± 0.9	Kualoa Point
Maximum accretion	1.7 ± 0.6	Pokai Bay, north of harbor breakwall[2]	1.7 ± 0.6	Pokai Bay, north of harbor breakwall
Maui				
Maximum erosion	−1.5 ± 1.1	Baldwin Park, sand mining	−2.2 ± 1.1	Baldwin Park, sand mining[2]
Maximum accretion	1.6 ± 0.4	Kawililipoa, accretional cusp	2.1 ± 0.2	Kanaha Beach Park, groins

[1] Locations shown in Figure 1.
[2] Maximum erosion or accretion for all three islands (Kauai, Oahu, and Maui, Hawaii).

variable, which was not apparent when reporting regional averages. Cells of erosion and accretion were typically separated by hundreds of meters along continuous beaches or by short headlands that divided the coast into many small embayments. Averaging rates across a coastal region "smooths out" much of the detail afforded by high spatial resolution in this type of study (20 m transect spacing). For coastal resource management, identification of "hotspots" of chronic erosion is more valuable than an average of all rates for an island region—especially where shoreline change is highly variable along the shore. Shoreline-change data provided to county and state government from related studies is used on a property-by-property basis to manage coastal building setbacks. That provided a buffer for coastal retreat at properties fronting an erosion hot spot, reducing the need for erosion control structures like sea walls and, hopefully, preserving beaches.

About 22 km or 9% of beaches studied were completely lost to erosion during the period of analysis. In Hawaii, the historically common response to beach erosion has been to armor the back-beach in an effort to protect beachfront property with seawalls or other engineered structures. Fletcher, Mullane, and Richmond (1997) and Romine and Fletcher (2012) show that armoring eroding beaches in Hawaii has led to much of the beach loss observed in this study. Armoring eroding beaches typically leads to narrowing and, ultimately, complete loss of a beach because the waterline continues to recede landward toward the fixed shoreline. Evidence for increased flanking erosion adjacent to armoring was documented in Romine and Fletcher (2012).

Rates of shoreline change were influenced by other human activities on some beaches in Hawaii. Removal of beach sand by mining operations was common on island beaches in early and mid-1900s. Those operations were observed in aerial photographs used in this study. That practice caused tens to hundreds of meters of shoreline retreat at many beaches, including Waimea Bay, Kahuku, and Maile on Oahu, Hawaii, and Baldwin Park on Maui, Hawaii. Sand removal from beaches was outlawed in the early 1970s, and erosion appears to have slowed in recent decades at several mined beaches. Other examples of human influences on shoreline change rates included construction of groins and breakwalls and artificial beach fills. Reduction in the average shoreline change rate for the islands in the short term (−0.06 ± 0.01 m/y) compared with the long term (−0.11 ± 0.01 m/y) may be attributed, in part, to the cessation of sand mining and the increased artificial stabilization of shorelines in the second half of the 1900s.

When comparing one side of an island to a similar side of another island, assuming similar wave conditions, no clear correlation emerged. In general, high alongshore rate variability made this sort of comparison difficult. A comparison of the west regions of Kauai and Oahu, Hawaii, provided the most interesting example of dissimilarity in shoreline behavior between similar geographic regions. The Mana Plain of west Kauai, Hawaii, has been accreting through the late Holocene based on interpretation of the coastal geomorphology (Moberly *et al.,* 1963) and appears to be stable to accreting during the past century. In contrast, the west side of Oahu, Hawaii, is erosional along most of its length. Differences in gross island morphology may be the primary reason for the difference in shoreline behavior among the west coasts. The approximately round shape of Kauai, Hawaii, and its lack of major headlands on NW and SW shores promote wave refraction and allow generally uninterrupted sand transport toward its western end from both the north and south. In contrast, the west Oahu shoreline is approximately linear as a whole and is punctuated by smaller headlands that divide the coast into distinct littoral cells. The north shores of the three islands seem to exhibit the most similar shoreline-change behavior among similar geographic regions with conclusive overall trends of erosion. However, the similarities appear to end there. Shoreline change on smaller spatial scales seems to be more related to local shoreline dynamics and sediment budgets, and other large-scale spatial correlations are not obvious.

Beach erosion is likely to increase in Hawaii and globally with accelerating sea level rise in coming decades (Merrifield, Merrifield, and Mitchum, 2009; Vermeer and Rahmstorf, 2009). It is not known how individual beaches will respond to increasing rates of sea level. It is likely that increasing sea level will raise the rate and extent of erosion in areas of historical shoreline retreat. Therefore, we have identified coastal areas most at risk for increasing erosion in coming decades—information that will be useful to those responsible for coastal hazard mitigation and management. Continued monitoring of beaches with updates to this and similar studies will be vital in coming decades to better understand beach response to changing climate.

CONCLUSIONS

Our results provide insight to shoreline change in the Hawaiian Islands during the past century. Shoreline change on Hawaiian beaches is dominated by erosion. More than 21 km or 9% of the total extent of beach on Kauai, Oahu, and Maui, Hawaii, was lost to erosion during the past century. Maui, Hawaii, was clearly the most erosional of the three islands with the greatest average long-term and short-term shoreline-change rates and the greatest percentages of transects indicating erosion; although, Kauai and Oahu, Hawaii, beaches were also erosional overall. Shoreline change in Hawaii is highly spatially variable. Cells of erosion and accretion were characterized by length scales of hundreds of meters on continuous beaches. Along much of the coast, headlands divide the shoreline into many small embayments with pocket beaches that exhibited a range of shoreline-change behavior—some erosional and some accretional. Significant areas of chronic beach erosion were found on all sides of the islands.

Chronic erosion threatens coastal development and will lead to further beach loss if beaches are not allowed to recede naturally where the coastal plain is composed of sand. Beach erosion will become an increasing problem in Hawaii in coming decades should the rate of sea level rise accelerate as predicted. With this study, we have identified sections of the shoreline that pose the highest risk of future erosion, assuming that past trends of shoreline change have a relationship to future vulnerability to erosion. Information from this study will help Hawaii decision-makers protect beaches for future generations. This work also provides information for the coastal research community, which is assessing shoreline change on coasts around the world in the face of changing climate and rising sea levels.

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