MEASURING HISTORICAL SHORELINE CHANGE, APPLYING NEW POLYNOMIAL CHANGE MODELS: SOUTHEAST OAHU, HAWAII

Bradley M. Romine, Charles H. Fletcher, Ayesha S. Genz, L. Neil Frazer, Mathew M. Barbee, Siang-Chyn Lim, Mathew Dyer, Amanda Vinson

Department of Geology and Geophysics
School of Ocean and Earth Science and Technology
University of Hawaii
1680 East West Road
Honolulu, HI 96822, U.S.A
romine@hawaii.edu
fletcher@soest.hawaii.edu

Abstract: Digital aerial photo mosaics and NOAA topographic survey charts (t-sheets) are used to map historical shoreline positions on southeast Oahu, Hawaii. The new PX (Polynomial in alongshore X) and PXT (Polynomial in X and Time) shoreline change rate methods are applied to calculate shoreline change rates from the time series of historical shoreline positions. These new methods utilize all historical shoreline data from a beach to calculate shoreline change rates and can find acceleration in the shoreline change rate with time. The methods are shown here and in previous works to produce more parsimonious models and more statistically significant and defensible rates than the previously used ST (Single-Transect) shoreline change rate calculation method. The ability to model acceleration in shoreline change rates with time provides insight into shoreline change processes, which was previously theoretical or observed in only small-scale studies. An overview of the methods is presented along with results from shoreline change analysis of four beach study sites on the southeast Oahu, Hawaii, shoreline.

INTRODUCTION

Beach loss due to chronic erosion has direct consequences for Hawaii's tourist-based economy and threatens private and public property. Within the last century many beaches on Oahu have narrowed or been completely lost to coastal erosion (Hwang 1981; Sea Engineering 1988; Fletcher, *et al*. 1997). Coastal development and sea-level rise due to climate change threaten Oahu's remaining beaches. With the goal of helping to protect southeast Oahu's beaches through science-based land use planning and regulation, historical shorelines are mapped from aerial photographs and survey charts and shoreline change rates are calculated.

The recently developed PX (Polynomial in alongshore X) and PXT (Polynomial X and Time) shoreline change methods are employed in modeling shoreline change. These new methods often produce statistically significant change rates (statistically discernible from a rate of 0 m/yr) where the previously used ST (Single-Transect) method cannot (Frazer, *et al*. in press; Genz, *et al*. in press). PXT can model acceleration in the shoreline change rate – an important advance, as beaches may not erode or accrete at a constant (linear) rate. Here we report on the overview of the PX and PXT shoreline change rate methods and present results from the applications of these methods on four beach sites on the southeast Oahu, Hawaii, shoreline (Figure 1).
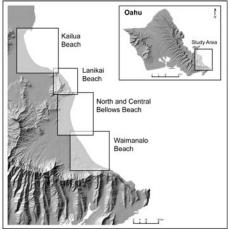

Figure 1. Southeast Oahu beach study sites.

METHODS
MAPPING HISTORICAL SHORELINES

For this study we adhere closely to the methods of Fletcher, *et al*. (2003) used in mapping historical shorelines on Maui, Hawaii. A combination of NOAA NOS topographic maps (t-sheets) and high-resolution (0.5 m) vertical aerial photo mosaics are used to determine historical shoreline positions (low water mark) and calculate long-term erosion rates.

Aerial photographs are orthorectified and mosaicked, usually achieving root mean square (RMS) positional error < 2 m. T-sheets are rectified through various

transformations in PCI with RMS errors < 4 m. Rectification of t-sheets is also verified by their fit to hard rocky shoreline and other typically unchanging geological features in aerial photo mosaics. Previous workers have addressed the accuracy of t-sheets (Shalowitz 1964; Crowell, *et al*. 1991; Daniels and Huxford 2001) 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 (NAS 1990). Historical shoreline positions are digitized in a GIS from the rectified images.

CALCULATING SHORELINE CHANGE RATES

Previous studies (e.g., Norcross, *et al*. 2002; Maui Shoreline Atlas 2003; Hapke 2006) have utilized the ST (Single-Transect) method to calculate shoreline change rates from a time series of historical shoreline positions. ST, employed in recent studies (Fletcher, *et al*. 2003), calculates a shoreline change rate and uncertainty at each shoreline transect using re-weighted weighted least squares linear regression. This method accounts for the total positional uncertainty, *Et,* at each historical shoreline position, excludes outliers, and fits a trend line to the time series of historical shoreline positions (Fletcher, *et al*. 2003; Genz, *et al*. 2007). The weight for each shoreline position is equal to the inverse of the uncertainty squared ($w_i = 1/Et^2$). Shoreline positions with higher uncertainty will have less influence on the trend line than data with smaller uncertainty. The slope of the line is the shoreline change rate.

Recent work by Frazer, *et al*. (in press) and Genz, *et al*. (in press) identify a number of problems with the ST method. ST often produces unparsimonious models, i.e., it tends to over-fit the data by using more mathematical parameters than necessary to model the change at a beach since it assumes adjacent transects are independent. In theory, adjacent transects should tell a similar story about the change occurring at a beach because beach positions share sand along the shore. Instead, ST assumes shoreline positions at a transect are independent of those at other transects, treating the beach as if it were a set of blocks centered at each transect that move independently of each other. In addition, ST produces many rates that are not statistically significant, i.e., the rates are statistically indistinguishable from a rate of 0.0 m/yr. Lastly, short-term fluctuations in the beach due to seasonal and tidal changes (high complexity) and a lack of historical shoreline data (poor sampling) can mask the long-term trend when attempting to calculate a change rate from a single transect's data.

To address these problems, Frazer, *et al*. (in press) and Genz, *et al*. (in press) developed the PX (Polynomial in alongshore X) method for calculating shoreline change rates to produce more meaningful, i.e., statistically significant and defensible, shoreline change rates. PX combines shoreline positions and uncertainties from all transects on a beach and models shoreline change for the entire length of beach using weighted least squares polynomial regression. Like the ST method, shoreline uncertainties are propagated to the calculated rate uncertainty using PX. Exponential decay functions are derived from the shoreline data and included in calculation of the shoreline change model to describe the correlation of data from adjacent transects.

The PX shoreline change models produce rates that vary continuously in the alongshore direction. These models employ information from the entire beach to model the rate at any one location.

An advancement of the PX method, called PXT (Polynomial in X and Time) method, was developed to model shoreline change rates that vary continuously in the alongshore direction <u>and</u> with time (Figure 2). For sufficient data, PXT can find acceleration in the shoreline change rate – an important advance, as some beaches may not erode or accrete at a constant (linear) rate. The PX and PXT methods often give meaningful, i.e., statistically defensible, change rates for beaches where ST cannot (Table 2).
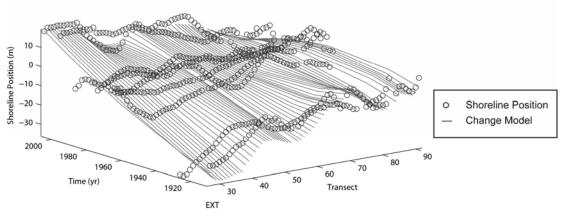

Figure 2. PXT polynomial shoreline change model for North Bellows Beach. Shoreline change rates (slope in shoreline position and time) vary in alongshore direction and with time.

Table 2. Percent of transects with statistically significant rates (statistically distinguishable from 0 m/yr). *Denotes a specific form of the PX model: LX: Legendre polynomials; RX: trigonometric functions; EX: eigenvectors of the shoreline position data; LXT, RXT, EXT: specific forms of the PXT model.

rate method	Kailua	Lanikai	Bellows and Waimanalo	Totals
ST	81%	66%	13%	42%
LX*	85%	91%	71%	78%
RX*	90%	91%	74%	81%
EX*	89%	94%	85%	87%
LXT*	65%	89%	71%	70%
RXT*	74%	87%	72%	74%
EXT*	90%	94%	88%	89%

The PX and PXT methods calculate a range of possible models to describe shoreline change, which vary in type of basis function and number of parameters. Three basis functions are tested: Legendre polynomials (LX), trigonometric functions (sines and cosines, RX), and principal components (eigenvectors, EX) of the shoreline data. For PXT, in which the rate of shoreline change varies through time (acceleration or deceleration), the models are referred to as LXT, RXT, and EXT. For a transect

where acceleration or deceleration is identified, the reported shoreline change rates and uncertainties are from the most recent shoreline position, i.e. the "present" rate. However, a rate may be calculated from the model at any point in the time series.

IC (objective Information Criteria, we use Akaike method) is used to find the optimal polynomial for each of the six different model types (LX, RX, EX, LXT, RXT, EXT) and in a similar manner identifies the overall "best" shoreline change model among all models tested. Various IC's have been tested and may be employed in comparing shoreline change models (Frazer, *et al*. in press). In general, IC's provide an optimal compromise between limited number of model parameters (parsimony) and goodness of fit (residual errors). The IC formula calculates a relative score for each model, which increases as the number of model parameters increases and decreases as the residual errors decrease. The model with the lowest IC score is determined to be the best model to describe the shoreline change at a beach. IC may choose a model with no change (0 m/yr or "null model") if it is determined to be a better fit than models with parameters (showing shoreline change).

RESULTS
Kailua Beach (Figure 3), 4 km long, is a crescent-shaped beach bounded to the north by Kapoho Point and to the south by Alala Point. Low vegetated dunes have formed in front of many properties in central Kailua, evidence of an accreting beach. Erosion has affected the beach fronting Kailua Beach Park in the south. Analysis of Kailua Beach is divided into two sections with a boundary at Kaelepulu Stream. The two study regions are named Kailua Beach (Kapoho Pt – Kaelepulu Stream) and South Kailua Beach (Kaelepulu Stream – Alala Pt). The shoreline data from the beach at Kaelepulu Stream mouth is not considered reliable, as it is prone to fluctuations related to stream flow.

In the Kailua Beach section, IC identifies EXT as the best model to describe shoreline change for the years 1928 - 2005. A maximum accretion rate of 0.70 ± 0.15 m /yr occurs toward the north end of Kailua Beach. The maximum erosion rate is -1.02 ± 0.12 m/yr at the north side of Kailua Beach Park. The shoreline change rate for Kailua Beach averaged along the length of the beach is 0.06 (accretion). The average uncertainty of the EXT rates is ± 0.13 m/yr versus ± 0.22 m/yr for ST. EXT finds statistically significant rates at 90% of transects versus for 81% for ST. The EXT shoreline change model finds a trend of decelerating accretion shifting to accelerating erosion at the southern end of Kailua Beach.
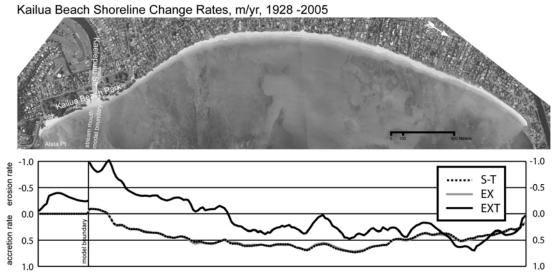
Figure 3. Shoreline change rates (m/yr) at Kailua Beach, 1928-2005. The study site is divided into two sections by a model boundary at Kaelepulu Stream. IC determines EXT, with acceleration in the change rate with time, is the best shoreline change model for Kailua Beach. ST and EX (non-acceleration) rates are shown for comparison.

Lanikai (Figure 4) is a slightly embayed 2 km-wide headland between Alala and Wailea Points with a narrow 800 m long beach in the north-central portion. The remainder of the northern and southern Lanikai shoreline presently has no beach at high tide and has been armored with concrete seawalls and other revetments. Shoreline change analysis for Lanikai Beach looks at historical shorelines from 1911-2005 and includes only the areas with beach in the most recent air photos.

Again, IC identifies EXT as the best model to describe shoreline change. The maximum accretion rate of 1.58 ± 0.18 m/yr occurs near the north-central section. The maximum erosion rate, -0.63 ± 0.13 m/yr occurs near the northern end. The beach is presently accreting at 0.55 m/yr, when averaged along the entire length. The mean uncertainty of the EXT rates is ± 0.13 m/yr versus ± 0.21 m/yr for ST. EXT finds statistically significant rates at 94% of transects versus 66% for ST. The EXT model finds recent accelerating accretion around the center of the study area. EXT also finds accelerating erosion at the far north and south ends. These results suggest that a significant fraction of the sand from eroded areas of Lanikai is accreting at central Lanikai.

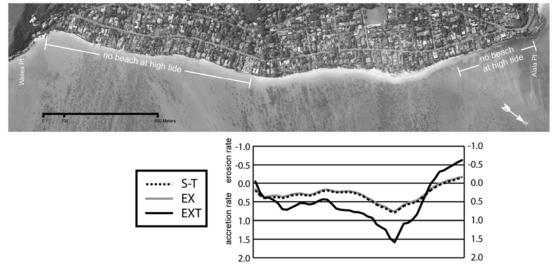Lanikai Beach: Shoreline Change Rates, m/yr, 1911 -2005

Figure 4. Shoreline change rates (m/yr) at Lanikai, 1911-2005. IC determines EXT, with acceleration in the change rate with time, is the best shoreline change model. ST and EX (non-acceleration) rates are shown for comparison. Areas of Lanikai with no beach in the most recent aerial photographs are not analyzed.

Bellows and Waimanalo Beach (Figures 5 and 6), 6.2 km long, is a nearly continuous beach extending from the northern end of Bellows Field (near Wailea Point) to Kaiona Beach Park in southern Waimanalo. The beach is interrupted at two locations by jetties at Waimanalo Stream and the remains of a similar structure at Inaole Stream. The shoreline at the northern end of Bellows Field has been armored with stone revetments. No beach currently exists in this area at high tide. All available historical shoreline years (1911 – 2005) are included in the analysis of Bellows and Waimanalo Beach. The area is divided into three sections based on physical boundaries in the littoral system: North Bellows, from the north end to the jetties at Waimanalo Stream mouth; Central Bellows, from Waimanalo Stream to Inaole Steam; and South Bellows and Waimanalo Beach, from Inaole Stream to Kaiona Beach Park. For ST, IC identifies the null model (0 m/yr) as the best model for all three beach sections.

In the North Bellows section, IC identifies EXT as the best model. EXT finds erosion in the northern half of the section, with a maximum erosion rate of -0.70 ± 0.17 m/yr at the northern end and accretion in the southern half, with a maximum accretion rate of 0.60 ± 0.15 m/yr near the southern end. The shoreline change rate is -0.19 ± 0.13 m/yr (erosion) averaged along the entire section.

In the Central Bellows section, IC identifies EXT as the best model. EXT finds erosion in the northern half of the section with a maximum erosion rate of -0.59 ± 0.10 m/yr at the northern end and accretion in the southern half with a maximum accretion rate of 0.26 ± 0.11 m/yr. The shoreline change rate is -0.11 ± 0.11 m/yr (erosion) averaged along the entire section.

In the South Bellows and Waimanalo section, IC identifies LXT as the best model. LXT finds accretion from Inaole Stream to Bellows Field Beach Park, erosion near the northern end of Waimanalo, and accretion along the rest of the beach fronting Waimanalo, except for a small area of erosion near the southern end of Waimanalo. The maximum erosion rate of -0.70 ±0.11 is found in northern Waimanalo. The maximum accretion rate of 0.66 ±0.10 is found in front of Waimanalo Bay Beach Park. The shoreline change rate is 0.10 ± 0.09 m/yr (accretion) averaged along the entire beach.
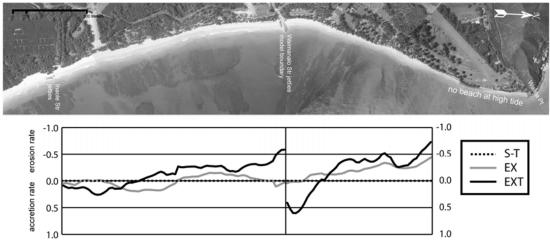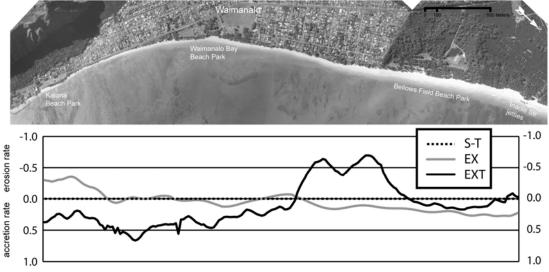

Figure 5. Shoreline change rates (m/yr) for the north and central portions of Bellows Beach 1911-2005. A boundary is included in the model at Waimanalo Stream. IC determines EXT, with acceleration in the change rate with time, is the best shoreline change model. ST and EX (non-acceleration) rates are shown for comparison. The north end of Bellows, with no beach in the most recent air photos, is not analyzed.

Figure 6. Shoreline change rates (m/yr) for southern Bellows and Waimanalo Beach 1911-2005. IC determines LXT, with acceleration in the change rate with time, is the best shoreline change model. ST and LX (non-acceleration) rates are shown for comparison.

DISCUSSION

A goal of most shoreline studies is to analyze historic shoreline change for the purpose of predicting future shoreline positions and identifying potential erosion hazard areas. IC provides a statistical means of finding the most parsimonious model to describe historical shoreline change at a beach. Genz, *et al.* (in press) shows the PXT shoreline change models (with acceleration in the change rate with time) often over-estimate future shoreline positions in synthetic shoreline data sets. 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. Or, several models may be utilized to forecast a range of possible shoreline positions. The credibility of erosion hazard forecasts is increased if different shoreline change models agree in their prediction.

For all four southeast Oahu study areas, EXT has the lowest IC score and is identified as the best model. The basis functions used in calculating the EX and EXT models (principal components, Eigen vectors) are derived directly from the shoreline data. In all other methods a polynomial is fit to the change model. It is not surprising then that the EX and EXT methods often require fewer parameters and produce lower residual errors in fitting a model (and low IC score). Whether the EX and EXT methods actually produce the best models is an area of ongoing research. Principle components provide the exciting prospect of describing the unknown physics driving change at a beach.

Beaches may not erode or accrete in a constant (linear) manner. In a well-configured shoreline data set (many shorelines, low uncertainty), PXT shoreline change models can detect acceleration in the shoreline change rate with time. In this case, the PXT models can provide a better depiction of how a shoreline is changing at present and how change itself has changed with time. Time series of historical shorelines in this study span less than 100 years. It is not unreasonable to wonder if the PXT models may be capturing decadal-scale fluctuations (e.g., ENSO, tradewind oscillations) in shoreline position at some beaches. Correlating shoreline change with these atmospheric fluctuations would be an exciting advance for coastal studies. However, it may discourage coastal managers from using PXT models for long-term erosion hazard planning. The greatest potential for the PXT method is the ability to detect accelerating shoreline change that should be expected with accelerating sea-level rise from global temperature increase (Church and White 2006). Continued studies with the addition of new shoreline data in the future will help to answer these questions.

CONCLUSIONS

Shoreline change rates are calculated from historical shoreline positions to better understand trends of erosion and accretion and to project future shoreline positions. Erosion hazard predictions may be used by coastal managers to design shoreline development policies that will better protect public and private coastal resources. It is vital that shoreline change studies provide significant and defensible results if the data is to be used for the development of public policy.

The new PX and PXT shoreline change rate calculation methods are shown to provide more significant and defensible shoreline change rates than the previously used ST method for beaches of southeast Oahu. The PX and PXT methods produce statistically significant rates for up to 89% of shoreline transects versus 42% of transects using the ST method. For Kailua and Lanikai ST produces rates very similar to the PX models. However, the uncertainties of PX models are significantly lower than ST for these beaches. Using the ST method to analyze South Kailua, Bellows, and Waimanalo beaches, IC picks the null model (0 m/yr) as the beast change model for this method. The null model indicates that there was no significant shoreline change or that the shoreline positional uncertainty was too high for the method to reliably fit a model to the shoreline data. PX and PXT are able to find significant rates at these beaches by utilizing shoreline data from all transects on a beach in calculating the change model. PXT models provide new insight on shoreline change in southeast Oahu as they reveal changing rates through time.

REFERENCES
Church, J.A. and White, N.J. (2006). "20th century acceleration in global sea-level rise," *Geophysics Research Letters*, 33(1), L01602

Crowell, M.; Leatherman, S.P.; Buckley, M.K. (1991). "Historical shoreline change: Error analysis and mapping accuracy." *Journal of Coastal Research*, 7 (3), 839-852.

Daniels, R.C. and Huxford, R.H. (2001). "An error assessment of vector data derived from scanned National Ocean service topographic sheets," *Journal of Coastal Research*, 17 (3), 611-619.

Ellis, M.Y. (1978). "Coastal mapping handbook," U.S. Department of the Interior, Geological Survey; U.S. Department of Commerce, National Ocean Survey; U. S. Government Printing Office, Washington, D.C., 199p.

Fletcher, C.H.; Mullane, R.A.; Richmond, B.M. (1997). "Beach loss along armored shorelines on Oahu, Hawaii Islands," *Journal of Coastal Research*. 13(1), 209-215.

Fletcher, C.H.; Rooney, J.; Barbee, M; Lim, S.C.; Richmond, B.R. (2003). " Mapping shoreline change using digital orthophotogrammetry on Maui, Hawaii," *Journal of Coastal Research* (38) 106-124.

Frazer, L.N.; Genz, A.S.; Fletcher, C.H (in press). "Toward parsimony in shoreline change prediction (I): new methods," *Journal of Coastal Research*.

Genz, A.S.; Fletcher, C.H.; Dunn, R.A.; Frazer, L.N.; Rooney, J.J. (2007). "Predictive accuracy of shoreline change rate methods and alongshore beach variation on Maui, Hawaii," *Journal of Coastal Research*

Genz, A.S.; Frazer, L.N.; Fletcher, C.H. (in press). "Toward parsimony in shoreline change prediction (II) Applying statistical methods to real and synthetic data,"

Journal of Coastal Research.

Hapke, C.J.; Reid, D.; Richmond, B.M.; Ruggiero, P.; and List, J. (2006). "National assessment of shoreline change: part 2, historical shoreline changes and associated coastal land loss along sandy shorelines of the California coast," U.S. Dept of the Interior, U.S. Geological Survey, open-file report 2006-1219, 79p.

National Academy of Sciences, (1990). "Managing coastal erosion," National Research Council, Committee on Coastal Erosion Zone Management, National Academy Press, Washington, 182p.

Norcross, Z.M.; Fletcher, C.H., and Merrifield, M. (2002). "Annual and interannual changes on a reef-fringed pocket beach; Kailua Bay, Hawaii," *Marine Geology*, 3203, 1-28.

Shalowitz, A.L. (1964). "Shore and sea boundaries, with special reference to the interpretation and use of Coast and Geodetic Survey data, United States," U.S. Dept. of Commerce, Coast and Geodetic Survey. *Coast and Geodetic Survey* 10-1, Vol. 2.