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Annual and interannual changes on a reef-fringed pocket beach: Kailua Bay, Hawaii

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Abstract

Historical aerial photographs and topographic survey sheets are used to establish a 70-year shoreline history (1926–1996) for Kailua Beach, Oahu, Hawaiian Islands. The shoreline has migrated seaward over this period at an average rate of 0.5 m/yr, with a maximum net accretion along the beach of 58.7 m and a maximum net erosion of −13.2 m. Net accretion has taken place even while sea levels have risen on the order of 0.1 m. Semi-annual and monthly beach profile surveys (1995–1999) at seven transects reveal short-term variations of shoreline position, sand volume, and beach shape. A relationship between beach width and corresponding sand volume fluctuations, established from the beach profile data, is applied to the historical shoreline change data to establish a history of sand volume fluctuations. Results show that Kailua has experienced a net accretion of 673 000 m^3 of sand over the period 1926–1996, with average annual rates of volume change varying between 6.8 m^3/m/yr and −0.1 m^3/m/yr. The most recent period (1989–1996) shows a net volume increase of 41 000 m^3. Given the lack of sand inputs at the ends of the beach, exchange with offshore deposits is a likely mechanism for long-term accretional trends. Seasonal fluctuations in Kailua Beach morphology dominate the variability with a response to seasonal wave state that varies along the length of the beach in magnitude and sign. At least four alongshore zones are observed, with the first and third zones exhibiting high/low sand volumes during the summer/winter, and the second and fourth zones exhibiting opposite behavior with high/low volumes during the winter/summer. Although seasonal sand accumulation varies along the beach, the overall beach profile is largely maintained. Moreover, changes in sand volume occur in phase over the subaqueous and subaerial sections of the beach. This behavior suggests that longshore rather than cross-shore sand transport is important at annual time scales. A simple seasonal transport pattern is proposed to account for these observed fluctuations, which depends in part on the topography of the offshore reef. © 2002 Published by Elsevier Science B.V.

Keywords: beaches; beach erosion; Hawaii; photogrammetry; shorelines; sediment transport

1. Introduction

Hawaii's economy is heavily dependent on revenue generated by the state's billion-dollar tour-

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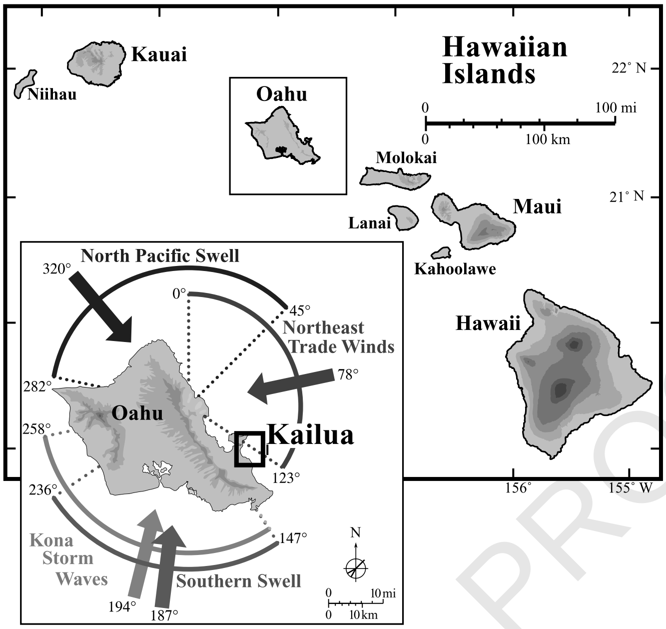


Fig. 1. Kailua Bay receives the direct impact of the northeasterly trade winds, which are dominant 90% of the summer months and 50–80% of the winter months (Harney, 2000).

ism industry. The Hawaiian Islands (Fig. 1) have long been a popular destination due to the attraction of their beautiful white sandy beaches. As a result of rising sea level and widespread human impacts to beach sediment budgets, many sandy coastlines are eroding (NRC, 1995). It is important, therefore, to gain an understanding of short- and long-term morphodynamic beach behavior patterns, as well as an understanding of beach responses to varying environmental conditions and stresses (Fletcher et al., 1997).

While many beaches in Hawaii have been eroding to a point of societal hazard, others are accreting through time despite a trend of rising sea level (1.8 cm/decade). In many cases, beaches that are eroding are adjacent to beaches that are accreting (Fletcher et al., 1997), with both exposed to similar wind and oceanic forcings. Clearly, long-term beach behavior is governed by details of the local littoral sediment budget, which in turn is presumably a function of the local topography controlling incident wave forcing. In general, beaches in Hawaii each have a unique topographic setting and wave exposure making it necessary to assess factors contributing to long-term trends on a case by case basis. Prior to this study, however, no sediment budget governing beach evolution has been described quantitatively for Hawaiian beaches.

To address these issues, we examine one particular beach system in detail, namely Kailua Beach on the eastern shore of Oahu, Hawaii. Kailua is characterized by a broad embayed setting and a wide fringing reef. Here, we integrate sand volume and beach width data from beach profile monitoring on Kailua Beach, with historical shoreline position and beach width data to obtain 70 years of sand volume fluctuations extending to the depth of the fringing reef. We describe the dominant temporal and spatial patterns of sand volume with emphasis on the seasonal cycle and the secular trend over the study period. We find that longshore transport contributes significantly to seasonal changes while cross-shore transport, primarily at a sand-filled paleostream bed, is important at longer time scales. Ultimately, it is anticipated that results obtained from Kailua may assist regulators and planners in understanding and managing coastal erosion for other Hawaiian and insular shorelines.

2. Previous work

Smith and Zarillo (1990) used beach profiles to quantify potential errors that result from seasonal and short-term variability in shoreline position in order to determine the effect on the accuracy of historical shoreline change based on aerial photographs. This study concluded that short-term fluctuations in shoreline position might be the largest source of quantitative error in calculations of long-term variations in shoreline position.

Coyne et al. (1999) conducted end-point analysis of shoreline change in Hawaii. Our research builds upon this work. In Coyne et al., aerial photographs from 1949 and 1996, digitally rectified using Differential Global Positioning System ground control points, were used to create georeferenced photomosaics. Delineation (on-screen digitizing) of the shoreline change reference feature (SCRF) provided the basis from which average annual shoreline change rates were calculated and erosion hazard zones were projected. The beach toe was used as the SCRF.

Dail et al. (2000) measured beach volume changes for nearly 1 year at Waimea Beach on the north shore of Oahu. Beach elevation was mapped using RTK-GPS and, as such, only the subaerial portion of the beach was studied. Seasonal variations dominated the observed variability with the entire subaerial beach eroding and accreting in unison.

Rooney (2002) uses a time-series analysis of aerial photographs and beach profiles in the examination of a 5-km segment of the Kihei coastline on Maui, Hawaii, to produce a database of historical changes in sediment volume. They determine that, despite a trend of significant erosion over the southern portion of the study area, the overall sediment budget for the area records a net gain (2.9×10^5 m^3) as the accretion over the northern portion greatly exceeds the lost volume from the southern portion. They show that sediment movement along this coast likely results from variations in Kona storm activity (strong rain-bearing winds that blow from the south or south-southwest), which is modulated by the Pacific Decadal Oscillation.

Harney (2000) determined the late Holocene sediment budget for Kailua Bay by examining gross carbonate framework construction, bioerosion and direct sedimentation. She found that sand storage accounts for 73% (±23%) of the carbonate sediments estimated to have been produced since 5000 yr BP across the reef, beach and adjoining coastal plain. The imbalance likely represents sediment loss due to the natural processes of dissolution, abrasion and transport offshore.

Richmond et al. (2002) measured sediment transport within a large, shore-normal channel in Kailua Bay. They documented onshore transport under weak to moderate trade wind conditions and offshore transport when trade winds were stronger. They were not able to document net seasonal or annual transport. The shoreward head of the channel is characterized by a broad sand field in only 5 m of water adjacent to the beach in the center portion of the study area.

3. Study area

Kailua Bay is located on the northeast coast of Oahu, in the Hawaiian Island chain. Conditions along this shoreline are dominated by northeast trade winds that average 10–20 knots for 90% of the summer season (April–September) and 50–80% of the winter season (October–March) (Harney, 2000). Trade wind waves dominate summer conditions, with average heights of 1–3 m and periods of 6–9 s. During the winter, swell waves from the North Pacific occasionally reach up to 4 m in height with periods of 10–20 s. The typical tide range in Hawaii is less than 1 m.

Kailua Beach is approximately 4 km in length, 20–40 m in subaerial width, with a beach face slope that ranges between 0.09 and 0.13. The crest and seaward face of the low frontal dune are typically vegetated with low ground cover. During high wind and wave events, small erosional scarps (<0.5 m) often form at or near the vegetation line. There is no continuous well-defined saturation line on the beach face. At the base of the foreshore is a step, the top of which, the beach toe, occurs approximately at the intersection of the uprush and backwash on the foreshore. This position often corresponds to mllw.

The Kailua nearshore often consists of a sand substrate in the form of a shallow terrace punctuated with short, shore-parallel troughs and rip channels. Kailua Beach fluctuates between reflective and dissipative states (Wright and Short, 1983), often approximating the ridge-runnel or low tide terrace configuration. In this state, rip channels are infilled and troughs, runnels and ridges are formed as the bar or terrace welds to the beach. As welding progresses, troughs and runnels are filled in. According to Wright and Short (1983), the proximity of the bar and beach face in this configuration facilitates rapid exchange of sand, which leads to high temporal variability.

Seaward of the terrace, the sand profile drops off relatively quickly, terminating at the surface of a broad fringing reef crest (Fig. 2). The reef is bisected by a sand-filled paleostream channel 200–300 m wide. The channel originates in a central nearshore sand field and opens up onto a broad reef-front sand field approximately 3 km offshore, in a water depth of > 25 m. The depth of the fringing reef flat surface varies between 1.5 and 5 m below mean sea level (MSL) and is encountered approximately 40–100 m offshore from the berm crest. Living coral growth is found in variable density on the reef top. The principal locus of coral growth is on the reef front approximately 10–20 m below sea level.

Studies have concluded that Kailua is an isolated littoral system that does not receive significant sand influx from neighboring shorelines (Noda, 1989). Kailua sand is > 90% well-sorted carbonate, dominated by skeletal fragments of coralline algae and the calcareous green alga *Halimeda*, with coral fragments, mollusc fragments and benthic foraminifera contributing a lesser amount (Harney, 2000). Median sand grain diameter on the beach face is 0.3 mm.

4. Methods

4.1. Short-term shoreline and volume change

4.1.1. Beach profiles

We established seven beach profile transects along the length of the bay. Profiles were surveyed randomly with respect to tide level and wave state. Six semi-annual sets of beach profiles at four transects (transects 1, 4, 5 and 6) were collected between 1995 and 1998. In 1998, three new transects (transects 2, 3 and 7) were added for more complete coverage, and surveys were conducted monthly at all seven transects for 13

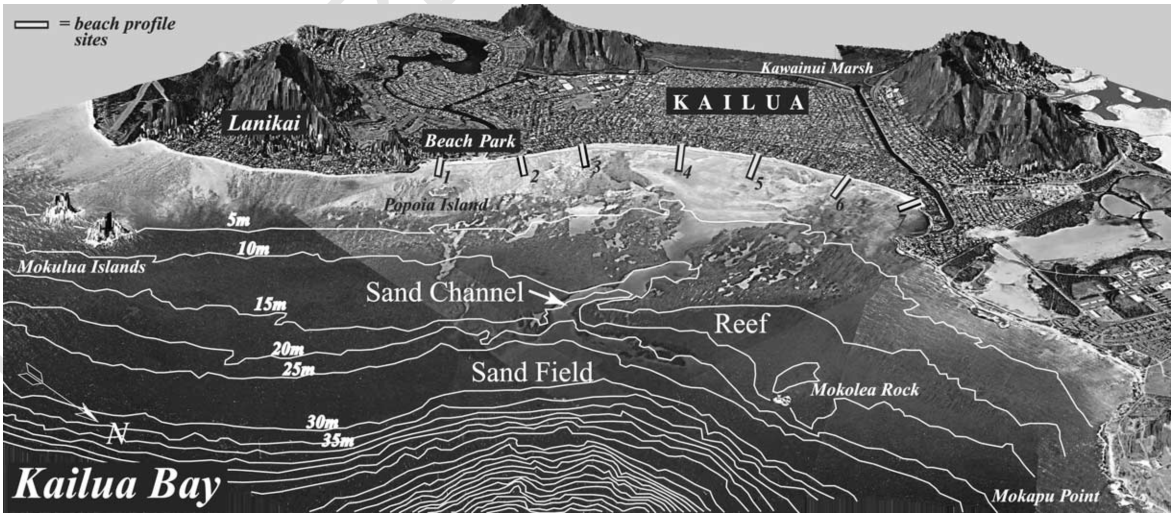


Fig. 2. The offshore environment of Kailua Bay is characterized by a shallow fringing reef bisected by a sand-filled paleostream channel.

months. The surveys, originally established in 1994 as part of an ongoing cooperative study by the University of Hawaii Coastal Geology Group and the U.S. Geological Survey Coastal and Marine Geology Program, were conducted with a Geodimeter Total Station and a swimmer carrying a prism on a telescoping rod, measuring points at approximately 1–5-m intervals and at every major break in slope and geomorphic feature (USGS, 2001).

Beach profiles extend from the back of the dune to beyond the depth at which the fringing reef surface is encountered (Fig. 3). This depth varies along the length of the bay from 1.3 m at the north end, 2.1 m at the south end and 3.9 m in the center of the bay. The profiles do not reach what would be considered to be a depth of closure as per Hallermeier (1978), in that the profile depth is limited by the presence of a shallow fringing reef. On two occasions in the winter of 1999, hard substrate was not encountered at the central transect, profile 4. In this case, the profiles were continued to a point where it was determined by the swimmer that the depth of the profile was not increasing significantly. Volume calculations are based on the observation that sand extends continuously to the depth of the fringing reef along the entire length of the profile.

4.1.2. *Beach profile response to environmental forcing*

Volumetric and morphologic changes in the beach profiles are compared to time series of daily averages of wave heights and wind speeds and tidal range, and no strong correlations are recognized. Wind speed and wave height data were provided by the University of Hawaii NOAA data center, Honolulu, Hawaii. Wave heights are based on daily visual observations of breaking wave height from the closest available location to Kailua, Makapuu Beach, located 12 km to the southeast. Although such observations are subjective by nature, they are found by Dail et al. (2000) to be significantly correlated with wave buoy heights at Waimea Bay, Oahu. As the wave field that affects Kailua is limited by the bay's northeast exposure, it was determined in this case that the use of visual observation data would be more representative of the wave field at Kailua than the data from non-directional offshore wave buoys. Daily averages of wave heights for the entire survey period, filtered with a moving average, are compared to corresponding beach volumes at each profile site, following Wright et al. (1985) and Dail et al. (2000). A seasonal cycle is apparent in both the wave conditions and profile volumes (Fig. 4). We investigate this signal further in 5.1.2. Beach profile response to environmental forcing. Such a correspondence is not found for filtered winds and tides.

4.1.3. *Empirical orthogonal function (EOF) analysis*

EOF analysis is used to quantify coherent spatial and temporal modes of variability in the beach profile data (Winant et al., 1975; Aubrey, 1979; Dick and Dalrymple, 1984; Losada et al., 1991). These empirical modes are ranked by the amount of variance explained, i.e. mode 1 accounts for the maximum covariability over the transect, mode 2 the next highest, etc. Each mode is described by a spatial and temporal component. The modes are uncorrelated, or orthogonal, in both space and time. We use EOF analysis on each profile to isolate energetic patterns of variability and to examine profile changes associated with variations in sand volume. The time average is removed from each point along the profile, thus the EOF describes variations from the mean beach profile. For the profile data, mode 1 typically dominates, explaining over 50% of the total variance (Fig. 5). Mode 2 typically explains between 10% and 30%, while remaining modes generally represent less than 10% of profile variations. We focus on the dominant mode 1 in 5.1.3. EOF analysis, which largely describes seasonal changes.

4.2. *Historical shoreline change*

4.2.1. *Photogrammetry*

We expand on the end-point historical shoreline change analysis of Coyne et al. (1999) in order to calculate more statistically robust long-term rates of shoreline change by studying a complete time

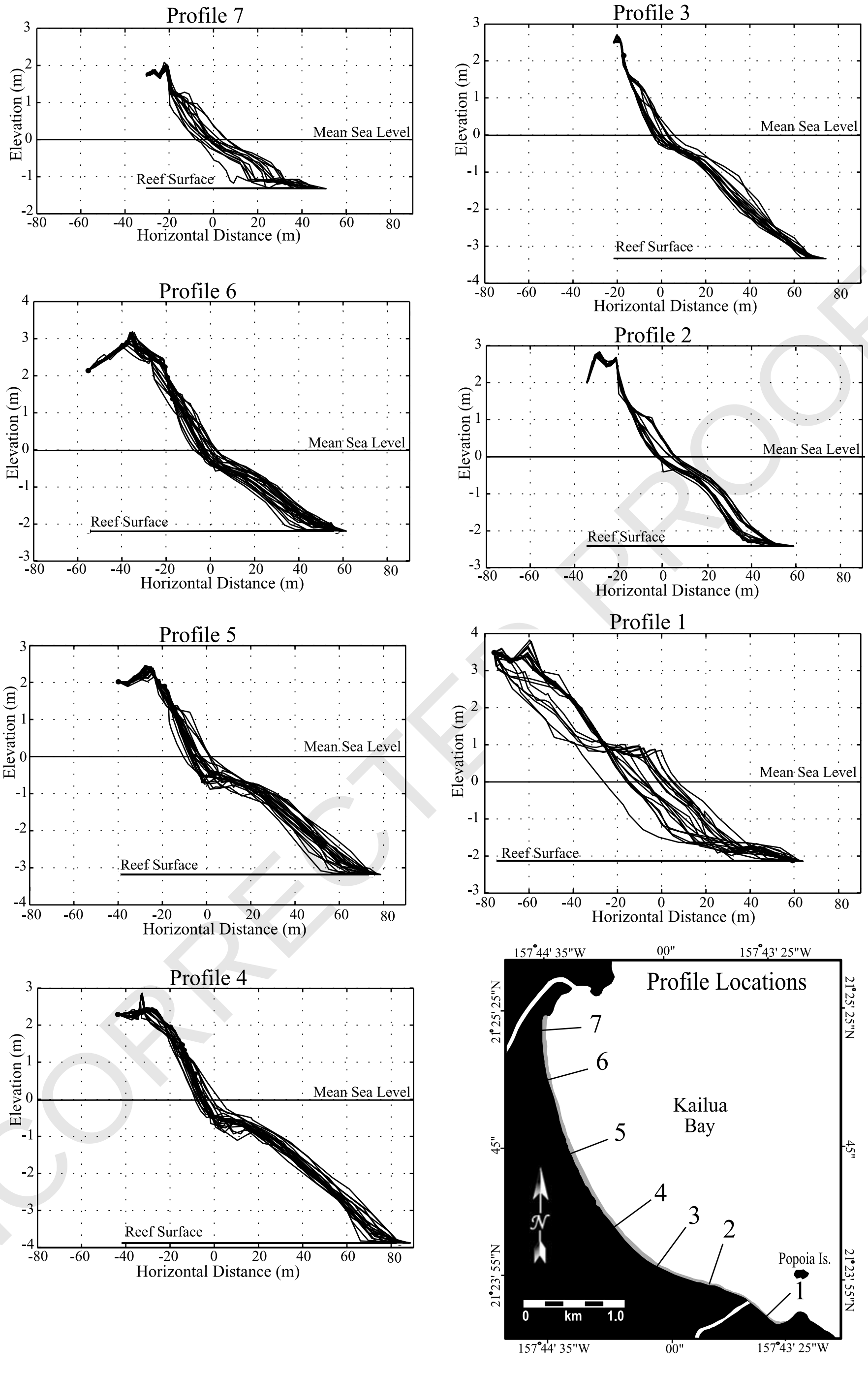


Fig. 3. Kailua Beach profiles and their locations. Profiles 1, 4, 5 and 6 were established in September 1995, and were initially surveyed on a semi-annual basis. Profiles 2, 3, and 7 were added in April 1998, after which all seven lines were surveyed on a monthly basis for approximately 1 year.

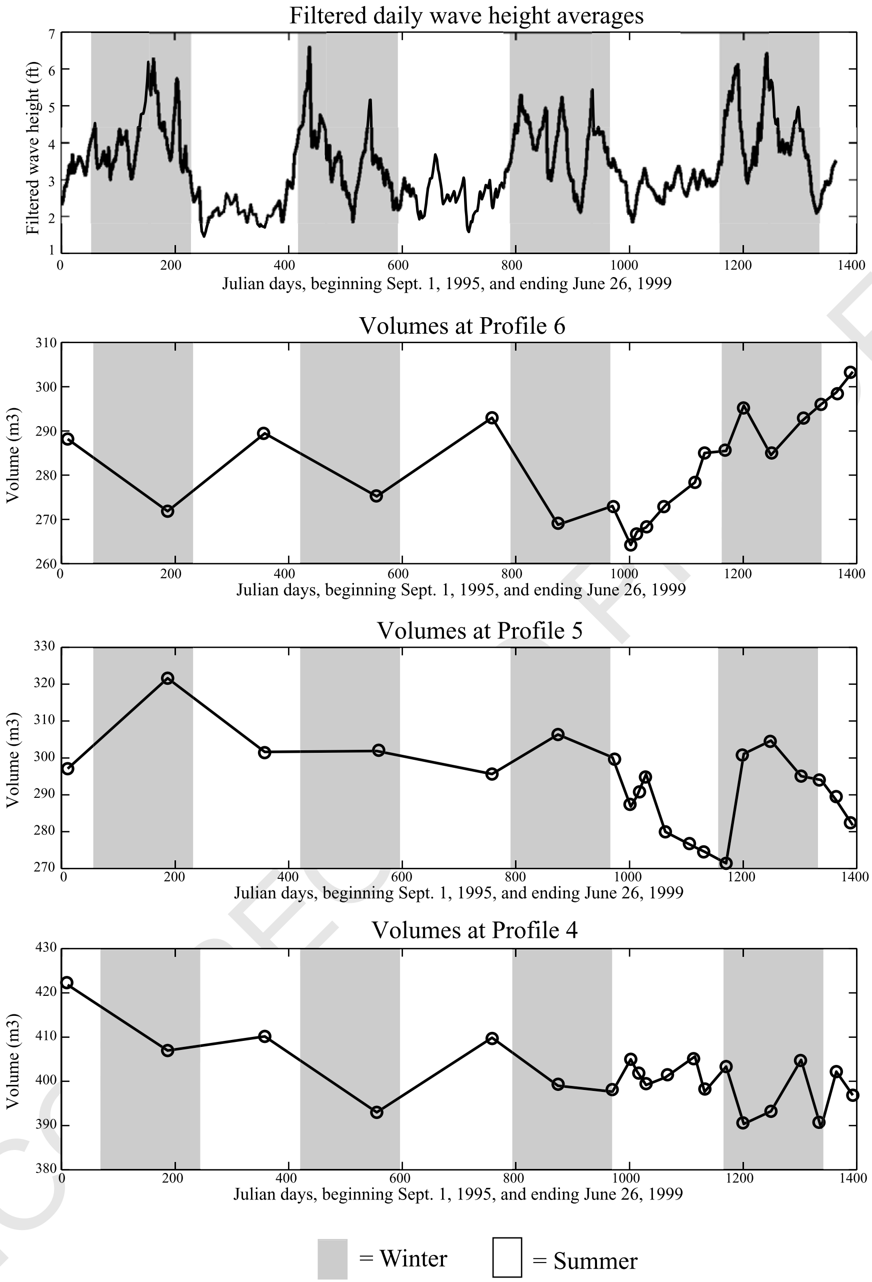
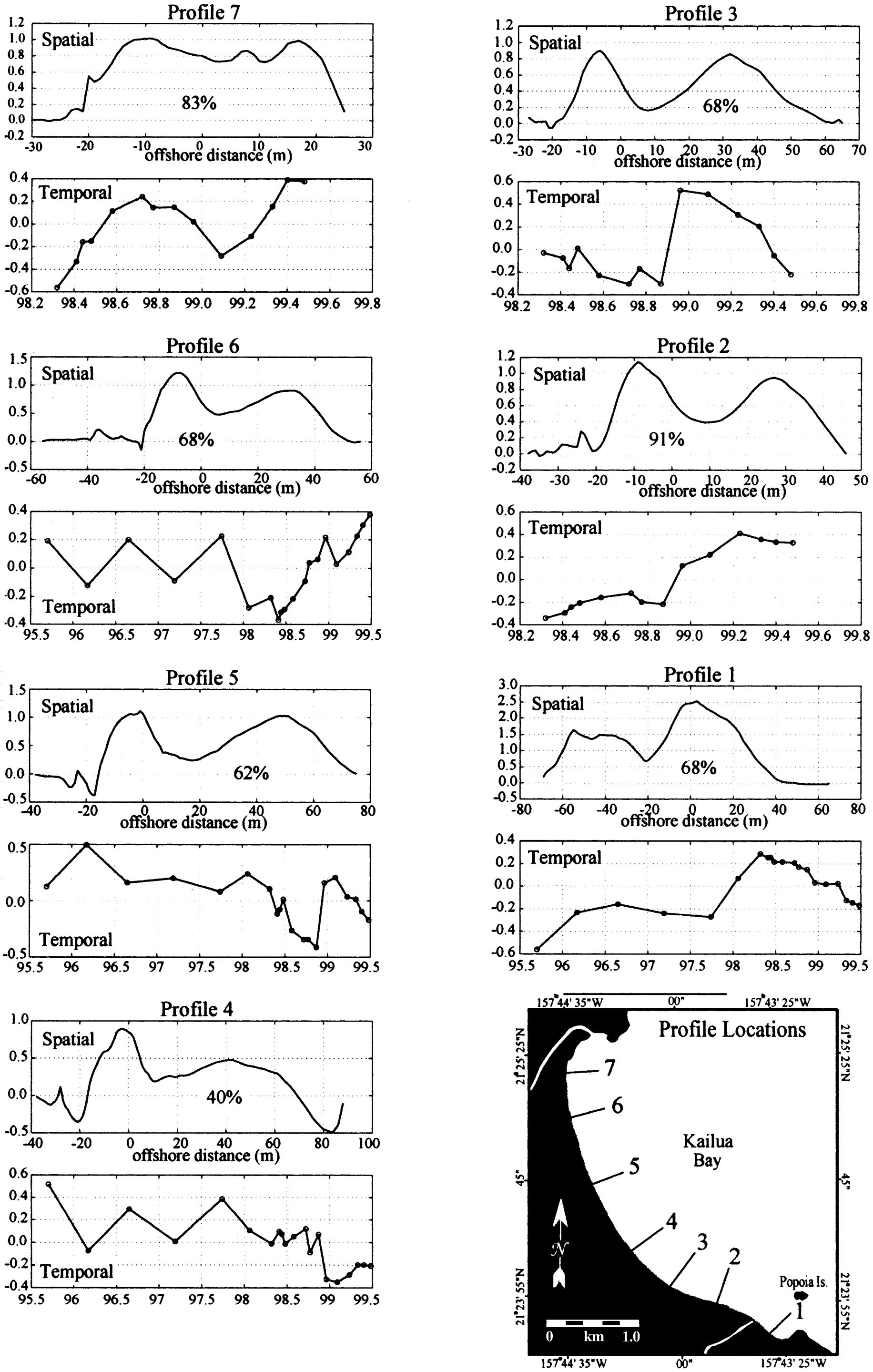


Fig. 4. Daily wave heights (from visual observation, Makapuu Beach) are filtered with a moving average to reduce high frequency fluctuations in the wave time series to emphasize the seasonal wave height pattern over the 4-year survey period. Filtered wave heights are compared with seasonal beach volume changes for profiles 4, 5, and 6. Profiles 4 and 6 experience a decrease in volume with increased winter wave heights, while profile 5 experiences an increase in volume under the same conditions. Under lower summer wave heights, profiles 4 and 6 experience an increase in volume while profile 5 experiences a volume decrease. Although not shown here due to the fact that they represent only 1 year of data and thus only one seasonal cycle, profile 7 displays behavior similar to profiles 4 and 6, and profiles 3 and 2 display behavior similar to profile 5.


Profile 7
Spatial
83%
offshore distance (m)
Temporal
Profile 3
Spatial
68%
offshore distance (m)
Temporal
Profile 6
Spatial
68%
offshore distance (m)
Temporal
Profile 2
Spatial
91%
offshore distance (m)
Temporal
Profile 5
Spatial
62%
offshore distance (m)
Temporal
Profile 1
Spatial
68%
offshore distance (m)
Temporal
Profile 4
Spatial
40%
offshore distance (m)
Temporal
Profile Locations
157°44' 35"W
00"
157°43' 25"W
21°25' 25"N
45"
21°23' 55"N
Kailua Bay
7
6
5
4
3
2
1
Popoia Is.
N
0 km 1.0

series of eight sets of historical aerial photographs and one NOS T-sheet. A least-squares linear regression is used as described by Crowell et al. (1999) to provide historical shoreline change rate trends (Fig. 6). Uncertainties associated with the photogrammetry method are not biased, uncorrelated and random in nature. Hence, measurement errors can be absorbed within the uncertainty term provided by our linear regression model of the long-term shoreline change rate (Neter and Wasserman, 1974). Shoreline change rates have an average uncertainty of ±0.13 m for the northernmost 150 transects, and ±0.29 m for the southernmost 50 transects. The 1926 high-water line as indicated on NOS T-sheets is digitized, converted from Old Hawaii Datum to WGS84, and overlain on our 1996 photomosaic. Small adjustments are then made to line up digitized fixed rock outcrops with corresponding outcrops on the photomosaic. The horizontal distance between the high-water line and the beach toe is averaged at seven monthly profile locations and added to the digitized high-water line from the T-sheet, to produce an estimated beach toe vector for 1926.

The delineated beach toe vectors from each of eight photomosaics representing past shoreline positions are overlain onto the 1996 mosaic for a complete time series of shoreline positions. Rates of change are determined at 200 shore-normal transects with a spacing of ~20 m alongshore, through the entire series, for a total database of 1600 rate determinations. Transects are numbered 1–200 from north to south. A spline function is used on these rates to interpolate between data points in order to more easily distinguish patterns of erosion and accretion. Variations of historical shoreline change rates are calculated for all 200 transects (Fig. 7).

Historical vegetation line positions are also digitized for all photomosaics. No vegetation position data are available for the 1926 NOS T-sheet. From the vegetation line positions along with the beach toe positions, beach width is determined for all photo years.

4.2.2. Historical volume change

Sand volume fluctuations are estimated from historical changes in beach width by developing a relationship between beach volume and beach width using the profile surveys. In addition, we multiply the movement of the historical vegetation line by the difference in elevation between the coastal plain and the depth of the fringing reef (Rooney and Fletcher, 2000) to calculate long-term coastal plain accretion. The following model, modified from Bodge (1998), compares changes in volume (ΔV) between consecutive beach profile surveys with changes in beach width (ΔX) for all seven profiles (Fig. 8), to establish the G_p value, which represents the slope of a linear regression:

$$G_p = \frac{\Delta V_1}{\Delta X_1} = \frac{\text{volume change per unit shorelength}}{\text{change in beach width}} \quad (1)$$

The G_p relationship is applied to the historical beach width fluctuations at each transect. To this, we add the product of the change in vegetation line with the depth of the fringing reef (at each transect), to determine the historical volume change (ΔV_2) of the area landward of the beach face (Rooney and Fletcher, 2000) (Fig. 9). Net volume change for each 20-m transect is then obtained using:

$$\Delta V_2 = [(G_p * \Delta X_2) + (\Delta\text{Veg} * \Delta Z)] * 20 \quad (2)$$

where ΔV_2 = total volume change for a 20-m-wide, shore-normal transect, G_p = slope of least median

Fig. 5. EOF analysis (mode 1) of the beach profiles. Spatial components reveal two dominant antinodes for each profile, representing an onshore and an offshore location of primary sand volume change at each transect. Notably, volume changes are occurring largely in phase across each profile, as evidenced by the dominantly positive values across the spatial components. Temporal components reveal the seasonal nature of the profile volume changes. Note the different time scales, with profiles 1, 4, 5 and 6 representing 4 years of data and profiles 2, 3, and 7 representing only 1 year of data. Due to the longer period of data collection, seasonal signals are most easily distinguished at profiles 4, 5, and 6. Percentages indicate the amount of variance characterized by mode 1 at each site. MSL is located at 0 m offshore distance on all spatial plots.

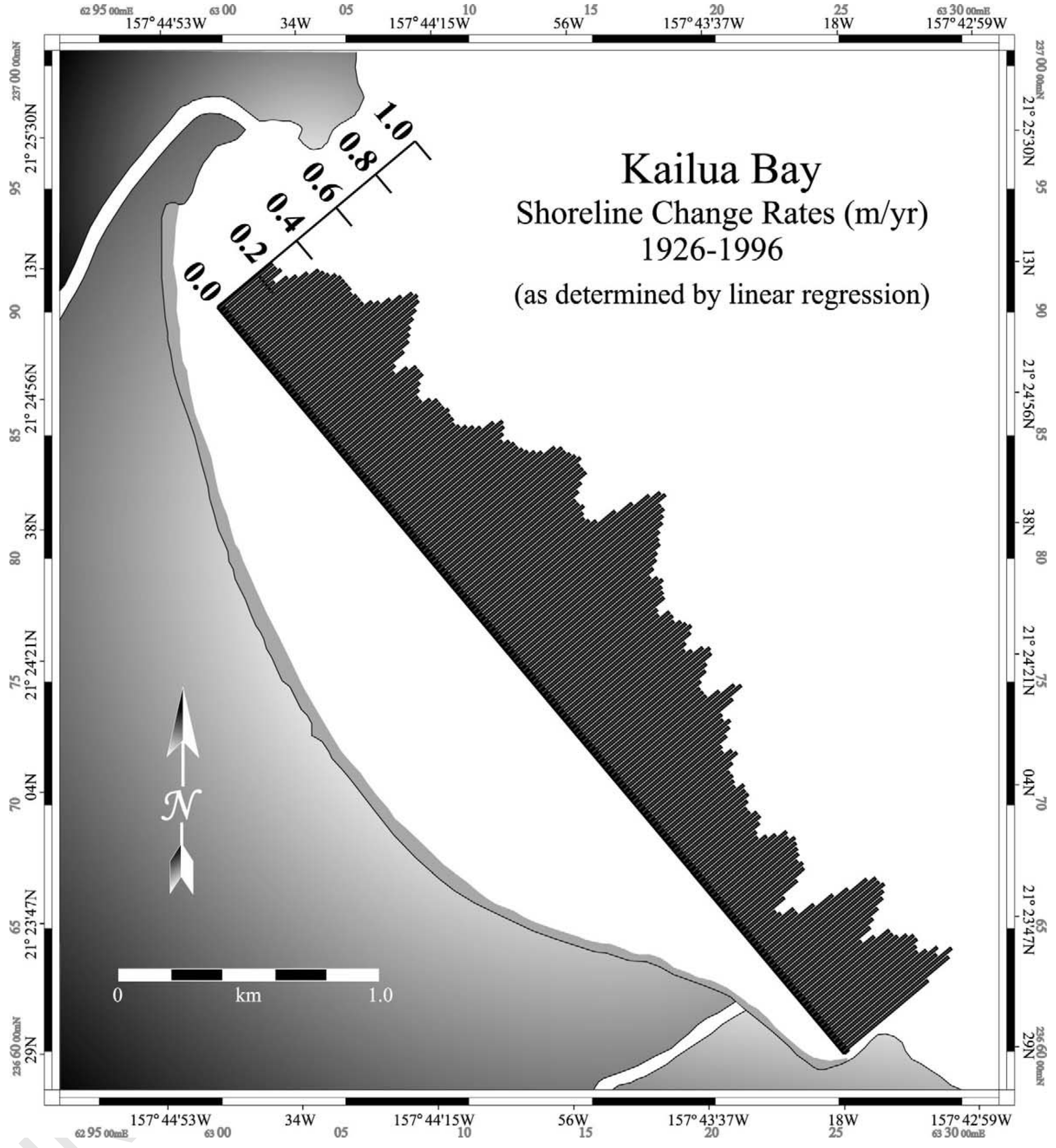


Fig. 6. Linear regression is used to establish shoreline change rate trends along each of the 200 shore-normal transects over the 70-year study period.

of squares regression relating ΔV and ΔX_1, ΔX_2 = horizontal change in shoreline position, ΔVeg = horizontal movement of vegetation line, and ΔZ = elevation difference between the coastal plain and the depth of the fringing reef, as seen in beach profile data. Due to anthropogenic impacts at profile 1, a separate value of G_p was determined and applied to the south end of the beach.

Total volume change rates were calculated for every 20-m transect, for each of the eight incre-

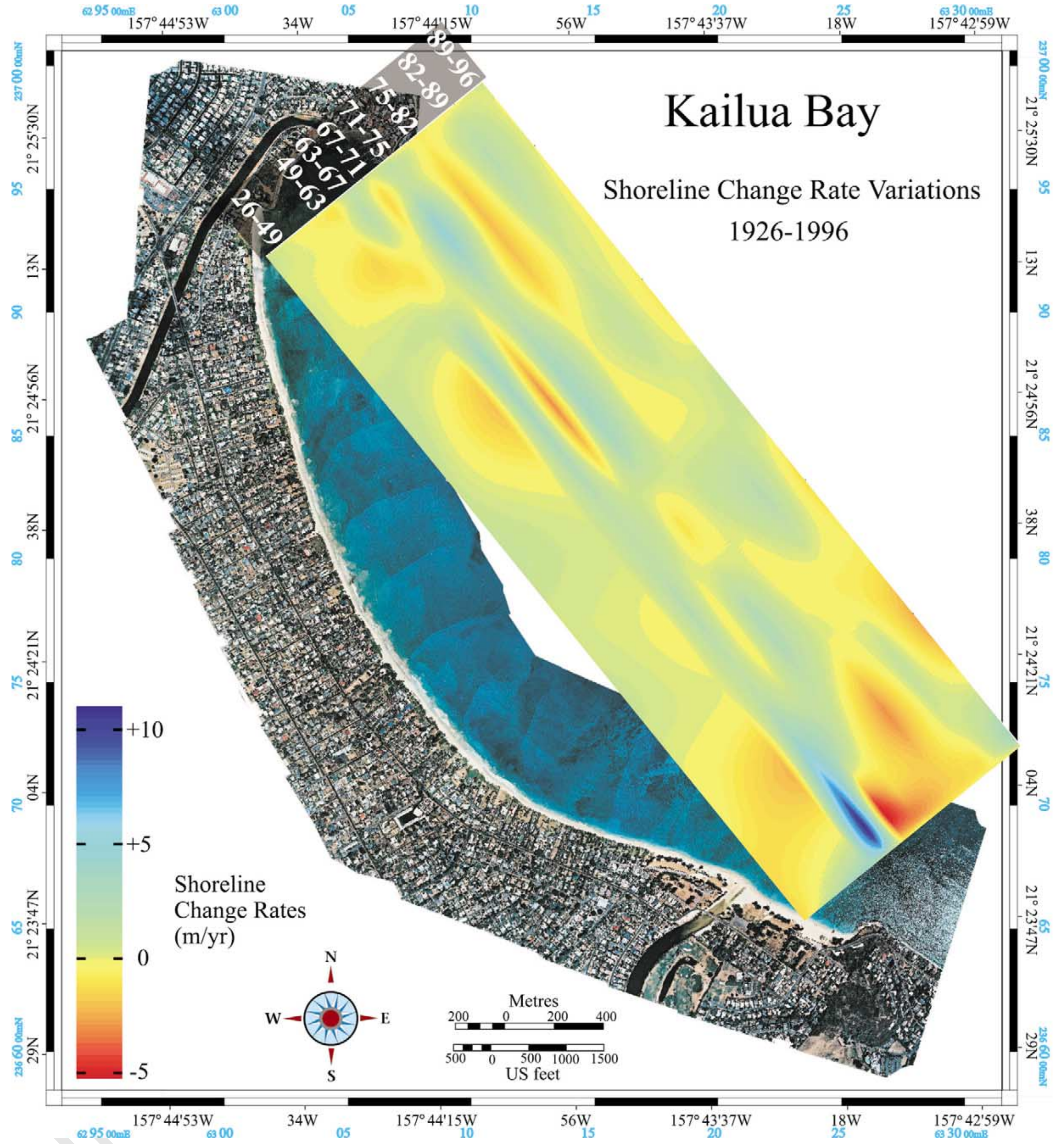


Fig. 7. Interpolated shoreline change rates calculated between photo years along 200 transects, over a 70-year study period. The vertical axis on the graph represents the years covered by the aerial photographs and T-sheet, broken down into the time periods between photo years. The horizontal axis represents the length of the shoreline.

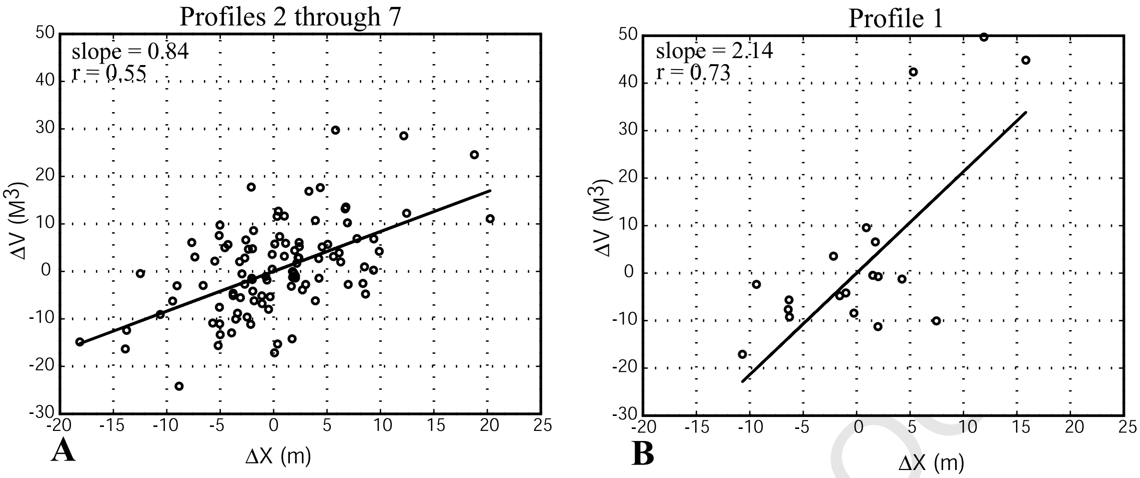


Fig. 8. Relationships between change in volume (Δ*V*) and change in beach width (Δ*X*).

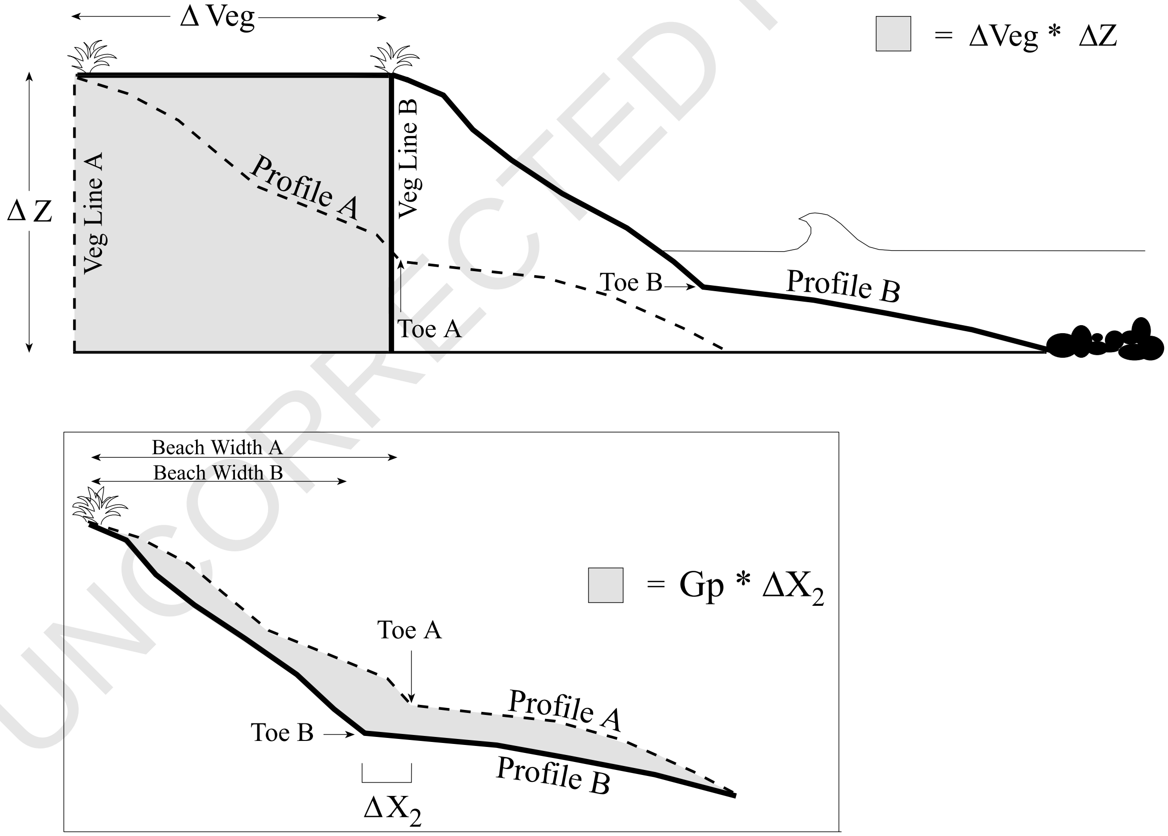


Fig. 9. Method of calculating historical volume change. This involves two separate components: (1) volume change based on vegetation line movement, and (2) volume change based on change in beach width. Total volume change between successive photo years is represented by the sum of the shaded areas.

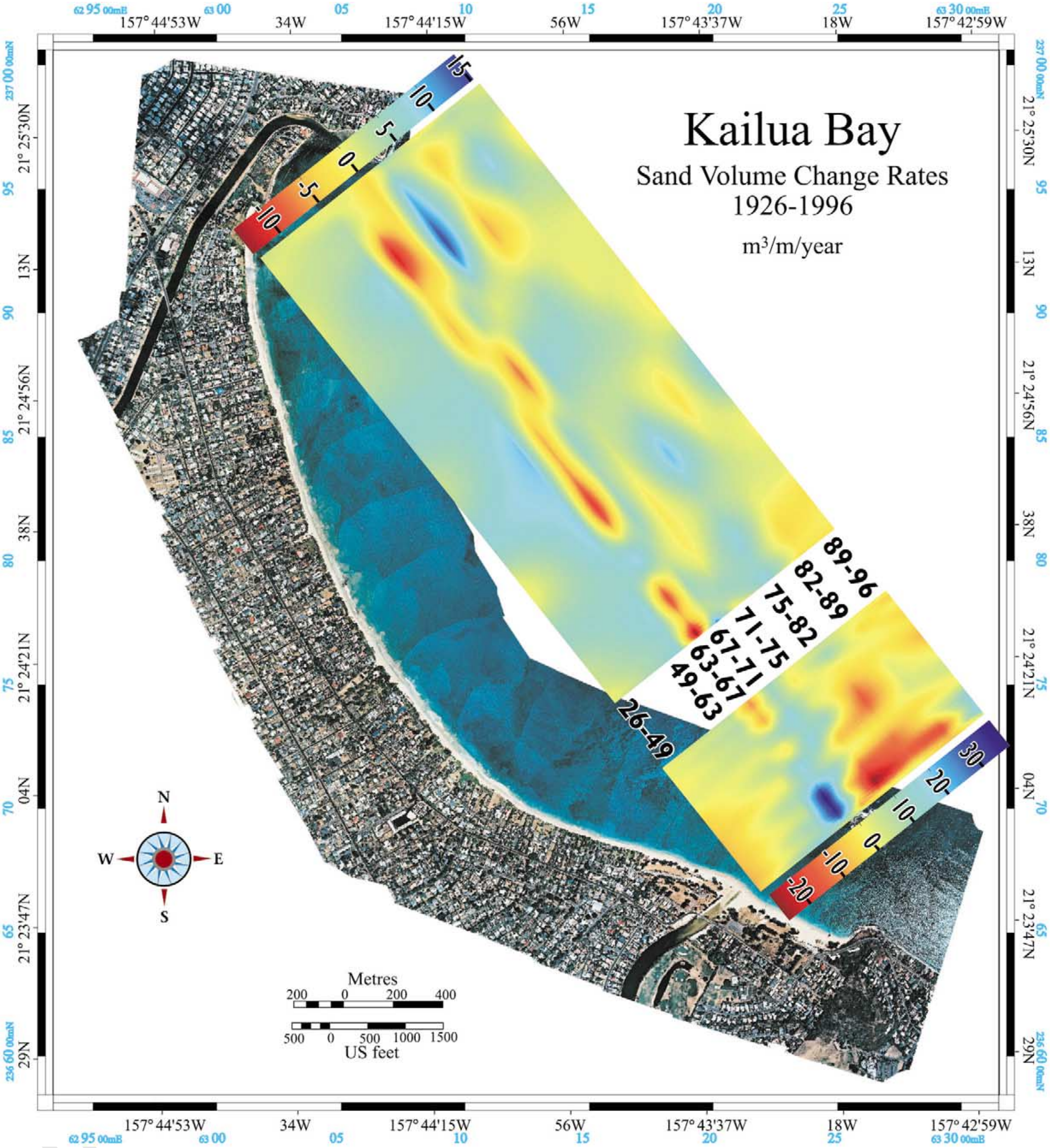


Fig. 10. Interpolated historical volume change rates; separated into the northernmost 150 transects and the southernmost 50 transects. Note the different scales of volume change. Rates are calculated between successive photo years. The vertical axis on the graph represents the years covered by the aerial photographs and T-sheet, broken down into the time periods between photo years. The horizontal axis represents the length of the shoreline.

ments in the time series. A spline interpolation is run on these rates, in the same manner as with the shoreline change rates, to more easily distinguish patterns of volume addition and loss (Fig. 10).

5. Results

5.1. Short-term change

5.1.1. Beach profile volume and beach toe fluctuations

Onshore and offshore characteristics for each of the beach profiles are presented in Table 1. Profile 1, located at Kailua Beach Park, is mechanically altered by park managers and exhibits morphodynamic behavior quite different from the other sites. The presence of a rocky headland 200 m to the south of this transect and a small island approximately 600 m offshore, separated from the beach by a shallow fringing reef, may also contribute to the behavior difference we observe. Accordingly, the sector containing profile 1 and 50 aerial photo transects (totaling a distance of 1 km) is treated separately in this analysis.

The depth and seaward extent of the profiles are determined by the depth and proximity of the fringing reef. In general, profiles extend farther offshore and reach greater depths toward the center of the bay where the fringing reef is deepest and farthest offshore.

The total sand volume is calculated under each profile. With the exception of the southernmost profile (1), profiles towards the ends of the beach have the lowest volumes, steadily increasing toward the most central profile (4), which has the greatest volume (Table 2). This is directly related to the depth and proximity of the fringing reef, as mentioned above. Average volume (per alongshore distance) ranges from 94 m^3/m for the northernmost profile to 402 m^3/m for the central profile. The beach toe was found to vary up to 5.3 m horizontally over the course of a spring tidal cycle. Over the last 14 months of data, the maximum range of beach toe fluctuation varied from 9.2 to 13.6 m for the six northernmost lines, while profile 1 experienced a range in beach toe movement of 32.1 m.

5.1.2. Beach profile response to environmental forcing

A comparison of the filtered daily wave height to the net sediment volume at each site reveals a clear relationship between seasonal wave behavior and profile volume. An increase in wave energy from North Pacific swells wrapping into the bay, coupled with lighter and more infrequent trade winds between November and April, corresponds with a period of volume decrease at profiles 7, 6 and 4, and volume increase at profiles 5, 3 and 2. Strong, consistent trade winds generating short-period wind waves coupled with minimal long-period swell energy from the north between May and October corresponds to volume increases at profiles 7, 6 and 4, and volume decreases at profiles 5, 3 and 2. From this behavior, we divide these six profiles into four groups, based on their relative location and seasonal behavior: profiles 7 and 6 represent the northernmost group, hereafter referred to as group A; profile 5 represents a sec-

Table 1
Beach profile characteristics

Profile	Approx. distance from south end of beach (m)	Approx. subaerial beach width (m)	Approx. distance to offshore reef flat from shoreline (m)	Approx. depth to offshore reef flat (m)
1	200	40	50	2.1
2	1050	23	50	2.4
3	1500	20	65	3.3
4	2050	28	80	3.9
5	2900	23	70	3.2
6	3500	25	50	2.2
7	3950	18	40	1.3

Table 2
Beach profiles, August 1994 to June 1999

Profile	Maximum volume (m^3/m)	Minimum volume (m^3/m)	Average volume (m^3/m)	Maximum seasonal toe position difference (m)	Location of peak onshore variation (horiz. distance from MSL) (m)	Location of peak offshore variation (horiz. distance from MSL) (m)
1[a]	374	237	327 ± 69	32.1	−55	3
2	218	185	200 ± 17	12.3	−8	27
3	230	201	213 ± 15	13.4	−6	33
4	422	390	402 ± 16	13.1	−4	44
5	322	271	294 ± 26	9.2	−2	50
6	303	264	282 ± 20	13.6	−7	33
7	112	74	94 ± 19	13.5	−10	17

[a] Note that profile 1 is examined separately due to the distinctly different conditions present at this location.

ond behavioral group, B; profile 4 represents group C, and profiles 3 and 2 represent group D. Again, we treat profile 1 separately in this analysis. During the final year of the surveys, profile 1 experienced continuous volume decrease.

5.1.3. EOF analysis

The dominant EOF for each of the seven profile lines describes elevation changes that are in phase across the profile. Thus erosion occurs simultaneously at both subaerial and submarine regions. Likewise, the entire profile will accrete si-

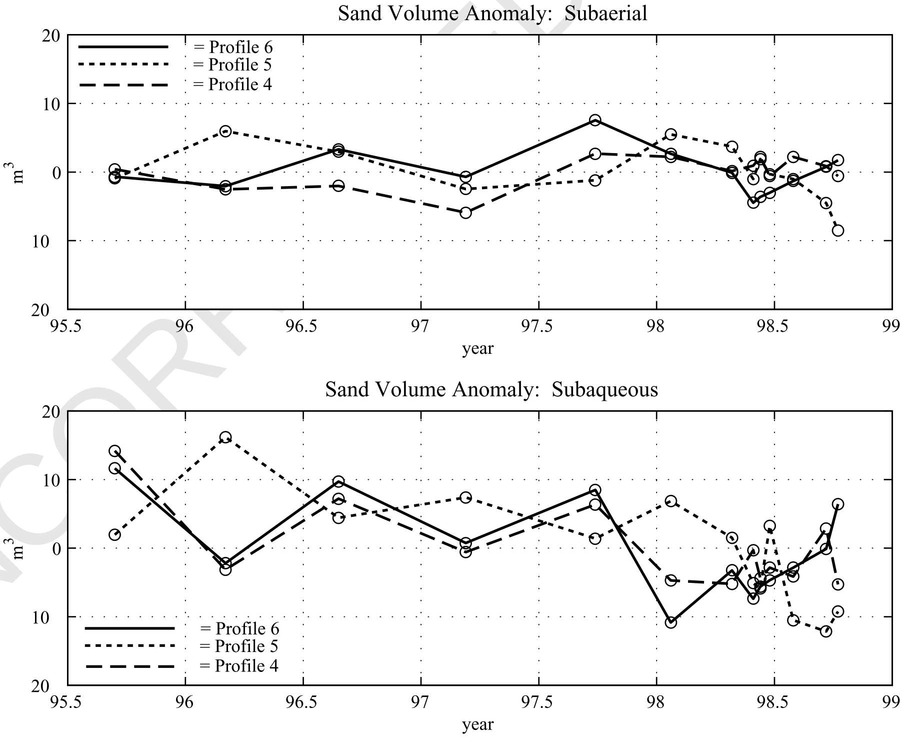


Fig. 11. The sand volume anomaly (volume change after the mean profile is removed from the sum of the profiles) reflects changes occurring primarily below the water line. While changes in the subaerial beach are relatively small with little evidence of a temporal trend, the subaqueous portion of the beach profiles accounts for much of the net volume change and is where net erosion is occurring.

multaneously, with the occasional exception of very slight out-of-phase behavior at the dune crest or at the seaward extent of the profile. This suggests that the mode describes net volume changes at each profile line that are associated predominantly with longshore sand transport. However, there does not appear to be a terminal region of net gain or loss to counterbalance alongshore changes in the middle of the system. This suggests that alongshore sand delivery extends only as far as the neighboring profile group rather than throughout the entire beach. Alongshore sediment sharing is very localized on the beach.

The dominant EOF modes do not indicate sand moving directly from the beach face to an offshore location during an erosional event at any of the profiles, or vice versa during an accretional event. Such a pattern describes the classic bar-berm exchange of sand associated with seasonal changes in wave climate (Komar, 1998). Instead, each of the mode 1 spatial profiles has anti-nodes (section of maximum spatial amplitude) onshore and offshore of MSL where most of the sand changes occur, separated by a nodal region located 10–20 m offshore from MSL where sand does not accumulate and elevation changes are small. The exception is profile 1 with a nodal point 20 m onshore of MSL. There is much greater variability in the position of the offshore anti-nodes compared to the relative similarity of the onshore anti-nodes for all the profiles. Offshore anti-nodes vary from 18 to 50 m offshore and onshore anti-nodes peak close to 10 m landward of the water line. When divided into subaerial and subaqueous portions, the EOF analysis reveals that the offshore region of the profile exhibits greater volume changes than the onshore region (Fig. 11).

Although the mode 1 EOF accounts for volume changes at each of the profiles, the overall profile shape is for the most part maintained. That is, even as the beach moves onshore and offshore with a net gain or loss of sand, the profile is characterized by steep foreshore and offshore zones seperated by a flat terrace. A possible explanation for this is that occasional energetic wave events cause sand redistribution along the beach, however, the cross-shore profile at any given time is more a reflection of a relatively persistent shore break owing to ongoing trade wind forcing and the shallow reef offshore limiting the range of wave heights that reach shore.

While the spatial structure of mode 1 fluctuations is consistent at each profile line, the mode 1 temporal behavior differs at each profile. An accretionary trend component is evident at the terminal profiles (1, 2 and 7), an erosional trend occurs at the central profiles (4 and 5), with little trend evident at the intermediary profiles (3 and 6). A strong seasonal cycle is also apparent in the more densely sampled portion of the record beginning in 1998.

To confirm that the mode 1 EOF describes net volume change, the mean profile from each site was removed, and a plot of volume change through time was compared to the time dependence plot for the mode 1 EOFs (Fig. 12). The strong resemblance of these plots to one another suggests that mode 1 is dominated by changes in net sand volume.

The EOF analysis is consistent with the four morphodynamic groups (A, B, C, and D) along Kailua Beach associated with seasonal profile change. The groups alternate in terms of their seasonal response, creating the effect of standing wave behavior in the form of large-scale rhythmic volume fluctuations. Groups A and C experience summer volume increases and winter volume decreases, while groups B and D experience winter increases and summer decreases. This corresponds with our observations of volume change in comparison to seasonal wave forcing. Profile 1 demonstrates little seasonality, with the exception of increased volume resulting from the strong northerly fronts that can push sand into this region in the winter.

5.2. Historical shoreline and volume change

5.2.1. Photogrammetry results

The Kailua shoreline experienced net accretion over the 70-year study period with a maximum net seaward migration of 58.7 m at transect 91 (Figs. 13A,B). The trend of net accretion peaks toward the center of the bay, dropping off slightly toward both ends. Within the southernmost 50

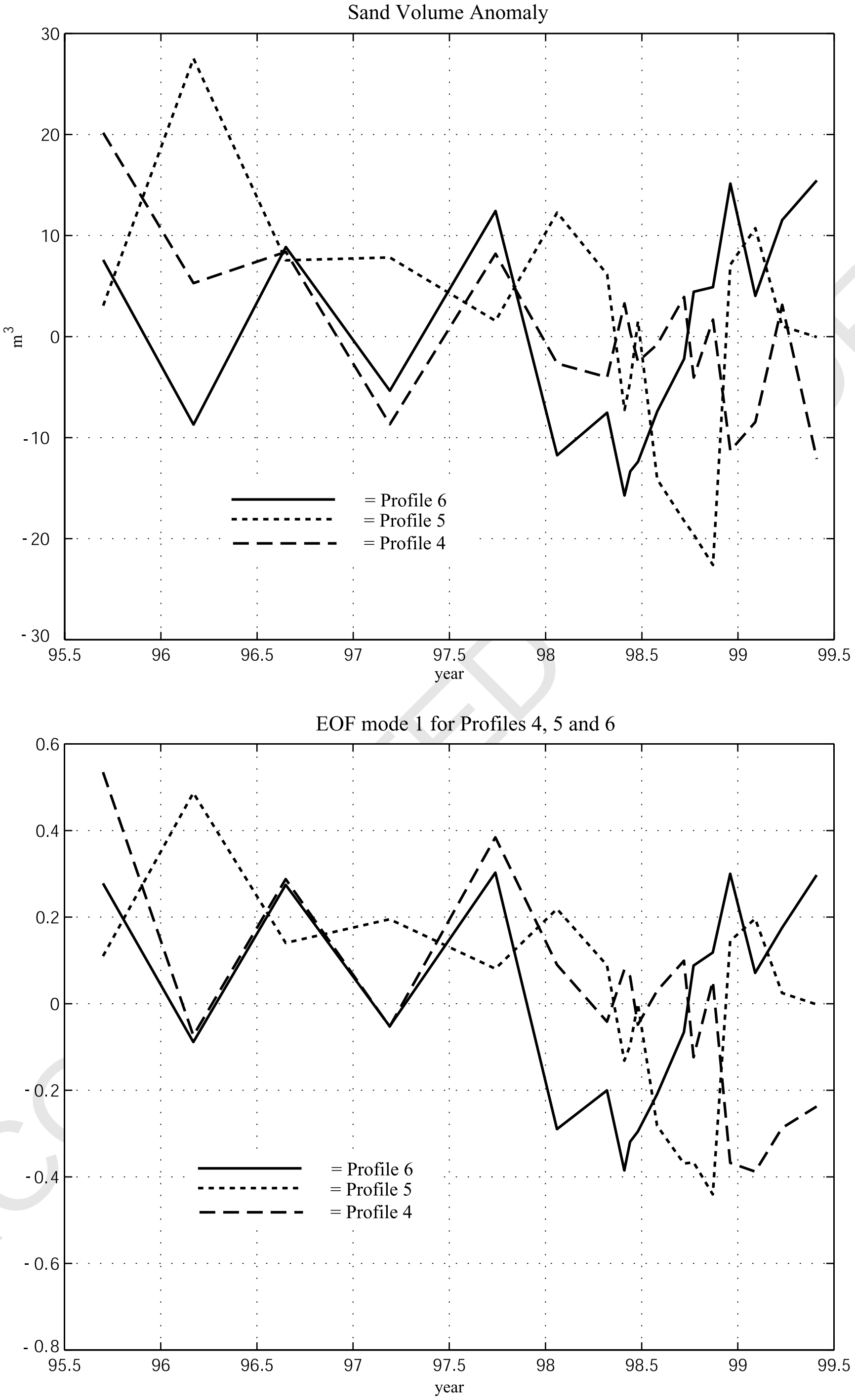


Fig. 12. The mode 1 variability matches net changes in total sand volume at each of the profiles. Sand volume is strongly seasonally modulated. In addition, sand volume appears to be decreasing through time, and out-of-phase spatial behavior is evident.

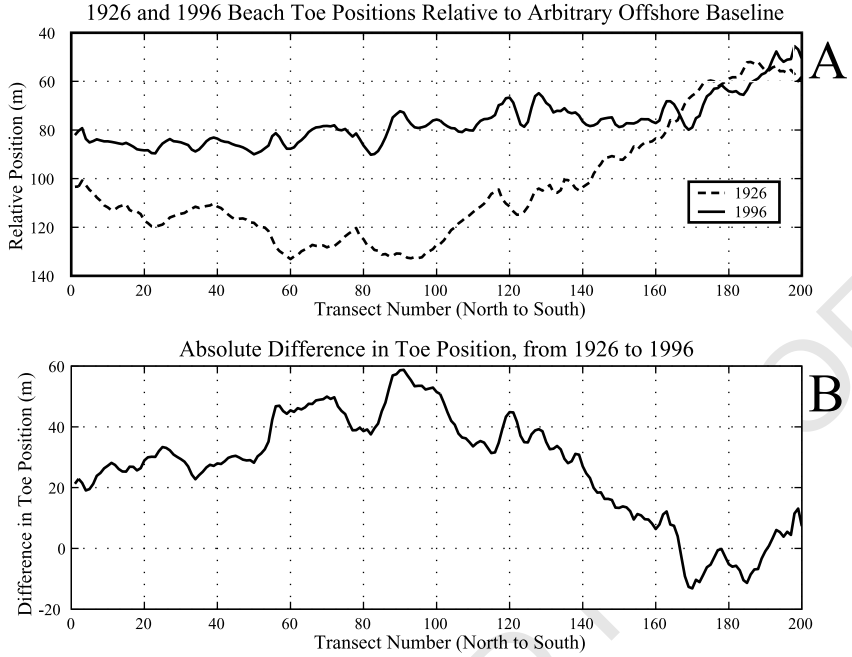


Fig. 13. Beach toe positions relative to an arbitrary offshore baseline (used as a basis from which to measure beach toe and vegetation line change along shore-normal transects) demonstrate significant net accretion between 1926 and 1996 (A). Absolute difference in beach toe positions between 1926 and 1996 (B) shows that net accretion has been most significant toward the center of the bay, tapering off toward both ends. Erosion at the south end is due to poor sand management by authorities.

transects, some net erosion has occurred, with a maximum net erosion of −13.2 m.

Shoreline change rates varied across the eight time intervals and northernmost 150 transects from a maximum accretion rate of 4.7 m/yr between 1971 and 1975, to a maximum erosion rate of −4.0 m/yr between 1967 and 1971. Average annual rates of shoreline change between photo years varied between 2.0 m/yr and −0.7 m/yr (Table 3). The percentage of eroding transects ranged

Table 3
Historical shoreline change

Time interval	Maximum toe change rate		Minimum toe change rate		Average toe change rate		Percent erosional transects	
	(m/yr)		(m/yr)		(m/yr)			
	Northern 150 transects	Southern 50 transects	Northern 150 transects	Southern 50 transects	Northern 150 transects	Southern 50 transects	Northern 150 transects	Southern 50 transects
1926–1949	1.3	0.2	−0.2	−1.4	0.6	−0.7	4.7	80
1949–1963	1.7	3.2	−0.4	−0.3	0.8	0.7	1.3	12
1963–1967	4.2	14.0	−2.3	−0.4	1.4	6.1	16.7	4
1967–1971	2.8	4.5	−4.0	−7.1	−0.7	−0.5	67.3	44
1971–1975	4.7	1.7	−2.2	−3.5	2.0	−0.2	18.7	48
1975–1982	1.2	−0.1	−2.7	−4.5	−0.7	−2.1	81.3	100
1982–1989	2.5	2.4	−0.4	−1.0	1.1	0.8	12.0	10
1989–1996	2.1	3.3	−1.7	−2.8	−0.2	−0.2	74.7	50

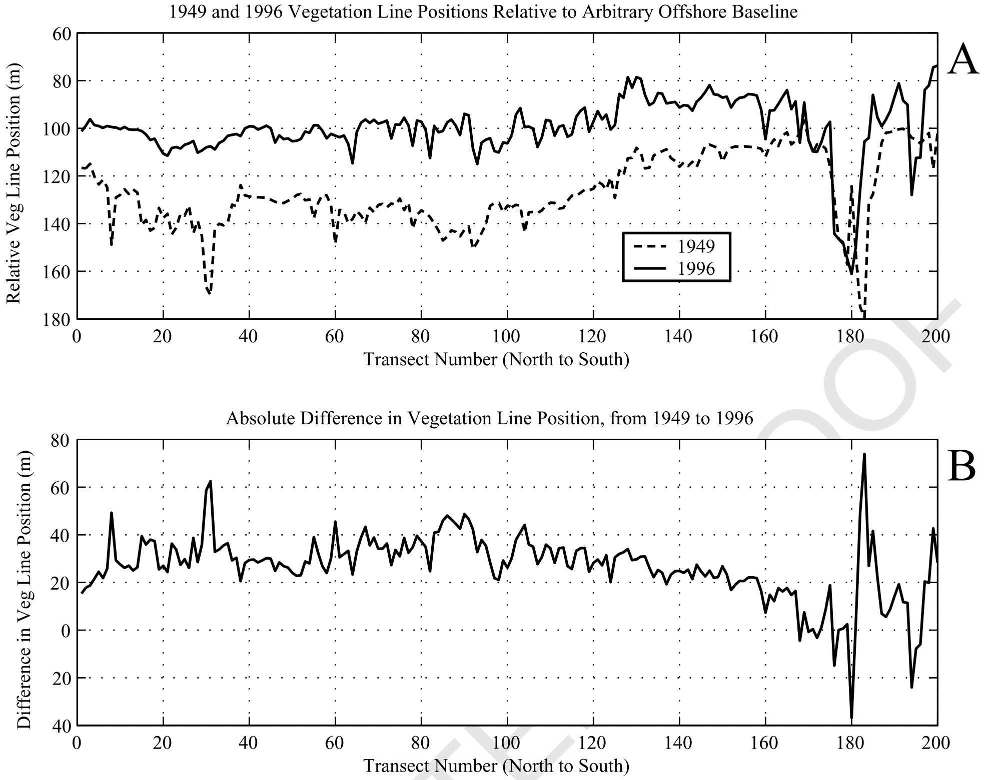


Fig. 14. Vegetation line positions relative to an arbitrary offshore baseline (used as a basis from which to measure beach toe and vegetation line change along shore-normal transects) demonstrate a significant accretion of the vegetation line between 1926 and 1996 (A). Absolute difference in vegetation line positions between 1926 and 1996 (B) shows that net progradation of the vegetation line has been relatively uniform along the length of the bay. For both A and B, the large fluctuations surrounding transect 180 are due to the presence of a stream channel.

from 1.3% between 1949 and 1963, to 81.3% between 1975 and 1982.

The central 300 m of the bay has accreted during the 70-year study period. Transects 97 and 98, a 40-m-long section of beach located almost directly at the center of Kailua Bay, have consis-

Table 4
Historical beach width change

Year	Maximum beach width (m)		Minimum beach width (m)		Average beach width (m)		
	Northern 150 transects	Southern 50 transects	Northern 150 transects	Southern 50 transects	Northern 150 transects	Southern 50 transects	All 200 transects
1949	64.3	95.5	16.6	15.7	28.4	31.9	29.3
1963	53.1	76.7	10.4	18.2	25.6	24.8	19.4
1967	55.1	115.2	19.8	22.3	27.3	49.9	33.0
1971	56.4	110.0	11.6	11.4	23.5	37.7	27.0
1975	59.6	104.6	18.3	20.0	28.6	40.0	31.5
1982	50.1	95.5	8.9	14.5	21.1	26.4	19.4
1989	47.4	97.8	12.1	17.8	23.2	40.4	24.8
1996	37.6	97.1	6.9	8.3	18.6	35.6	22.9

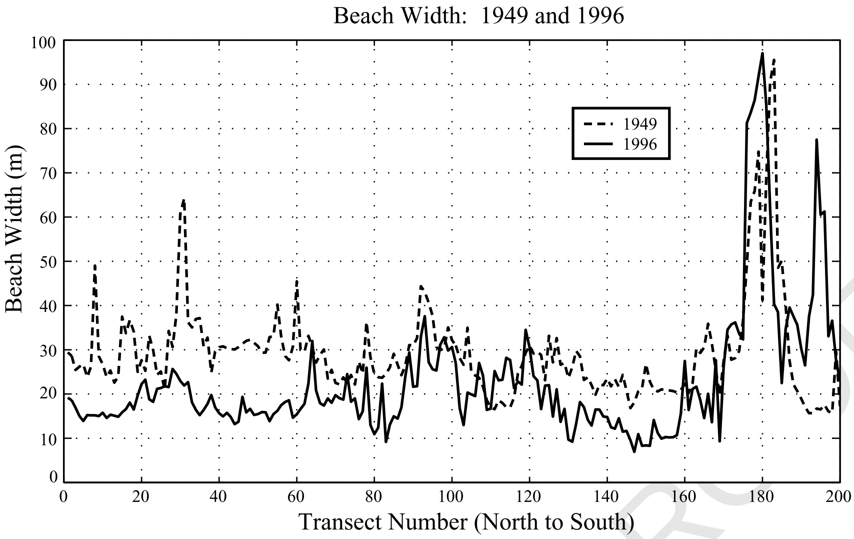


Fig. 15. Average beach width has decreased significantly over the 70-year study period. Beach width is greatest at the south end due to human foot traffic at Kailua Beach Park.

tently experienced accretion over the entire 70-year period. There appear to be distinct behavior patterns along the beach, based on shoreline change rates throughout the time series, which show inherent variability in the alongshore structure and alternation of alongshore erosion and accretion.

Least-squares regression of the eight annual shoreline change rates along each of the 200 shore-normal transects over the 70-year period from 1926 to 1996 shows a consistent accretional trend along the entire beach, with a maximum rate of +0.8 m/yr of accretion occurring toward the center of the bay, generally decreasing toward the ends of the bay with a minimum rate of +0.1 m/yr toward the south.

In addition to the historical trend of beach toe accretion, the vegetation line has also been moving seaward at up to 1.6 m/yr since 1949 (Figs. 14A,B). The accretion rate of the vegetation line has been slightly faster than that of beach toe accretion, which has resulted in a narrowing of the average beach width along the majority of

Table 5
Historical volume change

Time interval	Maximum volume change rate (m^3/m/yr)		Minimum volume change rate (m^3/m/yr)		Average volume change rate (m^3/m/yr)		Total volume change (m^3/m/yr)	
	Northern 150 transects	Southern 50 transects	Northern 150 transects	Southern 50 transects	Northern 150 transects	Southern 50 transects	Northern 150 transects	Southern 50 transects
1926–1949	8.1	1.5	−1.4	−8.6	3.2	−4.1	9 500	−4 000
1949–1963	16.6	18.0	−6.4	−5.4	7.2	6.3	21 700	6 300
1963–1967	60.3	32.9	−27.3	−13.6	−4.5	8.0	−13 600	8 000
1967–1971	17.9	35.0	−12.0	−18.1	1.3	10.1	4 000	10 000
1971–1975	20.8	22.1	−7.3	−25.8	4.0	−3.8	12 000	−3 800
1975–1982	14.1	9.2	−9.8	−20.7	3.5	−5.4	10 600	−5 400
1982–1989	9.8	5.3	−10.1	−25.7	1.4	−3.3	4 100	−3 300
1989–1996	17.3	29.4	−6.3	−8.1	1.4	1.8	4 100	1 800

Kailua Beach (Fig. 15), from an overall average of 29.3 m in 1949 to 22.9 m in 1996 (Table 4).

5.2.2. Historical volume change

Profile volume changes are compared to corresponding changes in beach width. This relationship is used to account for historical fluctuations in sediment volume resulting from variations in historical beach width. Volume changes under the profiles represent 12–93% of the total volume change (when added to the coastal plain volume change) between successive photo years.

Total volume increases of up to 60.3 m^3/m/year, and decreases of up to -27.3 m^3/m/year occurred over the study period. Alongshore average rates of volume change for the northernmost 150 transects vary from 7.2 m^3/m/yr in the 1949–1963 interval, to -4.5 m^3/m/yr in the 1963–1967 period (Table 5). Total volume changes range from a 28 000 m^3/yr rate of increase between 1949 and 1963, to a 5600 m^3/yr rate of loss between 1963 and 1967. The most recent period (1989–1996) shows a net volume increase of 41 000 m^3. Over the 70-year study period, there has been a total net gain of 673 000 m^3 (Table 6). An additional point of interest is that the southernmost 50 transects, which we examine separately, experienced zero net change over the 70-year period.

6. Discussion

6.1. Short-term behavior

6.1.1. Profile response and antecedent conditions

We had hoped to develop a model of beach response to a given set of environmental conditions, however, we did not find significant correlations between available wave, wind, and tide data with various measures of beach change. We attribute this lack of correspondence to the premise that the beach response will depend on the antecedent state of the beach as well as the instantaneous forcing (Wright and Short, 1983). For example, accretion occurred at five of seven profile sites after the highest wind and wave event over the final 2 years of surveys. This is most likely a result of the beach being in a heavily eroded state prior to the storm due to sustained periods of elevated wind and wave energy in the preceding months. Wright and Short (1983) also found that a beach that was already highly eroded might experience accretion under heavy wave conditions, and that often the same set of wave conditions could cause erosion at one beach and accretion on a neighboring beach. In addition, in Kailua, we often see periods of high wind and wave activity interspersed with calm periods; thus, as concluded by Dail et al. (2000), averaging these conditions with the goal of predicting resultant morphology may not adequately integrate erosion and accretion cycles.

Table 6
Net volume change 1926–1996 (m^3)

Entire beach	673 000
Northernmost 50 transects	159 000
North-central 50 transects	293 000
South-central 50 transects	227 000
Southernmost 50 transects	−6 000

Clarke and Eliot (1988) studied sediment transport on a 2-km pocket beach in Australia, and concluded that short-term changes in beach morphology resulted from longshore transport, whereas long-term changes could be explained by onshore–offshore sediment movement. Our findings agree with this, and indicate that longshore transport dominates the annual to interannual shoreline variability whereas decadal variability, though not documented by our profile time series, is dependent on cross-shore profile changes governed by sediment availability.

6.1.2. Applicability of equilibrium profile theory for Kailua Beach

The concept of an equilibrium beach profile, originally proposed by Bruun, 1954, describes an average profile shape maintained by the shoreface, related to sediment size and wave climate, with slight seasonal and wave-related fluctuations. Bruun (1962) expanded on this theory to predict the response of a beach profile to rising sea level. The resulting ‘Bruun Rule’ has since been used as the basis behind most approaches to modeling shoreline response to sea level rise. The original models have undergone several modifications to account for some of the shortcomings and to expand on their uses. For example Dean (1997) developed models to describe the destructive forces acting in the surf zone that may assist in maintaining an equilibrium profile, and Kriebel et al. (1991) expanded the equilibrium profile model to predict storm-induced profile changes due to storm surge. Equilibrium profile theory is also used in the SBEACH model (Larson and Kraus, 1989) for predicting shoreline change due to cross-shore sediment transport, as well as the GENESIS model (Hanson and Kraus, 1989), for predicting shoreline change due to fluctuations in longshore sediment transport. It has been noted by Pilkey et al. (1993) and Komar (1998) that there are problems with the underlying assumptions with the concept of an equilibrium beach profile, for example: (1) there must exist a closure depth beyond which sediment transport to or from the system by wave action does not occur, (2) underlying geology is not a factor in determining profile shape, and (3) the equilibrium condition is a two-dimensional system dominated by cross-shore transport. These three factors, amongst others, raise the question of the applicability of both the equilibrium profile model and the Bruun Rule to Kailua Beach.

(1) The equilibrium profile theory employs the concept of closure depth - the depth beyond which surface waves cease to affect the ocean floor sediments. Closure depth was calculated at Kailua as per the methods of Hallermeier (1981) and Birkemeyer (1985), and was found to be 6.5 m and 4.9 m, respectively. These results for closure depth can not be applied to the Kailua Beach profiles, due to the fact that hard bottom is encountered at a depth of between 1.3 m and 3.9 m.

(2) Thieler et al. (1995) examine the Wrightsville Beach, North Carolina shoreface, and determine that the underlying geology (an irregular bathymetry ranging from bare rock outcrops to mud) is the predominant factor controlling sediment transport processes and profile shape. Based primarily on this evidence, they conclude that an equilibrium profile is not possible for Wrightsville Beach. In Kailua, the underlying geology consists of an immobile limestone substrate. Munoz-Perez et al. (1999) address the issue of reef-protected beaches by taking into account waves breaking over a submerged reef and the corresponding change in wave energy flux, and find that no equilibrium profile is possible within a distance of about 10 to 30 h_r from the edge of a reef, where h_r is the water depth over the reef. As all profiles at Kailua fall within this minimum distance, we conclude that no equilibrium condition can be achieved by Kailua Beach relative to the incident deepwater wave energy. As to whether or not the presence of the hard bottom amplifies or absorbs wave energy, there is some discrepancy. While Munoz-Perez et al. (1999) find that waves shoaled on a sandy beach are higher than those shoaled over a hard bottom, Smith (2001) finds the opposite result on the Gold Coast of Australia, noting that shoaling wave energy is absorbed by unconsolidated sediment and not by hard bottom substrate.

(3) The issue of applying a two-dimensional model to a three-dimensional system is perhaps the strongest argument against applying the equilibrium profile theory to Kailua Beach. Although sand may be moving onshore and offshore near the center of the bay depending on physical conditions, it is distributed along the length of the beach by longshore transport. This is evidenced by simultaneous inflation or deflation across each profile, in all cases. We conclude that despite efforts to address some of the assumptions underlying equilibrium profile theory and to incorporate these factors into variations of the original model, the application of the various models is still not appropriate at Kailua.

The Bruun Rule implies that sea level rise results in a retreat of the shoreline as the upper beach is eroded and deposited offshore. The shoreline at Kailua, however, has been advancing relatively steadily over the past 70 years, despite rising sea level. Thus, the Bruun Rule clearly would not work for Kailua Beach. In concurrence, Bruun (1983) points out (regarding the Bruun Rule), ‘the theory is first of all an erosion and not an accretion theory’, as the forces causing erosion are different than those causing accretion and provide a clear indication that the local sediment budget can override the influence of sea level change in modulating beach behavior.

A conceptual model similar to equilibrium profile theory is the fair-weather/storm model describing beach-nearshore profile evolution in response to wave activity. Lee et al. (1995) and Lee et al. (1998) examined 10 1/2 years of biweekly profile data from Duck, North Carolina during 4 major groups of storms. They observed a cycle whereby a rapid, storm-induced transfer of sediment from the nearshore and transitional bar to an offshore bar, would be followed by a gradual return of sediment from the offshore bar to the nearshore zone during fair-weather conditions, while maintaining a relatively stable volume across the length of the profile. This model describes a system that is again essentially two-dimensional, suggesting that sand is transferred from the nearshore zone to the offshore zone and back based on wave conditions. Despite the fact that no major storms occurred in Kailua over the 4-year study period, high wind and wave events occurred periodically, interrupting periods of calm and moderate activity. Throughout all types of behavior, the beach profiles responded with either an increase or a decrease in volume across the entire profile, rather than a transfer in volume from onshore to offshore (or vice versa), differing considerably from the fair-weather/storm model.

6.1.3. *Large-scale rhythmic shoreline behavior*

Although short-term environmental conditions are not a predictor of beach morphology at Kailua, over a longer time interval a strong seasonal mode of behavior emerges, coinciding with a seasonal environmental forcing pattern. In Kailua, we observe large-scale rhythmic shoreline behavior in the form of four alternating cells exhibiting opposite seasonal volume fluctuations. This pattern of rhythmic shoreline behavior emerges in three separate parts of the analysis. First, volume calculations from beach profile data reveal strong seasonal patterns of erosion and accretion at each location. These alternate along the length of the beach: groups A and C display opposite seasonal behavior from groups B and D. Second, EOF analysis of the beach profiles identifies the same seasonal pattern of profile variability as the dominant empirical mode of variability. In addition, EOF analysis identifies the sediment movement pattern as being in phase across the transect, i.e. not accounted for by cross-shore transport. Third, the results of the historical shoreline-change and volume-change analysis reveal variability in terms of erosion and accretion along the length of Kailua Beach for every interval between photomosaics. From this evidence we conclude that shoreline dynamics in Kailua are characterized by rhythmic behavior, occurring in four or more groups along the length of the beach.

This rhythmic behavior on a scale larger than that of normal beach cusps, whose wavelengths are typically <100 m (Sallenger, 1979), is also seen by Morton et al. (1995) on the Texas Coast, Sallenger et al. (2002) at Pacifica and Montara, CA, USA, and Dingler and Reiss (2002) at Moss Landing, CA, USA. Morton et al. (1995) find that the alongshore variations are a result of fluctuations in sediment transport rates along with temporary storage and release of sand on the beach and shoreface. However, contrary to our results, which suggest that the alternating erosion and accretion patterns are a result of longshore transport, Morton et al. (1995) find that alternations in volume increases and decreases at adjacent sites are due to wave-driven cross-shore transport, whereas longshore transport explains systematic increases or decreases in sand volume. Sallenger et al. (2002) attribute the giant cusps observed at Pacifica and Montara, CA, USA, to a reversal in the net sediment transport direction caused by the 1997–98 El Nino, and Dingler and Reiss (2002) find that the rhythmic shoreline at Moss Landing is the result of complex wave conditions due to refraction over Monterey Canyon. The shoreline rhythms at Kailua may be due to a similar effect resulting from wave refraction over the fringing reef and paleostream sand channel.

6.1.4. *Seasonal transport patterns*

This rhythmic behavior is contrary to what one might expect for Kailua given the seasonal wind and wave climate. The dominant easterly summer trade winds are in a direction conducive for sand transport from the southeast end of the bay towards the northwest end. Indeed, we do find a volume increase at the northern end (group A,

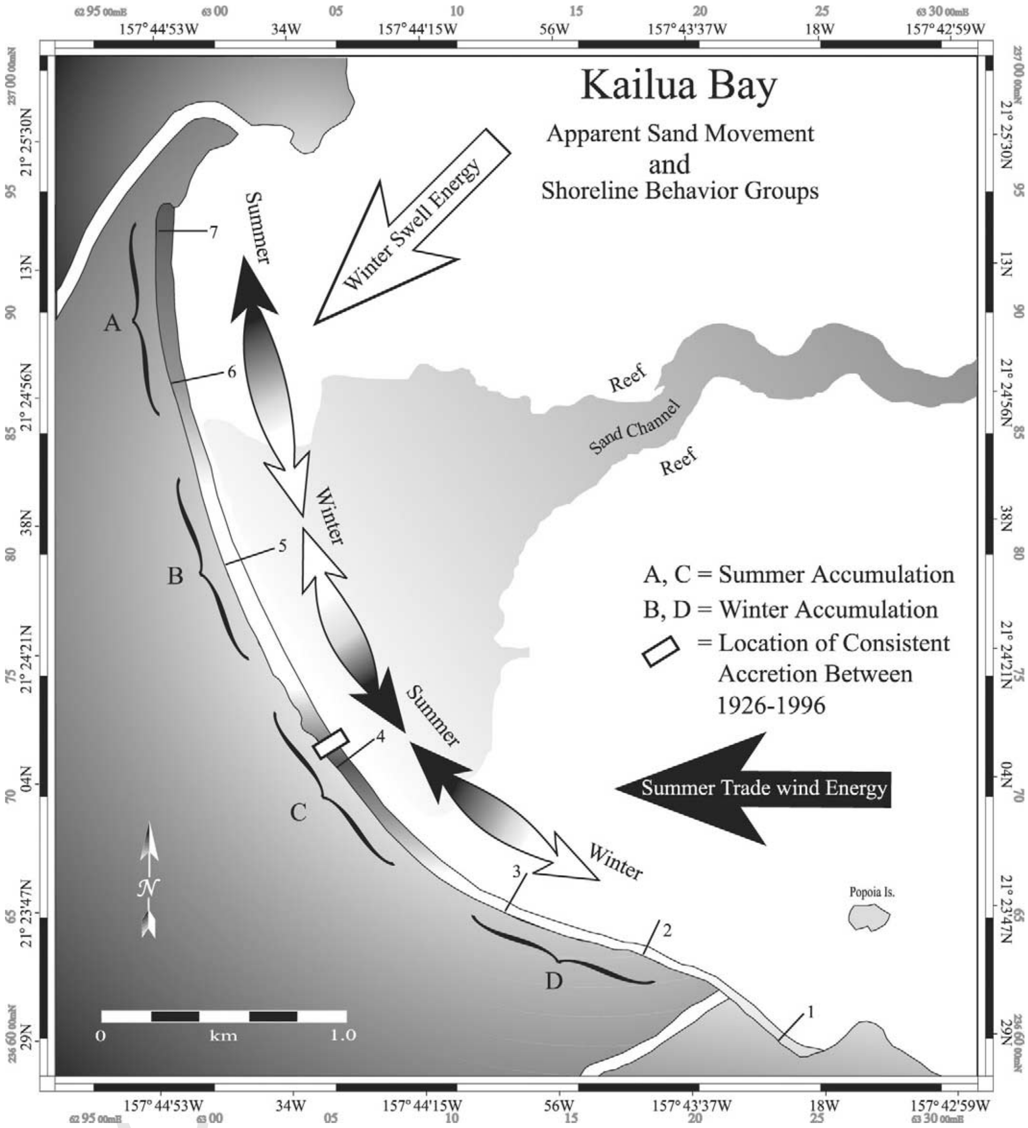


Fig. 16. Seasonal patterns of change in Kailua Bay, based on sand volume behavior observed from beach profiles.

Fig. 16) and a volume decrease at the southern end (group D), but there is an interruption of this pattern in the center of the bay with group B experiencing a volume decrease and group C experiencing a volume increase. Likewise, given the wrap of the winter northerly swells into the bay, it would seem likely for sand to be transported from the northwest end of the bay toward the southeast end during the winter months. Accordingly, we do see a volume decrease at the northwest end (group A) and a volume increase at the southeast end (group D), but again there is an interruption of this pattern in the center of the bay with group B experiencing a volume increase and group C experiencing a volume decrease. This interruption, seen in both winter and summer sand transport patterns, may be caused by the interaction of the waves with the broad fringing reef at both ends of the bay, and perhaps more significantly by their interaction with the paleostream sand channel bisecting the reef in the center of the bay.

It is also possible that the seven profile lines we have established in Kailua are insufficient to represent all of the patterns of erosion and accretion that occur, which could cause our results to represent an aliased signal of alternating erosion and accretion. In support of our data, however, the historical shoreline change and volume change plots reveal that the number of alternating patterns of erosion and accretion along the length of the beach may range from three to possibly five groups. This corresponds well with the four alternating groups of erosion and accretion we see in our beach profile analysis, despite the different time scales.

6.2. *Historical behavior*

6.2.1. *Historical shoreline change patterns*

The historical shoreline change plot reveals that erosion and accretion do not occur uniformly along the length of the beach for any given time period. Rather, there appear to be divisions that alternate in accretional/erosional behavior similar to the observed seasonal changes.

In terms of the historical shoreline change analysis, it is difficult to classify beach behavior in Kailua based on seasons, due to the fact that typical summer environmental conditions are not uncommon in the winter, and vice versa. As a result, the snapshot nature of the photogrammetric time series provides a poor representation of typical seasonal conditions. However, since the uncertainties introduced in shoreline position by the random nature of the aerial photo dates are uncorrelated and not biased, they can be absorbed within the uncertainty term provided by our linear regression model of the long-term shoreline change rate (Neter and Wasserman, 1974). Thus, the long-term changes inferred from the historical change analysis are an accurate reflection of shoreline behavior on Kailua Beach.

Average beach width (distance between the vegetation line and the beach toe) in Kailua has decreased by almost 7 m between 1949 and 1996. This is the result of the vegetation line accreting at a slightly faster rate than the shoreline.

6.2.2. *Historical volume change*

When volume changes at each profile site are plotted against corresponding changes in beach width in the $\Delta V/\Delta X$ models, we see that a number of points indicate an increase in beach volume with a decrease in subaerial beach width, or a decrease in beach volume with an increase in the subaerial beach width. This may be the result of beach cusps that change in size and location from one survey to the next, which would have an impact on the beach volume but not necessarily beach width. This effect on the beach volume–beach width relationship by shifting cusps was also experienced by Dingler and Reiss (2002).

6.2.3. *Sand source*

Despite net relative sea level rise of 10–20 cm over at least the last century, Kailua Beach has experienced a sustained long-term accretional trend, as evidenced by historical shoreline change rates over the 70-year study period. Because the shoreline has clearly been moving seaward and there are no sources of sand from either the north or south ends of the bay, the most likely source is the shallow sand field and channel in the central portion of Kailua Bay. The highest rates of shoreline accretion are found toward the center of the bay, directly onshore from the sand field and channel. In addition, the 40-m section of beach that has experienced consistent accretion over the entire 70-year period, is adjacent to the channel.

Harney (2000) studied the age of sands in Kailua Bay and found an average age of 1890 yr BP. Sands throughout the bay are dominantly fossil, with the oldest ages found on the beach face (4522 yr). This strongly indicates that there is an important sand reservoir in the bay that operates on a long-term basis, modulating sediment availability to sandy environments. Harney measured sand storage in Kailua Bay and found it to be on the order of 3 726 000 m^3. The portion of sand stored in only the nearshore sand field and the sand channel amounts to 2 585 000 m^3 (the remainder is stored in pockets on the reef). The total area of the nearshore sand field and the sand channel is approximately 1 150 000 m^2, which would indicate an average sand depth of 2.25 m. Thus, a shift of 670 000 m^3 of sand from storage to the beach would amount to a decrease in depth of stored sand of 0.58 m, suggesting that the accretion we measured has an immediate and reasonable source.

Furthermore, the sand channel is not full (Casciano, 1979) suggesting that sand is moving through it in either an onshore or offshore direction, or perhaps in a bi-directional mode in response to seasonal wave changes, feeding both the beach and the reef-front sand field. Cacchione et al. (2002) studied sediment dynamics in the channel during brief multi-day periods in September to November 1996, July 1997 (5 days), and June to July 1998, and found overall net offshore transport. In 1996 when the trade winds were light to moderate, they found sediment transport to be in an onshore direction; in 1997 when the trade winds were moderate to strong, offshore transport was observed; and in 1998, when trade winds were again moderate to strong, transport direction was mixed. This suggests that sediment transport direction is influenced by the strength of the trade winds. Strong winds may set sea level up along the shoreline, forcing the water to escape back offshore through the channel. During periods of lighter winds, wave-driven transport could produce onshore sediment movement in the channel. Over the 5-day period in July 1997, Cacchione et al. found sediment transport to be on the order of 6700 kg/day (approximately 4–6 m^3/day).

Although past reports have indicated the presence of strong erosion along many of Hawaii's shorelines (Fletcher et al., 1997), there are some littoral cells that record accretion where local sediment budgets are not in deficit. Kailua historically is one such location. Calhoun et al. (2002) report a maximum net sediment deposition rate of 15 500 m^3/yr between 5000 and 3000 years ago at Hanalei Bay on the north shore of the island of Kauai. Calculations by Calhoun et al. suggest that approximately 2490 m^3/yr of carbonate sediment has been imported into Hanalei Bay since 11 700 years ago, and that this influx is driven by trade wind-generated transport. It is possible that a similar mechanism is moving sediment into Kailua Bay.

7. Conclusions

(1) The integration of sand volume and beach width from beach profile analysis with data on historical beach width from orthorectified aerial photographs and T-sheets is useful in establishing a record of historical sand fluctuations and understanding the manner in which the beach evolves and responds to environmental forcing conditions.

(2) Shoreline variability at Kailua can be characterized by an alongshore rhythmic pattern of alternating seasonal behavior. Four or more behavioral groups exist along the length of the beach that exhibit a consistent pattern of seasonally alternating erosion and accretion from group to group. This result is supported by beach profile volume changes, EOF analysis of beach profiles, and historical shoreline and volume change analyses. A simple transport pattern associated with seasonal changes in wind and wave climate is proposed, and requires further testing. Simultaneous erosion or accretion occurring in the onshore and offshore portion of all profiles (with a relatively small volume change at the position of the toe) suggest that Kailua Beach may require a more complex model than the equilibrium profile theory to predict profile response.

(3) Kailua Beach has experienced a net accretion of 673 000 m^3 over the period of 1926 to 1996. Offshore sand deposits are believed to be the primary source for this beach accretion.

8. Uncited references

Cacchione, 1998

Acknowledgements

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