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Historical Shoreline Change, Southeast Oahu, Hawaii; Applying Polynomial Models to Calculate Shoreline Change Rates

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ABSTRACT

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Here we present shoreline change rates for the beaches of southeast Oahu, Hawaii, calculated using recently developed polynomial methods to assist coastal managers in planning for erosion hazards and to provide an example for interpreting results from these new rate calculation methods. The polynomial methods use data from all transects (shoreline measurement locations) on a beach to calculate a rate at any one location along the beach. These methods utilize a polynomial to model alongshore variation in the rates. Models that are linear in time best characterize the trend of the entire time series of historical shorelines. Models that include acceleration (both increasing and decreasing) in their rates provide additional information about shoreline trends and indicate how rates vary with time. The ability to detect accelerating shoreline change is an important advance because beaches may not erode or accrete in a constant (linear) manner. Because they use all the data from a beach, polynomial models calculate rates with reduced uncertainty compared with the previously used single-transect method. An information criterion, a type of model optimization equation, identifies the best shoreline change model for a beach. Polynomial models that use eigenvectors as their basis functions are most often identified as the best shoreline change models.

ADDITIONAL INDEX WORDS: *Coastal erosion, shoreline change, erosion rate, polynomial, PX, PXT, EX, EXT, ST, single-transect, information criterion, Hawaii.*

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 goals of the Oahu Shoreline Study are 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.* (2009) and Genz *et al.* (2009) have developed polynomial methods for calculating shoreline change rates. The new methods may calculate rates that are constant in time or rates that vary with time (acceleration, both increasing and decreasing). The polynomial models without rate acceleration are generally referred to as PX models (for polynomials in the alongshore dimension, X) and the models with rate acceleration are PXT (polynomials in X and time). The PX methods, with a linear fit in time, best characterize the trend of the whole time series of historical shorelines and, therefore, describe the long-term change at a beach. The PXT methods may provide additional information about recent change at a beach and can show how rates may have varied with time. These methods are shown here and in the Frazer *et al.* and Genz *et al.* papers (2009) to produce statistically significant shoreline change rates more often than the commonly used single-transect (ST) method using the same data.

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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 and south, respectively, by basalt Mokapu and Makapuu points (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 to 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.,* 2009).

The beaches in the study area face predominantly toward the northeast. The study area is exposed to trade wind swell from the northeast (typically 1–3 m with 6- to 8-second period) throughout the year (Bodge and Sullivan, 1999). Trade winds are most common during the summer (April to September, 80% of the time) and are less persistent, though still dominant, in winter. Moderately high to very high energy refracted long period swells from the north (typically 1–5 m with 12- to 20-second period) impinge in winter. Significant offshore wave heights of 8 m recur annually (Vitousek and Fletcher, 2008). The fraction of open-ocean wave energy reaching the inner reef and shoreline varies throughout the study area 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 14 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. Between Mokapu Point and Kapoho Point is primarily hard limestone and basalt shoreline (no beach). 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 because 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.

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

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 Lanikai 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. The shallow reef platform extends 2 km offshore to the Mokulua Islands. Wave heights along the Lanikai shoreline are typically small (<1 m) because of refraction and breaking of open-ocean waves on the shallow fringing reef and shores of the offshore Mokulua Islands. The community of Lanikai is built on the foot of the basalt Keolu Hills and on a narrow coastal plain composed of carbonate sands and terrigenous alluvium (Sherrod *et al.,* 2007).

Bellows and Waimanalo Beach

Bellows and Waimanalo Beach is a nearly continuous 6.5 km long beach extending from near Wailea Point to southern Waimanalo. In the northern end of the Bellows shoreline (from Wailea Point 700 m to the south), waves break against a stone revetment at high tide. The beach was lost to erosion in the northern portion by 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 offshore. 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.,* 2009). Bellows Field and the town of Waimanalo are built on a broad plain of 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 needed because of gaps in reliable shoreline data at the stream mouths, though sand is undoubtedly transported around the jetties.

Kaupo and Makapuu Beaches

Between southern Waimanalo and Makapuu beaches are a series of narrow pocket beaches separated by natural and anthropogenic hard shoreline, which divide this study section into eight beach segments for shoreline change analysis. The broad carbonate coastal plain found to the north is absent from most of this section. The steep basalt Koolau cliffs rise within a few hundred meters behind the shoreline. Beaches in the northern two-thirds of the study section are generally narrow (5–20 m). Seawalls front homes along the northern portion of Kaupo Beach. To the south the beaches are backed by a low rock scarp (1–2 m) or by man-made revetments.

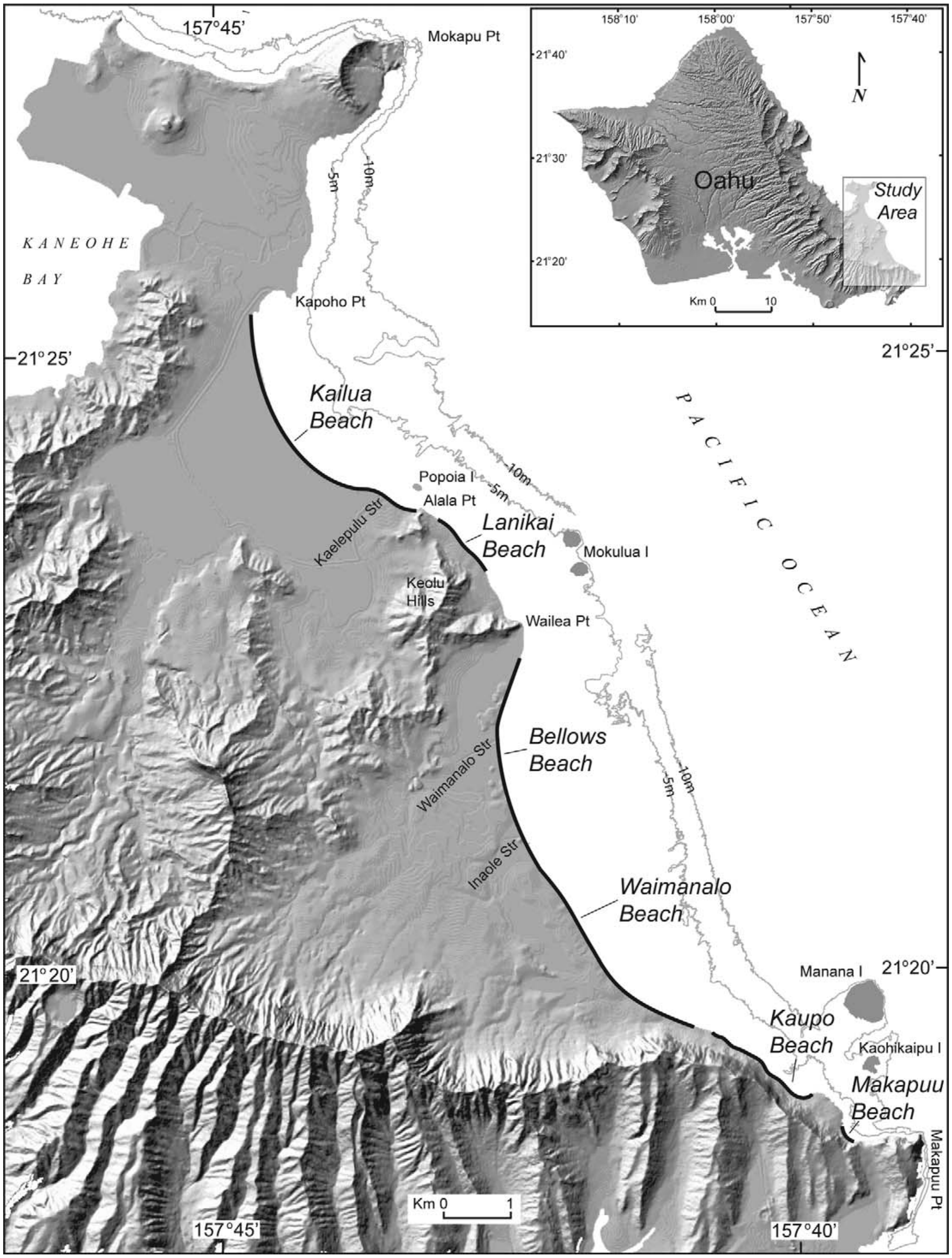

Figure 1. Southeast Oahu study area and beaches. The 5- and 10-m bathymetry contours mark the approximate seaward edge of the nearshore reef platform. The heavy black line along the shore indicates the modern extent of the beach.

Along Kaupo Beach the shallow fringing reef blocks most wave energy. The fringing reef disappears offshore of Makapuu Beach allowing the full brunt of easterly trade wind waves and refracted northerly swells to reach the shoreline there. Makapuu Beach, popular with bodysurfers, is well known for its large shore-breaking waves. Makapuu Beach is wide (50 m) and sediment-rich compared with 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.

PREVIOUS WORK

Hwang (1981) was the first to compile historical shoreline change for beaches of Oahu. His study utilized a vegetation line and a waterline as the shoreline proxies. Historical shoreline positions were measured from aerial photographs along shore-perpendicular transects roughly every 1000 ft (328 m). His 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 waterline through the time span of the study. Annual rates were not calculated from the data. Movement of the vegetation line at Kailua Beach indicated long-term (net) accretion along the whole length of the beach. Historical shorelines at Kailua Beach Park indicated erosion between 1971 and 1978. Long-term accretion was found at most transects at Lanikai Beach, except at the north and south ends. Erosion was also noted at north and south Lanikai for the more recent years of historical shorelines (the beach has since disappeared in these areas). Most transects at Bellows and Waimanalo beaches indicated erosion over the long term. Hwang reports the beach was effectively lost (submerged at high tide) at north Bellows Beach by 1980.

Sea Engineering (1988) produced an update to the Hwang (1981) study with a more recent aerial photo set, while using the same methods and transects. More recent aerial photographs (1988) indicated that long-term accretion continued at all transects at Kailua Beach. Erosion slowed or turned to accretion at Kailua Beach Park from 1980 to 1988. Their study reported extensive areas of erosion and beach loss at north and south Lanikai between 1980 and 1988. However, this erosion was not apparent in their shoreline change measurements because the vegetation line was effectively fixed at the seawalls now fronting homes along the eroded portions of the Lanikai shoreline.

Norcross, Fletcher, and Merrifield (2002) calculated annual shoreline change rates and interannual beach volume change at Kailua Beach. They used orthorectified aerial photographs and NOAA topographic maps (T-sheets) to map a 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 and recent (prior to 1996) 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 modern aerial photograph set (2005) provides more recent shoreline positions 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 (pixel) orthorectified aerial photo mosaics. Only large-scale (typically <0.5 m scanned pixel resolution, media-dependent), vertical, survey-quality air photos with sufficient tonal and color contrast to delineate a high-resolution shoreline proxy were chosen for this study. Orthorectification and mosaicking was performed using PCI Geomatics' Geomatica Orthoengine software (2007) to reduce displacements caused by lens distortion, Earth curvature, refraction, camera tilt, radial distortion, and terrain relief. The orthorectification process typically resulted in root mean square (RMS) positional errors of <2 m based on the misfit of the orthorectification model to a master orthorectified image and a digital elevation model (DEM).

New aerial photography of study beaches was acquired in late 2005. Aircraft position (global positioning system locations) and orientation data (*e.g.,* altitude, pitch, roll, and yaw) were recorded by 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 (5-m horizontal, submeter vertical) DEMs. The orthorectified 2005 photo mosaics serve as master images for the orthorectification of older aerial photographs.

T-sheets are georeferenced using polynomial mathematical models in PCI with RMS errors <4 m. Rectification of T-sheets is also verified by overlaying them on orthophoto mosaics to examine their fit to rocky shorelines and other unchanged geological features also visible in the modern photography. T-sheet shorelines may be discarded if a satisfactory fit to a hard shoreline cannot be achieved and/or if the RMS error grossly understates the misfit. Previous workers have addressed the accuracy of T-sheets (Crowell, Leatherman, and Buckley, 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 extending the time series of historical shoreline position (National Academy of Sciences, 1990).

The beach toe, or base of the foreshore, is digitized from orthophoto 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 short-term (interannual to hourly) 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 a LWM is less prone to spurious position changes typical of other shoreline proxies (*e.g.,* wet–dry line, high water mark) (Norcross, Fletcher, and Merrifield, 2002). The bright white carbonate sands typical of Hawaii beaches often hinder interpretation of water line 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 LWM.

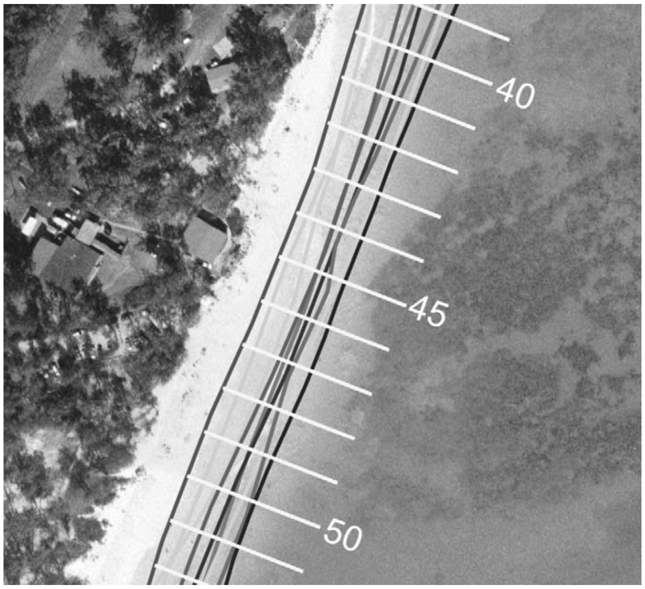

Figure 2. Historical shorelines and shore-perpendicular transects (measurement locations, 20-m spacing) displayed on a portion of a recent aerial photograph.

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 LWM shorelines, the HWM is migrated to a LWM using an offset calculated from measurements in beach profile surveys. HWM and LWM positions have been measured in beach profile surveys collected at nine locations in the study area in summer and winter for 8 years. The offset used to migrate the T-sheet HWM to a LWM is the median distance between HWM and LWM positions measured in the profiles at a beach or a nearby beach with similar littoral characteristics (*e.g.,* wave exposure, beach morphology).

Six to thirteen historical orthomosaics 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 (Figure 2).

Uncertainties in Shoreline Position

Shoreline position is highly variable on short time scales (interannual to hourly) because of tides, storms, and other natural fluctuations. Procedures for mapping historical shorelines introduce additional uncertainties. It is vital that these uncertainties be 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 because of short-term variability (noise). Building on Fletcher *et al.* (2003), Genz *et al.* (2007), and Rooney *et al.* (2003), 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 errors. 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 uncertainties for southeast Oahu historical shorelines are between ±4.5 and ±10.8 m (Table 1). Please note: This is the range of actual uncertainties. No historical shoreline had the highest values for all individual uncertainty sources.

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

Uncertainty Source	± Uncertainty Range (m)
E_d, digitizing error	0.5–5.7
E_p, pixel error, air photos	0.5
E_p, pixel error, T-sheets	3.0
E_s, seasonal error	3.6–6.2
E_r, rectification error	0.6–3.0
E_{td}, tidal error	2.5–3.4
E_{ts}, T-sheet plotting error	5.1
E_{tc}, T-sheet conversion error	3.4–5.7
E_t, total positional error (see text)	4.5–10.8

Digitizing Error, E_d. Only one analyst provides the final digitized shorelines from all orthomosaics 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 orthomosaic, a value from a mosaic with similar attributes (*e.g.,* resolution, photo year) is used. E_d values range from ±0.5 to ±5.7 m.

Pixel Error, E_p. The resolution (pixel size) of our orthomosaics limits our ability to resolve the position of a feature (*e.g.,* LWM) finer than 0.5 m. Therefore, E_p equals ±0.5 m. T-sheets are digitally scanned at a lower resolution than aerial photographs. E_p for T-sheets is ±3 m.

Seasonal Error, E_s. We do not attempt to identify and remove storm shorelines based on *a priori* knowledge of major storm and wave events for two reasons. One, our study (and most shoreline studies) have limited historical shoreline data (*e.g.,* aerial photography years) and removing one or more shorelines comes at the cost of reducing an already limited data set. Two, storms tend to affect shoreline position in a nonuniform manner in an island setting. Instead, we calculate an uncertainty in shoreline position due to seasonal changes (waves and storms). To measure seasonal variability, we surveyed beach profiles summer and winter for 8 years at 33 beaches on Oahu. The seasonal change is the difference between shoreline (LWM) positions along a survey transect between summer and winter. A randomly generated uniform distribution (>10,000 points) is calculated incorporating the standard deviation of the measured seasonal changes. A uniform distribution is an adequate approximation of the annual probability of shoreline positions resulting from seasonal fluctuations because an aerial photo has equal probability of being taken at any time of year. The seasonal error, E_s, is the standard deviation of this randomly generated distribution. For beaches without profile data, an E_s value from a nearby beach with similar littoral characteristics is used. E_s values range from ±3.6 to ±6.2 m.

Rectification Error, E_r. Aerial photographs are orthorectified to reduce displacements caused by lens distortion, Earth curvature, camera tilt, and terrain relief using PCI Orthoengine software. The software calculates an RMS error from the misfit of the orthorectification model to the master orthorectified image and DEM. E_r values range from ±0.6 to ±3.0 m for orthophoto mosaics. T-sheets are georeferenced in PCI Orthoengine using polynomial models. E_r for T-sheets ranges from ±1.4 to ±2.9 m.

Tidal Fluctuation Error, E_{td} (aerial photographs, only). Aerial photographs are obtained without regard to tidal cycles, and the time of day each photo is collected is typically unknown, 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. Hawaii is situated in a microtidal zone of the Pacific Ocean with maximum tidal fluctuations of 1 m. Therefore, tides have less of an effect on shoreline position at Hawaii beaches than at most beaches on the continental United States, where tides typically vary by several meters. Surveys of the horizontal movement of LWMs (beach toe) between a spring low and high tide at three beaches in the study area found that the beach toe migrated horizontally landward 8 to 12 m from low to high tide. 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 LWM positions due to tidal fluctuation in an aerial photograph. 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 ±2.5 to ±3.4 m for this study.

T-Sheet Plotting Error, E_{ts} (T-sheets only). Surveyors working on T-sheets mapped the high water mark (HWM) as a proxy for shoreline position. The T-sheet plotting error is based on Shalowitz's (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 root sum of squares of the three distinct errors, ±5.1 m.

Conversion Error for T-Sheets, E_{tc} (T-sheets only). To compare historical shorelines from T-sheets and aerial photographs, we migrated the surveyed HWM from a T-sheet to a LWM position using data from beach topographic profile surveys. The offset used to migrate the T-sheet HWM to a LWM is the median distance between HWM and LWM positions measured in surveys at a beach. The uncertainty in this conversion, E_{tc}, is the standard deviation of the distances between surveyed HWM and LWM positions. For beaches without profiles, the offset and E_{tc} value from a similar nearby littoral areas is used (Fletcher *et al.,* 2003). E_{tc} values for southeast Oahu range from ±3.4 to ±5.7 m.

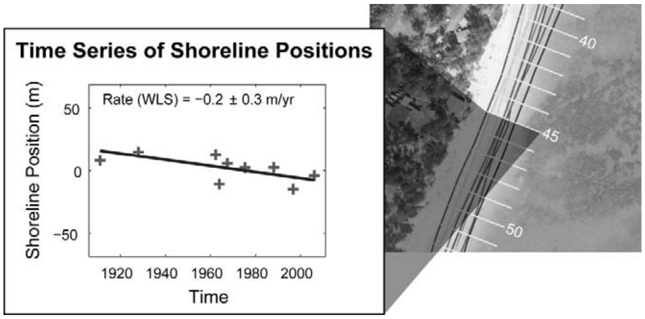

Figure 3. Calculating shoreline change rate using the single-transect (ST) method (weighted least squares regression, WLS). The slope of the line is the annual shoreline change rate.

Calculating Shoreline Change Rates

Single Transect

In previous studies, our research team and other coastal research groups have utilized the ST method to calculate shoreline change rates (*e.g.,* Fletcher *et al.,* 2003; Hapke *et al.,* 2006; Hapke and Reid, 2007; Morton and Miller, 2005; Morton, Miller, and Moore, 2004) (Figure 3). ST calculates a shoreline change rate and rate uncertainty at each transect using various methods to fit a trend line to the time series of historical shoreline positions (*e.g.,* end point rate, average of rates, least squares).

Our group employs weighted least squares regression with the ST method, which accounts for uncertainty in each shoreline position when calculating a trend line (Fletcher *et al.,* 2003; Genz *et al.,* 2007). The weight for each shoreline position is the inverse of the total shoreline positional uncertainty squared (*e.g.,* $w_i = 1/E_t^2$). 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. Model (rate) uncertainties are calculated at the 95% confidence interval.

Recent work by Frazer *et al.* (2009) and Genz *et al.* (2009) identifies a number of shortcomings with the ST method. ST tends to overfit the data by using more mathematical parameters than necessary. Models that overfit data are unparsimonious. 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. The classic example of an unparsimonious model is an $n - 1$ degree polynomial used to fit n noisy data points: The model fit to the data is perfect, but the model is so sensitive to noise that its predictions are usually poor. The problem of overfitting with ST is made worse by limited data (often less than 10 historical shorelines) and high uncertainty (noise) in shoreline positions, both typical of shoreline studies.

Another problem with the ST method is that it treats the

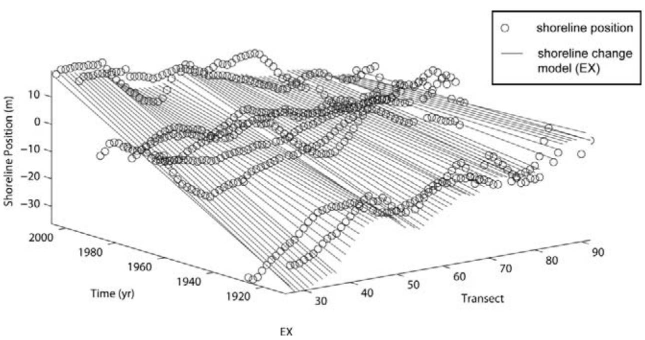

Figure 4. PX (EX) shoreline change model for North Bellows Beach. Rates (slope) vary continuously in the alongshore direction but are constant (linear) in time (no acceleration).

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 independently at each transect. High rate uncertainty can result in rates at many transects that are not statistically significant. For this study we consider a 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

Here we provide a summary of the recently developed polynomial methods to assist the reader in interpreting the results and conclusions in this study. Please refer to Frazer *et al.* (2009) and Genz *et al.* (2009) for more detailed information on these rate calculation methods.

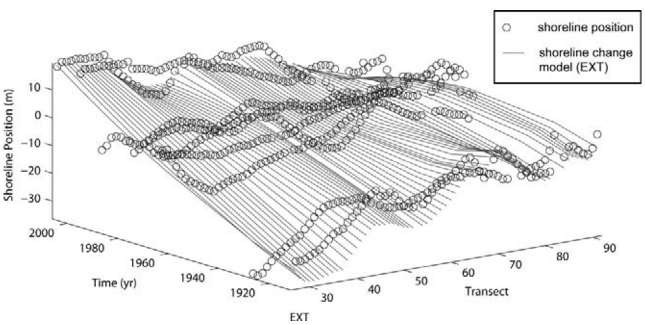

Figure 5. PXT (EXT, includes acceleration in the rate with time) shoreline change model for North Bellows Beach. Rates (slope) vary continuously in the alongshore direction and with time.

The ST method calculates a rate at each transect by fitting a linear trend to shoreline positions plotted in distance along a transect and time. Shoreline change rates vary independently along the shore (from transect to transect) with the ST method. Polynomials can be used to model this variation in shoreline change rates in the alongshore direction. 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 overfitting). In addition, a single polynomial model correctly assumes that the shoreline data from adjacent transects is related (*e.g.,* dependent).

Frazer *et al.* (2009) and Genz *et al.* (2009) have developed polynomial shoreline change rate calculation methods that include the alongshore variation of shoreline change rates in their models. These methods build polynomial models in the alongshore direction using linear combinations of mathematical basis functions. These 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 time and 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 time), in addition to modeling rate variations spatially alongshore. Detecting acceleration in the rates is easier with these methods because of the reduced number of parameters in the model compared with ST. The ± uncertainties with the rates calculated using the polynomial methods are invariably lower than with the ST method because they use 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.

The polynomial methods use one of three types of basis functions, combined in a finite linear combination, to build a model for the alongshore variation of rates. All of the methods use 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 known as "eigenbeaches" utilizes eigenvectors (*i.e.,* principal components) of the shoreline data as the basis functions. The eigenvectors are calculated from the shoreline data using all transects on a beach.

Models that do not include acceleration in their rates 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 in time but vary continuously in the alongshore direction. The rates from the LXT, RXT, and EXT models vary continuously with time as well as in the alongshore dimension, and we refer to these models generally as PXT models (Figure 5). A PXT model that does not identify

Table 2. *Average shoreline change rates and ± uncertainties for southeast Oahu beaches.*

Beach	ST Avg Rate (m/yr)	PX Avg Rate (m/yr)	PXT Avg Rate (m/yr)
Kailua	0.4 ± 0.2	0.4 ± 0.0	0.1 ± 0.1
Lanikai	0.3 ± 0.2	0.3 ± 0.1	0.5 ± 0.1
Bellows and Waimanalo	0.0 ± 0.3	0.0 ± 0.1	0.0 ± 0.1
Kaupo (all)	−0.1 ± 0.1	−0.1 ± 0.1	0.1 ± 0.1
Makapuu	0.0 ± 0.0	0.0 ± n/a	0.0 ± n/a
Southeast Oahu, all	0.2 ± 0.2	0.1 ± 0.1	0.1 ± 0.1

Rate and uncertainty of all transects averaged along the length of the beach.
Negative = erosion; positive = accretion.
n/a = not applicable.

acceleration in the rates at a particular beach reverts to a PX model.

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

With the Matlab codes developed by Frazer *et al.* (2009) and Genz *et al.* (2009), many possible models are calculated for the three basis function model types, with and without acceleration in the rates (LXT, RXT, EXT, LX, RX, EX). The models vary in the number (parameters) of basis functions of each type used in linear combination.

An information criterion (IC) is used to compare the parsimony of the various models. We use a version of Akaike information criterion (AICu) (Burnham and Anderson, 2002; Frazer *et al.,* 2009; Genz *et al.,* 2009). 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 or, more accurately, the lack of it, the IC score is increased for models with a greater number of model parameters and reduced for improved fit to the data. The model with the lowest IC score is the most parsimonious model and is the best model to describe shoreline change at a beach. A model with a rate of 0 m/yr (showing no change) is also given an IC score for comparison with the models with rates.

The IC scores are used to select the best model within each of the six polynomial model types (LXT, RXT, EXT, LX, RX, EX). The ST model and its IC score are calculated for comparison with the polynomial models. The polynomial models invariably produce results with lower IC scores than ST. Rates from the seven model types (including ST) are plotted together for comparison (Figure 6a), providing a qualitative assessment of the agreement of the rates from the various models. The results may be considered more robust if most or all of the models agree in their rates.

We attempt to provide the best information about long-term and more recent shoreline change occurring at a beach to help shoreline managers in planning for future erosion hazards. The favored model among the PX models (*i.e.,* models without rate acceleration) and the PXT models (*i.e.,* models with rate acceleration) are identified using IC scores. The PX models provide a better assessment of the trend of the whole time series of historical shorelines. Inspection of PXT models shows that these models typically capture the trend of the most recent few shorelines. Therefore, we use the PX models to estimate the long-term rate and the PXT models to obtain additional information about more recent shoreline change and how the rates may have varied with time. As with the ST method, bounds for the rates are calculated at the 95% confidence interval.

Using the PXT models we attempt to identify erosion hazards not recognized by the PX models. For example, a beach that is shown to be accreting over the long term (with PX) may still present a future erosion hazard if the PXT model indicates the rate of accretion is slowing (decelerating). Conversely, a beach that is eroding presents less of a future erosion hazard if the PXT model indicates the erosion rate is decelerating. We use the rate acceleration from the PXT models to provide more information about the "fitness" of the littoral sediment budget at a beach. Beaches with decelerating erosion rates and accelerating accretion rates have improving fitness because these beaches present less of a future erosion hazard. Beaches with accelerating erosion rates and decelerating accretion rates have deteriorating fitness because they present a greater future erosion hazard.

Rates presented from the PXT models (*e.g.,* Figure 6) are from time of the most recent shoreline and are referred to as the "present rate." This distinction is important because the rates from the PXT models can vary with time and a rate may be calculated for any point in the time series of historical shorelines. In any case, it is helpful to compare the model fit to individual transect plots (ST) to better understand the shoreline change behavior through time as described by the PX and PXT models.

Shoreline change rates are reported to the nearest tenth of a meter resulting in some rates with uncertainty ±0.0 m/yr. To clarify for the reader, these rates do not have zero uncertainty. This is simply a result of rounding to the nearest tenth of a meter.

RESULTS

Historical Shoreline Change

Kailua Beach

The EX shoreline change model has the lowest IC score among the PX (nonaccelerated) models at both beach study segments at Kailua Beach (separated by Kaelepulu Stream). The EX method calculates erosion rates similar to those of the ST method (Figure 6b–6d), indicating long-term accretion throughout most of Kailua Beach. However, the average rate uncertainty is reduced with the EX model compared with the ST model (±0.1 m/yr *vs.* ±0.2 m/yr, respectively) (Table 2), resulting in a greater percentage of transects that have significant rates with the EX model (Figure 7).

In the segment south of Kaelepulu Stream, the EX model shows no long-term change, in contrast to results from the

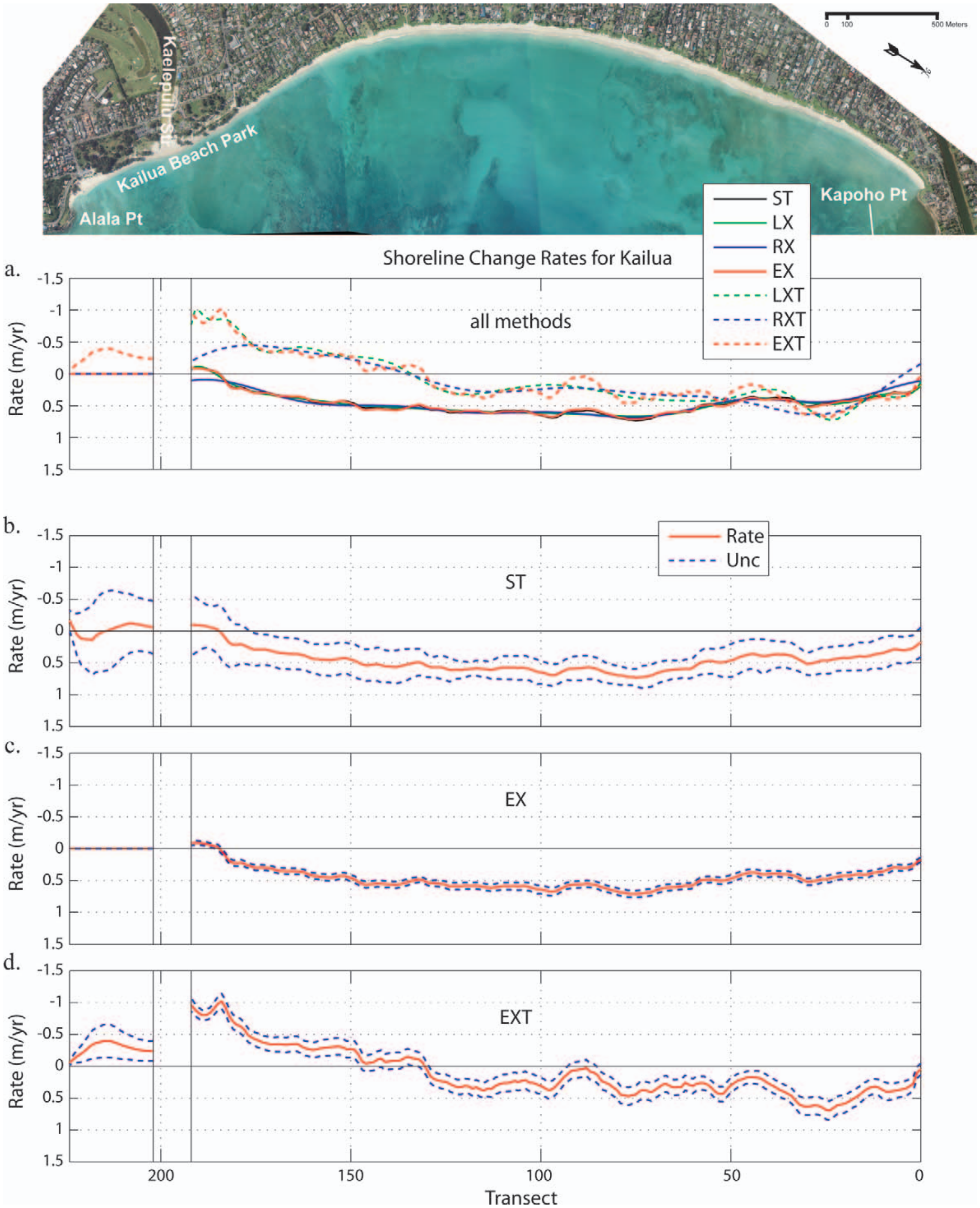

Figure 6. Shoreline change rates (m/yr) at Kailua Beach, 1928–2005. Negative rates indicate annual erosion. (a) Rates from ST, PX, and PXT models (±uncertainties not shown). (b) ST rates with ±uncertainties. (c) EX (lowest IC score among the PX models) rates with ±uncertainties. (d) EXT (lowest IC score among the PXT models) rates with ±uncertainties.

ST model and previous studies. The selection of an EX model (based on IC scores) that shows no significant change may be interpreted two ways. One, the historical shorelines data for this portion of beach is too highly variable (noisy) to calculate a statistically significant long-term trend. Or, two, this segment of beach is stable in the long term, and any erosion or accretion is episodic within the time frame of the study. The ST method (which always produces a model with rates) has higher rate uncertainties in this segment, further suggesting a highly variable data set. High uncertainty with the ST mod-

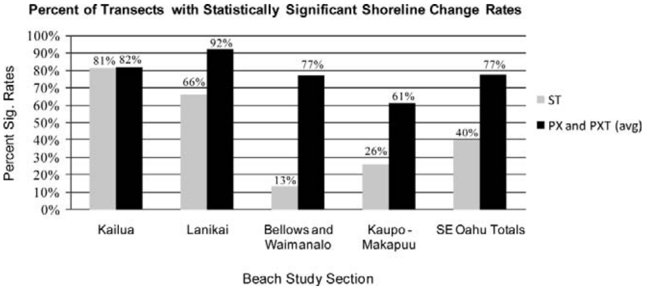

Figure 7. Percentage of transects with statistically significant shoreline change rates using the ST method and PX and PXT methods. Statistically significant rates are those with a ±uncertainty that does not overlap a rate of 0 m/yr.

el results in insignificant rates (± uncertainties overlap 0 m/yr) at all transects, essentially in agreement with the EX model results showing no long-term change.

EXT has the lowest IC score among the PXT models. In contrast to ST and EX, EXT estimates recent erosion at Kailua Beach Park with rates up to −1.0 ± 0.1 m/yr. EXT also indicates that the extent of erosion may be spreading north from Kailua Beach Park toward central Kailua. Recent beach erosion (2006–2008) has cut a scarp and undermined trees in the beachfront dunes at Kailua Beach Park. Looking at the movement of historical shorelines in an individual transect plot from Kailua Beach Park, we see a previous episode of accretion from 1947 to 1967 and erosion from 1967 to 1978 (Figure 8). According to the EXT model, erosion rates at Kailua Beach Park have been accelerating since the late 1960s or early 1970s. Inspection of the shoreline data in the transect plots shows that the trend toward erosion probably began more recently, beginning with the 1988 or 1996 historical shoreline.

EXT results for Kailua Beach provide a warning of potential erosion hazards not indicated by the EX model. EXT results indicate recent accelerating erosion at 39% of transects (all in the south). EXT also shows recent decelerating accretion at 48% of transects (in the center area). These transects could become erosive if the trend of deceleration continues. Therefore, based on EXT results, the fitness of the littoral sediment budget along most of Kailua Beach (87% of transects) has recently deteriorated.

Lanikai

At Lanikai, 1229 m of beach were lost to erosion in the time span of this study (306 m at north Lanikai, 923 m at south Lanikai) (Figures 9a–9c). Present-day Lanikai Beach is bounded on both ends by extensive seawalls constructed in areas where the beach has been lost to erosion. Aerial photographs show the beach at north Lanikai was completely 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 in the north-central portion of Lanikai Beach. Accretion ended and erosion took over in the late 1970s and much of the beach was lost by 1989. We calculate shoreline change rates only for the remaining portion of Lanikai Beach.

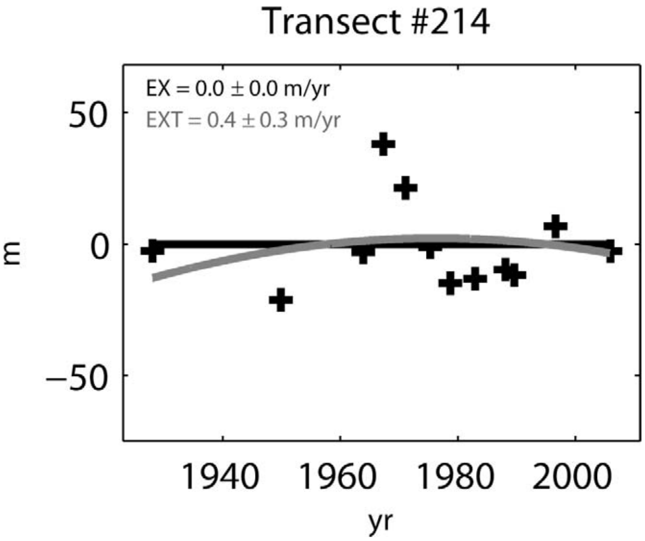

Figure 8. Individual transect plot (transect 214) from Kailua Beach Park showing the fit of the EX and EXT model. Note apparent previous episode of accretion (1949–1967) and erosion (1967–1978).

At Lanikai, the EX model has the lowest IC score among the PX models. EX measures long-term accretion at all transects at Lanikai Beach, except for a small area of erosion at the northern end of the beach. EX calculates the highest accretion rates (up to 0.8 ± 0.1 m/yr) aligned with the middle of the accretion point in the north central portion of the beach.

The EXT model has the lowest IC score among the PXT models at Lanikai Beach. Similar to EX, the EXT model calculates the highest accretion rates (up to 1.6 ± 0.2 m/yr) at the center of the accretion point in north central Lanikai Beach. The EXT model indicates accelerating erosion at the north end of Lanikai Beach. Based on the EXT model, the central portion of Lanikai Beach began undergoing accelerating accretion prior to 1949 (Figure 10). The EXT model at the southernmost transects indicates that accretion is slowing in this area and may be turning to accelerating erosion. Recent beach profile surveys have shown that the extent of beach loss in south Lanikai continues to expand to the north. All of Lanikai Beach could eventually disappear if the pattern of encroaching beach loss continues.

Bellows and Waimanalo Beaches

At north Bellows (Figure 11), the northern end (690 m) of the beach was lost to erosion prior to 1996. Waves break against a stone revetment at high tide in this area. At the remaining portion of north Bellows Beach (Wailea Point to Waimanalo Stream) and central Bellows Beach (Waimanalo Stream to Inaole Stream), the EX model has the lowest IC score among the PX models. At south Bellows and Waimanalo

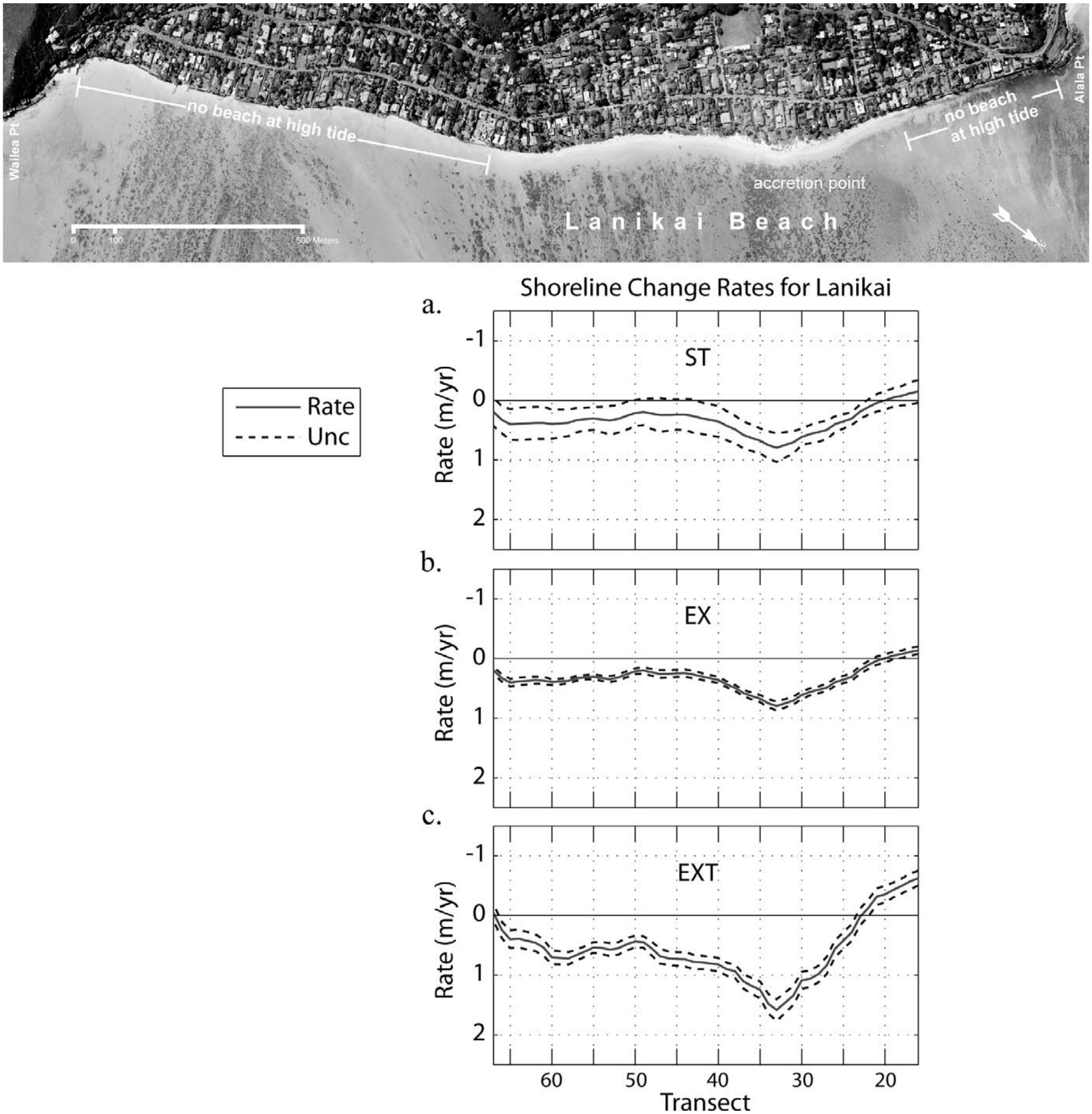

Figure 9. Shoreline change rates (m/yr) at Lanikai Beach, 1911–2005. Negative rates indicate annual erosion. (a) ST rates with ±uncertainties. (b) EX (lowest IC score among the PX models) rates with ±uncertainties. (c) EXT (lowest IC score among the PXT models) rates with ±uncertainties.

beaches (Inaole Stream to Kaiona Beach Park) (Figure 12), the LX model has the lowest IC score among the PX models.

The EX model indicates long-term erosion at nearly all transects at north Bellows with the highest erosion rates at the northern end of the beach (up to −0.4 ± 0.1 m/yr). The EX model at central Bellows indicates long-term erosion in the northern half of the beach study segment and long-term accretion in much of the southern half of the segment. At south Bellows and Waimanalo the LX model indicates long-term accretion in the northern half of this beach study segment and an area of long-term erosion (up to −0.4 ± 0.1 m/yr) in the south at Kaiona Beach Park. Again, the alongshore pattern of shoreline change rates from PX models is similar to rates from the ST model. However, the PX models result in a higher per-

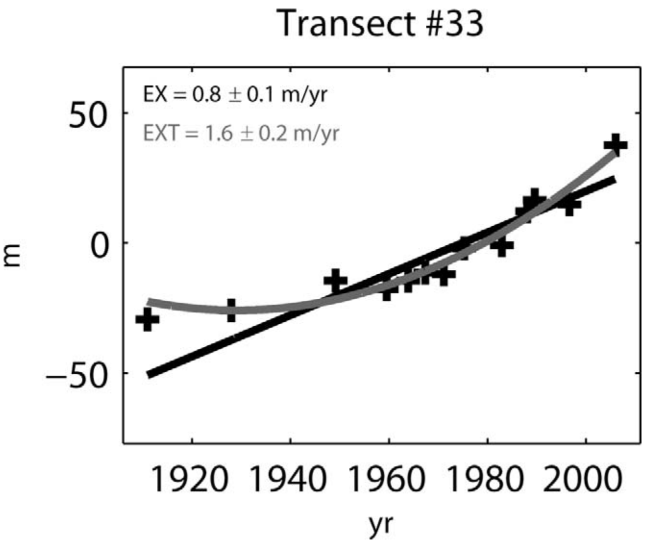

Figure 10. Individual transect plot (transect 33) from north-central Lanikai Beach. The EXT model results indicate accelerating accretion in this area beginning prior to 1949.

centage of transects with significant rates because the rate uncertainties are reduced compared with ST results.

EXT has the lowest IC scores among the PXT models in the three study segments at Bellows and Waimanalo beaches. In the northern end of Bellows Beach (area of beach loss) the EXT model indicates accelerating erosion throughout the time series of historical shorelines (Figure 13), with the highest rates at the north end of the beach adjacent to the revetments (up to −0.7 ± 0.2 m/yr). The extent of recent erosion indicated by the EXT model in northern Bellows is similar to the extent of erosion indicated by the ST and EX models. Agreement among the three models in this area further supports the indication that the remaining beach at north Bellows is threatened by continued erosion and potential beach loss. The EXT model indicates accelerating accretion in the south of the north Bellows segment (against Waimanalo Stream jetty), suggesting that eroded sediment is being transported from the north end of the beach to the south and is accumulating against the jetty.

In the south Bellows and Waimanalo segment, the EXT model indicates a pattern of recent erosion that is significantly different than indicated by the ST and LX models over the long term. At the south end of Bellows Field Beach Park, the EXT model finds an area of recent erosion with rates up to −0.7 ± 0.1 m/yr. Recent (1994–2007) biannual beach profile surveys near the middle of this erosive area (as modeled by EXT) do not indicate significant erosion in this area. The EXT model indicates recent accretion in the south of Waimanalo Beach near Waimanalo Bay Beach Park. Beach profile surveys (1994–2007) at Waimanalo Bay Beach Park have shown recent erosion, evidenced by a steep scarp in the beachfront dunes causing undermining of large trees on the dunes. The EXT models and beach surveys at south Bellows and Waimanalo provide a warning that this beach may be subject to episodic erosion even if the beach is relatively stable over the long term (as modeled by ST and LX).

The EXT models indicate recent accelerating erosion at 43% of transects and recent decelerating accretion at 14% of transects. Thus, the EXT models indicate deteriorating fitness of the littoral sediment budget at 57% of transects at Bellows and Waimanalo beaches. The areas of deteriorating fitness are in the northern portion of each the three beach study segments, whereas the areas of improving fitness (43% of transects) are in the south of each study segment.

Kaupo and Makapuu Beaches

At Kaupo and Makapuu beaches the ST models and PX find a similar alongshore pattern of shoreline change for all beaches, except at Kaupo Beach Park (Figures 14a–14c). Other than at Kaupo Beach Park, the ST and PX models with the lowest IC scores estimate erosion rates under 0.3 m/yr or find no significant change. The rate uncertainty is improved with PX models compared with ST models, resulting in significant rates at a greater percentage of transects. The PXT models with the lowest IC scores detect recent accretion or find no significant change at all beaches, except Kaupo Beach Park.

At Kaupo Beach Park the RX model has the lowest IC score among the PX models. Here, the RX model finds long-term erosion (up to −1.7 ± 0.2 m/yr) at the southern end of the beach and long-term accretion at the northern end of the beach (up to 1.2 ± 0.1 m/yr). The LXT model, with the lowest IC score among the PXT models, indicates a pattern of shoreline change rates at this beach that is similar to the results of the RX model, with erosion in the south and accretion in the north. However, the results of the RX and LXT models do not agree with the results of the ST, EX, nor EXT models at Kaupo Beach Park, bringing into question the validity of the RX and LXT models at this beach. Nonetheless, the results of the RX and LXT models here point out that Kaupo Beach Park should be monitored closely for future erosion hazards.

At Makapuu Beach the PX and PXT models indicating no significant change (rates = 0 m/yr) have the lowest IC scores. The LX model (0 m/yr) has the lowest IC score among the PX models. The LXT model reverts to the LX model (0 m/yr and finds no acceleration) and has the lowest IC score among the PXT models. The ST model rates at Makapuu are statistically insignificant at all transects. Examination of the historical shorelines shows high variability in their position throughout the time span of the study (Figure 15). 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 calculate a long-term trend.

DISCUSSION

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 11 of 14 beach segments. EX and EXT may be calculating models with better fit to the data and fewer parameters be-

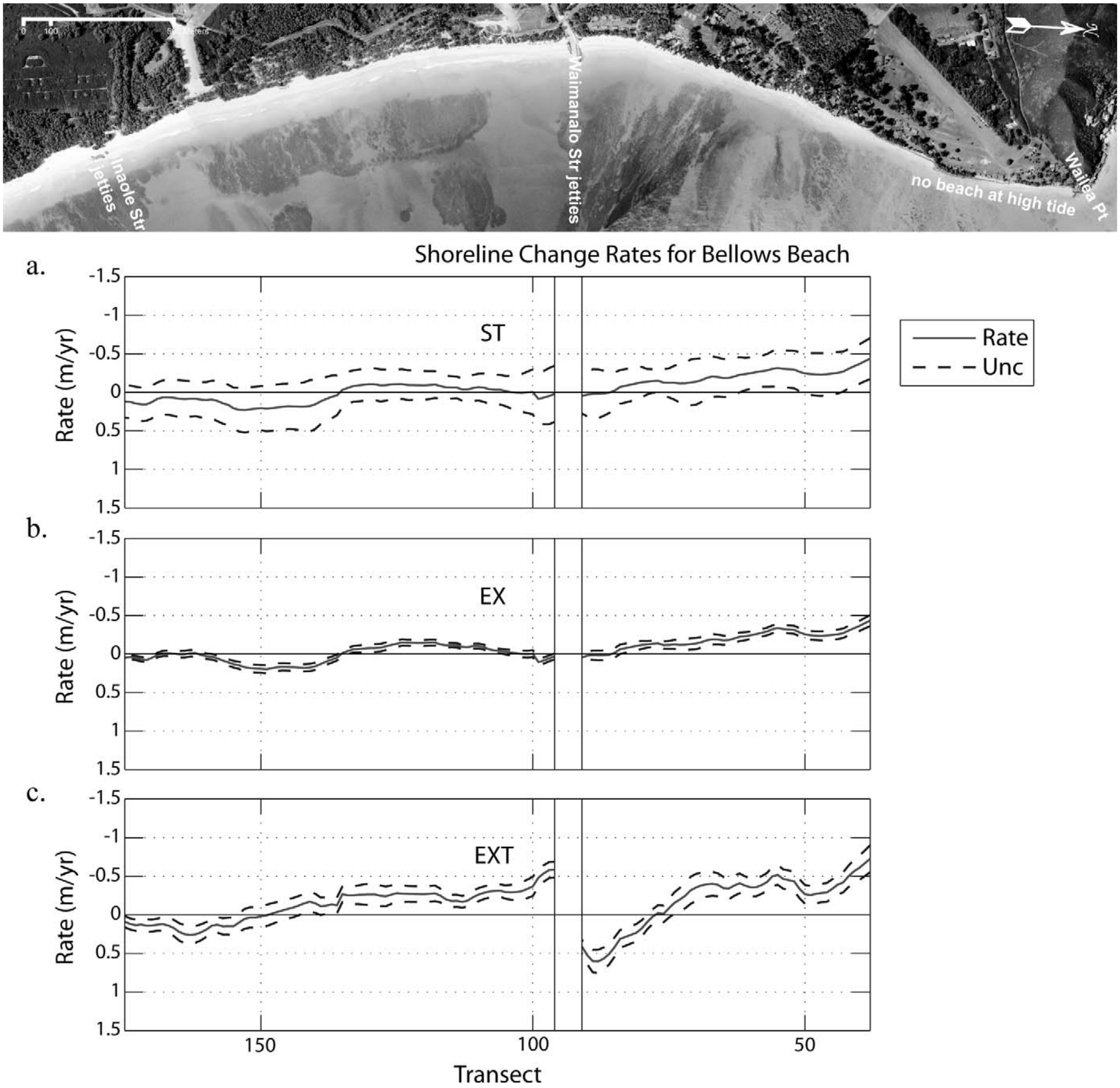

Figure 11. Shoreline change rates (m/yr) at Bellows Beach, 1911–2005. Negative rates indicate annual erosion. (a) ST rates with ±uncertainties. Note the high number of transects with insignificant rates (±rate uncertainties overlap 0 m/yr) with ST at this beach. (b) EX (lowest IC score among the PX models) rates with ±uncertainties. (c) EXT (lowest IC score among the PXT models) rates with ±uncertainties.

cause the alongshore polynomial model is composed of basis functions that are derived from the shoreline data itself. The other PX and PXT methods (LX, RX, LXT, RXT), which attempt to fit a series of predetermined mathematical basis functions to the data, often require a greater number of these basis functions (parameters) to produce a satisfactory fit to the data, resulting in higher IC scores. This may be especially true at beaches with one or more sudden sign changes in the shoreline change rates along the shore (*e.g.,* erosion to accretion from one transect to the next). The LX and RX models may fit the shoreline data better where the rates vary smoothly alongshore (*e.g.,* South Bellows and Waimanalo Beach).

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

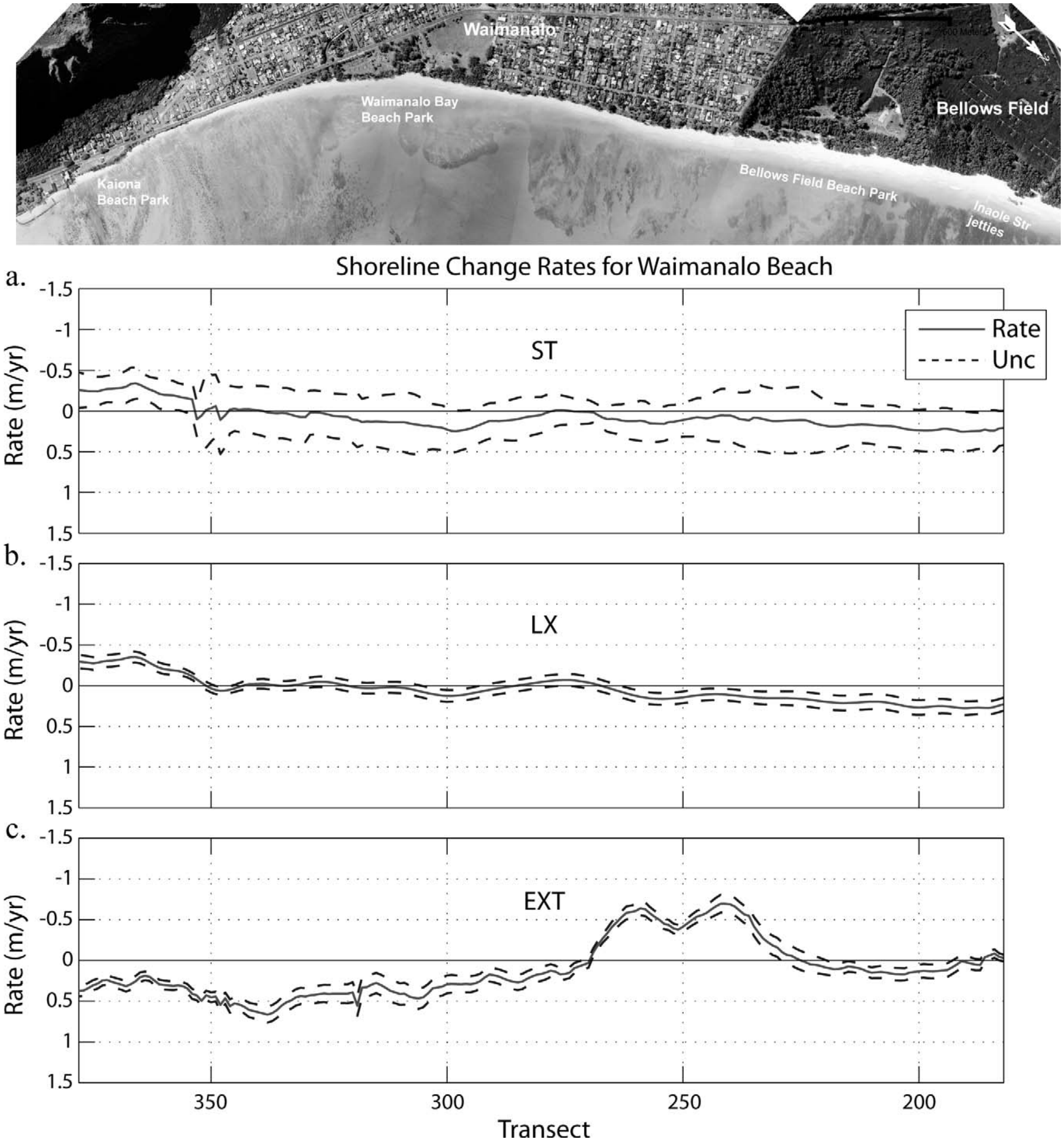

Figure 12. Shoreline change rates (m/yr) at south Bellows and Waimanalo beaches, 1911–2005. Negative rates indicate annual erosion. (a) ST rates with ±uncertainties. Note the high number of transects with insignificant rates (±rate uncertainties overlap 0 m/yr) with ST at this beach. (b) LX (lowest IC score among the PX models) rates with ±uncertainties. (c) EXT (lowest IC score among the PXT models) rates with ±uncertainties.

linear combinations of sine and cosine functions. The temporal dynamics of shoreline change are unknown. Because they are calculated from the beach data, eigenvectors (in EX and EXT) may provide a better description of the unknown dynamics of change at a beach than a model with predetermined basis functions (*e.g.,* LX and RX).

Whether the EX and EXT methods actually produce better shoreline change models at most beaches is an area of on-

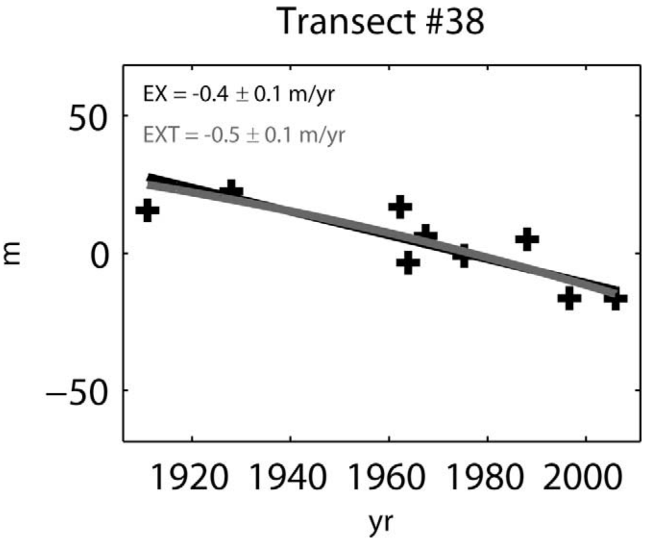

Figure 13. Individual transect plot (transect 38) from northern Bellows Beach. The EXT model results indicate accelerating erosion throughout the time series of historical shorelines in this area.

going research. Further research could include comparison of predictions of the most recent shoreline(s) in truncated shoreline data sets by the various PX and PXT models, as in Genz *et al.* (2009). Updates to this study using modern 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 of future shoreline positions made by the models in this study.

Inspection of the PXT models from this study in individual transect plots shows that the most recent trend of accelerating or decelerating rates, as indicated by these models, is often less than 50 years. In other words, the present rates (*i.e.,* rates from the most recent shoreline time) from the PXT models are strongly influenced by the trend of the last several shorelines. Thus, the PXT models are better suited for describing the recent change at a beach and for showing how the rates may have changed throughout the time series of shorelines. The PX models, with a linear fit to the entire time series of shoreline data, provide a better characterization of the long-term change occurring at a beach.

In three 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 showing no change may be interpreted two ways. One, the historical shoreline data are not adequately configured (not enough shorelines, too much positional uncertainty) to calculate statistically defensible shoreline change rates. Or, two, the beach is stable over the time span of the study. For the purpose of shoreline management, a model without rates provides statistically supported evidence that a beach has not changed significantly in the time span of the study. Thus, a result showing no significant change may be as valuable for erosion hazard planning as a model that indicates significant erosion or accretion.

Here we provide the rates and uncertainties from the PX and PXT model with the lowest IC score. However, the specific goals of an agency's coastal management plan may influence planners to choose another of the parsimonious PX or PXT models for erosion hazard planning. It is important that coastal scientists and coastal managers are clear on what question is being asked regarding shoreline change at a beach before reporting shoreline change results. Are we interested in long-term change or more recent change? Are we looking for the worst-case scenario or the most likely scenario? For example, an agency may determine that the most conservative or safest course is to select the model that calculates the highest erosion rates and predicts the greatest erosion hazard. Or, coastal planners may use results from several shoreline change rate calculation methods to present a range of possible future shoreline change scenarios. Ultimately, the credibility of erosion rates and erosion hazard forecasts is improved if the results from various shoreline change rate calculation methods agree.

Time series of historical shorelines in this study span nearly 100 years. As discussed previously, the recent trend in PXT models often illustrates an erosion or accretion trend of the most recent shorelines (<50 years). Littoral processes along most Hawaiian beaches are driven primarily by waves from frequent easterly trade winds and powerful seasonal swells (Vitousek and Fletcher, 2008). It is possible that some PXT models are detecting shorter term (*e.g.,* decadal) fluctuations in shoreline position, as opposed to chronic, *i.e.,* long-term, shoreline change. An example of this may be the most recent episode of accelerated erosion as modeled by PXT at Kailua Beach Park. There we see at least one other prior episode of erosion and accretion in the movement of the historical shoreline positions. The PXT models (and the PX models) cannot identify multiple erosion and accretion events in a data set. Doing so would require fitting more complex models (*e.g.,* a sinusoid) to a limited shoreline data set, leading to overfitting of the data. In addition, the PXT models are limited by their inability to model the inevitable deceleration that should follow any period of accelerated shoreline change, such as seen at Kailua Beach Park. Theoretically, a rate that continues to accelerate into the future will eventually become unrealistically high. Therefore, the PXT models may not be appropriate for forecasting future shoreline positions in the long term (*e.g.,* 50 years) at most beaches.

Because the PXT methods can detect acceleration, these methods have the prospect of detecting accelerating shoreline change that should be expected with accelerating sea-level rise from global temperature increase (Church and White, 2006). We will attempt to investigate shoreline change due to sea-level rise in our continued studies of all the beaches in the Hawaiian Islands with the PX and PXT methods. Thus far, it appears shoreline change at Hawaii beaches is dominated by the dynamics of the local littoral sediment budget. If Hawaii beaches are changing because of sea-level rise, it appears difficult, at present, to detect this change signal in the background of typically noisy historical shoreline data.

CONCLUSIONS

The EX and EXT methods are the preferred methods for calculating shoreline change rates from historical shoreline

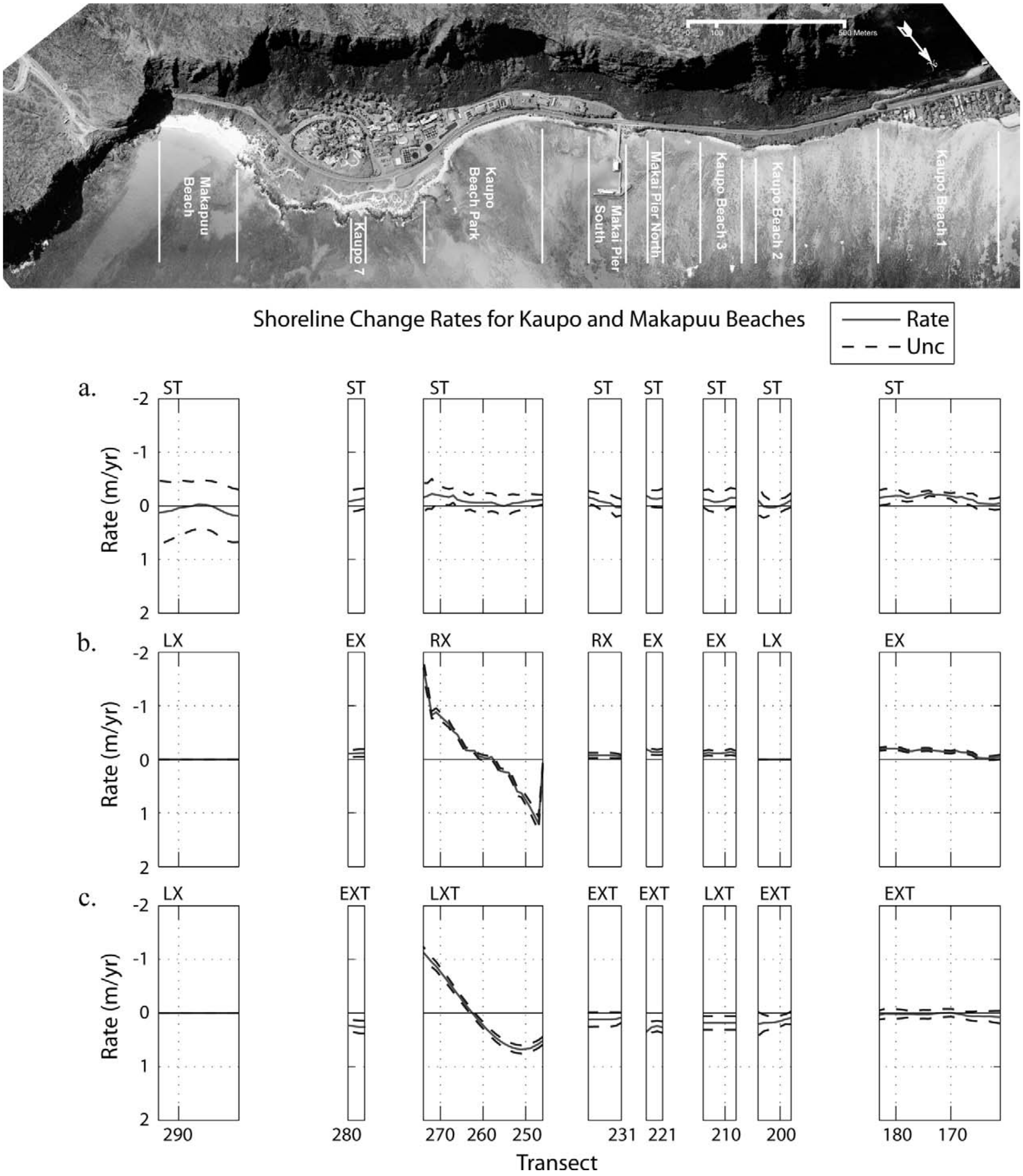

Figure 14. Shoreline change rates (m/yr) at Kaupo and Makapuu beaches, 1911–2005. Negative rates indicate annual erosion. (a) ST rates with ±uncertainties. (b) Rates and ±uncertainties calculated by PX model with lowest IC score in each study segment. (c) Rates and ±uncertainties calculated by PXT model with lowest IC score in each study segment.

data. The most parsimonious model is selected from a range of models utilizing IC. The EX and EXT models have the lowest IC scores among the PX and PXT models (with and without rate acceleration) at most southeast Oahu beaches.

The PX method, with a linear fit to the time series of historical shoreline positions, provides a better characterization of the change that has occurred throughout the time series of shorelines (*i.e.,* long-term). The PXT method, which is able to detect acceleration in the shoreline change rates, may provide additional information about recent change occurring at

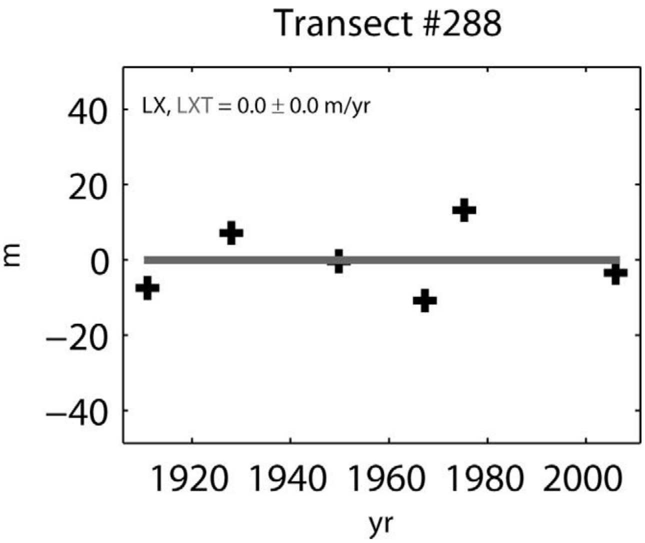

Figure 15. Individual transect plot (transect 288) from Makapuu Beach. The LX and LXT models (with the lowest IC scores among the PX and PXT models) find no significant change at Makapuu Beach, likely a result of the high temporal variability of the shoreline position here.

a beach and can show how the rates may have varied with time. Ability to detect accelerating shoreline change is an important advance because a beach may not change at a constant (linear) rate. The PXT models may identify potential erosion hazards not detected by the ST and PX models. Recent accelerated shoreline change detected by the PXT models provides additional valuable information that will help shoreline managers better plan for future erosion hazards.

The PX and PXT methods calculate shoreline change rates from an improved data set, compared with the ST method, by utilizing data from all shoreline transects on a beach. Therefore, the PX and PXT methods invariably calculate rates with lower uncertainties than the ST method. The result is a greater percentage of transects with significant rates and increased confidence in results from these models. Improved confidence in results from shoreline change studies will help shoreline managers to make better-informed decisions to protect against future erosion hazards.

In the time span of this study (1911–2005) nearly 2 km (1919 m) of beach were lost to erosion along the southeast Oahu shoreline, most notably at Lanikai and North Bellows. Calculating shoreline change rates with the PX methods indicates areas of significant long-term erosion at northern and central Bellows Beach and in the south of Waimanalo Beach. The PX methods indicate long-term accretion along most of Kailua Beach and Lanikai Beach. The PXT methods detect recent accelerating erosion at southern Kailua Beach, northern Bellows Beach, and at Kaupo Beach Park.

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