DYNAMICS OF SANDY SHORELINES IN MAUI, HAWAII: CONSEQUENCES AND CAUSES

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Abstract: Beaches serve as important recreational, cultural, and ecological resources, and as an indispensable economic asset. The dramatic degradation of sandy beaches over the last several decades has become widely recognized as a serious problem in the Hawaiian Islands. A key component of Maui County's beach preservation strategy is the quantification of site-specific erosion hazards. The study reported here investigates shoreline change to provide erosion hazard rates for all significant sandy shoreline on the island, which will serve as the basis for improved regulations governing siting of coastal construction. Horizontal movement of the landward and seaward boundaries of the beach from orthorectified aerial photographs and topographic surveys (T-sheets) is used to develop a multidecadal database of shoreline movement every 20 m along the coast of the island of Maui. Annual erosion hazard rates (AEHRs), calculated using a reweighted least squares regression and smoothing routine, average -0.26 m y^{-1}. Island wide changes in beachwidth show a 26% decrease. Erosion rates on Maui's north shore are double those on the western and southwestern sides of the island. Although experiencing erosion rates twice as large, beachwidths on the relatively undeveloped north shore have decreased half as much as those on the western side of the island. In-depth studies of two sites along Maui's coast suggest that interannual to century scale shoreline sediment dynamics are strongly influenced by Pacific Decadal Oscillation and El Niño/Southern Oscillation related storm variability. Human impacts and other factors are likely to be important as well.

INTRODUCTION

Sand beaches are a common feature of many coastlines in the Hawaiian Islands. They are of vital importance to the state of Hawaii, serving as a key attraction for the visitor industry, which provides more that 60% of all jobs and brings in several times more income than from all other sources combined. Their prevalence is perhaps part of the reason why they have not been widely recognized as a vital resource until recently. This lack of recognition has contributed to the use of shoreline hardening as the management alternative of choice for mitigating erosion problems. Most of the 6 km of beach that has been lost on Maui is in front of coastal armoring. Recognizing the importance of their beaches, and aware of the serious loss of this resource, Maui County has taken the lead within the state in implementing measures designed to prevent further loss and sustainably manage their remaining beach resources.

Although other management options such as beach renourishment may be feasible for some areas, the high and recurring costs involved and lack of identified suitable sand sources and the uncertainty of funding, at present preclude this approach in most cases (Bodge 1998, 2000). A cost-

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effective way for Maui and other counties to protect many of their beaches is with a policy of adaptation and avoidance, altering development patterns to allow natural erosion/accretion cycles to continue without interference. Such a policy requires that erosion hazard zones are identified so that human activities there may be modified to avoid future damage to the beach as well as to reduce homeowner hazard expense (Bay and Bay, 1996; Fletcher, 1998). Accordingly, the Maui Planning Department (MPD) commissioned the present study to quantify historical shoreline change and identify erosion hazard areas.

Physical Setting

Sandy beaches on Maui are composed of variable percentages of coralline algae, foraminifera, coral, mollusc and echinoderm fragments, with volcanic grains generally contributing a minor fraction to the total volume (Rooney, 2002). The largest reservoirs of beach sand, in Maui and other Hawaiian Islands, are typically found on the coastal plains, where they were deposited during a period of (~2 m) higher than present sea level approximately 2,000 to 4,000 years ago (Calhoun and Fletcher, 1996; Grossman and Fletcher, 1998; Harney et al., 1999). Hawaiian beaches are the exposed and eroding edge of these coastal plain deposits. Beach dynamics dominated by longshore transport characterize Hawaiian littoral systems (Calhoun et al., 2002; Eversole, 2002; Norcross et al., 2002; Rooney, 2002). Although the amount of sand released by erosion from coastal plain sediments to the beaches is relatively small compared to annual longshore sediment fluxes, it is the primary source of material for maintaining long-term sediment budgets on Hawaiian beaches (Harney et al., 1999, Rooney and Fletcher, 2000).

Hawaiian littoral sediment dynamics are largely driven by four types of seasonal waves (Figure 1). These include North Pacific swell, originating with storms in the North Pacific, generally between October and April with typical significant wave heights and periods of 1.5 to 6 m and 12 to 20 seconds. Trade wind waves occur about 70% of the time, particularly in the summer months of May

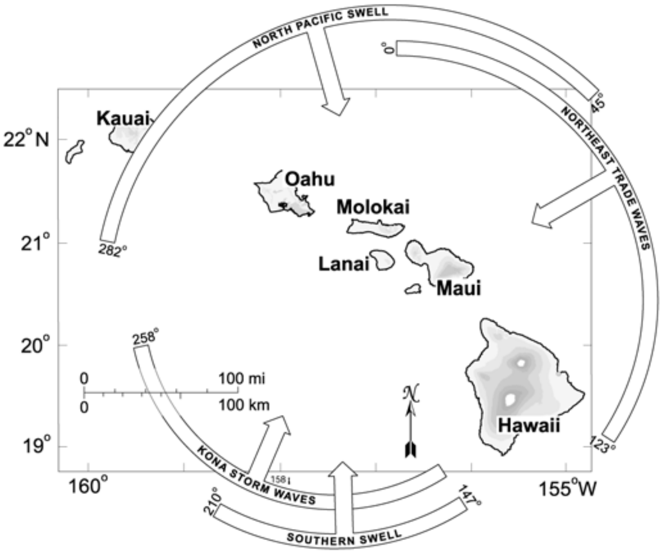

Fig. 1. Directional range of seasonal waves affecting Hawaiian beaches.

through September, with heights and periods of <1 to 3 m and 6 to 8 seconds. South swell, generated by distant southern hemisphere storms, also occurs during the summer, typically with heights of <1 to 3 m and periods of 12 to 20 seconds. Kona storms occur occasionally during the winter months, generating waves 3 to 6 m high with 6 to 10 second periods, and frequently accompanied by strong winds from the southwest. Hurricane and tsunami waves occur less predictably, although the hurricane season in Hawaii is generally considered to run from about April through November.

METHODS

The primary source of historical shoreline positions is aerial photographs. Photographs are vertical, survey quality and generally of 1:12,000 or larger scale for contact prints. A series of photographs also needs to cover enough distance along the shoreline to include an adequate number of ground control points (GCPs) to ensure accurate orthorectifcation. Photographs meeting these criteria are available for 1949, 1960, 1963, 1975, 1987, and 1988. We contracted for a new series of photographs of the entire sandy shoreline in 1997, and for the north shore only in 2002. Photos were scanned at 500 dpi (600 dpi for black and white images) to produce the desired ground resolution of 0.3 to 0.5 m. The 2002 series has a scale of 1:19,500 but were provided in digital format at 2000 dpi thereby maintaining the same ground resolution.

Orthorectification

Methods used in the study have evolved through time as new technologies have become available. In the current iteration, an orthorectified set of aerial photomosaics is obtained from commercial sources to use as base imagery. With position and orientation systems (POS) that integrate differential GPS and inertial technology, motion of aerial camera systems can be quickly and accurately compensated. This technology, in conjunction with digital elevation models (DEMs) and limited numbers of ground control points, is resulting in reasonably economical orthophotomosaics, with horizontal accuracies of 0.5 m to 2.5 m, becoming available in Hawaii.

The base imagery is used to pinpoint the horizontal position and elevation of clearly identifiable natural or cultural features on the ground to be used as GCPs. The shoreline is divided into map areas typically extending between three to seven photo frames in the alongshore direction. Within a single map area, the GCPs are labeled on each photo. We use the aerial orthorectification module from PCI Geomatics, Inc. and USGS 10 m DEMs to orthorectify all the photos covering a map area. Orthorectified images are mosaicked together to produce a shore parallel orthorectified photomosaic constituting the map area.

Shoreline Change Reference Feature

We track movement of the toe of the beach to measure changes in historical shoreline position . The toe, also designated as the crest of the step or base of the foreshore, represents the approximate position of mean lower low water (MLLW) (Bauer and Allen, 1995). The toe of the beach is the preferred shoreline change reference feature for several reasons. Studies indicate that Hawaiian beaches are dominated by longshore rather than cross-shore seasonal profile changes, suggesting that the toe provides an accurate representation of the volume of sand under the profile. (Eversole, 2002; Norcross, 2002; Rooney, 2002). The high visual reflectivity of Hawaiian carbonate beaches tends to mask the visual prominence of other types of reference features such as the wet-dry line, the water line and the high-water line, especially in historical black and white aerial photos that are acquired as contact prints rather than higher resolution diapositives. A high degree of water clarity in Hawaiian waters however does allow the delineation of the beach toe during onscreen digitizing activities. We use the toe of the beach as a relatively stable natural feature that is readily obtained from historical materials and accurately reflects long-term erosional and accretional beach movement.

The vegetation line on the other hand is cultivated on all developed beaches and does not represent the natural movement of the shoreline. However, we define the vegetation line as the landward boundary of the beach and digitize this feature, as well as the shoreline, or seaward beach boundary. This provides the means to track both shoreline movement and beachwidth, defined as the horizontal, shore-normal distance between the two boundaries.

T-Sheets

Using aerial photos, the record of historical changes to sandy shorelines can be extended to 1949 for most of Maui. To increase the period covered by this study we also include shorelines taken from NOS topographic or hydrographic surveys (T-sheets or H-sheets). Georectified digital files of inked T-sheets and H-sheets were provided for this project by the NOAA Coastal Services Center, in scales of 1:2,500, 1:5,000, 1:10,000 and 1:20,000. Shorelines were digitized on-screen from the files provided. We test the accuracy of a T-sheet shoreline by comparing the position of erosion-resistant basalt headlands, piers and other stable features from survey shorelines against orthorectified base imagery. Although most survey shorelines are accurately located, two were rejected as unusable based on this test. Our results indicate that, except in the instances mentioned above, T-sheets we have used meet or exceed the national map accuracy standards of ±10.4 m for 1:20,000 T-sheets, ±8.5 m for 1:10,000 T-sheets and ±3 m for 1:5,000 T-sheets.

Survey shorelines delineate the position of mean high water (MHW). Since we use the toe of the beach as the shoreline change reference feature, the survey shoreline must be migrated to the contemporaneous position of the toe in order to reduce the positional uncertainty of our analysis. We migrate survey shorelines landward a distance equal to the median horizontal distance between the toe and MHW from a five-year data set of semiannual beach profiles (Gibbs et al., 2002; http://geopubs.wr.usgs.gov/open-file/of01-308/) from twenty-seven beaches on Maui. Where shoreline movement is calculated on beaches lacking profile data, an offset is used from the nearest appropriate site experiencing similar littoral processes. In a few cases, such as along a few cobble beaches not represented in the beach profile database, the median offset of the toe and position of MHW was estimated from the earliest aerial photograph of the area. It is assumed that since the photographs used for this purpose precede the development of almost all coastal armoring, this is a reasonably reliable estimate.

Shoreline Change Rates

The position of each historical shoreline and vegetation line is measured from an arbitrarily located offshore baseline, on transects spaced approximately every 20 m along the coast. Data tables of shoreline position and date are collected for analysis at each transect and used to calculate rates of change. We calculate two types of shoreline change rate: the end-point rate (EPR) and AEHR. The EPR is a simple measure of rate of change between the earliest shoreline, usually the 1900 or 1912 T-sheet and the 1997 or 2002 shoreline vectors. The AEHR is calculated using a reweighted least squares (RLS) regression for each transect, followed by the application of a smoothing routine.

Considerable debate in recent years has failed to produce consensus on the best method for predicting future shoreline positions and the point has been made that no single method may be the best in every situation (Foster and Savage, 1989; Honeycutt et al., 2001). Linear regression has been found from multiple studies to yield overall better results than most other methods (e.g. Fenster et al., 1993; Crowell et al., 1997; Galgano et al., 1998; Honeycutt et al., 2001).

A standard least squares (LS) regression however, is particularly susceptible to clustered data and outliers, which may completely distort the true long-term trend of shoreline behavior (Dolan et al., 1991; Fenster et al., 1993). In Hawaii, additional problems inherent in predicting erosion hazard areas include limited availability of historical data (typically 6 to 9 shorelines) and exposure to widely varying wave conditions on different sides of a single island. Because storms and tsunamis tend to impact shorelines on one side of an island at a time, not all beaches experience all events. Because Hawaiian littoral systems tend to be dominated by longshore rather than cross-shore dynamics, different areas within a single littoral cell may respond quite differently to a major wave or storm event. The temporal distribution of historical shorelines and varying responses to wave event forcing lead to considerable scatter and clustering of Hawaiian shoreline position data.

Given the susceptibility of the LS regression to these problems, we know that it will often yield misleading results, at least in Hawaii. A method is needed to accurately identify long-term behavior that will be minimally distorted by shoreline positions that are non-representative of the true trend. To meet this need we have adopted the RLS regression technique. This two-part method uses a least median of squares (LMS) regression, which is able to accurately identify the trend dictated by the majority of the data up to the point at which 50% of the data is outlying (Rousseeuw and Leroy, 1987). Points lying off the trend dictated by the LMS regression are given a weight of zero, while other points are given a weight of one. It is important to note that points with a weight of zero are not considered "bad" data. They are only identified, within the context of other shoreline positions from that same measurement transect, as being non-representative of the trend described by the majority. An LS regression is then fit to the weighted data set, allowing calculation of an accurate trend as well as the application of the wide range of statistical tests, which have been developed for this regression.

Although the RLS regression correctly identifies the trend much more reliably than does an LS regression, one shortcoming is that small differences in shoreline positions from one transect to the next can result in the selection of different years of data to be included in the regression. This may produce sudden jumps in the alongshore distribution of erosion hazard rates. Alongshore smoothing of erosion rate data has been recommended as a means to minimize random variability between measurement locations (Foster and Savage, 1989; Dolan et al., 1991). It can also be utilized to reduce the measurement time interval needed to accurately determine the trend (National Academy of Sciences, 1990; Crowell et al., 1993). To minimize the variability encountered within short segments of coastline due to random variability, we apply an alongshore smoothing technique over five adjacent shoreline change measurement transects, or 100 m of shoreline. The scheme used is similar to and based on that used in Ohio to help manage coastal erosion on Lake Erie (Guy, 1999). It is a center-weighted five-point moving average, with the weighting for each group of transects being 1,3,5,3, and 1. However, approaching a rocky headland or other boundary, our scheme truncates, so that when the moving average is one transect to the left of a boundary the weights will be 1,3, 5, and 3 (Figure 2). At the transect adjacent to the boundary the weights will be 1,3, and 5.

This approach appears to function well on Hawaiian shorelines, removing spikes in the erosion rates without unduly distorting them.

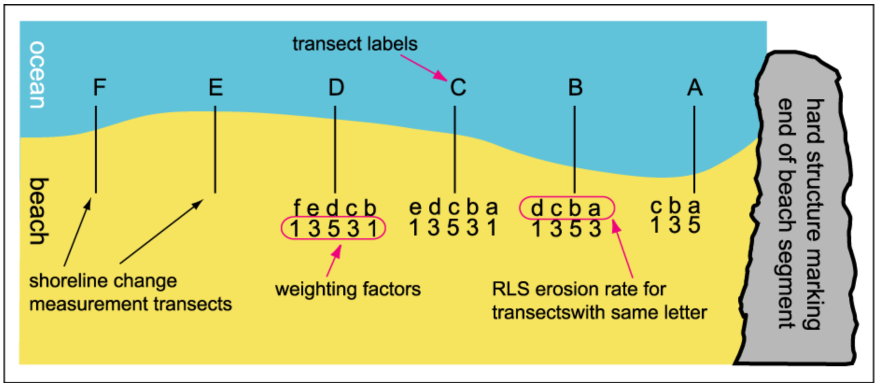

Fig. 2. Alongshore smoothing procedure. Weighting factors are multiplied by the RLS erosion rate of the appropriate transect, summed, and normalized by the sum of weighting factors to determine the AEHR.

Uncertainty

Several sources of uncertainty impact the accuracy of historical shoreline positions and shoreline change rates. Tidal uncertainty is estimated at 3.0 m, based on measurements of the maximum displacement of the beach toe at multiple locations over the course of a spring tidal cycle. The seasonal uncertainty is defined as the difference in toe position as measured in a winter 1988 aerial photograph compared to a summer 1987 aerial photograph of the same coast. These photos are available for almost all Maui study sites and a measurement is calculated for every beach in the study. Seasonal uncertainty is usually the single largest source of uncertainty, with a mean value of 8.6 m and ranging from a single extreme measurement of 20 m to a minimum of 3 m.

Measurement uncertainty is also estimated. For photos, it is related to the orthorectification process and onscreen delineation of the shoreline reference feature. The orthorectification software calculates root mean square (RMS) errors from measures of the misfit between points on a photo and established GCP's, and typically ranges from 0.5 to 3 m. Digitizing errors are estimated from the mean of the absolute value of differences between multiple digitization of the same stretch of shoreline. Uncertainty estimates associated with plotting on surveys are 5 m, and with accurately picking the shoreline from aerial photos are 2 m. Error resulting from migrating survey shorelines to the toe position are estimated from the mean of the residuals of MHW to toe distances taken from the beach profile database. Values range from < 3 to almost 20 m, depending on the dynamism of the beach area under investigation. These uncertainties are random and uncorrelated and may be represented by a single measure calculated by taking the square root of the sum of their squares. The total position uncertainty for a 1:10,000 T-sheet, the most common scale on T-sheets available for the Maui coast, is typically < 10 m.

Because the sources of uncertainty are random, uncorrelated and unbiased across the study regions, they can be absorbed into the confidence interval calculated by the linear regression model used in determining the AEHR (Neter and Wasserman, 1974). The slope of the straight line fitted to the historical shoreline data represents a model of the long-term trend of the shoreline. The residuals, or distances that individual shorelines are separated from the line, provide a measure of the goodness of fit. We calculate a model uncertainty associated with every annual erosion hazard rate providing a confidence interval at the 80th percentile (Douglass et al. 1999).

RESULTS

There are three segments of significant sandy shoreline on Maui, separated by predominantly basalt cliffs (Figure 3). These are further divided into map areas covering an average of approximately 2 km of coastline. Each segment has a unique wave regime and suite of features characterizing the coast and hinterland.

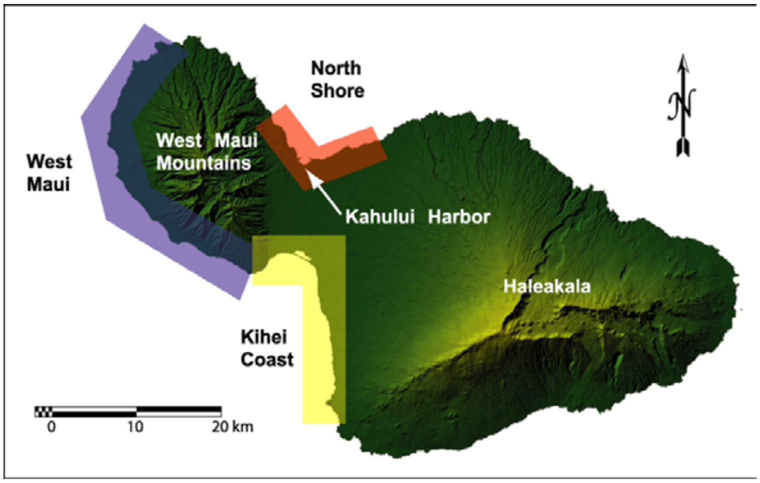

Fig. 3. Sandy shoreline areas on Maui, Hawaii.

West Maui

The West Maui coast has a generally western exposure with more southerly localities exposed to summer swell patterns as well as local seas generated by Kona storms and hurricanes. The northern localities are exposed to heavy winter swell. Central regions experience refracted energy related to both sets of swell patterns. The West Maui shore is characterized by heavily dissected highlands with watersheds that produce large alluvial fans. Coral reefs, often dominated by calcareous algae, are found along much of this coast. Narrow, often sand depleted, beaches line the shoreline both where reefs are present as well as along open shore. The mean AEHR for West Maui is 0.22 (+/- 0.09) m y^{-1} and the mean EPR is 0.18 m y^{-1}. Between 1949 and 1997 the average beach width narrowed by nearly 40 percent over this region. Approximately 3 km of beach has been completely lost in front of coastal armoring in West Maui and approximately 3 km of coastal highway is threatened by chronic erosion over the next thirty years based on the AEHR (Table 1).

Kihei

The Kihei Coast has a generally western exposure but sits in the wave shadow of Molokai, Lanai and Kahoolawe and so only experiences significant swell energy from the south. Local seas generated by Kona storms are also a significant factor in the historical behavior of the shoreline. The Kihei Coast is characterized by relatively young highlands with watersheds that lack heavily dissected valleys. The coastal plain is a flat, sand rich terrace that is fronted by a fringing reef in the central area only. Map areas to the north and south in the region host coral growth on the seafloor but lack a true fringing reef. Narrow, often sand depleted, beaches line the fringing reef while generally wider, more sand-rich beaches are found to the south and north where human impact is less. The average annual erosion rate for Kihei is 0.28 (+/- 0.31) m y^{-1} and the end point rate is 0.14 m y^{-1}. Between 1949 and 1997 the average beach width on the Kihei coast narrowed by 26 percent (Table 3). Total beach loss on the Kihei coast is 2.22 km and over the next 30 years approximately 0.8 km of coastal highway is threatened by erosion hazards (Table 2).

Table 1. Shoreline Changes, West Maui[1], Hawaii

	Mean Rates (m/yr)			BW[2] Change	Beach Loss	Highway Threatened
Poster Area	AEHR	Uncert	EPR	(%)	(km)	(km)
Hawea & Honolua	-0.06	0.09	-0.05	-35	0.00	0.00
Alaeloa	-0.25	0.09	-0.22	-42	0.00	0.00
Kahana	-0.18	0.07	-0.12	-36	0.31	0.05
Honokowai	-0.25	0.04	-0.28	-79	0.51	0.00
North Kaanapali Beach	-0.12	0.09	-0.08	-8	0.00	0.00
Kaanapali	-0.32	0.13	-0.27	-29	0.00	0.00
Wahikuli	-0.14	0.17	0.08	-64	0.06	0.02
Lahaina	-0.43	0.07	-0.41	-51	0.68	0.52
Puamana	-0.27	0.04	-0.23	-34	0.26	0.08
Launiupoko	-0.22	0.05	-0.17	-30	0.56	1.01
Awalua	-0.19	0.13	-0.05	-36	0.00	0.10
Olowalu	-0.17	0.11	-0.02	-2	0.00	0.26
Hekili Point	-0.15	0.07	-0.16	-44	0.42	0.47
Ukumehame & Papalaua	-0.35	0.12	-0.30	-22	0.24	0.60
Average or (Total)	-0.22	0.09	-0.16	-37	(3.04)	(3.11)

[1] Data for individual map areas, covering an average of 2 km of shoreline, are listed in order from north to south.
[2] Beach width, the shore-normal horizontal distance between the vegetation line and toe of the beach

North Shore

The North Shore has a generally northern exposure and receives seasonal winter North Pacific swells as well as trade wind seas. The shoreline is dominated in the west by cobble and sand beaches, in the central region by sand beaches interrupted by shoreline structures and in the east by sand beaches interspersed with rocky headlands. The North Shore region is characterized by heavy rainfall and run off from the dissected watersheds of the West Maui highlands in the northern map areas. The Kahului area features a sand-rich coastal plain and a fringing reef is found offshore of both northern and central map areas. The eastern portion of the North Shore segment is demarked by a steeper coastal plain and coastline with short pocket beaches in embayments and narrow perched beaches located on low elevation rocky terraces. The average annual erosion rate for the North Shore is 0.38 (+/- 0.13) m y^{-1} and the end point rate is 0.29 m y^{-1}. Between 1949 and 1997 the average beach width on the North Shore narrowed by 12% (Table 3). Total beach loss for the North Shore is 0.81 km and approximately 0.41 km of highway is threatened by erosion hazards over the next 30 years.

DISCUSSION

Methodology

For the first time in the state of Hawaii, a highly detailed and accurate analysis of historical shoreline migration has been completed for all the significant sandy shoreline on an entire island. Methods presented above are the result of a continuing evolutionary process, responding to both changes in technology and needs of the coastal management community. The size and scope of the project made it necessary to establish a methodology of determining the rate of shoreline change that was sufficiently robust to handle the multiplicity of coastal processes and histories that characterize the Maui coast as well as maximize the information yield to resource managers. Hence, we provide two rates of change each of which has their advantages and disadvantages. The EPR describes the longest possible trend in shoreline change and minimizes the potential for inaccuracies due to short-term shoreline fluctuations. However, either (or both) of the two shorelines used to determine the

Table 2. Shoreline Changes, Kihei Coast, Maui[1], Hawaii

Poster Area	Mean Rates (m/yr) AEHR	Uncert	EPR	BW[2] Change (%)	Beach Loss (km)	Highway Threatened (km)
Maalaea	-0.18	0.02	-0.15	-9	0.40	0.16
Kealia Pond	-0.18	0.02	-0.18	-10	0.00	0.38
North Kihei	-0.21	0.09	-0.18	-30	0.14	0.20
Kawililipoa	-0.24	1.49	0.43	-26	0.00	0.00
Halama St./ Kalama Park	-0.61	0.61	-0.27	-83	1.50	0.09
Kamaoles	-0.34	0.06	-0.34	-5	0.00	0.00
North Wailea	-0.29	0.10	-0.45	-36	0.06	0.00
South Wailea	-0.30	0.21	-0.05	-26	0.03	0.00
Big Beach/Makena	-0.20	0.17	-0.04	-10	0.08	0.00
Average or (Total)	-0.28	0.31	-0.14	-26	(2.21)	(0.83)

[1] Data for individual map areas, covering an average of 2 km of shoreline, are listed in order from north to south.
[2] Beach width, the shore-normal horizontal distance between the vegetation line and toe of the beach.

Table 3. Shoreline Changes, North Shore, Maui[1], Hawaii

Poster Area	Mean Rates (m/yr) AEHR	Uncert	EPR	BW[2] Change (%)	Beach Loss (km)	Highway Threatened (km)
Waihee	-0.20	0.08	-0.04	-13	0.00	0.00
Waiehu	-0.21	0.08	-0.11	-31	0.12	0.06
Kahului Harbor	-0.52	0.12	-0.21	-32	0.35	0.35
Kanaha	-0.27	0.12	-0.27	31	0.11	0.00
Sprecklesville	-0.49	0.15	-0.49	-21	0.08	0.00
Baldwin	-0.64	0.21	-0.67	-21	0.06	0.00
Kuau	-0.29	0.17	-0.26	4	0.08	0.00
Average or (Total)	-0.37	0.13	-0.29	-12	(0.80)	(0.41)

[1] Data for individual map areas, covering an average of 2 km of shoreline, are listed in order from north to south.
[2] Beach width, the shore-normal horizontal distance between the vegetation line and toe of the beach.

EPR might itself be the product of a short-term fluctuation. Additionally it relies upon a T-sheet shoreline that is less accurate than a photogrammetrically corrected shoreline. The AEHR utilizes a reweighted linear regression and smoothing procedure to determine the trend in shoreline change. Calculating a reweighted dataset is a robust method of minimizing inaccuracies due to short-term shoreline fluctuations. One potential problem with this method is that the AEHR frequently ignores recent accelerations in shoreline erosion and so may not fully alert coastal managers to impending beach loss nor reflect the full hazard incident to landowners. That is, there may be cases where the true erosion rate is underestimated. It is also important to acknowledge that both the EPR and AEHR methods provide a description of chronic rather than episodic erosion rates.

It has been suggested that by assigning some shoreline positions a weight of zero we are not using all of the data available. This is not the case. All historical shoreline positions are considered, but the trend is determined from that portion of the data that best defines a trend. For clean orderly datasets with an obvious trend, the RLS regression gives results almost identical to those from an LS regression. For shoreline positions with even a single outlier data point, which is very often the case in Hawaii, the LS regression has a marked tendency to incorrectly identify the trend of the shoreline. The RLS regression however will continue to accurately identify the trend until half the data points are no longer representative to the long-term trend of the shoreline. This procedure also effectively removes extreme shorelines that fall off trend due to storm impacts, seasonal processes and human impacts so that the effect of these uncertainties significantly altering an erosion rate is unlikely.

On several beaches, significant jumps in alongshore variation in erosion rate may be an artificial result of the linear regression procedure and random variation in shoreline position. To minimize these problems, an alongshore smoothing procedure, tuned to the spatial scale of Hawaiian beach dynamics, is introduced. The minor error introduced along some transects is heavily outweighed by the advantages gained in reducing spikes in erosion rates between adjacent transects that clearly do not reflect how the shoreline will move in the future.

Results

Reasons for chronic erosion patterns are much harder to discern than the magnitude and timing of changes. However, the data described above provide researchers with important information for determining the cause of erosion in later studies. Additional studies have begun to mine these data in an effort to improve understanding of the causes of shoreline erosion on Maui. Eversole (2002) calculates the historical sediment budget for a site in the center of the West Maui coastal segment. He found that erosion over the 48 yr period of study (1949 – 1997) was mostly related to the episodic occurrence of Kona storms (early 1960's) and Hurricane Iniki (1992). The beach (430,000 m^3) experienced 220,000 m^3 of gross change over the period. Of this, 62 percent was attributed to storm erosion, another 33 percent was accreted and 5 percent (a budget residual) was attributed to erosion due to relative sea-level rise. This residual erosion occurs in the form of slow but chronic shoreline recession equivalent to 73,000 m^3 over the ~50 year period.

Rooney and Fletcher (2000) calculate the historical sediment budget for a 5 km segment of the north central Kihei coast. They found that between 1912 and 1949, the southern part of this area experienced erosion while the northern portion accreted. The most severe erosion occurred along the southern portion of their study site, averaging -1.8 m/y-1. In successively later years, the focus of erosion migrated almost 2 km north while the northern end of the site continued accreting. A shift from net accretion to erosion across the entire area started around 1975. Low rates of net sediment transport since 1975 are primarily due to sediment impoundment by coastal armoring. They identify the combined influence of coastal armoring and a series of strong Kona storms associated with an earlier phase of the Pacific Decadal Oscillation that transported sediment to the north, opposite the present regime, as being responsible for recent erosion trends.

Although no specific research has been published regarding the causes of erosion patterns on the North Shore, local residents report that extensive run-up associated a large tsunami last century caused extensive shoreline recession. This is consistent with our observations of a large offset between the T-sheet shoreline of 1912 and the earliest photographic shoreline in 1949. The 1946 tsunami, which killed over 100 people throughout Hawaii, occurred immediately prior to the 1949 photo series and is a likely candidate for causing the observed erosion. Widespread sand mining to furnish lime for agriculture also took place for decades along the North Shore and is likely to have contributed to erosion in some areas.

Although not necessarily representative of all shoreline areas, results from both of the Kihei and West Maui sites suggest that interannual to century scale shoreline sediment dynamics are strongly influenced by PDO and ENSO-related storm variability. Both Kona storm and hurricane activity is modulated by the phase of the PDO and ENSO. Konas tend to occur with greater frequency during negative phases of the PDO and La Niña periods (Rooney, 2002). Hurricane activity on the other hand increases during El Niño periods, and appears to coincide with positive PDO phases as well (Chu and Clark, 1999; Chu, 2002; Clark and Chu, 2002). Hence, shoreline change patterns may reflect periods of enhanced storminess on the decadal scale in the history of some beaches

Human impacts, although also difficult to quantify, are likely to be important as well. Damaging practices such as impounding coastal plain sand with armoring and removing beach sand for lime production have been widespread along the Maui shoreline. It is unlikely that their cumulative impact is insignificant. These are especially likely to be important given the slow rate of sediment production associated with fringing reefs (Harney et al., 1999; Rooney and Fletcher, 2000). Given that largest sediment reservoirs maintaining most Hawaiian beaches lie immediately landward of them on the coastal plain, it seems appropriate to infer that sand impoundment and sand mining act to destabilize Maui beaches rendering them vulnerable to storm impacts governed by regional-scale climatic processes. We note that erosion rates on Maui's north shore are about double those on the western and Kihei sides of the island. Although experiencing erosion rates twice as large, beachwidths on the relatively undeveloped north shore have decreased half as much as those on the more developed and partially armored Kihei and West Maui coastlines.

All the main Hawaiian Islands are exposed to approximately similar storm histories. Hence, it is significant to note that Richmond et al. (2000) identify Maui as having island-wide erosion rates that exceed those on the other islands (Figure 4). On other islands the mean shoreline change rates are low and generally lie within the statistical uncertainties of the methods used. We infer from this pattern that variations in relative sea level rise (RSLR) may be a part of the reason for Maui's greater erosion rate. Although no definitive, widely accepted relationship has yet been established between sandy shoreline behavior and RSLR, it has been proposed by numerous authors that sea level increases do lead to beach recession (c.f., Leatherman et al., 2000). Tide gauge data from Hawaii reveals that Maui is experiencing a RSLR that is ~40% greater than that on Oahu or Kauai.

However, RSLR on the island of Hawaii is larger still, yet erosion rates there are significantly less than those on Maui. Explaining this contradiction remains a challenging research objective whose answer may enhance our understanding of the role of RSLR on shoreline sediment dynamics of oceanic islands.

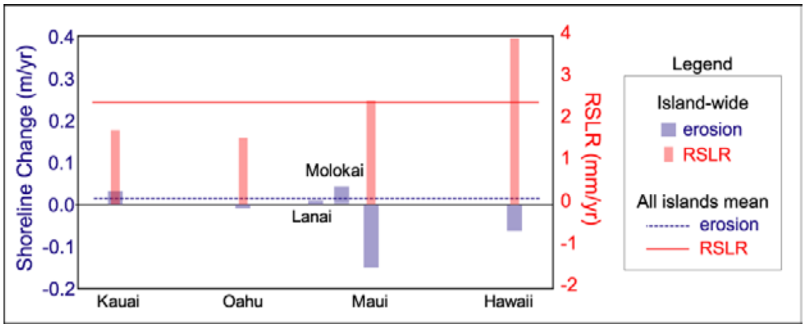

Fig. 4. Island wide erosion and relative sea level rise.

Management

Other issues still requiring resolution include how AEHRs will be updated, and ways to take advantage of future studies that improve existing projections of erosion hazards. A statewide general permit for small-scale beach renourishment has recently become available in Hawaii. Decreases in net erosion rates resulting from this potentially valuable beach management tool need to be addressed as well. Considering the significant role of human impacts to the Maui beach environment and given the economic and natural resource value of beaches to the Maui economy, it is appropriate for the Maui Administration to continue their recent efforts to implement the most effective measures possible for managing beach resources.

CONCLUSIONS

Sandy beaches are a primary attraction driving the visitor industry on Maui. We document the island-wide degradation of this valuable resource with a high degree of accuracy and spatial resolution. More than a quarter of the recreationally usable beach area has eroded away over the past half century and 5.25 km of beach has been completely lost, almost all of which has been in front of seawalls and revetments protecting poorly sited buildings and infrastructure. Movement of historical shorelines and landward beach boundaries every 20 m along sandy coastlines over the past century provide the data necessary to improve the beach management regime to one based on hazard avoidance. A statistically robust method is presented to project future chronic erosion hazards while minimizing the undue influence of episodic storm and wave events. The mean island-wide AEHR and EPR are estimated to be -0.28 m y^{-1} ± 0.16 m y^{-1} and -0.19 m y^{-1} respectively. The mean AEHR may underestimate the erosion hazard in some areas, but suggests that over the next 30 years, an additional 4 km of highway will be threatened, with the beach currently in front of it lost as well.

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