HAWAIIAN BEACHES DOMINATED BY LONGSHORE TRANSPORT

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Abstract

The offshore environment of many of Hawaii's sandy beaches is characterized by shallow limestone surfaces related to either fossil reef development or modern fringing reef ecosystems. Recent studies of sediment transport for 2 beaches on Oahu (Kailua and Waikiki), and 2 beaches on Maui (Kaanapali and Kihei) reveal evidence that seasonal sand transport is strongly influenced by longshore movement and limited cross-shore movement – contrary to the common model of two-dimensional, cross-shore profile adjustments. At the Kailua study site, empirical orthogonal function (EOF) analysis was used to explain alongshore patterns of alternating sand volume increases and decreases potentially related to seasonal offshore circulation, and at the Waikiki study site, a detailed analysis of historical human intervention was performed to determine its effect on sand transport patterns and develop a basis for planning future sand replenishment efforts. At the Kaanapali study site, observed longshore transport volumes were compared to three predictive models, namely CERC (1984), CERC, 1991 (GENESIS) and Kamphius (1991), and it was found that while the Genesis model best approximated predicted longshore transport, the presence of the fringing reef significantly affects the ability of the models to accurately predict sediment transport. At the Kihei study site, cycles in longshore sediment transport patterns were compared with periods of increased and decreased Kona storm activity (rain-bearing winds from the southwest), and a significant correlation was found. In all cases longshore transport dominated seasonal beach development despite the study sites being located in different meteorologic and oceanographic settings.

INTRODUCTION

Coastal Zone Management in the Hawaiian Islands has entered a critical period of policy and regulation review and improvement, as an increasing number of coastal structures built prior to, as well as following, the inception of current regulations, are being threatened by erosion. It has become evident that many of the existing regulations are inadequate in both protecting coastal structures from erosional damage, as well as preserving Hawaii's priceless beach resources. The need for improved management policies has prompted investigations to better understand sediment transport dynamics for Hawaii's unique coastlines.

Four individual research efforts were undertaken over the period of 1998-2002 to study historic and short-term sediment transport patterns for 4 beaches on 2 islands (Figure 1), each experiencing different wind and wave forcing as well as varying levels of human intervention. Using combined historical aerial photogrammetry and beach profile monitoring, patterns of sediment transport were established at each site. For all locations, patterns of sediment transport

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were clearly longshore-dominated, with limited cross-shore transport evident at some locations where sand-filled paleostream channels cut through the fringing reef.

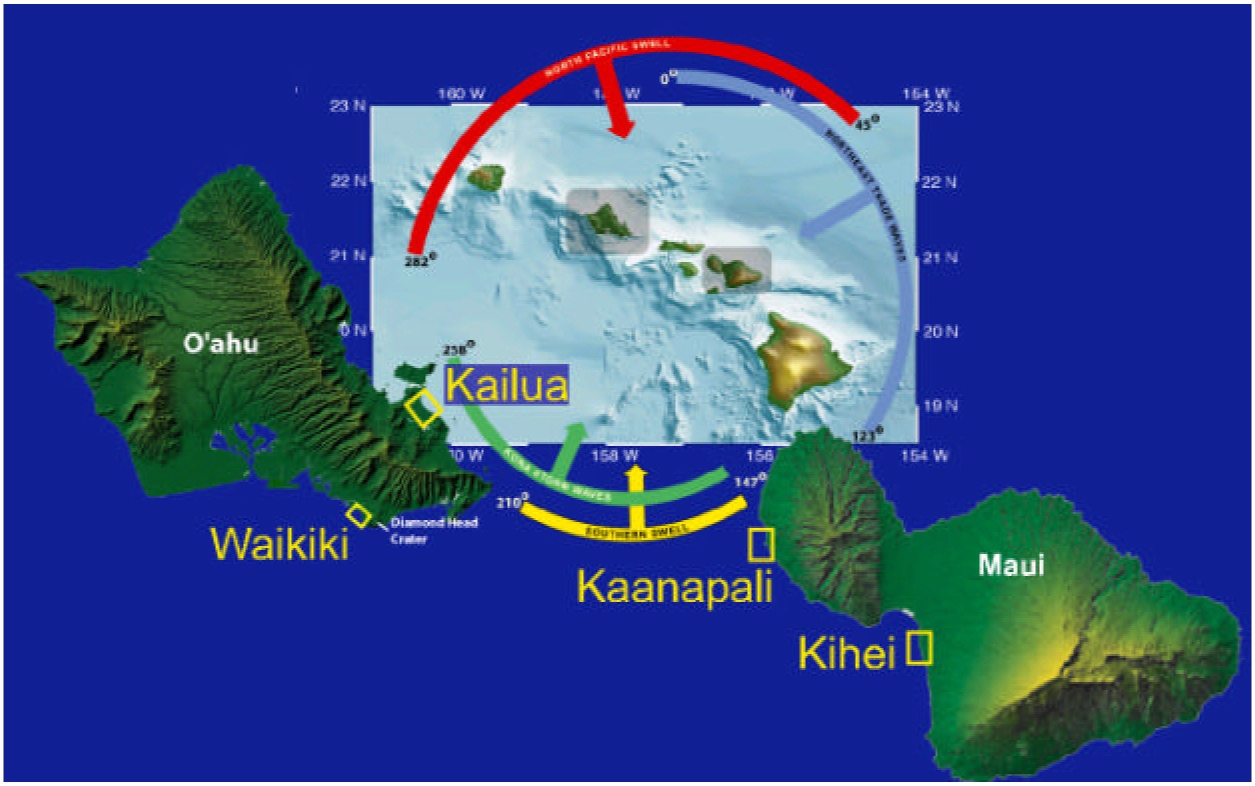

Figure 1. Sediment transport patterns were studied at 4 locations of varied exposure in the Hawaiian islands: 2 locations on Oahu and 2 locations on Maui.

STUDY SITES

Kailua Bay is located on the northeast coast of Oahu, and is exposed to 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). Kailua beach is approximately 4 km in length, 20 to 40 m in subaerial with, with a beach face slope that ranges between 0.09 and 0.13. 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. Seaward of the terrace, the sand profile drops off relatively quickly, terminating at the surface of a broad fringing reef crest. The reef is bisected by a sand-filled paleostream channel 200-300 m wide.

Waikiki beach is located on the southeast coast of Oahu, and is relatively sheltered from trade wind energy. In the summer, Waikiki is exposed to long period swells generated in the southern hemisphere, and in the winter, short period, locally-generated Kona storm waves impact this coast. The shoreline of Waikiki is 3.2 km in length, but supports only 2.6 km of beach ranging from approximately 6 to 48 m in width. Physical structures established during past engineering projects create morphologically distinct cells. Seven study cells were established based on the locations of these structures, and are numbered 1 through 7 from South to North. The Waikiki nearshore is characterized by a fringing fossil reef that extends offshore about 1 mile (Gerritsen, 1978). The reef is intersected by several paleostream channels and has been altered by dredging activities at a few sites.

Kaanapali beach is located on the west coast of Maui, and like Waikiki, is relatively sheltered from the dominant northeast trade winds. The nearby islands of Molokai and Lanai shelter this area from most swells, except for 3 distinct windows; one each from the south, the west, and the north. The strongest influences on Kaanapali beach come from north swells in the winter, south swells in the summer, and the occasional southerly Kona storm in the winter. A shallow fringing reef dominates the northern and southern extents of the study area, with an intermittently deeper section in the central area. At approximately 500 m intervals, the fringing reef is broken by shore-normal paleostream channels. The study area consists of a 4.6 km carbonate sand beach that is bisected by a prominent basalt headland (Kekaa Point).

The Kihei study area extends along a 5 km segment of west-facing coastline on the south shore of Maui. A fringing reef 300 to 400 m wide exists alongside the entire length of the study area, at a depth of approximately 1 to 2 m. The study area is defined on the north end by Koieie fishpond, and to the south by a small rocky headland. Kihei is located in the lee of both East and West Maui, and is further sheltered from swells by the islands of Molokai, Lanai, and Kahoolawe. Trade winds wrapping around East Maui funnel through Maui’s central valley, and approach the Kihei area from the northwest. Although largely protected from south swells, some wave energy penetrates through to the Kihei area between Kahoolawe and the southwest corner of Maui. Similarly to Waikiki, this study site is susceptible to Kona storm energy approaching from the southwest.

METHODS

Beach profiles at all 4 locations were used to identify short-term and seasonal fluctuations in sand volume and beach morphology. The number of profiles at each site varies from 2 at Kihei, 7 at Kailua, and 11 at Kaanapali, to 22 at Waikiki. The number of profiles at each location was determined based on the size of the littoral cells and the conjectured contribution of beach profile behavior to the determination of major sediment transport trends.

For all study sites, vertical survey-quality historical aerial photographs of 1:12,000 scale or larger, and NOAA topographic survey sheets (T-sheets), were used to establish a history of shoreline positions. The aerial photographs (with dates ranging from 1949 to 2002) were scanned, the distortions were corrected, and the photographs were then mosaicked together using software from PCI Geomatics, Inc., and following the method of Coyne et al. (1999). Mean high water lines, depicted on T-sheets, were digitized and shifted seaward a distance equal to the median distance between the MHWL and the crest of the beach step, as measured from beach profiles, to provide shoreline positions for the early 1900’s (Rooney, 2000). Changes in shoreline position were measured at a spacing of 20 m along the length of each study area.

Relationships between beach volume and changes in shoreline position as determined from the beach profiles were then applied to historical changes in shoreline position to establish a history of beach volume fluctuations, taking into account volume changes resulting from advance or retreat of the coastal plain.

At Kailua, Oahu, EOF analysis was 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). EOF analysis allowed us to isolate energetic patterns of variability and to examine profile changes associated with variations in sand volume.

A history of engineering events and anthropogenic events at Waikiki, Oahu was established to explain trends of sediment gain and loss, as well as the creation of artificial cells which affect sediment transport.

Observed seasonal and annual volume fluctuations at Kaanapali were compared with 3 numerical sediment transport models; CERC (1984), CERC 1991 (GENESIS), and KAMPHIUS (1991). In order to run these models, wave energy flux was specified based on offshore buoy data and coastal observations. Offshore wave data was converted to breaking wave heights for use in the models using a modified Airy-Wave theory from Komar and Gaughan (1972).

At Kihei, Maui, early results showed an unusual decadal variability in sediment transport patterns. To better understand this pattern, a record of Kona storms was compiled from several published sources, and augmented in a few cases by anecdotal reports (National Weather Service, 1959-1998; U.S. Army Corps of Engineers, 1967; Shaw, 1981; U.S. Department of Agriculture, 1905-1948). Due to shortcomings in this record, winter season precipitation records from Waianae, Oahu, were used as a less subjective measure of Kona activity. Waianae was chosen due to the nature of its geographic location, as it is isolated from orographic rainfall, thus rainfall in this area is more reflective of typical Kona events. Kona storm records and rainfall records were compared with calculated net longshore transport (NLST), as well as records of the Pacific Decadal Oscillation (PDO) - which is described as an El Nino-like climatic fluctuation with warm and cool phases that generally last 20-30 years (Mantua et al., 1997; Zhang et al., 1997) - to determine if a significant relationship exists.

RESULTS

Beach Width, Volume and Depth of Closure

Beach profiles at Kailua suggest that beach width and volume are controlled by the presence of the fringing reef (Figure 2). Where the reef is closer to shore and shallower (toward the ends of the bay), profile extents and volumes are considerably smaller than towards the center of the bay where the fringing reef is the deepest and farthest offshore. Cross-shore transport is evident only at profile 1, the southernmost profile, which was analyzed individually for the purpose of this study due to the presence of a small island located directly offshore of this line, which significantly affects the wave climate.

At Waikiki beach, profile widths are also found to be controlled by the depth and proximity of the fringing reef, with profiles extending farther offshore and reaching greater depths where the reef is absent or least distinct. However, the presence of groins constructed in early- to mid-1900 also influences beach widths, with greater beach widths typically occurring at the northwest ends of the cells.

Beach widths and volumes at Kaanapali are similarly determined to be restricted by the presence of the fringing reef, which reduces the total area that is available for sediment exchange and mobilization. A rocky headland at the center of the study area also contributes to seasonal sediment impoundment, influencing beach width.

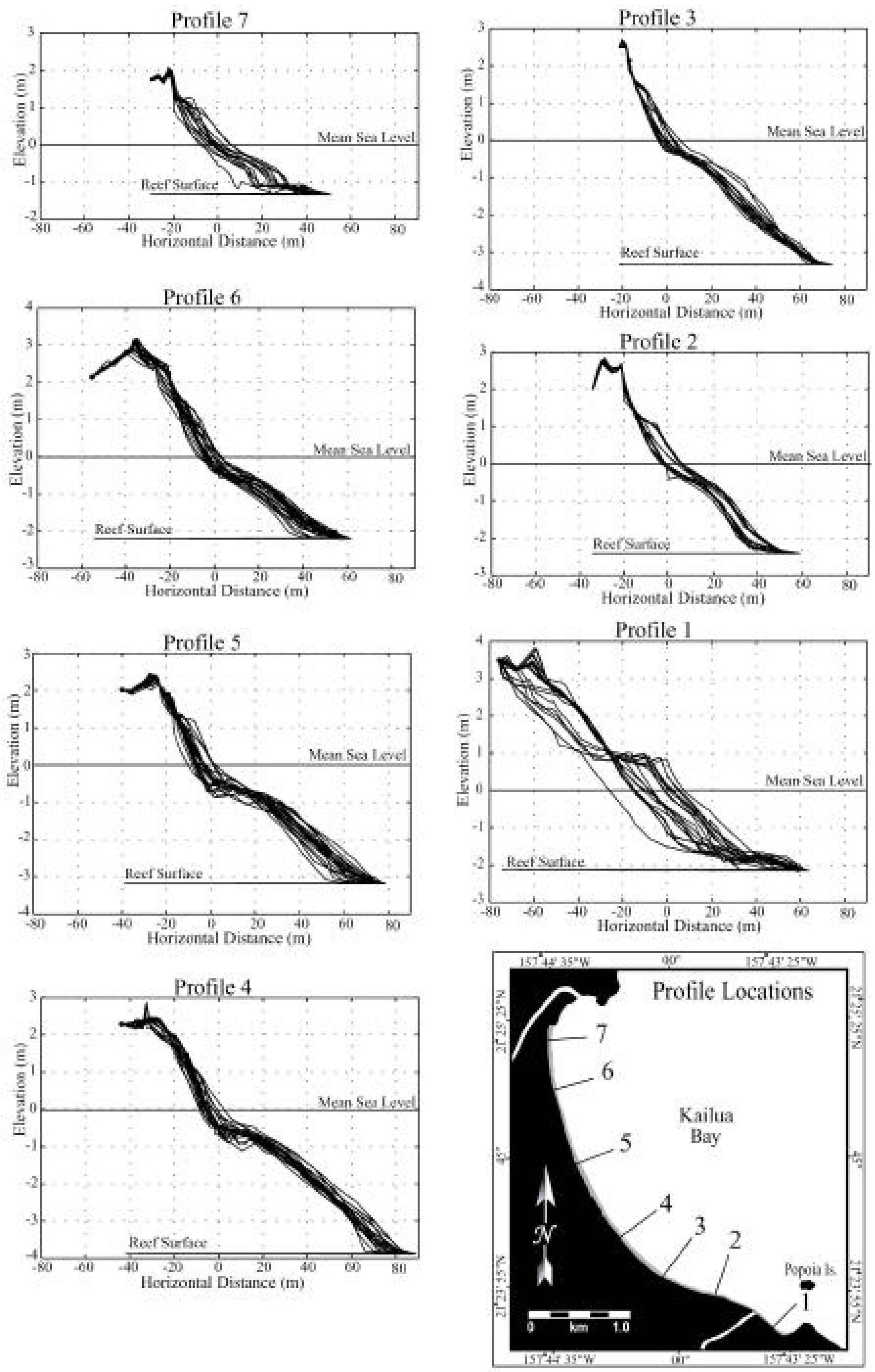

Figure 2. Kailua Beach, Oahu, profiles demonstrate the variability in sand volume and depth of the fringing reef along the length of the bay.

Beach profiles were not an in-depth focus of the Kihei study, as seasonal changes were determined to be of a much smaller magnitude than decadal-scale changes. However, as the depth of the fringing reef surface is 1 to 2 m, it could be conjectured that at Kihei as well, the presence of the fringing reef plays an important role in the lateral extent and volume of the beach profile. At this location, it is found that shoreline armoring has resulted in a 50 percent decrease in mean beach width, and is estimated to have resulted in a loss of 4.2×10^4 m^3 of sediment to the active beach system between 1975 and 1997.

It was determined at Kailua, Kaanapali, and Waikiki, that beach profiles do not reach a depth of closure as defined by Hallermeier (1981), due to the presence of the fringing reef which truncates the beach profiles. However, where no reef is present, it was found that profile closure more closely approximated predicted depth of closure. Hence reef-fringed sites operate as perched beaches.

Longshore Transport

At Kailua Beach, Oahu, EOF analysis identified patterns of sediment transport that clearly demonstrate longshore dominance. Each of the beach profiles was shown to inflate and deflate in-phase over the entire length of the profile, while neighboring profile groups experienced opposing behavior (Figure 3). This alternation of volume increase and decrease alongshore is a strong indicator of longshore transport of discrete volumes (packages) of sand. There was little to no evidence of cross-shore transport based on the beach profiles. It was determined from the Photogrammetry that Kailua beach has gained 670,000 m^3 of sand over the 70-year study period. Previous work by Noda (1989), however, showed that there is no input of sand to the Kailua system via longshore transport from a neighboring beach (Lanikai), which is separated from Kailua by a rocky headland. A possible avenue for sand input to Kailua beach may be via transport from the mouth an offshore sand-filled channel bisecting the fringing reef.

Due to the presence of extensive shoreline hardening and groins at Waikiki, Oahu, there is a considerable amount of interruption to natural sediment transport patterns. Seven small, artificial cells have been created. Nevertheless, consistent patterns of alternating and opposing seasonal inflation and deflation amongst neighboring profiles, similar to the patterns seen at Kailua, were identified, and are again indicative of longshore-dominated sediment transport (Figure 4). However, long-term accretion in cell #1 and long-term erosion at cells # 5 and #6, as determined from historical photogrammetry, are attributed to cross-shore transport occurring at the location of a sand-filled paleostream channel (or absence of fringing reef) in each of these cells.

Beach profiles at Kaanapali, Maui, exhibit little to no cross-shore sediment transport while displaying considerable seasonal changes in volume, in a manner similar to that of the Kailua and Waikiki beach profiles. Again, alternating patterns of seasonal inflation and deflation are observed alongshore (Figure 5), with neighboring profiles exchanging sediment over the entire lengths of the profiles. The overall trend in beach volume, based on the beach profiles, indicates net northward transport in the summer, net southward transport in the winter, and a net annual transport to the north. The three numerical models used to predict sediment transport all agree with this result; however there is great discrepancy in terms of the actual volumes of sediment transport calculated by each model (Table 1). CERC (1984), CERC 1991 (GENESIS),

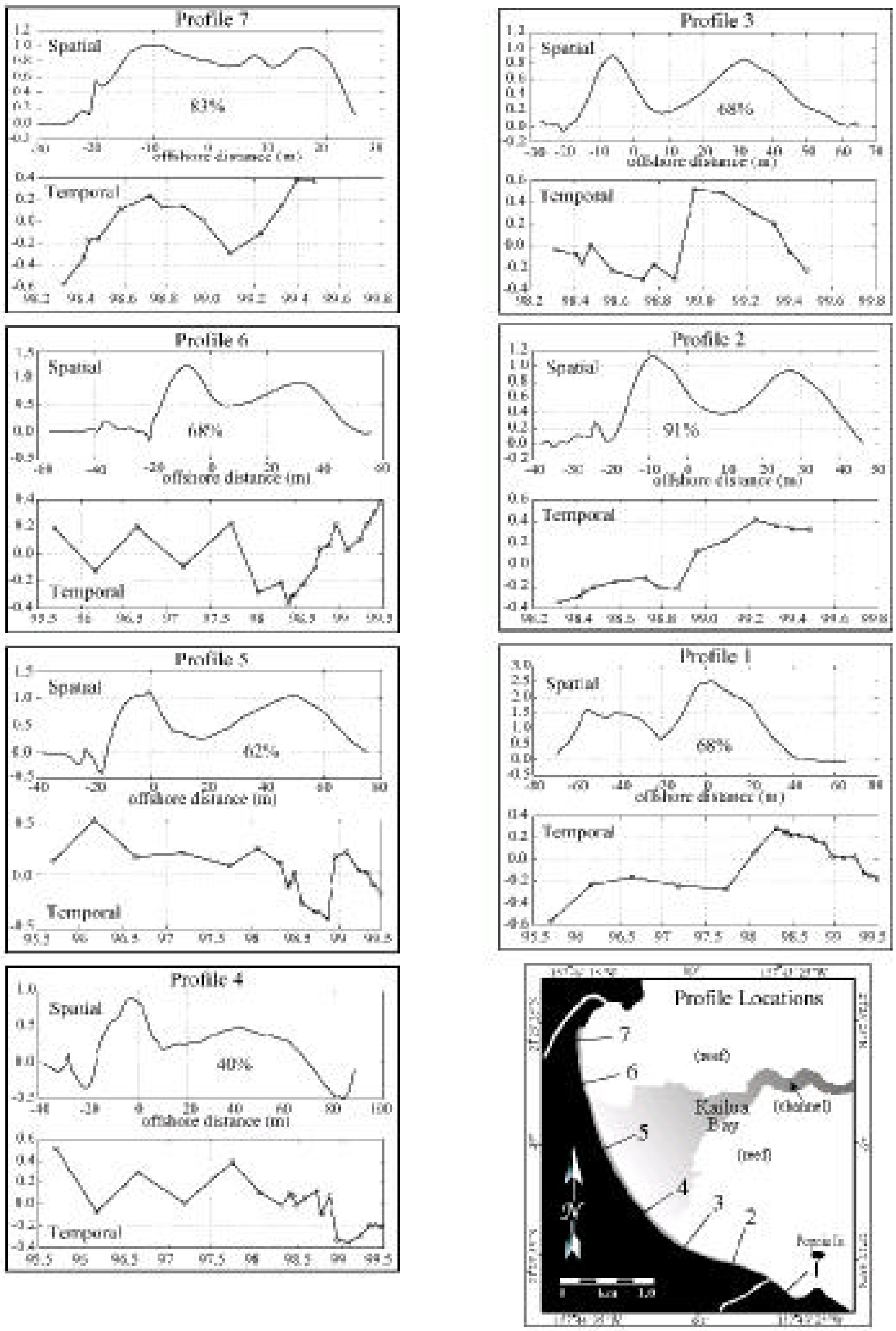

Figure 3. Spatial components of the EOF analyses of beach profiles at Kailua, Oahu, reveal inflation and deflation occurring in-phase over the entire profile, with seasonal alternations in volume increase/decrease evident in the Temporal components. Note the different time scales, as profiles 2, 3, and 7 were only surveyed during the final year of data collection.

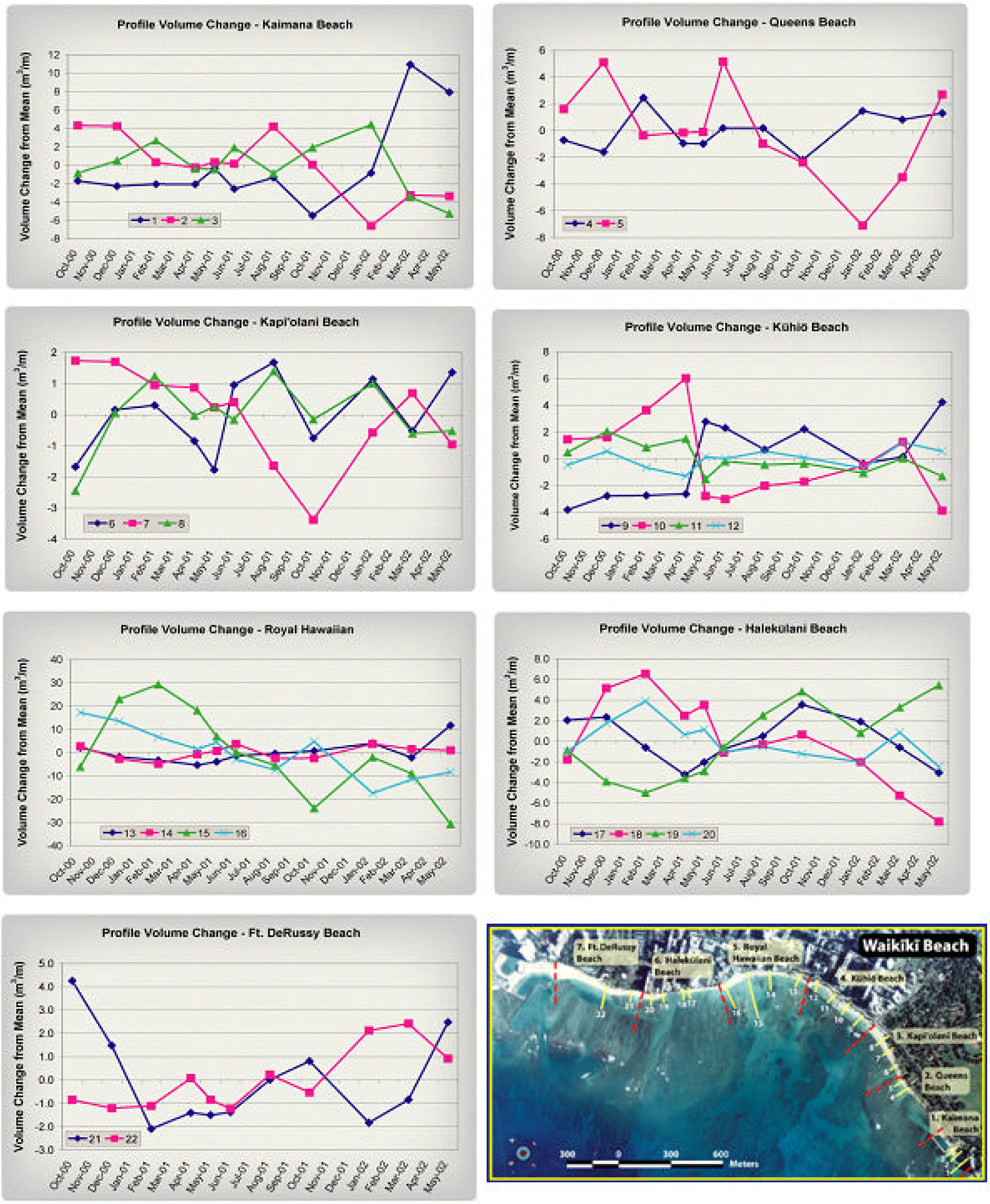

Figure 4. Beach profile volume changes at Waikiki, Oahu, relative to the mean, for 22 profiles in 7 littoral cells (Miller, 2002). Note the opposing inflation/deflation occurring at neighboring profiles in a given cell.

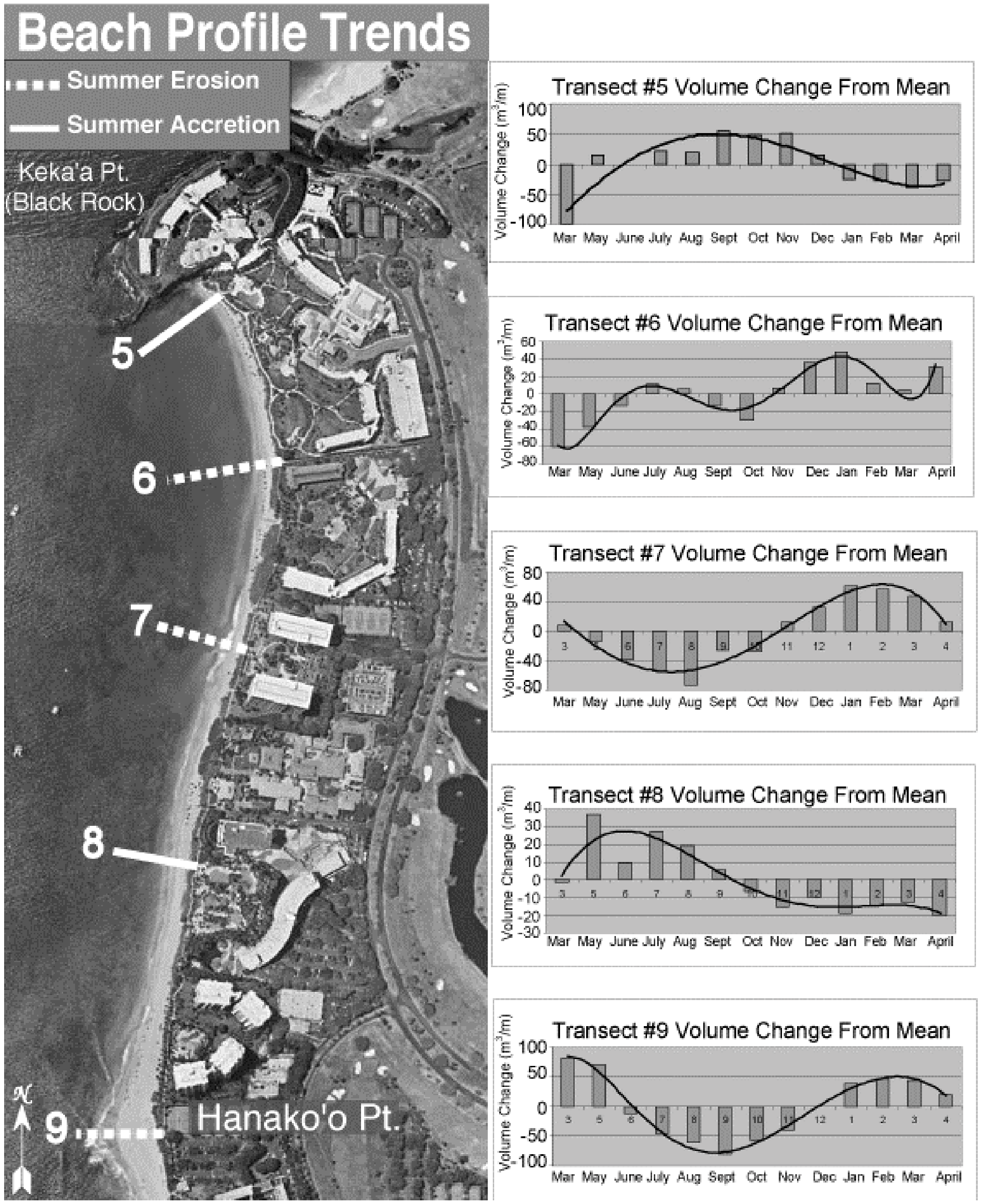

Figure 5. Beach profile trends at Kaanapali, Maui, with alternating patterns of erosion and accretion demonstrated on the photomosaic by solid versus dashed lines. Volume plots to the right reveal the cyclic nature of the profiles as seen by the best fit trend line (Eversole, 2002).

Table 1. Observed Volume Change and Predicted LST Rates. The CERC (1991) model best fits the net observed LST at profile 7 with 77% of the observed net annual transport (Eversole, 2002).

(Negative indicates northward transport)

Observed Profiles	Volume Change	Transport Volume (m^3/yr)	
Kaanapali	Cumulative Gross Summer Transport	-29,379	
Cumulative Volume	Cumulative Gross Winter Transport	22,358	
Change at Profile 7	Net Annual TLST	-7,021	
	Annual Mean Total Beach Volume	432,731	
Modeled TLST	**CERC, 1991 Genesis Model**	**Transport (m^3/yr)**	**% of Observed**
Predicted	Cumulative Gross Summer Transport	-22,955	78%
Cumulative Volume	Cumulative Gross Winter Transport	17,558	79%
Change at Profile 7	Net Annual TLST	-5,397	77%
	CERC, 1984 Model		
	Gross Summer Transport	-446,651	1520%
	Gross Winter Transport	189,288	847%
	Net Annual TLST	-257,363	3665%
	Kamphius, 1991 Model		
	Gross Summer Transport	-895,022	3046%
	Gross Winter Transport	427,210	1911%
	Net Annual TLST	-467,813	6663%

and KAMPHIUS (1991) predict net annual transport rates at 3 x 10^3 percent, 77 percent and 6 x 10^3 percent of the observed transport rates respectively. The large differences in these results are attributed to each model's ability to accurately assess wave energy. Further, the ability of all models to accurately predict sediment transport is believed to be affected by the presence of the fringing reef. The relative predictive success of the Genesis model is attributed to its ability to account for short-term changes in near-shore parameters.

At Kihei, Maui, it was found that while seasonal patterns of sediment transport are observed, they are relatively insignificant in comparison with long-term trends. Statistically significant correlations are found between rainfall records (related to Kona Storm activity), the PDO cycle, documented Kona storm activity, and net longshore sediment transport in Kihei (Figure 6). Seasonal observations of sediment transport consist of localized updrift accretion and downdrift erosion resulting from variations in longshore sediment transport, rather than beach-wide erosion or accretion resulting from cross-shore transport. Of much larger magnitude, however, is longshore transport driven by Kona storm activity. Photogrammetry, geomorphic evidence, and anecdotal reports suggest that these short-duration events have transported high volumes of sediment northward along the Kihei coast (Rooney and Fletcher, 2000). While over the last century, periods of years to decades of minimal Kona storm activity have occurred during positive PDO phases, the corresponding southward transport of sediment due to regular tradewind-generated swells has been exceeded by northward transport of sediment resulting from strong Kona storm activity during negative PDO phases.

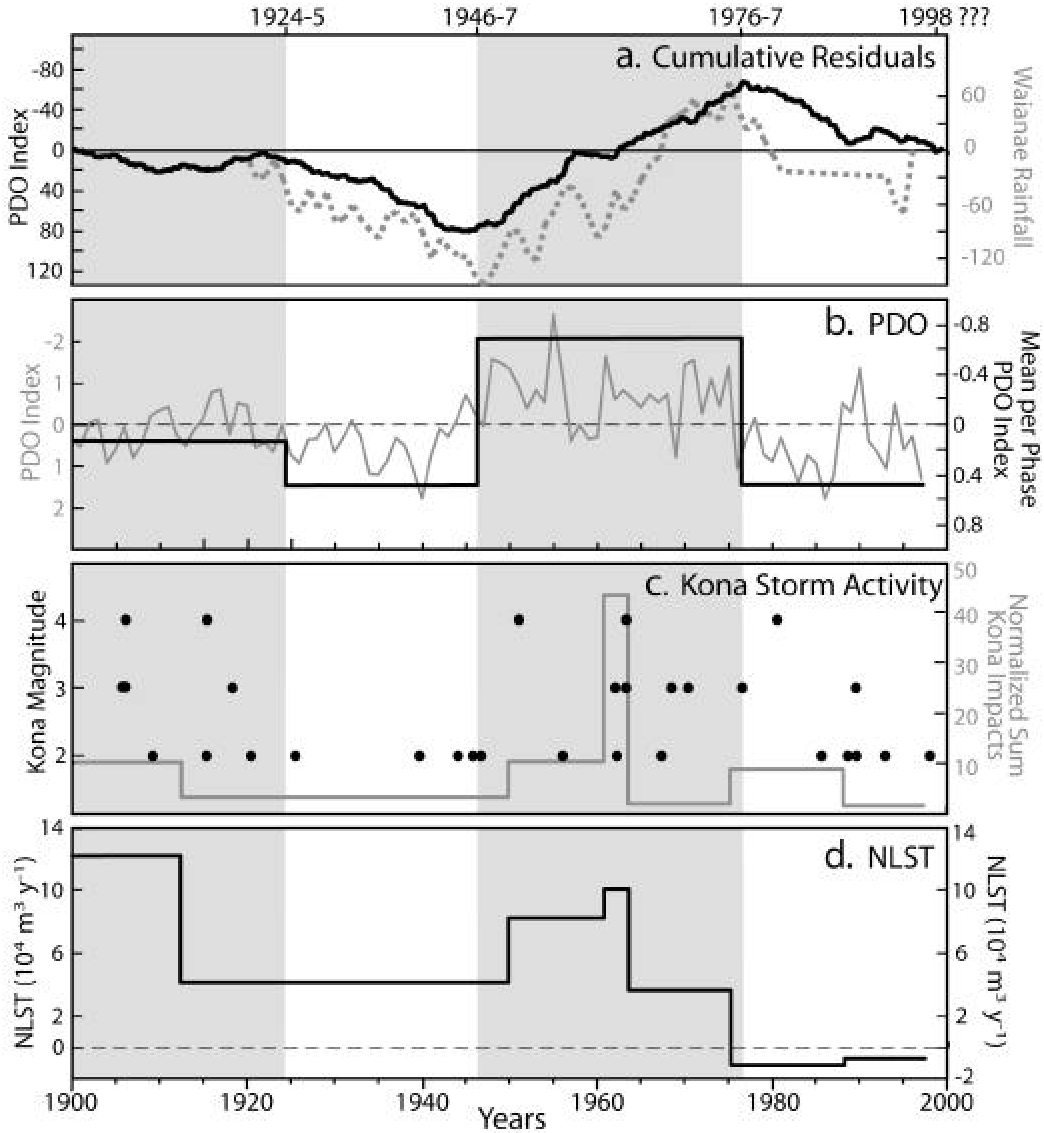

Figure 6. Relationship between rainfall records, PDO cycles, Kona storm activity, and net longshore transport at Kihei, Maui (Rooney, 2002).

DISCUSSION

While longshore transport quite clearly dominates sediment dynamics at all 4 study locations, the spatial and temporal patterns of variability have unique components at each site. At Kailua, Oahu, sediment meanders alongshore in a rhythmic, seasonal pattern involving at least 4 cells. Waikiki, Oahu, experiences general erosion under shorter period winter wave conditions, but recovers in the summer under longer-period southern swell conditions. Waikiki shows some evidence of cross-shore sand transport at 3 locations where sand-filled channels through the fringing reef exist, yet longshore transport is clearly dominant at most locations. Seven beach cells defined primarily by man-made structures such as groins display evidence of alongshore alternating inflation and deflation patterns along the lines of those observed at Kailua.

Similarly, at Kaanapali, Maui, transport patterns are seasonal with alternating patterns of volume change along the beach. However, while Waikiki experiences winter erosion and summer accretion, Kaanapali follows a trend of winter accretion and summer erosion, with this difference attributable to the dissimilar exposures of the two locations to wind and wave energy.

At Kailua, the meandering pattern does not appear to react strongly to individual high-energy wave events, whereas sand transport at Kaanapali is event-responsive. Similarly, at Kihei, Maui, longshore transport direction and magnitude is primarily influenced by high-energy events, namely Kona storms. However, the temporal scale for the reversals in sediment transport direction at Kihei differs with that of Kaanapali since the events affecting Kaanapali tend to be seasonal (such as typical winter and summer swells), while sediment transport at Kihei reverses direction over decadal intervals corresponding significantly with the PDO.

The findings of longshore-dominated sediment transport, both seasonally as well as in response to storm events, are significant in that this type of response differs from previously-documented cross-shore transport in response to wave events generally associated with seasonal variations. The conceptual fair-weather/storm model of Lee et al. (1995) describes beach-nearshore profile evolution in response to wave activity, and suggests that during high wave or storm events, sand is transferred from the nearshore to the offshore where it is deposited as a sand bar. Then during periods of calmer weather, gentler wave energy gradually shifts the offshore deposit back toward land, rebuilding the beach. Lee et al. (1995) and Lee et al. (1998) examined 10 ½ years of bi-weekly profile data from Duck, North Carolina during 4 major groups of storms, and observed cycles of cross-shore exchange. At all 4 sites in our study, we observed predominantly longshore transport in response to storm events, with the direction of longshore transport reversing during periods of calm weather.

A possible explanation for the longshore transport we observe could be that water from waves breaking over the reefs builds up landward of the reefs, then travels alongshore along the inside of the reefs, before moving back out to sea through a channel. A study of littoral sedimentary processes on the island of Kauai, Hawaii, by Inman et al. (1963), determined that pairs of fringing reefs bisected by sand-filled channels constitute distinct cells for the circulation of water and distribution of sediments. They observed waves shoaling over reefs, and nearshore currents converging on and subsequently returning to sea through sand-filled channels. According to this study, the longshore currents result primarily from the mass transport of water breaking over the reefs, and have been known to directionally oppose brisk winds.

CONCLUSION

Based on evidence obtained from 4 meteorologically and oceanographically distinct beaches, sediment transport in the Hawaiian Islands may be characterized as mainly longshore-dominated, even in response to storm conditions. This differs considerably from fair-weather/storm-type models which have been used to describe cross-shore sediment exchange seasonally as well as in response to storm or high surf events. The reason for this difference could be related to the presence of fringing reefs which may alter nearshore current patterns leading to longshore sediment transport.

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