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Executive Summary

Beach erosion is a chronic problem along most open-ocean shores of the United States. As coastal populations expand and community infrastructure comes under increasing threat from erosion, there is a demand for accurate information about trends and rates of shoreline movement. There is also a need for comprehensive analysis of shoreline movement that is consistent from one coastal region to another. To meet these national needs, the U.S. Geological Survey is conducting an analysis of historical shoreline changes along open-ocean sandy shores of the conterminous United States and parts of Hawai‘i and Alaska. One purpose of this work is to develop methodology for mapping and analyzing shoreline movement so that periodic updates regarding coastal erosion can be made nationally that are systematic and consistent.

This report on shoreline changes on three (Kauai, Oahu, Maui) of the main eight Hawai‘i islands is one in a series of reports that includes California, the Gulf of Mexico Region, the Southeast Atlantic Coast, and will eventually include the Northeast Atlantic Coast, the Pacific Coast, and parts of Alaska. The report summarizes the methods of analysis, interprets the results, provides explanations regarding the historical and present trends and rates of change, and describes how various communities are responding to coastal erosion. Shoreline change evaluations for Hawai‘i are based on comparing historical shorelines derived from topographic surveys and processed vertical aerial photography. The historical shorelines generally represent the period of the last 90 years. Linear regression is used to calculate rates of change with the single transect method: long-term rates use all shorelines (1900s to most recent shoreline), and short-term rates use post WWII shorelines.

The beaches of Kauai, Maui, and Oahu are eroding with an average long-term rate for all beaches of -0.07 ± 0.01 m/yr and -0.06 ± 0.01 m/yr in the short term. Sixty-six percent of transects (shoreline measurement locations) on the three islands are erosional in the long term and 64 percent are erosional...
in the short term. Maui beaches have the greatest annual erosion with an average long-term shoreline change rate of \(-0.17 \pm 0.01\) m/yr. Maui beaches are eroding at 85 percent of transects. Kauai has the second-highest average long-term erosion rate of all transects at \(-0.11 \pm 0.01\) m/yr. Oahu beaches (all transects) are roughly stable at \(0.01 \pm 0.01\) m/yr, though short-term analysis indicates a more erosional trend at \(-0.05 \pm 0.01\) m/yr. The single-transect method of rate calculation finds significant rates at 30 percent of transects in the long term and 22 percent of transects in the short term. Twenty-two km of beach (measured alongshore) was lost to erosion on the three islands in the time span of this study.
National Assessment of Shoreline Change: Historical

Shoreline Changes in the Hawaiian Islands

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Introduction

U.S. Geological Survey National Assessment of Shoreline Change

Sandy ocean beaches of the United States are some of the most popular tourist and recreational destinations. They also constitute some of the most valuable real estate in the country. Beaches are an ephemeral environment between water and land with unique and fragile natural ecosystems that have evolved in equilibrium with the ever-changing forces of wind, waves, and water levels. Beachfront lands are the site of intense residential and commercial development even though they are highly vulnerable to several natural hazards including marine inundation, flooding and drainage problems, storm impacts, sea-level rise, and coastal erosion. Because the U.S. population continues to shift toward the coast where valuable coastal property is vulnerable to erosion, the U.S. Geological Survey (USGS) is conducting a National Assessment of Coastal Change. One aspect of this effort, the National Assessment of Shoreline Change, uses shoreline position as a proxy for coastal change because shoreline position is one of the most commonly monitored indicators of environmental change (for example, Fletcher, 1992; Dolan and others, 1991; Douglas and others, 1998; and Galgano and others, 1998), and it is easily understood by those who are interested in historical movement of beaches.
Additionally, the National Research Council (National Research Council, 1990) recommended historical shoreline analysis in the absence of a widely accepted model of shoreline change.

A principal purpose of the USGS shoreline change research is to develop a methodology so that shoreline change analyses for the continental U.S., and portions of Hawai‘i, and Alaska can be periodically and systematically updated in a consistent manner. The primary objectives of this project are: (1) to develop and implement improved methods of assessing and monitoring shoreline movement and (2) to obtain a better understanding of the processes controlling shoreline movement.

Achieving these ongoing long-term objectives requires research that (1) examines the original sources of shoreline data (maps, air photos, global positioning system (GPS), lidar), (2) evaluates the utility of different shoreline proxies (geomorphic feature, water mark, tidal datum, elevation) including the errors associated with each, (3) investigates bias and potential errors associated with integrating different shoreline proxies from different sources, (4) develops standard uniform methods of shoreline change analysis, (5) examines the effects of human activities on shoreline movement and rates of change, and (6) investigates alternative mathematical methods for calculating historical rates of change and uncertainties associated with them.

This report summarizes historical shoreline changes on three of the main eight Hawaiian Islands (Kauai, Oahu, and Maui).

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expertise in collecting and processing beach profiles from 1996 through 2001. Mark Merrifield at the University of Hawai‘i Sea Level Center provided updated sea level rise numbers. We would like to acknowledge Matthew Niles, Daren Suzuki, and Thorne Abbott previously with the Maui Planning Department for their support of erosion studies on Maui and, along with Sam Lemmo of the Hawai‘i Department of Land and Natural Resources, in the larger context of managing shoreline change in the state of Hawai‘i. The University of Hawaii Sea Grant extension faculty have been a valuable asset in coastal studies and policy development. We also appreciate Kauai County Planning Department and City and County of Honolulu Department of Planning and Permitting for funding erosion studies on Kauai and Oahu. In addition, we would like to thank the USGS Coastal & Marine Center project staff and researchers in Menlo Park, Santa Cruz, St. Petersburg, and Woods Hole. Without their guidance and toolsets, a National Assessment of shoreline change would not be possible. Specifically we want to acknowledge Rob Thieler, Abby Sallenger, Peter Howd, Jeff Williams, and Bob Morton for their encouragement.

The Coastal Geology Group is an informal network of faculty, graduate students, technicians, and support staff studying nearshore environments within the School of Ocean and Earth Science and Technology (SOEST) at the University of Hawai‘i. The authors extend their gratitude to those that have contributed to this study and the methodology of studying shoreline change over the years: William Morrison, Torsten Heinen, Ole Kaven, Robert Mullane, John Rooney, Tara Miller, Dolan Eversole, Christopher Conger, Scott Calhoun, Melanie Coyne, Zoe Norcross-Nuu, Craig Senter, Angela Stevens, Eden Fierstein, Jillian Luis, Caroline Jackson, Haunani Kane, and Morgan Smith. William Morrison and Torsten Heinen contributed greatly to the initial layout and data composition of this report allowing further refinements and developments to reflect the unique characteristics of the shoreline of Hawai‘i. Thank you to Nancy Hulbirt at SOEST Publications for help with illustrations and shoreline rate plots.
Importantly, we wish to recognize critical partners in this study without whom the project would not have been completed. These include the county governments of Maui, Kauai, and City and County of Honolulu, the University of Hawai‘i Sea Grant Program and its outstanding team of extension agents, the H.K.L. Castle Foundation, the U.S. Army Corps of Engineers, Mark and Joann Schindler, the Hawai‘i Coastal Zone Management Program, the Hawai‘i Department of Land and Natural Resources, the NOAA Coastal Services Center, and FEMA. The authors extend their sincere thanks to the hard working and dedicated individuals at each of these agencies who share the vision of managing the Hawai‘i shoreline.

**The Role of State and Federal Governments**

One reason for conducting this National Assessment of Shoreline Change is that there is no widely accepted standardized method of analyzing shoreline changes. Each state has its own data needs and coastal zone management responsibilities (for example, construction set-back lines, dune protection zones, public access), and therefore each state uses a different technique and standard to compile shorelines and to calculate rates of shoreline movement. Consequently, calculated rates of shoreline change and projected erosion hazard zones are inconsistent from state to state and often cannot be compared directly. These inconsistencies were clearly demonstrated by the Federal Emergency Management Agency (FEMA) sponsored erosion studies (Crowell and Leatherman, 1999) that were used as the basis for evaluating erosion hazards (Heinz Center, 2000).

Several federal agencies (USGS, FEMA, NOAA, U.S. Army Corps of Engineers (USACE)) have regulatory or administrative responsibilities pertaining to shorelines. Yet these responsibilities are quite different, requiring differing approaches and offering substantial opportunities for cooperation. For example, the USACE is authorized and funded by Congress to report on the economic and environmental implications of shoreline change and the costs of erosion mitigation. Their National
Shoreline Management Study (Stauble and Brumbaugh, 2003) is being conducted using existing shoreline data. The USGS will share data and information, such as the lidar-derived shoreline and rates of change, in support of their effort. NOAA has the mandate to establish the official shoreline boundary for the nation using tidal datums. Their emphasis is on safe navigation and using the shoreline to generate nautical charts. NOAA also has the V datum program, which assists agencies in establishing shorelines for a variety of purposes. Congress authorized and funded FEMA to report on the economic impact of erosion hazards on coastal communities, and on claims to the National Flood Insurance Fund. To accomplish this, FEMA contracted state agencies and academic researchers to conduct a pilot study of erosion hazards that included shoreline change data for limited geographic areas (Coyne and others, 1999). The USGS is responsible for conducting research pertaining to coastal change hazards including shoreline change, understanding the processes that cause coastal change, and developing models to predict future change. The USGS is the only government agency that has a dedicated program to monitor coastal change into the future using consistent methods nationwide. Such a program is critically important to assess national issues, such as the coastal impacts of sea-level rise.

Prior National and Hawai‘i Shoreline Assessments

The USACE (1971) conducted the first national assessment of coastal erosion. That study identified areas of critical and non-critical erosion on the basis of economic development and potential for property loss, but rates of shoreline movement were not evaluated. Dolan and others (1985) conducted a comprehensive analysis of shoreline changes for the mainland U.S. Their analysis was based on compilation of rates of shoreline change provided by other contributors and derived from their own studies. Rates of change were presented on maps, and the long-term trends of erosion and accretion were summarized in an accompanying text.
In the state of Hawai‘i, process oriented research exploring the dynamic and unique nature of Hawaiian beach morphology was first studied by Moberly (1963). Hwang (1981) published a methodology incorporating aerial photographs to analyze vegetation line position changes since 1928 for the island of Oahu. That methodology was continued by Makai Ocean Engineering and Sea Engineering and Moon (1991) expanding onto neighboring islands and updating the database to include aerial photography up to 1988. Sea Engineering and Moon (1991) produced a shoreline change study of Oahu for the City and County of Honolulu based on updates to Hwang (1981). With this report the University of Hawai‘i has updated the database for the islands of Oahu, Maui, and Kauai with aerial photography from 2005, 2006, 2007, and 2008. This study also augments past studies with additional photographs and maps of historical shorelines.

The County of Maui contracted the University of Hawai‘i to develop methodology for a parcel resolution (20 m) shoreline study of the Maui sandy shoreline. In 2003 the Maui Planning Commission included the university study methodology and initial results into a revision of setback guidelines for beachfront property development. Since 2003, the County of Maui contracted the University of Hawai‘i to update the shoreline study with 2007 aerial photography. The City and County of Honolulu contracted the University of Hawai‘i to use aerial photography to develop a database of shoreline change rates on sandy beaches around the island of Oahu. The County of Kauai also contracted the University of Hawai‘i to conduct a similar study of all sandy beaches on the island of Kauai other than along the Na Pali coastline. In 2008 the Kauai County Council adopted a new setback law that included rates of coastal erosion. The university has published several reports in the basis of their studies of shoreline change: Coyne and others (1996), Fletcher and others (1997), Coyne and others (1999), Fletcher and Lemmo (1999), Harney and others (2000), Rooney and Fletcher (2000), Richmond and others (2001), Norcross and others (2002), Miller and Fletcher (2003), Eversole and Fletcher (2003),
Norcross and others (2003), Rooney and others (2003), Fletcher and others (2003), Rooney and Fletcher (2005), Genz and others (2007a), Vitousek and others (2007), Genz and others (2007b), Genz and others (2009), Frazer and others (2009), Romine and others (2009), Anderson and others (2009). Additionally, the university maintains a website serving shoreline change data to the public and partnering agencies: http://www.soest.hawaii.edu/asp/coasts/index.asp.

Since the work of Dolan and others (1985), methods of obtaining, analyzing, displaying, and storing shoreline data have improved substantially, and coastal change has continued. Furthermore, coastal scientists have not agreed on standard methods for analyzing and reporting shoreline changes, nor have they identified rigorous mathematical tests that are widely accepted for quantifying the change and associated errors. Consequently, there are critical needs for (1) a nationwide compilation of reliable shoreline data including the most recent shoreline position, and (2) improvement of methods for obtaining and comparing shoreline positions and mathematically analyzing the trends.

**Environmental Framework of the Hawaiian Shoreline**

The Hawai‘i hotspot lies in the mantle under, or just to the south of, the Big Island of Hawai‘i where it feeds magma to two active subaerial volcanoes (Mauna Loa and Kilauea) and one active submarine volcano (Loihi). Centrally located on the Pacific Plate, the hotspot is the source of the Hawai‘i Island Archipelago and its northern arm, the Emperor Seamount Chain (fig. 1).

**Figure 1.** Topographic maps showing the Hawai‘i Island Archipelago and its northern arm, the Emperor Seamount Chain.

The main Hawaiian Islands are all built of shield volcanoes composed of basaltic lavas, intrusive dike complexes, and tephra deposits. Valley floors between volcanoes and coastal plains surrounding them consist of alluvial sediments eroded from the interior and carbonate deposits around the shoreline.
Outcropping volcanic bedrock, lithified tephra, and carbonate deposits (eolianite, beach rock, unconsolidated carbonate sand, and reef rock) characterize the geology of most coastlines in Hawai‘i. Unconsolidated calcareous and clastic sediment, eroded from either the offshore reef or upland sources, or directly produced by calcareous marine organisms, collects along the shore to form relatively narrow beaches.

**Carbonate Geology of Hawai‘i**

Hawaiian white sand beaches are derived from fringing reefs. Hence, beach origin and history are intimately connected to the geologic framework of reefs. The fossil reefs of Oahu have been the subject of several studies (for example, Dollar, 1982; Grigg, 1983) that are reviewed by Fletcher and others (2008). Offshore of island beaches, the insular shelf typically dips gently seaward to near the -20 m contour. There, a limestone drop off usually marks the end of the shallow portion of the shelf. The base of this wall typically occurs near -30 m depth where a deeper, partially sand-covered terrace extends seaward to approximately -50 m. Below -50 m a second wall and third terrace are found (Fletcher and Sherman, 1995).

The past half million years of geologic history has been characterized by dramatic swings in global climate occurring approximately every 100,000 years. Oscillating between cold episodes (glacials or ice ages) and warm intervals (interglacials), climate changes have caused global sea level to rise and fall across a range of approximately 130 m. Interglacials are times of high sea level and lead to the construction of reefs on island margins. Because sea level reaches different heights in successive glacial cycles, the carbonate history of Hawaii is complex.

The insular shelf is constructed from multiple carbonate units representing reef accretion and erosion over recent glacial cycles (fig. 2). Specifically, the shallow shelf is a fossil reef complex dating from Marine Isotope Stage (MIS) 7 (ca. 190,000–210,000 years ago; Sherman and others, 1999;
Grossman and Fletcher, 2004). The front of this shelf accreted separately during MIS 5a–d (ca. 80,000–110,000 years ago). Eolianites (lithified dunes) of late last interglacial (ca. 80,000 years ago) and Holocene (ca. 10,000 years ago to present) age (Fletcher and others, 2005) are found in nearshore and coastal plain regions of most islands. Most modern Holocene reef accretion is limited to environments on the deeper front of the reef where wave energy is not destructive. Grossman and Fletcher (2004), Conger and others (2006a), and Bochicchio and others (2009) infer that rugosity in depths less than 10 m atop the fringing reef is largely the result of karstification of limestone, not reef accretion, during times of lower sea level, most recently since the last interglacial. Modern wave scour has prevented accretion in this zone. In depths greater than 10 m the karst surface may be overgrown by Holocene accretion where wave energy permits (Conger and others, 2006b).

Figure 2. Diagram showing principal stratigraphic components of the Oahu carbonate shelf (Fletcher and others, 2008).

Reef Growth

Hawaiian reef morphology (fig. 3) exerts strong control on shoreline sediment supply and dynamics. Studies by Dollar (1982) and Dollar and Tribble (1993) identified physical disturbance from waves as the most significant factor determining the structure of Hawaiian coral reef communities. Expanding on this, Grigg (1983) articulated the “intermediate disturbance hypothesis” and presented two models of coral community succession: (1) an undisturbed (lack of wave impact) community that reaches peak diversity due to recruitment followed by a reduction due to competition; (2) and a disturbed community where diversity is set back to zero in the case of a large disturbance, or diversity is ultimately increased in the case of intermediate disturbance (substrate is opened for new recruitment). In the case of geological studies, interpreting paleo-communities and their role in sediment production must be grounded in an understanding of the roles of succession and disturbance. Hence, it is common
to develop community assemblage models related to wave energy during studies of Hawaiian reef stratigraphy (Engels and others, 2004).

Figure 3. Aerial photograph showing carbonate sand in Hawai‘i as the result of reef bioerosion and direct calcareous production among reef organisms. Reef morphology exerts strong control on shoreline sediment supply and dynamics.

To improve understanding of reef community assemblage in the Hawaiian Islands, Harney and others (2000), Harney and Fletcher (2003), Grossman and Fletcher (2004), Engels and others (2004), and Grossman and others (2006) employed surveys of benthic communities to develop coral assemblage models marking distinct environments. In their work along the south shore of the island of Molokai, Engels and others (2004) developed a community zonation model related to wave-generated bed shear stress as modeled by Storlazzi and others (2002). Engels and others (2004) define three assemblages; (1) a low-energy assemblage, (2) a mid-energy assemblage, and (3) a high-energy assemblage. The zonation model relates bed shear stress with percent living coral cover, relative percent coralline algae cover, dominant coral species, dominant coral morphologies, and water depth. Each assemblage is divided into three depth zones, <5 m, 5–10 m, and >10 m. All observed coral types that account for at least 10 percent of living coral cover are represented in the model.

Modern reef communities in wave-exposed settings are suppressed to a veneer (Grigg, 1998). North Pacific winter swell produces the largest and most frequently damaging energy. Yet waves of greatest magnitude and impact are likely to occur only rarely, associated most often with strong El Nino years (for example, 1998) perhaps a decade or more apart (Rooney and others, 2004). Intervening coral growth able to survive the strong annual pounding by waves may be wiped out by these interannual waves of extraordinary size and energy. Radiocarbon dates of fossil corals show that coral growth in wave-exposed settings has been continually suppressed since ca. 5,000 years ago on northerly exposed
coasts (Rooney and others, 2004) and ca. 3,000 years ago on southern shorelines (Grossman and others, 2006).

**Hawaiian Beach Sediments**

Understanding aspects of sediment production is especially important for sustainable management of Hawaiian beach systems, as many coastal sediment budgets are sediment deficient. Hawaiian beach sands are derived primarily from calcareous debris eroded from the insular reef shelf, which is re-worked into sand-size grains by breaking waves on the reef shelf and at the shoreline. Hawaiian beach sands are, on average, medium in size (classification of (Wentworth, 1922a; Inman, 1952; Dunbar and Rodger, 1957), though individual beaches can vary dramatically between coarse and fine sand. Moberly and Chamberlain’s (1964) analysis of littoral sediment grain size around the Hawaiian Islands shows that grain size is closely related to wave and current energy, which is strongly related to shoreline aspect in Hawai‘i (table 1). Islands generally have beaches with finest grain sizes on their windward or northeastern facing coasts. This is due to persistent working of sediment by trade wind waves with fairly consistent heights and periods so sediment is quickly sorted and reduced in size.

| Table 1. Relationships of littoral sand grain size to exposure. Modified from Moberly and Chamberlain (1964). |
| South shore beaches tend to have coarse and poorly sorted sediments. This is the result of runoff from strong but infrequent Kona storms washing coastal plain sediments back into the littoral system and high wave energy fragmenting the reef in shallower water. These high-energy wave conditions are short lived so that new sediments are not significantly abraded or sorted. Strong surf generated on western and northern coasts by winter north Pacific swell leads to coarse-grained beaches as sediments are only abraded during a portion of the year. In general, the grain size diameter of sand on all beaches tends to be finer in the summer months (June to September) and coarser in the winter months (November to March). |
Beach and reef morphology is similarly dependant on shoreline aspect (Moberly and Chamberlain, 1964; Grigg, 1998). North and west facing shorelines tend to have the longest and widest beaches of all the islands, while reefs tend to be narrower, deeper, and more irregular. Northern and western beach gradients transition from gently sloping wide beaches in the summer to steep sloped winter beaches as sand is moved seaward from the beach.

Lacking a continental source, sand in the Hawaiian Islands is often highly calcareous with a smaller contribution from eroded volcanic rock. The volcanic component of beach sediments is often controlled by the bedrock geology adjacent to the shoreline (Stearns and Vaksvik, 1935; Macdonald and others, 1960). The light color of most Hawaiian beaches is due to the dominance of grains from fragmented marine invertebrate animals and algae. Moberly and Chamberlain (1964) show that the composition of many Hawaiian beaches is dominated by larger (approaching 1 mm diameter) species of foraminifera (27 percent; 80 percent of which was Amphistegina), followed by mollusks, red algae, and echinoids. Coral fragments are only the fifth greatest contribution, with Halimeda, sponge spicules, crab fragments, and similar rare components less abundant. The concentration of foraminifera in beach sand is thought to be more an effect of their relative durability in wave action rather than their ecological abundance (Moberly, 1968).

In contrast to the island-wide surveys of beach sands mentioned above, Harney and others (2000) performed a more detailed study of sand compositions in Kailua Bay, windward Oahu (beach face to -20 m depth). They found >90 percent of sand grains were biogenic carbonate, dominated by skeletal fragments of coralline algae (for example Porolithon, up to 50 percent) followed by the calcareous green algae Halimeda, coral fragments, mollusk fragments, and benthic foraminifera. Results of this work indicate that sand composition and age can vary considerably across the seafloor. It is
interesting to note that these results indicate a relatively low foraminifera portion in benthic sands, whereas Moberly and Chamberlain (1964) show significantly higher portions in beach sand.

Radiocarbon dating of carbonate sands has been used as an indicator for longevity, production rate, and transport of coastal sediments (Kench, 1997; Gischler and Lomando, 1999). Dates retrieved from Hawaiian coral and skeletal fragments show sediment is produced, transported, and lost to the system on a millennial scale. Dates retrieved from Kailua beach and offshore sediment bodies show they range from 500–2,000 yr BP (Harney and others, 2000). Similarly, radiocarbon dates of Amphistegina tests in surface beach sands of Oahu show ages of more than 1500 years (Resig, 2004). The dominance of older sediment grains may reflect changes in carbonate productivity during the Holocene. As an example, Kailua’s broad, flat coastal plain was flooded during a +1–2 m mid- to late Holocene sea-level high stand (Stearns, 1935; Fletcher and Jones, 1996; Grossman and Fletcher, 1998). An expanded shallow nearshore environment (Kraft, 1982; Athens and Ward, 1991) may have resulted in a proliferation of calcareous algae and their sediments. This implies that a significant portion of sediment volume in Hawaiian beaches is the result of a period of higher productivity that has since passed, related to higher sea levels (Calhoun and Fletcher, 1996; Harney and others, 2000).

Beach Sediment Storage

Sediment storage in Hawaiian beach systems occurs as either beach reservoirs or nearshore bodies of sediment. Beach reservoirs in the Hawaiian Islands are low when compared to continental settings. The most compressive study of Hawaiian beach volume is presented by Moberly and Chamberlain (1964). As of 1964, a total of $39.56 \times 10^6$ m$^3$ of sand was stored in beaches. Over one-third of all beach sand in the Hawaiian Islands is found on the beaches of Kauai and more than one-fourth on the beaches of Oahu. The two islands together hold 61.4 percent of the total beach sand found in the State of Hawai‘i.
Nearshore Sediment Storage

Nearshore sediment reservoirs have gained considerable attention from researchers as they may contain sands that are potentially still part of the active sand exchange system. A comparison of beach volume and reef-top sediment volume in Kailua Bay showed there is over $10^6$ m$^3$ of sediment stored in the nearshore sand bodies other than the beach (Bochicchio and others, 2009).

Reef karstification is an important aspect of sediment storage in Hawaiian sediment budgets (Conger, 2005; Bochicchio and others, 2009). Unconsolidated sediment accumulates on the reef surface either by erosion of reef framework or directly produced as skeletal components (Harney and Fletcher, 2003). In many cases this sediment fills reef-top depressions creating discrete isolated sediment deposits. Sediment deposits are conspicuous features on reef-flats, displaying large variation in size, shape, and location and easily recognized in remotely sensed imagery (Conger and others, 2006a). Sediment deposits also represent a prominent component of the geologic framework of insular shelves and potentially play an active role in littoral sediment budgets. Sediment exchange between sand deposits and the beach face could be an important component of shoreline stability and in some cases provide quantities of affordable sand for beach replenishment (Moberly and Chamberlain, 1964; Casciano and Palmer, 1969; Moberly and others, 1975). A majority of reef-top sand bodies are in <10 m of water depth (Conger, 2005). Detailed volume analysis of sand bodies in Kailua Bay, windward Oahu, shows a similar relationship for sediment volume if the contribution from large sand channels is excluded (fig. 4) (Bochicchio and others, 2009).

Figure 4. Graph showing volume of sediment by depth zone in Kailua Bay. Dark bar shows all sediment. Light bar excludes the Kailua sand channel (Bochicchio and others, 2009). These data are applicable to other coastal settings in Hawaii with similar oceanographic and geologic characteristics.
Sediment trapping on the reef surface keeps sand potentially available for circulation within a littoral cell rather than lost to offshore sites (Grossman and others, 2006). Most sediment in reef systems is produced on the shallow nearshore platform where carbonate productivity and erosion are the highest. Sediment will remain on the reef platform in storage or as part of the active littoral system unless it is transported seaward of the reef crest and insular shelf (Harney and Fletcher, 2003). Once sediment crosses this threshold, the comparatively steep angle of the fore reef slope likely prevents most shoreward transport, effectively removing sediment from littoral circulation unless it makes its way back into shallow water through paleochannels cut into the reef (Grossman and others, 2006). On many islands steep sub-marine terraces at >20 m depth exacerbate sediment loss by presenting a seaward facing sharp break in topography (Coulbourn and others, 1974). In some cases large channels are incised, perpendicular to the shoreline and through the reef crest, creating a potential pathway for sediment exchange between inner and outer portions of the reef platform (Grossman and others, 2006).

The majority of reef-top depressions are relict features incised into the surface of Hawaiian reef platforms via dissolution or fluvial erosion during periods of lower sea level when subaerially exposed limestone is in contact with meteoric waters (Purdy, 1974). The resulting channel and karst—doline landscape is drowned by rising sea level and subsequently filled with sediment, unless depressions are closed by new reef accretion (Grigg, 1998; Grossman and Fletcher, 2004; Rooney and others, 2004; Conger, 2005; Grossman and others, 2006). A majority of the shallow reef-top sediment storage (deposits) occurs in depressions (fig. 5) likely eroded during periodic subaerial exposures of fossilized reefal limestone. Therefore, the potential for modern sediment storage is, to some degree, a function of pre-Holocene erosion (increasing storage space) and post-Holocene reef accretion infilling of eroded features (reducing storage space).
**Figure 5.** Shaded-relief topography and bathymetry of Kailua Bay, Oahu. Sand bodies are shown in black on the seafloor (Conger and others, 2009).

A study of sediment body distribution on the reef of southeastern Oahu (Bochicchio and others, 2009) suggests two factors as controls for the pre-Holocene karst and fluvial erosion that formed the reef-top depressions: (1) availability of fresh water drainage and (2) topographic slope of the reef. Meteoric runoff from onshore watersheds is a major contributor to erosion of the exposed limestone reef. It follows that proximity to an onshore watershed is a major control on depression formation and consequently offshore sand storage. Similarly, complexes of sand bodies are observed more commonly on low reef slopes than high on the southeast Oahu reef (Bochicchio and others, 2009).

**Sea Level**

Local relative sea level at Honolulu Harbor (fig. 6) is not only dependent on the global eustatic average trend (~ 3 mm/yr; Merrifield and others, 2009) but is also affected by local oceanographic patterns, basin-scale meteorology, and localized flexure of the oceanic lithosphere, which responds elastically to the heavy load of volcanic rocks over the Hawaiian hotspot. It is estimated that one half of the upward construction of Hawaiian volcanoes is reduced by subsidence and that most of the volcanoes have subsided 2–4 km since emerging above sea level (Moore, 1987). Subsidence associated with active volcanism causes upward plate flexure at a radius that correlates to the modern-day position of Oahu. Oahu, as evidenced by the presence of emerged fossil reefs, is undergoing long-term geological uplift. However, the rate of uplift is less than 1 percent of the rate of sea level rise.

**Figure 6.** Graphs showing mean sea level trends in Hawaii

Sea level has risen in Hawaii at approximately 1.5 mm/yr over the past century. This may not seem like a substantial rate, however, long-term sea-level rise can lead to chronic coastal erosion, coastal flooding, and drainage problems, all of which are experienced in Hawaii. This long-term trend also increases the impact of short-term fluctuations due to extreme tides leading to episodic flooding and erosion along the coast (Firing and Merrifield, 2004; Fletcher and others, 2010).

Although coastal erosion is not uniquely tied to global warming, it is a significant factor in managing the problem of high sea levels. Sea-level rise accelerates and expands erosion, potentially impacting beaches that were previously stable. Chronic erosion in front of developed lands has historically led to seawall construction resulting in beach loss (Fletcher and others, 1997).

Although the rate of global mean sea level rise has approximately doubled since 1990 sea level not only did not rise everywhere, but actually declined in some large areas (see NASA website: http://climate.nasa.gov/keyIndicators/index.cfm#SeaLevel).

The pattern of global sea level change is complex due to the fact that winds and ocean currents affect sea level, and those are changing also. In Hawaii, improving our understanding of sea-level impacts requires attention to local variability with careful monitoring and improved modeling efforts. Because of global warming, sea-level rise is expected to continue, and accelerate, for several centuries. Research indicates that sea level may exceed 1 m above the 1990 level by the end of the 21st century (Fletcher, 2009b; Vermeer and Rahmstorf, 2009). Continued sea-level rise will increase marine inundation of coastal roads and communities. Salt intrusion will intensify in coastal wetlands and groundwater systems, taro lo‘i, estuaries, and elsewhere. Extreme tides already cause drainage problems in developed areas.
Sea-level rise threatens Hawaiian beaches (fig. 7), tourism, quality of life, and infrastructure. Hawaiian communities located at the intersection of intensifying storm runoff and rising ocean waters will endure increased flooding.

**Figure 7.** Photograph showing sea-level rise threatens beaches and waterfront development.

The groundwater table in the coastal plain moves with sea level; hence, drainage problems will grow into a major problem among coastal communities. (Photograph by C. Conger)

**The Hawaiian Wave Climate**

The four dominant regimes responsible for large swells in Hawaii are: north Pacific swell, trade wind swell, south swell, and Kona storms (including hurricanes). The regions of influence of these regimes, outlined by Moberly and Chamberlain (1964), are shown on figure 8. A wave rose depicting annual swell heights and directions (Vitousek and Fletcher, 2008) have been added to their original graphic. The average directional wave spectrum in Hawaiian waters is bimodal and dominated by the north Pacific and trade wind swell regimes (Aucan, 2006). Although important to describe the complete Hawaiian wave climate, south swell and Kona storm regimes do not occur with the high magnitude and frequency that characterize the north Pacific and trade wind swell regimes. The buoy network around Hawai‘i is managed by the NOAA National Data Buoy Center (NDBC), shown in figure 8. These sensors provide the local wave climate data. Buoy reports are available via the World Wide Web at: http://www.ndbc.noaa.gov/maps/Hawaii.shtml.

**Figure 8.** Diagram showing Hawai‘i dominant swell regimes after Moberly and Chamberlain (1964), and wave monitoring buoy locations (Vitousek and Fletcher, 2008).

Inter-annual and decadal cycles including El Niño Southern Oscillation (ENSO; Goddard and Graham, 1997), and Pacific Decadal Oscillation (PDO Mantua and others, 1997; Zhang and others,
are also important to understand the variability of the Hawaiian wave climate. These large-scale oceanic and atmospheric phenomena are thought to control the number and extent of extreme swell events, for example strong ENSO events are thought to result in larger and more frequent swell events (Seymour and others, 1984; Caldwell, 1992; Inman and Jenkins, 1997; Seymour, 1998; Allan and Komar, 2000; Graham and Diaz, 2001; Wang and Swail, 2001; Aucan, 2006). Understanding the magnitude and frequency of extreme wave events is important as they may control processes such as coral development (Dollar and Tribble, 1993; Rooney and others, 2004) and beach morphology in Hawai‘i and elsewhere (Moberly and Chamberlain, 1964; Ruggiero and others, 1997; Kaminsky and others, 1998; Storlazzi and Griggs, 2000; Rooney and Fletcher, 2005; Ruggiero and others, 2005).

North Pacific Swell

Located in the middle of the large swell-generating basin of the north Pacific, Hawai‘i receives large ocean swell from extra-tropical storms which track predominantly eastward from origins in the northwest Pacific. The north Pacific storminess reaches a peak in the boreal winter, as the Aleutian low intensifies and the north Pacific high moves southward. Strong winds associated with these storms produce large swell events, which can travel for thousands of miles until reaching the shores of Hawai‘i. In summer months, the north Pacific high moves northward and storms in the north Pacific become infrequent (Flament and others, 1996). Figure 9 shows the satellite-derived average wave heights over the north Pacific in the winter and summer. The average winter wave heights in the north Pacific are around 3 m or greater while the summer wave heights are around 2 m or less. While figure 9 gives the average state of the north Pacific, the dynamic system typically involves individual storm events tracking eastward with wave heights on the order of 5–10 m. These swell-producing storms occur during winter months with typical periods of 1–1.5 weeks (for 5–7 m swells), 2–3 weeks for (for 7–9 m swells) and one month (for swells 9 m or greater). Many north Pacific storms do not produce swells that
reach Hawai‘i. Storms that originate in high latitudes and those that track to the northeast send swells to the Aleutians and the Pacific northwest. Swells that originate from storms in lower latitudes and those that track slightly to the southeast reach Hawai‘i with the largest wave heights.

**Figure 9.** Satellite (JASON-1) derived average wave heights [m] over the north Pacific in the summer and winter.

Hawai‘i receives its largest swell from the north Pacific with an annually recurring maximum deep-water significant wave height of 7.7 m (Vitousek and Fletcher, 2008) with peak periods of 14–18 s. However, the size and number of swell events in Hawai‘i each year is highly variable by a factor of 2 (Caldwell, 2005). The annual maximum wave height recorded from buoy 51001 (fig. 8) ranges from about 6.8 m (in 1994, 1997, 2001) to 12.3 m (1988).

The seasonal cycle of north Pacific swell peaks in winter with a daily average significant wave height around 4 m (fig. 10). Aucan (2006) depicted the monthly average directional spectra from buoy data at Waimea (buoy 51201) and Mokapu (buoy 510202) that showed the dominance of north Pacific swell out of the northwest in winter months, and relatively persistent energy out of the northeast in higher frequency bands associated with trade wind swell.

**Figure 10.** Graph showing the daily average significant wave heights from buoy 51001. This plot outlines the seasonal variability of the north Pacific swell, which begins to increase in October, reaching a peak in winter and subsequently decreases in March reaching a trough in summer.

Trade Winds and Trade Wind Swell

Occurring about 75 percent of the year, the trade winds are northeasterly (average 73°) winds with an average speed of 16 mph (25 kph). Anticyclonic (clockwise) flow around the north Pacific high
bolsters the trade winds in Hawai‘i in summer months causing them to be more persistent. In winter
months, the north Pacific high flattens and moves closer to the islands decreasing the trade wind
persistence (fig. 11). Although the number of days characterized by trade winds increases in summer
months, the mean trade wind speed in summer and winter months remains relatively similar.

**Figure 11.** Bargraph showing the number of days per season that the trade winds occur with a
particular speed (data from Buoy 51001). The days per season are shown in red for winter
months and blue for summer months. Notice the persistence of typical trade winds around
16 mph (~25 kph) during summer months.

The persistent trades generate limited fetch swell on north, northeast, east, and southeast facing
coasts (fig. 8). Choppy seas with average wave heights of 2 m and peak periods of 9 s from the northeast
characterize trade wind waves in Hawai‘i. While these represent nominal conditions, trade wind waves
can exceed 5 m in height and have periods of 15–20 s.

**Southern Swell**

Southern swell arriving in Hawai‘i is typically generated farther away than north Pacific swell.
These swells are generated from storms south of the equator near Australia, New Zealand and as far as
the Southern Ocean and propagate to Hawai‘i with little attenuation outside the generation region
(Snodgrass and others, 1966). South swell occur in summer months (southern hemisphere winter
months) and reach Hawai‘i with an annual significant wave height of 2.5–3 m and peak periods of 14–
22 s, which are slightly longer than north Pacific swell (Armstrong, 1983; Vitousek and Fletcher, 2008).

**Kona Storms**

Kona storms are “low-pressure areas (cyclones) of subtropical origin that usually develop
northwest of Hawai‘i in winter and move slowly eastward, accompanied by southerly winds from whose
direction the storm derives its name, and by the clouds and rain that have made these storms synonymous with bad weather in Hawai‘i (Giambelluca and Schroeder, 1998). Strong Kona storms generate wave heights of 3–4 m and periods of 8–11 s, along with wind and rain, and can cause extensive damage to south and west facing shores (Rooney and Fletcher, 2005). Minor Kona storms occur nearly every year in Hawai‘i. However, major Kona storms resulting in significant shoreline change tend to occur every 5–10 years, during the negative PDO cycle (Rooney and Fletcher, 2005). Consequently, positive (warm) PDO, and El Niño phases tend to suppress Kona Storm activity (Rooney and Fletcher, 2005).

Maximum Annual Recurring Wave Heights in Hawai‘i

While each wave regime (trade wind swell, north Pacific swell, south swell, and Kona storms) has its own underlying processes and mechanics, the sum of all of these regimes contribute to the wave heights and shoreline change in Hawai‘i, and thus evaluating extreme wave heights on a continuous scale around the islands is informative. Breaking waves at the shoreline are composed of swell sources from many different storms and swell regimes. The most common combination of swell modes for north facing shores is north Pacific swell and trade wind swell. The most common combination of swell modes for south facing shores is south Pacific swell and trade wind swell. Thus the spectral approach to understanding swell and surf patterns following Aucan (2006) is quite informative.

The maximum annually recurring significant wave heights (Hₚ) and the largest 10 percent (H₁/₁₀) and 1 percent (H₁/₁₀₀) wave heights for various directions in 30° windows around Hawai‘i are given in table 2 (Vitousek and Fletcher, 2008), these annual wave heights are also depicted on figure 8.

| Table 2. The observed maximum annually recurring significant wave heights (Hₚ) and the largest 10 percent (H₁/₁₀) and 1 percent (H₁/₁₀₀) wave heights for various directions around Hawai‘i (Vitousek and Fletcher, 2008). |
Tides

The tide range in Hawai‘i is comparatively quite small, having a typical range [Mean Higher High Water (MHHW)–Mean Lower Low Water (MLLW)] of 0.58 m and a spring tide range around 1 m. While the astronomic tide typically represents the largest water level variability at a particular location, there are other factors such as atmospheric pressure, wind setup, ENSO cycles, and oceanic disturbances, which can produce water level variability on the order of tens of centimeters. One important process influencing extreme sea level events in Hawai‘i is the occurrence of mesoscale eddies, which are large oceanic disturbances [>100 km], having elevated sea levels of around 15 cm (Firing and Merrifield, 2004).

Coincidence of Waves and Tides

As discussed earlier there are many sources that contribute to the maximum water level on a beach, including tide, wave setup, wave run-up and other sources of water level variability. Coincidence of large swell and tide events can cause severe coastal flooding and overtopping in Hawai‘i, whereas swell events occurring on low tides or neap cycles can be less severe (Caldwell and others, 2009).

Shoreline Change

All the processes considered thus far influence beach morphology in Hawaii. Morphologic changes include: seasonal beach profile changes, extreme events and chronic trends. Seasonal beach profile changes result from the seasonal variability of the Hawaiian wave cycle (see the Hawaii beach profile website, last viewed June 23, 2009: http://geopubs.wr.usgs.gov/open-file/of01-308/). In winter months, north facing shorelines are exposed to increased wave activity from north Pacific swell. In summer months, south facing shorelines are exposed to increased wave activity from south Pacific swell. Associated with this wave activity are increased run-up and impacts to the beach, and coastal dunes. Elevated energy at the shoreline transports sand offshore or alongshore with dominant currents.
The beach profile remains in an adjusted state until wave heights decrease or swell patterns change to allow the displaced volume of sand to return. A conceptual example of cross-shore sand transport and profile change is shown on figure 12.

**Figure 12.** Diagrams showing seasonal beach profile adjustments induced by seasonal swell variations and resulting cross-shore sediment transport.

Extreme beach profile changes, whose magnitude exceeds typical seasonal levels, result from extreme swell, storm, and sea-level events often associated with a corresponding ENSO or PDO cycle. Examples of extreme beach changes in Hawaii include the erosion that has occurred at Kailua Beach Park near the boat ramp 2005–present during persistent windy conditions (La Niña), followed by short-lived return of sand associated with the windless (El Niño) conditions of winter 2009/2010. As the El Niño ended and La Niña winds returned, the sand once again disappeared at Kailua and erosion has since dominated. Another example of extreme beach fluctuations occurred at Kaanapali Beach, Maui 2003 as a result of the combination of high water levels due to a mesoscale eddy juxtaposed with spring high tide, late summer heating, and a modest south swell event (Vitousek and others, 2007).

Chronic changes are also an important process on Hawaii’s beaches. Chronic changes are long-term (decades to centuries) changes that do not show a cyclical pattern. Chronic beach changes or chronic erosion in Hawaii can result from long-term sea-level rise and sediment budget deficiency (often due to human activities). One of the main goals of this report is to quantify the extent of chronic erosion on Hawaiian shorelines.

Coastal property in many areas of Hawai‘i is at a premium, and the encroachment of the Pacific Ocean onto multimillion-dollar residential and commercial lands and development has not gone unnoticed by landowners. In many cases, the response is to armor the shoreline with seawalls, revetments, sand bags and other devices. Artificial hardening of the shoreline protects coastal land at the
expense of the beach where there is chronic erosion, preventing waves from accessing the sand reservoirs impounded behind hard structures. Sandy shoreline adjacent to armoring experiences flanking, extending the erosion problem along the shoreline and subjecting adjacent properties to the challenges of managing erosion. Thus, efforts to mitigate coastal erosion have created a serious problem of beach loss and flanking due to sand deficiency, and wave reflection off hard structures along many shorelines in the state, particularly on the most populated and developed islands. The need to address this issue is acknowledged by state and local communities, with the hope that a broadly scoped management plan will keep the Hawaiian shorelines in balance between natural coastal morphology and human resource needs (Hwang, 2005).

Beach Alterations Influence Rates of Change

Rates of shoreline change can be influenced by shore stabilization practices. Artificial beach replenishment or engineering structures tend to alter coastal processes, sediment availability, and shoreline position. For example, beach nourishment artificially causes rapid, temporary shoreline accretion. Depending on the frequency of beach nourishment, the placement of large volumes of sand on the beach will bias the rates of observed shoreline change toward accretion or stability, even though the natural beach, in the absence of nourishment, would be eroding.

In Hawaii, nourishment has not played a significant role in the management of beach resources around the state other than Waikiki. Shoreline hardening in the form of seawalls has been the most common stabilization approach. Nourishment has largely been restricted to sites and locations where erosion poses a significant immediate threat to development. Sites of beach nourishment include Sugar Cove on Maui, Waikiki, and Lanikai on Oahu as well as other isolated locations.

On the island of Oahu, research conducted by Fletcher and others (1997) revealed that a significant amount of sandy beach (~25 percent) has been narrowed or completely lost since 1949 due to
artificial hardening of the shoreline. Differentiating between natural rates of erosion and the influences of beach nourishment is difficult because experiments have not been conducted to specifically address this issue.

Another factor that has influenced shoreline positions in Hawai‘i is sand mining. Although not well documented, there are a number of beaches where residents report that sand was taken for construction materials and for use as lime fertilizer by the agriculture industry (fig. 13). Sand mining may cause a deficiency in the sediment budget leading to temporary or chronic erosion.

**Figure 13.** Shaded-relief topography showing evidence of sand mining in the 1949 photo of Kahuku golf course. The dunes were flattened, plowed into the surf, and shoveled to the loading machine. The beach width decreased approximately 60 m from 1949 to 1967.

**Methods of Analyzing Shoreline Change**

**Compilation of Historical Shorelines**

Coastal scientists have been quantifying rates of shoreline movement and studying coastal change for decades. Time series of shoreline positions document coastal change and are interpreted to improve our understanding of shoreline stability. The most commonly used sources of historical shoreline data have traditionally been National Ocean Service (NOS) Topographic Sheets (T-sheets; Shalowitz, 1964) and vertical aerial photographs. Ideally, extraction of past shoreline positions from these data sources involves geo-referencing and removing distortions from maps and aerial photographs, followed by digitizing the shoreline position.

Depending on location, data source, and scientific preference, different proxies for shoreline position are used to represent the position of the shoreline. Common shoreline proxies include the high water line (HWL) (Shalowitz, 1964), a wet-dry line (Moore and others, 2006), the first line of
vegetation (for example, Hwang, 1981), the toe or crest of the abutting dune (Moore and Griggs, 2002), a low water line such as the toe of the beach (for example, Fletcher and others, 2003), a cliff base or top (for example, Hapke and Reid, 2007), and a tidal datum or elevation—typically the location where the plane of mean high water (MHW) intersects the beach face (for example, Morton and others, 2004).

This study adheres closely to the methods of Fletcher and others (2003) and Romine and others (2009) for mapping historical shorelines. Historical shorelines are digitized from NOS topographic maps (T-sheets) orthorectified aerial photo mosaics with pixel resolution of 0.5 m (fig. 14).

Figure 14. Aerial photograph showing historical shorelines and shore-perpendicular transects (measurement locations, 20 m spacing) displayed on recent aerial photograph.

Aerial photographs are orthorectified and mosaicked in PCI Geomatica Orthoengine software to reduce displacements caused by lens distortion, Earth curvature, refraction, camera tilt, and terrain relief; usually achieving Root Mean Square (RMS) positional error < 2 m. T-sheets are georeferenced using polynomial mathematical models in PCI with RMS errors < 4 m. Rectification of T-sheets is also verified by overlaying them on aerial photomosaics to compare their fit to unchanged features. Previous workers have addressed the accuracy of T-sheets (Shalowitz, 1964; Crowell and others, 1991; Daniels and Huxford, 2001) finding that they meet national map accuracy standards (Ellis, 1978) and recommending them for use in shoreline change studies as a valuable source for extending the time series of historical shoreline positions (National Academy of Sciences, 1990).

Delineation of Topographic Survey (T-sheet) Shorelines

T-sheets were rectified using ERDAS Imagine geographic imaging software by placing at least 6 well-spaced ground control points (GCPs) on selected T-sheet graticules in geographic coordinates. Some T-sheets produced before 1930 required additional coordinate transformation information from
NOAA to convert from the United States Standard Datum (USSD) to the North American Datum of 1927 (NAD27). The datum transformation was applied to T-sheet graticule coordinates prior to rectification. Total Root Mean Square (RMS) error for the rectification process was maintained below 1 pixel, which is approximately 4 m at a scale of 1:20,000 and approximately 1.5 m at a scale of 1:10,000. Typically the resulting RMS was much lower than one pixel.

In the Hawaiian Islands, the adoption of the NAD27 datum for mapping and the emergence of several unsupported local and island-specific datums have led to significant confusion among cartographers and surveyors. Several T-sheet products used in this study were re-rectified to correct significant errors associated with incorrect projection datum definitions. Such errors would have otherwise rendered the sheets unusable. To verify T-sheets and datum transformations, shoreline features which change little over the period of study (for example, basaltic headlands, cinder cones, and engineered structures) were used.

Newly geo-referenced T-sheets were loaded in ArcGIS. ArcGIS (ArcToolBox) was used to transform these into the Universal Transverse Mercator (UTM) projection on the North American Datum of 1983 (NAD83) for digitizing and vector analysis. A verification of the T-sheet shoreline was carried out where possible using control marks or physical shoreline features that are present on the T-sheet by comparing them with a reliable current image. Where verification failed, T-sheets were re-rectified using ground control points on existing control stations and identifiable shoreline features. In all cases, shoreline feature verification produced a higher quality data product.

**Mapping Historical Shorelines**

In Hawai‘i, the high reflectivity of Hawaiian white carbonate beaches reduces the visibility of the HWL on historical aerial photographs (Fletcher and others, 2003). Norcross and others (2002) and Eversole and Fletcher (2003) found that the LWM or toe of the beach played a significant role as a pivot
point for cross-shore and along-shore sediment transport processes at their study sites at Kailua Beach, Oahu and Kaanapali Beach, Maui, respectively. Excellent water clarity and the absence of significant flotsam in Hawaiian waters allow the delineation of the LWM on historical aerial photomosaics as a black and white or color tonal change at the base of the foreshore, most easily identified during wave run-up on the beach.

A low water mark (LWM) was digitized from aerial photo mosaics as the shoreline proxy. The beach toe, or base of the foreshore, is a geomorphic representation for the LWM. Removing or quantifying sources of uncertainty related to temporary changes in shoreline position is necessary to achieve our goal of identifying chronic long-term trends in shoreline behavior. A LWM offers several advantages as a shoreline proxy on Hawaiian carbonate beaches toward the goal of limiting uncertainty. Studies from beach profile surveys have shown that the LWM is less prone to geomorphic changes typical of other shoreline proxies (for example, wet-dry line, high water mark) on the landward portions of the beach (Norcross and others, 2002). The vegetation line was used as the shoreline proxy in some previous Oahu studies (Hwang, 1981; Sea Engineering, Inc., 1988). However, on many Hawaiian beaches the vegetation line is cultivated, fixed by shoreline revetments, obscured by overhanging trees, or dominated by aggressive species and thus may not represent natural erosion and accretion patterns.

The original surveyors working on T-sheets mapped the high water line (HWL) as a shoreline proxy. To include T-sheet shorelines in the time series of historical shorelines, the HWL is migrated to a LWL in our study using an offset calculated from measurements in beach profile surveys at the study beach or a similar nearby location. To determine patterns of historical shoreline movement, changes in shoreline position are measured relative to an offshore baseline along shore-perpendicular transects spaced 20 m apart.
The migration of the HWL to the LWL was possible using topographic beach profiles. The USGS, in coordination with the University of Hawai‘i, conducted a 5 year beach profile study at beaches on the islands of Oahu and Maui (USGS OFR 01–308, see http://walrus.wr.usgs.gov/reports/ofr01-308.html). Distances between the two shoreline features are calculated at the nearest representative beach profile location and an average offset distance was calculated. University researchers have extended this survey to include the period 2006–2008 on Oahu (35 locations) and on Kauai (27 locations).

**Uncertainties and Errors**

Several sources of error impact the accuracy of historical shoreline positions and final shoreline change rates. We define two types of uncertainty: positional uncertainty and measurement uncertainty. Following methods of Romine and others (2009); building on work by Fletcher and others (2003), Genz and others (2007a), Morton and others (2004), and Rooney and others (2003); we quantify 7 different sources of error in identifying shoreline positions on aerial photographs and T-sheets (3 positional and 4 measurement errors). The 7 different sources of error are summed in quadrature (the square root of the sum of the squares) to get a total positional uncertainty ($U_t$). Table 3 contains values of each error for each island.

**Table 3.** Range of errors for Maui, Oahu, and Kauai historical shorelines.

Positional uncertainties; including errors related to seasons, tides, and T-sheet HWM to LWM shoreline conversions; are related to all phenomena that reduce the precision and accuracy of defining a shoreline position in a given year. These uncertainties mostly center on the nature of the shoreline position at the time an aerial photo is collected.

Seasonal error ($E_s$) is the error associated with movements in shoreline position from waves and storms. In Hawaii this is largely a seasonal process with swell from the north Pacific in winter and south
Pacific in summer (see section: The Hawaiian Wave Climate). Some beaches (or sections of beach) tend to accrete in summer and erode in winter while other beaches tend to do the opposite due to seasonal shifts in predominant swell direction. Because seasonal change is cyclical, the probability of a photograph depicting a summer shoreline is equal to the probability of a photograph depicting a winter shoreline. Therefore, a uniform distribution is an adequate approximation of seasonal uncertainty.

Seasonal differences in shoreline position (LWM) are quantified from summer and winter beach profile measurements at a study beach or nearby beach with similar littoral characteristics. If available, seasonal shoreline positions from aerial photographs taken in adjacent seasons may be used in place of beach profile data. The mean and standard deviation of seasonal changes are calculated from the absolute values of differences between summer and winter shoreline positions. A uniform distribution is generated (with MatLab rand function) incorporating the mean and two times the standard deviation as minimum and maximum values. The standard deviation of the distribution is the seasonal error.

Tidal fluctuation error ($E_{td}$) is the error from horizontal movement in shoreline position along a beach profile due to vertical tides. Aerial photographs were obtained without regard to tidal cycles, which can influence the position of the digitized shoreline. The horizontal movement of the LWM during a spring tidal cycle is monitored on several beaches to assess this error. Because the tides are cyclically fluctuating between low and high, a photograph may capture the shoreline at any tidal stage. Therefore, like seasonal error a uniform distribution is an adequate approximation of tidal uncertainty. A uniform distribution is generated incorporating the mean and two times the standard deviation as minimum and maximum values. The tidal error is the standard deviation of the distribution.

Conversion error ($E_c$) is only calculated for T-sheets. The surveyed shoreline on T-sheets is the HWL. To compare shorelines from aerial photographs that use the LWM with shorelines from T-sheets that use HWL, we migrate the HWL from T-sheets to the LWM using an offset calculated from beach
profile measurements (Fletcher and others, 2003). The error associated with this migration is the standard deviation of the differences between the offset and HWL to LWM profile measurements.

Measurement uncertainties; including errors related to shoreline digitization, image resolution, image rectification, and T-sheet plotting; are related to analyst manipulation of the map and photo products. For T-sheets, we adopt National Map Accuracy Standards that provide a measure of both position and measurement uncertainties. For photos, measurement uncertainty is related to the orthorectification process and onscreen delineation of the shoreline.

Digitizing error \( (E_d) \) is the error associated with digitizing the shoreline. Only one analyst digitizes the shorelines for all photographs and T-sheets to minimize different interpretations from multiple analysts. The error is the standard deviation of the differences between repeat digitization measurements. The error is calculated for photos/T-sheets at different resolutions.

Pixel error \( (E_p) \) is the pixel size of the image. The pixel size in orthorectified images is 0.5 m, which means anything within 0.5 m cannot be resolved. The pixel size in T-sheets is 1.0 to 3.0 m.

Rectification error \( (E_r) \) is calculated from the orthorectification process. Aerial photographs are corrected, or rectified, to reduce displacements caused by lens distortions, refraction, camera tilt, and terrain relief using remote sensing software. The RMS values calculated by the software are measures of the offset between points on a photo and established ground control points (GCP). The rectification error is the RMS value.

T-sheet plotting error \( (E_n) \) is only calculated for T-sheets. The error is based on Shalowitz (1964) analysis of topographic surveys. There are three major errors involved in the accuracy of T-sheet surveys: (1) measured distance has an accuracy of 1 m, (2) planetable position has an accuracy of 3 m, and (3) delineation of the actual high water line has an accuracy of 4 m. The three errors are summed in quadrature to get the plotting error.
These errors are random and uncorrelated and may be represented by a single measure calculated by summing in quadrature (the square root of the sum of the squares, equation 1). The total positional uncertainty ($U_t$) is:

$$U_t = \pm \sqrt{E_s^2 + E_{td}^2 + E_{ts}^2 + E_{d}^2 + E_p^2 + E_r^2 + E_{ts}^2}$$  

(1)

For aerial photographs, $E_c$ and $E_{ts}$ are omitted. For T-sheets, $E_{td}$ is omitted. $U_t$ is used as the accuracy attribute field for each shoreline year. These uncertainty values can be propagated into the shoreline change result using Weighted Linear Regression (or Weighted Least Squares) in the Digital Shoreline Analysis System (DSAS). The resulting uncertainty of the rate will incorporate the uncertainty of each shoreline and the uncertainty of the rate determining model.

**Calculation and Presentation of Rates of Change**

Rates of shoreline change were generated in ArcGIS with the Digital Shoreline Analysis (DSAS) version 4.0, an ArcMap extension developed by the USGS (Thieler and others, 2009). DSAS employs the Single Transect method (ST) to calculate change rates and rate uncertainties at regularly-spaced transects (measurement locations) alongshore. ST uses various methods (for example, End Point Rate, Least Squares, Weighted Least Squares) to fit a trend line to the time series of historical shoreline positions at a transect. ST is the most commonly utilized method for calculating shoreline change (for example, Fletcher and others, 2003; Morton and others, 2004; Morton and Miller, 2005; Hapke and others, 2006; Hapke and Reid, 2007).

Transects are spaced approximately 20 m alongshore, approximately perpendicular to the trend of the shoreline. Hawaiian beaches are typically narrower and shorter than mainland beaches. To adequately characterize change on Hawaiian beaches we use narrower transect spacing than typically
employed in studies of mainland U.S. beaches (for example, 50 m; Morton and others, 2004; Morton and Miller, 2005).

Shoreline change rates are calculated with ST using Weighted Least Squares regression (WLS), which accounts for uncertainty in each shoreline position when calculating a trend line. The weight for each shoreline position is the inverse of the uncertainty squared (for example, \( w_i = 1/U_i^2 \)). Shoreline positions with higher uncertainty will have less of an influence on the trend line than data points with smaller uncertainty. The slope of the line is the shoreline change rate (fig. 15).

**Figure 15.** Graph and aerial photograph of calculating shoreline change rate using the Single-Transect (ST) method (Weighted Least Squares regression, WLS). The slope of the line is the annual shoreline change rate.

Rates are calculated for long- and short-term shoreline data. All shorelines are used for long-term rate calculations, and post-WWII shorelines are used for short-term rate calculations. In some instances, the beach disappears over the course of the study period. In these cases, rates are calculated using only shorelines where the beach is present.

Historical shoreline data is typically sparse (often < 10 shorelines) and noisy (high positional uncertainty). Consequently, shoreline change rates tend to have high uncertainty resulting in many rates that are not statistically significant. For this study we define an insignificant rate as a rate that is indistinguishable from a rate of 0 m/yr. In other words, the calculated ± rate uncertainty overlaps 0 m/yr. Rates that are statistically insignificant still provide coastal managers with a most likely scenario of shoreline change—valuable information in assessing risk of future shoreline erosion. Reducing the uncertainty in shoreline change rates using improved statistical methods will assist coastal managers in making better-informed decisions in planning for future erosion hazards.
Regionally-averaged shoreline change rates are the average of rates from all transects in a coastal region. The 95-percent confidence interval on the linear regression at each transect is assumed to be random and independent. Thus, the uncertainty of an average rate \( U_{avg} \) may be calculated as the root sum of squares of rate uncertainties \( U_i \) at all transects divided by \( n \):

\[
U_{avg} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} U_i^2}
\]  

(2)

The resulting average rate and uncertainty are often small relative to rates from individual transects. The greater the number of transects over which the uncertainty is averaged, the smaller the uncertainty of the average rate. To avoid reporting statistically significant average rates as indicating no change or having zero uncertainty, average rates are reported at higher precision (cm/yr, 0.00 m/yr) than rates from individual transects (dm/yr, 0.0 m/yr).

**Historical Shoreline Change Analysis**

**Summary: Historical Shoreline Changes in the Hawaiian Islands**

Erosion is the general long-term trend of Maui, Kauai, and Oahu beaches (table 4). Twenty-two km or 9 percent of the total length of beach analyzed was lost to erosion in the time-span of analysis. Oahu lost the highest total length of beach to erosion (8.7 km) while Maui has the highest percent of beach loss (11 percent). The average of all long-term rates is \(-0.11 \pm 0.01\) m/yr. Erosion is also the short-term trend \((-0.06 \pm 0.01\) m/yr). A majority of transects are erosional in both the long and short term (70 percent long term and 63 percent short term). The maximum long-term erosion rate \((-1.8 \pm 0.3\) m/yr) is found at Kualoa Point, Oahu. The maximum short-term erosion rate \((-2.2 \pm 1.1\) m/yr) is found at Baldwin Park, Maui. The maximum long-term accretion rate \((1.7 \pm 0.6\) m/yr) is found at Pokai Bay,
Oahu. The maximum short-term accretion rate (2.8 ± 6.2 m/yr) is found at the north end of Polihale Beach, Kauai. Although, this rate has high uncertainty due to seasonal variability. Of the three islands, Maui has the highest average long- and short-term erosion rates (-0.17 ± 0.01 and -0.15 ± 0.01 m/yr) of the three islands. Oahu has the least erosional long-term rate (-0.06 ± 0.01 m/yr). Kauai is the only island with a short-term average rate that is not erosional (0.02 ± 0.02 m/yr).

Table 4. Shoreline change trends for Kauai, Oahu, and Maui.

Kauai

General Characteristics of Study Areas

Kauai is the northernmost populated island in the state, lying less than 30 km northeast of Niihau (fig. 16). Kauai is over 5 million years old and has a roughly circular shape due to at least one, perhaps two, shield volcanoes. More than 1.5 million years after the primary shield-building stage had ceased on Kaua‘i, rejuvenated volcanism, the Koloa Volcanic Series, began resurfacing two thirds of the eastern side of the island. There are approximately 75 km of sandy beach separated into four regions: North, East, South, and West.

Figure 16. Map showing four regions of Kauai: North, East, South, and West.

North Kauai

The backshore of Kauai’s north coast is made of rejuvenated volcanic basalt. The shoreline is mostly characterized by embayments and fringing reef systems. The shore is exposed to large north swell in winter and northeast trade winds throughout the year. The beaches tend to be steep and are composed of coarse-grained calcareous sand (Fierstein and Fletcher, 2004).
The eastern end contains extensive fringing reef systems and pocket beaches between volcanic headlands. Hanalei, the largest bay on Kauai, is a mix of calcareous and terrigenous sand. The Na Pali cliffs are west of Haena and contain patches of pocket calcareous beaches (Fierstein and Fletcher, 2004). The beaches of the Na Pali region were not analyzed in this study.

East Kauai

Kauai’s east coast is characterized by embayments and fringing reef systems. The shore is exposed to northeast trade winds. Streams and rivers flow into the embayments, sometimes causing coastal flooding (Fierstein and Fletcher, 2004).

The Kapaa region of this coast was once a series of embayments, but has been straightened due to sediment infilling (Moberly and Chamberlain, 1964; Fierstein and Fletcher, 2004).

South Kauai

Kauai’s south coast is characterized by gently sloping beaches exposed to Kona storm waves, trade wind waves, and south swell. Longshore currents transport sediment westward from the mouths of large rivers (for example, Hanapepe Stream) (Fierstein and Fletcher, 2004). Hurricane Iwa (1982) and Hurricane Iniki (1992) devastated this area, with inundation up to 300 m inland at Poipu (Fletcher and others, 2002).

The Waimea subregion lacks a shallow near-shore reef and has wide steep beach with high proportion of terrigenous sediment (relative to typical calcareous Hawaiian beaches) from the Waimea River. The west end of the Hanapepe subregion is composed of narrow, gently sloping, calcareous beach. The remainder of the Hanapepe and the Poipu subregions are composed of rejuvenated volcanic basalt with calcareous pocket beaches and fringing reef. The Mahaulepu subregion contains lithified sand dunes (fig. 17) (Makai Ocean Engineering and Sea Engineering, 1991; Fierstein and Fletcher, 2004).
West Kauai

Kauai’s west coast is located on the Mana coastal plain, and is characterized by gently sloping beaches. The Mana Plain extends 5 km inland and is the product of converging longshore sediment transport from the north and the southeast. The sediment transport from the north is driven by winter swell and trade winds. The transport from the southeast is driven by summer swell and trade winds (Moberly, 1968). The shoreline is composed of calcareous sand with outcrops of beach rock. A majority of the beaches in this area are wide and backed by an extensive sand dune system (fig. 18).

Analysis of Kauai Data

There are between three and eleven high-quality historical shorelines available for Kauai ranging from 1927 to 2008 (table 5). The shoreline from the first time period is derived from a T-sheet. The 1930 shoreline is from a hydrographic chart. All other shorelines are derived from vertical aerial photographs.

Table 5. Number and range in years of shorelines for long- and short-term analysis on Kauai.

Erosion is the general long-term trend of Kauai beaches (table 4). Six km or 8 percent of the total extent of Kauai beaches was lost to erosion in the time-span of analysis. The average of rates for all Kauai transects is \(-0.11 \pm 0.01\) m/yr. Kauai beaches are stable to accretional in the short term with an average rate of \(0.02 \pm 0.02\) m/yr. A majority of transects are erosional (71 percent in the long term and 57 percent in the short term). The minimum and maximum long-term shoreline change rates on Kauai are found near Koki Point in South Kauai (erosion, \(-1.5 \pm 0.4\) m/yr) and at Major’s Bay in West Kauai.
(accretion, 1.6 ± 1.8 m/yr) (table 6). The maximum short-term rates are found at Lawai Bay in South Kauai (erosion, -1.7 ± 9.9 m/yr) and at Polihale in West Kauai (accretion, 2.8 ± 6.2 m/yr). The rate at Lawai has high uncertainty because the beach was lost to erosion and a truncated data set is used to calculate the rate up to the time the beach disappeared. The rate at Polihale has high uncertainty due to seasonal variability.

Table 6. Location of maximum and minimum shoreline-change rates on Kauai.

North Kauai

The North region is composed of three subregions (fig. 17). For the North region of Kauai there are between four and eleven shorelines, ranging in years from 1927 to 2008 (table 5). Of the 1,104 transects, 13 percent of short-term rates and 18 percent of long-term rates are statistically significant (fig. 19). Low rate significance on North Kauai beaches may be attributed, in part, to high seasonal variability (noise) from short-term erosion during large winter waves.

Figure 19. Map and plots of North Kauai: long-term and short-term shoreline change rates.

The average long-term rate of all transects in the North Kauai is -0.11 ± 0.02 m/yr (table 4). Seventy-six percent of transects are erosional in the long term and 23 percent are accretional. The remaining 1 percent of transects have rates of 0 m/yr or are not analyzed due to limited data. The maximum long-term erosion rate (-0.7 ± 0.6 m/yr) is immediately west of Haena Point. Other locations with significant long-term erosion include Moloaa (up to -0.4 ± 0.2 m/yr) and Anini (up to 0.4 ± 0.1 m/yr). The maximum long-term accretion rate (0.7 ± 0.7 m/yr) is found near the middle of the 3.5 km crescent-shaped beach at Hanalei, which is accreting along most of its length. The Hanalei subregion is the most notable exception to the predominant trend of erosion along North Kauai. The beach at Hanalei
Bay is accreting at an average long-term rate of 0.11 ± 0.03 m/yr while the Kilauea and Haena subregions are eroding at -0.13 ± 0.03 m/yr and -0.23 ± 0.03 m/yr, respectively (table 7).

Table 7. Shoreline-change trends for Kauai subregions.

The average short-term rate (-0.06 ± 0.02 m/yr) is less erosive than the average long-term rate in North Kauai. Sixty percent of transects are erosional in the short term—a 16 percent decrease from the long term. As with the long-term rates, Hanalei is the largest exception to the overall trend of short-term erosion. The maximum short-term erosion rate (-1.0 ± 2.6 m/yr) is found at a rocky outcrop at Kauapea (table 6). This section of beach is susceptible to seasonal changes, which is reflected in the high rate uncertainty. The maximum accretion rate (0.8 ± 1.5 m/yr) is located at Kahili Beach near Kilauea Stream mouth. This beach is also highly unstable related to seasonal fluctuations from large waves and stream flow.

Along the North Kauai coast, short and long-term rates follow similar trends (fig. 19). Predictably, the short-term rates have greater uncertainty than the long-term rates (due to fewer shorelines). Kauapea and Lumahai have high uncertainty bands for both short-term and long-term trends, likely related to strong seasonal influence on the data. Hence, linear methods do not fit these data well. Spikes in short-term uncertainty values at Moloaa, Mokolea, and Pali Ke Kua are due to rate calculations with a truncated data set (few shorelines) where the beach has been lost to erosion.

East Kauai

East Kauai is the most erosional region of Kauai based on average rates and percents of eroding transects (table 4). The East region consists of three subregions (fig. 20). There are between three and nine shorelines, ranging in years from 1927 to 2008 (table 5). Of the 867 transects, 34 percent of long-term rates and 16 percent of short-term rates are significant (fig. 20). The average long-term rate is -0.15 ± 0.02 m/yr, the most erosive of the four Kauai regions. Seventy-eight percent of transects are erosional
in the long term. East Kauai has the lowest percentage of accreting transects (19 percent) of the four Kauai regions. The maximum long-term erosion rate (-0.7 ± 0.4 m/yr) is located at the west end of Anahola. Other areas of significant long-term erosion are found at Nukolii (up to -0.5 ± 0.3 m/yr), north of Waipouli (up to -0.3 ± 0.2 m/yr), and Kapaa (up to -0.7 ± 0.4). The maximum long-term accretion rate (0.7 ± 0.4 m/yr) is located at Anahola Beach, south of Anahola River (table 6). This area is influenced by the river discharge and is dynamic (Makai Ocean Engineering and Sea Engineering, 1991). All subregions of East Kauai are erosional in the long and short term (table 7). The Kapaa subregion is the most erosional of the three with average long-term rate -0.17 ± 0.02 and short-term rate -0.08 ± 0.02 m/yr.

Figure 20. Map and plots of East Kauai: long-term and short-term shoreline change rates.

The average short-term rate for east Kauai is -0.06 ± 0.02 m/yr. Sixty-three percent of the short-term rates are erosional, the highest percentage of the four Kauai regions (table 4). East Kauai has the lowest percentage of accretional rates (33 percent). The maximum short-term erosion rate (-1.6 ± 0.3 m/yr) is located in Anahola, north of Kuahnu Point (table 6) adjacent to a stone revetment. The maximum short-term accretion rate (1.1 ± 0.6 m/yr) is found in the same location as the maximum long-term accretion rate (south of Anahola River).

Along the coast, long-term and short-term rates followed similar trends (fig. 20). The long- and short-term confidence bands for Lae Lipoa are relatively wide because rates are calculated with only three to four shorelines.

South Kauai

Summary statistics for South Kauai are somewhat conflicting, Average long- and short-term rates suggesting approximately stable to accreting shorelines. Percents of erosional and accretional
transects suggesting a predominance of erosion. The South region is made up of four subregions (fig. 21). The South region of Kauai has between three and eight shorelines (table 5), ranging in years from 1926 to 2007. Of the 790 transects, 28 percent of short-term rates and 32 percent of long-term rates are significant (fig. 21).

**Figure 21.** Map and plots of South Kauai: long-term and short-term shoreline change rates.

The average long-term rate for South Kauai is approximately stable at -0.01 ± 0.02 m/yr. Sixty-three percent of transects are erosional in the long term. The maximum long-term erosion rate (-1.5 ± 0.4 m/yr) is found at a small pocket beach north of Koki Point (table 6) where most of the remaining beach is now perched on a rock bench or has completely disappeared. Other locations with significant long-term erosion rates include Salt Pond (up to -0.8 ± 0.5 m/yr), Poipu (up to -0.3 ± 0.1), Shipwreck (up to -0.7 ± 0.4 m/yr), and Mahaulepu (up to -0.5 ± 0.4). The maximum long-term accretion rate (1.4 ± 0.7 m/yr) is located at Waimea, east of Kikiaola Small Boat Harbor (table 12, fig. 6). The beach on the west side of the harbor (Oomano) has the highest erosion in the West Kauai region (see West Kauai). The harbor, built in 1959, disrupts alongshore transport of sand and acts as a groin impounding sand on the Waimea (east) side and preventing sand from nourishing the beach at Oomano (Makai Ocean Engineering and Sea Engineering, Inc., 1991).

Unlike the long-term average rate, the short-term rate of 0.05 ± 0.01 m/yr suggests an overall trend of accretion along South Kauai (table 4). However, the beach is erosional at 57 percent of transects in the short term, suggesting an overall trend of erosion. The maximum short-term erosion rate (-1.7 ± 9.9 m/yr) is located at the end of a pocket beach in Lawai Bay where an overall trend of erosion in the bay has resulted in loss of the beach at the east end of the bay prior to 1984. High uncertainty with this rate is a result of using truncated data (3 shorelines) to calculate a rate in an area of beach loss. The
maximum short-term accretion rate \((1.7 \pm 0.3 \text{ m/yr})\) is located at the same position as the maximum long-term rate (Waimea—east of Kikiaola Small Boat Harbor).

Long-term and short-term rates follow similar trends along the South Kauai coast (fig. 21). The short-term uncertainty bands at Kipu Kai are especially large due to limited available shoreline data. Long-term rates at Kipu Kai are calculated using 4–5 shorelines, while short-term rates are calculated using only 3 shorelines. A spike in the short-term confidence band at Poipu (transect 586) is also a result of truncated (limited) data in an area of beach loss.

West Kauai

As a whole, West Kauai is erosional in the long term and accretional in the short term. The West region is made up of three subregions (fig. 22). Analysis for West Kauai employs between three and nine shorelines ranging from 1927 to 2006 (table 5). Of the 962 transects, only 12 and 13 percent of rates are significant in the long term and short term, respectively (fig. 22). Only a few isolated transects outside of the Oomano subregion have significant rates. West Kauai is exposed to refracted swells from the north in winter and south in summer. The seasonal shift in predominant wave direction results in high seasonal variability in shoreline position (noise)—a likely culprit of low rate significance along South Kauai.

Figure 22. Map and plots of West Kauai: long-term and short-term shoreline change rates.

The average long-term rate within this region is erosional at \(-0.13 \pm 0.04 \text{ m/yr}\) and 64 percent of transects are erosional in the long term (table 4). All subregions have average rates that are erosional in the long term (table 7). The Oomano subregion is the most erosional with an average rate of \(-0.64 \pm 0.03\). The maximum long-term erosion rate \((-1.4 \pm 0.2 \text{ m/yr})\) is found at Oomano, just west of Kikiaola Small Boat Harbor (table ??). As discussed in the South Kauai region, the harbor blocks sediment
transport from Waimea to the east that would, otherwise, nourish Oomano Beach. The maximum accretion rate (1.6 ± 1.8 m/yr) is in Majors Bay fronting the Pacific Missile Range. This segment of beach experiences large seasonal fluctuations resulting in high rate uncertainty.

In contrast to long-term analysis, short-term analysis at West Kauai indicates an overall trend of accretion. The short-term average of all rates is accretional at 0.16 ± 0.08 m/yr (table 4). A slightly higher percentage of transects are accretional (49 percent) than erosional (48 percent). The maximum short-term erosion rate (-1.5 ± 0.3 m/yr) is located at the same position as the maximum long-term erosion rate (Oomano—just west of the harbor). The maximum short-term accretion rate (2.8 ± 6.2 m/yr) is located at the northern end of Polihale, which is exposed to the full energy of large winter waves resulting in seasonal fluctuations (table 4).

Overall, short-term shoreline trends are similar to long-term trends throughout most of the Oomano and Barking Sands subregions. Though, erosion rates are somewhat lower and accretion rates are somewhat higher in the short term compared to the long term in these subregions. The most notable difference between long- and short-term trends is in the Polihale subregion where the majority of transects suggest a trend of erosion in the long term and, conversely, in the short term, the majority of transects suggest a trend of accretion. Other than Oomano, few transects produce significant rates suggesting that short-term variability (seasonal to decadal) is the dominant mode of shoreline change at West Kauai.

Oahu

General Characteristics of Study Areas

Oahu is the third-largest and most populated island of the Hawaiian chain. Oahu is made up of eroded remnants of two shield volcanoes (Waianae Range and Koolau Range, fig. 23) separated by
central Schofield Plateau (Macdonald and others, 1986). Explosive eruptions from the Honolulu Volcanic Series created several of the headlands on the south and southeast side of the island, including Diamond Head, Koko Head, and Mokapu Point. Emerged carbonate reefs formed under higher sea levels in the late Pleistocene compose many of the smaller headlands and underlie much of the coastal plain around the island. There are approximately 107 km of sandy beach separated into four regions: North, East, South, and West.

**Figure 23.** Map showing four regions of Oahu: North, East, South, and West.

North Oahu

Oahu’s north shore is seasonally dynamic. This region is exposed to strong winter north Pacific swell that causes steepening of the foreshore and narrowing of the beaches. During relatively calm summer conditions the beaches are flat and wide (Hwang, 1981).

A fringing reef of variable width and depth is present offshore. The coastal plain is variable in width and is comprised largely of a fossil reefrock bench. Outcrops of fossil reef form many of the short headlands in this region, including those at Puaena Point, Sharks Cove, Kawela Bay, and Turtle Bay (fig. 24).

**Figure 24.** Aerial photograph of fossil reef limestone headlands at Turtle Bay and Kawela Bay, North Oahu.

The North region is divided into two subregions: Sunset and Mokuleia (fig. 28). The Sunset subregion extends from Kahuku Point at the northern tip of the island to Haleiwa. A continuous 6 km beach extends from Waialae to Ke Iki. The remainder of beaches in the Sunset subregion are in pockets between basalt or limestone headlands. The Mokuleia subregion is between Kaiaka Bay and Kaena Point. Mokuleia Beach is a continuous 12 km beach extending from Waialua to Camp Erdman.
East Oahu

Oahu’s east coast faces into the predominant easterly tradewinds. As a result, the shoreline is exposed to short-period easterly waves year-round. Large refracted northerly swell also impacts this coast in winter. The coast is mostly a low-lying plane and is moderately to highly developed with the densest development in the southeast around Kailua and Lanikai (fig. 25).

Figure 25. Aerial photograph of Lanikai (foreground) and Kailua Beaches, East Oahu.

Shallow fringing reef lines much of East Oahu protecting the shoreline from the full energy of large waves. However, beaches backing shallow protective reefs are typically low and narrow and are prone to inundation during large waves and storms. Even low rates of chronic erosion have led to beach loss along portions of these narrow beaches. Seawalls have been constructed along much of the coast to protect homes and the coastal highway and contribute to beach loss in many areas. East Oahu is divided into two subregions, Northeast and Southeast separated by Kaneohe Bay.

South Oahu

Oahu’s south shore is heavily developed on a predominantly low-lying coast, with much of the shoreline lined with hardened structures such as seawalls, revetments, and groins. This shore is exposed to strong tradewinds that tend to blow alongshore, Kona conditions, and southerly swell. Tsunamis and hurricanes pose a problem due to the low-lying coastal plain and dense urban development (Fletcher and others, 2002). With the exception of Diamond Head, the coast is gently sloping and a fringing reef is present throughout most of this region.

Waikiki is the hub of Hawaii’s tourist economy and the health of its beaches is critical to the state economy (Miller and Fletcher, 2003). Waikiki was originally a wetland with a narrow strip of sandy beach. Development in this region started in the late 1800s and the construction of a canal was
proposed to divert streams from Waikiki, making more development possible, thus attracting tourists.

As development increased in the early 20th century, beach erosion became an increasing problem. Seawalls and groins were constructed and beach nourishment projects were pursued to maintain a healthy beach. Beach nourishment continues into the 21st century, with the most recent nourishment project occurring in late 2006–early 2007. There are 4 subregions along South Oahu: Ewa, Honolulu, Maunalua, and Kaiwi.

**Figure 26.** Aerial photograph of the engineered shoreline at Waikiki, South Oahu.

**West Oahu**

Oahu’s west leeward coast consists of sandy beach embayments and basaltic and limestone headlands. The shore is exposed to refracted northwesterly swells in winter and southerly swells in summer. Easterly tradewinds blow offshore along most of this coastline. Southerly “Kona” storm winds blow onshore and can cause temporary beach erosion. Shoreline position is highly variable at many beaches in this region as sand typically shifts from one end of the beach to another between the northerly and southerly swell seasons. There is a moderate risk of coastal flooding from large winter waves and when tropical storms pass near this region (Fletcher and others, 2002).

Most of the coast is gently sloping. The coast becomes more rocky and narrow near Kaena Point (northwest point of Oahu). The shoreline is composed of carbonate sand and limestone rock and beachrock is prevalent (Fletcher, 2009a). The West region is made up of three subregions: Makua, Waianae, and Nanakuli.

**Figure 27.** Aerial photograph of Maili Beach, West Oahu.
Analysis of Oahu Data

A maximum of twelve high-quality historical shorelines are available for Oahu ranging from 1910 to 2007 (table 8). The earliest shoreline is derived from a 1910 or 1927 T-sheet or 1928 aerial photograph. A 1932–1933 shoreline from a T-sheet is also included for some study areas. All other shorelines are derived from vertical aerial photographs from 1928 to 2007.

Table 8. Number and range in years of shorelines for long- and short-term analysis on Oahu.

Erosion is the general long- and short-term trend of Oahu beaches (table 4). Nine km or 8 percent of the total length of beach analyzed was completely lost to erosion in the time-span of the study. The average of long-term rates for Oahu is erosional at -0.06 ± 0.01 m/yr. The average short-term rate is also erosional at -0.05 ± 0.01 m/yr (table 9). A majority of transects are eroding in the long and short term (60 and 58 percent, respectively). The maximum long- and short-term erosion rates on Oahu are found at Kualoa Point in East Oahu (-1.8 ± 0.3 m/yr and -1.9 ± 0.9 m/yr). The maximum accretion rates are found at Pokai Bay in West Oahu (1.7 ± 0.6 m/yr). The long- and short-term rates at Pokai are equal because they were calculated using a truncated data set (1967–2007) following the construction of harbor breakwalls. The long-term rates at Kualoa and Pokai are the highest in the three islands.

Table 9. Location of maximum and minimum shoreline-change rates on Oahu.

North Oahu

Of the 1287 transects along North Oahu, 24 percent of short-term rates and 31 percent of long-term rates are significant—the lowest percentages of the four Oahu regions (fig. 28). The percent of significant rates in this region is low due to high seasonal variability (noise) in shoreline position. Large winter swells cause variations in beach width by up to two thirds. The rates at some North Oahu beaches are also unreliable due to poor seasonal distribution of the available aerial photographs. For example,
along much of the Sunset subregion the most recent historical shorelines (1996 and 2005) are from summer months, whereas earlier air photo shorelines are from winter–spring shorelines.

**Figure 28.** Map and plots of North Shore of Oahu: long-term and short-term shoreline change rates.

The overall trend of North Oahu beaches is erosion (table 4). The average long- and short-term rates on the north shore are erosional at -0.11 ± 0.01 m/yr and -0.07 ± 0.01 m/yr, respectively. Seventy-three percent of the total extent of North Oahu beaches is eroding in the long term and 68 percent is eroding in the short term. The two subregions of North Oahu (Sunset and Mokuleia) have an overall trend of long- and short-term erosion based on average rates (table 10).

**Table 10.** Shoreline-change trends for Oahu subregions.

The maximum long-term erosion rate (-1.3 ± 0.8 m/yr) is found at Haleiwa Beach Park at a segment of shoreline where the beach has been lost behind a small breakwater (table 9). This beach has undergone significant modification throughout its history, including construction of a groin, breakwater and sea wall and two beach nourishment projects (Hwang, 1981; Sea Engineering, Inc., 1988). Other areas with significant erosion rates include Kuilima (up to -0.4 ± 0.2 m/yr), Waimea (up to -0.8 ± 0.4 m/yr, due to sand mining), and Mokuleia (up to 0.6 ± 0.1 m/yr). The maximum long-term accretion rate (0.8 ± 0.8 m/yr) is found at Rocky Point in the Sunset subregion, though; this rate is likely influenced by seasonal variability. The only significant exception to the overall trend of erosion along Mokuleia Beach is found at an accreting cusp fronting Waialua with rates up to 0.8 ± 0.8 m/yr (North Oahu maximum erosion rate).

The maximum and minimum short-term change rates are found at the same locations as the long-term maximum and minimum. Long- and short-term rates follow similar trends with increasing
uncertainty in the short term from a shortened data set (fewer shorelines) and high seasonal variability (fig. 28).

East Oahu

Overall, the beaches of East Oahu are approximately stable to slightly erosional based on long- and short-term average rates and percents of eroding and accreting transects. East Oahu beaches have between five and twelve shorelines ranging from 1910 to 2006 (table 8). Of the 2108 transects, 24 percent of short-term rates and 35 percent of long-term rates are significant (fig. 29).

**Figure 29.** Map and plots of East Oahu: long-term and short-term shoreline change rates.

The average long-term rate for East Oahu beaches is roughly stable at 0.01 ± 0.01 m/yr. Fifty percent of transects are eroding and 47 percent are accreting (table 4). The maximum and minimum erosion rates in the windward section are found within a few hundred meters at Kualoa at the northern end of Kaneohe Bay (table 9). The shoreline at Kualoa Point has retreated over 100 m with rates as high as -1.8 ± 0.3 m/yr. Eroded sand is transported around Kualoa Point to the west where it is deposited inside the bay forming a spit that is accreting at up to 1.5 ± 0.4 m/yr—the maximum long-term accretion rate in the East Oahu region. Other locations with significant erosion rates include Kahuku (up to 1.2 ± 0.6 m/yr, due to sand mining), Laniloa (up to -0.7 ± 0.2 m/yr), Hauula (up to -0.3 ± 0.1 m/yr), Makalii Point (up to -0.3 ± 0.2 m/yr, beach lost to erosion), Kaaawa (up to -0.3 ± 0.1 m/yr), and Bellows (up to -0.6 ± 0.3 m/yr).

Some of the longest extents of accreting shoreline in Hawaii are found along East Oahu. Other areas of significant accretion in East Oahu include Laie (up to 0.4 ± 0.2 m/yr), Kahana (up to 0.7 ± 0.3 m/yr), Mokapu (up to 0.6 ± 0.5 m/yr) and Kailua (up to 0.7 ± 0.2 m/yr). The beach at central Lanikai is accreting at up to 0.8 ± 0.3 m/yr. However, along adjacent shoreline to the north and south the beach has
been completely lost its beach to erosion (seawalls) in the last few decades. Most of the accretion along East Oahu is concentrated in the Southeast subregion. The average long- and short-term rates for Northeast Oahu are erosional (-0.07 ± 0.01 m/yr and -0.09 ± 0.02 m/yr) while the average rates for Southeast Oahu are accretional (0.12 ± 0.01 m/yr and 0.09 ± 0.02 m/yr) (table 10).

The short-term rates follow similar trends to the long-term rates (fig. 29). Like the average long-term rate, the average short-term rate is approximately stable at -0.01 ± 0.01 m/yr. More transects are erosional in the short term than long term with 54 percent of transects eroding and 44 percent accreting (table 15). The maximum short-term erosion and accretion rates are also found at Kualoa (-1.9 ± 0.9 m/yr and 1.3 ± 1.8 m/yr, resp., table 9).

South Oahu

Along south Oahu there are between three and ten shorelines ranging in years from 1927 to 2005. Of the 1319 transects, 36 percent of long-term rates and 34 percent of long-term rates are significant (fig. 30). The modern shoreline from Sand Island to Diamond Head (Honolulu subregion) bears little resemblance to its natural condition and is largely the result of engineering efforts (for example, groins, sand-fill, and seawalls) intended to widen the beach and move the beach seaward (Miller and Fletcher, 2003; Wiegel, 2008). Due to extensive shoreline reconstruction, only historical shorelines for the modern configuration of artificially altered beaches are used to calculate change rates.

Figure 30. Map and plots of South Oahu: long-term and short-term shoreline change rates.

The average long-term rate in the south (-0.04 ± 0.01 m/yr) and percent of eroding transects (50 percent) and accreting transects (48 percent) suggest a slight overall prevalence of erosion (table 4). The Ewa subregion is the most erosional section of south Oahu with a long-term average rate of -0.06 ± 0.01
m/yr. The Honolulu subregion is also erosive in the long term (-0.05 ± 0.02 m/yr). The average long-term rate for the Maunalua subregion is slightly erosional to stable (-0.02 ± 0.02 m/yr) (table 10).

The maximum long-term erosion rate (-1.6 ± 2.7 m/yr) is at Queens Beach, Waikiki (table 9) where the shoreline is hardened and much of the beach disappeared prior to 1975. Erosion up to -1.6 ± 0.4 m/yr is also occurring at the east end of the Ewa study area near the Pearl Harbor entrance channel (Keahi Point) where erosion of a sandy headland has forced the removal of several homes and prompted construction of a boulder revetment. Other areas with significant long-term erosion rates include Nimitz Beach (up to -0.3 ± 0.1 m/yr), Oneula (up to -0.3 ± 0.2 m/yr), Sand Island (up to -0.3 ± 0.2 m/yr), Ala Moana (up to -0.8 ± 0.3 m/yr), Ft DeRussy (up to -0.8 ± 0.4 m/yr), and Kahala (-0.8 ± 0.7 m/yr, beach lost). The maximum long-term accretion rate (0.8 ± 0.2 m/yr) is found at Kaimana Beach in Waikiki, on the east side of the natatorium. The natatorium walls act as a groin disrupting the westerly longshore transport of sediment, resulting in accretion on the east side of the natatorium (Kaimana) and erosion on the west side (Queens).

The average short-term rate of -0.03 ± 0.02 m/yr is similar to the average long-term rate. Like the long-term rates, the percent of eroding and accreting transects is about even (table 15). The maximum short-term erosion rate and maximum accretion rate are at the same locations as the maximum long-term rates (Kaimana and Queens, Waikiki) (table 9).

The long-term and short-term rates follow similar trends (fig. 30). At the east end of Aina Haina the short-term rates have exceptionally high uncertainty due to low confidence in the model fit to the three available historical shorelines.
West Oahu

The three subregions in west Oahu have between six and twelve shorelines, ranging in years from 1910 to 2007 (table 8). Of the 628 transects, 46 and 26 percent of the rates are significant in the long term and short term, respectively (fig. 31).

**Figure 31.** Map and plots of West Oahu: long-term and short-term shoreline change rates.

West Oahu is the most erosional region of the island with an average long-term rate $-0.25 \pm 0.01$ m/yr and 83 percent of transects indicating erosion in the long term (table 4). All three subregions are erosional in the long term with average rates of at least $-0.20$ m/yr. The maximum long-term erosion rate ($-1.2 \pm 0.5$ m/yr) is found in the north of Maili Beach (table 9) and is at least partially the result of removal of sand by mining operations in the mid-1900s (Hwang, 1981; Sea Engineering, Inc., 1988). Sand mining was widespread along west Oahu beaches and also likely influences shoreline change rates at Makua and Yokohama (Campbell and Moberly, 1978 and Hwang, 1981). Other areas with significant erosion rates include Makua (up to $-0.4 \pm 0.3$ m/yr, sand mining), Keaau (up to $1.0 \pm 0.3$ m/yr), Mauna Lahilahi (up to $-0.3 \pm 0.1$ m/yr), Pokai (up to $-0.4 \pm 0.3$ m/yr), Nanakuli (up to $-0.3 \pm 0.1$ m/yr), and Tracks (up to $-0.5 \pm 0.2$ m/yr). The maximum accretion rate ($1.7 \pm 0.6$ m/yr) is found in the southern end of the Pokai Bay. This section of beach has been accreting since the construction of a breakwater in the 1950s.

The average short-term rate of $-0.13 \pm 0.02$ m/yr is less erosive than the long-term average rate (table 4). Seventy-five percent of transects indicate erosion in the short term, compared to 86 percent in the long term. The maximum short-term erosion rate ($-1.0 \pm 0.3$ m/yr) is at the south end of Yokohama Beach (table 9), where sand mining occurred between 1949 and 1972 (Hwang, 1981). The maximum short-term accretion rate ($1.7 \pm 0.6$ m/yr) is located at Pokai Bay, the same location as the maximum
long-term rate as rates were calculated here with a truncated data following construction of the breakwater.

The long-term and short-term rates follow similar trends (fig. 31). Short-term rates typically have higher uncertainty as a result of a shortened dataset. The long-term rates at Maili are more erosive than the short-term rates indicating that shoreline recession may have slowed since sand mining operations ceased.

Maui

General Characteristics of Study Areas

The Island of Maui is the third largest of the Hawaiian Islands. It is composed of two shield volcanoes, West Maui and Haleakala, with a low-lying isthmus separating them. There are approximately 90 km of sandy beach separated into three distinct regions: North Maui, Kihei, and West Maui (fig. 32).

Figure 32. Map showing the three distinct regions of Maui: North, Kihei, and West.

North Maui

The north shore of Maui (fig. 37) is a gently embayed coastal system exposed to the northeast, north, and northwest. The shore experiences large swell during winter months, and short period, trade wind waves throughout the year. The area also has a history of tsunami inundation.

The North Maui region is divided into three subregions for further analysis. The eastern Waihee–Waiehu subregion is affected by heavy rainfall and run off from the dissected watersheds of the West Maui highlands and are dominated by cobble and sand beaches. The central study beaches, from Kahului to Baldwin Park (Kahului and Kanaha–Paia subregions) have low-lying hinterlands and a sand-rich coastal plain. A fringing reef is found along both the eastern and central study areas. The western
study beaches, beginning at Paia, have a narrow, rocky coastal plain due to the rising slopes of Haleakala volcano. This coastline contains short, embayed pocket beaches and narrow perched beaches located on low elevation rocky terraces (fig. 33).

**Figure 33.** Aerial photograph of North Maui beaches: looking west from Paia toward Baldwin Park.

**Kihei Maui**

The Kihei coast (fig. 37), in the shape of a southwest-opening fishhook, is partially protected by the islands of Molokai, Lanai, and Kahoolawe from large ocean swell. However, winter season north Pacific swell does impact the southern portion of the coast while south swell strikes the entire coastline during summer months and can dramatically change the profile of the beach. Historically, Kona storms are the largest individual events to influence the shoreline, particularly the northern part of this coast.

Three subregions make up the Kihei coast: Makena–Wailea, Central Kihei, and Maalaea Bay. Coastal headlands mark watersheds that typically do not have dissected valleys. The coastal plain is a flat, sand-rich terrace with aquatic wetlands in the north. It is fronted by a calcareous dune that has been heavily impacted by development (fig. 34). A fringing reef is located along the central portion of the Kihei region. The north and south sections of Kihei generally have wider beaches than the central portion, and lack a fringing reef (fig. 35).

**Figure 34.** Aerial photograph of Maalaea Bay Beach with dunes and wetlands, north Kihei coast, Maui.

**Figure 35.** Aerial photograph of Makena Beach, southern Kihei coast, Maui.
West Maui

West Maui (fig. 38) has a gently arcing convex coast. From south to north, the shoreline changes exposure from southwesterly, to westerly, to northwesterly. The islands of Molokai, Lanai, and Kahoolawe offer partial protection from swell. However, West Maui beaches do experience energetic seasonal swell that cause significant changes in the beach profile and shifts in sediment movement along the coast. The region is influenced by alternating seasonal south-southwest and north-northwest swell events. The shoreline is characterized by lengths of sandy beach interrupted by rocky headlands and engineered structures (fig. 36).

**Figure 36. Aerial photograph of Kaanapali Beach, West Maui.**

This region is characterized by heavily dissected watersheds that produce large alluvial fans during low sea-level stands. Fringing reefs are found along this coast. Most beaches are narrow and often sand-depleted. Three subregions compose West Maui: Lahaina, Kaanapali, and Napili–Kapalua.

**Analysis of Maui Data**

There are between three and ten high-quality historical shorelines available for Maui ranging in years from 1899 to 2007 (table 4). The shoreline from the earliest time period is derived from a T-sheet. All other shorelines are derived from vertical aerial photographs spaced approximately every decade. Long-term rates were calculated using all shorelines and short-term rates were calculated using post-WWII shorelines.

Maui beaches are the most erosional of the three islands (table 4). All analysis regions and subregions have average rates that are erosional (tables 4 and 12). The average long-term rate of all transects is \(-0.17 \pm 0.01 \text{ m/yr}\) and the average short-term rate is \(-0.15 \pm 0.01 \text{ m/yr}\). A majority of Maui
transects display erosion (85 percent of long term and 76 percent of short term). Seven km or 11 percent of the total extent of Maui beaches studied were lost to erosion in the time span of analysis.

North Maui

Along North Maui the number of historical shorelines ranges between four and eight, and the years range from 1899 to 2002 (table 11). Of the 903 transects, 38 percent of long-term rates and 27 percent of short-term rates are statistically significant (fig. 37). In spite of seasonal variability in shoreline position from large winter waves, North Maui has the highest percents of significant rates of the three Maui regions—a result of an overall trend of chronic erosion.

Table 11. Number and range in years of shorelines on Maui.

Table 12. Average shoreline-change rates at each subregion on Maui (m/yr).

Figure 37. Map and plots of North Maui: long-term and short-term shoreline change rates.

The long-term average of all rates for north Maui (-0.26 ± 0.02 m/yr) is the most erosive of the three Maui regions (table 4). All three subregions on the North Shore have average long-term rates that are erosional. Eighty-seven percent of this coast is erosional in the long term and 74 percent is erosional in the short term (table 4). The maximum erosion rate (-1.5 ± 1.1 m/yr) is found in front of an offshore rock bench at Baldwin Park (table 13). Shoreline recession at Baldwin is due, in part, to sand mining operations by now defunct lime kiln. A bench of beachrock previously acted as a tombolo, but is now isolated offshore (Genz and others, 2009). Other areas of significant erosion are found at Waiehu Beach Park (up to -0.5 ± 0.3 m/yr, long term) and Kanaha Beach Park (up to -1.5 ± 0.7 m/yr, long term). Long-term accretion occurs at 12 percent of transects at North Maui. The maximum long-term accretion rate (1.5 ± 1.3 m/yr) occurs at Kanaha Beach Park between two groins.
The average of all short-term rates on the North Shore is $-0.22 \pm 0.03$ m/yr, roughly equal to the long-term average. Seventy-four percent of the beach is erosional in the short term (table 4). The maximum short-term erosion rate ($-2.2 \pm 1.1$ m/yr) is found in the same location as the maximum long-term erosion rate—Baldwin Park (table 13). Only 16 percent of North Maui beaches are accreting in the short term. As with the long-term rates, the maximum short-term accretion rate ($2.1 \pm 0.2$ m/yr) is found in Kanaha Beach Park. Short-term rates follow a similar pattern to long-term rates, though uncertainty is higher in the short term due to a shortened dataset.

**Kihei Maui**

Kihei is the least erosional region of Maui based on average long- and short-term rates and percents of erosional transects (table 4). However, relative to study regions on Kauai and Oahu, Kihei is still highly erosional. Of the 1011 transects in Kihei, statistically significant change rates are found at 22 percent of transects in the long term and 19 percent of transects in the short term—the lowest of the three Maui regions (fig. 38). A relative lack of significant rates at Kihei may be a result of high short term (noise), as numbers and range of historical shorelines are similar to other Maui regions. Between 3 and 9 historical shorelines between 1900 and 2007 are available in the Kihei region (table 11).

**Figure 38.** Map and plots of Kihei coast, Maui: long-term and short-term shoreline change rates.

Two km or 11 percent of the total length of Kihei beaches analyzed in this study was completely lost to erosion. The average long-term rate of shoreline change at Kihei is $-0.13 \pm 0.01$ m/yr. Eighty-three percent of transects are erosional in the long term and 77 percent of transects are erosional in the short term. The maximum long-term erosion rate ($-1.1 \pm 0.6$ m/yr) is found at Kawililipoa in the remains
of a fishpond (table 13). Other areas with significant long-term erosion include South Wailea (up to -0.5 ± 0.2 m/yr), North Wailea (up to -0.4 ± 0.2 m/yr), Kalama Beach Park (up to -0.8 ± 0.5 m/yr, beach lost), and Maalaea (up to -0.6 ± 0.2 m/yr). The maximum long-term accretion rate (1.6 ± 0.4 m/yr) is also found at Kawililipoa, along an accretional cusp.

The average short-term rate is -0.12 ± 0.02 m/yr and 77 percent of short-term rates are erosional (table 4). The maximum short-term erosion rate (-1.8 ± 7.5 m/yr) is found at Kalepolepo Beach Park where the beach has been lost to erosion. The maximum short-term accretion rate is found at the same location as the long-term maximum accretion rate (Kawililipoa, 1.8 ± 0.8 m/yr). Long- and short-term rates have similar overall trends.

West Maui

West Maui has five to ten historical shorelines between 1912 and 1997 (table 11). Of the 1,519 transects, 27 percent of long-term rates and 18 percent of short-term rates are significant (fig. 39). Four km or 14 percent of the total length of beach analyzed was lost to erosion in the time span of the study.

**Figure 39.** Map and plots of West Maui: long-term and short-term shoreline change rates.

The average of all long-term rates for West Maui is -0.15 ± 0.01 m/yr and 85 percent of transects are erosional in the long term. All subregions in West Maui are erosional in the long- and short-term based on average rates. The Napili Kapalua subregion has the highest average erosion rates at -0.22 ± 0.02 m/yr in the long term and -0.19 ± 0.03 m/yr in the short term. The maximum erosion rate (-0.9 ± 0.6 m/yr) is found at Ukumehame adjacent to a boulder revetment installed to protect the coastal highway (table 13). Other areas of significant long-term erosion include Hekili Point (up to -0.3 ± 0.2 m/yr), Olowalu (up to -0.3 ± 0.2 m/yr), Launiupoko (up to -0.5 ± 0.3 m/yr), Puamana (up to -0.5 ± 0.2 m/yr), Mala Warf (up to -0.5 ± 0.4 m/yr), Honkowai (up to -0.5 ± 0.4 m/yr), Kahana (up to -0.4 ± 0.1
m/yr), and Napili Bay (up to -0.4 ± 0.2) The maximum accretion rate (0.6 ± 0.2 m/yr) is found at Puuonoa Point. Puuonoa Point between erosional cells fronting Lahaina and Mala Wharf.

Erosion at West Maui is somewhat reduced, overall, in the short term compared to long term with an average short-term rate of -0.13 ± 0.01 m/yr and 77 percent of transects erosional. The maximum short-term erosion rate (-0.7 ± 1.7 m/yr) is located at Mokuleia Beach (table 13). The percent of accretion increased from 14 percent (long-term rates) to 18 percent (short-term rates). The maximum accretion rate is at the same location as the maximum rate in the long-term analysis (Puunoa Point at Lahaina).

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