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HISTORICAL SHORELINE TRENDS AND MANAGEMENT IMPLICATIONS:

SOUTHEAST OAHU, HAWAI'I

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE

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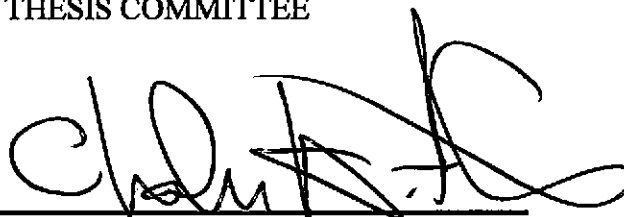IN

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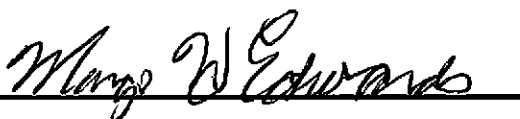
By
Bradley M. Romine

Thesis Committee:

Chip Fletcher, Chairperson
Scott Rowland
Margo Edwards

We certify that we have read this thesis and that, in our opinion, it is satisfactory in scope and quality as a thesis for the degree of Master of Science in Geology & Geophysics.

THESIS COMMITTEE

_____
Chairperson

_____

_____

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ABSTRACT

Here we present shoreline change rates for the beaches of southeast Oahu, Hawaii using recently developed polynomial methods to assist coastal managers in planning for erosion hazards and to provide an example for interpreting results. Polynomial methods use data from all transects (measurement locations) on a beach to calculate a shoreline change rate at any one location on a beach. These methods are shown to produce rates with reduced model uncertainty compared to previously used methods and can detect acceleration in the shoreline change rates. An information criterion, a type of model optimization equation, is used to identify the best shoreline change model for a beach. Polynomial models that use Eigenvectors as their basis functions are identified as the best models most often. Using polynomial models that are constant (linear) in their rates, we find erosion along 36% of the study area beaches, including North Bellows Beach, South Waimanalo Beach, and at most beaches between Kaiona and Kaupo Beach Park in the south of the study area. The ability to detect accelerating shoreline change with the polynomial methods is an important advance as a beach may not erode or accrete at a constant (linear) rate. Acceleration models may detect erosion hazards not detected by other methods that use linear models. Using polynomial models that include acceleration in their rates, we find accelerating erosion at 33% of transects, including the south of Kailua Beach, much of northern Bellows Beach, and in the south half of Kaupo Beach Park.

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INTRODUCTION

Tourism is Hawaii's leading employer and its largest source of revenue. Island beaches are a primary attraction for visitors, and some of the most valuable property in the world occurs on island shores. Beaches are also central to the culture and recreation of the local population. During recent decades many beaches on the island of Oahu, Hawaii, have narrowed or been completely lost to erosion (FLETCHER *et al.*, 1997; HWANG, 1981; SEA ENGINEERING, 1988) threatening business, property, and the island's unique lifestyle.

Results from a Maui Shoreline Study (FLETCHER *et al.*, 2003) resulted in the first erosion rate-based coastal building setback law in the state of Hawaii (NORCROSS-NU'U and ABBOTT, 2005). Concerns about the condition of Oahu's beaches prompted federal, state, and county government agencies to sponsor a similar study of shoreline change for the Island of Oahu. The primary goal of the Oahu Shoreline Study is to analyze trends of historical shoreline change, identify future coastal erosion hazards, and report results to the scientific and management community.

It is vital that coastal scientists produce reliable, i.e., statistically significant and defensible, erosion rates and hazard predictions if results from shoreline change studies are to continue to influence public policy. To further this goal FRAZER *et al.* (in press) and GENZ *et al.* (in press) have developed polynomial methods for calculating shoreline change rates. The new methods calculate rates that are constant in time or rates that vary with time (acceleration). We refer to polynomial models without rate acceleration as PX models (for Polynomials in the alongshore dimension, X) and the models with rate acceleration as PXT (Polynomials in X and Time). These methods are shown here and in

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the FRAZER *et al.* and GENZ *et al.* papers (in press) to produce statistically significant shoreline change rates more often than the commonly used ST (Single Transect) method using the same data. Here we employ the polynomial methods to calculate shoreline change rates for the beaches of southeast Oahu.

PHYSICAL SETTING

The study area consists of the northeast-facing beaches along the southeast coast of Oahu, Hawaii. The area is bounded to the north by limestone Kapoho Point and to the south by the high basalt cliffs of Makapuu Point (Figure 1). This shoreline is fronted by a broad fringing reef platform extending 1 to 3.5 km from the shoreline except in the far south. The reef crest shallows to -5 to 0 m depth, 0.3 - 1.0 km from shore, along 70% of the study area. This fringing reef protects most beaches from the full energy of open-ocean waves (BOCHICCHIO *et al.*, in press).

As a result of its windward location, the southeast Oahu coast is exposed to moderate northeast tradewind swell during 90% of the summer and 55 – 65% of the winter (1-3 m height, 5-9 s period) (VITOUSEK and FLETCHER, in press). Moderately high to very high energy refracted long period swell from the north (1.5 – 15 m, 14 – 20 s) impinge in the winter, and occasional short-lived (< 2 week) high tradewind swells (3-5 m) are possible year-round, most commonly in the winter. The fraction of open-ocean wave energy reaching the inner reef and shoreline varies along the coast and is controlled by refraction and shoaling of waves on the complex bathymetry of the fringing reef. The study area contains four beach study sections, which are additionally subdivided into
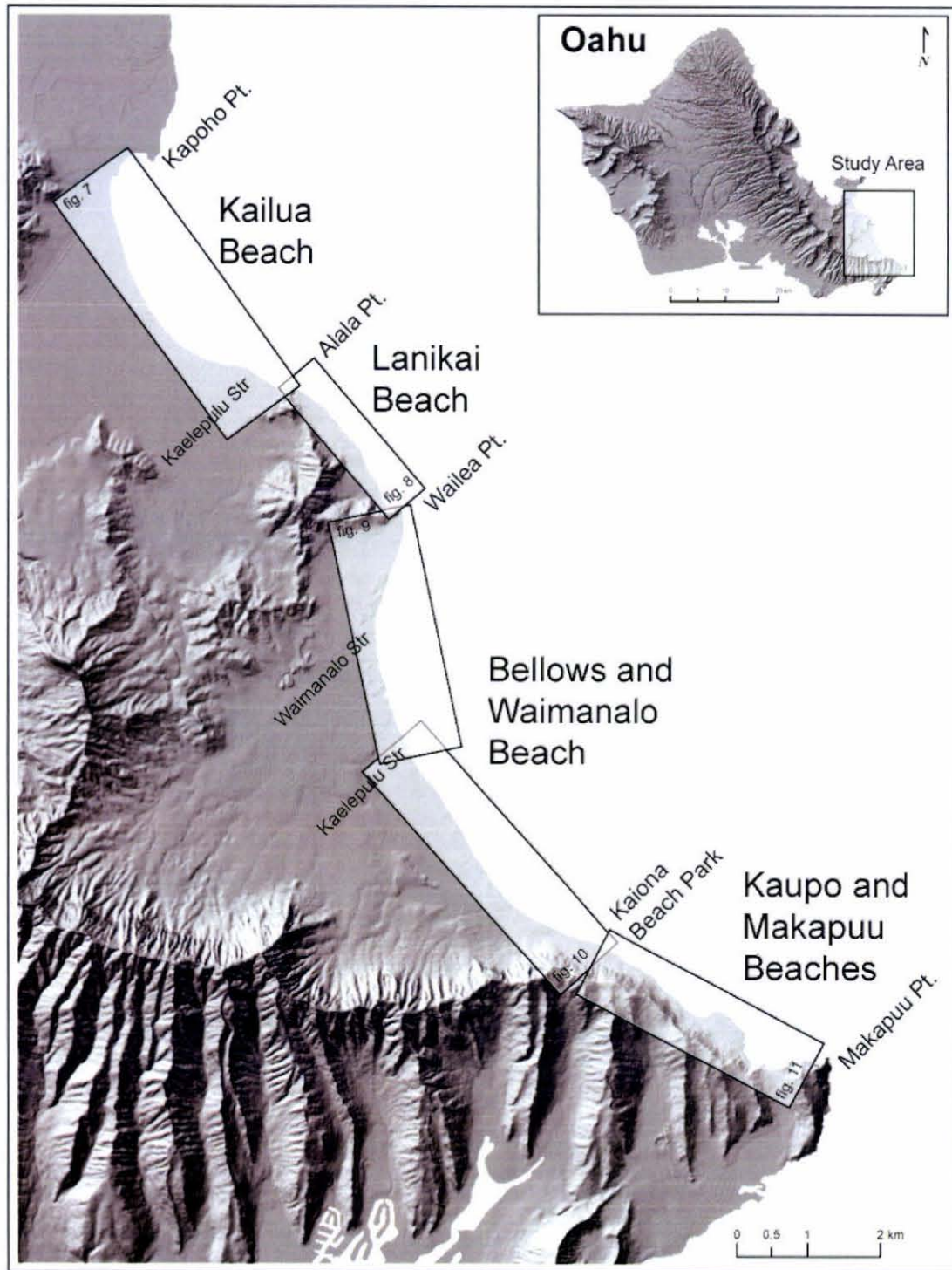
Figure 1. Southeast Oahu shoreline study area and beach study sections.

fourteen study segments by natural and anthropogenic barriers to sediment transport and/or gaps in reliable shoreline data.

Kailua Beach

Kailua Beach is a 3.5 km crescent-shaped beach bounded to the north by limestone Kapoho Point and to the south by basalt Alala Point. A sinuous 200 m-wide sand-floored channel bisects the reef platform. The channel widens toward the shore into a broad sand field at the center of Kailua Beach.

The inner shelf and shoreline are protected from large, long period swell by the fringing reef. Wave heights become progressively smaller toward the southern end of Kailua Beach as shallow reef crest and Popoia Island refract and dissipate more of the open ocean swell.

The residential area of Kailua is built on a broad plain of Holocene-age carbonate dune ridges and terrestrial lagoon deposits (HARNEY and FLETCHER, 2003). Low vegetated dunes front many of the homes on Kailua Beach. Kaelepulu Stream empties at Kailua Beach Park at the southern end of Kailua Beach. Episodes of wave erosion can cut a steep scarp into the shorefront dunes at any point along the beach.

For shoreline change analysis, Kailua Beach is divided into two study segments with a boundary at Kaelepulu stream mouth. The boundary is required due to a gap in reliable shoreline data at this location. Specifically, shoreline positions from the stream mouth itself are not considered reliable, as they are prone to high variability related to stream flow, and this is not accounted for in our uncertainty analysis. The two study

segments are referred to here as North Kailua (Kapoho Pt – Kaelepulu Stream) and South Kailua (Kaelepulu Stream – Alala Pt).

Lanikai Beach

The Lanikai shoreline is a slightly embayed 2 km-wide headland between the basalt outcrops of Alala Point and Wailea Point. Lanikai Beach is a narrow 800 m long stretch of sand in the north-central portion of the Lanikai shoreline. The remainder of the Lanikai shoreline has no beach at high tide, except for a small pocket of sand stabilized by a jetty in the far south. Waves break against seawalls in areas without beach.

The fringing reef fronting Lanikai is shallower than the reef fronting the adjacent areas of Kailua and Waimanalo. Scattered coral heads grow above thin sand deposits on the comparatively flat fossil reef platform. The shallow reef platform extends 2 km offshore to the Mokulua Islands. Wave heights along the Lanikai shoreline are typically small (< 1 m) due to refraction and breaking of open-ocean waves on the shallow fringing reef and shores of the offshore Mokulua. The community of Lanikai is built on the foot of the basalt Keolu Hills and on a narrow coastal plain comprised of carbonate sands and terrigenous alluvium.

Bellows and Waimanalo Beach

Bellows and Waimanalo Beach is a nearly continuous 6.5 km long beach extending from the northern end of Bellows Field (near Wailea Point) to Kaiona Beach Park in southern Waimanalo. In the northern end of the Bellows shoreline (from Wailea Pt - 700 m to the south) waves break against stone revetments at high tide. The beach

was lost to erosion in the north prior to 1996. The beach is partially interrupted at two other locations by stone jetties at Waimanalo Stream and remains of a similar structure at Inaole Stream.

A broad reef platform extends to a shallow reef crest 1.5 – 0.5 km off shore. Paleochannels, karst features, and several large depressions on the reef platform contain significant sand deposits and likely play an important role in storage and movement of beach sand (BOCHICCHIO *et al.*, in press). Bellows Field and the town of Waimanalo are built on a broad plain of Holocene-age carbonate and alluvial sediments.

Bellows and Waimanalo Beach are divided into three study segments for analysis with boundaries at the Waimanalo and Inaole Stream mouth jetties. These boundaries are located due to gaps in reliable shoreline data at the stream mouths, though sand is undoubtedly transported around these structures. The three study segments are: North Bellows Beach, from Wailea Point to the Waimanalo Stream jetties; Central Bellows Beach from the Waimanalo Stream jetties to the remains of the Inaole Stream jetties; and South Bellows and Waimanalo Beach from the Inaole Stream jetties to Kaiona Beach Park.

Kaupo and Makapuu Beaches

To the south of Waimanalo, between Kaiona Beach Park and Kaupo Beach Park are a series of narrow pocket beaches separated by natural and anthropogenic hard shoreline. The broad carbonate coastal plain found to the north is absent from most of this section and the steep basalt Koolau cliffs rise within a few hundred meters behind the shoreline.

Beaches in the northern two-thirds of the Kaupo to Makapuu section are generally narrow (5 – 20 m) and often covered in small basalt and/or coral cobbles. Seawalls front some homes to the south of Kaiona Beach Park. Further to the south, the beaches are backed by a low rock scarp (1 – 2 m) or man-made revetments. The longest continuous beach in the study section is Kaupo Beach Park (500 m). Kaupo Beach Park is a semi-crescent-shaped beach on the north side of a low basalt peninsula.

Along the northern 2/3 of this section the shallow fringing reef blocks most wave energy. The fringing reef disappears at Makapuu Beach allowing the full brunt of easterly tradewind waves and refracted northerly swells to reach the shoreline. Makapuu Beach, popular with bodysurfers, is well known for its large shore-breaking waves.

Makapuu Beach is wide (50 m) and sediment-rich compared to beaches to the north. The back-beach area is characterized by vegetated dunes sloping against the base of the Koolau cliffs. A sand-filled channel extends offshore.

The Kaupo and Makapuu study section is divided into eight beach segments by intermittent sections of rocky shoreline. From north to south we refer to the beach study segments as: Kaupo Beach 1, 2, 3, Makai Pier North Beach, Makai Pier South Beach, Kaupo Beach Park, Kaupo Beach 7, and Makapuu Beach.

PREVIOUS WORK

NODA (1977) produced a detailed analysis of coastal processes at Kailua Beach. The study was initiated in response to significant erosion at Kailua Beach Park in 1975 and 1976 with the goal of assessing the effectiveness of possible erosion control measures.

HWANG (1981) was the first to compile historical shoreline change for beaches of Oahu. His study utilized the vegetation line and the water line as shoreline proxies. Historical shoreline positions were measured from aerial photographs along shore-perpendicular transects roughly every 1000 ft (328 m). The study reported position changes of the vegetation line from one aerial photo to another, and from these the net change in the vegetation line and water line through the time span of the study. Annual rates were not calculated from these data. SEA ENGINEERING (1988) produced an update to the HWANG (1981) study with a more recent aerial photo set.

FLETCHER (1997) quantified beach narrowing and loss on Oahu related to seawall and revetment construction. The study found that roughly 24% of originally sandy shoreline on Oahu was lost to erosion between 1928 and 1995 and replaced with coastal armoring.

NORCROSS, et al. (2002) calculated annual shoreline change rates and interannual beach volume change at Kailua Beach. Norcross used orthorectified aerial photographs and NOAA topographic maps (T-sheets) and used the low water mark as a shoreline proxy. Annual shoreline change rates were calculated using the ST method. Interannual

beach volume changes were calculated using data from beach profile surveys. The study concluded that Kailua Beach experienced annual shoreline accretion from 1926-1996 (the span of available air photo data at the time of the study) and recent *(dates)*net increase in beach sand volume.

Our study provides an important update and comparison to the results of previous studies. We aim to improve on all of the previous studies by utilizing improved photogrammetric methods for measuring historical shoreline positions and statistical methods for calculating shoreline change rates. In addition, a newly acquired aerial photograph set (2005) provides more recent shoreline position for our study beaches.

METHODS

Mapping Historical Shorelines

For this study we adhere closely to the methods of FLETCHER *et al.* (2003) for mapping historical shorelines on Maui, Hawaii. Historical shorelines are digitized from NOAA NOS topographic maps (T-sheets) and 0.5 m spatial resolution orthorectified aerial photo mosaics (Figure 2). Orthorectification and mosaicking was achieved using PCIGeomatics' Geomatica Orthoengine™ software (www.pcigeomatics.com) to reduce displacements caused by lens distortion, Earth curvature, refraction, camera tilt, radial distortion, and terrain relief; usually achieving Root Mean Square (RMS) positional errors of < 2 m.

New aerial photography of study beaches was acquired in late 2005. Aircraft position (e.g. GPS) and orientation data (e.g. altitude, pitch, roll, and yawl) was recorded

in an on-board Positional Orientation System (POS). The recent images are orthorectified and mosaicked in PCI using polynomial models incorporating POS data and high-resolution Digital Elevation Models (DEM). The 2005 orthomosaics serve as master images for the orthorectification of older aerial photographs.
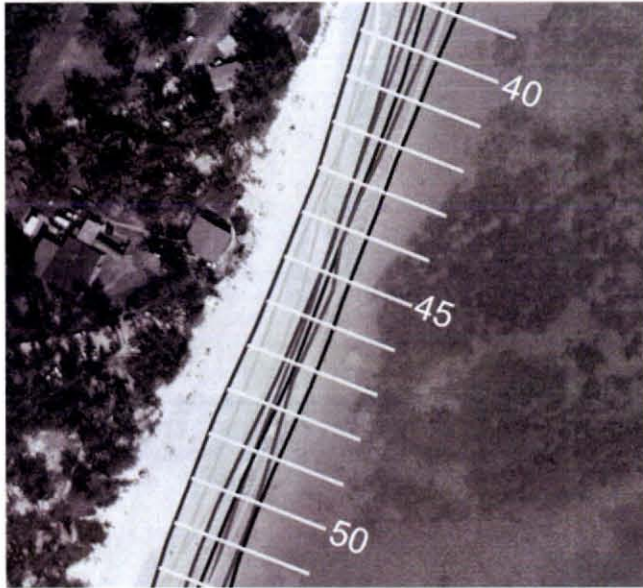
Figure 2. Historical shorelines and shore-perpendicular transects (measurement locations, 20 m spacing) displayed on recent aerial photograph (North Bellows Beach, Oahu).

T-sheets are georeferenced using various polynomial mathematical models (e.g. polynomial, thin-plate spline) in PCI with RMS errors < 4 m. Rectification of T-sheets is also verified by overlaying them on aerial photomosaics to compare their fit to rocky shoreline and other unchanged geological features. Previous workers have addressed the accuracy of T-sheets (CROWELL et al., 1991; DANIELS and HUXFORD, 2001; SHALOWITZ, 1964) finding that they meet national map accuracy standards (ELLIS, 1978) and recommending them for use in shoreline change studies as a valuable source for

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extending the time series of historical shoreline position (NATIONAL ACADEMY OF SCIENCES, 1990).

The beach toe, or base of the foreshore, is digitized from aerial photo mosaics and is a geomorphic proxy for the low water mark (LWM). The LWM is what we define as the shoreline for our change analysis. Removing or quantifying sources of uncertainty related to temporary changes in shoreline position is necessary to achieve our goal of identifying chronic long-term trends in shoreline behavior. A LWM offers several advantages as a shoreline proxy on Hawaiian carbonate beaches toward the goal of limiting our uncertainty. Studies from beach profile surveys have shown that the LWM is less prone to geomorphic changes typical of other shoreline proxies on the landward portions of the beach (e.g. wet-dry line, high water mark) (NORCROSS et al., 2002). The bright white carbonate sands typical of Hawaii beaches often hinder interpretation of these other shoreline proxies in aerial photographs - especially in older black and white images with reduced contrast and resolution. The vegetation line was used as the shoreline proxy in some previous Oahu studies (HWANG, 1981; SEA ENGINEERING, 1988). However, on most Oahu beaches the vegetation line is cultivated and, therefore, often does not track the natural movement of the shoreline. Nonetheless, we create a vector of the vegetation line so that it is available to track historical changes in beach width between the vegetation line and the low water mark.

Surveyors working on T-sheets mapped the high water mark (HWM) as a shoreline proxy. To include the T-sheet shorelines in the time series of historical shorelines, the HWM is migrated to a LWM using an offset calculated from measurements in beach profile surveys at the study beach or a similar nearby location.

HWM and LWM positions have been measured in beach profile surveys collected at nine locations in the study area in summer and winter over eight years. The offset used to migrate a T-sheet HWM to a LWM position is the median of the HWM − LWM distances measured in the profile surveys from that beach or a similar littoral cell. Six to thirteen historical photo mosaics and T-sheets comprise our time series (between 1911 and 2005). To determine patterns of movement, relative distances of the historical shorelines are measured from an offshore baseline along shore-perpendicular transects spaced 20 m apart.

Uncertainties in Shoreline Position

Shoreline position is highly variable on short time scales (interannual to hourly) due to tides, storms, and other natural fluctuations. Procedures for mapping historical shorelines introduce additional uncertainties. It is vital that these uncertainties are identified, rigorously calculated, and included in shoreline change models to ensure that the shoreline change rates reflect a long-term trend and are not biased due to short-term variability (noise). Building on FLETCHER, *et al.* (2003); ROONEY, *et al.* (2003); and GENZ, *et al.* (2007), we calculate seven different sources of error in digitizing historical shoreline position from aerial photographs and T-sheets. Identifying the probability distribution (e.g. normal, uniform) for each error process (e.g. tidal fluctuation, seasonal variance) provides the tools to calculate the individual error uncertainty. The total positional uncertainty, E_t, is the root sum of squares of the individual uncertainties. We assume E_t follows a normal distribution, because the Central Limits Theorem states that the sum of many sources of uncertainty tends toward a normal distribution(DRAPER and

SMITH, 1998). E_t is applied as a weight for each shoreline position when calculating shoreline change models using weighted regression methods. Total positional uncertainty for southeast Oahu historical shorelines is ± 4.49 to 10.78 m (Table 1).

Table 1. *Shoreline uncertainties: southeast, Oahu, Hawaii.*

Uncertainty source	± Uncertainty range (m)
Ed, Digitizing error	0.54 - 5.73
Ep, Pixel error, air photos	0.50
Ep, Pixel error, t-sheets	3.00
Es, Seasonal error	3.59 - 6.23
Er, Rectification error	0.55 - 3.01
Etd, Tidal error	2.54 - 3.42
Ets, T-sheet plotting error	5.00
Ec, T-sheet conversion error	3.40 - 5.70
Et, Total positional error (see text)	4.49 - 10.78

Table 1. Shoreline uncertainties: southeast, Oahu, Hawaii.

Digitizing Error, E_d: Only one analyst provides the final digitized shorelines from the photo mosaics and T-sheets to ensure consistency in the criteria used to locate each shoreline. Uncertainties in interpreting the shoreline position in aerial photographs are calculated by measuring variability in shoreline position when digitized by several experienced analysts working on a sample portion of shoreline. The digitizing error is the standard deviation of differences in shoreline position from a group of experienced operators. If an E_d value has not been calculated for a particular photo mosaic, a value from a mosaic with similar attributes (e.g. resolution, photo year) is used. E_d values range from 2.54 – 3.42 m.

Pixel Error, E_p: The pixel size of orthophoto mosaics used in this study is 0.5 m. E_p equals 0.5 m.

Seasonal Error, E_s: Due to the limited number of historical shoreline data sets available for this study and the tendency for storms to affect shoreline position in a uniform manner in an island setting, we do not attempt to identify and remove storm shorelines based on *a priori* knowledge of major storm and wave events. Instead, we include the fluctuation in shoreline position due to seasonal changes (waves and storms) as an uncertainty in the shoreline position. Shoreline positions (LWM) have been measured in seven years of summer and winter beach profiles at over thirty beach sites on Oahu to measure seasonal variability. A random uniform distribution (>10,000 points) is generated from the standard deviation of shoreline positions between summer and winter. A uniform distribution is an adequate approximation of the probability of any shoreline position due to seasonal fluctuations because an aerial photograph has equal probability of being taken at any time of year. The seasonal error, E_s, is the standard deviation this distribution. For beaches without profile data an E_s value from a similar littoral area is used. E_s values range from 3.59 – 6.23 m.

Rectification Error, E_r: Aerial photographs are orthorectified to reduce displacements caused by lens distortion, Earth curvature, refraction, camera tilt, and terrain relief using PCI Orthoengine software. The software calculates RMS error from the orthorectification process. E_r values range from 0.55 – 3.01 m for orthophoto mosaics. T-sheets are georeferenced in PCI Orthoengine using polynomial math models. E_r for T-sheets ranges from 1.37 - 2.85 m.

Tidal Fluctuation Error, E_{td} (aerial photographs, only): Aerial photographs are obtained without regard to tidal cycles and the times of day each photo is collected in unknow, resulting in inaccuracies in digitized shoreline position from tidal fluctuations. Rather than attempting to correct the shoreline position, the possible fluctuations due to tides are included as an uncertainty. The horizontal movement of the LWM between a spring low and high tide was surveyed at several locations in the study area. The probability of an aerial photograph being taken at low or high tide is assumed to be equal. Thus, a uniform distribution is a conservative estimate of the probability distribution of tidal fluctuation in LWM position. E_{td} is the standard deviation of a randomly generated uniform distribution derived from the standard deviation of the surveyed tidal fluctuations. E_{td} values range from 2.54 – 3.42 m for this study.

T-Sheet Plotting Error, E_{ts} (T-sheets, only): Surveyors working on T-sheets mapped the high water line (HWL) as a proxy for shoreline position. The T-sheet plotting error is based on SHALOWITZ (1964) analysis of topographic surveys. He identifies three major errors in the accuracy of these surveys: (1) measuring distances, ± 1 m; (2) plane table position, ± 3 m; and (3) delineation of the high water line, ± 4 m. The total plotting error, E_{ts}, for all t-sheets is the sum of squares of the three distinct errors,± 5.1 m.

Conversion Error for T-sheets, E_c (T-sheets, only): To compare historical shorelines from T-sheets and aerial photographs the surveyed HWL from each T-sheet must be migrated to a LWM using an offset calculated from data from seasonal beach profiles. The uncertainty in this conversion, E_c, is the standard deviation of the measured HWM – LWM distances in the beach profiles. For beaches without profiles, the offset

from similar littoral areas is used (FLETCHER *et al.*, 2003). E_c values for southeast Oahu range from 3.40 – 5.70 m.

Calculating Shoreline Change Rates

Single-Transect

In previous studies, our research team and other coastal research groups have utilized the Single-Transect (ST) method to calculate shoreline change rates (e.g., FLETCHER *et al.*, 2003;HAPKE *et al.*, 2006; HAPKE and REID, 2007; MORTON *et al.*, 2004; MORTON and MILLER, 2005). ST calculates a shoreline change rate and rate uncertainty at each transect using various methods (e.g., End Point Rate, Average of Rates, Least Squares) to fit a trend line to the time series of historical shoreline positions. An End Point Rate is calculated using only the first and last data points in a time series of shoreline positions to define a trend line. Average of Rates is the average of End Point Rates for every combination of pairs of data points in a time series of shoreline positions. Various mathematical optimization methods to fit a trend lines have been utilized including weighted and unweighted least squares and least absolute deviation.

Our group employs weighted least squares regression with the ST method, which account for uncertainty in each shoreline position when calculating a trend line (GENZ *et al.*, 2007, FLETCHER *et al.*, 2003). The weight for each shoreline position is the inverse of the uncertainty squared (e.g., $w_i = 1/E_i^2$). Shoreline positions with higher uncertainty will, therefore, have less of an influence on the trend line than data points with smaller uncertainty. The slope of the line is the shoreline change rate (Figure 3).
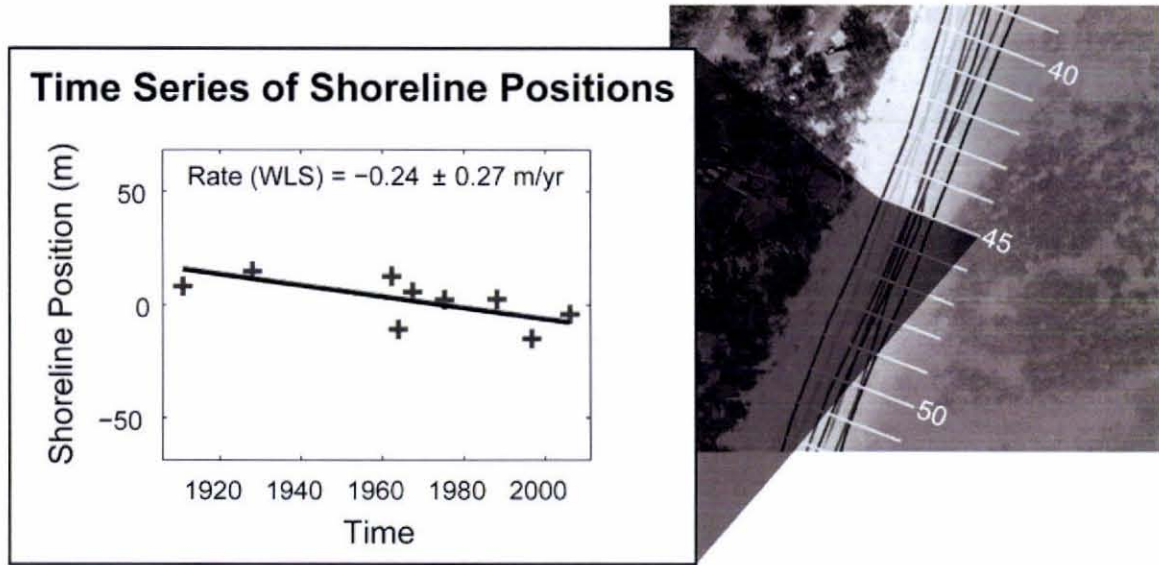
Figure 3. Calculating shoreline change rate using the Single-Transect (ST) method (Weighted Least Squares regression, WLS). The slope of the line is the annual shoreline change rate. Shoreline position is plotted relative to the average shoreline position (normalized).

Recent work by FRAZER *et al.* (in press) and GENZ *et al.* (in press) identifies a number of shortcomings with the ST method. ST tends to over-fit the data by using more mathematical parameters than necessary. The principle of parsimony, when applied to mathematical modeling, states that a model with the smallest number of parameters that provides a satisfactory fit to the data is preferred. Satisfactory fit is quantified by minimizing the residuals of the model fit. Models that over-fit data are also referred to as unparsimonious. The problem of over-fitting with ST is made worse by limited data (often less than 10 historical shorelines) and high uncertainty (noise) in shoreline positions, typical of shoreline studies. FRAZER *et al.* (in press) provides an extreme example of an unparsimonious model, which uses an *n-1* degree polynomial fit to *n* noisy

data points. The model fit to the data in this example is perfect but the model teaches us nothing about underlying processes and has no predictive power.

Another problem with the ST method is that it treats the beach as if it were a set of isolated blocks of sand centered on each transect, which do not share sand with adjacent transects and move independently of adjacent transects. However, on an actual continuous beach, the positions of each transect share sand with adjacent positions along the shore. Thus, the shoreline positions and shoreline change rates at each transect on a beach are related. Shoreline transects need to be closely spaced to effectively characterize shoreline change along a beach. We use a 20 m transect spacing for easy comparison of our methods and results with other recent studies.

The rates calculated using the ST method tend to have high uncertainty because ST is modeling shoreline change at each transect independently. High rate uncertainty results in many rates that are not statistically significant. For this study we consider any rate to be insignificant if it is indistinguishable from a rate of 0 m/yr (i.e., ± rate uncertainty overlaps 0 m/yr). If we can reduce the uncertainty in shoreline change rates we will aid coastal managers in making better-informed decisions in planning for future erosion hazards.

Polynomial Methods

The ST method calculates a rate at each transect by fitting a line to a plot of cross-shore distance vs. time. Importantly, polynomials can be used to model variation in shoreline change rates in the alongshore direction (i.e. from one transect to the next). By modeling shoreline data in the alongshore direction as well, we can incorporate shoreline

positions from all transects on a beach in a single model. The single model will invariably require fewer mathematical parameters to calculate change rates at each transect than the ST method, leading to more parsimonious models (reducing over-fitting). In addition, a single polynomial model correctly assumes that the shoreline data from adjacent transects is related (e.g. dependent).

FRAZER *et al.* (in press) and GENZ *et al.* (in press) have developed polynomial shoreline change rate calculation methods that include the alongshore variation of shoreline change rates in their models. The polynomial methods use finite linear combinations of mathematical basis functions to build a polynomial model for the alongshore dimension. The polynomial methods employ data from all transects along a beach to calculate a rate at any one location. Similar to ST, a line is fit in the cross-shore dimension at each transect. However, unlike ST, calculation of this line is dependent on data from all transects on a beach.

The polynomial methods allow detection of rate variations (acceleration), in addition to variations spatially alongshore. Acceleration in the rates is possible with these methods because of improved data sampling when incorporating all of the beach data in a single model. The rate uncertainties calculated with the polynomial methods are invariably lower than with the ST method because they utilize all of the data on a beach to calculate the rates. Thus, the basis function methods produce statistically significant rates at a higher percentage of transects than ST.

FRAZER *et al.* (in press) provides the simple example of a polynomial (quadratic) equation that could be used to model alongshore variation of shoreline change rates:

$$y(x,t) = y(x,t_1) + (t - t_1)(a + bx + cx^2)$$

The shoreline positions at location x and time t is y and t_1 is the first time position. The basis functions in this equation are 1, x, and x^2. The parameters a, b, and c are the coefficients of the basis functions and are calculated using regression analysis. GENZ *et al.* (in press) describes basis functions as the "building blocks" of the functions. In practice we use other types of basis functions that provide better model fit to the shoreline data.

The polynomial methods use three types of basis functions, rather than the powers of x in the previous example. The basis functions are used in a finite linear combination (a finite convolution) to build a model for the alongshore dimension. All of the methods utilize Generalized Least Squares regression (GLS) to calculate the parameters of the model. GLS incorporates the uncertainty (E_t) of each shoreline position in weighting each shoreline's influence on the model. LXT uses Legendre polynomials as the basis functions. RXT utilizes trigonometric functions (e.g. sines and cosines) as the basis functions. EXT, also know as "Eigenbeaches" utilizes Eigenvectors (i.e., principle components) of the shoreline data as the basis functions. The Eigenvectors are calculated from the shoreline data using all transects on a beach. The basis functions in EX and EXT are called eigenvectors, which are calculated by first collecting the shoreline

positions of all transects at each year into a matrix and then computing the principal components of this matrix. There is one eigenvector for each shoreline position. The first eigenvector describes the pattern of the shoreline data with respect to transect location. This eigenvector typically contains the most information pertaining to the pattern in the shoreline data. Each successive eigenvector has additional, yet less, information of the pattern inherent in the shoreline data.

LXT, RXT, and EXT will not find acceleration in the rates at all beaches. If the models do not identify acceleration, the models are referred to as LX, RX, and EX, respectively. Generally, we refer to these as PX models (Figure 4). The rates from PX models are constant (linear) in time but may vary continuously in the alongshore direction. The rates from the LXT, RXT, and EXT models vary continuously in the alongshore dimension and with time and we refer to these models generally as PXT models (Figure 5).

Rates are first calculated using the ST method for comparison to the rates from the polynomial method. In addition, results from the ST model are used in estimating the spatial (alongshore) correlation of the shoreline data for the polynomial methods. A decaying exponential function is fit to the autocorrelation of the ST data residuals. The best-fit exponential decay function is incorporated in the polynomial shoreline change model to represent decreasing dependence of the shoreline data with distance from each transect.

Using the Matlab code developed by FRAZER (in press)and GENZ(in press), many possible models are calculated for the six basis function model types(three PXT and three

PX). The models vary in the number of basis functions of each type (parameters) used in linear combination.
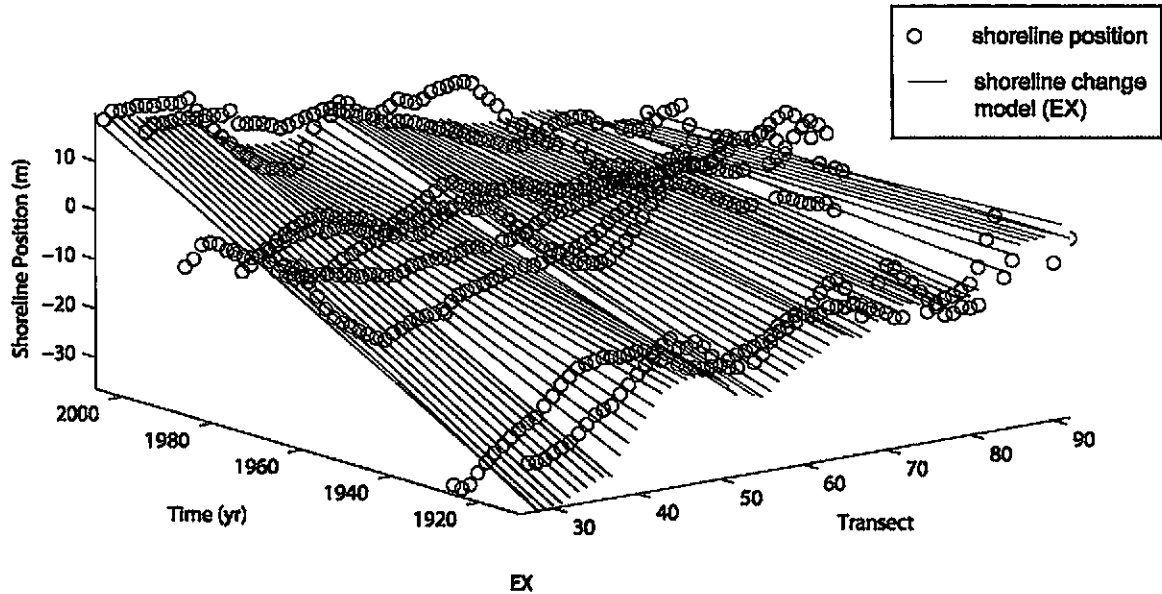

EX

Figure 4. PX (EX) shoreline change model for North Bellows Beach. Rates (slope) vary continuously in the alongshore direction but are constant (linear) in time (no acceleration).
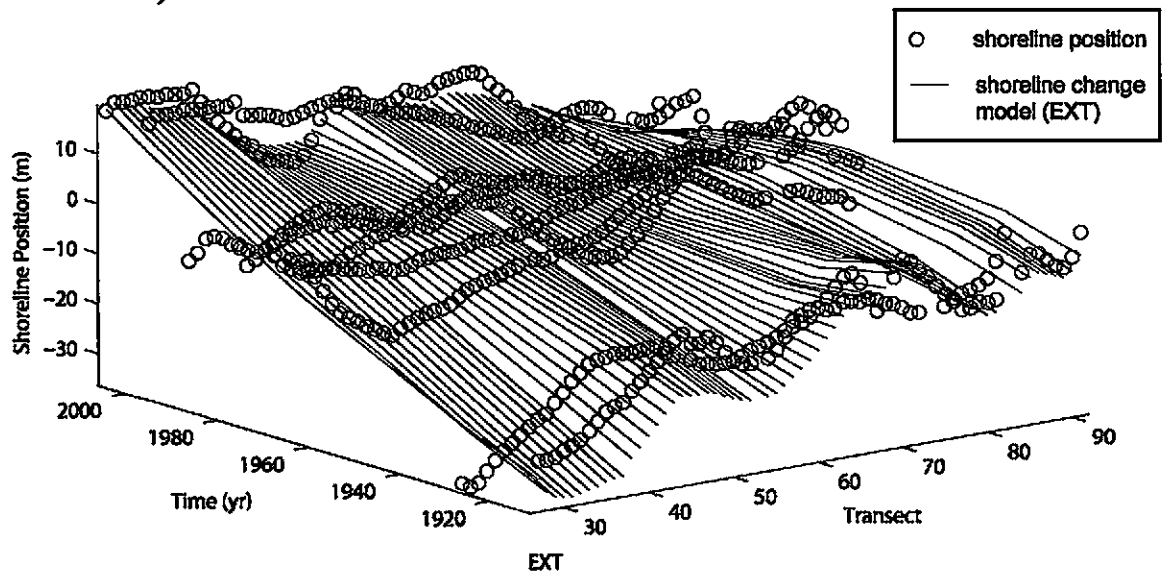

EXT

Figure 5. PXT (EXT, includes acceleration in the rate with time) shoreline change model for North Bellows Beach. Rates (slope) vary continuously in the alongshore direction and with time (acceleration).

Information Criteria (IC) are used to compare the parsimony of the various models. We use a version of Akaike criterion (AICu) (BURNHAM and ANDERSON, 2002; FRAZER *et al.*, in press; GENZ *et al.*, in press). In general, an IC is a comparative statistic or score based on the residual errors of the model (i.e., 'goodness of fit') and the number of mathematical parameters used in the model. As a measure of parsimony, the IC score is 'penalized' as the number of model parameters increases and 'rewarded' for improved fit to the data. A model with a rate of zero (showing no change) is also given an IC score for comparison with the models with rates. The model with the lowest IC score is the most parsimonious model and is the best model to describe shoreline change at a beach. The AICu formula is:

$$AICu = \log[RSS\,/N] + \log[N\,/(N-K)] + (N+K)/(N-K-2)$$

RSS is effectively a sum of squared residuals; N is the number of data points; the best-fit parameter vector has length M; and K is the number of parameters in the statistical model. The first term ($\log[RSS\,/N]$) rewards the models (decreases) with improving model fit. The second term ($\log[N\,/(N-K)] + (N+K)/(N-K-2)$) penalizes the models (increases) with increased number of model parameters (higher model complexity). The model with the lowest IC score is an optimization between goodness of fit to the data and limited model complexity.

The IC is used to select the best model within each of the six PXT and PX model types. The IC scores are also used to identify the optimal model of all PXT and PX

models tested and ST. The polynomial methods invariably produce models with lower IC scores than ST models.

For this study we plot the rates (alongshore) calculated by the model with the lowest IC score within each of the six polynomial model types and ST for comparison of the results. With the PXT models the shoreline change rates are from the most recent shoreline time (2005; because the rates vary with time) and are referred to as the present rate. For additional comparison of the model results and to assist coastal managers in their planning for erosion hazards, we provide additional description of the results from the best model among the models without acceleration in the rates (the PX models) and the best model among the models with acceleration in the rates (the PXT models). All rates are calculated at the 95% confidence interval.

The PXT models, which allow the rates to vary with time, may provide additional information about future erosion hazards at a beach. For example, a beach that is accreting may still present a future erosion hazard if the accretion rate is slowing (decelerating). Conversely, a beach that is eroding may present less of a future erosion hazard if the erosion rate is decelerating. Here, we use the rate acceleration calculated by the PXT models to provide more information about the "fitness" of a beach. Beaches with decelerating erosion rates and accelerating accretion rates have improving fitness. Beaches with accelerating erosion rates and decelerating accretion rates have deteriorating fitness.

Often shoreline change models are used to project future shoreline positions to identify areas of future erosion hazards (Figure 6). GENZ *et al.* (in press) presents a comparison of 50-year erosion hazards projections from polynomial models and other

methods for Maui beaches. Here we present a comparison of the shoreline change rate results. A comparison of projected erosion hazards from this study would lead to the same conclusions as a comparison of rates.
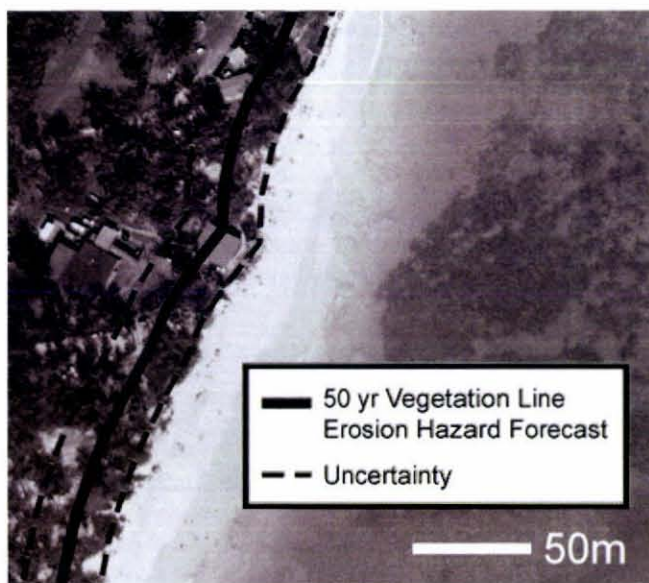
Figure 6. 50-year erosion hazard forecast (North Bellows Beach, Oahu). In this example, the most recent vegetation line position has been projected forward 50 years with the shoreline change model (EX) calculated for this beach.

To make the alongshore rate plots more intuitive, erosion rates are presented here as negative and accretion rates are presented as positive. In actuality, our calculations produce erosion rates that are positive because the distance of the shorelines from an offshore baseline is increasing with time at an eroding beach. Using the original values (erosion positive), projecting a shoreline change model with erosion into the future will result in landward movement (recession) of the shoreline.

RESULTS

Historical Shoreline Change

Kailua Beach

At the North Kailua beach study segment, EX has the lowest IC score among the PX (non-accelerated) models. EX finds accretion throughout the segment, except for a small area of erosion at Kailua Beach Park (Figure 7). The rate of all transects averaged along the length of the segment is 0.46 ± 0.05 m/yr (accretion) (Table 2). The maximum accretion rate, 0.71 ± 0.05 m/yr, is found near the middle of the segment and maximum erosion, -0.09 ± 0.04 m/yr, is found at the southern end at Kailua Beach Park.

At North Kailua Beach, EXT has the lowest IC score of all of the models. In the northern end of the segment EXT finds accelerating accretion throughout the time series of historical shorelines. In the central portion of the segment EXT finds decelerating accretion throughout the time series of historical shorelines. In the southern one-third of the study segment EXT finds decelerating accretion (1911 – ca. late 1970's / early 1980's) and recent accelerating erosion (ca. late 1970's / early 1980's – 2005). The EXT average present (2005) rate of all transects along the length of the segment is 0.10 ± 0.12 m/yr (accretion-stable),a lower accretion rate than with EX. EXT finds the highest accretion rate, 0.70 ± 0.15 m/yr, near the north end of the segment and the highest erosion rate, -1.02 ± 0.12 m/yr, in the south at Kailua Beach Park.

At South Kailua, the EX model with no rate (0 m/yr) has the lowest IC score of the PX models, indicating that statistically significant long-term change has not occurred in this segment. EXT has the lowest IC score of all of the models for this segment. EXT

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is the only method for which IC favors a model with rates. For all other PX and PXT methods the models with a rate of 0 m/yr have the lowest IC scores. EXT finds decelerating accretion (1911 – late 1960's / early 1970's) trending to accelerating erosion
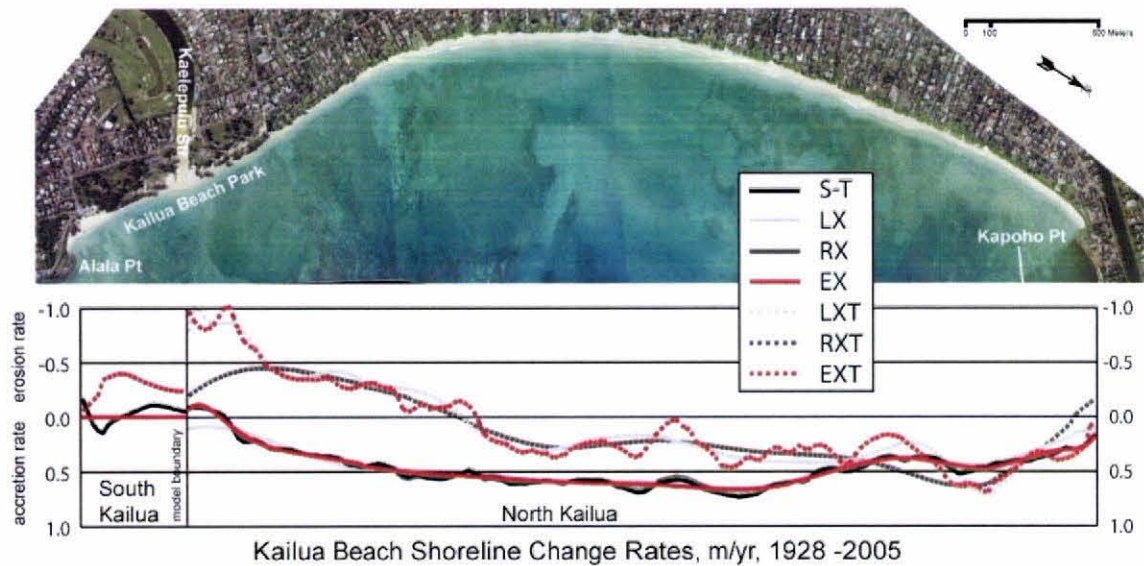
Figure 7. Shoreline change rates (m/yr) at Kailua Beach, 1928-2005. The beach is divided into two study segments with a boundary at Kaelepulu Stream. EX (solid red line) has the lowest IC score among the PX models for both segments. EXT (dashed red line) has the lowest IC score among all models for both segments. The EX model indicating no change (0 m/yr) has the lowest IC score among the PX models for South Kailua. Rates from ST and other PX and PXT models are shown for comparison.

Table 2. *Average shoreline change rates: beach study segments and entire beaches.*

Beach segment or beach	ST avg rate (m/yr)			PX avg rate (m/yr)			PXT avg rate (m/yr)		
Kailua North	0.46	±	0.22	0.46	±	0.05	0.10	±	0.12
Kailua South	-0.04	±	0.47	*0.00	±	n/a	-0.28	±	0.19
Kailua Beach	0.41	±	0.24	0.42	±	0.05	0.06	±	0.13
Lanikai Beach	0.33	±	0.21	0.33	±	0.06	0.55	±	0.13
North Bellows	-0.19	±	0.24	-0.19	±	0.06	-0.19	±	0.13
Central Bellows	0.05	±	0.24	0.02	±	0.04	-0.11	±	0.11
South Bellows & Waimanalo	0.08	±	0.26	0.06	±	0.07	0.10	±	0.09
Bellows & Waimanalo Beach	0.03	±	0.25	0.01	±	0.06	0.00	±	0.10
Kaupo 1	-0.14	±	0.09	-0.13	±	0.03	0.03	±	0.08
Kaupo 2	-0.03	±	0.16	-0.12	±	0.05	0.16	±	0.13
Kaupo 3	-0.11	±	0.18	-0.12	±	0.05	0.19	±	0.13
Makai Pier North	-0.15	±	0.17	-0.15	±	0.06	0.28	±	0.11
Makai Pier South	-0.06	±	0.14	-0.07	±	0.05	0.11	±	0.13
Kaupo Beach Park	-0.10	±	0.17	-0.11	±	0.07	0.04	±	0.07
Kaupo 7	-0.11	±	0.20	-0.11	±	0.07	0.25	±	0.11
Makapuu	0.06	±	0.50	*0.00	±	n/a	*0.00	±	n/a
Kaupo and Makapuu Beaches	-0.08	±	0.20	-0.10	±	0.04	0.08	±	0.08
Southeast Oahu, all	0.15	±	0.24	0.14	±	0.05	0.07	±	0.11

Rate and uncertainty of all transects averaged along the length of the beach segment or beach.

*negative = erosion; positive = accretion, *no rate (0 m/yr)*

Table 2. Average shoreline change rates for southeast Oahu beach segments, totals for whole beaches (bold), and total for southeast Oahu study area (bold).

(late 1960's / early 1970's – present) at all transects in the segment. The average EXT present (2005) rate of all transects for South Kailua is -0.28 ± 0.19 m/yr (erosion). EXT finds the highest rate of erosion, -0.39 ± 0.26 m/yr, is occurring near the middle of the segment.

Lanikai

At Lanikai (Figure 8), the beach was lost to erosion along 1229 m of the shoreline in the time span of this study (306 m at North Lanikai, 923 m at South Lanikai). The beach at north Lanikai was lost to erosion between 1975 and 1982 and has not returned.

At south Lanikai the shoreline advanced seaward between 1949 and 1975 forming an accretion point similar in size to the accretion point presently growing at the center of Lanikai Beach. This accreted area of beach at south Lanikai began eroding in the late 1970's and much of the beach in this area was lost to erosion by 1989. Sea walls and revetments now protect valuable shorefront properties along much of north and south Lanikai where the beach has been lost. Aerial photographs show that seawalls existed in some portions of the Lanikai shoreline prior to 1949. Here we calculate shoreline change rates only for the remaining portion of Lanikai Beach (areas where the beach has not been lost).

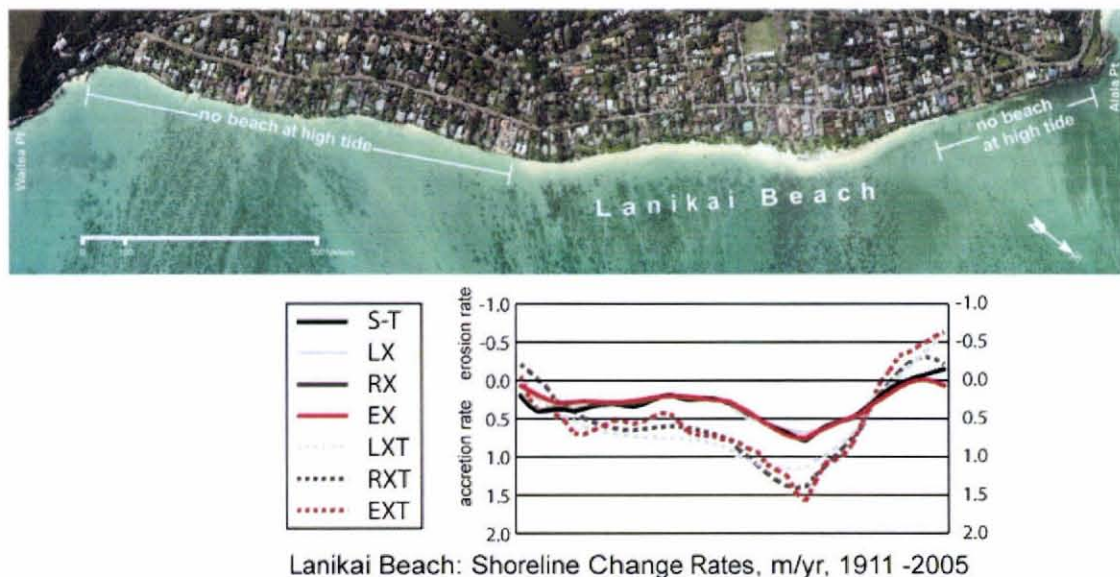Figure 8. Shoreline change rates (m/yr) at Lanikai Beach, 1911-2005. EX (solid red line) has the lowest IC score among the PX models. EXT (dashed red line) has the lowest IC score among all models. Rates from ST and other PX and PXT models are shown for comparison.

At Lanikai, EX has the lowest IC score among the PX models. EX finds accretion at all transects at Lanikai Beach, except for the northern end of the beach where

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EX finds erosion. The rate of all transects averaged along the length of Lanikai Beach is 0.33 ± 0.06 m /yr (accretion). EX finds the highest erosion rate, -0.14 ± 0.06 m/yr, at the north end of Lanikai Beach and the highest rate of accretion, 0.80 ± 0.08 m/yr, near the center of the beach.

EXT has the lowest IC score of all of the models at Lanikai Beach. EXT finds decelerating accretion (1911 – early 1960's) trending to accelerating erosion (early 1960's – 2005) at the north end of Lanikai Beach and accelerating accretion throughout most of the time series of historical shorelines (1927 – 2005) in the central portion of the beach. The EXT present (2005) rate of all transects averaged along the beach, 0.55 ± 0.13 m/yr (accretion), is higher than with EX. EXT finds the highest rate of accretion, 1.58 ± 0.18 m /yr, is occurring near the middle of the beach and the maximum rate of erosion, -0.63 ± 0.13 m/yr, is occurring at the north end of the beach.

Bellows and Waimanalo Beach

At North Bellows (Figure 9), the beach along the northern most portion of the shoreline (690 m) was lost to erosion prior to 1996. Waves break against stone revetments at high tide in this area. Rates are calculated only for the remaining portion of beach in this segment. At North Bellows Beach, EX has the lowest IC score among the PX models. EX finds erosion at most transects in this segment, except for a small area of accretion in the south of the segment against the north Waimanalo Stream jetty. The rate of all transects averaged along the length of this segment is -0.19 ± 0.06 m /yr (erosion). EX finds the highest erosion rate, -0.43 ± 0.07 m /yr, at the north end of the segment and the highest rate of accretion, 0.05 ± 0.04 m /yr, in at the south end of the segment.
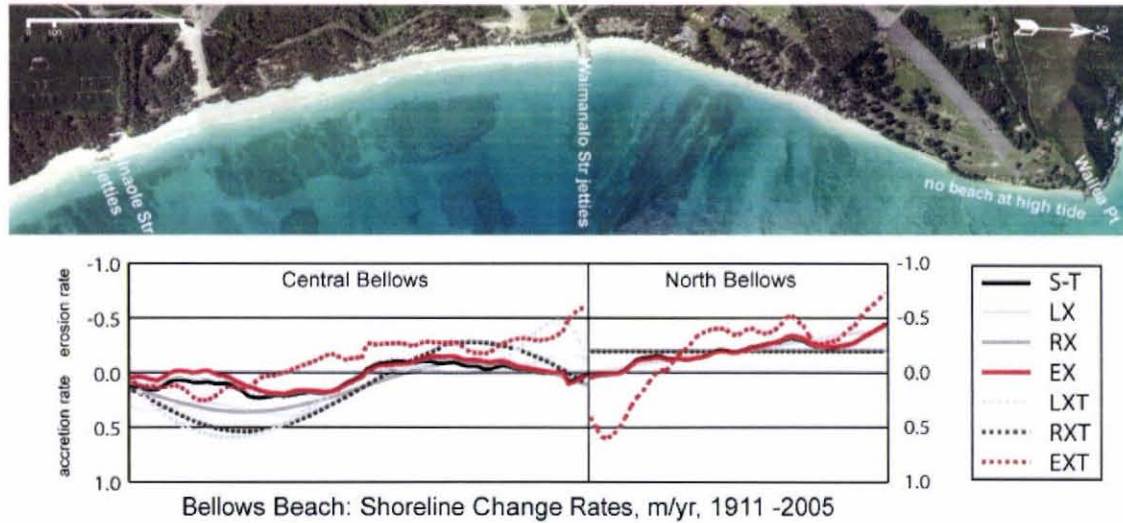
Figure 9. Shoreline change rates (m/yr) at Central and North Bellows Beach 1911-2005. The jetties at Waimanalo Stream divide the beach into two study segments. EX (solid red line) has the lowest IC score among the PX models for both segments. EXT (dashed red line) has the lowest IC score among all models for both segments. Rates from ST and other PX and PXT models are shown for comparison.

In the North Bellows segment, EXT has the lowest IC score of all of the models. EXT finds accelerating erosion throughout the time series of historical shorelines (1911 – 2005) in the northern three-quarters of the segment and decelerating erosion (1911 - late 1960's / early 1970's) trending to accelerating accretion (late 1960's / early 1970's – 2005) in the south. EXT is the only model that finds high rates of recent accretion in the south of the segment. The EXT present (2005) rate of all transects averaged along the segment is very similar to EX, -0.19 ± 0.13 m/yr (erosion). EXT finds maximum erosion and accretion in the same locations as EX but rates are higher with EXT. EXT finds the highest erosion rate, -0.72 ± 0.17 m /yr, at the north end of the segment and the highest accretion rate, 0.60 ± 0.15 m /yr, in the south end of the segment.

At Central Bellows, EX has the lowest IC score among the PX models. EX finds erosion in most of the north half of the segment and accretion in most of the south half.

The rate of all transects averaged along the length of this segment is 0.02 ± 0.04 m/yr (accretion-stable). EX finds the highest erosion rate, -0.15 ± 0.04 m/yr, in the middle of the northern half of the segment and the highest accretion rate, 0.20 ± 0.05 m/yr, in the middle of the southern half of the segment.

At Central Bellows, EXT has the lowest IC score of all of the models. EXT finds decelerating accretion (1911 – 1960's) trending to accelerating erosion (1960's – 2005) in the northern two-thirds of the segment, and small areas of recent decelerating and accelerating accretion in the southern third. The EXT present (2005) rate of all transects averaged along the length of the segment is -0.11 ± 0.11 m/yr (erosion - stable). EXT finds the highest rate of erosion, -0.59 ± 0.10 m/yr, at the north end of the segment and the highest rate of accretion, 0.26 ± 0.11 m/yr, near the south end of the segment.

In the South Bellows and Waimanalo segment (Figure 10), LX has the lowest IC score among the PX models. LX finds small amounts of accretion throughout the northern half of the segment, little or no change throughout most of the southern half, except where it finds erosion in the southernmost ten percent of the segment. The rate of all transects averaged along the length of the segment is 0.06 ± 0.07 m/yr (accretion-stable). LX finds the highest accretion rate, 0.28 ± 0.08 m/yr, in the north of the segment, and maximum erosion, -0.35 ± 0.07 m/yr, in the south.

EXT has the lowest IC score of all of the models in the South Bellows and Waimanalo segment. EXT finds decelerating accretion throughout the time series (1911 – 2005) for most of the north of the segment. Near the boundary between Waimanalo Beach Park and the town of Waimanalo, EXT finds an area that is characterized by decelerating accretion in the first half of the time series (1911 – 1960's) trending to

accelerating erosion (1960's – 2005). EXT finds recent accelerating erosion (1960's – present) in the southern half of the segment. The EXT present (2005) rate of all transects averaged along the length of the South Bellows and Waimanalo segment is 0.10 ± 0.09 m/yr (accretion). EXT finds the highest rate of erosion, -0.70 ± 0.11 m/yr, near the boundary between Bellows Field Beach Park and Waimanalo and highest rate of accretion, 0.66 ± 0.10 m/yr, in the south between Waimanalo Bay Beach Park and Kaiona Beach Park.
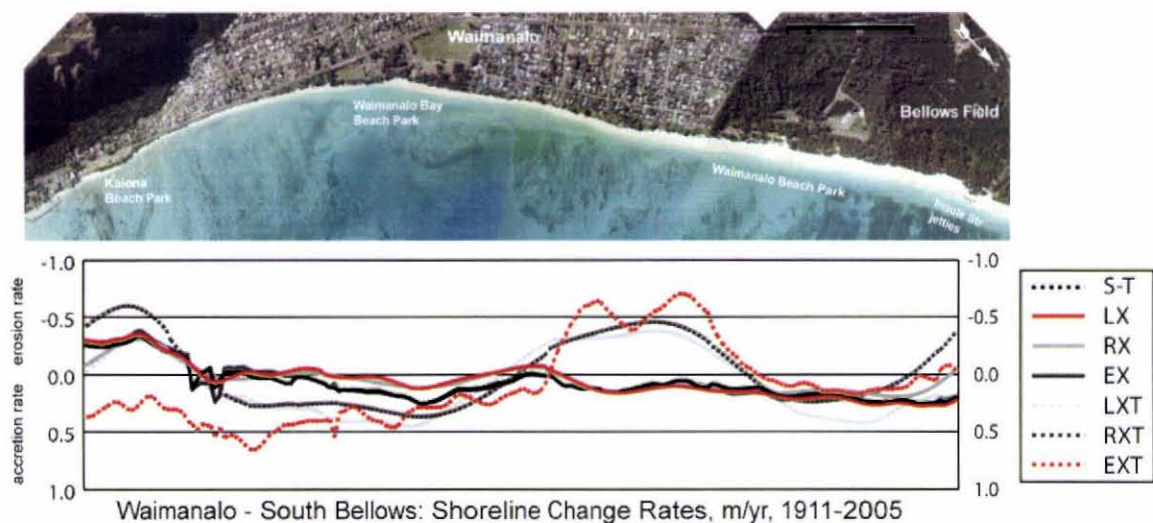
Figure 10. Shoreline change rates (m/yr) at Waimanalo and South Bellows Beach, 1911-2005. LX (solid red line) has the lowest IC score among the PX models. EXT (dashed red line) has the lowest IC score among the all models. Rates from ST and other PX and PXT models are shown for comparison.

Kaupo and Makapuu Beaches

At Kaupo Beach 1 (Figure 11), EX has the lowest IC score among the PX models. EX finds erosion at all transects in this segment. The EX rate of all transects averaged along the length of the segment is -0.13 ± 0.03 m/yr (erosion). EX finds the highest rate of erosion, -0.20 ± 0.03 m/yr, near the south end of the beach. EXT has the lowest IC

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score among all of the models. EXT finds accelerating accretion at most transects in this segment. However, the rates are statistically insignificant. The EXT rate of all transects averaged along the length of the segment is 0.03 ± 0.05 m/yr (accretion-stable).

Kaupo - Makapuu Beaches: Shoreline Change Rates, m/yr, 1911 - 2005
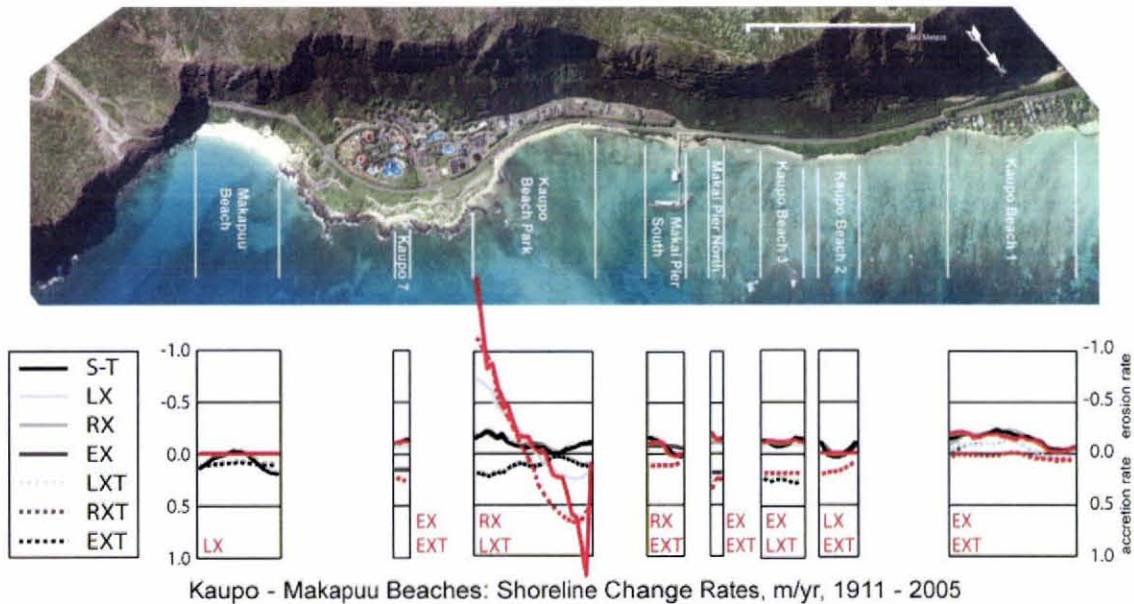
Figure 11. Shoreline change rates (m/yr) at Makapuu and Kaupo Beaches 1928-2005. The study site is divided into eight beach study segments by areas of hard shoreline (no beach). The model with the lowest IC score among the PX models is displayed as a solid red line and noted at the bottom of each plot. The model with the lowest IC score among the PXT models is displayed as a dashed red line and noted at the bottom of each plot. Rates from ST and other PX and PXT models are shown for comparison.

At Kaupo Beach 2, the LX and RX null models have the lowest IC score among the PX models indicating no statistically significant long-term change. EXT has the lowest IC score of all of the models and is the only PXT model for which IC selects a model with rates. EXT finds statistically significant accretion rates at most transects in the segment. The EXT rate of all transects averaged along the length of the segment is 0.16 ± 0.13 m/yr (accretion).

For Kaupo Beach 3, EX, with the lowest IC score among the PX models, finds erosion at all transects. The rate of all transects averaged along the length of the segment is -0.12 ± 0.05 m/yr (erosion). The highest erosion rate, -0.13 ± 0.06 m/yr, is found near the south end of the segment. LXT and RXT models, with the lowest IC score of all of the models, find accretion at all transects. LXT and RXT produce the same rates with one linear alongshore model basis function. The rate at each transect for these models is 0.19 ± 0.13 m/yr (accretion).

At Makai Pier North, EX has the lowest IC score among the PX models. EX finds statistically significant erosion rates at all transects in this segment. The rate of all transects averaged along the length of the segment is -0.15 ± 0.06 m/yr (erosion). EXT has the lowest IC score of all of the models. EXT finds significant accretion rates for all transects in this segment. The EXT rate of all transects averaged along the length of this segment is 0.28 ± 0.11 m/yr (accretion).

At Makai Pier South, EX has the lowest IC score among the PX models. EX finds significant erosion rates at all transects in this segment. The EX rate of all transects averaged along the length of the segment is -0.07 ± 0.05 m/yr (erosion). EXT has the lowest IC score of all of the models. EXT finds accretion rates for all transects in this segment. The EXT rate of all transects averaged along the length of this segment is 0.11 ± 0.13 m/yr (accretion-stable).

At Kaupo Beach Park, RX has the lowest IC score among the PX models. RX finds accretion in the north half of the segment and erosion in the south half. The rate of all transects averaged along the length of the segment is -0.11 ± 0.07 m/yr (erosion). However, this calculation masks the bimodal distribution of erosion and accretion in this

segment. The highest rate of accretion, 1.20 ± 0.13 m/yr, is found at the north end of the segment and the highest rate of erosion -1.71 ± 0.16 m/yr, is found at the south end of the segment. LXT has the lowest IC score of all of the models. LXT also finds accretion in the north half of the segment and erosion in the south half. However, the rates are somewhat lower with LXT than with RX. The LXT rate of all transects averaged along the length of the segment is 0.04 ± 0.07 m/yr (accretion-stable). LXT finds the highest rate of accretion, 0.68 ± 0.08 m/yr, at the north end of the segment and the highest rate of erosion -1.30 ± 0.10 m/yr, at the south end of the segment.

At Kaupo Beach 7, EX has the lowest IC score among the PX models. The EX rate of all transects averaged along the length of the segment is -0.11 ± 0.06 m/yr (erosion). EXT has the lowest IC score of all of the models. The EXT rate of all transects averaged along the length of the segment is 0.25 ± 0.11 m/yr (accretion).

At Makapuu Beach, the LX and RX models with no rates (0 m/yr) have the lowest IC scores of all of the models indicating no statistically significant change. EX is the only model for which IC selects a model with rates. However, the rates calculated with EX are statistically insignificant at all transects. The EX rate of all transects averaged along the length of the segment is 0.09 ± 0.10 m/yr (accretion-stable).

DISCUSSION

Area Specific

Kailua Beach

At the North Kailua Beach segment, the PX models (including EX) and ST find long-term accretion, in agreement with results of the previous studies (HWANG, 1981; NORCROSS *et al.*, 2002; SEA ENGINEERING, 1988). The PXT models (including EXT) agree that the northern two-thirds of the segment is accreting. However, they also indicate that accretion rates have slowed (decelerated) through the time span of the study. In contrast to the findings of the PX and ST models and previous studies, the PXT models find recent accelerated erosion in the south of the segment near Kailua Beach Park. Recent (2006 – 2008) erosion to the beachfront dunes at Kailua Beach Park supports the PXT models' findings. Inspection of the historical shorelines at Kailua Beach Park shows a previous episode of accretion followed by erosion between 1963 and 1971. EXT appears to be correctly modeling the recent trend of erosion at Kailua Beach Park. However, if the previous episode of accretion followed by erosion is any indication of the future, the recent trend of accelerated erosion in the south of the segment, as modeled by EXT, is unlikely to continue. The PXT models are unable to model the inevitable deceleration in the rates following a period of accelerating shoreline change. Theoretically speaking, accelerating erosion or accretion cannot continue indefinitely. Otherwise, the rates will eventually approach infinity or at least become unrealistically high.

At the South Kailua segment, models with rates of 0 m/yr have the lowest IC scores for each of the PX models indicating no statistically significant long-term change. The inability of the PX models to identify significant change in this segment may be interpreted two ways. One, the historical shorelines from this segment are too variable (noisy) to calculate a statistically significant long-term trend. Or, two, this segment of beach may be considered stable in the long term and any erosion or accretion is episodic within the time frame of the study. Inspection of the historical shoreline positions supports the former. Shorelines were approximately stable between 1911 and 1963, accreting between 1963 and 1967, erosive between 1967 and 1978, fairly stable between 1978 and 1988, accreting between 1988 and 1996, and erosive between 1996 and 2005. The EXT model finds recent accelerating erosion, in agreement with EXT's findings for the north side of Kailua Beach Park. Recent (2006 – 2008) erosion to the beachfront dunes has also been observed at the south side of Kailua Beach Park, also supporting the EXT result in this segment.

Looking at Kailua Beach as whole, previous studies found long-term accretion throughout the length of the beach, including at Kailua Beach Park. However, recent observed erosion at Kailua Beach Park is the most conclusive evidence that the southern Kailua shoreline is vulnerable to erosion, even if the beach is accreting over the long-term. By calculating erosion rates using a PXT model and including more recent historical shorelines we provide statistical evidence of recent accelerated erosion in the southern portion of Kailua Beach. The shorefront dunes in southern Kailua have likely provided a natural repository of sediment that replenished the beach during previous

episodes of erosion. Maintaining the shorefront dunes at Kailua Beach Park in a more natural condition may reduce the impact of future episodes of erosion on the beach park.

EXT finds recent accelerating erosion at 39% of transects (in the south) and recent decelerating accretion at 48% of transects (around the middle of the beach). Thus, EXT finds deteriorating fitness at 87% of transects at Kailua Beach. Only two small areas in the north of Kailua show improving fitness (13%).

The pattern of shoreline change modeled by PXT suggests two possible scenarios for sediment transport along Kailua Beach. The PXT models find accretion in the north of Kailua Beach and erosion in the south of Kailua Beach with the highest rates of accretion and erosion at either end. The boundary between the areas of erosion and accretion is located near the landward end of a submerged sand-filled channel cut into the reef at the center of Kailua Bay. The pattern of erosion and accretion may indicate recent net northward transport along the length of Kailua Beach, eroding sand in the south and depositing sand in the north. Alternatively, the results may support the presence of two distinct littoral cells on either side of the channel with recent erosion in the southern cell and recent accretion in the northern cell. CACCHIONE et al. (2002) studied sand ripple migration in the reef channel at Kailua Beach. Their study concluded that sand migrated onshore during periods of low to moderate tradewind waves and offshore during periods of larger tradewind waves and refracted north swells. Long-term accretion, as calculated by the PX models, ST, and previous studies, provides convincing evidence that the reef channel is a net source of sand for Kailua Beach because these methods find the highest rates of accretion in nearest proximity to the channel.

Lanikai Beach

Lanikai Beach is bounded on either side by extensive sea walls constructed in areas where the beach has been lost to erosion. Aerial photographs show the beach at north Lanikai was lost to erosion between 1975 and 1982 and has not returned. At south Lanikai the shoreline advanced seaward between 1949 and 1975 forming an accretion point similar in size to the accretion point presently growing at the center of Lanikai Beach. This accreted area of beach at south Lanikai began eroding in the late 1970s and much of the beach in this area was lost to erosion by 1989. Aerial photographs and recent beach surveys confirm that beach loss in south Lanikai continues is expanding to the north.

The PXT models find accelerating accretion at most transects at Lanikai Beach throughout the time span of this study. The concurrent timing of beach loss at north and south Lanikai and onset of accelerating accretion at Lanikai Beach suggests that the sand in the area of accretion is from eroded areas to the north and south.

Previous studies (HWANG, 1981; SEA ENGINEERING, 1988) and the results from the PX, PXT, and ST models indicate that most of the remaining portion of Lanikai Beach is accreting. However, the PXT models, which find accelerating erosion at the north and south ends of the beach, best depict the threat of further beach loss at Lanikai. Recent aerial photographs and beach profile surveys at Lanikai Beach show that beach loss continues to encroach from the north and south. The remainder of Lanikai Beach may eventually be threatened with erosion if the pattern of beach loss continues.

EXT finds recent accelerating erosion at 17% of transects (at the north and south ends) and recent decelerating accretion at 9% of transects (toward the north and south

ends). Thus, EXT finds improving fitness for most transects (75%, around the middle of the beach) at Lanikai.

The Lanikai shoreline (Wailea Point to Alala Point) likely comprises a single littoral cell, as it is free of significant barriers to alongshore sediment transport. It is unknown how much sand is lost to or gained from offshore sources. Episodic accretion and erosion is observed in the historical shorelines at southern Lanikai. The remaining beach at central Lanikai may be prone to similar episodic behavior because Lanikai Beach shares sand with the now lost southern Lanikai shoreline. Hence, an important sand source has been lost – an additional warning that accretion at Lanikai Beach is not certain to continue.

Bellows and Waimanalo Beach

In the North Bellows segment, the EX, EXT, and ST models find similar patterns of erosion and accretion with the highest erosion rates in the north of the segment and decreasing rates toward the south. The highest rates of erosion from all of the models are found at the northern end of the segment near the area of beach loss and seawalls at the northern end of the Bellows shoreline. Agreement between all these models indicates that the northern end of Bellows Beach is threatened with additional beach loss. The EXT model finds accelerating accretion in the south of the segment, suggesting that eroded sediment is being transported to the south and accumulating against the Waimanalo Stream jetty.

In the Central Bellows segment, all of the PX, PXT, and ST models find a pattern of erosion and accretion similar to North Bellows with erosion in the northern portion of

the segment and accretion in the south indicating net southerly sand transport. The long-term erosion rates calculated by the PX models for Central Bellows are not as high as North Bellows, suggesting that the long-term risk of erosion is not as high for this segment.

Within the South Bellows and Waimanalo segment, the PX models identify a different pattern of erosion and accretion than the PXT models. The PX models (and ST) find that all but the southern portion of the segment is essentially stable over the time span of the study, i.e. statistically insignificant rates at most transects. In contrast, the PXT models identify a zone of recent accelerating erosion fronting the north end of the town of Waimanalo. However, beach profiles surveys in this area over the last eight years do not support high rates of recent erosion in this area. Beach profile surveys at Waimanalo Bay Beach Park show evidence of recent erosion, in disagreement with the PX and PXT models' finding of accretion in this area. The results from the PX models should be considered more reliable than the PXT models for long-term (50-year) erosion hazard planning for this segment. The PX models characterize the trend of the entire data set, while the PXT models characterize the trend of more recent shorelines (< 50 years). However, a responsible shoreline management plan for South Bellows and Waimanalo should recognize the threat of short periods (< 30 years) of accelerated erosion even if the beach can be considered stable over the long-term.

Looking at the whole of Bellows and Waimanalo Beach, the patterns of erosion and accretion indicate net southerly sediment transport for the northern half of the beach. This is supported by the pattern of erosion on the south side of the northern Bellows

revetments, and erosion on the south side of the Waimanalo and Inaole Stream jetties and accretion against the north side of the jetties.

Previous studies (HWANG 1981 and SEA ENGINEERING 1988) found net landward movement (erosion) of the vegetation line at North Bellows in agreement with our findings of erosion in this area. These studies also found accretion at the north side of the Waimanalo Stream jetties and at the northern end of Waimanalo.

EXT finds recent accelerating erosion at 43% of transects and recent decelerating accretion at 14% of transects. Thus, EXT finds deteriorating fitness at 57% of transects at Bellows and Waimanalo Beach. The areas of deteriorating fitness are in the northern portion of each study segment, whereas the areas if improving fitness (43% of transects) are in the south of each study segment.

Kaupo and Makapuu Beaches

In the Kaupo and Makapuu Beaches section we find less agreement between the models than in the other beaches in this study, which imparts less support for the results of any of the individual models. At Kaupo Beach segments 1, 2, 3, Makai Pier North, Makai Pier South, and Kaupo7, the PX methods and ST methods find erosion at most transects while the PXT methods find accretion at most transects. In some of these beaches, the different rates calculated by the PX and PXT models are attributed to the addition of one model parameter for rate acceleration in the PXT models. For example, at the Makai Pier North segment the EX and EXT models are comprised of the same, single, alongshore basis function (an Eigen vector function). However, the EXT model includes one additional model parameter (time) to incorporate acceleration in the

shoreline change rate. The effect of adding an acceleration parameter can be seen in the rate plot for Makai Pier North beach segment. The EX and EXT models appear as reflections of each other on either side of 0 m/yr. This effect may be more visible in these beaches than beaches to the north due to the small size of the beaches in this section (few transects). Fewer alongshore parameters are used in the models for these beaches. So, the effect of adding an acceleration parameter is more visible.

We interpret the PX and PXT results from the Kaupo and Makapuu Beaches section as we do for other beaches in this study. The model with the lowest IC score among the PX models provides the best description of the long-term change at these beaches. The model with the lowest IC score among the PXT model provides additional information about more recent trends of shoreline change at these beaches. The PX model finding of long-term erosion is supported by chronic erosion to the vegetation line at some areas and the general sediment-poor nature of these beaches (narrow, cobble-covered). Stone revetments were recently installed near Makai Pier to protect the highway roadbed additional erosion.

At Kaupo Beach Park the RX and LXT models, with the lowest IC scores among the PX and PXT models, find erosion in the south half of the segment and accretion in the north half of the segment. This distribution of erosion and accretion suggests net northerly sediment transport. However, we do not find accretion at the adjacent shoreline to the north, e.g. Makai Pier, as should be expected. EX and ST find erosion at all transects in this segment, which may be a better depiction of the long-term trend of shoreline change at Kaupo Beach Park.

At Makapuu Beach, the LX, RX, LXT, RXT models without significant rates have the lowest IC scores. Makapuu may be considered a stable beach or the long-term shoreline trend may be masked by short-term variability. Examination of the time series of the historical shorelines shows high variability in their position throughout the time span of the study. High seasonal variability is also recorded in beach profile surveys at Makapuu Beach. A lack of available shoreline data (six historical shorelines) for Makapuu may also be limiting our ability to find a long-term trend. Results for Makapuu from HWANG (1981) were also inconclusive. HWANG (1981) found net landward movement of the vegetation line from 1950 to 1975 (possibly due to increasing use of the beach and foot traffic) and net seaward movement of the water line over the same time period.

The PXT methods find recent accelerating erosion at 3% of transects and recent decelerating accretion at no transects between Kaupo and Makapuu Beaches. Thus, PXT finds improving fitness at 97% of transects at Bellows and Waimanalo Beach.

Methodological

The PXT models have lower IC scores than the PX models in all beaches in the study area where acceleration is identified in the shoreline change rate. An additional model parameter is required to include acceleration in the PXT shoreline change models. However, in the IC optimization equation, the reward for the improved fit of the PXT accelerated models to the data appears to outweigh the penalty from the additional model parameters, resulting in lower IC scores for the PXT models than the PX models. The shoreline data sets for most beaches in this study may be considered well configured (i.e.,

many shorelines, up to 13) in comparison to other shoreline change studies. This may help to explain why the PXT models receive lower IC scores at nearly all beaches in this study. The PXT methods will not identify acceleration for beaches where the data are not well configured (few shorelines, high uncertainty).

At several beaches in this study we have shown that the results of the PXT models are supported by recent observation of erosion at the beaches. Further inspection of the PXT models from this study shows that the trends of accelerating erosion and/or accelerating accretion have persisted for less than 50 years. In other words, the rates from the PXT models are strongly influenced by the trend of the most recent shorelines (often less than 30 years in our data). A goal of this study is to provide shoreline change rates to be used in long-term (> 50 years) shoreline erosion hazard planning.

GENZ *et al.* (in press) tested future shoreline prediction of polynomial models with real and synthetic data sets, but the results were inconclusive. Their study found that the PXT shoreline change models are not as accurate as the PX models at predicting the most recent shoreline position in real shoreline data sets where the most recent shoreline position has been removed. The PXT models in their study were more accurate than the PX models at predicting 50-year shorelines in synthetic shoreline data sets that are known to include acceleration in the rates. However, the EXT models are shown in their study to erroneously identify acceleration in synthetic data sets that are known not to include acceleration in the rates.

The results of this study and GENZ *et al.* (in press) indicate that the PX models (without acceleration) provide a more reliable characterization of the long-term change occurring at a beach. The PXT models, which allow for characterization of acceleration,

provide valuable information about recent change occurring at a beach and describe how a rate may have varied with time. Additionally, the PXT models may identify potential erosion hazards, e.g. episodic accelerated erosion that is not seen in the PX models (Figure 12).

In two of fourteen beach segments in this study the model showing no change (0 m/yr) had the lowest IC score among the PX models. IC's selection of a model without rates may be interpreted two ways. One, the historical shoreline data are not adequately configured (i.e., not enough shorelines, too much uncertainty) to calculate statistically defensible shoreline change rates. Or, two, the beach is stable over the time span of the study. In either case, a model without rates provides statistically defensible evidence that a beach has not changed significantly in the time span of the study. This information is as valuable for erosion hazard planning as a model that finds significant erosion or accretion.

The specific goals of an agency's coastal management plan may influence planners to choose another of the parsimonious PX or PXT models for projecting future shoreline hazards. For example, coastal managers may determine that the model with the highest erosion rates provide the best information about the risk of future erosion hazards. Or, all the parsimonious PX and PXT methods may be utilized to forecast a range of possible future shoreline positions. The credibility of erosion rates and erosion hazard forecasts is improved if the results from shoreline change models calculated using different methods agree. If models do not agree, the reliability of their rate calculations is reduced. In this case coastal managers must determine which model provides the best information for their purpose.
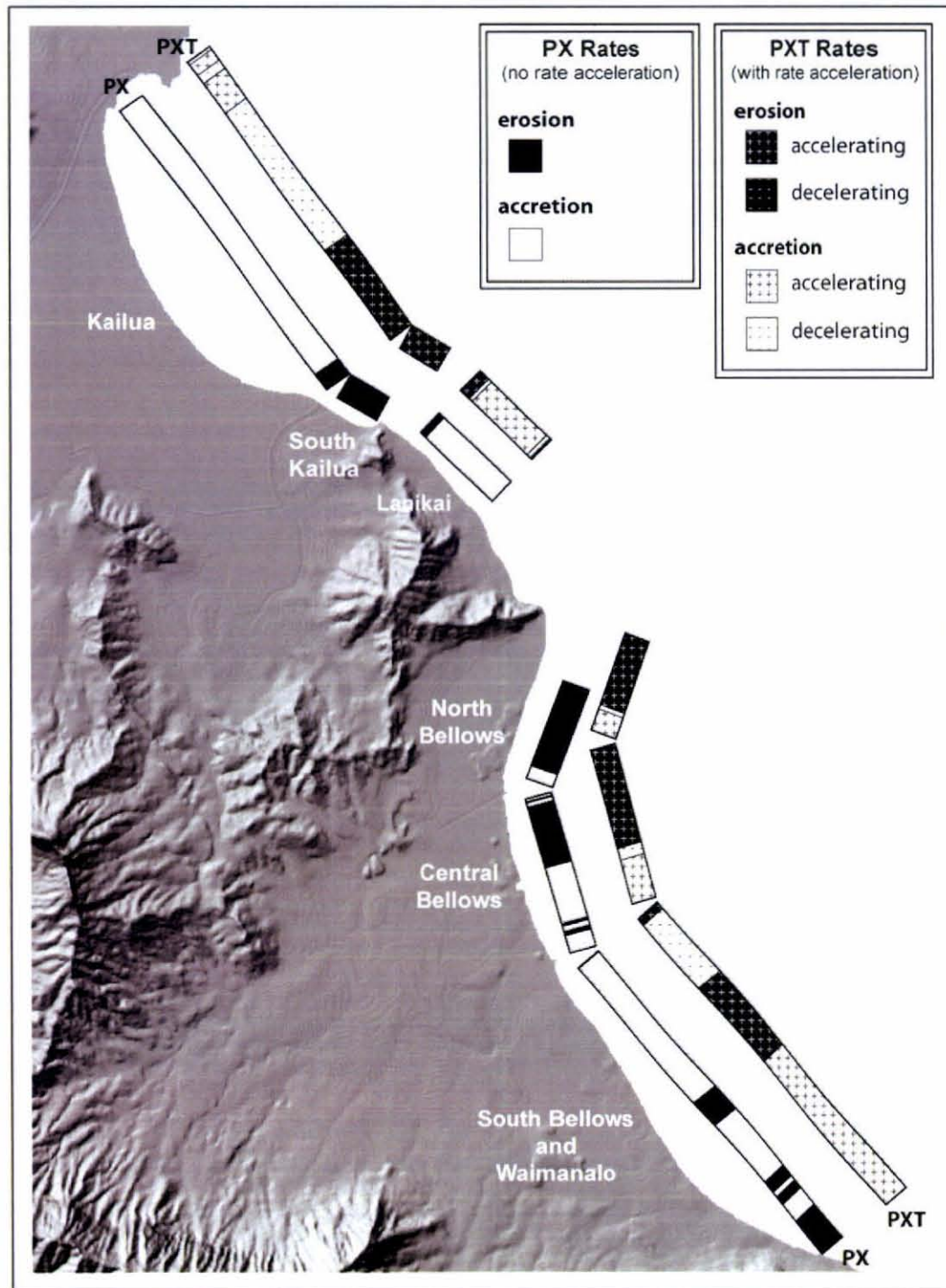
Figure 12. Shoreline change behavior: Kailua, Lanikai, Bellows and Waimanalo Beaches (South Bellows and Makapuu not shown). The bars closest to the shoreline illustrate the shoreline behavior as calculated by the PX (non-accelerated) models. The second set of bars (offshore position) illustrates the shoreline behavior as calculated by the PXT (accelerated) models. Rates are from the model with the lowest IC in each beach segment.

The EX model has the lowest IC score among the PX models in eight of fourteen beach segments in this study. The EXT model has the lowest IC score among the PXT models in ten of fourteen beach segments. EX and EXT may be calculating models with better fit to the data and fewer parameters because the model is comprised of basis functions (Eigen vectors) that are derived from the shoreline data, themselves. The other PX and PXT methods (LX, RX, LXT, RXT), which attempt to fit a polynomial model to the data, most often require a greater number of mathematical parameters (basis functions) to produce a satisfactory fit to the data, resulting in a higher IC scores.

Model parameters should be constrained by our knowledge of the physics and/or limits of a system. For example, periodic phenomena such as tides and waves are best modeled using linear combinations of sine and cosine functions. The temporal dynamics of shoreline change are unknown. Eigenvectors (in EX and EXT) derived from shoreline data have the exciting prospect of describing some of the unknown dynamics of change at a beach.

Whether the EX and EXT methods actually produce better shoreline change models at most beaches is an area of ongoing research. Additional research may include comparison of predictions by the various PX and PXT models of the most recent shoreline(s) in truncated shoreline data sets from this study. Updates to this study using new historical shorelines (new aerial photography) are necessary to continue monitoring Oahu's beaches for changes in shoreline trends. New shoreline data may be used to test predictions made by the models from this study.

Time series of historical shorelines in this study span less than 100 years. As discussed above, the recent trend in PXT models often illustrate an erosion or accretion

trend of the most recent shorelines (<30 years). Littoral processes along most Hawaiian beaches are driven primarily by waves from frequent easterly tradewinds and powerful seasonal swells (VITOUSEK and FLETCHER, in press). It is not unreasonable to wonder if the PXT models may be detecting decadal-scale fluctuations in shoreline position related to atmospheric variability (e.g., ENSO, PDO, tradewind oscillations) at some beaches (ROONEY et al., 2003). Multiple episodes of accelerated erosion and accretion are seen in the time series of historical shorelines at Kailua Beach Park and south Lanikai. At some beaches the PXT models may be detecting recent affects anthropogenic development (e.g. sea-walls, groins). The PXT models are limited by their inability to model the inevitable deceleration that must follow any period of accelerated shoreline change. Correlating shoreline change with periodic atmospheric fluctuations would be an exciting advance for coastal studies and would greatly improve our ability to plan for future erosion hazards (BOCHICCHIO et al., in press).

The greatest potential for the PXT methods is in the detection of accelerating shoreline change that is expected with accelerating sea-level rise from global temperature increase (CHURCH and WHITE, 2006). However, shoreline changed attributed directly to sea level rise can easily be masked by more dominant processes driving change at a beach (e.g. the local littoral sediment budget). Continued studies of all the beaches in the Hawaiian Islands and other locations using the PX and PXT methods have the potential for detecting accelerated shoreline change that is anticipated with accelerating sea-level rise.

CONCLUSIONS

Shoreline Change

For the southeast Oahu study area, shoreline change rates are calculated using the polynomial methods and ST for 651 shoreline transects in 14 beach segments. The PX methods, which calculate shoreline change rates that are constant in time, finds erosion at 36% of transects in the study area and accretion at 64% of transects. The PX shoreline change rate averaged along all transects in the Southeast Oahu study area is 0.69 ± 0.11 m/yr (accretion). For individual study areas, the average PX rates are: Kailua Beach 0.06 ±0.12 m/yr (accretion - stable), Lanikai Beach 0.55 ± 0.13 m/yr (accretion), Bellows and Waimanalo Beach 0.00 ± 0.10 m/yr (stable), and Kaupo and Makapuu Beaches 0.08 ± 0.08 m/yr (accretion-stable). The PX method finds significant areas of erosion in the north half of the North Bellows segment; the north half of the Central Bellows segment, in the south of the South Bellows and Waimanalo segment, and at most beaches in the Kaupo and Makapuu Beaches section. In the time span covered by this study, 1911 – 2005, nearly 2 km (1919 m) of beach was lost to erosion along the Southeast Oahu shoreline.

The PXT methods, which can allow the rates to vary with time (acceleration), provide valuable insight on recent shoreline change at many of the beaches in the study area. The PXT methods find recent accelerating erosion at south Kailua Beach, most of northern Bellows Beach; at the beach fronting the northern Waimanalo, and at the south end of Kaupo Beach Park. The PXT methods find recent accelerating erosion at 33% of transects and recent decelerating accretion at 22% of transects in the study area. Thus,

55% of transects show a recent trend of decreasing fitness and 45% of transects show a recent trend of increasing fitness. At this time we are unable to determine if sea-level rise is having an adverse effect on southeast Oahu beaches. Ongoing study of beaches on all shores of Oahu, Kauai, and Maui islands with the PXT methods may provide more conclusive evidence of effects of sea-level rise on Hawaii beaches.

Methods

By calculating shoreline change rates for the beaches of southeast Oahu with the polynomial methods (PX and PXT) and the ST method and comparing the results, we make the following conclusions about the shoreline change rate calculation methods used in this study. (1) The PX and PXT methods produce statistically significant shoreline change rates at a greater percentage of shoreline transects than the ST method (Figure 13). The PX and PXT methods find statistically significant shoreline change rates at 70% of transects in the study area versus 40% with ST. The PX and PXT methods utilize historical shoreline positions from all transects at a beach or segment of a beach. This results in lower uncertainty in the shoreline change rates with PX and PXT and, thus, more statistically significant rates.

Percent of Transects with Statistically Significant Shoreline Change Rates
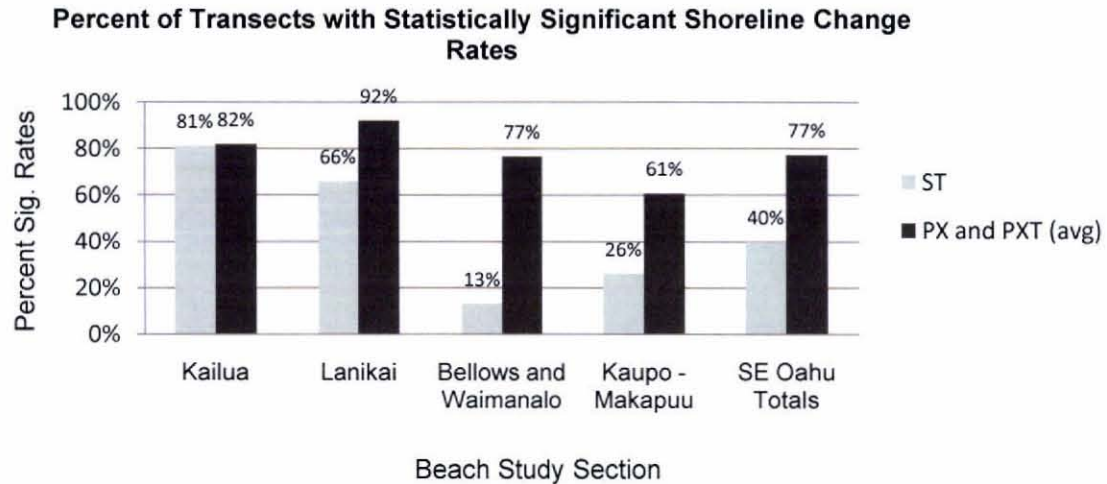

Figure 13. Percent of transects with statistically significant shoreline change rates using the ST method and the basis function (PX and PXT) methods for rate calculation. For this study, statistically significant rates are defined as those with a ± uncertainty that is less than the rate (does not overlap 0 m/yr).

(2) A range of possible models is calculated and the model with the lowest IC score (the most parsimonious model) is determined to be the best model to describe shoreline change at a beach. By utilizing an IC to identify the most parsimonious shoreline change models the PX and PXT methods produce rates that are more statistically defensible than with ST. (3) EXT shoreline change models detect accelerating shoreline change and have the lowest IC scores among all polynomial models and ST in 11 of 14 beach segments. EX shoreline change models have the lowest IC scores among the PX models in 9 of 14 beach segments. Therefore, we conclude that the EX and EXT methods are the preferred methods for calculating shoreline change rates. (4) The PX models provide the best depiction of the long-term change occurring at a beach by using a linear model (no acceleration) throughout the time span of historical shorelines. (5) The PX shoreline change rates are often statistically indistinguishable from the rates calculated by ST. However, the uncertainty of the PX rates is lower than with ST. The uncertainty of the

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PX shoreline change rates averaged along all transects in the southeast Oahu study area is ± 0.05 m/yr versus ± 0.24 m/yr with ST. Future shoreline predictions using PX models also have reduced model uncertainty. Improved confidence in future shoreline predictions will help shoreline managers better plan for future erosion hazards. (6) The PXT shoreline change models provide new information about recent shoreline change by allowing for acceleration in the shoreline change rate with time. Ability to detect accelerating shoreline change is an important advance, as a beach may not change at a constant (linear) rate. The PXT models may identify potential erosion hazards that are not detected by the ST and PX models. Recent accelerated shoreline change or episodic shoreline change detected by the PXT models provide additional valuable information that will help shoreline manages better plan for future erosion hazards.

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