Journal of Coastal Research	19	0	000–000	West Palm Beach, Florida	Season 0000

Longshore Sediment Transport Rates on a Reef-Fronted Beach: Field Data and Empirical Models Kaanapali Beach, Hawaii

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ABSTRACT

EVERSOLE, D. and Fletcher, C.H., 2003. Longshore sediment transport rates on a reef-fronted beach: field data and empirical models Kaanapali Beach, Hawaii. *Journal of Coastal Research,* 19(0), 000–000. West Palm Beach (Florida), ISSN 0749-0208.

Longshore sediment transport (LST) measured at monthly beach profiles on Kaanapali Beach, Maui is compared to three predictive models. We observe cumulative net sediment transport rates of approximately 29,379 ±4400 m^3/yr to the north and 22,358 ±1300 m^3/yr to the south for summer and winter respectively. Kaanapali Beach experiences a net annual rate of 7,021 ±700 m^3/yr to the north and a gross annual rate of 51,736 ±5100 m^3/yr. Transport models, namely CERC (1984), CERC, 1991 (*GENESIS*) and Kamphius (1991) predict net annual LST rates at 3×10^3 percent, 77 percent and 6×10^3 percent of the observed rates respectively. The success of the Genesis model is attributed to its ability to account for short-term changes in near-shore parameters. The use of CERC (1984) is prone to practical errors in its application including use of the recommended K coefficient and wave averaging that may significantly overestimate LST. The use of Kamphius (1991) is more sensitive to beach slope and wave period than CERC (1984) and may over-predict transport on steep sloped beaches with high wave energy. Presence of fringing reef significantly affects the ability of LST models to accurately predict sediment transport. When applying CERC (1984, 1991) and Kamphius (1991) formulas, functional beach profile area available for sediment transport is assumed much larger than actually exists in Kaanapali. None of the models evaluated account for the presence of a reef system. This may contribute to overestimations of LST as they assume the entire profile is mobile sediment. However, the fact that CERC (1991) underestimates the observed transport implies that environmental parameters employed in these models (such as wave height, direction and period) play a more substantial role than the influence of the reef in model results.

ADDITIONAL INDEX WORDS: *Longshore sediment transport, sediment transport modeling, fringing reef, beach profiles, coastal erosion, Hawaii, beaches.*

INTRODUCTION

Many coastal science and engineering studies attempt to predict rates of longshore and cross-shore sediment transport. The scope of predictive formulas are largely empirical and reflect results based on field studies from around the world (Komar and Inman, 1970; Dean, 1989; Bodge and Kraus, 1991; Kraus *et al.,* 1991; Short, 1999). Researchers have found that sediment concentration and transport at the breaker line is strongly influenced by breaker type and thus wave energy (Kana and Ward, 1980; Nielsen, 1984; van Rijn, 1993). Field techniques for measuring total and suspended longshore sediment transport include sediment tracer, impoundment and streamer traps. Here we employ the impoundment technique for comparison with three predictive longshore transport models.

The near-shore sediment transport system of Kaanapali Beach, Maui is examined using 13 monthly beach surveys. We describe the dominant spatial and temporal patterns of sediment transport and volume variability and evaluate three commonly used Longshore Sediment Transport (LST) formulas: (CERC, 1984; Kamphius, 1991; and The Army Corps of Engineers (ACOE) Generalized Model For Simulating Shoreline Change (*GENESIS*) model (CERC, 1991). We find the CERC (1991) model fits observations of LST best while the CERC (1984) and Kamphius (1991) models are prone to overestimate the observed longshore transport by roughly an order of magnitude.

ENVIRONMENTAL SETTING

Kaanapali Beach is located on the west coast of the island of Maui, Hawaii in the lee of the dominant northeast trade winds. Meteorological conditions of this coast are variable but typically calm with moderate trade winds and infrequent but strong onshore storm winds (Kona Storms). The surrounding islands shelter the area from most swells except for three pronounced swell windows. The southern swell window rang-

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02120 received and accepted in revision 21 November 2002.

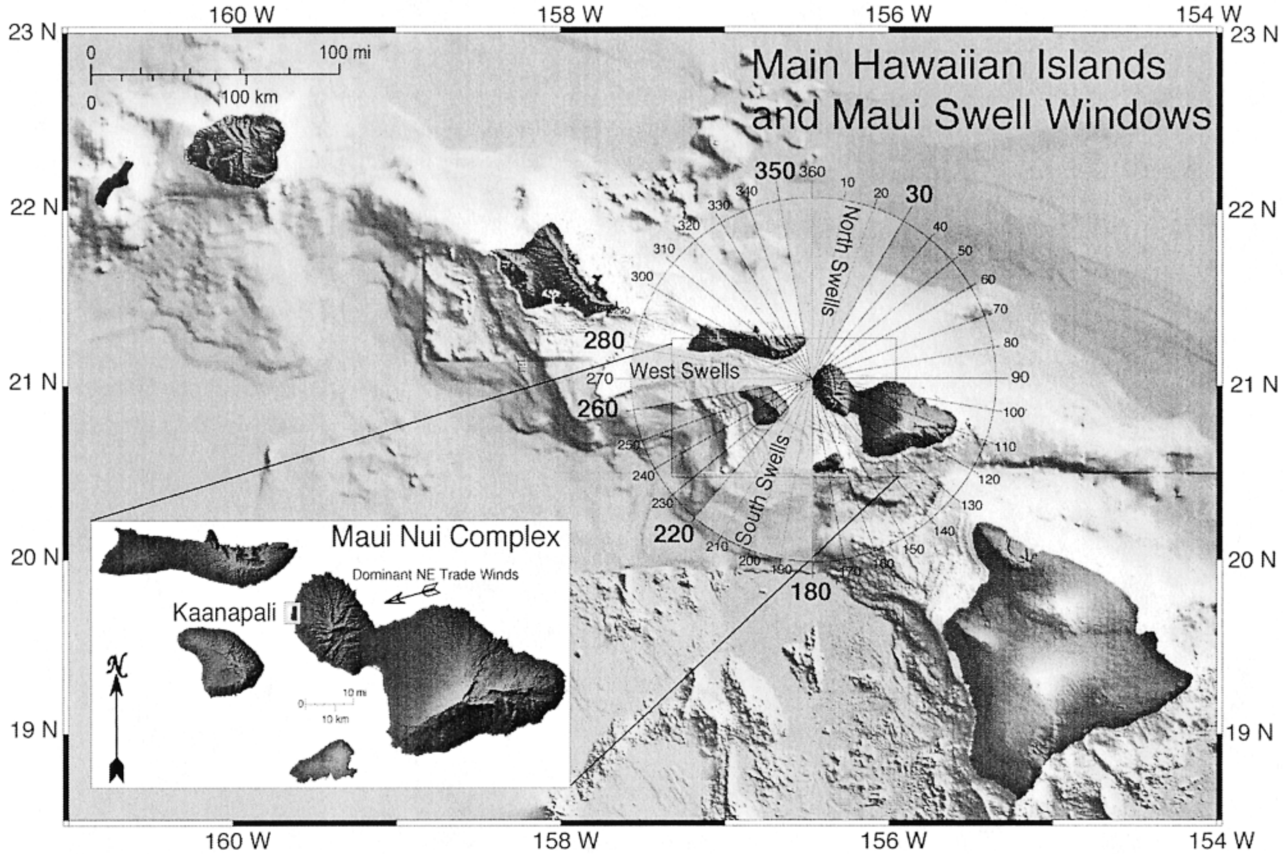

Figure 1. Kaanapali Location Map and Swell Windows.

es from approximately 180° to 220°, west swells 260° to 280° while the northern swell window extends from 350° to 30° (Figure 1).

The area is exposed to an opposing bi-modal swell regime that subjects the beach system to seasonal wave forcing from opposite directions, while west swells rarely enter their respective swell window. North Pacific deep-water swells in the winter months can exceed 10 m in height with periods of up to 25 s. Similarly south swells are commonly 1 to 3 m but can exceed 6 m in height with periods of up to 22 s ARMSTRONG (1983). Kona storms are locally produced low-pressure systems that approach from the south or southwest. Kona storms can generate wave heights up of 3 to 5 m and periods of 8 to 14 s. Although these storms occur infrequently, they are the cause of extensive coastal damage to south and west facing shorelines (MAKAI OCEAN ENGINEERING, INC. and SEA ENGINEERING INC., 1991; ROONEY and FLETCHER, 2000).

Shallow fringing reef (<1 m depth) dominates the northern and southern extents of the study area with deeper outcrops of fossil reef (5–10 m depth) observed intermittently in the central area. The fringing reef is composed of fossil reefal limestone and beachrock that dominate the reef flat and shallow reef segments. Encrusting coralline algae and branching corals are found at deeper regions of the reef front forming spur and groove features in the reef slope at depths of 10–20 m. At approximately 500 m intervals, the fringing reef is broken by shore-normal channels (Aawa) that direct the flow of nearshore water and sediment seaward (Figure 2). The fringing reef constitutes a geologic framework that plays a significant role in the stability and replenishment of the beach system in this area. The southern portion of the study area is largely fronted by fringing fossil coral reef that restricts the sub-aqueous beach profile area actively involved in sediment transport and can be idealized as a perched beach atop a fossil reef. This shallow fringing reef truncates the surface area of the beach profile, reducing the total area that is available for sediment exchange and mobilization.

The study area consists of a 4.6 km continuous carbonate beach that is bisected by a prominent basalt headland, Kekaa Point. Kekaa Point divides the area into two distinct littoral cells, the Honokowai cell to the north and the Kaanapali cell to the south with seasonal sediment impoundment occurring on both sides. The beach is composed of moderately-sorted carbonate sand with a minor basalt component (< 10 percent) and a median grain size diameter of 0.23 mm. The beach generally displays a steep foreshore slope (vertical: horizontal) mean 1:8, and a gentler backshore (sub-aerial) slope mean of 1:11. The foreshore slope was applied as input to the LST models described.

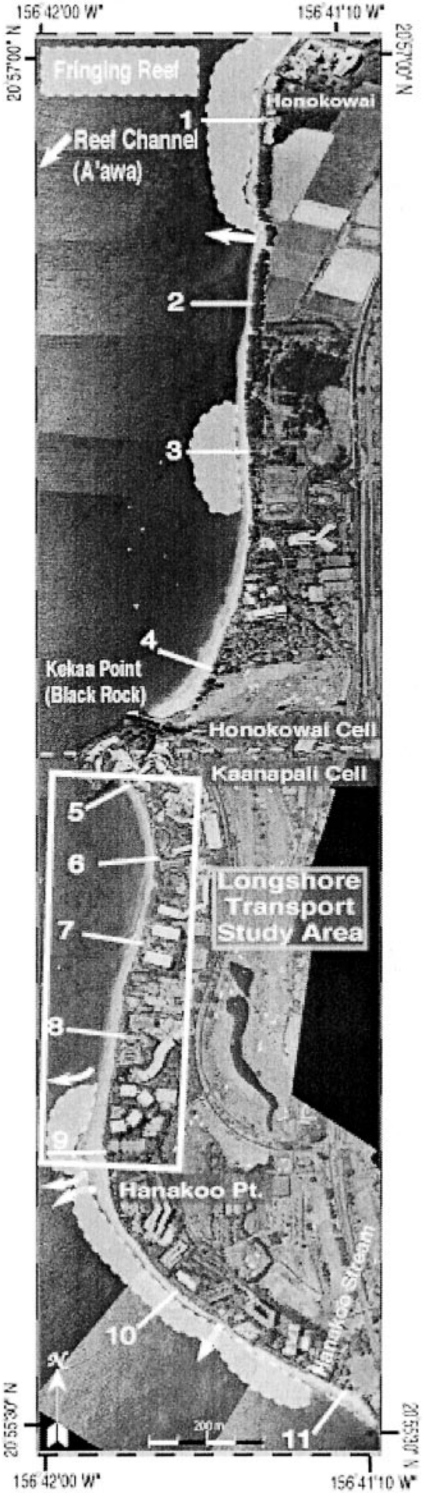

Figure 2. Kaanapali Beach fringing reef (gray shading), reef channels, beach survey locations and transport study area.

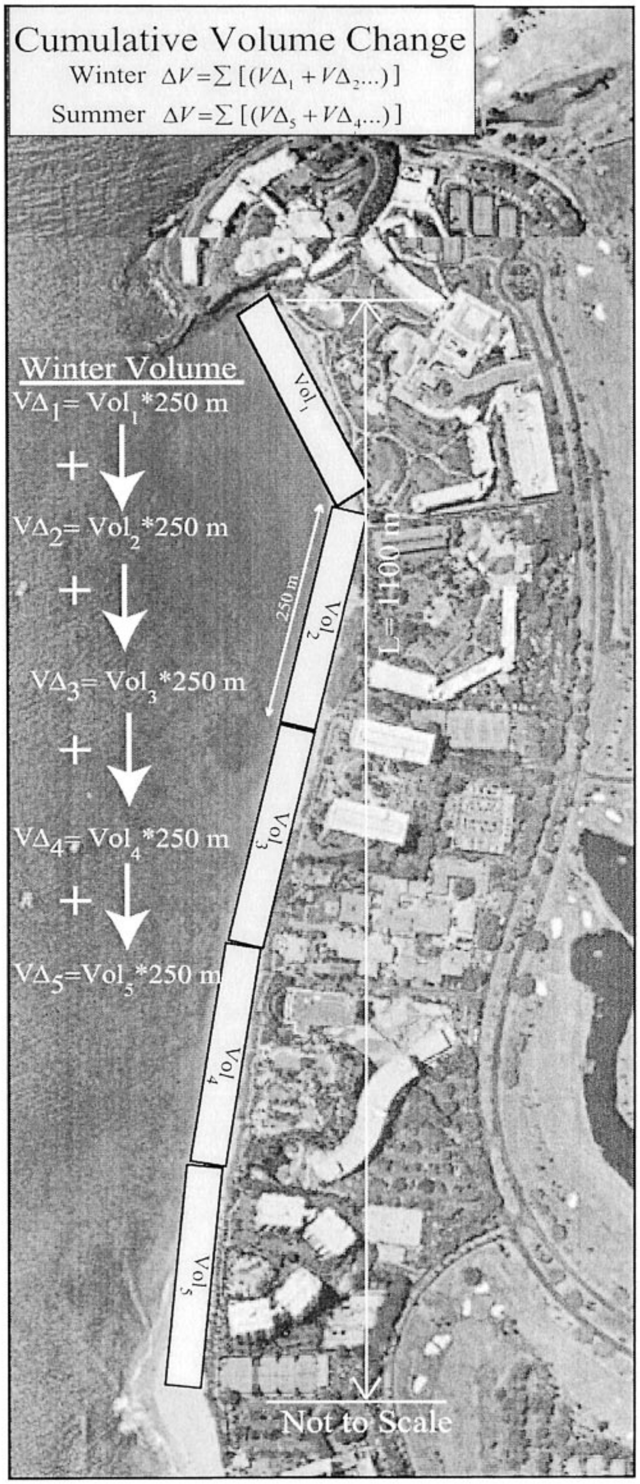

Figure 3. Cumulative profile volume change. Cumulative alongshore volume change derived from profile volumes (vol_1, vol_2, etc.) Winter cumulative volume change calculated from profile vol_1 to vol_5, while summer is calculated from vol_5 to vol_1.

Table 1. *Beach profiles March, 2000 to April 2001. Note the larger volumes and volume ranges of profiles 5 and 6.*

Profile	Maximum Volume (m^3/m)	Minimum Volume (m^3/m)	Volume Range (m^3/m)	Mean Volume (m^3/m)	Mean Volume Rate Change ($m^3/m/month$)	Net Volume Change (m^3/m)
1	29.23	9.26	19.97	18.26	−0.22	−2.83
2	94.71	83.37	11.34	87.64	−0.54	−6.97
3	137.80	112.17	25.63	128.35	0.99	12.91
4	476.42	349.83	126.59	396.96	−7.50	−97.49
5	707.66	552.36	155.30	651.81	5.47	71.16
6	733.00	625.62	107.38	685.14	7.00	90.96
7	379.11	244.52	134.59	317.91	0.33	4.24
8	222.70	165.94	56.76	185.64	−1.42	−18.44
9	206.82	45.88	160.94	126.47	−4.70	−61.15
10	107.13	92.16	14.97	98.50	−0.48	−6.18
11	305.80	261.58	44.22	283.22	0.35	4.50
Mean	309.13	231.15	77.97	270.90	−0.06	−0.84

METHODOLOGY

Monthly Beach Surveys

Observations of monthly beach profile changes were collected at a series of 11 shore-normal beach profile transects situated along the length of the study area. Thirteen monthly surveys were performed from March, 2000 to April, 2001. Beach profiles and volumes were measured using a Geodimeter® total station and a 7 m telescoping rod with reflecting prism. Shore-normal profiles extended over the sub-aerial and sub-aqueous portions of the beach with measurements at approximately 2 m intervals or at each significant change in slope or bottom type. Surveys were conducted randomly with respect to tide and swell conditions and typically extended approximately 100 m offshore into water depths of 5 to 7 m.

Sediment-Reef Interface

In carrying out the surveys, continuous and patchy hard reef was encountered along many of the profiles in Kaanapali. The presence of a fringing reef significantly alters the profile by truncating that portion of the beach and creating a shallower than expected sand-reef interface, often referred to as the Depth of Closure (DOC). The first occurrence of hard substrate is considered the depth at which the profile is no longer adjusting to wave energy and hence operates as the prescriptive depth of closure (DOC). In Kaanapali, we find a shallow DOC where there is reef present and a deeper DOC where the profile remains sandy.

Cumulative Beach Volume

Beach volumes are calculated as the volume under the profile extending from the landward edge of the subaerial beach to the first occurrence of submerged hard substrate often just seaward of the toe of the beach. The profiles extend from the landward edge of the dune system (where present) beyond the beach toe to the edge of the reef slope. We calculate the spatial cumulative beach volume alongshore based on each sectional volume (profile volume per alongshore unit of beach). The section volumes are in turn multiplied by the alongshore distance between each profile to account for the monthly volume change for each section of beach. In order to integrate over the entire area and reduce the effect of seasonal outliers, we calculate the cumulative net sum alongshore as a proxy for longshore transport rates (Figure 3).

Wave Data

Wave parameters such as height, period and direction are utilized for transport model input parameters and were obtained from two sources. We specify the wave energy flux for Kaanapali based on offshore buoy data and coastal observations. For north swells we use wave data provided by the Coastal Data Information Program (CDIP) at the Scripps Institute of Oceanography for the Mokapu Datawell Waverider buoy #98, located at 21° 24.900 N 157° 40.700 W. Buoy #98 roughly approximates the north to north-east swell window observed at our study site in Kaanapali, Maui. North swells are described by significant wave height, period and direction filtered to the dominant wave direction thus eliminating the effect of local wind swell on the wave readings. Offshore wave data was converted to breaking wave heights for use in the LST models using a modified Airy-Wave theory from KOMAR and GAUGHAN (1972).

For south swells we employ the National Oceanographic Atmospheric Administration (NOAA) data base for coastal surf observations for Oahu provided by National Oceanographic Data Center's (NODC) and the National Coastal Data Development Center (NCDDC) Hawaii/Pacific Liaison Office. This public-domain data set includes breaking wave surf heights and estimated direction for the south shore of Oahu and adequately approximates the south swell exposure of the Kaanapali region. Seasonal wave data such as height, period and direction from these sources is applied as input to the longshore transport formulas discussed below.

Uncertainty Analysis

Three main sources of error are identified in the uncertainty analysis for profile area volume. Where: Volume Uncertainty (*VU*)

$$VU = [(\text{meander error})^2 + (\text{basement error})^2 + \text{cross-shore error})^2]^{1/2}$$

Measurement error is considered negligible as the profiling

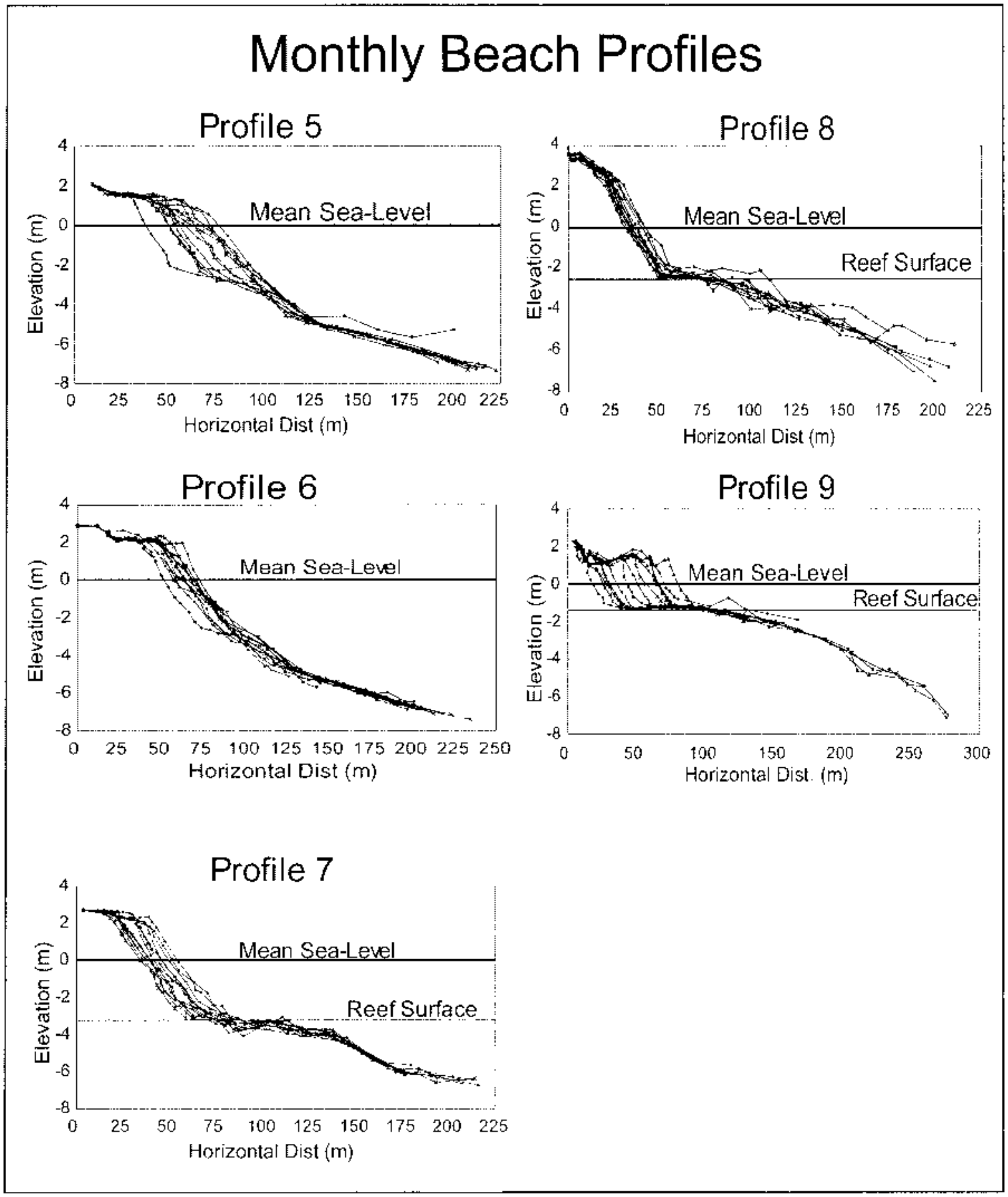

Figure 4. Monthly beach profiles. Note the lack of significant cross-shore morphology exchange. We attribute the observed profile volume changes to longshore transport.

technique used has centimeter accuracy. Likewise, the landward margin of the profile is fixed and thus induces no uncertainty. Meander error (±500 m^3), is associated with variation in the seaward margin of the sub-aerial profile as observed in foreshore meanders at the shoreline. Meander error is calculated by taking the mean observed meander width (±10 m) times the alongshore wavelength of the meander (50 m) times the profile area (1 m). Basement error (±2 m × 500 m × 1 m = ±1000 m^3), caused by variable relief of the basement strata, (which constitutes the lower boundary of the profile volume) is assumed to be horizontal landward from the first occurrence of hard basement. Cross-shore error (±1120 m^3), calculated from the seasonal profile net volume difference between profile 5 and 9, represents sediment lost

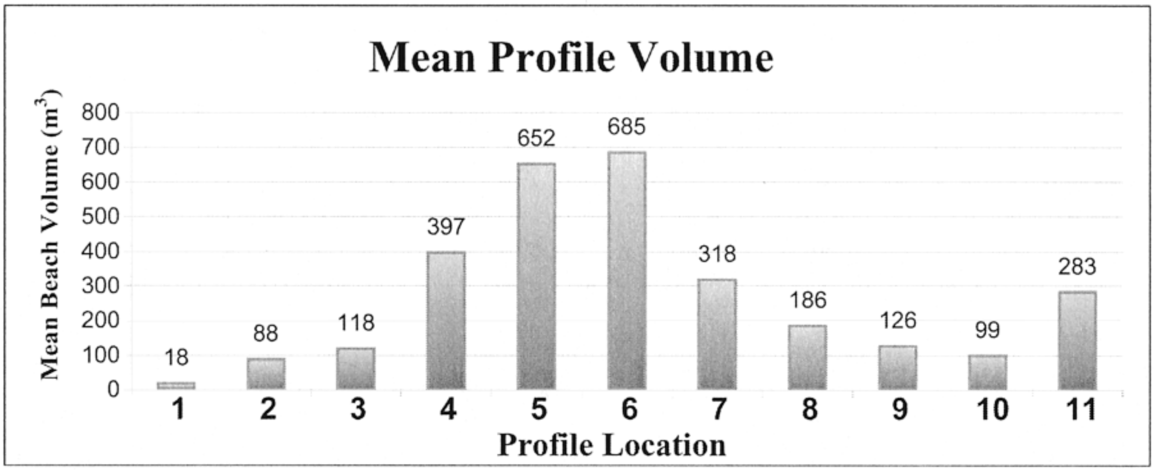

Figure 5. Mean profile volume by location.

outside the profile due to cross-shore transport. Using the additive error process described above, volume uncertainty for observed net annual volume change is estimated to be ±1100 m^3/month and is reported as the mean percentage of each monthly cumulative volume.

Longshore Transport Models

Sediment transport modeling was carried out using three LST formulas: (CERC, 1984; KAMPHIUS, 1991; and the *GENESIS* model (CERC, 1991). Each of these models utilizes different environmental input parameters including; wave height, period, direction, sand size, sand porosity, beach slope, sand and water density, wave breaker index and empirical coefficients. The CERC (1991) model employs the most detailed environmental parameters including the nearshore bathymetry and antecedent conditions in a cumulative time-series of calculations rather than a snapshot calculation of given conditions as the CERC (1984) and KAMPHIUS (1991) models.

The CERC (1991) model calculates longshore transport on a modeled cell by cell (20 m cell) basis alongshore which allows the user to estimate transport at any point along the study area after a given computational run is completed. None of the models utilized in this study account for hard substrate such as a fringing reef, and each model assumes the entire study area is transportable sediment.

Longshore transport observations were carried out in the southern (Kaanapali) area for the section of beach between profile numbers 5 and 9. This section of beach exhibits the highest longshore transport rate and represents the most dynamic portion of the beach system. The average observed cumulative annual net volume change at profile 7 is compared to the predicted cumulative volume change from the Genesis

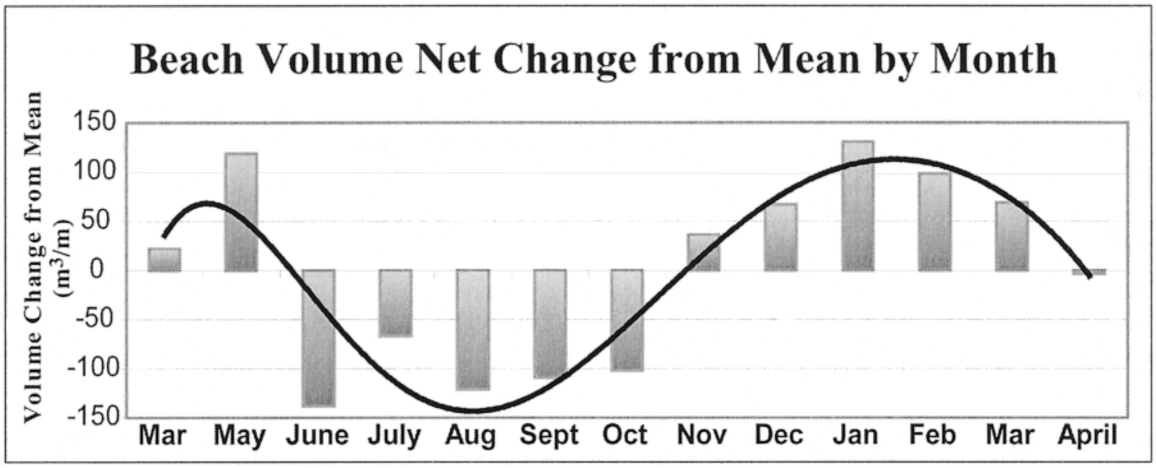

Figure 6. Monthly net profile volume change from the mean showing trend line of best-fit polynomial regression.

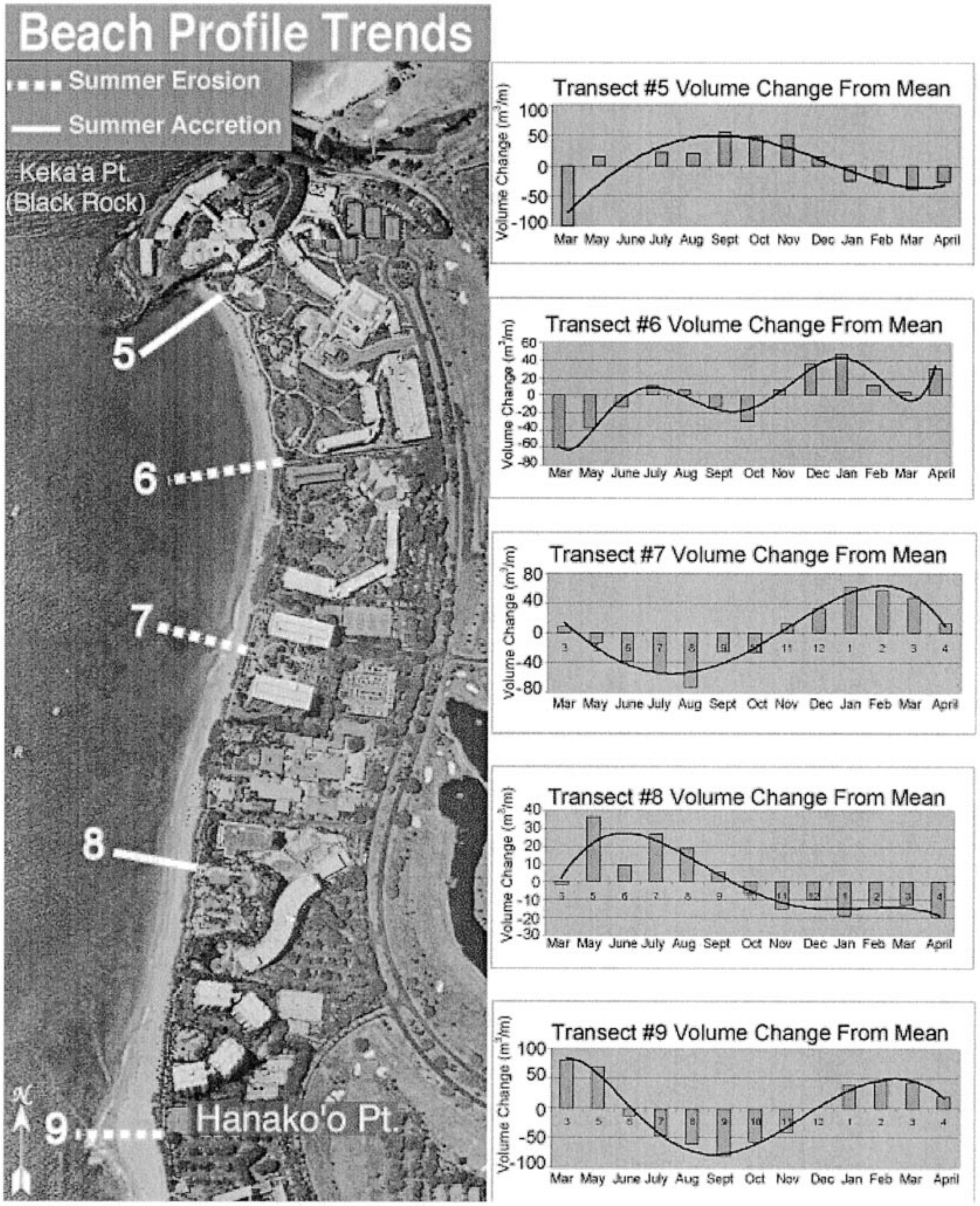

Figure 7. Beach Profile Trends. Note the alternating pattern of erosion and accretion as indicated by the alternating transect types. Volume plots to the right reveal the cyclic nature of the profiles as seen by the best fit (black) trend line.

model. Each of these is compared with the predicted LST rates of the CERC (1984) and Kamphius (1991) models. Profile 7 was selected as a common location for comparative analysis of observations to models and exhibits an inflection or hinge point in the trend of the data. Results indicate the Genesis prediction closely approximates the observed net annual transport at profile 7.

RESULTS

Seasonal Beach Volume Change

Surveyed beach profiles at Kaanapali reveal a clear cyclic pattern of erosion and accretion due to seasonal wave forcing. While the profile volumes are highly variable alongshore we see that the mean volume, volume range and net volume are

Table 2. *Observed and predicted profile depth of closure. Note the deeper depth of closure at profiles 4–6 where there is no reef structure. Predicted DOC is based on mean annual wave height and period.*

Profile	Observed Depth of Closure (m)	Hallermeier Prediction
1	−0.70	−7.54
2	−1.80	−7.54
3	−2.10	−7.54
4	−8.00	−7.54
5	−6.00	−7.54
6	−6.00	−7.54
7	−3.00	−7.54
8	−2.50	−7.54
9	−1.20	−7.54
10	−1.70	−7.54
11	−2.30	−7.54

all significantly higher in the central portion of the study area (profiles 4–6 surrounding Kekaa Point) (Table 1). Beach profiles exhibit little to no transport of sediment offshore but they do show a significant change in beach face profile volume, which suggests longshore transport is acting upon the profiles (Figure 4). The distribution of profile volume change reveals the dynamic nature of the central portion of the study area and the clear decrease in mean profile volume away from the central area (Figure 5). We find that 65 percent of the net volume change occurs south of Kekaa Point confirming the increased variability of the southern portion of the area.

Most profiles reveal a strong seasonal signal with net erosion in the summer and accretion in the winter. A closer look at the dynamics of the profile volume shows that the net volume for all profiles is highly variable over the 13 month period with the peak summer and winter months showing the largest net loss or gain from the mean (Figure 6). Net volume change from the mean suggests that June and January are the most dynamic months with approximately 14 percent and 13 percent of the total annual volume change respectively. In addition to seasonal trends, we find an alternating pattern of erosion and accretion alongshore (Figure 7). The alternating nature of the profile state switches alongshore with one profile contributing sediment to the neighboring profile seasonally.

Sediment-Reef Interface and Depth of Closure Estimates

The calculated profile DOC as defined by Hallermeier (1978) is in most cases significantly deeper than the first occurrence of hard substrate at Kaanapali (Table 2, Figure 8). Shallow continuous fringing reef is attached to the shoreline at profiles 1, 2, 9 and 10. Where no reef is present, as in profiles 4 to 6, the actual DOC closer approximates the predicted depth. Beach width variability is considerably more pronounced on those profiles not protected by fringing reef, while those landward of fringing reef tend to be narrow but more stable presumably due to the wave buffering effect of the reef. This is also consistent with there being less active sediment due to the hard substrate of the profile.

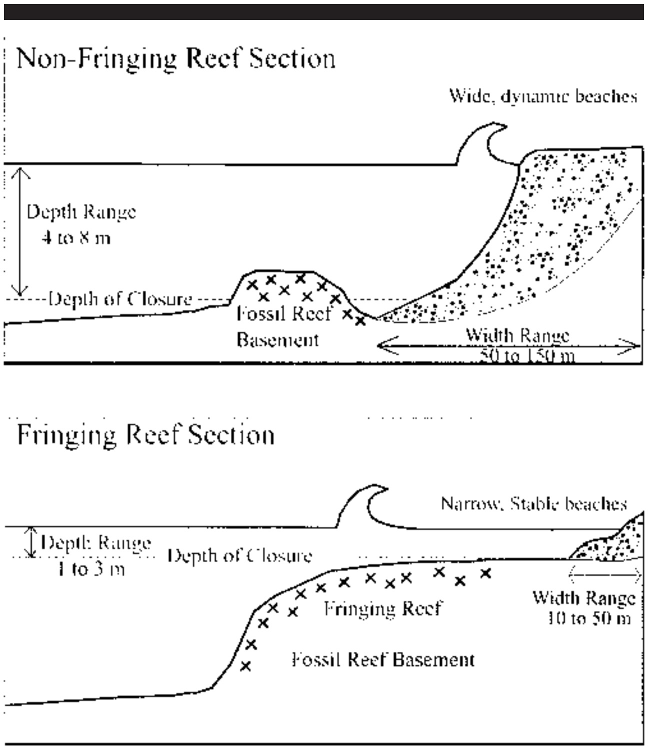

Figure 8. Non-fringing and fringing reef cross-section. We see a significantly shallower DOC where fringing reef is present.

Cumulative Beach Volume

The central Kaanapali region at profile 7 exhibits a strong seasonal volume change and reveals an inflection point in the trend of cumulative profile volume alongshore. We use the cumulative volume change of profile 7 as a proxy for LST because it represents the alongshore location where seasonal cumulative volume trends reverse sign and acts as a hinge point in the sediment transport regime, yielding a consistent location alongshore for comparative analysis with LST models (Figure 9). The observed cumulative net annual volume change at profile 7 is compared with the predicted transport rates of CERC (1991) *Genesis* model, Kamphius (1991) and CERC (1984).

Wave Energy Flux

Incident wave energy flux given by

$$F_b = \frac{\rho g^2 T H^2}{16\Pi}$$

(CEM, 2001), where T and H are breaker height and period, and is used to compare the seasonal incident wave energy to the monthly total combined beach volume change (Figure 10). We observe a strong correlation of the total beach volume and thus LST, to the incident wave energy monthly mean. Total beach volume appears to be inversely related to south swell wave energy while beach volume is directly correlated to north swell wave energy. Thus in general, south swells tend to decrease the total beach volume while north swell tend to induce recovery of the volume.

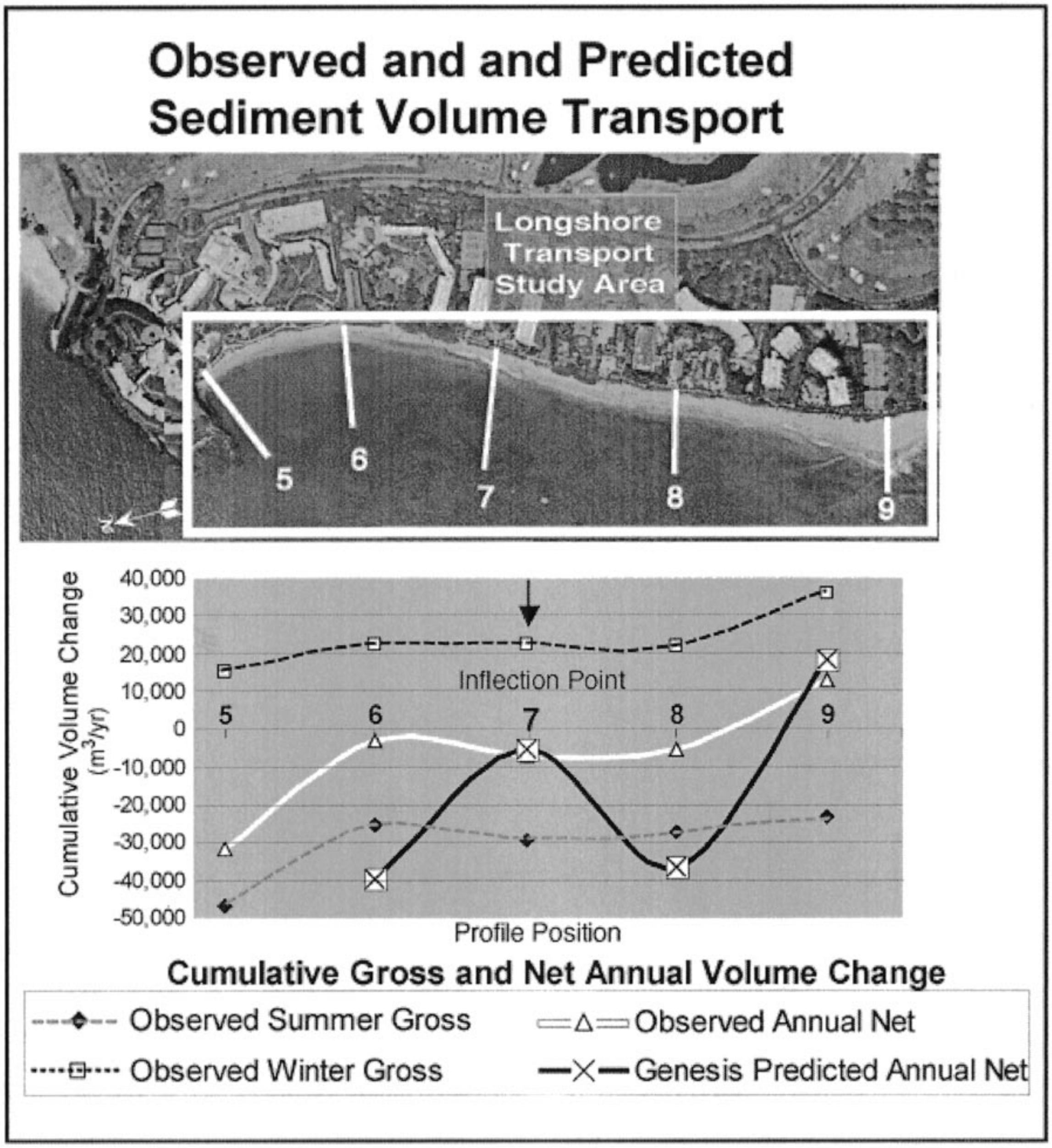

Figure 9. Cumulative seasonal gross and annual net volume change. Cumulative alongshore volume change derived from profile volumes (observed) and Genesis model (CERC, 1991). Note common seasonal inflection point at profile 7 and the coincidence of the net annual transport for the observed and Genesis.

Longshore Sediment Transport

Longshore Sediment Transport is of great importance to the seasonal and long-term dynamics of the Kaanapali coastline. Beach profile results indicate sediment impoundment occurs seasonally in the north-south longshore sediment transport system. Observations of net seasonal sediment volume change reveal a balanced seasonal exchange of net sediment at profile 9 and profile 5 (Table 3). The balanced alongshore net sediment flux suggests the profile volume change in the Kaanapali area is dominated by longshore transport and significant cross-shore transport is negligible.

Total longshore transport rates measured by Ping Wang *et al.* (1998) suggest the CERC (1984) model predicts rates unrealistically high for low energy settings. Ping Wang *et al.* (2002) further tested the application of the Kamphius (1991) model in a wave tank and found it to be very sensitive to breaker type. They found significantly greater LST rates were measured under plunging breakers than spilling breakers with similar height, implying wave period significantly

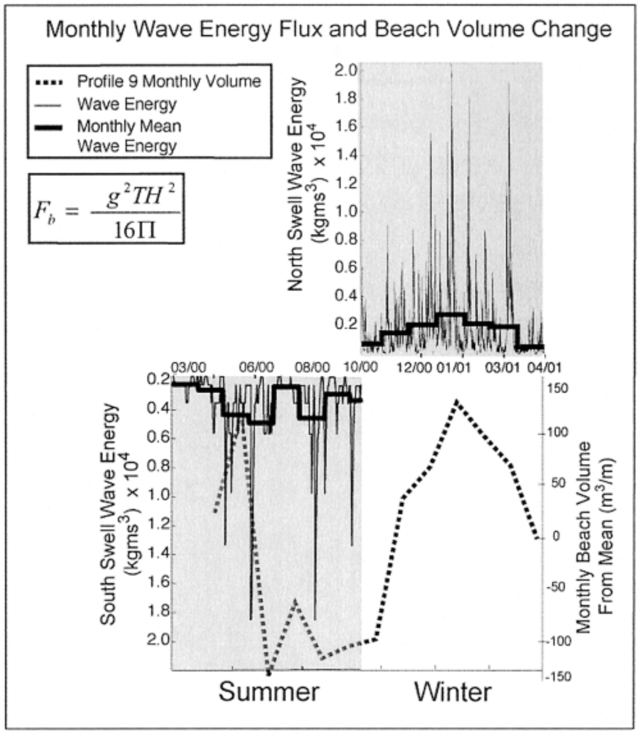

Figure 10. North (upper) and South swell (lower) wave energy flux. Monthly mean shown in bold. Monthly beach volume from the mean (dashed line) is well correlated to the seasonal wave energy flux.

alters the LST rates for the Kamphius (1991) model. Similarly, we find that the predicted CERC (1984, 1991) and Kamphius (1991) modeled LST rates for Kaanapali are sensitive to wave direction, period and height and closely follow wave energy non-linearly.

Estimated LST rates from beach profile volumes are compared to the predicted CERC (1984, 1991) and Kamphius (1991) predictions (Table 4). The CERC (1991) *Genesis* model best predicts the observed LST rates for Kaanapali (Figure 11) with a net annual LST rate within 77 percent of our observed mean gross annual rate. The Kamphius (1991) model overestimates the net annual observed transport by approximately 6 × 10^3 percent while the CERC (1984) model overestimates observed transport by approximately 3 × 10^3 percent. The Kamphius (1991) model utilizes several parameters that the CERC (1984) model does not such as; period, beach slope and mean grain size diameter. Although the predicted magnitude varies widely, all three models agree on the seasonal gross and annual net LST direction. We find agreement in the models of a net northward transport in the summer, net southward transport in the winter and a net annual LST to the north.

DISCUSSION

Seasonal Beach Volume and Shoreline Features

The Kaanapali nearshore generally exhibits a reflective beach state with plunging to surging waves as described by Wright and Short (1984). This beach state favors coarser sediments and/or longer period swells and generally displays a steep narrow beach with a well-defined toe at the base of the foreshore. The strong swash and coarse sediment often form sub-aerial beach cusps. Occasionally the area will fluctuate states between the reflective and intermediate transverse bar and beach with surging waves. In the latter state, crescentic attached beach cusps (megacusp horns) form alongshore and segregate individual rip systems approximately every 100 m.

The presence of a distinct, migrating pattern of erosion and accretion suggests neighboring profiles exchange sediment seasonally and supports the theory that longshore transport is controlled by seasonal wave energy. A three-dimensional plot of profile volume change confirms a seasonal cyclic pattern and highlights the migration of erosion and accretion along the coast (Figure 12). Along the horizontal axis of Figure 12 we see an alternating pattern of erosion and accretion alongshore from north to south for a given month. A similar pattern of alongshore alternating beach state was observed on Kailua Beach, Oahu and was described as a meandering beach morphology feature (Norcross *et al.,* in press). The vertical axis reveals the seasonal pattern of erosion and accretion through time for a given shoreline position. We see the seasonal migration of erosion and accretion "hot spots" alongshore as indicated by the arrows in Figure 12. The trends observed in this analysis support longshore sediment transport as the dominant mode for this region.

Nearshore Reef Influence and Depth of Closure

The orientation of the fringing reef plays a significant role in the stability of the beach in this area (Inman and Waldorf, 1978). Mean beach volumes, beach volume range and longshore transport rates are significantly lower adjacent to fringing reefs, implying the reefs stabilize the beach. Landward of the fringing reefs, the beach is subject to less direct wave exposure due to wave energy decay over the reef flat. The reduced wave energy appears to decrease sediment transport. The presence of fringing reef in Kaanapali, con-

Table 3. *Observed net profile sediment volume change. Note the balanced seasonal longshore transport of sediment between profile 9 and 5.*

Observed Profiles	Net Volume Change (m³/m/yr)	Profile 9	Profile 5	Percent Change
Kaanapali	Net Summer Change	−138	147	107%
	Net Winter Change	77	−76	99%
	Annual Gross Change	315	306	97%
	Annual Net Change	−61	71	116%

Table 4. *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 (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 each 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%

trols the incident wave energy and sediment transport capacity as well as provides a source of nearshore sediment. The estimated sediment production of the nearshore fringing reefs here (based on HARNEY *et al.,* 1999), is approximately 82 m^3/yr (Figure 13). Hence, reef-supplied sediment is insignificant in comparison to the magnitude of seasonal sediment volume changes observed.

MUNOZ-PEREZ *et al.* (1999) present a beach equilibrium profile model for reef-protected beaches of the Spanish coast. They examine wave decay due to shoaling over a hard substrate and conclude that no equilibrium beach profile is possible within a distance of 10 to $30h_r$ from the landward edge of the reef, where h_r is water depth over the reef. Similar results are found at profiles 1, 3, 8, 9 and 10 where shallow fringing reef extends to the shoreline.

Beach profiles for segments of Kaanapali landward of fringing reef exhibit narrower but more stable characteristics than non-protected profiles, suggesting the reef may inhibit a true beach equilibrium profile. The actual first occurrence of hard bottom, or effective DOC, near these fringing reefs is much shallower than predicted by HALLERMEIER (1978). The fossil coral reef that fronts Kaanapali restricts the beach profile area actively involved in sediment transport and can be idealized as a perched beach atop a fossil reef. This shallow fringing reef truncates the surface area of the beach profile, reducing the total area that is available for sediment exchange thus yielding less sediment available for transport than expected from a full-sand profile beach system that the LST models are calibrated for. The presence of a fringing reef may help explain why these models over-predict the observed LST.

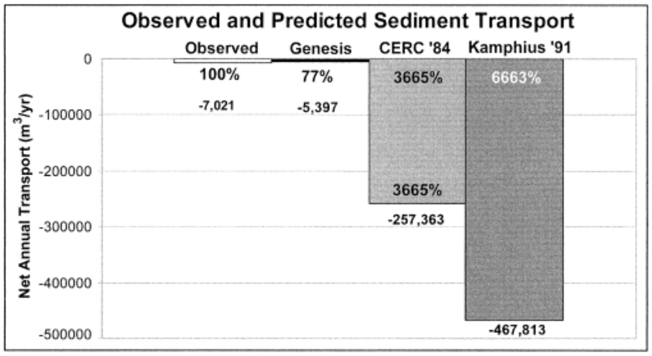

Figure 11. Observed and predicted transport rates. Observed transport compared to predictive models. Note the relatively high over-estimate of the KAMPHIUS model. Percentage of observed transport given.

Wave Modeling

LST models are very sensitive to incident wave angle and height therefore detailed wave modeling or field measurements of wave conditions are essential for accurate results. Based on modeling carried out in the *Genesis* model (CERC, 1991) we find a mean summer incident swell angle of 7.1°, and a mean winter incident swell angle of 3.5°. Modeled wave angles and heights roughly match observed wave characteristics from field observations. The approach angle has a direct influence on the direction and magnitude of the LST rate and is one of the primary influences of seasonal transport of sediment in the study area.

Longshore Transport Models

The sediment impoundment technique (sediment blocking by a structure) has been successfully used to estimate longshore sediment transport (JOHNSON, 1957; BRUNO and GABLE, 1977; BODGE, 1986; DEAN, 1989). In this technique, the volumetric transport rate is estimated from the updrift sediment volume change. PING WANG *et al.* (1998) measured longshore sediment transport from streamer traps at 20 lo-

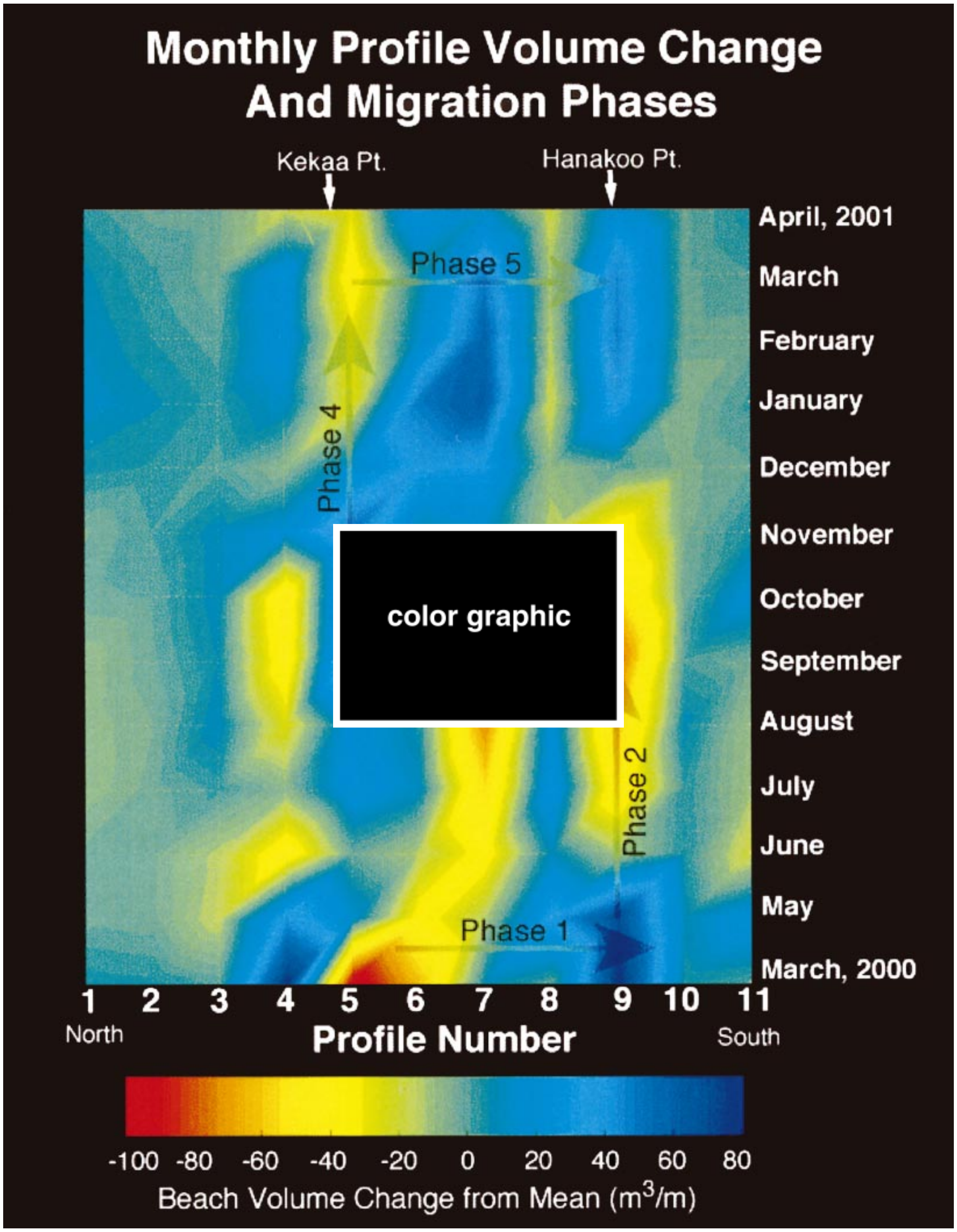

Figure 12. Three-dimensional plot of beach volume change from the mean. Note the sign reversal of the volume change as the seasons change from summer to winter bottom to top of upper plot. Arrows indicate the seasonal migration of erosion and accretion alongshore through time.

cations along U.S. East and Florida Gulf coasts. They concluded that longshore sediment transport on low energy coasts was considerably lower than predicted by published empirical transport formulas. They found that KAMPHIUS (1991) predicted sediment transport three times lower than the commonly used CERC (1984) formula and approximated the measured transport. The KAMPHIUS (1991) formula includes a non-linear function of wave period that may account for it's low prediction in the PING WANG *et al.* (1998) study and the large over-prediction in this study. The KAMPHIUS (1991) formula is especially sensitive to extremes in wave period and tends to deviate from observed transport estimates for unusually high (this study) and low (PING WANG *et al.* (1998)) wave periods.

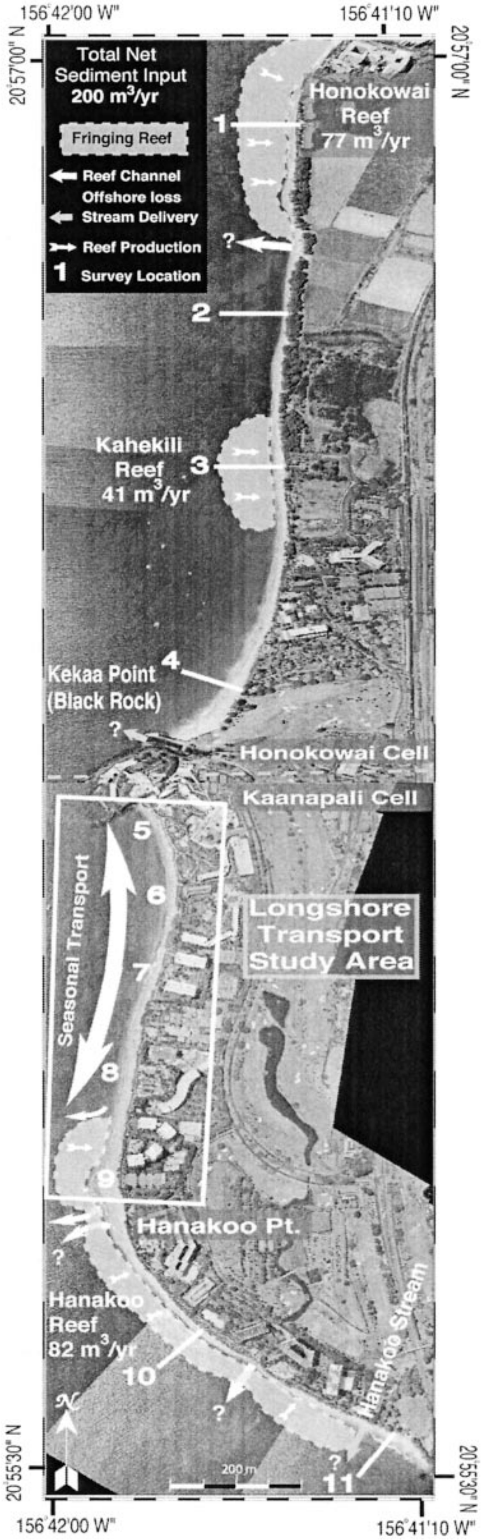

Figure 13. Sediment transport conceptual model.

We attribute the large difference in the model results to each model's ability to accurately assess wave energy. The success of the *Genesis* model is attributed to its' ability to account for wave energy flux for individual events rather than a time-averaged mean as applied to the CERC (1984) and Kamphius (1991) formulas. The *Genesis* model also employs near-shore parameters such as antecedent beach conditions, bathymetry, wave shoaling, diffraction, and several shore face parameters not accounted for in the CERC (1984) or Kamphius (1991) formulas.

Overestimates of longshore transport using the CERC (1984) and Kamphius (1991) models may be partly attributed to the use of seasonal significant wave height, period and direction as input parameters where as the CERC (1991) model utilizes an internal wave model that accounts for each wave event and considers the antecedent conditions of the shoreline. We attribute the large over-prediction of transport of the Kamphius (1991) model partially due to the relatively large wave periods of Hawaii. Additionally, these formulas may overestimate transport of coarse, poorly sorted or dense sediment like Kaanapali Beach, due to the calibration of specific density of these formulas in finer, well-sorted silica beaches. This however does not account for the order of magnitude over-prediction observed in the models, which can partially be attributed to each model's ability to accurately assess wave energy.

Although the CERC (1984) and Kamphius (1991) formulas overestimate the observed transport by an order of magnitude they are still useful as a qualitative interpretive tool of the transport direction. Problems with the practical application of these formulas such as improper adjustment of the K coefficient of proportionality, recommended at 0.77 by the Shore Protection Manual, (CERC 1977; 1984) are common and can result in significant over prediction of LST.

Bodge and Kraus (1991) examined several inconsistencies in the practical application of the CERC (1984) formula and conclude that errors in field measurements can potentially yield errors in the LST formula by a factor of 2 to 4 times. Due to an a prevailing overestimate of the LST by the CERC (1984) formula, the use of the suggested empirical "K" coefficient of 0.77 should be modified for practical applications. Reduction of "K" by an order of magnitude was found to yield more reasonable results (Ping Wang *et al.,* 1998; Bodge and Kraus, 1991). This was found to be especially true on coarse, poorly sorted beaches with higher wave energy such as Kaanapali Beach. It is common practice to lower the K coefficient by an order of magnitude in order to achieve reasonable results of LST. We find similar results with the use of the CERC (1984) formula in this study with LST estimates approximately an order of magnitude higher than observed. If we apply a new K value of 0.07 instead of the suggested 0.77 we find a much better fit to the observed LST (Table 5).

In using the LST models and formulas, it is important to recognize each model's strength and weakness and utilize the formulas collectively as an interpretive tool rather than an absolute gauge of LST. Each model should be used in conjunction with at least one other formula in order to confirm the gross and net transport direction and secondly as a rough

Table 5. *Predicted TLST rates for CERC (1984) with $K = 0.07$. With a modified empirical coefficient* ($K = 0.07$ *instead of* $K = 0.77$) *we see the better fit of the predicted transport to the observed transport (negative indicates northward transport).*

Modeled TLST	CERC, 1984 Model ($K = 0.07$)	Transport (m³/yr)	% of Observed
Predicted	Gross Summer Transport	−40,605	177%
Cumulative Volume	Gross Winter Transport	18,338	104%
Change at Profile 7	Net Annual TLST	−22,266	413%

estimate of LST magnitude. We find this method works very well in this study and yields consistent results on the direction of transport. All the models we employed agree on the direction of seasonal gross and net annual LST even though they vary widely on the magnitude.

CONCLUSIONS

Surveyed beach profiles reveal a strong seasonal variability with net erosion in the summer and accretion in the winter. An alongshore-alternating pattern of erosion and accretion is identified from our beach profile surveys, manifested as large alongshore meanders (Norcross *et al.,* in press). We find that 65 percent of the net volume change occurs south of Kekaa Point confirming the more dynamic nature of the southern (Kaanapali Cell). Net volume change from the mean suggests that June and January are the most dynamic months each with approximately 14 percent of the total annual volume change.

Observations of gross seasonal sediment volume change reveal a nearly balanced longshore sediment transport system with the gross sediment loss at profile 9 accounted for by a nearly equivalent gain at profile 5 and confirms the presence of a strong seasonal longshore transport mechanism. We attribute the longshore transport of sediment from seasonal wave forcing with minimal cross-shore displacement. In general, south swells tend to decrease the total beach volume while north swell tends to induce volume recovery.

Longshore transport rates are derived from seasonal cumulative beach volume change in the middle of Kaanapali Beach at profile 7. We observe cumulative net sediment transport rates of 29,379 ±4400 m^3/yr to the north and 22,358 ±1300 m^3/yr to the south for summer and winter respectively, a net annual rate of 7,021 ±700 m^3/yr to the north and a gross annual rate of 51,736 ±5100 m^3/yr. Predictive transport formulas such as the CERC (1984), CERC (1991) and Kamphius (1991) predict net annual transport rates at 3×10^3 percent, 77 percent and 6×10^3 percent of the observed transport rates respectively.

The fossil coral reef that fronts Kaanapali plays a significant role in the accuracy of the LST models. Shallow fringing reef truncates the subaqueous area of several of the beach profiles restricting the beach profile area actively involved in sediment transport and reducing the total volume that is available for sediment exchange. This effectively restricts the available sediment relative to the full sand profile beach system that the LST models are calibrated for. Great care must be used when applying LST models in areas with significant hard bottom or shallow reefs that alter the beach profile shape.

Although the predicted magnitude varies widely, all three LST models utilized agree on the seasonal gross and annual net direction. Adjustment of the empirical K value in the CERC (1984) model to 0.07 significantly improves the fit to observed data. The models agree in a gross northward transport in the summer, gross southward transport in the winter and a net annual LST to the north.

The position and orientation of the fringing reef plays a significant role in the stability of the shoreline creating narrow steep beaches that are often significantly more seasonally stable than the surrounding non-reef beaches. The narrow but stable seasonal morphology of the reef-protected beaches is attributed to decreased onshore wave energy, decreased near shore sediment transport and sediment transport offshore through the reef channels.

ACKNOWLEDGMENTS

The authors would like to thank Kevin Bodge for his technical assistance in applying the LST formulas. We thank Mark Merrifield, Jerome Aucan and Pat Caldwell for their assistance in retrieving and compiling wave data for the Hawaiian Islands. Thanks to John Rooney, Chris Conger, Tara Miller, Ole Kaven, Matt Barbee and Mary Engels of the Coastal Geology Group at the University of Hawaii, Manoa for their assistance in the field and conceptual support. Additional thanks go to Lee Butler of Veri-Tech Inc, for his dedicated technical support of the Genesis software applications. This study was partly funded by Maui County, Hawaii, NOAA, USGS, Sea Grant and the State of Hawaii, DLNR.

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