HISTORICAL SHORELINE CHANGES ON BEACHES OF THE HAWAIIAN ISLANDS WITH RELATION TO HUMAN IMPACTS, SEA LEVEL, AND OTHER INFLUENCES ON BEACH DYNAMICS

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ABSTRACT

Historical changes in shoreline position are measured along the beaches of Kauai, Oahu, and Maui (Hawaii) using shorelines digitized from aerial photographs and survey charts dating back to the early 1900s. Over the past century, erosion (recession) was the dominant trend of shoreline change in Hawaii with an overall average shoreline change rate of -0.11 m/yr and 70% of beaches eroding, including 21km of beach (9% of beaches studied) that completely disappeared. Maui beaches were the most erosional of the three islands (85% erosional, island-wide average rate of -0.17 m/yr). Seventy-one percent of Kauai beaches eroded (average rate -0.11 m/yr), including 8% that completely disappeared. Sixty percent of Oahu beaches eroded (average rate -0.06 m/yr), including 8% that completely disappeared. Coastal armoring (e.g., seawalls) contributes to beach narrowing and loss by limiting the ability of an eroding beach to migrate landward. On Oahu 72% of beaches that narrowed were fronting coastal armoring, including 8.6 km of beach that completely disappeared. This is in comparison to unarmored beaches where beach widths remained relatively stable (53% of beaches narrowed). Island-wide shoreline trends are recalculated for Oahu and Maui after optimizing the data to control for human impacts and applying a series of consistency checks on the results. Differing rates of relative sea-level rise around Oahu and Maui (~65% faster around Maui) remain as the best explanation for the difference in island-wide shoreline trends after examining other influences on shoreline change including waves, sediment supply and littoral processes, and anthropogenic changes. Patterns of historical shoreline change along the northeast coast and other regions of the island of Oahu are examined for spatial relationships to coastal geomorphology and temporal relationships to late-Holocene sea-level changes. Multiple lines of geologic evidence indicate that headlands, comprised largely of unconsolidated carbonate beach and eolian sediments, were formed during late-Holocene sea-level fall. We infer that a change from headland beach accretion to the observed modern pattern of headland beach erosion is related to the initiation of sea-level rise around Oahu following an earlier period of falling sea level over the past few thousand years.

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INTRODUCTION

Beaches are ephemeral environments that develop in equilibrium between winds, waves, sediment availability, and sea level. Beaches and coastal dunes, if left in their natural condition, can provide an effective buffer between coastal development and hazards of coastal erosion and inundation due to large waves, storms, and tsunamis. Beach loss threatens homes, businesses, infrastructure, ecosystems, and public resources. The threat of coastal erosion is even more urgent in Hawaii than along most continental coasts because most of Hawaii's population lives and works within a few miles of the coast.

With rapid growth of the tourism and military-based economy in the second half of the 20^{th} century, Hawaii beaches became the focus of intense development. Little consideration was made for planning for natural hazards, such as coastal erosion. As a result, beachfront homes, roads, and hotels built too close to eroding shores are regularly threatened by inundation and damage from waves. Historically, the typical response to beach erosion in Hawaii has been to armor the coast with seawalls and other structures to protect coastal property – often resulting in complete loss of the beach fronting the armoring. A historical lack of proactive planning for coastal hazards in Hawaii, including coastal erosion, is due largely to limited scientific data and understanding of the risks of building on our highly dynamic shores.

In response to rising awareness of problems related to coastal erosion in Hawaii, the State and counties commissioned several studies in the 1980s and early 1990s to investigate shoreline change – finding areas of extensive beach erosion throughout the islands (Hwang, 1981; Makai Ocean Engineering and Sea Engineering, 1991; Sea Engineering Inc, 1988). These studies provided valuable information on historical shoreline trends for individual beaches by measuring historical shoreline changes at one or more representative locations at a beach using aerial photographs.

Recent improvements in photogrammetric and geographic software systems provide opportunities to measure shoreline change with greatly improved spatial resolution and accuracy. Historical shoreline changes may now be analyzed at the scale of individual properties providing planners and resource managers with information needed to make responsible and proactive coastal land use planning decisions to preserve coastal resources and protect coastal property. As an example, historical shoreline change rates calculated in studies related to this dissertation are utilized in erosion rate-based set-backs throughout Hawaii in an improved effort to locate new construction landward, away from eroding shorelines and other coastal hazards.

With funding support from County, State, and Federal government agencies, the University of Hawaii Coastal Geology Group (including the author) has completed a 10-year effort to map and analyze historical shoreline changes on Kauai, Oahu, and Maui. This endeavor resulted in over 12,000 individual shoreline change measurements along the beaches of the three most densely-populated Hawaiian Islands over the past century. Together, these islands represent about 60% of the sandy beaches found in Hawaii (Moberly and Chamberlain, 1964). The remaining Hawaii islands were not surveyed in this study primarily due to funding constraints. The methods for measuring historical shoreline change described in this dissertation are designed to be easily transferable to other islands, and with the intention of promoting regular updates to the results, which will be vital to monitor changing shoreline trends with expected increasing sea-level rise in coming decades. This extensive data set and the unique physical setting of the Hawaii archipelago affords new opportunities to explore spatial and temporal patterns of shoreline change.

Chapter One of this dissertation presents a quantitative summary of results from historical shoreline change mapping projects for the island Counties of Kauai (Fletcher *et al.*, 2009), Oahu (Fletcher *et al.*, 2011), and Maui (Fletcher *et al.*, 2004); and a contribution to the U.S. Geological Survey's National Assessment of Shoreline Change for the Hawaiian Islands (Fletcher *et al.*, 2012). Island-wide and regional shoreline changes in Hawaii indicate a widespread problem of coastal erosion in Hawaii. The results show that the majority of beaches eroded over the past century, including many kilometers of beach that disappeared fronting coastal armoring (e.g., seawalls).

On many beaches in Hawaii, the historical response to beach erosion has typically been to armor the backshore in an effort to protect coastal properties. Coastal armoring has had a profoundly negative effect on Hawaii beaches by contributing to beach narrowing and in many locations complete loss of beaches. Chapter Two details the effects of coastal armoring on the beaches of Oahu, the most densely-populated and developed island in Hawaii, in form of beach narrowing and beach loss.

In this era of accelerating global sea-level rise (Merrifield *et al.*, 2009; Vermeer and Rahmstorf, 2009) there is much interest in how beaches will respond. Historical shoreline data sets provide the only opportunity to observe historical shoreline changes on multi-decadal to century timescales, allowing investigations into possible relations between shoreline change and sea-level rise. The islands of Oahu and Maui, with significantly different rates of sea-level rise (approximately 65% higher rate on Maui) over the past century, provide a unique setting to investigate possible relations between historical shoreline changes and sea-level rise. Shoreline change is a function of many variables, including waves, storms, sediment supply, littoral processes, human impacts, and sea-level rise. In Chapter Three, historical shoreline data for the islands of Oahu and Maui are optimized to limit human influences on shoreline change. A series of consistency checks are also applied on island-wide and regional shoreline trends to determine if differing rates of relative sea-level rise between the islands remains as the best explanation for the observed differences in shoreline changes.

Chapter Four probes further into relationships between sea level and shoreline change in Hawaii through investigations of spatial and temporal patterns of change on individual beaches along the northeast coast and elsewhere on Oahu. The results have implications for improved understanding and forecasting of shoreline change with continued sea-level rise, specifically, determining whether sea-level rise may result in "preferential" erosion and, even, accretion of certain coastal geomorphic features.

The author hopes that the information provided in this dissertation and related maps and reports will contribute to improved understanding and planning for coastal hazards, including sea-level rise along Hawaii coasts. Continued monitoring of Hawaii's beaches, building on the results of this and previous studies is needed over coming decades to continue to improve our understanding of shoreline response to changing climate, changing oceanographic conditions, and human impacts, with the primary goal of preserving Hawaii's beaches and reducing our exposure to coastal hazards for future generations.

CHAPTER 1. A SUMMARY OF HISTORICAL SHORELINE CHANGES ON BEACHES OF KAUAI, OAHU, AND MAUI, HAWAII

Bradley M. Romine and Charles H. Fletcher
Related Publication: Romine and Fletcher (2012b)

Abstract

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. This comprehensive report on shoreline change throughout Hawaii supplements 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 on plots of shoreline position versus time. 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, 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 beaches were erosional, including 8% lost, with an average change rate of −0.11 ± 0.01 m/y. Most (60%) of the Oahu beaches were erosional, including 8% lost, with an average change rate of −0.06 ± 0.01 m/y. Short-term results for Maui and Oahu were roughly the same as those found in the long term. Short-term analysis for Kauai 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 with individual cells of erosion or accretion typically extending for hundreds of meters along the shore. Areas of chronic erosion were identified on all sides of the islands.

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 and Fletcher, 2012b). This work reports on shoreline changes throughout the Hawaiian archipelago at high spatial and temporal resolution and contributes to understanding of shoreline changes on U.S. coasts and for carbonate beach systems throughout the world. In an era of accelerating sea-level rise (Merrifield *et al.*, 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 Leatherman (1999); Fletcher *et al.* (2004); Hapke *et al.* (2010); Hapke *et al.* (2006); Morton and Miller (2005); and Morton *et al.* (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 (covering the post-World War II period of intensive coastal development, 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 1.1). The islands increase in age to the northwest with distance from actively growing Hawaii Island. The islands are built of one or 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.

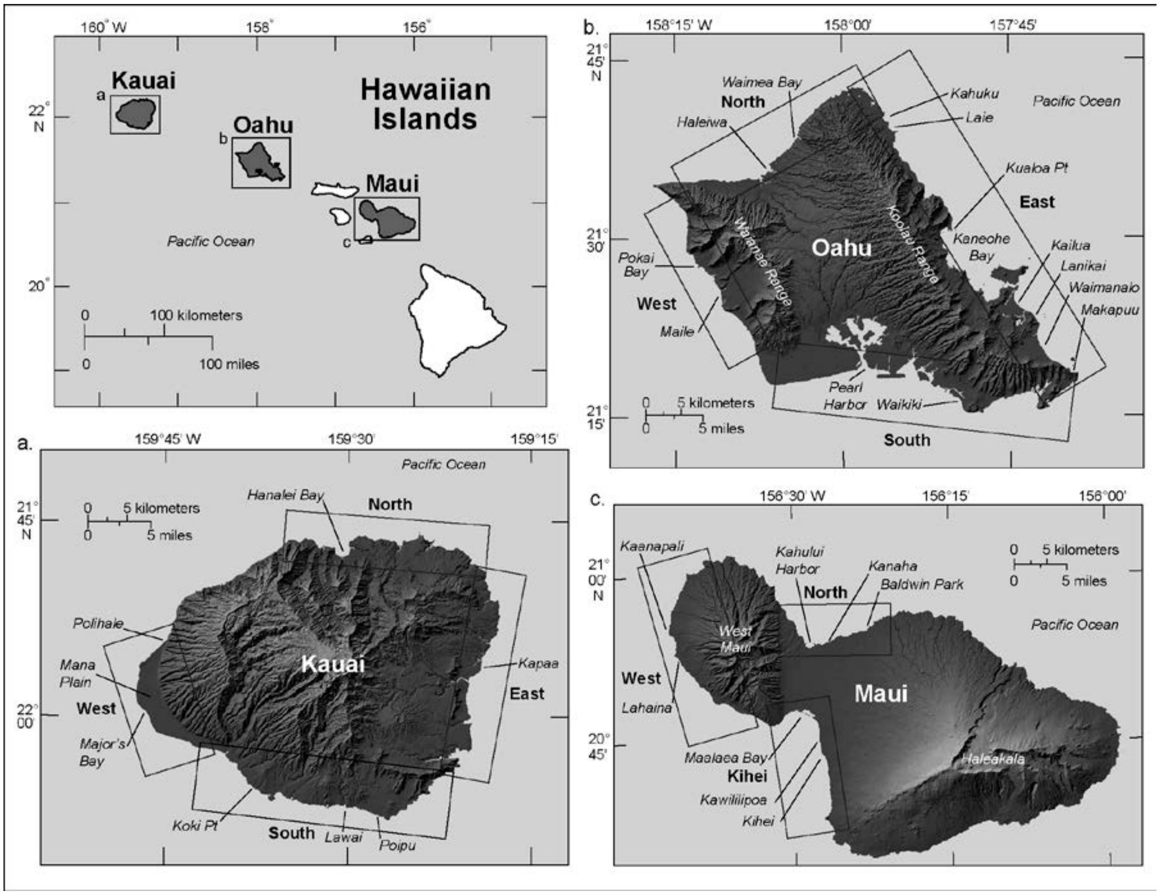

Figure 1.1. Shoreline study regions of Kauai, Oahu, and Maui; Hawaii (map scale varies).

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 1.2). 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.

Figure 1.2. Photographs representing typical Hawaii beach types: (a) ‘pocket’ beach at Makapuu, east Oahu; (b) partially-embayed and deeply-embayed beaches at Lanikai (foreground) and Kailua (background), east Oahu; (c) coastal strand plane and dunes on the Mana coastal plain, west Kauai; (d) the highly urbanized and engineered beaches at Waikiki, south Oahu (Photographs b and d by Andrew D. Short, University of Sydney).

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 vary with distance from Hawaii Island because of differences in lithospheric flexure from the weight of actively growing volcanoes (Moore, 1987). Maui, closest of the three islands in this study to Hawaii Island, has the greatest rate of relative sea-level rise at 2.32 ± 0.53 mm/y (http://tidesandcurrents.noaa.gov/, last viewed May 30, 2012). Sea-level rise is roughly 65% slower around Kauai and Oahu at 1.53 ± 0.59 mm/y and 1.50 ± 0.25 m/y, respectively. The accelerated sea-level rise seen in some global records (Church and White, 2006; Merrifield *et al.*, 2009) has not been detected in the Hawaii tide-gauge records (Merrifield, 2011). Rates of sea-level rise have been greater in the western tropical Pacific relative to Hawaii over the past several decades and has been attributed to intensification of tradewinds over the time period (Merrifield and Maltrud, 2011)

Ocean waves arrive from four dominant directions 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. Occasional tsunamis have caused extensive damage in Hawaii, though it is not known if tsunamis typically lead to erosion or accretion on Hawaii beaches. Damaging tsunamis in the past century in Hawaii include 1946, 1957, and 1960, and 1964 (Fletcher *et al.*, 2002).

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 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 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, 1910 for Oahu, and 1899 for Maui 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 a time series of 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 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.

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 1.1). The individual uncertainties were combined as a root sum of squares to arrive at a total positional uncertainty, U_t, for each historical shoreline (±2.2-29.07 m, average 7.19 m).

Table 1.1. Sources and ranges of positional errors for historical shorelines.

Source of error	Magnitude range (meters) 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

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 1.3). 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 1.2).

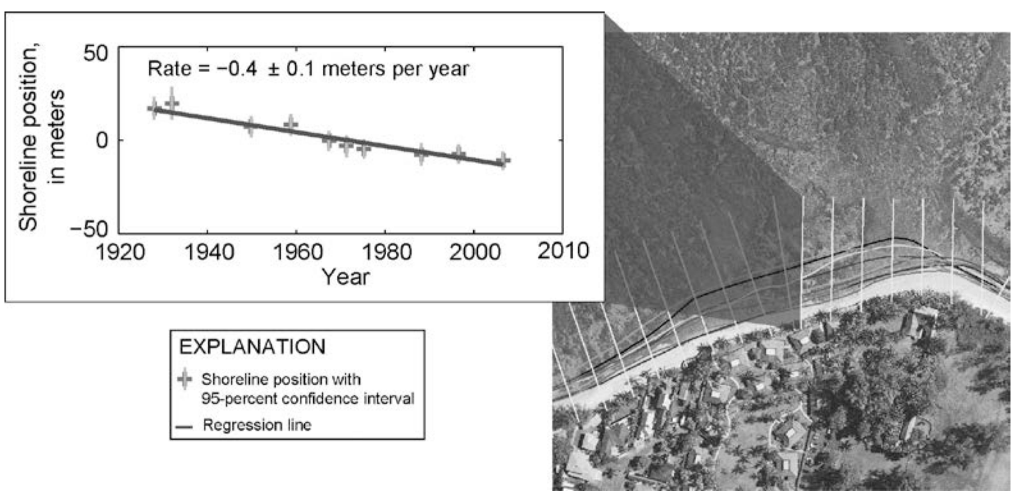

Figure 1.3. Historical shorelines (shore-parallel lines) are measured at regularly-spaced transects (roughly shore-perpendicular lines, ~20 m spacing). Shoreline change rates are calculated using weighted least squares (WLS) linear regression.

Table 1.2. Number and range in years of historical shorelines for long- and short-term shoreline change analysis on Kauai, Oahu, and Maui.

	Long-term		Short-term	
	Number of shorelines[1]	Range in years[1]	Number of shorelines[1]	Range in years[1]
Kauai	3 - 11	1927 - 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.

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 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 12,498 transects (20-m spacing) of Kauai, Oahu, and Maui. Erosion was the dominant trend of shoreline change on the islands, with 70% of transects indicating an erosional trend and an overall average shoreline change rate of −0.11 ± 0.01 m/y (Table 1.3) during the long term. Only 28% of beaches indicated an accretional trend during the long term. 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, beaches were lost to seawalls or other coastal armoring constructed in response to a pre-existing trend of erosion (see Chapter 2). 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.

Table 1.3. Shoreline change trends for Kauai, Oahu, and Maui.

[km, kilometers; m/yr, meters per year]

Region	Number of transects	Beach loss (km)	Beach loss (percent)	Average rate (m/yr) Long-term (LT)	Average rate (m/yr) Short-term (ST)	Percent eroding LT	Percent eroding ST	Percent accreting LT	Percent 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

Maui 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 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 1.4). North Maui 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 included the beaches adjacent and to the east of Kahului Harbor; Kanaha among a series of groins; and at Baldwin Park. Kihei and west Maui had similar overall erosional trends 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 and west regions were less erosional than was the north region, they are highly erosional compared with most regions of Kauai and Oahu. Substantial erosion and beach loss were found along the beaches fronting Kihei town and adjacent to Maalaea Harbor. The beaches fronting Lahaina in west Maui were largely replaced by seawalls (beach lost). The beach fronting the resort area of Kaanapali was experiencing chronic erosion and was subject to large seasonal changes in beach width (Eversole and Fletcher, 2003).

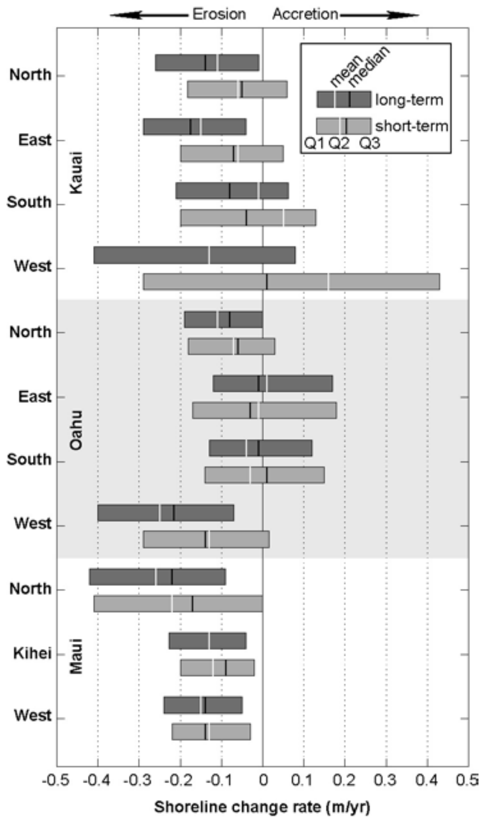

Figure 1.4. Box plot of long- and short-term shoreline change rates for coastal regions of Kauai, Oahu, and Maui. The width of a box depicts the upper and lower quartiles (Q1 and Q3) of the distribution of shoreline change rates for a region (i.e., the middle 50% of the data). Results outside Q1 and Q3 are not shown.

The highest erosion rates on Maui (long term, −1.5 ± 1.1 m/y and short term −2.2 ± 1.1 m/y; Table 1.4) were found at Baldwin Park, in north Maui 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) 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 coast.

Table 1.4. Maximum shoreline change rates for Kauai, Oahu, and Maui.

[m/yr, meters per year; max., maximum]

Region	Long-term rate (m/yr)	Location[1]	Short-term rate (m/yr)	Location[1]
Kauai				
Max. erosion	-1.5 ± 0.4	pocket beach near Koki Point	-1.7 ± 9.9	Lawai Bay; east end, beach lost
Max. accretion	1.6 ± 1.8	Major's Bay, seasonal variability	2.8 ± 6.2	Polihale, seasonal variability[2]
Oahu				
Max. erosion	-1.8 ± 0.3	Kualoa Point[2]	-1.9 ± 0.9	Kualoa Point
Max. accretion	1.7 ± 0.6	Pokai Bay, north of harbor breakwall[2]	1.7 ± 0.6	Pokai Bay, north of harbor breakwall
Maui				
Max. erosion	-1.5 ± 1.1	Baldwin Park, sand mining	-2.2 ± 1.1	Baldwin Park, sand mining[2]
Max. 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).

Kauai and Oahu beaches had less erosion than did Maui, Hawaii; although the islands all had an overall trend of shoreline retreat. Kauai 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 beaches lost 6 km or 8% of their total extent to erosion during the period of analysis. Results were less conclusive for Kauai 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 beaches were erosional in the short term, suggesting an overall erosional trend. The difference between long- and short-term trends on Kauai was due largely to the increased accretion along west Kauai in the short term, although rates also slowed considerably for north and east Kauai in the short term.

East Kauai 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 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 was found at Hanalei Bay where the beach was accreting at an average rate of 0.11 ± 0.03 m/y (long term). Results for south Kauai 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 beaches were completely lost to erosion - the most of the four Kauai regions. Beach loss along south Kauai was concentrated around Poipu and Pakala. 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 1.4, short-term rates for west Kauai varied widely, with the distribution skewed toward accretion. Much of the increasing, short-term accretion was found at the north end of the region (Polihale) and along the central portion of the Mana Plain.

The maximum erosion rates on Kauai were found in the south region at Koki Point (−1.5 ± 0.4 m/y long term), and Lawai Bay (−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 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 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 ± 6.2 m/y, was found at the north end of Polihale Beach where the beach also varied widely with the season.

Oahu 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%) Oahu 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 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 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 beaches were erosional in the long term, and 71% were erosional in the short term. Less than 1% of west Oahu beaches were completely lost to erosion because, in part, of the limited seawall construction on this coast (Romine and Fletcher, 2012a). North Oahu 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 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 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 (47% long term; 44% short term) was most prevalent in several deep bays including Laie, Kailua, and Waimanalo. The north half of east Oahu 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 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 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 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 variable, which is 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 "smoothes-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 *et al*. (1997) and Romine and Fletcher (2012a) 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 erosion adjacent to armoring ('flanking' erosion) was documented in Romine and Fletcher (2012a).

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 and Baldwin Park on Maui. 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 provided the most interesting example of dissimilarity in shoreline behavior between similar geographic regions. The Mana Plain of west Kauai 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 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 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 *et al.*, 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 was lost to erosion during the past century. Maui 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 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 additional 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.

CHAPTER 2. ARMORING ON ERODING COASTS LEADS TO BEACH NARROWING AND LOSS ON OAHU, HAWAII

Bradley M. Romine and Charles H. Fletcher
Related Publication: Romine and Fletcher (2012a)

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 almost 9 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/yr, on average. In comparison, beach widths along unarmored coasts were relatively stable with only slightly more than half (53%) of beaches experiencing some 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, west and north shore beaches are still significantly narrowed (61% and 70%, respectively). We find at these sites that cultivation (planting and propagation) of coastal vegetation may be a factor in beach narrowing, along with beach erosion. Increased 'flanking' erosion (accelerated 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.

Introduction

A recent study (Fletcher *et al.*, 2012) finds that erosion dominates shoreline change on the beaches of Kauai, Oahu, and Maui. Because a strand plain of unconsolidated carbonate sand backs much of the Hawaii shoreline (Fletcher *et al.*, 2012; Sherrod *et al.*, 2007), one may assume there is adequate sediment on the backshore for an eroding beach that is migrating landward to maintain an equilibrium profile (e.g., Bruun (1954); Davidson-Arnott (2005)). 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 (Fletcher, 1992; Fletcher *et al.*, 1997; Hwang, 1981; Makai Ocean Engineering and Sea Engineering, 1991; Sea Engineering Inc, 1988). In such cases, the water line continues to migrate landward as sand is eroded from the beach face 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.

Fletcher *et al*., (1997) found that coastal armoring led to narrowing or complete loss along ~24% of beaches on the island of Oahu, Hawaii. 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)).

Seawalls and other armoring styles are often blamed for 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 narrowing and loss, which 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.

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 degrees north latitude, is the most populated of the main islands. The island is fringed by a Pleistocene 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 and Fletcher, 2003; Harney *et al.*, 2000). 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 (Figure 2.1). East Oahu, from Kahuku Point in the north to Makapuu Point in the southeast, is moderately developed with single-family homes lining most beaches. Beach Parks and a coastal highway line other portions of the shoreline. 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 and extensive coastal armoring has been emplaced along northeast shores. Beaches in the southeast (south of Kaneohe Bay) are wider, relative to the northeast, with a deeper fringing reef.

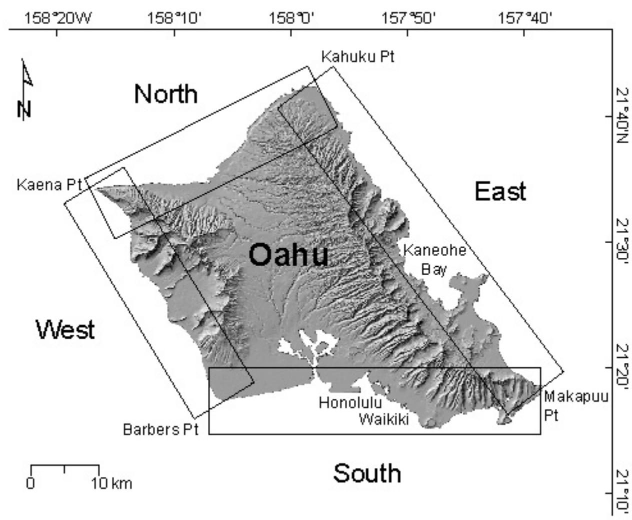

Figure 2.1. Four coastal regions of Oahu.

South Oahu, from Makapuu Point in the southeast to Barbers Point in the southwest, 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 southwest to Kaena Point in the west, 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 Keana 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.

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*. (2004), Fletcher *et al*. (2012) and Romine *et al*. (2009).

Measuring Beach Width

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) (Figure 2.2).

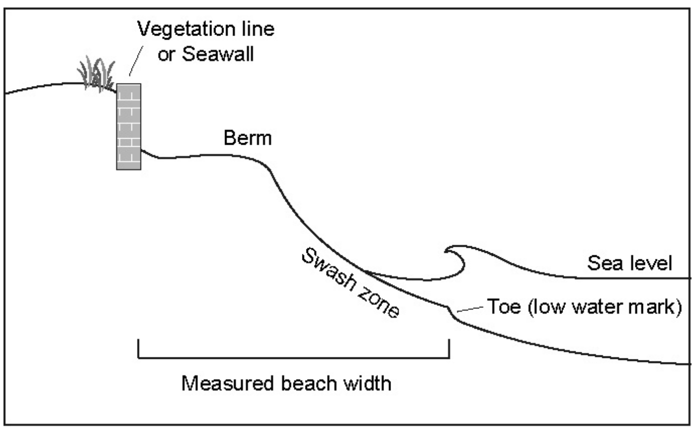

Figure 2.2. Beach width is the distance between the beach toe (low water mark) and vegetation line (or armoring) (modified from Fletcher, *et al*. (1997)).

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.

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, we wish to identify the modern trend of shoreline change.   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 time of the year. Typically, these are designed to prevent coastal recession and/or to retain sand. Materials used for armoring include rubble or stone revetments (with or without mortar); cement, brick, or stone walls; wood or metal bulkheads; and sand bags. 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 that the wall is impacted by wave run-up.

Coastal armoring is mapped using the most-recent (2005-2008) 0.5 m resolution orthophoto mosaics. Locations are verified with the original full-resolution (~10 cm resolution) digital aerial photographs 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.

Beach Width Uncertainties

LWM shoreline positions are highly variable due to tides, storms, and waves resulting in positional uncertainties in 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*., (2004); Romine *et al*., (2009); and Fletcher *et al*., (2012), 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:

Equation 2.1. Beach width error.

$$Ev\text{-}t = (Ed^2 + 2*Ep^2 + Etd^2 + Es^2 + Evid^2)^{0.5}$$

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 ($1/Ev\text{-}t^2$). Thus, beach widths with higher uncertainty values have less influence on the trend line. This method is similar to recent studies (Fletcher *et al.*, 2012; Hapke *et al.*, 2010; Romine *et al.*, 2009) – only here, beach width data is used instead of shoreline positions. The annual rate of beach width change (m/yr) is the slope of the trend line (Figure 2.3). 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 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.

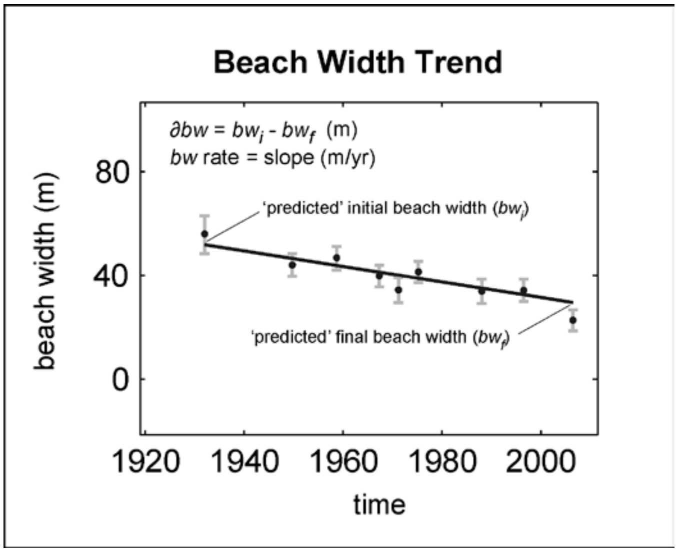

Figure 2.3. Calculating beach width change with weighted least squares (WLS). Regional average beach widths, average beach width changes, and average beach width rates are the average of values from all transects in a beach section. Following Equation 9 of Hapke *et al*. (2010), the uncertainty of regional 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 (at 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/yr, we report rates and uncertainties to the nearest cm/yr (± 0.00 m/yr) 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*. (2012).

Results

Beach width changes were measured at 5332 shore-normal transects spaced roughly 20 m apart, along 107 km of Oahu beaches, with data from 1928 or 1949 to near-present (2005-2008; Table 2.1). Approximately 29 km (27%) of Oahu beaches (or locations of former beaches) are armored. Over 9 km (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 2.2). A majority (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 one-quarter (24%) is backed by coastal armoring. Island-wide, average beach width decreased by 11% ± 4 % (2.6 ± 0.9 m) at a rate of -0.03 ± 0.03 m/yr (Table 2.3). Forty-two percent of beaches widened (19% significantly), overall, with most of the widening (82%) occurring along unarmored beaches.

Table 2.1. 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	2101	42.0	734	14.7	35%	1367	27.3	65%
South	1316	26.3	512	10.2	39%	804	16.1	61%
West	628	12.6	61	1.2	10%	567	11.3	90%
North	1287	25.7	157	3.1	12%	1130	22.6	88%
Total	5332	106.6	1464	29.3	27%	3868	77.4	73%

Table 2.2. 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%	28%	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.

Table 2.3. Average beach width changes for Oahu (all beaches, armored beaches, and unarmored beaches).

All beaches (armored and unarmored)

Region	Initial average beach width (m)[a]	Final average beach width (m)[a]	Average beach width change (m)[a]	(%)[a]	Average beach width change rate (m/yr)[b]
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

Region	Initial average beach width (m)[a]	Final average beach width (m)[a]	Average beach width change (m)[a]	(%)[a]	Average beach width change rate (m/yr)[b]
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

Region	Initial average beach width (m)[a]	Final average beach width (m)[a]	Average beach width change (m)[a]	(%)[a]	Average beach width change rate (m/yr)[b]
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 uncertainty, calculated using effective number of independent observations (n*), see text.

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

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/yr.

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%).

Discussion

Coastal armoring on eroding beaches of Oahu has resulted in beach narrowing and loss as beaches that are prevented from migrating inland 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 additional construction of armoring to protect abutting property, a process that leads to alongshore proliferation of seawalls, and in turn alongshore beach loss. Here we provide analysis of the different Oahu coastlines and present several case studies documenting the effects of coastal armoring on Oahu beaches.

East Oahu

Of the four island regions, the relatively narrow (average ~18 m based on the most recent data) beaches of east Oahu suffered the most damage from beach erosion and coastal armoring (Figure 2.4). 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%), meaning that many of the narrowed beaches fronting armoring become unusable at high tide. Almost 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.

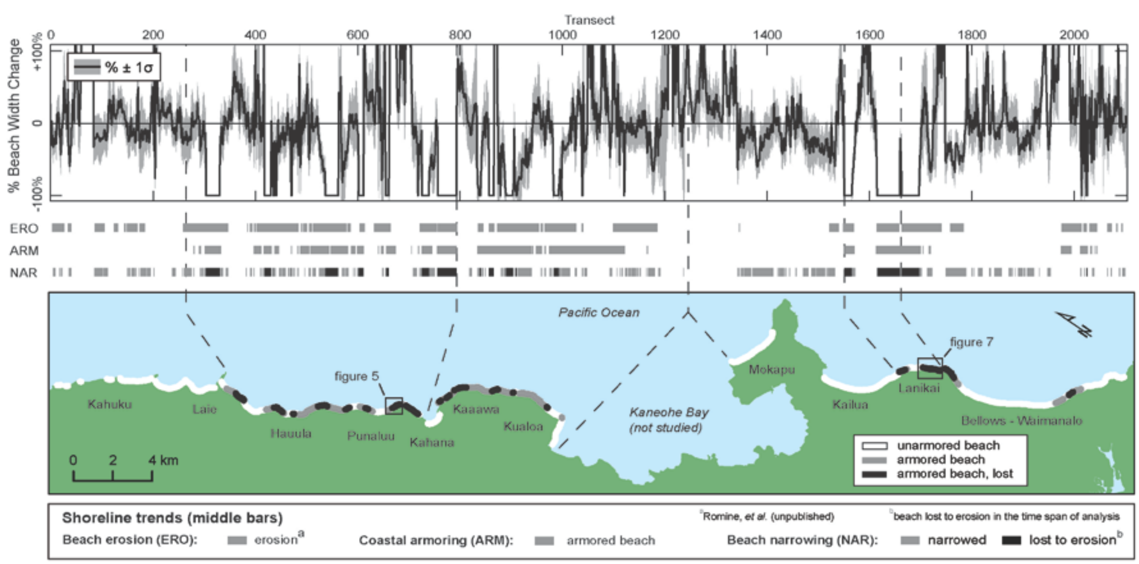

Figure 2.4. East Oahu beach width percent changes (plot, 1928 or 1949 to near present), shoreline trends (middle bars), and coastal armoring (map).

Although 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.*, 2012). 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 (Figure 2.5 and Figure 2.6).

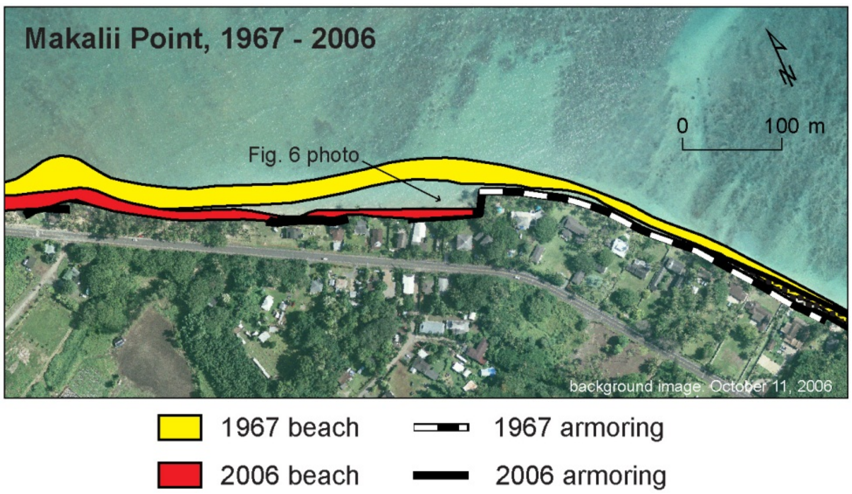

Figure 2.5. Beach loss and flanking erosion at Makalii Point, east Oahu (1967-2006, location shown in Figure 2.4). The unmarked area between the 1967 and 2005 beach was vegetated sand, which has since been lost to erosion.

Figure 2.6. Flanking erosion at Makalii Point (photo location shown in Figure 2.5; photo date, March 15, 2011). Note that beach has been lost fronting the armoring in the background. Accelerated erosion of the beach in the foreground is attributed to flanking effects of the armoring in the background. Though the shoreline is receding, a beach remains along the foreground area in the absence of coastal armoring.

There is strong evidence that coastal armoring has contributed to accelerated flanking erosion at Makalii Point following installation of armoring in the 1960s (Figure 2.6). Stone armoring was installed sometime around 1967. Prior to this, the coastline was accreting at a rate of 0.5 ± 0.4 m/yr. From 1967 until 2005 (i.e., after the armoring was installed), the beach was retreating at a rate of -1.0 ± 0.5 m/yr. Erosion also increased fronting the northern half of the 1967 armoring itself, 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.

At south Lanikai beach a trend of natural accretion transitioned to natural retreat in the late 1970s. Unfortunately, during the time of accretion, houses were built close to the shoreline, so that when the coastline trend reversed, they soon became threatened. 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 (Figure 2.7). 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.

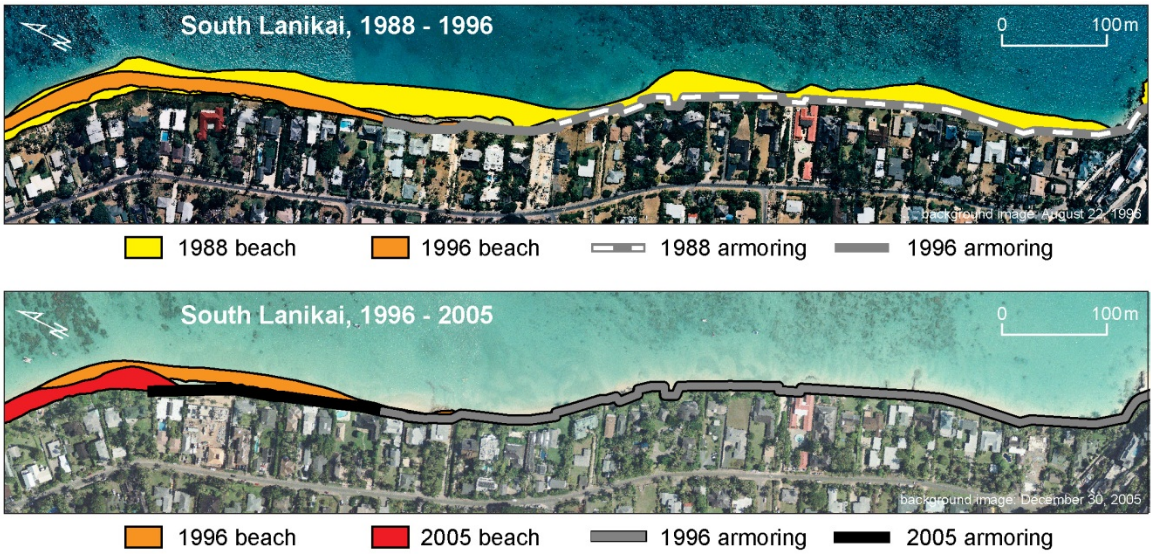

Figure 2.7. Beach loss and flanking erosion at south Lanikai (1988-2005, location shown in Figure 2.4).

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 (3 shorelines, each).

South Oahu

Along south Oahu (Figure 2.8), 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 only calculated for the modern configuration of the shoreline following major engineering efforts to document the modern trend of shoreline change.

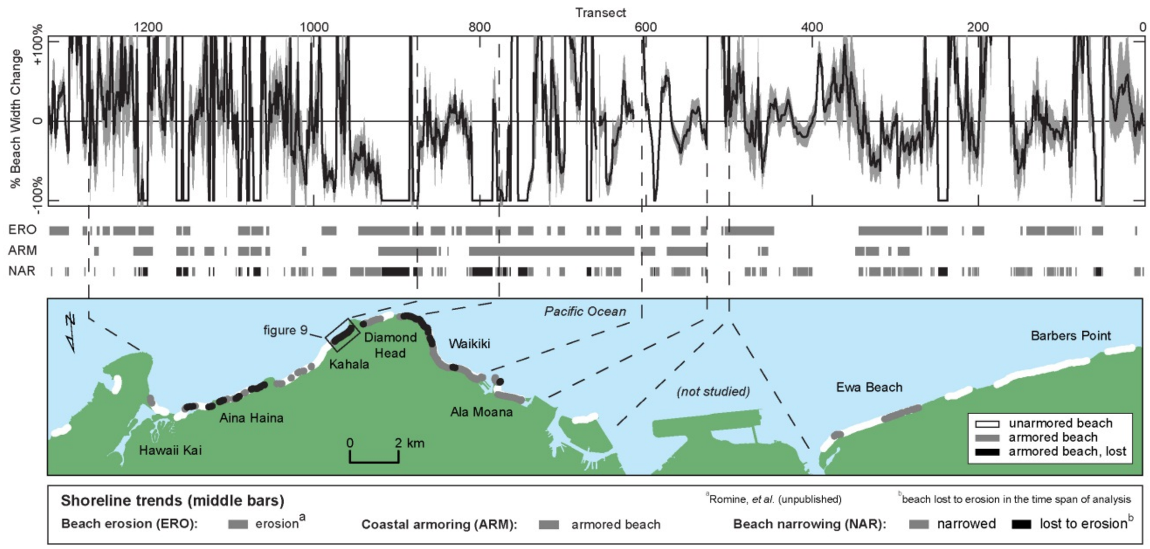

Figure 2.8. South Oahu beach width percent changes (plot, 1928 or 1949 to near present), shoreline trends (middle bars), and coastal armoring (map).

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 whole, roughly half of the beaches are narrowed (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 longshore drift 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 (Figure 2.9). 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 (Figure 2.10). 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.

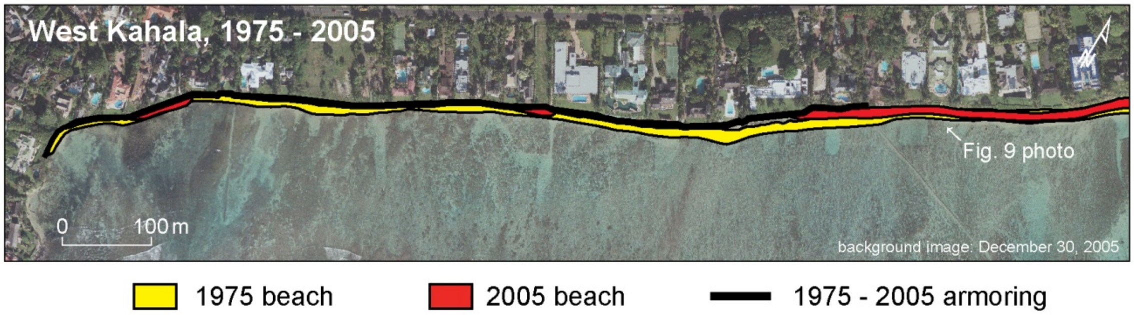

Figure 2.9. Beach loss at Kahala, south Oahu (1975-2005, location shown in Figure 2.8).

Figure 2.10. Flanking erosion and temporary armoring (sand bags), west Kahala Beach (location shown in Figure 2.8; photo date, March 21, 2011).

West Oahu

The west Oahu coast (Figure 2.11) 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 erosional (Fletcher *et al.*, 2012) and coastal armoring has contributed to much of this 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, although beaches narrowed by 9% ± 8% (3.1 ± 2.8 m).

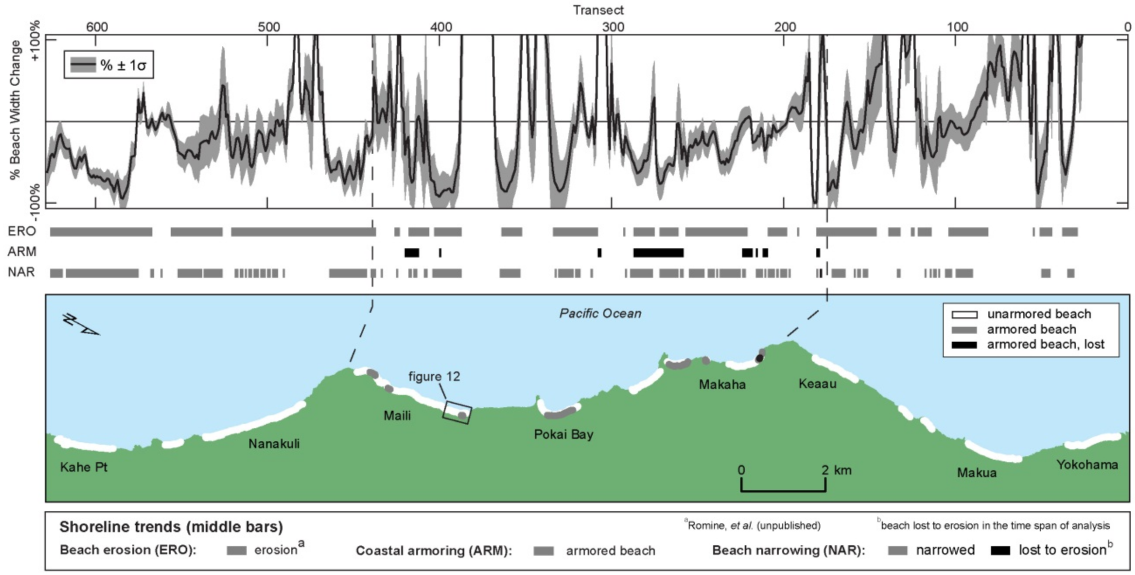

Figure 2.11. West Oahu beach width percent changes (plot, 1928 or 1949 to near present), shoreline trends (middle bars), and coastal armoring (map).

Of the 10% of beaches that are armored along west Oahu, 82% are degraded with 80% narrowed (59% significantly) and 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) (Figure 2.12). 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.

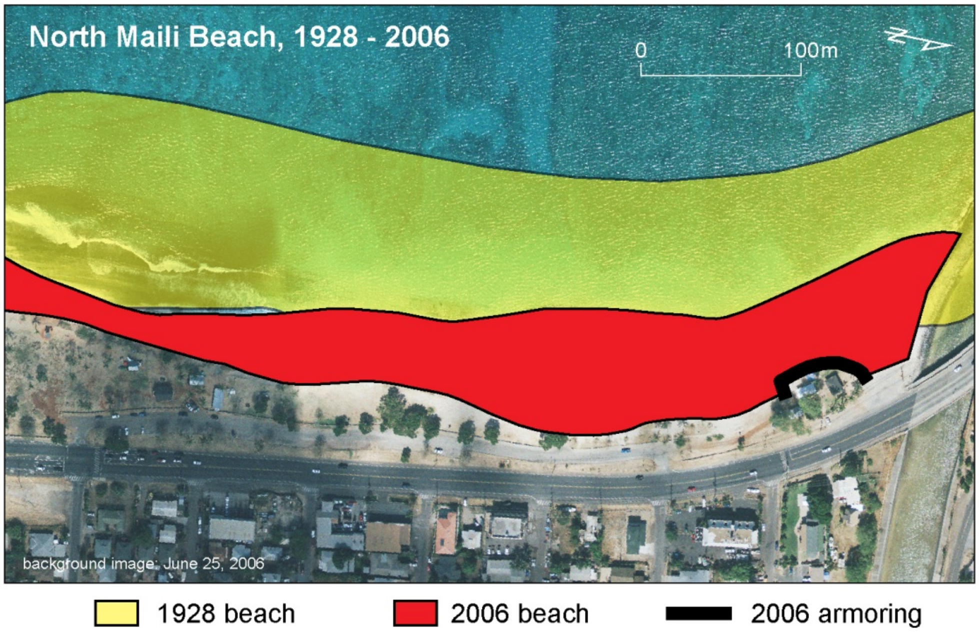

Figure 2.12. In spite of shoreline recession of over 100 m, substantial beach remains along the (mostly) unarmored northern end of Maili Beach (1928-2006, location shown in Figure 2.11).

North Oahu

Over 3 km or 12% of north Oahu beaches are armored (Figure 2.13). 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.

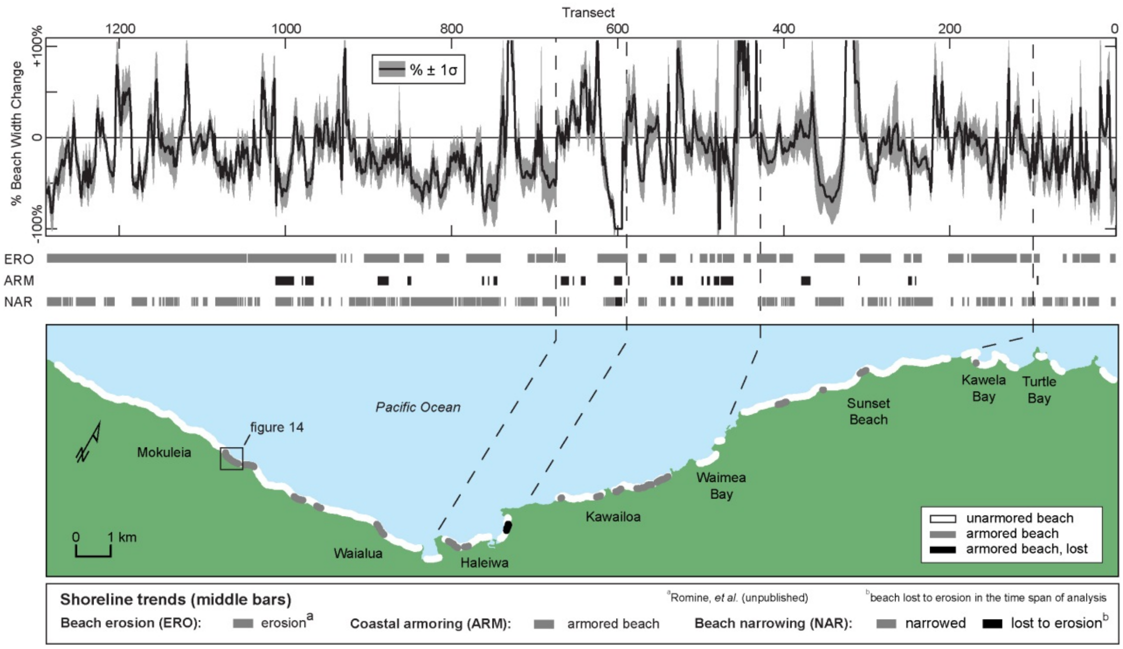

Figure 2.13. North Oahu beach width percent changes (plot, 1928 or 1949 to near present), shoreline trends (middle bars), and coastal armoring (map).

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 (16% ± 6% or 5.3 ± 1.9 m) was less than along armored sections. Never the less, the north coast shows the greatest amount of narrowing of 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 (Figure 2.14). 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 (Figure 2.15).

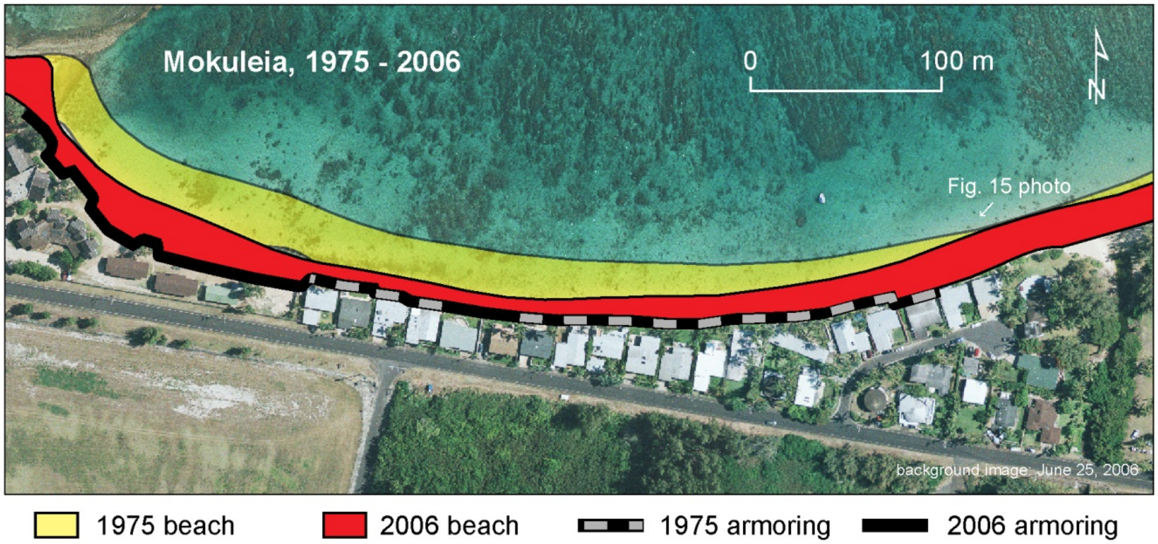

Figure 2.14. Beach narrowing and flanking erosion at Mokuleia, north Oahu, as of June, 2006 (1975-2006, location shown in Figure 2.13).

Figure 2.15. Beach loss at Mokuleia, north Oahu (location shown in Figure 2.14; 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.

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/yr, 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? Analysis of shoreline change rates proceeding 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. 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.*, 2012) 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 what we perceive as 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 locations of beach erosion and narrowing on Oahu. This data may assist coastal resource managers in protecting beaches for future generations through improved management practices, such as promoting erosion management alternatives that preserve public beach resources; including beach nourishment, sand retention structures (*e.g.*, groins), dune rehabilitation, and managed retreat from eroding coasts.

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.

CHAPTER 3. ARE BEACH EROSION RATES AND SEA-LEVEL RISE RELATED IN HAWAII?

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Abstract

The islands of Oahu and Maui (Hawaii Islands) with significantly different rates of sea-level rise (SLR) - approximately 65% higher rate on Maui over the past century - provide a unique setting to investigate possible relations between historical shoreline changes and SLR. Island-wide and regional historical shoreline trends are calculated for the islands using shoreline positions measured from aerial photographs and survey charts. Historical shoreline data are optimized to reduce anthropogenic influences on shoreline change measurements. Shoreline change trends are checked for consistency using two weighted regression methods and by systematic exclusion of coastal regions based on coastal aspect (wave exposure) and coastal geomorphology. Maui experienced the greatest extent of beach erosion over the past century with 78% percent of beaches eroding compared to 52% on Oahu. Maui also had a significantly higher island-wide average shoreline change rate at -0.13 ± 0.05 m/yr compared to Oahu at -0.03 ± 0.03 m/yr (at the 95% Confidence Interval). Differing rates of relative SLR around Oahu and Maui remain as the best explanation for the difference in overall shoreline trends after examining other influences on shoreline change including waves, sediment supply and littoral processes, and anthropogenic changes. The results of this study confirm that historical rates of shoreline change are about two orders of magnitude greater than the rate of SLR in Hawaii, and perhaps elsewhere.

Introduction

It has not been widely documented if historical rates of sea-level rise (SLR) are an important factor in shoreline changes observed on coasts around the world. Zhang *et al.* (2004) document that on the U.S. East Coast rates of coastal erosion are about two orders of magnitude greater than the rate of SLR. However, this has not been confirmed elsewhere and the relative contribution of SLR to regional shoreline change patterns remains debatable. Improved understanding of the influence of SLR on historical shoreline trends will aid in forecasting beach changes with increasing SLR. Globally-averaged sea level rose at about 2 mm/yr over the past century. Studies indicate that the rate of rise is now approximately 3 mm/yr (Church and White, 2006; Merrifield *et al.*, 2009) and may accelerate over coming decades (Vermeer and Rahmstorf, 2009).

Few datasets embody detailed multi-decadal to century-scale historical shoreline positions on sandy beaches of wave-dominated coasts, with relations to SLR. List *et al.* (1997) examined beach profile response to accelerated SLR on barrier coastal islands of Louisiana since the 1880s, concluding that relative SLR is not the primary factor forcing the region's shoreline change. Leatherman *et al.* (2000) investigated the relationship between long-term (century-scale) shoreline change and varying rates of SLR along the U.S. east coast, finding a correlation between regionally-averaged shoreline change rates and localized rates of relative SLR. Brunel and Sabatier (2009) examined historical shoreline changes on the French Mediterranean coast in comparison to theoretical predictions of shoreline change due to SLR and found that sea-level rise is one of, but not the major, factor influencing shoreline retreat on wave-dominated coasts in that region. Webb and Kench (2010) described the response of central Pacific atoll islands to SLR using historical aerial photography over a 19 to 61 yr period and concluded that reef islands are dynamic landforms that undergo a range of physical adjustments to changing SLR and other boundary conditions.

Recently completed shoreline change studies for the islands of Kauai, Oahu, and Maui, Hawaii (Fletcher *et al.*, 2012; Romine and Fletcher, 2012b) indicate substantially higher erosion rates for the beaches of Maui compared to Oahu and Kauai. Tide gauge data from the individual islands indicates higher rates of localized SLR around Maui compared to Oahu and Kauai (approximately 65% higher, http://tidesandcurrents.noaa.gov/). Coincidentally, the relative rate of SLR around Kauai and Oahu (1 to 2 mm/yr) is similar to the global-average rate of SLR over the past century, while the relative rate of SLR around Maui is similar to the present rate of global-average SLR (2 to 3 mm/yr). Oahu and Maui Islands provide a unique opportunity to investigate shoreline trends between two adjacent islands in similar physical settings and with similar geomorphologic history (including anthropogenic changes), but with significantly differing rates of relative SLR. SLR is only one of many factors driving shoreline change. Other drivers of shoreline change that must be considered carefully include sediment availability, anthropogenic changes, littoral processes, wave conditions, and coastal and nearshore geomorphology. Because of these multiple factors, establishing a direct causative link between historical shoreline change and SLR remains a challenge.

Using historical shoreline measurements from Fletcher *et al*. (2012), augmented with new data for the north and west coast of Maui, we provide further investigation of trends for the islands of Oahu and Maui to determine if there are significant differences between the islands and if SLR is an important factor in observed shoreline changes. We control for influences other than SLR to determine if SLR remains as the best explanation for observed changes. We also utilize a series of consistency checks to determine if results are significant and to eliminate other possible explanations.

Regional Setting

The Hawaii archipelago, including the islands of Oahu and Maui (Figures 3.1 and 3.2), is comprised of eight volcanic islands in the tropics of the central north Pacific. The islands are fringed by carbonate reef platforms built from a complicated patchwork of fossil Pleistocene reefs during interglacial sea-level high stands of the past 500 kyr or so (Fletcher *et al.*, 2008).

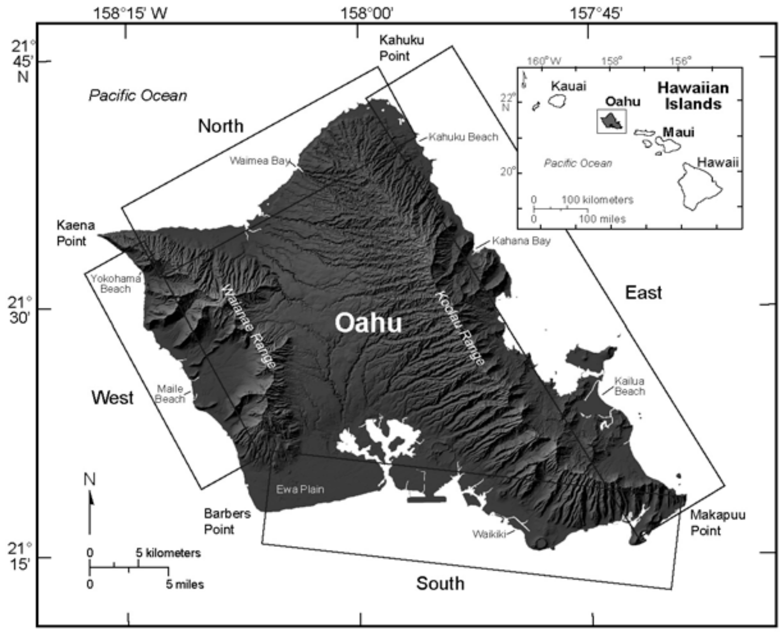

Figure 3.1. Oahu island, Hawaii, showing four beach study regions: north, east, south, and west.

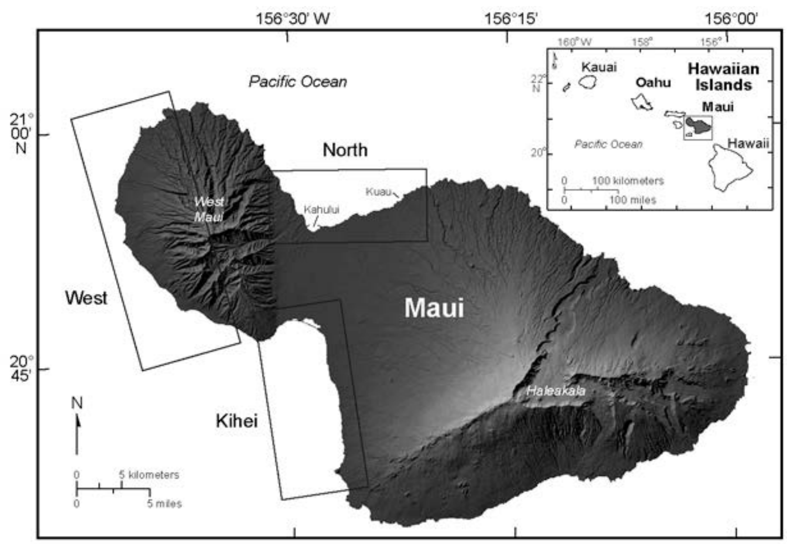

Figure 3.2. Maui island, Hawaii, showing three beach study regions: north, Kihei, and west.

Most Hawaii beaches are comprised of a mix of calcareous and volcaniclastic sediment eroded from the nearshore reef and adjacent watersheds (Harney and Fletcher, 2003). Sediment storage on the inner reef platform in paleo-karst depressions and channels plays an important role in beach sediment supply (Bochicchio *et al.*, 2009). Sediment may be lost from beaches by abrasion, longshore transport, transport offshore by wave-driven currents, landward transport by onshore winds, and human activities. Hawaii beaches, like most carbonate beaches, are generally narrower than siliciclastic beaches due to limited available sediment from the nearshore reef and coastal plain.

While similar to global averages for SLR over the 20th century (~2 mm/yr; (Church and White, 2006)), localized rates of SLR vary along the Hawaii island chain. SLR rates were similar for Kauai and Oahu (Kauai: 1.53 ± 0.59 mm/yr and 1.50 ± 0.25 mm/yr, resp.) and higher around Maui (2.32 ± 0.53 mm/yr) (Figure 3.3, http://tidesandcurrents.noaa.gov). SLR rates for Kauai and Maui where not significantly different at the 95% Confidence Interval (95% CI) likely due to shorter time series for these tide stations compared to Oahu (~60 years for Kauai and Maui vs. ~100 years for Oahu). Fletcher *et al.* (2012) and Romine and Fletcher (2012b) found that island and regional shoreline trends for Kauai have high uncertainties likely due to high seasonal variability on some Kauai beaches, especially west Kauai. Kauai is excluded from this study where we attempt to relate SLR and shoreline trends due to the lack of a significant difference between SLR trends for Kauai and Maui and high uncertainty with island-wide shoreline trends for Kauai.

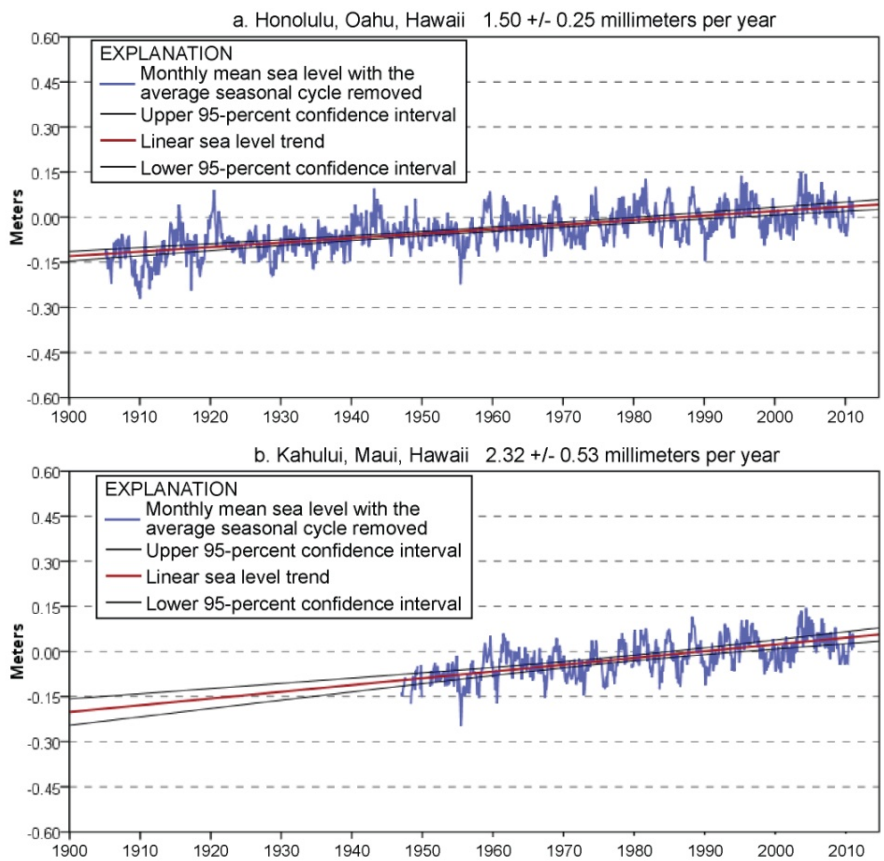

Figure 3.3. Mean sea-level trends at a. Honolulu, Oahu 1905-2011; and b. Kahului, Maui 1947-2011 (http://tidesandcurrents.noaa.gov).

The variation in long-term SLR rates along the Hawaii archipelago may be related to variations in lithospheric flexure with distance from actively growing Hawaii Island (Moore, 1987) and/or decadal variations in upper ocean water masses (Caccamise *et al.*, 2005). Acceleration of local SLR has not been detected in Hawaii tide gauge records, likely related to climatological variability (*e.g.*, tradewinds; Merrifield and Maltrud (2011)).

Hawaii islands have two dominant wave "seasons." In winter, large North Pacific swells affect north and west exposed shorelines while relatively calm conditions prevail along sheltered southern shores (Vitousek and Fletcher, 2008). In summer, southern hemisphere swells affect exposed southern and western shorelines and calm conditions are typical on north shores. At any time of year, extended periods of high tradewind waves from the east to northeast can cause short-term beach erosion and damage to coastal property on windward shores. Winter storm fronts and occasional hurricanes bring onshore "Kona" (westerly and southerly) winds and damaging waves to typically leeward shores.

Materials and Methods

We utilize historical shoreline measurements for Oahu and Maui from Fletcher *et al*. (2012), augmented with new data for the west Maui and north Maui regions, to calculate historical shoreline trends. Below, we provide a summary of the methods for mapping historical shorelines and measuring shoreline change, and refer the reader to Fletcher *et al.* (2012) for more detail.

Mapping Historical Shorelines

Shoreline positions were manually digitized using photogrammetric and geographic information system (GIS) software from orthorectified aerial photo mosaics and topographic and hydrographic survey charts (T-sheets and H-sheets) provided by the National Ocean Service (NOS) (http://oceanservice.noaa.gov/). Following Fletcher *et al*. (2004) and Romine *et al*. (2009) the low water mark position (LWM) or "beach toe" was mapped as a shoreline proxy. Roughly one historical shoreline is available per decade over the past century. Only survey-quality high-resolution (≤ 0.5 m pixel) vertical aerial photographs with sufficient tonal quality and contrast to resolve shoreline features were used. T-sheets and H-sheets extend the time-span of historical shoreline data beyond available air photos (National Academy of Sciences, 1990). Survey charts are available as early as 1910 for Oahu and 1899 for Maui.

Positional Uncertainties

Up to seven sources of positional uncertainty were combined to arrive at a total positional uncertainty for each historical shoreline (U_t, ± 3.2 m to 18.8 m, average 6.8 m).

Positional uncertainty was calculated as the root mean square (RMS) of: image rectification (±0.0 to 13.5 m, average 1.9 m), digitization of shoreline position (±0.3 to 8.9 m, average 1.8 m), image pixel size (0.5 m for air photos, 1 to 3 m for charts), seasonal shoreline change (waves) (±1.3 to 14.6 m, average 4.3 m), and tidal fluctuations (±2.5 to 3.1 m, average 3.4 m). Two additional sources of uncertainty are included for T-sheet and H-sheet shorelines: original field survey and plotting of the High Water Mark (HWM) shoreline (±5.1 m) (Shalowitz, 1964) and conversion of the HWM shoreline to a LWM position (±1.2 m to 13.7 m, average 4.3 m). Shoreline positional uncertainties are applied as weights when calculating annual shoreline change rates with weighted least-squares regression (see: section 3.3, below).

Calculating Shoreline Change

Shoreline movement through time was measured in a GIS at shore-perpendicular transects spaced approximately 20 m along the shore (Figure 3.4). Annual rates of change are calculated from the time series of shoreline positions at each transect using two methods of weighted least-squares (WLS) regression as a consistency check on shoreline trends: single-transect (ST) and Eigen Beaches (EX) (Frazer *et al.*, 2009; Genz *et al.*, 2009).

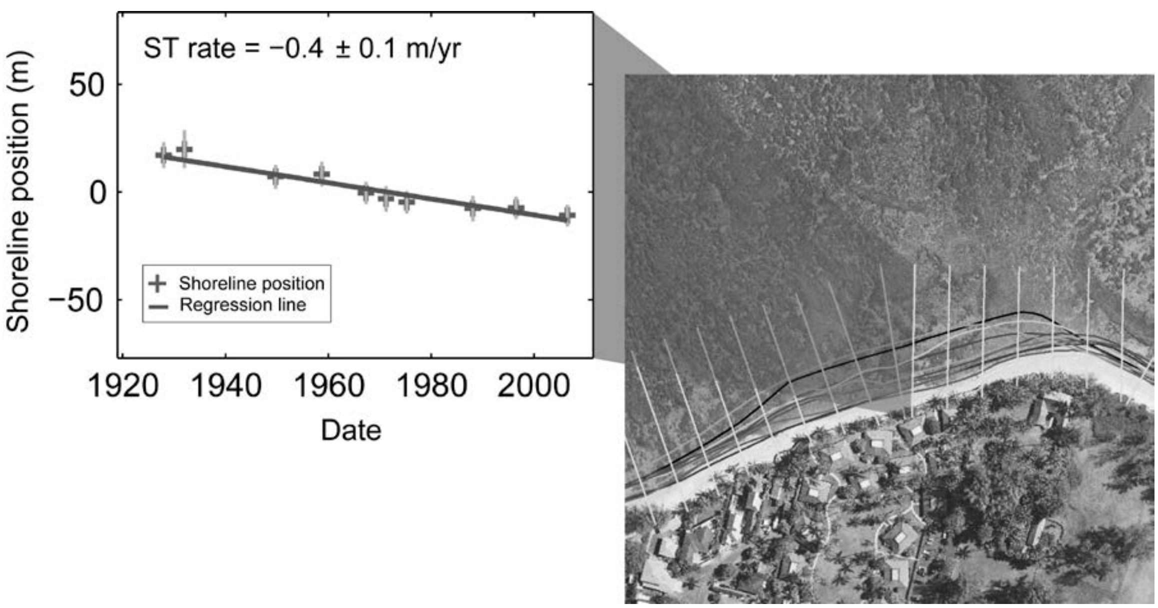

Figure 3.4. Calculating shoreline change rate from historical shoreline positions with the single-transect (ST) method (using weighted least squares, WLS). Historical shoreline positions and transect locations are shown on a portion of a recent aerial photograph.

For some beaches historical shoreline trends may have been influenced by human activities. Examples include removal of beach sand by mining operations along north Maui and Oahu beaches in the first half of the 20th century and beach nourishment projects at Waikiki, south Oahu. For this study, we calculate shoreline changes only for the period following major shoreline alterations in an effort to control for human impacts on shoreline changes and identify the natural components of beach change. Where the beach has been completely lost to erosion (e.g., replaced by a seawall), we calculate shoreline change rates up to and including the first shoreline where the beach was lost.

The ST method is the most commonly utilized method for calculating shoreline change rates (*e.g.*, USGS National Assessment of Shoreline Change Project). We utilize WLS, with a weight equal to the inverse of the shoreline positional uncertainty ($1/U_t$) (*e.g.*, (Romine *et al.*, 2009) and (Hapke *et al.*, 2010)). Shorelines with high uncertainty (*e.g*., T-sheets) will thereby have less influence on the fit of the trend line.

We utilize the EX rate calculation method as a consistency check for rates calculated using ST. The EX method (Frazer *et al.*, 2009; Genz *et al.*, 2009) uses shoreline data from all transects on a beach to calculate a rate at each transect, recognizing that shoreline change among neighboring transects is related. A linear combination of eigenvectors - principle components calculated from the shoreline position data - are used as basis functions for modeling alongshore rate variation. Information criterion (Akaike Information Criterion, corrected for small samples with an unbiased estimator (Mcquarrie and Tsai, 1998)) serves to identify the optimal number of basis functions required to produce the most parsimonious (best fit, least parameters) model.

Uncertainties of the ST rates are the RMS error (misfit) of the WLS regression line. The EX method as utilized in Frazer *et al.* (2009) and Genz *et al.* (2009) may underestimate uncertainties with shoreline change rates. The Frazer *et al*. and Genz *et al*. studies effectively treat the Eigen vectors as independent of the shoreline data when estimating uncertainties when, in fact, the Eigen vectors are calculated from the shoreline data. For this study, uncertainties with EX rates are estimated using a non-parametric bootstrap method (Efron, 1981; Efron and Tibshirani, 1993) to re-sample the data with replacement 500 times, producing a probability distribution from which an uncertainty can be calculated. This method produces individual rate uncertainties similar in magnitude to those from the ST method. Rate uncertainties are reported at the 95% confidence interval (95% CI).

Shoreline change rates and uncertainties are reported from the ST method to remain consistent with other recent studies. The EX method is used only as a consistency check for the ST trends. A rate from ST (or EX) is considered statistically “significant” if the absolute value of the rate is greater than the uncertainty (95% CI); or, in other words, the ± rate uncertainty band does not overlap 0 m/yr.

Regionally-averaged rates are the average of rates from all (*n*) transects on beaches within a region. Uncertainty of a regionally-averaged rate may be estimated in a number of ways. Simply averaging the uncertainty values from all transects overestimates the uncertainty of a regionally-averaged rate because this method assumes there is no advantage in having multiple closely-spaced transects (Hapke *et al.*, 2010). The root sum of squares of uncertainty values from all transects likely underestimates the uncertainty of a regionally-averaged rate (*e.g.*, the method used in Fletcher *et al*., 2012) as the results are typically on the order of ± 1 cm - often an order of magnitude smaller than an associated average rate.

Uncertainties of regionally-averaged shoreline change rates are estimated following Hapke *et al*. (2010) utilizing an adaptation of an autocorrelation method from Bayley and Hammersley (1946). Results from this method typically fall between the extremes of uncertainty estimates calculated using an average (likely an overestimate) and root sum of squares (likely an underestimate) of rate uncertainties. Hapke *et al.* (2010) use an effective number of independent observations (n^*) calculated from a spatially-lagged autocorrelation (ρ) of the individual rate uncertainties in the following equation from Bayley and Hammersley (1946) (Equation 3.1).

Equation 3.1.

$$\frac{1}{n^*} = \frac{1}{n} + \frac{2}{n^2}\sum_{j=1}^{n-1}(n-j)\rho(j\tau)$$

The uncertainty of a regional average rate, U_{R^*}, is estimated following Hapke *et al*. (2010) with Equation 3.2, where U_R is the mean of the individual uncertainties:

Equation 3.2.

$$U_{R^*} = \frac{1}{\sqrt{n^*}}U_R$$

A shoreline trend is identified as erosion or accretion at transects where the ST and EX method agree on the general direction (sign) of the shoreline trend (Table 3.1). A trend of erosion or accretion is considered "significant" at transects where the ST and EX methods agree on the direction of the shoreline trend and rates from both methods are statistically significant (95% CI). A trend is "undetermined" if the ST and EX models do not agree on the direction of shoreline change or if insufficient number (< 2) of historical shorelines are available.

Table 3.1. Shoreline trend criteria.

Shoreline Trend Criteria	
Erosion	ST and EX methods indicate erosion or beach was lost to erosion
Significant Erosion	ST and EX methods indicate erosion and rates are statistically significant at 95% CI.
Accretion	ST and EX methods indicate accretion
Significant Accretion	ST and EX methods indicate accretion and rates are statistically significant at 95% CI.
Undetermined	ST and EX methods do not agree on direction (sign) of trend or insufficient data.
Beach Lost	No dry beach is visible in the most recent aerial photograph(s)

The total percent of erosional beach for a region is the sum of percent of transects where the ST and EX methods agree on a trend of erosion plus the percent of transects where the beach has been completely lost to erosion. The total percent of accretional beach for a region is the percent of transects where the ST and EX methods agree on a trend of accretion.

Results

To examine a possible relationship between island shoreline trends and localized rates of SLR, this study provides a re-analysis of the Oahu and Maui shoreline trends from Fletcher *et al.* (2012) augmented with new data from north and west Maui, and with further consideration of anthropogenic changes to beaches, and using consistency checks of shoreline trends,. Shoreline changes are analyzed along 107 km of beach (5332 transects) on Oahu island. Shoreline changes are analyzed along 67 km of beach (3329 transects) on Maui island.

Beaches on Oahu were slightly erosional to stable with an overall average shoreline change rate of -0.03 ± 0.03 m/yr (median rate = -0.03 m/yr), whereas Maui beaches were significantly more erosional with an average rate -0.13 ± 0.05 m/yr (median rate = -0.12 m/yr) (Table 3.2). Percentages of eroding and accreting beaches on the two islands, checked for consistency using the ST and EX rate methods, also indicate that Maui beaches are substantially more erosional. Fifty-two percent of beaches on Oahu were erosional over the past century (including 8% completely lost to erosion, Table 3.3), whereas 78% of beaches on Maui were erosional (including 12% completely lost to erosion). On Oahu, 39% of the beaches were accretional and 9% of beaches had an undetermined trend. On Maui, 17% of beaches were accretional and 5% of beaches had an undetermined trend on Maui.

Table 3.2. Shoreline trends for the beaches of Oahu and Maui corrected for anthropogenic beach changes and with proportions of eroding, accreting, or undermined beach checked for consistency using the ST and EX rate calculation methods.

	Shoreline change rate[a] (m/yr)		Proportion of beach eroding, accreting, or undetermined (% of beach[b] (% significant[c]))		
Region	Mean	Median	Eroding	Accreting	Undetermined[d]
Oahu	-0.03 ± 0.03	-0.03	52% (23%)	39% (12%)	9%
Maui	-0.13 ± 0.05	-0.12	78% (31%)	17% (3%)	5%

[a] Mean and median of all shoreline rates in a region. Negative is erosion.
[b] Percent of beach where ST and EX rate calculation methods agree on trend plus percent of beach lost.
[c] Percent of beach where ST and EX rate calculation methods both find significant rates at 95% CI.
[d] Percent of beach where ST and EX rate calculation methods disagree on trend.

Table 3.3. Kilometers and percent of island beaches completely lost to erosion over the time period of analysis for Oahu and Maui islands.

	Beach Lost	
Region	km	% of beach
Oahu	8.6	8%
Maui	7.9	12%

Shoreline change is analyzed on a regional basis to explore possible relations between shoreline change and shoreline aspect (wave exposure). No particular side of the two islands (e.g., the north regions) stands-out as more erosional than the others (Table 3.4), thus eliminating unique wave exposure as a causative factor behind island-wide trends.

Table 3.4. Shoreline trends for the distinct coastal regions of Oahu and Maui corrected for anthropogenic beach changes and with proportions of eroding, accreting, or undermined beach checked for consistency using the ST and EX rate calculation methods.

		Shoreline change rate[a] (m/yr)		Proportion of beach eroding, accreting, or undetermined (% of beach[b] (% significant[c]))		
Region		Mean	Median	Eroding	Accreting	Undetermined[d]
Oahu	North	-0.09 ± 0.06	-0.06	63% (23%)	25% (4%)	12%
	East	0.04 ± 0.04	0.01	46% (22%)	47% (19%)	7%
	South	-0.05 ± 0.02	-0.01	48% (24%)	45% (13%)	7%
	West	-0.09 ± 0.11	-0.11	62% (21%)	30% (5%)	9%
Maui	North	-0.15 ± 0.14	-0.13	73% (31%)	20% (2%)	7%
	Kihei	-0.13 ± 0.07	-0.13	82% (21%)	15% (5%)	2%
	West	-0.12 ± 0.02	-0.11	78% (36%)	17% (2%)	5%

[a] Mean and median of all shoreline rates in a region. Negative is erosion.
[b] Percent of beach where ST and EX rate calculation methods agree on trend plus percent of beach lost.
[c] Percent of beach where ST and EX rate calculation methods both find significant rates at 95% CI.
[d] Percent of beach where ST and EX rate calculation methods disagree on trend.

Looking at the four distinct coastal regions of Oahu (north, east, south, and west) and three distinct coastal regions of Maui (north, Kihei, and west), we find that all three coastal regions of Maui are substantially more erosional than the four coastal regions on Oahu (Table 3.5). In spite of different exposure to seasonal waves, north, Kihei, and west Maui had similar shoreline trends over the past century with regionally-averaged shoreline change rates between -0.12 (west Maui) and -0.15 m/yr (north Maui) (median rates between -0.11 and -0.13 m/yr). Between 73% (north Maui) and 82% (Kihei Maui) of beaches in the three coastal regions of Maui were erosional (including 10% to 14% of beach lost to erosion, Table 3.5). This is in contrast to the four Oahu coastal regions where regionally-averaged shoreline change rates varied from 0.04 m/yr (east) to -0.09

my/yr (north and west). Between 46% (east Oahu) and 63% (north Oahu) of beaches on Oahu were erosional including between 0% (west) and 13% of beaches completely lost to erosion.

Table 3.5. Kilometers and percent of beaches completely lost to erosion over the time period of analysis for the coastal regions of Oahu and Maui.

		Beach Lost	
Region		km	% of beach
Oahu	North	0.2	1%
	East	5.5	13%
	South	2.9	11%
	West	0.0	0%
Maui	North	1.6	10%
	Kihei	2.1	11%
	West	4.2	14%

Unlike Maui, one region of Oahu stands-out as substantially less erosional than the other island regions. The east region of Oahu is the least erosional of the four Oahu regions with a regionally-averaged shoreline change rate of 0.04 ± 0.04 m/yr (stable to accreting) (median rate = 0.01 m/yr) and roughly the same percentage of beach eroding as accreting (46% and 47%, respectively). No particular region of Maui stands-out as the most erosional.

Discussion

The islands of Maui and Oahu have similar physical settings and a history of anthropogenic coastal change. However, with significantly differing relative rates of SLR, they provide a unique opportunity to investigate if SLR may be an important driver of shoreline change in Hawaii and elsewhere. Historical shoreline data used in this study provides the only opportunity to observe shoreline changes over the modern period of sea-level rise.

Given the number of other factors driving beach processes, it remains a challenge to conclusively relate observed shoreline changes solely to SLR. Shoreline change is typically a result of multiple physical drivers including impacts to sediment availability, wave conditions, sediment supply, as well as coastal and nearshore geomorphology. To investigate the role of SLR on Oahu and Maui, we control for the influence of other physical drivers on historical trends.

Coastal structures including seawalls, groins, breakwalls, and other features designed to protect coastal property and retain beach sand are found in all coastal regions of Oahu and Maui. Coastal armoring in Hawaii has, historically, been a common response to preexisting beach erosion (Fletcher *et al.*, 1997; Romine and Fletcher, 2012a). In many locations, beaches have been completely lost to erosion fronting coastal armoring as the water line recedes toward a fixed position. To control for the influence of artificially-fixed shorelines (which would tend to indicate no shoreline change), we calculate trends up to and including the first shoreline after a beach has been lost.

Coastal armoring structures may have localized impacts on sediment availability. For example, groins typically lead to impoundment (accretion) of sand on the updrift sides and erosion on downdrift sides. Seawalls lead to “flanking” erosion of adjacent beaches in Hawaii (Romine and Fletcher, 2012a). However, the localized effects of these structures, such as accretion and erosion on either side of a groin, should “average-out” when calculating island-wide and regional shoreline trends.

Beach sand mining and beach nourishment were common on some Oahu and Maui beaches over the past century. Sand mining is documented on Oahu at Waimea Bay, Kahuku, Maile, and Yokohama (Fletcher *et al.*, 2011; Hwang, 1981). On Maui, sand mining was extensive along north shore beaches between Kahului and Paia (Fletcher *et al.*, 2012; Makai Ocean Engineering and Sea Engineering, 1991). Visual inspection of historical shoreline positions shows rapid shoreline recession during the time period of sand mining in these regions with trends typically slowing (or in some cases reversing) following the termination of mining after it was made illegal in the late 1960s. To limit the influence of human-induced shoreline change due to sand mining, we calculate shoreline change rates for these areas using only the historical shorelines post-dating the end of sand mining. Beach nourishment projects were common over the past century along the highly engineered shoreline at Waikiki, south Oahu. Similar to areas of sand mining, we calculate shoreline trends in these areas using shorelines following the most recent beach fill to capture a better representation of natural shoreline trends at these beaches.

Located in the central north Pacific, Hawaii beaches are exposed to large waves year-round from varying directions. Waves are the primary driver of sediment transport in Hawaii (Fletcher *et al*., 2012; and references therein). In an island setting, overall shoreline trends are less likely to be influenced by variability in wave energy from one particular source region (wave direction). This is in comparison to mainland settings where beaches throughout a large region are typically exposed to only one or two predominant wave directions and, therefore, shoreline trends are more likely to be affected (biased) by changes in wave climate than in an island setting. Calculating overall shoreline trends for an island environment with exposure to waves from all directions provides an opportunity to control for the influence of variability in wave climate from any particular direction.

No particular region (coastal aspect, wave exposure) of Maui stands out as the most erosional. On Oahu the east region is noticeably less erosional than the other regions. None of the Maui study regions have a similar east-facing coastal aspect. Perhaps the unique coastal aspect of east Oahu is responsible, in part, for the differences in overall shoreline trends between Oahu and Maui? Recalculating the overall island trend for Oahu with the east Oahu region removed still indicates that Maui beaches are substantially more erosional than Oahu. Removing the east Oahu region from the Oahu island data we find that Oahu remains less erosional than Maui with an average rate for Oahu beaches of -0.07 ± 0.04 m/yr (median rate -0.05 m/yr) and 57% of beaches eroding. This is in comparison to the island-wide results for Maui (including all coastal regions) with an average rate of -0.13 ± 0.05 m/yr (median rate -0.12 m/yr) and 78% of beaches eroding.

Sediment supply is undoubtedly an important driver of localized shoreline changes in Hawaii. However, we find no evidence that beach sediment processes are substantially different between Oahu and Maui on an overall island-wide scale. Beach sand in Hawaii is originally derived from erosion of carbonate sources from nearshore reefs (Calhoun *et al.*, 2002; Harney and Fletcher, 2003). Nearshore sediment bodies are an important part of the active beach sand sharing system (Bochicchio *et al.*, 2009). Beaches on Oahu and Maui are generally fronted by fringing reefs with similar geomorphologic history - constructed from a patchwork of carbonate units accreted and eroded over recent glacial cycles (Fletcher *et al.*, 2008). Similar sand reservoirs have been identified on both islands, typically contained in submerged karst features and channels in reefs (Bochicchio *et al.*, 2009; Conger *et al.*, 2009; U.S. Army Corps of Engineers Honolulu District, 2009; U.S. Army Corps of Engineers Honolulu District, 2011). Beaches in Hawaii often represent the leading edge of a sand-rich coastal plain with erosion of coastal plain and dune deposits nourishing beaches (Fletcher *et al.*, 2012). The beaches of both Oahu and Maui are generally backed by similar carbonate sand-rich coastal plains and low-lying coastal dune systems (Sherrod *et al.*, 2007).

There are two notable differences between the coastal geomorphology of the shoreline study areas on Oahu and Maui. The older, more eroded volcanic edifice of Oahu (relative to Maui) features several deep bays created from submerged stream valleys, which are not found in the beach study regions on Maui. Two bays at Kahana and Kailua, east Oahu contain crescent-shaped beaches that are accreting at high annual rates of roughly half a meter per year (Fletcher *et al.*, 2012). Shoreline trends are recalculated for Oahu after removing the shoreline data for the two deep bays to examine whether these unique accreting beaches have a substantial effect on the results for Oahu. After removing Kahana and Kailua from the Oahu data, we find that Oahu remains less erosional than Maui with an average rate of -0.05 ± 0.03 m/yr (median rate -0.04 m/yr) and 54% of beaches eroding. Emerged fossil reefs and eolianite formations dating to the Eemian interglacial (Muhs and Szabo, 1994) are a common feature on Oahu coasts, forming many of the headlands and underlying much of the coastal plain. But, Eemian deposits have not been identified on Maui. Headlands on Maui are typically composed of basalt. The emerged limestone formations do not appear to be an important contributor of beach sands on Oahu, though they do support numerous pocket beaches. In general, areas on Oahu with the most extensive limestone outcrops, including Kahuku, the Ewa Plain, and much of west Oahu are not characterized by particularly large accreting beaches.

Zhang *et al*. (2004) document that on the U.S. East Coast rates of coastal erosion are about two orders of magnitude greater than the rate of SLR. We find that island-wide rates of shoreline change in Hawaii (centimeters to tens of centimeters per year) are one to two orders of magnitude greater than rates of SLR (millimeters per year).

Conclusions

The islands of Oahu and Maui, with significantly different rates of relative SLR (roughly 65% higher on Maui) over the past century, provide a unique setting to investigate shoreline changes and possible relations to SLR. Results of island-wide historical trends, optimized to limit anthropogenic influences and checked for consistency using two methods of weighted least squares regression (ST and EX method), indicate that Maui beaches are significantly more erosional than beaches on Oahu. Seventy-eight percent of beaches on Maui eroded over the past century with an overall (island-wide) average shoreline change rate of -0.13 ± 0.05 m/yr, while 52% of Oahu beaches eroded with an overall average shoreline change rate of -0.03 ± 0.03 m/yr.

All three coastal regions of Maui, distinguished by unique coastal aspect (wave exposure), are substantially more erosional than the four coastal regions of Oahu. No particular region of the two islands (e.g., the north regions) stands out as the most erosional. The east region of Oahu is the only region of the two islands that has an overall stable to accretional trend. Recalculation of Oahu trends with the east region omitted still indicates that Oahu beaches are less erosional than Maui beaches. Therefore, we conclude that overall island trends are not influenced by shoreline changes or unique wave exposure of one or more island regions.

Littoral processes and sediment supply (including human impacts) are undoubtedly an important influence on localized shoreline changes. However, we find no evidence that littoral processes and sediment availability are substantially different between Oahu and Maui in an overall, island-wide sense. Beaches on both islands are fronted by similar fringing reef platforms supporting nearshore sediment bodies contained in depressions and channels. Beaches on both islands are typically backed by carbonate sand-rich coastal plains. As the older of the two volcanic islands and having undergone more fluvial erosion, Oahu features two deep bays (submerged stream valleys) with accreting beaches unlike found in the Maui beach study regions. Removing the historical shoreline data for the accreting beaches on Oahu at Kahana and Kailua bays we find that Oahu remains less erosional than Maui. Prominent emerged fossil reef formations on the Oahu coast have not been identified on Maui. These formations typically do not support accretional beaches on Oahu and, therefore, are not likely to be an important contributor to differing shoreline trends between the islands.

Differing rates of relative SLR around Oahu and Maui remain as the best explanation for the difference in overall shoreline trends between the islands after examining other influences on shoreline change including waves, sediment supply and littoral processes, coastal geomorphology, and human impacts. The results of this study show that historical rates of SLR in Hawaii, and perhaps elsewhere, are an important factor in historical shoreline change.

CHAPTER 4. SPATIAL PATTERNS OF SHORELINE CHANGE ALONG NORTHEAST OAHU, HAWAII, RELATED TO LOCALIZED CHANGES IN LATE-HOLOCENE SEA LEVEL

Bradley M. Romine, Charles H. Fletcher, L. Neil Frazer, Tiffany R. Anderson

Abstract

Patterns of historical shoreline change along the northeast coast and other regions of the island of Oahu, Hawaii are examined for spatial relationships to coastal geomorphology and temporal relationships to late-Holocene sea-level changes. Headland and embayed sections of sinuous beaches are located, in part, using polynomial models fit to historical shoreline positions to identify changes in curvature (concavity) along the coast. Using statistical analysis of historical shoreline trends, we show that higher rates of erosion occur along headland beaches relative to embayed beaches. Headland beaches along northeast Oahu are erosional along 88% of their length with an average rate of -0.12 ± 0.03 m/yr. In contrast, 55% of embayed beaches in this region have a trend of accretion with an average rate of 0.03 ± 0.05 m/yr (stable to accreting). This trend of headland beach erosion is also documented at other locations on Oahu. Headland beach erosion is likely driven by wave refraction across the nearshore reef platform. Multiple lines of geologic evidence indicate that headlands, comprised largely of unconsolidated carbonate beach and eolian sediments, were formed during late-Holocene sea-level fall. We infer that a change from headland beach accretion to the observed modern pattern of headland beach erosion is related to the initiation of sea-level rise around Oahu following an earlier period of falling sea level over the past few thousand years. Our results have implications for improved understanding and forecasting of shoreline change with continued sea-level rise, specifically, that sea-level rise may result in 'preferential' erosion of certain coastal geomorphic features and even, accretion of beaches down-drift from highly erosional sections of beach. Thus, even under conditions of sea-level rise, beach response will depend largely on littoral sediment transport.

Introduction

Beach erosion and shoreline recession are certain to increase on a regional to global scale with increasing sea-level rise in coming decades (Rahmstorf *et al.*, 2012). However, coastal scientists are limited in their ability to predict shoreline change on the scale of individual beaches and littoral cells because shoreline change can be dominated by localized sediment availability and longshore drift, both of which can act partially or totally independent of sea-level change. Understanding of how beaches will change in a future dominated by sea-level rise requires improved understanding of the processes governing historical and modern shoreline changes in response to sea level and other factors.

In addition to an overall trend of beach erosion, shoreline change on the Hawaiian Island of Oahu is characterized by high alongshore variability with cells of erosion and accretion having lengths typically of 100s of m along continuous beaches (Fletcher *et al.*, 2012; Romine and Fletcher, 2012b). For this study we utilize results of historical shoreline change rates from Fletcher *et al*. (2012) and Romine *et al*. (2012) to analyze spatial patterns of beach response in relation to coastal geomorphology and late Holocene sea-level changes.

Physical Setting

The island of Oahu, Hawaii is located in the tropics of the central north Pacific (Figure 4.1). The coast is fringed by a carbonate reef platform comprised of a patchwork assemblage of fossil Pleistocene reefs from interglacial high sea-level stands of the past several hundred thousand years (Fletcher *et al.*, 2008) .

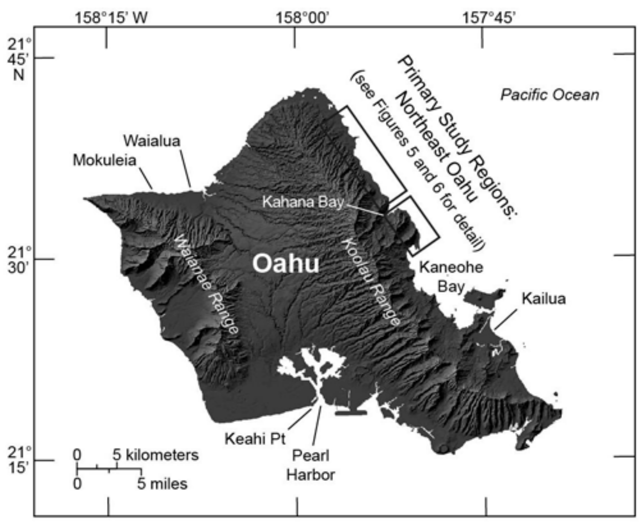

Figure 4.1. Map of study locations on the island of Oahu, Hawaii. The black boxes outline the primary study regions along the northeast Oahu coast.

Hawaii beaches are typically composed of calcareous sand derived from nearshore reefs with a smaller fraction of volcanoclastic sediment eroded from inland watersheds (Harney and Fletcher, 2003). Beaches are typically backed by low-lying coastal plains comprised of a mixture of beach deposits and dunes, lithified carbonate deposits (including fossil reef, beachrock, and eolianite), and alluvium. In many locations, beaches are simply the eroded leading edge of a sand-rich coastal plain (Fletcher *et al.*, 2012) (Figure 4.2). Hawaii is located in the microtidal zone (tide range ≤ 1 m) of the central North Pacific and is exposed to seasonal large waves year-round from the north and south Pacific. As a result, wave-generated currents are the primary drivers of sediment transport (Norcross *et al.*, 2003).

Figure 4.2. Low-lying sand-rich coastal plain and beach at Punaluu, east Oahu. Note the embayed beach fronting the channel in the nearshore reef (left) and headland beach fronting the shallow nearshore reef (right) (Photograph by Andrew D. Short, University of Sydney).

Multiple lines of evidence, including stranded beach deposits, wave-cut notches, and geophysical models indicate that sea level stood roughly 2 m higher than present approximately 3500 yr B.P. around Hawaii (the 'Kapapa high stand'), (Fletcher and Jones, 1996; Grossman and Fletcher, 1998; Stearns, 1978) (Figure 4.3) and other "far-field" sites in the Pacific (Clark *et al.*, 1978). Studies of the lithology and geochronology of coastal plain and beach deposits on Oahu and neighboring Kauai indicate a late-Holocene age (~5000 years BP – near present) for most carbonate sediments with few samples of sand indicating a modern origin (Calhoun *et al.*, 2002; Harney and Fletcher, 2003; Harney *et al.*, 2000).

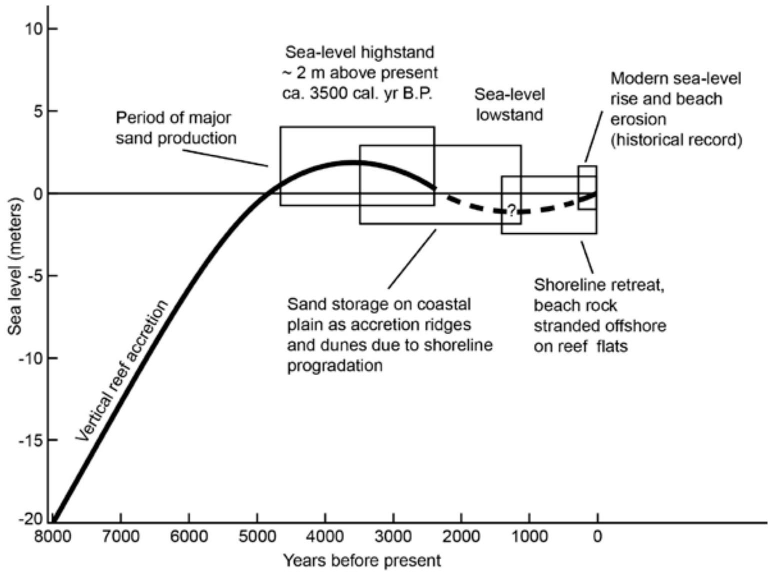

Figure 4.3. Conceptual Holocene sea-level curve for Oahu (adapted from Fletcher *et al*. (2008)) indicating sea level ~2 m higher than present ca. 3500 years BP, followed by a period of falling sea level prior to the initiation of modern sea-level rise observed in tide gauge records.

Modern tide gauge records indicate sea-level rise of 1.5 ± 0.25 mm/yr on Oahu over the past century (http://tidesandcurrents.noaa.gov/). We assume that modern sea-level rise was preceded by a period of falling sea level following the Kapapa high stand. The Kapapa high stand was a period of invigorated marine carbonate sediment production and deposition (Calhoun and Fletcher, 1996; Harney and Fletcher, 2003; Harney *et al.*, 2000) due to increased accommodation space for reef growth and flooding of the upper coastal plain around Oahu. Sea-level fall following the Kapapa stand resulted in an overall trend of shoreline progradation as former beach ridges were stranded on the coastal plain developing into coastal dunes and cuspate sandy headlands that shape much of the modern-day geomorphology of the low-lying sandy coastal plains.

Several kilometer-long sinuous beaches are found along the east and north coasts of Oahu characterized by a sequence of headland beaches and embayed beaches. Embayed beaches are typically aligned with watersheds including paleo-stream channels incised in the shallow reef platform. Cuspate headland beaches are typically aligned with the shallowest portion of the fringing reef platform between channels (drowned interfluves). Because of their pronounced seaward position, the accretion strand plain morphology, and the late-Holocene age of the sediments, we assume that the unlithified sand-rich headland beaches formed during the period of late-Holocene sea-level fall. Embayed beaches formed simultaneously, though in a more landward position due to their location in the paleo-stream system.

Modern sea-level rise is likely an important driver of the overall (island-wide average) trend of beach erosion (shoreline recession) observed on Oahu (Fletcher *et al.*, 2012;

Romine and Fletcher, 2012b). The relative role of sediment availability, human influences, and sea-level change are not well understood, nor is it clear how coastal geomorphology influences these factors. To refine understanding of these relationships, we focus primarily on beaches of northeast Oahu, which is characterized by a low-lying coastal plain composed of carbonate beach deposits and alluvium from upland valleys. We also investigate shoreline trends at other select areas on Oahu to determine if the observed trends constitute island-wide processes.

The shorelines in our study areas are characterized by sandy beach, with occasional outcrops of beachrock. Our primary study area on northeast Oahu faces directly into the predominant tradewinds and is exposed to large refracted North Pacific swells in winter. A wide fringing reef, with reef crest typically located a few hundred meters offshore, and incised by sand filled paleo-channels and paleo-karst features, moderates open ocean wave energy reaching the shoreline. The beaches of northeast Oahu are typically narrow (10-30 m wide) compared to most continental settings. Numerous streams cross the coastal plain from inland watersheds, often emptying at the landward 'head' of a reef channel carved by the stream during past lower sea levels.

Materials and Methods

Preliminary inspection of shoreline trends along the northeast coast of Oahu and elsewhere from Fletcher *et al.* (2012) suggests an overall pattern of higher annual rates of erosion at headland beaches and comparatively lower rates of change at embayed beaches. In this study we examine spatial relationships among these patterns of shoreline change, the coastal geomorphology, and temporal relations with late-Holocene sea-level trends.

Historical Shorelines

Historical shoreline positions and rates of change over the past century are adapted from previous work. Below we provide a summary of the methods used to measure historical shoreline change and refer the reader to Fletcher *et al*. (2012) and Romine and Fletcher (2012b) for more detail.

Historical shoreline changes were calculated from shoreline positions mapped using photogrammetric and geographic information system (GIS) software from orthorectified aerial photographs and survey charts over the period 1927 - 2008. Changes in shoreline position were measured at regularly-spaced transects (20 m) along the shore. A total positional uncertainty is calculated for each historical shoreline based on studies of short-term (hourly to intra-annual) shoreline variability and errors inherent in the mapping processes (Fletcher *et al.*, 2004). Shoreline change rates were calculated using weighted least squares (WLS) regression in the Digital Shoreline Analysis System (DSAS, (Thieler *et al.*, 2009)) with shoreline positional uncertainties applied as the weights so that historical shorelines with higher uncertainty have less influence on the shoreline trend.

Geomorphology

Sections of headland and embayed beaches are identified through visual interpretation of historical shoreline positions in a GIS supported by numerical modeling of shoreline curvature (concavity). Shoreline curvature is modeled using Legendre Polynomials fit to historical shoreline locations (positional measurements). The polynomial shoreline model provides a continuous mathematical function that may be differentiated to locate inflection points (changes in concavity), identifying boundaries between headland (convex seaward) beaches and embayed (concave seaward) beaches (Figure 4.4).

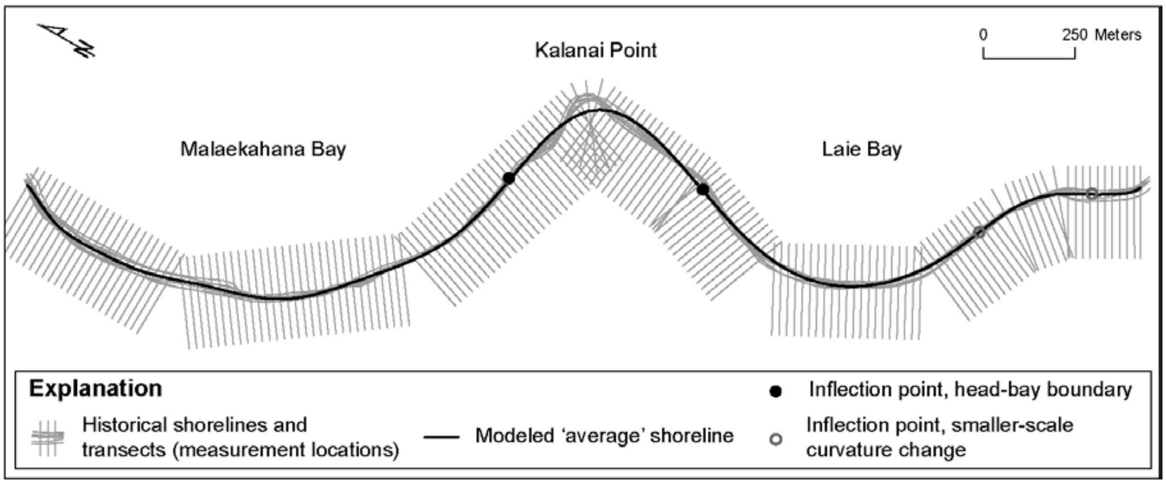

Figure 4.4. To delineate headland beaches and embayed beaches, a polynomial shoreline model (Legendre Polynomial) is fit to historical shoreline positions with least squares regression. Boundaries between headlands and bays are located by differentiation of the shoreline model to identify inflection points (changes in curvature) between headland (convex seaward) beach sections and embayed (concave seaward) beach sections (example shown from Malaekahana and Laie Bays, northeast Oahu).

Multiple overlapping shoreline models are calculated along a coast, each with length no greater than three headlands and two embayments. Limiting the individual models to such shorter sections of coast allows for an optimal fit to the historic shorelines while limiting model complexity (few model parameters, N). Shoreline models with increasing complexity (increasing N, up to a maximum N=20) are calculated until the highest parameter model is identified that indicates only one inflection point between each headland and bay (head-bay boundary). Inflection points (headland/embayment boundaries) are utilized only from the central portion of each individual shoreline model to avoid any 'end effects' that result in poor fit of model shorelines near their extremities.

Statistical Analysis

Once headland and embayed beaches are identified, a comparison between shoreline change trends is conducted for the different geomorphic segments. Mean and median shoreline change rates, as well as percent of beach with an erosion or accretion trend are calculated. A mean rate for a section of beach is the average of all shoreline change rates from transects within that section. The uncertainty of an average rate is calculated following Hapke *et al.* (2010) using an effective number of independent uncertainty observations (n^*) calculated from a spatially-lagged autocorrelation of the rate uncertainties at individual transects along the shore. Uncertainties with individual and average shoreline change rates are reported at the 95% confidence interval (95% CI). A shoreline change rate is considered statistically significant if the absolute value of the rate is greater than the uncertainty (at the 95% CI).

Meta-analysis of shoreline trends provides further examination of the difference between shoreline changes at headland and embayed beaches. The study area is divided into individual headland/bay pairs, each containing one half of a headland beach and the adjoining half of embayed beach. The rates and uncertainties for each pair are scaled (normalized) from -1 to 1. Similarly, the alongshore distance (transect locations) is scaled between -1 and 1. After scaling each headland/embayment pair individually, the data are combined in a single plot, and an overall correlation between shoreline changes at headlands and embayments is examined.

Inspection of shoreline change rates along northeast Oahu suggests reduced erosion along sections of beach fronting sand-filled channels cut into the fringing reef. Location of sand deposits along much of northeast Oahu is provided by Conger *et al.* (2009) and, where sand field data is not available, through visual identification using aerial photographs and LiDAR bathymetric models. Transects fronting the landward 'head' of sand filled channels are visually identified to allow comparison of shoreline trends with beaches that are not fronting sand-filled channels.

We also identify spatial patterns of shoreline change along northeast Oahu that indicate longshore transport and deposition of sediment. Transects at headland and embayed beaches are divided into north and south subsections. Similar to the statistical comparison of shoreline change within bays and headlands, we calculate average and median shoreline change rates, as well as percent of transects that eroded or accreted, within the north or south subsections. The goal of this analysis is to identify patterns of change related to specific geomorphic regimes.

Results

Patterns of historical shoreline change over the past ~80 years (1927-2006) are analyzed along roughly 19 km of beach along northeast Oahu from Malaekahana through Kaaawa (Figures 4.5 and 4.6). Shoreline trends for the accreting beach at Kahana are not included in the overall results because the beach at the back of a deep bay is not connected along the shoreline to beaches to the north and south. Nine segments (9.3 km) of shoreline are identified as headland beaches and ten segments (9.6 km) of shoreline are identified as embayed beaches. Of particular note, the shoreline at Lanioloa has characteristics of both a headland and embayed beach and may be classified as a partially-embayed headland. For this study, we identify Laniloa as a headland beach to be consistent with the spatial scale of other headlands identified in the study region and because earlier historical shorelines at this location displayed stronger headland-like morphology.

Overall, beaches within the northeast Oahu study region had an erosional trend over the past century with an average rate of -0.04 ± 0.04 m/yr (median rate -0.05 m/yr) (Table 4.1). The majority (66%) of transects had a trend of erosion and approximately 3.4 km of beach was completely lost to erosion in the past century – nearly all of it (98%) fronting coastal armoring (e.g. seawalls).

Table 4.1. Shoreline change trends for all beaches, embayed beaches, and headland beaches within the study region of northeast Oahu, Hawaii (Malaekahana through Kaaawa).

		Shoreline Change Rates (m/yr)		Proportion of Beach Eroding and Accreting (% (% significant @ CI95))	
Region		Mean	Median	Eroding	Accreting
Malaekahana - Laie	Heads	-0.03 ± 0.08	-0.03	67% (0%)	33% (0%)
	Bays	0.10 ± 0.13	0.08	31% (0%)	69% (36%)
	All	0.07 ± 0.09	0.02	38% (0%)	62% (29%)
Laniloa - Makalii Point	Heads	-0.13 ± 0.05	-0.12	89% (30%)	11% (3%)
	Bays	0.01 ± 0.06	0.00	48% (18%)	52% (7%)
	All	-0.07 ± 0.06	-0.07	70% (25%)	30% (5%)
Kaaawa	Heads	-0.11 ± 0.04	-0.10	94% (25%)	6% (0%)
	Bays	-0.04 ± 0.03	-0.03	67% (1%)	33% (0%)
	All	-0.08 ± 0.03	-0.08	83% (15%)	17% (0%)
Total	Heads	-0.12 ± 0.03	-0.11	88% (26%)	12% (2%)
	Bays	0.03 ± 0.05	0.00	45% (10%)	55% (14%)
	All	-0.04 ± 0.04	-0.05	66% (18%)	34% (8%)

Over the past century headland beaches were substantially more erosional than embayed beaches. Headland beaches eroded at an average rate of -0.12 ± 0.03 m/yr (median rate -0.11 m/yr) while embayed beaches were stable to accretional, overall, with an average rate of 0.03 ± 0.05 m/yr (median rate 0.00 m/yr). The majority (88%) of transects along headland beaches had a trend of erosion, whereas the majority (55%) of transects along embayed beaches had a trend of accretion. Of eroding transects, 65% were located along headlands and 35% were located within embayments. Of accreting transects, 83% were located within embayments and 17% were located along headlands.

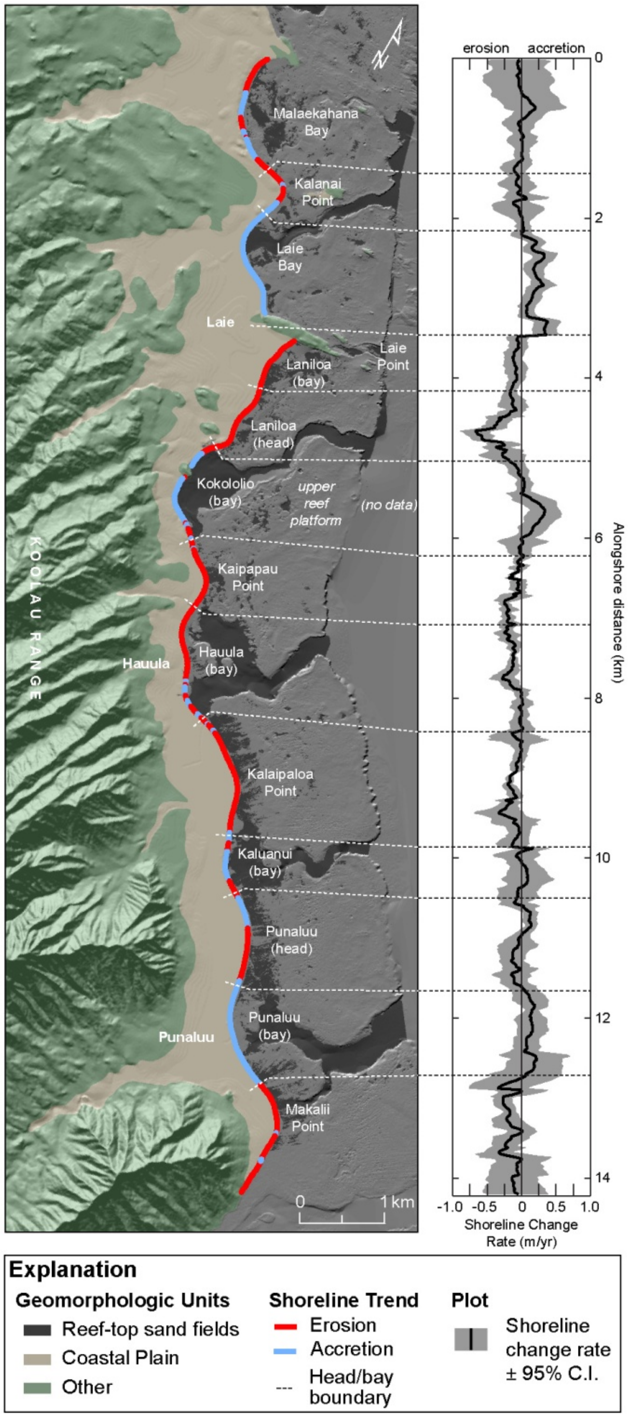

Figure 4.5. Shoreline change trends for the beaches of Malaekahana through Makalii Point, northeast Oahu, Hawaii (see Figure 4.1 for location). Historical shoreline trends (plot, color-coded alongshore bars) indicate greater erosion along headland beaches than along beaches within embayments. The surficial geology of the low-lying coastal plain (tan) is primarily Holocene carbonate beach deposits and alluvium (Sherrod *et al.*, 2007). Locations of reef-top sand deposits are adapted from Conger (2009) and visual interpretation of aerial photographs and bathymetric models.

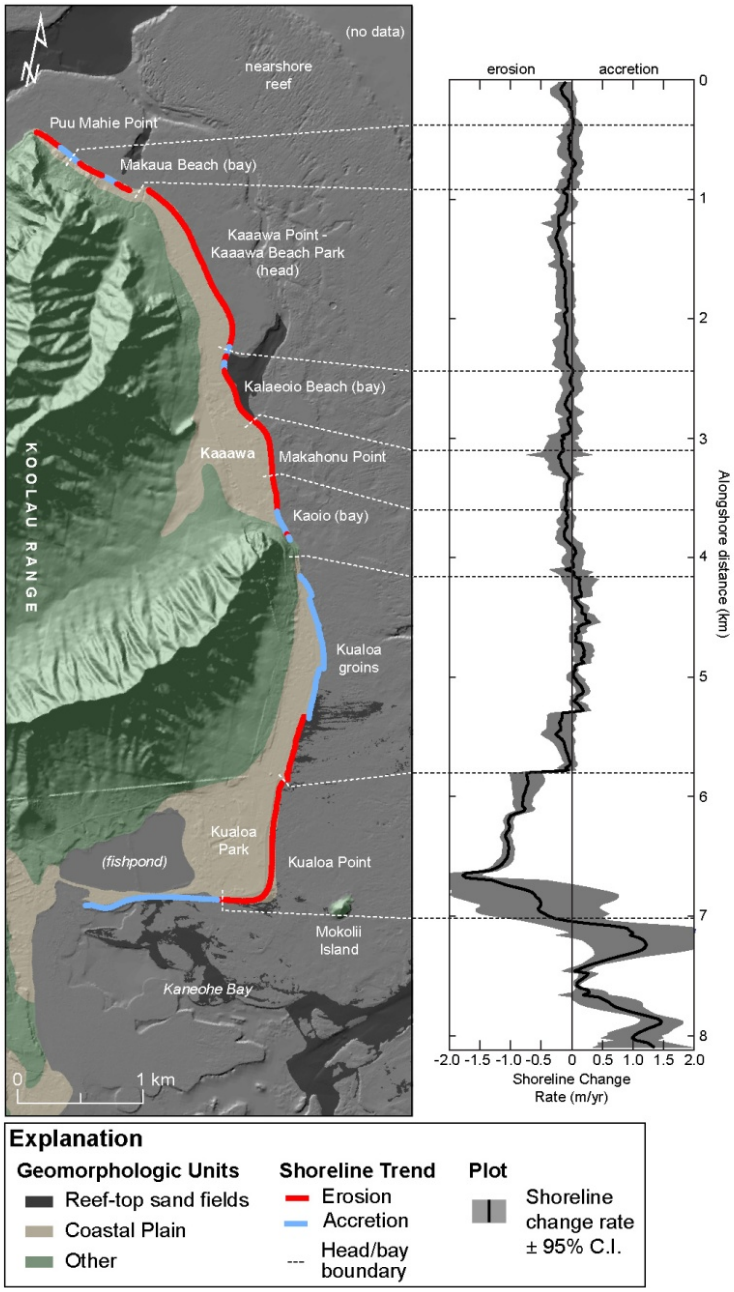

Figure 4.6. Shoreline change trends for the beaches of Kaaawa through Kualoa Point, northeast Oahu, Hawaii (see Figure 4.1 for location). Historical shoreline trends (plot, color-coded alongshore bars) indicate greater erosion along headland beaches than along beaches within embayments. Note: shoreline trends for Kualoa (‘Kualoa groins’ through Kualoa Point) are not included in overall shoreline change analysis for northeast Oahu (Table 4.1). Accretion within the Kualoa groins is due largely to efforts to stabilize the shoreline with engineered structures. The surficial geology of the low-lying coastal plain (tan) is primarily Holocene carbonate beach deposits and alluvium (Sherrod *et al.*, 2007). Locations of reef-top sand deposits are adapted from Conger (2009) and visual interpretation of aerial photographs and bathymetric models.

Looking at sections of contiguous (uninterrupted) sandy shoreline, the beach between Malaekahana and Laie Point (Figure 4.5) had an overall trend of accretion with an average rate 0.07 ± 0.09 m/yr (median 0.02 m/yr) and 62% of the beach had a trend of accretion. There was a notable, though not statistically significant, difference in the shoreline trends along the embayed beaches of Malaekahana and Laie in comparison to the headland beach at Kalanai Point. The average rate of all transects within the embayed portions of this region indicated an overall trend of accretion with an average rate of 0.10 ± 0.13 m/yr and median rate of 0.08 m/yr. The majority of transects (69%) within the two bays had a trend of accretion. In contrast, the headland beach at Kalanai Point had an overall trend of erosion with an average rate -0.03 ± 0.08 m/yr and median rate -0.03 m/yr. The majority (67%) of transects along the headland beach indicated a trend of erosion.

The beach from Laniloa through Makalii Point (Figure 4.5) was erosional over the past century with an average rate of -0.07 ± 0.06 m/yr (median rate of -0.07 m/yr) and the majority of transects (70%) showed a trend of erosion. Looking at headland and embayed beaches along this shoreline, we find an overall trend of erosion at headland beaches and stable to accreting shorelines at embayed beaches. Average shoreline change rates were significantly more erosional at headland beaches (average rate -0.13 ± 0.05 m/yr, median rate -0.12 m/yr) than at embayed of beaches (average rate 0.01 ± 0.06 m/y, median rate 0.00 m/yr). Percents of beach that eroded or accreted also indicated a predominance of erosion at headland beaches, and stable to accretional beaches within embayments. Eighty-nine percent of transects on headland beaches had a trend of erosion, while slightly more than half (52%) of transects within embayed sections of beach had a trend of accretion.

The beaches fronting Kaaawa (from Puu Mahie Point to Kaoio Bay, Figure 4.6) were erosional, with an average rate of -0.08 ± 0.03 m/yr and median rate of -0.08 m/yr. Eighty-three percent of transects had a trend of erosion and only 17% of transects had a trend of accretion. Although, erosion is the overall trend, there is a substantial difference between the rate of erosion along headland and embayed beaches. The average rate for embayed beaches, -0.04 ± 0.03 m/yr, was less erosional than for headland beaches at -0.11 ± 0.04 m/yr. Additional evidence of differing shoreline change trends along embayed and headland beaches at Kaaawa is provided by the median rates (embayed beaches: -0.03 m/yr, headland beaches: -0.10 m/yr) and percents of beach that eroded (embayed beaches: 67% eroded, and headland beaches: 94% eroded).

Statistical analysis of shoreline change trends between headland and embayed beaches is supported by the results of a meta-analysis (Figure 4.7). The study area shoreline is divided into separate embayment-headland beach segments prior to scaling distances and rates from -1 to 1. Plotting all the scaled embayment-headland pairs together indicates a correlation between headland beach erosion and embayed beach accretion for northeast Oahu (correlation coefficient = 0.58).

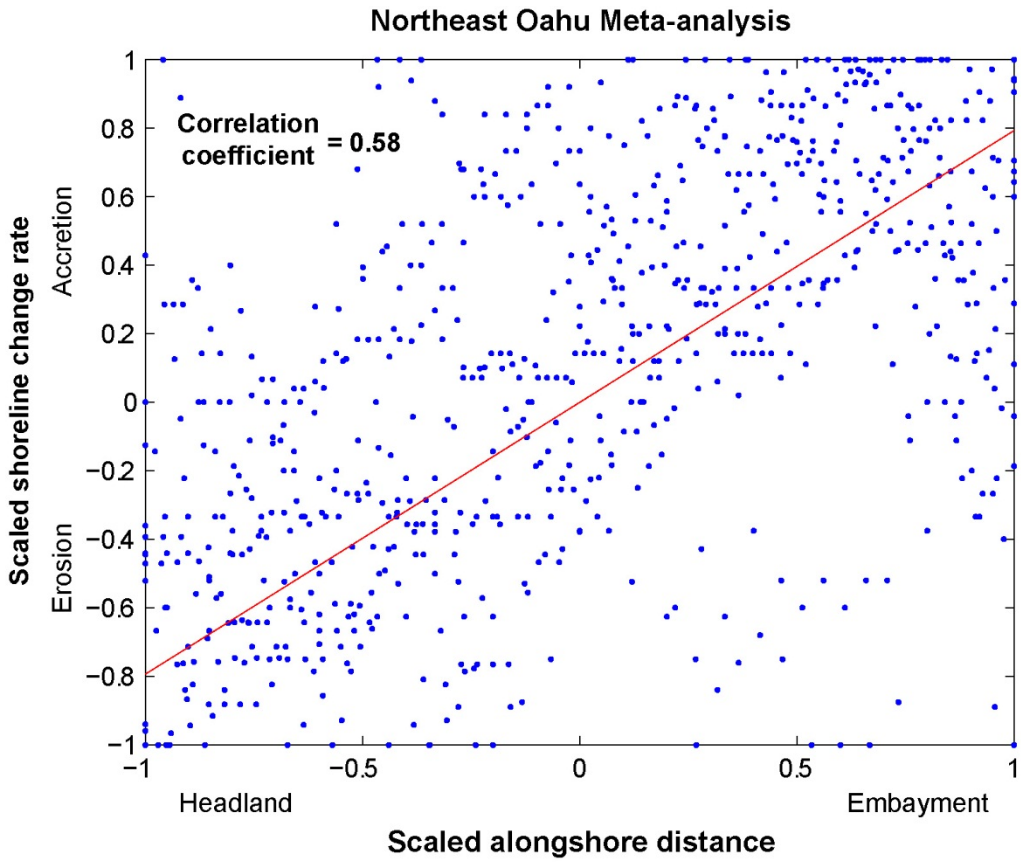

Figure 4.7. Meta-analysis of scaled shoreline change rates and alongshore distance for embayed and headland beach segments of northeast Oahu indicates a correlation between headland erosion and embayment accretion (correlation coefficient = 0.58, regression line shown in red).

Additional evidence of preferential erosion along headland beaches is found between Mokuleia and Waialua on the north coast of Oahu (see Figure 4.1 for location) and elsewhere on Oahu, indicating that this is an island-wide process. Overall, the sinuous beach between Mokuleia and Wailua is characterized by a trend of erosion with an average shoreline change rate of -0.12 ± 0.04 m/yr (median rate -0.11 m/yr). Analysis of erosion trends at headland and embayed portions of the beach indicates higher rates and a greater prevalence of erosion along headland sections; though, the difference in average rates is not statistically distinguishable at the 95% confidence interval. The average rate at headland portions of the beach was -0.15 ± 0.04 m/yr while the average rate at embayed portions of the beach was -0.09 ± 0.04 m/yr. Eighty-seven percent of headland portions of the beach was erosional while 80% of embayed portions of the beach was erosional. While the average rates and percentages of eroding beach supported increased headland erosion for this region, meta-analysis failed to produce a distinct correlation.

Rapid erosion of headland beaches is also documented in other regions of Oahu. At Kualoa Point, at the southern end of the Kaaawa-Kualoa region, the shoreline has retreated at rates as high as -1.8 ± 0.3 m/yr over the past century – among the highest rates calculated for a Hawaiian beach (Fletcher *et al*., 2012) (Figure 4.8). Eroded sand from Kualoa Point is transported inside Kaneohe Bay and has formed an accretional beach cusp of similar scale and at similar rates to the erosion observed at the point (accretion rates as high as 1.5 ± 0.4 m/yr).

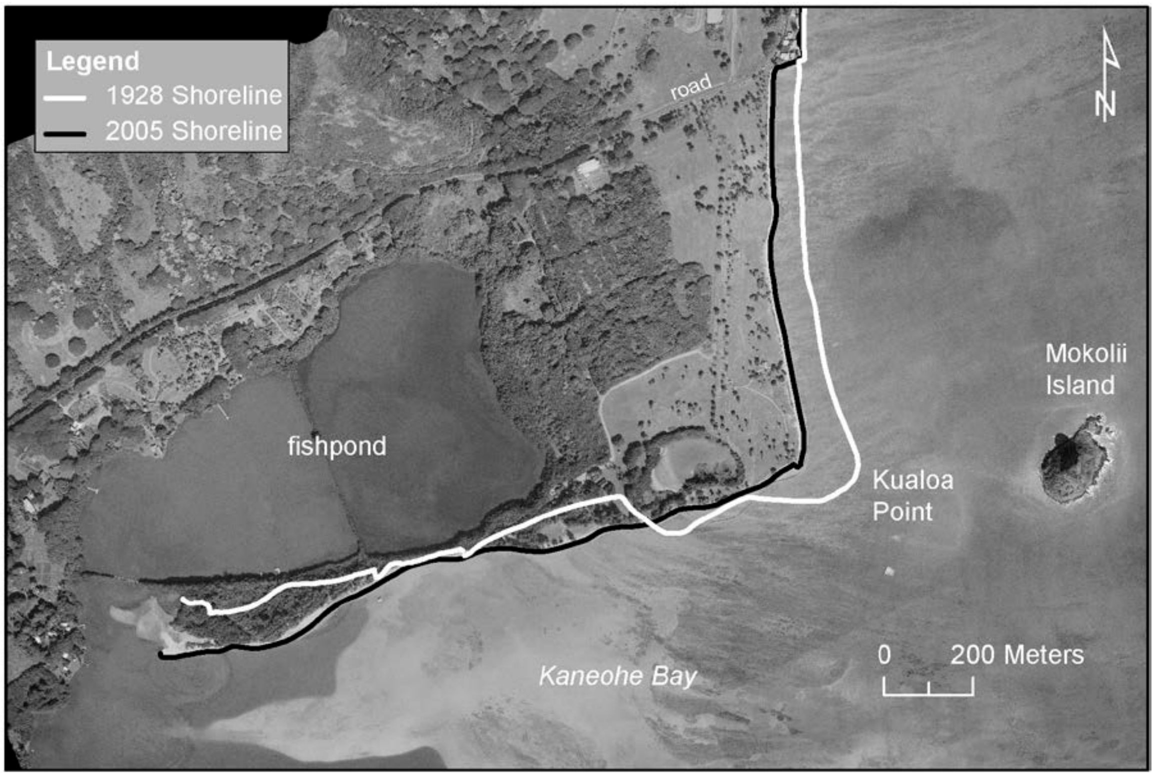

Figure 4.8. Aerial photograph (2005) and historical shoreline positions (1928 and 2005) documenting erosion along the headland beach at Kualoa Point, east Oahu, Hawaii (see Figure 4.1 for location). Note the accretion cusp within Kaneohe Bay formed by eroded sand transported into Kaneohe Bay from Kualoa Point.

At Keahi Point on the southern coast of Oahu (Figure 4.9), a sandy cuspate headland approximately 1 km to the west of the Pearl Harbor entrance channel, has eroded at rates as high as -1.6 ± 0.4 m/yr (Fletcher *et al.*, 2012). The erosion at Keahi Point prompted the removal of a row of beach front homes and installation of boulder revetments.

Figure 4.9. Aerial photograph (1996) and historical shoreline positions (1928, 1950, and 2005) documenting erosion along a beach cusp at Keahi Point, south Oahu, Hawaii (see Figure 4.1 for location).

Shoreline change patterns within the northeast Oahu study region show a distinct spatial relation with sand-filled channels in the nearshore reef platform. Major sand-filled channels are found at Laie Bay, Kokololio, Hauula, Kaluanui, Punaluu, and Kalaeoio (see Figures 4.5 and 4.6 for locations). Across the region, shoreline trends for transects located directly landward of major sand-filled channels were stable to slightly accretional with an average rate of 0.03 ± 0.05 m/yr (median rate 0.00 m/yr) and a slight majority, or 55%, of transects showed accretion (Table 4.2). Transects not fronting major sand-filled channels (fronting shallow reef) were more erosional overall with an average rate of -0.06 ± 0.03 m/yr (median rate -0.07 m/yr) and the majority (72%) had a trend of erosion.

Table 4.2. Comparison of shoreline change trends for beaches fronting sand-filled channels and beaches fronting shallow reef.

Beach Fronted By:	Shoreline Change Rates (m/yr)		Proportion of Beach Eroding and Accreting (% (% significant @ CI95))	
	Mean	Median	Eroding	Accreting
channel	0.03 ± 0.05	0.00	45% (13%)	55% (17%)
reef	-0.06 ± 0.03	-0.07	72% (19%)	28% (6%)

Analysis of shoreline trends from Laniloa to Makalii Point suggests increased erosion on the south side of headlands and adjacent northern portion of bays compared to the south side of the bays and adjacent north side of headlands (Table 4.3). This asymmetrical distribution of erosion and accretion trends along beaches in this region suggests predominant southerly transport of sediment – with sediment eroded from the south side of headlands and deposited toward the southern end of bays (Figure 4.10).

Table 4.3. Comparison of shoreline change trends for north and south portions of headland and embayed beaches from Laniloa to Makalii Point (see Figure 4.4 for location).

Region			Shoreline Change Rates (meters/year) Mean ± CI95	Median	Proportion of Beach Eroding and Accreting (percent (percent significant @CI95)) Eroding	Accreting
Laniloa - Makalii Point	Heads	North	-0.09 ± 0.04	-0.08	81% (29%)	19% (6%)
		South	-0.17 ± 0.09	-0.13	97% (31%)	3% (0%)
	Bays	North	-0.01 ± 0.05	-0.04	54% (27%)	46% (7%)
		South	0.03 ± 0.09	0.00	41% (9%)	59% (7%)

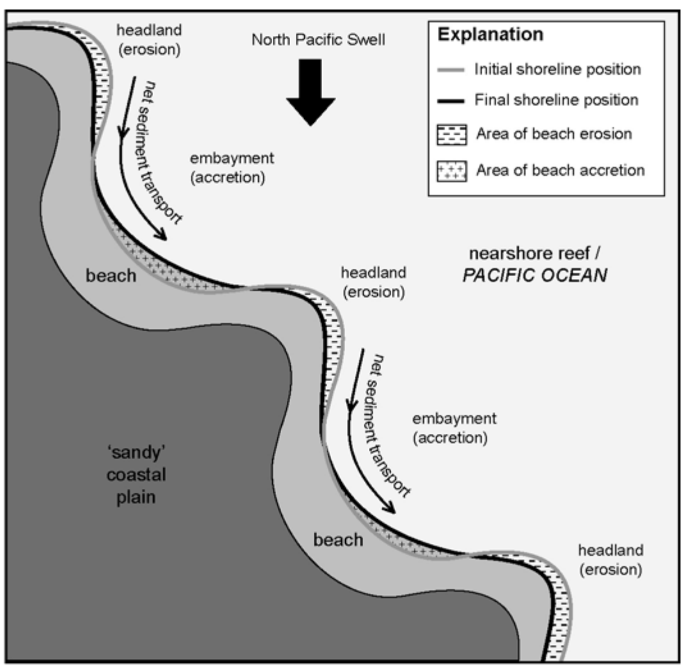

Figure 4.10. Conceptual diagram of erosion and accretion trends and inferred net sediment transport between Laniloa Beach and Makalii Point (see Figure 4.5 for location).

The southern sides of headland beaches from Laniloa to Makalii were more erosional (average rate of -0.17 ± 0.09 m/yr, median -0.13 m/yr) than the northern side of the headlands (average rate of -0.09 ± 0.04 m/yr, median -0.08 m/yr). The northern half of embayed beaches, were more erosional (average rate of -0.01 ± 0.05 m/yr, median -0.04 m/yr) than the southern sides of the embayments (average rate of 0.03 ± 0.09 m/yr, median 0.00 m/yr). Although the differences between average rates are not statistically significant at the 95% CI, there is added support for the observed alongshore asymmetry in shoreline trends provided by percents of transects that indicate erosion or accretion. On the north side of headland beaches 81% of transects had a trend of erosion, while 97% of transects on the south side of headlands had a trend of erosion. Fifty-four percent of transects in the north half of embayed beaches had a trend of erosion while 59% of transects in the south half of embayed beaches had a trend of accretion.

Discussion

We show that headland beaches in this study are more erosional than embayed beaches. This is likely due, in part, to refraction of waves toward headlands on the shallow nearshore reef typically fronting the headland beaches. This is a phenomenon assumed to operate on many coastlines and generally leads to an overall straightening of the coastline as headlands erode and bays infill (accrete) with eroded sediment. However, until now, detailed analysis of this phenomenon has not been possible on Hawaii coasts due to a lack of high resolution historical data.

Headland beaches on Oahu owe their existence, in large part, to accretion during sea-level fall after the Kapapa sea-level high stand ca. 3500 yrs B.P. (Fletcher and Jones, 1996; Stearns, 1978). Evidence includes the fact that headland beaches have a pronounced seaward position relative to embayed beaches. Had the observed pattern of preferential headland erosion continued indefinitely, we would expect an overall straightened coast, as opposed to the existing sinuous morphology. Additionally, geology of headland beaches indicates recent deposition as they are composed largely of unlithified carbonate beach and dune sand lying atop a fossil reef platform. Radiocarbon dates of similar deposits on Oahu and Kauai coastal plains indicate deposition following the Kapapa high-stand (typically 100s to a few thousand years) (Calhoun and Fletcher, 1996; Harney and Fletcher, 2003; Harney *et al.*, 2000) . Fringing reef platform typically emerges at or near the beach toe (base of the foreshore) at headland beaches, indicating that headlands are not simply exposures of larger sand bodies that emerged with sea-level fall. Rather, headlands are accretional features that experienced progradation atop the reef platform. Accretion of headland beaches may be attributed to increased deposition in the lee of the reef crest that became increasingly shallow or exposed with sea-level fall after the Kapapa high-stand. In contrast, embayed beaches, typically fronting a channel in the nearshore reef, would not have experienced a substantial decrease in wave energy with sea-level fall and, therefore, progradation was not as pronounced as at headlands.

We conclude that the pattern of shoreline change documented in this study - with relatively high erosion rates along headland beaches and relatively low erosion rates along embayed beaches - represents a change in shoreline erosion regimes with sea-level fall and rise after the Kapapa high sea-level stand (Figure 4.11). Headland beaches that were formerly characterized by accretion during falling sea level after the Kapapa high stand have subsequently shifted to a pattern of erosion with modern sea-level rise.

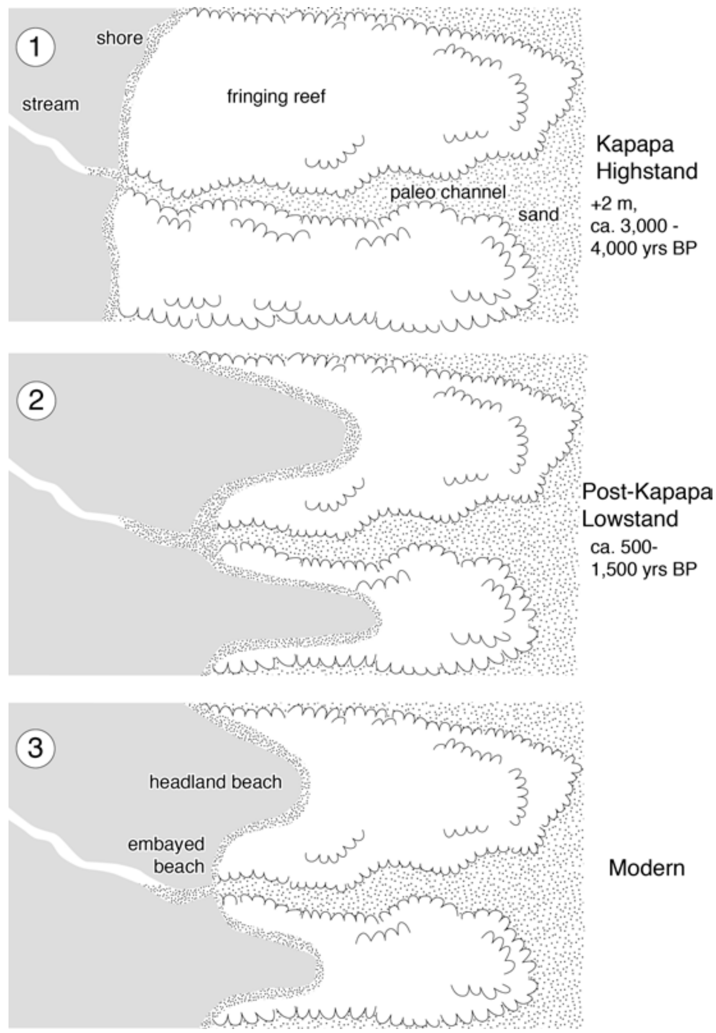

Figure 4.11. Conceptual illustration of inferred late-Holocene shoreline change regimes along the northeast coast and elsewhere on Oahu. The Kapapa sea-level high stand (ca. 3,500 yr BP, approx. +2 m) resulted in an overall trend of shoreline recession. A post-Kapapa sea-level low stand (ca. 500 – 1,500 yr BP) resulted in increased progradation (accretion) of headland beaches fronting shallow reef, relative to embayed beaches fronting channels, creating a sinuous beach morphology. Modern sea-level rise has resulted in a change in shoreline regimes to "preferential" erosion along headland beaches and in-filling (accretion) at embayed beaches.

The observed pattern of erosion at headlands is likely driven primarily by wave refraction. Much of the eroded sediment appears to move alongshore to adjacent embayments producing the observed pattern of stable to accreting beaches within the embayments. However, it was falling sea level that was primarily responsible for the pronounced seaward progradation of the headland beaches and subsequent sea-level rise that was responsible for a change to erosion of the headlands.

Our observations of historical shoreline change patterns runs counter to predictions by 'bathtub style' digital topographic flooding models and numerical models of beach profile change (e.g., The "Bruun Rule" (Bruun, 1954)), which would tend to predict relatively uniform shoreline recession. Attempting to predict shoreline change with sea-level rise using a bathtub style model or the Bruun Rule along northeast Oahu would fail to anticipate the direction of shoreline change at roughly half of the beaches as these models do not account for differential retreat, given similar alongshore topography.

Although modern sea-level rise may be an important factor in headland beach erosion, beach response depends highly on sediment availability. Maximum wave energy in the region occurs in winter when large refracted North Pacific swells impact reefs and beaches at oblique angles. The pattern of asymmetrical headland beach erosion and embayment accretion - with increased erosion on the south side of headlands and increased accretion on south side of embayments - suggests that winter swell is primarily responsible for net southerly sediment transport.

Our data show that beaches fronting sand-filled paleo-channels in the nearshore reef were substantially more stable than beaches fronting shallow reef flats or smaller sand deposits, which had an overall trend of erosion. Three possible drivers may be responsible for this: 1) There is net landward transport of sediment in the channels, nourishing the beaches. 2) Wave energy is more dissipated at the embayments relative to headlands. 3) Merging longshore currents carrying eroded sediment from the headlands at either end of a bay are depositing sediment in the embayments. An investigation of sediment movement in the Kailua channel at southeast Oahu by Cacchione *et al*. (1999) found that sedimentary bedforms (e.g., ripples and sand waves) in the channel migrate landward under typical tradewind conditions supporting the first explanation. However, seismic profiles of channel-fill sediments (Grossman *et al.*, 2006) suggest variable sediment transport. The results of this study provide the support for the third explanation. Further investigation is needed to determine if channels in the nearshore reef are typically a net source or sink for beach sands in Hawaii.

Conclusions

Several lines of geologic evidence indicant that headland beaches along the northeast Oahu coast and elsewhere on the island where formed by accretion during the falling sea level that followed the Kapapa sea-level high stand ca. 3500 yr B.P. We find that headland beaches are characterized by higher rates and greater prevalence of erosion compared to adjacent embayed beaches. Increased erosion of headland beaches, relative to adjacent embayed beaches is likely driven by wave refraction over the nearshore reef. Although wave energy may be the primary driver of shoreline change and longshore sediment transport, the pattern of shoreline change indicates a shift in erosion regimes at the headland beaches - from accretion with late-Holocene falling sea level to erosion with modern sea-level rise.

The results of this study show that beach response to sea-level rise will depend strongly on nearshore wave processes and longshore sediment transport. As a result, some portions of beach, such as at embayments or fronting channels in a nearshore reef, may be expected to accrete under sea-level rise as eroded sediment is transported in longshore currents from adjacent sections of beach undergoing erosion. Thus, even under conditions of sea-level rise, beach response will depend on sediment availability. In addition, asymmetrical patterns of erosion and accretion along headland and embayed beaches are inferred to result from predominant north wave direction and resulting southerly longshore sediment transport.

These observations of historical shoreline change have important implications for coastal management. Methods used to forecast shoreline change with sea-level rise, such as beach profile equilibrium models and digital elevation inundation models, tend to predict fairly uniform shoreline retreat along a shoreline, given similar alongshore topography. The results of this study show that differential erosion of certain coastal geomorphic features (e.g., headland beaches) and longshore sediment transport processes must be accounted for when attempting to forecast shoreline change with sea-level rise.

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