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Updating Historical Shoreline Change Rates of North Kāʻanapali, Honokōwai, and Kahana, West Maui

Cuong Tran

Senior Thesis (Global Environmental Science)
Mentor: Dr. Charles H. Fletcher

Tracking shoreline movement across the main Hawaiian Islands provides empirical data to assist in the development of better coastal management practices. We, the University of Hawai‘i at Mānoa Coastal Geology Group, use empirical data to calculate shoreline change rates on the islands of Kaua‘i, O‘ahu, and Maui. In this study, 2015 raw satellite imagery, provided by World View 3, was used to update the historical shoreline database of North Kāʻanapali, Honokōwai, and Kahana, West Maui. We calculated 2015 shoreline change rates and analyzed differences compared to an earlier database from 2007. The satellite imagery we used was orthorectified using ArcGIS and PCI Geomatica Inc., the low water mark and coastal vegetation line were digitized, and shoreline position locations were measured from transects spaced 20 meters alongshore. These locations were modeled using linear regression to identify long-term rates of change at each transect. Including the 2015 shoreline, the data revealed that 77% of all transects were erosional, compared to 73% in 2007. With regard to beach loss, the 2007 dataset experienced a loss of 80 meters whereas the 2015 dataset showed a loss of 920 meters. The expansion of eroding shoreline over the period 2007 to 2015 is consistent with the expected influence of rising sea levels and continued coastal hardening. However, a full analysis that would have identified whether the changes were due to short-term variability or a valid statistical trend was not conducted.

Introduction

Beaches are critical natural ecosystems, a buffer of marine hazards, and popular tourist and recreational destinations (Luttenberger, 2014). In Hawai‘i, beaches are valuable to the state economy, the preservation of native Hawaiian traditions, and the quality of life for residents (Kane et al., 2012; Penn et al., 2016). However, chronic coastal erosion and beach loss is a rising concern (Anderson et al., 2015).

Cuong, a SOEST graduate under the Global Environmental Science Program, is determined to lead Hawai‘i in becoming 100% renewable as well as bouncing forward to climate change impacts. He believes that the research he has done involving updating Maui’s shoreline change rates will be put into use to revise Hawai‘i’s coastal management laws. Cuong’s post-graduation plan is to obtain a Master’s Degree in Urban and Regional Planning at UH Mānoa. In addition, he plans to join opportunities that include environmental outreach for sustainable practices to the younger generations, to gain new knowledge on how to plan for climate change, and to conserve Hawai‘i’s resources for future generations.
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Fletcher et al. (2012) have found that 70% of all sandy shorelines on Maui, O‘ahu, and Kaua‘i are chronically eroding. Widespread erosion and beach loss have created an interest in tracking shoreline movement over the course of the 20th Century and up to present day (Romine et al., 2016). Using the position of historical shorelines, rates of change can be calculated and used to better understand the behavior of Hawaiian beaches.

This study documents the use of historical shorelines to calculate new rates of change in North Kā‘anapali, Honokōwai, and Kahana on the West Maui coast (Figure 1) using 2015 satellite imagery. Workers at the University of Hawai‘i last updated the dataset in 2007, in an ongoing project that used aerial imagery and T-sheets (topographic maps). The methodology and results sections chronicle identification and correction of past shoreline positions and how to generate rates of change. In analyzing the resulting data, we are interested in comparing any differences in beach loss and width as well as shoreline position between the 2015 dataset and the 2007 dataset. We predict that long-standing coastal hardening and increase of sea level rise from natural and anthropogenic contributions influence significant increases in erosion.

**Beach Dynamics**

Beaches exist in dynamic equilibrium with physical forces such as wave energy, sediment availability, and sea level change (Nicholls, 2010; Fletcher, 2010). However, offshore sand losses, erosive wave conditions, and human impacts may drive erosion and beach loss (Coyne et al., 1999; Defeo et al., 2009). In these cases, beaches may become narrow, property may be damaged, and critical habitat may be degraded.

In Hawai‘i, seasonal and trade wind swells are the predominant drivers of short-term shoreline change (Vitousek and Fletcher 2008; Romine and Fletcher, 2012). Swells, developed from surface winds, may cause coastal erosion. Typically, in the case of storms and seasonal waves, erosion is temporary and sand returns to the beach (Hwang, 2005) with the end of high-energy conditions. However, in extreme cases, sand may be permanently lost by abrasion or carried by currents farther offshore than can be returned by waves. Surface winds also move sand to supply backshore dunes, a natural system important for beach recovery (Hanley, 2014). Backshore dunes serve as a repository of sand that can naturally replenish beaches that are experiencing erosion.

Anthropogenic causes of erosion include shoreline hardening, sand mining, landscaping of the backshore dune (Fletcher et al., 1997), and sea level rise (SLR) (Anderson et al., 2015). Today, SLR is accelerating as a result of global warming (Nerem et al., 2018). In a regime of accelerating SLR, shoreline hardening may cause beach narrowing and beach loss (Figure 2; Summers et al., 2018). Shoreline hardening is the installation of seawalls or revetments to protect land from coastal erosion (Beatley, 2009; Basco, 2006).

Hardening is known to interfere with sediment availability (e.g., from dunes) and lead to flanking erosion (Summers et al., 2018; Romine and Fletcher, 2012). When a wave hits a seawall, its energy is reflected and dispersed to adjacent beach sections. The energy dispersed drives sediment in neighboring beaches offshore and cause erosion, which then initiates the development of more seawalls.

Accelerating SLR leads to the spread of coastal erosion as a shoreline migrates landward with rising water (Summers et al., 2018). Along a coast that has not been hardened under conditions of SLR, erosion will naturally threaten, and potentially damage private property and other assets. Yet to the benefit of beaches, this releases sand from the dune system and allows beaches to migrate landward and maintain an equilibrium position with the rising water (Anderson et al., 2015).

**Coastal Management Policy**

The presence of chronic coastal erosion and beach loss (Summers et al., 2018; Romine et al., 2016) signifies the need to improve coastal zone management. In Hawai‘i, beaches are critical environments for many reasons, thus preserving them is a necessity in times of rapid growth and development along the coastline.

In 1972, the United States Congress enacted the Coastal Zone Management Act (CZMA) (Chasis, 1985). The purpose of the CZMA was to “preserve, protect, develop, and where
possible, to restore or enhance the resources of the nation’s coastal zone” (16 USC §§ 1451-1466). The CZMA encourages coastal states to create their own management plans and policies with the support of federal funding.

Five years later in 1977, Hawai‘i created the Hawai‘i Coastal Zone Management Act (HCZMA), one of many federal-local partnerships under the National CZM Program. Under the HCZMA, Hawai‘i state and county CZM policies identified three primary goals: 1) to provide public access to and along the shoreline; 2) to preserve open space; 3) to protect coastal environments, especially beaches (HRS §§ 205A-1 to 6). The HCZMA established two policies to manage coastal development: 1) the shoreline setback, and 2) special management areas (SMA). These are regulated under county jurisdiction.

The HCZMA established a statewide setback law to prohibit development at a minimum distance of 40 feet from the shoreline (HRS §§ 205A-41 to 49). Each county administers this setback. They, additionally, have authority to establish their own setback provided that it is not less than the statewide setback. For example, Maui County established a shoreline setback line of 25 feet plus a distance of fifty times the annual erosion hazard rate from the shoreline. (HRS §§ 12-203).

Summers et al. (2018) discuss the influence of a hardship variance, which permits shoreline hardening where habitable structures are threatened by erosion. Under this variance, no facilities or improvements may be used to artificially fix the shoreline unless erosion will likely cause a hardship, such as depriving “reasonable use of the land.” Shoreline hardening leads to beach narrowing and loss as well as flanking erosion to neighboring properties.

SMAs are special planning districts beginning at the shoreline and extending landward, in many cases as much as 1500 feet. Within the SMA, development is subject to special controls (HRS §§ 205A-21 to 33). SMA permits assure that development like hotels, subdivisions, and commercial areas are in compliance with the HCZMA objectives and goals. However, a number of exemptions allow development in the SMA: single-family residences (SFR) less than 7,500 square feet, repair and maintenance of roads and highways, and others (Summers et al., 2018). In the case of SFR, redevelopment and expansion are subject to shoreline setback laws. However, SFR can simply disguise their redevelopment to a repair without the need for a SMA permit. Thus, SMA exemptions have contributed to the need for coastal hardening because they allow property such as single-family residences to be redeveloped and expanded regardless of any erosion threat.

**Figure 2** Hardening (e.g., seawalls) causes beach loss. As a result, neighboring properties typically experience increased erosion and this leads to additional shoreline hardening. This effect is known as “flanking.”

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**Purpose**

This project is focused on improving understanding of shoreline change behavior at West Maui, Hawai‘i. Here, the method of Fletcher et al. (2012) and Fletcher et al. (2003) was used to update the historical shoreline database in the adjoining West Maui regions of North Kā‘anapali, Honokōwai, and Kahana. The single-transect (ST) method was utilized to calculate updated shoreline change rates for each region in order to support coastal management decisions. Satellite imagery of Maui, acquired from 2015 by World View 3, was used to update the database with a new shoreline. The updated database provided an opportunity for comparison to the previous database, which ended in 2007.

Mapping historical shorelines and calculating change rates provide empirical data to develop coastal zone management plans and policies (Spirandelli et al. 2016; Anderson et al.
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For example, local coastal managers have used historical shoreline change rates to produce guidelines for development, to model future shoreline change, and to create new setbacks (Spirandelli et al. 2016). These data could also inform management decisions to protect native and indigenous species such as Ipomoea pes-caprae (pohuehue, or beach morning glory), Scaevola taccada (naupaka), Monachus schauinslandi (Hawaiian monk seals), Chelonia mydas (green sea turtles), and others.

**Study Area**

The West Maui shoreline is approximately 30 km long and trends southwest to northeast (Storlazzi and Jaffe, 2007). Wave exposure changes from north to south (Maui Shoreline Atlas, online). Annual northeast trade wind waves, winter northwest swells, and summer south swells are all incident to this coast (Storlazzi and Jaffe, 2007) (Figure 3). Molokai, Lana‘i, and Kaho‘olawe offer partial protection from swells arriving from the west. However, other marine hazards such as tsunamis and tropical storms may make landfall (Maui Shoreline Atlas, online).

The backshore geology in North Kā‘anapali and Honokōwai consists mainly of alluvium while the backshore geology of Kahana consists of both sand and alluvium (Hawaii Sea Level Rise Viewer, online). Alluvium is a deposit of gravel, sand, and silt formed in river systems and transferred to the coast (Rust, 1977). Under the scenario of higher sea level and a shoreline that has not been hardened, beaches in North Kā‘anapali and Honokōwai would not recover with alluvium.

Historically, pineapple and sugar plantations dominated land use in the area. More recently, however, urbanization and development have increased along the West Maui shoreline (Storlazzi and Jaffe, 2007).

North Kā‘anapali extends from Keka‘a Point to Mahana Condominium (Maui Shoreline Atlas, online) (Figure 4). The coastline has a long white sand beach with hotels and condominiums on the landward side (Maui Shoreline Atlas, online). Parts of the resort area have been recently developed and subject to Maui County setback requirements of 150 feet (Owens, 2018). As a result of this setback, large lots have been placed behind coastal dunes. The strategy of the Maui County Planning Department is to locate coastal development inland a sufficient distance to avoid significant damage from marine hazards and erosion (Owens, 2018). However, some older Kā‘anapali resorts are situated next to the shoreline and are threatened by continuing sea level rise and coastal erosion (Owens, 2018).

Honokōwai extends from the Mahana Condominium to the start of hardened shoreline at Laeokama Point (Maui Shoreline Atlas, online) (Figure 5). The shore is made of narrow sections of white sand beach, most of which are located in front of hotels and condominiums. These resort properties are protected from coastal erosion by seawalls that have been in place since the 1960s and 1970s. As a result, the region has experienced extensive beach loss (Owens, 2018).

![Figure 3](image-url) Annual northeast swells (white arrows), winter northwest swells (green arrows), and summer south swells (blue arrows) are incident to the West Maui coast. The aerial imagery was provided by Google Earth.

![Figure 4](image-url) North Kā‘anapali is the southern most region in the study area. It is characterized by a long white sand beach.
Kahana extends from Māhinahina Point to Haukoe Point (Maui Shoreline Atlas, online) (Figure 6). The northern portion of Kahana is composed of white sandy beach separated by headlands. The south and central portions of the shoreline are occupied by Kahana Beach, a long white sand beach that is artificially divided by shoreline hardening. Because the Kahana coast, in general, is densely developed with condominiums, most individual buildings are threatened by erosion, seasonally high waves, and marine hazards (Owens, 2018). The extensive shoreline hardening has caused widespread flanking (Owens, 2018).

Methods

The methodology used in this study to gather historical shoreline change data consisted of the following steps:

1. Orthorectification of shoreline satellite imagery
2. Digitizing principal geomorphic features
3. Establishing transects (measurement locations) at 20 meters alongshore spacing
4. Modeling shoreline change using linear regression (Fletcher et al. 2012)

A key geomorphic feature, the toe of the beach, was interpreted and digitized on each image to be used as a proxy for the changing position of the shoreline. This feature approximately marks the location of the low tide waterline, or low water mark (LWM; Romine et al. 2008). A second key geomorphic feature, the coastal vegetation line (VEG), does not represent natural movement of the shoreline, but is instead interpreted as the landward edge of the beach (Fletcher et al. 2003).

Transect locations were established from the LWM vector to quantify and model historical shoreline positions. Rates of shoreline change were calculated at each transect using a MATLAB script. Following the example of Romine et al. (2009), the location of the LWM and VEG at each transcript was collected to calculate beach width. We compared differences in shoreline change rates and beach widths between the 2007 and 2015 historical databases. We also compared any changes in beach loss that occurred.

Historical shoreline changes were measured along approximately 6.3 kilometers of shoreline at 313 transects in the study area. In order to study sub-regional trends, we nominally divided North Ka’anapali, Honokōwai, and Kahana into northern and southern regions (Fletcher et al. 2012). In general, with regard to the entire time series, one historical shoreline is typically mapped approximately every decade dating to the early 20th Century (Romine and Fletcher, 2012). The following narrative explains this methodology in more detail.
Clipping

The February 17, 2015 raw satellite imagery was received from the vendor distorted in multiple locations at low resolution (Figure 7). Color, brightness, and contrast tools in ArcGIS and PCI were used to bring higher resolution and help delineate features for orthorectifying and digitizing. The raw imagery was clipped (separated) into the three geographical regions of Maui: North Shore, West Maui, and Kīhei coast. The West Maui region was cut again into three study areas.

Photomosaic

The satellite imagery was orthorectified to reduce displacement caused by lens distortion, Earth curvature, camera tilt, and terrain relief using ArcGIS (Romine et al., 2008). Orthorectified photomosaics were created from the 2015 imagery by referencing 2007 ortho-photomosaics in the Universal Transverse Mercator coordinate system.

The orthorectification process involves the use of two georeferencing tools: affine and spline (triangulation) transformation. Each transformation requires the use of ground control points (GCPs). GCPs were placed at prominent geographic and cultural features along the coast such that they were approximately equally spaced. The GCPs served as digital benchmarks allowing the raw data to be corrected on the basis of the orthorectified data. In our study, a root mean square (RMS) value of less than 6 meters was considered satisfactory following orthorectification (see Uncertainty section).

Affine Transformation  The affine transformation is a linear mapping method that is provided by ArcGIS software. It skews, rotates, and translates data for optimizing local and global accuracy. The transformation requires a minimum of three GCP points. In our study, between three and twenty GCP links were used. These were adjusted to minimize distortion.

The placement and number of GCPs is a key aspect controlling the accuracy of transformation. Using too few GCPs results in a lack of control over large parts of the image. Using more GCPs but clumping them together rather than widely distributed tends to cause high image distortion. In our study, the best product involving this process produced an RMS value of 6.8 meters. This exceeds our criteria, 6 meters, and indicates that the affine transformation is not an optimal approach.

Spline Transformation  The spline transformation is a rubber sheeting method that optimizes for local accuracy. It is based on a piecewise function to maintain continuity and smoothness across the image. Spline requires a minimum of ten GCP points. For this study, approximately fifty GCP points were created between the raw imagery and the reference photomosaic. Because our study used more GCP points for the spline method, there can be risk in multiple distortion areas across the imagery. The best product involving this process produced an RMS value of 2.29 meters, an acceptable error.

Digitizing

The 2015 photomosaic was used to interpret the position of the LWM and VEG (Figure 8). These features were digitized onscreen to create vectors. Part of the digitizing process involves the display of 2007 vectors so that the operator may have them for comparison while digitizing the 2015 photomosaic. Where there is no beach, the two vectors come together and overlap.

Several visual onscreen indicators were used to identify the LWM: surface ocean color, wave characteristics, water clarity, and suspended sediment. Surface ocean color varies with depth. Usually, the LWM is within the zone before the ocean color changes from a light color (e.g., blue) to a darker color (e.g., dark green). The change in light to dark color is related to the shift from shallow to deeper water.

The swash zone is a function of slope and wave setup. In this zone, waves break due to shallow ocean depth and this can be used as a guide to the location of the LWM. Water clarity is an essential component for determining the LWM: turbid water disguises the LWM and biases the placement of the vector, typically, landward of its proper location.

The VEG was digitized by generally following the bound-
ary of open sand and vegetation cover. In identifying the position of the vegetation line, distortions are common at palm trees and other tall vegetation. Because of these distortions, three-dimensional features extracted from historical Google Earth aerial imagery were used to determine the appropriate position of tall and low vegetation as well as hardened structures. Tall vegetation is usually digitized through the base of the tree while low vegetation like beach morning glory and naupaka is digitized along the edge of the canopy. Hardened shorelines are also vectored in lieu of the vegetation line where it is located seaward of the true vegetation.

**Transects**

As part of the digitizing process, shoreline measurement locations, called transects, are digitally established using PCI software every 20 meters along the coast (Figure 9). Transects serve as locations for positions of the LWM vector and the VEG vector. Comparison of the history of LWM locations and VEG locations allows for analysis of their rate of change. The location of where these vectors intersect a transect is a nominal distance from a baseline. The operator creates a baseline an arbitrary distance offshore such that it mimics the general trend of the coast. PCI Modeler has a module called VECREP, which is used to collect LWM and VEG positions and calculate beach width, the distance between the two vectors at each transect.

**Uncertainty**

Previous workers have identified uncertainties in historical shoreline positions and rates of change (Anderson et. al, 2015; Fletcher et. al, 2012; Romine et. al, 2008; Fletcher et. al, 2003). Their methodology is applied in our study. Two types of uncertainty are defined: positional uncertainty and measurement uncertainty.
Positional Uncertainty  Positional uncertainty consists of three errors: seasonal error, tidal fluctuation error, and conversion error. It relates to phenomena that may affect the precision and accuracy of defining a shoreline position in a given year. Seasonal error (Es) is the error related to shoreline position movement caused by seasonal changes in wave energy. Seasonal error is quantified using photomosaics of the same shoreline but acquired from different seasons ideally within a 12-month period. Seasonal error is also quantified using summer and winter topographic profiles acquired at a nearby beach. The mean and standard deviation of the seasonal differences, and a uniform distribution, were generated in MatLab. The standard deviation of the distribution was the seasonal error. In this study, Es is 5.70 meters. 

Tidal fluctuation error (Ed) is the error related to horizontal movement in the LWM due to tide changes. Horizontal movement of the LWM was recorded on several Hawaiian beaches to quantify the difference in low and high tide shoreline position. A uniform distribution was generated in MatLab and the standard deviation was used as the tidal error. In this study, Ed is 3 meters. 

Conversion error (Ec) is only calculated for T-sheets and is not used in this study. 

Measurement Uncertainty Measurement uncertainty consists of four errors resulting from digitizing, pixel size, rectification, and T-sheet plotting. These sources of error are generated during the orthorectification process and on-screen digitizing. Digitizing error (Ed) is the error in digitizing the shoreline. It accounts for different interpretations of the LWM and VEG line from several analysts. The error is the standard deviation of the differences between repeated digitizing attempts. In this study, Ed was 0.8403 meters. 

Pixel error (Ep) is the pixel size of the image. The pixel size in orthorectified images is 0.5 meters. 

Rectification error (Er), calculated from the orthorectification process, is the RMS value provided by software. There are different ways of calculating the RMS value for both affine and spline transformations. RMS values are measures of the offset between GCPs on satellite imagery. Upon completion of the affine transformation, the ArcGIS software provides information including a proximity error in X and a proximity error in Y for every established GCP. RMSX and RMSY values for each point were calculated by taking the square root of the sum of the error in (X)² and the error in (Y)² respectively. The total RMS value was calculated by taking the square root of the sum of (RMSX)² and (RMSY)². 

\[
\text{RMS}_{\text{total}} = \sqrt{\text{RMS}_X^2 + \text{RMS}_Y^2}
\]

Data for the spline transformation was manually calculated. Two point shape-files were created for every established GCP: one shape-file for the 2007 reference mosaic and one shape-file for the 2015 photomosaic. The Near Table tool in ArcGIS was used to calculate the distance between both GCPs in a link. A 95% confidence interval was calculated using the “Near-Distance values” and the standard deviation of the values. The RMS values of 2007 reference imagery, along with the 95% confidence interval, were applied to calculate the true 2015 photomosaic RMS. 

\[
\text{RMS}_{\text{true}} = 95\% \text{ confidence interval} + \sqrt{\sum_{i=1}^{n} \text{RMS}_{\text{reference}}^2}
\]

T-sheeting error (EtS) is only calculated for T-sheets and is not used in this study. 

Weighted Least Squares  Weighted least squares (WLS) is a type of regression model that accounts for uncertainties when calculating a shoreline position trend line. WLS is applied by quantifying the seven different sources of error mentioned above. These seven sources of error are operated together (the square root of the sum of the squares of the errors) to get a total positional uncertainty (Uf). In this study, Uf is 6.91 meters. 

\[
U_f = \pm \sqrt{E_s^2 + E_t^2 + E_d^2 + E_p^2 + E_r^2 + E_t^2 + E_c^2}
\]

WLS is applied in individual transect plots. Individual transect plots model the change in historical shoreline position for a study period (Figure 10). Each historical shoreline position has an uncertainty of Uf, which is depicted as an error bar. The slope of the trend line is the shoreline change rate. A positive slope indicates beach accretion while a negative slope indicates erosion. Per standards of the Coastal Geology Group, a minimum of three historical shoreline positions is required when calculating a shoreline change rate. 

Shoreline Change Rates  

With the addition of the 2015 vectors, new shoreline change rates were calculated for each transect in the study area. The LWM vector was the primary indicator for this purpose. In the case of beach loss, the LWM and VEG vectors intercept and plot on top of one another. We calculate beach loss by implementing the truncation year, the year at which a beach is last seen in imagery. For a single transect, if the difference between the LWM and the VEG is zero, we can accurately interpret a beach loss of 20 meters. Typically, beach loss is located at a hardened shoreline. 

Because shoreline change rates vary alongshore, they are smoothed (averaged) so that from one transect to the next, variability is reduced. Smoothing uses a weighted, five transect filter. The filter calculates the average rate on five consecutive transects that are weighted [1,3,5,3,1]. The middle transect has
the highest weight while the outer transects are weighted less. The average of all weighted transects is applied to the middle transect. The filter then slides over one transect and repeats the same calculation. This smoothing filter is applied to all transect data.

Smoothed rates of shoreline change, assigned to specific transects, are used by planning agencies at county and state levels for various types of policy development and management. For instance, Maui County uses these data to calculate a construction setback distance, as does Kauai County. The City and County of Honolulu and the state of Hawaii use these data in evaluating permit applications for coastal activities as well as to educate landowners and the general public with regard to coastal erosion.

**Regionally Averaged Uncertainty**

Regionally averaged shoreline change rates are the average of rates from all transects in a coastal region. Adjacent rates of similar quantity may be averaged to obtain an overall approximate rate for that section of shoreline. The uncertainty calculated, Uavg, is described below.

\[
U_{avg} = \frac{\sqrt{\sum_{i=1}^{n} U_i^2}}{n}
\]

**Results**

Across the entire study area, the difference in the average rate of change for the 2007 and 2015 datasets was only \(-0.01\) meters per year. Calculated using the 2015 shoreline, 77% of transects indicates an erosional trend compared to 73% with the 2007 data. Overall, using the full 2015 dataset, the average of all transects was erosive at a rate of \(-0.09 \pm 0.02\) meters per year. From the 2015 dataset, the average rate of all eroding transects was \(-0.14 \pm 0.02\) meters per year while the average rate of all accreting transects was \(0.09 \pm 0.02\) meters per year. The beach width in 2007 was 9.4 meters wider than 2015, averaged over all 313 transects. Beach loss, which is the length of beach measured along the shoreline that existed in an earlier photomosaic that is not found in a recent photomosaic, was calculated for both 2007 and 2015 datasets. Beach loss in 2007 was 80 meters, and in 2015 920 meters. Results are provided in three tables: Table 1 presents rates of change; Table 2 provides changes in eroding and accreting transects; and Table 3 presents data on beach loss in the study area.

**North Kaʻanapali**

The 2015 rate of change in North Kaʻanapali was \(-0.002 \pm 0.01\) meters per year, a difference of \(-0.03\) meters per year compared to 2007. North Kaʻanapali was divided into a northern region of 63 transects and a southern region of 49 transects. Overall, 51% of all transects in North Kaʻanapali experienced erosion while 49% of all transects experienced accretion.

The average rate of change in the northern region was accretional, \(0.06 \pm 0.03\) meters per year. The average rate of change in the southern region was erosional, \(-0.09 \pm 0.02\) meters per year. The average rate of all accreting transects in the northern region was \(0.09 \pm 0.03\) meters per year and in the southern region, the average of all accreting transects was \(0.02 \pm 0.07\) meters per year. The average rate of all eroding transects in the northern region was \(-0.06 \pm 0.1\) meters per year and the average rate was \(-0.1 \pm 0.03\) meters per year in the southern region.

From 2007 to 2015, beach width increased in the northern region by 0.30 meters. In the southern region beach width decreased 0.12 meters. The northern region and southern region both experienced a beach loss of 20 meters. Eighty one percent of the northern region experienced accretion while 92% of the transects in the southern region experienced erosion.

**Honokōwai**

The study area of Honokōwai experienced extensive erosion with an average of all transects showing an eroding trend of \(-0.14 \pm 0.02\) meters per year. The Honokōwai study area was nominally divided into a northern region consisting of seven
Table 1  Rates of Change: An analysis of shoreline change rates between 2007 and 2015 datasets for different sections of transects.

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<td>Northern Section</td>
<td>63</td>
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<td>Southern Section</td>
<td>85</td>
<td>−0.15 ± 0.02</td>
<td>0.00</td>
<td>−0.16 ± 0.02</td>
<td>0.02 ± 0.11</td>
<td>−0.17 ± 0.02</td>
<td>0.05 ± 0.08</td>
</tr>
<tr>
<td>Overall</td>
<td>92</td>
<td>−0.14 ± 0.02</td>
<td>0.00</td>
<td>−0.15 ± 0.04</td>
<td>0.01 ± 0.11</td>
<td>−0.16 ± 0.02</td>
<td>0.05 ± 0.07</td>
</tr>
<tr>
<td>Kahana</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northern Section</td>
<td>10</td>
<td>0.18 ± 0.04</td>
<td>0.04</td>
<td>−0.08 ± 0.4</td>
<td>0.1 ± 0.04</td>
<td>−0.05 ± 0.19</td>
<td>0.14 ± 0.03</td>
</tr>
<tr>
<td>Kahana Beach</td>
<td>66</td>
<td>−0.14 ± 0.02</td>
<td>0.02</td>
<td>−0.14 ± 0.04</td>
<td>0.00</td>
<td>−0.15 ± 0.03</td>
<td>0.00 ± 0.09</td>
</tr>
<tr>
<td>Overall</td>
<td>109</td>
<td>−0.13 ± 0.04</td>
<td>0.04</td>
<td>−0.15 ± 0.04</td>
<td>0.1 ± 0.04</td>
<td>−0.16 ± 0.04</td>
<td>0.1 ± 0.03</td>
</tr>
<tr>
<td>TOTAL</td>
<td>313</td>
<td>−0.09 ± 0.02</td>
<td>−0.01</td>
<td>−0.13 ± 0.02</td>
<td>0.08 ± 0.03</td>
<td>−0.14 ± 0.02</td>
<td>0.09 ± 0.02</td>
</tr>
</tbody>
</table>
Table 2  Region Transect Change: Percent changes between 2007 and 2015 datasets for different sections of transects

<table>
<thead>
<tr>
<th>REGION</th>
<th>PERCENT OF 2015 TRANSECTS ERODING (%)</th>
<th>PERCENT OF 2015 TRANSECTS ACCRETING (%)</th>
<th>PERCENT OF 2007 TRANSECTS ERODING (%)</th>
<th>PERCENT OF 2007 TRANSECTS ACCRETING (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Kāʻanapali</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northern Section</td>
<td>19</td>
<td>81</td>
<td>5</td>
<td>95</td>
</tr>
<tr>
<td>Southern Section</td>
<td>92</td>
<td>8</td>
<td>79</td>
<td>23</td>
</tr>
<tr>
<td>Overall</td>
<td>51</td>
<td>49</td>
<td>37</td>
<td>63</td>
</tr>
<tr>
<td>Honokōwai</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northern Section</td>
<td>100</td>
<td>0</td>
<td>71</td>
<td>29</td>
</tr>
<tr>
<td>Southern Section</td>
<td>93</td>
<td>7</td>
<td>98</td>
<td>2</td>
</tr>
<tr>
<td>Overall</td>
<td>93</td>
<td>7</td>
<td>96</td>
<td>4</td>
</tr>
<tr>
<td>Kahana</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northern Section</td>
<td>20</td>
<td>80</td>
<td>10</td>
<td>90</td>
</tr>
<tr>
<td>Kahana Beach</td>
<td>97</td>
<td>3</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Overall</td>
<td>89</td>
<td>11</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>TOTAL</td>
<td>77</td>
<td>23</td>
<td>73</td>
<td>27</td>
</tr>
</tbody>
</table>
Table 3  Beach Loss: An analysis of beach loss and beach width between 2007 and 2015 datasets for different sections of transects.

<table>
<thead>
<tr>
<th>REGION</th>
<th>2015 BEACH WIDTH (M)</th>
<th>2007 BEACH WIDTH (M)</th>
<th>BEACH LOSS ALONGSHORE 2015 (M)</th>
<th>BEACH LOSS ALONGSHORE 2007 (M)</th>
<th>DIFFERENCE IN BEACH LOSS ALONGSHORE BETWEEN 2007 AND 2015 (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Kāʻanapali</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northern Section</td>
<td>30.29</td>
<td>29.99</td>
<td>20</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>Southern Section</td>
<td>20.21</td>
<td>20.33</td>
<td>20</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>Overall</td>
<td>25.86</td>
<td>25.77</td>
<td>40</td>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>Honokōwai</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northern Section</td>
<td>0</td>
<td>15.83</td>
<td>140</td>
<td>40</td>
<td>100</td>
</tr>
<tr>
<td>Southern Section</td>
<td>6.73</td>
<td>11.19</td>
<td>600</td>
<td>0</td>
<td>600</td>
</tr>
<tr>
<td>Overall</td>
<td>6.22</td>
<td>13.51</td>
<td>740</td>
<td>40</td>
<td>700</td>
</tr>
<tr>
<td>Kahana</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northern Section</td>
<td>9.86</td>
<td>12.50</td>
<td>40</td>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>Kahana Beach</td>
<td>12.59</td>
<td>15.32</td>
<td>100</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Overall</td>
<td>10.21</td>
<td>12.44</td>
<td>140</td>
<td>40</td>
<td>100</td>
</tr>
<tr>
<td>TOTAL</td>
<td>42.32</td>
<td>51.72</td>
<td>920</td>
<td>80</td>
<td>840</td>
</tr>
</tbody>
</table>

The average rate of change of all transects in the northern region was erosional, $-0.02 \pm 0.01$ meters per year. The average rate of change of all transects in the southern region was also erosional, $-0.15 \pm 0.02$ meters per year. The average rate of all eroding transects in the northern region was $-0.02 \pm 0.11$ meters per year while the average rate of all eroding transects in the southern region was $-0.17 \pm 0.02$ meters per year. The average rate of all accreting transects in the northern region was $0.00$ meters per year and in the southern region, the average rate of all accreting transects was $0.05 \pm 0.07$ meters per year.

Beaches in the northern region were completely lost by 2015, resulting in an average beach narrowing of 15.83 meters and a beach loss of 140 meters. The southern region experienced an average beach narrowing of 4.46 meters and an alongshore loss of 600 meters. The entire northern region and 93% of the southern region experienced erosion.

When considering all transects, the northern region was accretional with an average rate of $0.18 \pm 0.04$ meters per year. In the southern region, the average of all transects was $-0.14 \pm 0.02$ meters per year. The average rate of all eroding transects in the northern region was $-0.05 \pm 0.19$ meters per year. In the southern region, at Kahana Beach Park, the average rate of all eroding transects was $-0.15 \pm 0.03$ meters per year. The average rate of all accreting transects in the northern region was $0.14 \pm 0.03$ meters per year. At Kahana Beach Park, the average rate of all accreting transects was $0.00 \pm 0.09$ meters per year.

Averaged with all transects, the northern region experienced an average beach narrowing of 2.64 meters and a loss of 40 meters. At Kahana Beach Park, average narrowing of 2.73 meters occurred at the same time as a total loss of 100 meters of beach. Eighty percent of the northern section and 97% of Kahana Beach Park experienced erosion.

### Discussion

Shoreline change in North Kāʻanapali, Honokōwai, and Kahana is dominated by erosion. Along all regions, the number of eroding transects far exceeds the number of accreting transects. The number of eroding transects increased by 4% in the 2015 dataset when compared to the 2007 dataset. Although there was no significant change between 2007 and 2015 in regards to shoreline movement, erosion parallel to the shoreline is worth analyzing. Because this study area has large amounts of coastal hardening, its shoreline becomes more and more artificially fixed, leading to increased amounts of flanking.
Erosion rates can be related to a number of factors. These include nearby shoreline hardening which can cause flanking, local wave dynamics, and other processes that can interfere with sand availability. It is not informative to simply refer to back beach development because shoreline erosion or accretion can occur in front of any sort of back beach development. It is the availability of sand that is a critical factor thus flanking, wave processes, and other direct influences on the beach should be the target of analysis. Fletcher et al. (2012) describes historical shoreline change on Kauaʻi, Oʻahu, and Maui. An analysis comparing the results of our work and Fletcher et al. (2012) may be done by the reader.

A shoreline segment that consists of both accreting and eroding transects may provide statistics that underestimate the real threat of erosion. Such a shoreline results in an overall average rate that does a poor job in representing either trend. From a management point of view, it’s important to track eroding transects, and accreting transects separately, to fully understand the stability of the beach. Area where shoreline segments consist solely either with eroding transects or accreting transects have not been looked at in this study. However, shoreline change rates, illustrated in Table 1, a display of eroding transects in Table 2, and beach loss and width, illustrated in Table 3, provide an accurate assessment of regions that are most vulnerable to erosion.

Overall, the region of Honokōwai had the greatest amount of average beach loss and narrowing, when comparing the 2007 dataset to the 2015 dataset. Honokōwai experienced a loss of 740 meters in the 2015 dataset compared to 40 meters in the 2007 dataset, a 18-fold increase in beach loss. This significant change in beach loss and narrowing could be explained by the amount of shoreline hardening in the Honokōwai area. Although we have no information on new hardening development between 2007 and 2015, seawalls built in the 20th century have continued to protect the hotels and condominiums in the area. In return for protection, Honokōwai is losing beaches.

When comparing the datasets from 2007 to 2015, there are noticeable differences in alongshore beach loss and beach narrowing. These differences signify that erosion continues to increase up to present day, and may be the result of sea level rise, flanking from nearby shoreline hardening or interruptions of sediment availability through some unknown cause. Although natural causes of erosion (e.g., erosive wave conditions) do occur, erosion and beach loss was most apparent in areas that have been hardened with seawalls and revetments.

The presence of seawalls along the coast represents a choice by owners and managers that violates the goals of the networked coastal management system that extends from federal to local agencies (Summers et al., 2018). In Hawaiʻi, coastal property managers commonly protect their property with a range of hardening styles including vertical seawalls and sloping revetments, sandbags, and gabions. Shoreline hardening not only causes flanking but also blocks back beach sand reserves from being accessed by high waves and contributing sediment availability on a beach.

Sea level rise alone is not necessarily a negative impact on a beach. During the last ice age, 20,000 years ago, global sea level was over 120 meters lower than today. As the ocean rose into the current interglacial, beaches migrated with the expanding shoreline. An important aspect of this process is the release of sand in the backshore by coastal erosion, which feeds a retreating beach. Shoreline hardening prevents this process and beaches become sand-starved because hardening separates a beach from a dune field sand source (Carter et al.; 1986, Hall and Pilkey; 1991, Summers et al., 2018).

Seasonal storms may be responsible for influencing shoreline movement in the study area. Strong winter storms create northern swells. These swells have the capacity to move large amounts of sand offshore from the West Maui coast. Kona storm swells move a significant volume of sediment northward along the coast (Rooney and Fletcher, 2000). This movement of sand is evident in the northern region of North Kāʻanapali where accreting transects had increased by 19% from 2007 to 2015. Northward sand transport by Kona storm swells and/or summer swells is likely responsible for this trend.

El Niño Southern Oscillation (ENSO) events are also considered to influence shoreline movement. These events typically occur once every few years as cooling or warming phases of the equatorial Pacific Ocean, and last for several months. The warm water associated with El Niño in the area of Hawaiʻi and the East Pacific may be related to an increase in tropical cyclones as well as temporary higher sea level (PEAC, online). Rooney et al., (2003) explored this relationship along the Maui coastline. A moderate El Niño developed during 2009 to 2010. A weak El Niño developed during the period 2014 to 2015 (Null, 2018). Because the raw imagery was developed on February 17, 2015, the very strong 2015–2016 El Niño was not an influence on shoreline change in the period covered by our dataset. Additional, tropical cyclones between 2007 and 2015 did not approach Hawaiʻi and were not a significant factor in shoreline changes. As a result, we conclude that shoreline changes over the study period may have been influenced by temporary high sea levels associated with the two low levels El Niño events that occurred.

Human activities (e.g. sand bagging, sand replenishing, and destruction of sand dunes) are likely to influence shoreline movement. In West Maui, activities such as sand bagging and sand replenishing are common. Trampling on the sand by public beachgoers may have a negative impact on beach recovery following erosive events. Another negative impact occurs when beach sand is used to fill large sand bags that harden the shoreline. Mining the beach like this further promotes erosion not only at the immediate location but also at alongshore positions on the beach.

Furthermore, high-valued properties are located along...
the study area, of which some, if not all, are protected with seawalls. During the construction and maintenance of the hotels and condominiums in the study region, sand dunes previously common in the area were graded, filled with dirt, and built upon. Without sand dunes to contribute to sediment availability, a beach may fail to recover following episodes and seasons of erosion. Sand replenishing projects are typically authorized to artificially replenish beaches for public use, to maintain the hotel tourism industry, and to restore the beach ecosystem. These multiple negative influences on beach resources suggest that stronger management is needed if they are to be protected.

Conclusion

Periodically tracking shoreline movement as demonstrated in this study provides managers with data that defines the problem and allows decision-making and policy development that is appropriate to the scale of the problem. In this study, we collected empirical data to investigate the relationship between coastal development in West Maui and beach erosion, narrowing, and loss. We used a set of satellite photos from 2015 to update the shoreline dataset of North Kā‘anapali, Honokōwai, and Kahana.

Using the methodology of Fletcher et al. (2012) and Fletcher et al. (2003), shoreline movement can be analyzed to clearly quantify the level of impact that erosion causes to natural and human assets. For instance, this study found that in the past decade, beach narrowing and loss have continued in the West Maui area despite wide recognition that beaches need enhanced protective status in Hawai‘i.

We found that between an earlier dataset ca. 2007 and the updated 2015 dataset, the percentage of eroding transects increased by 4%, beach width decreased by 9.4 meters, and beach loss grew to 920 meters from 80 meters. Beach loss was most apparent along areas of shoreline hardening. Averaged over all transects, there was a −0.01 meter/year difference in the overall shoreline change rate between the 2007 and 2015 datasets.

North Kā‘anapali experienced the highest increase in eroding transects and the highest increase in erosion rates. Honokōwai and Kahana had a negligible difference in erosion rates between the 2007 and 2015 datasets. There was a minor increase in the average rate of accreting transects in Northern Honokōwai and Northern Kahana that helped to reduce the overall average shoreline change rate for the 2015 dataset.

We conclude that these data support previous studies identifying negative impacts to beach assets as a result of inappropriate backshore development. Although other causes such as temporary higher sea level from ENSOs and seasonal swell events may be responsible in influencing shoreline movement over the short term, in the context of long-term sea level rise, human development is the most significant factor contributing to beach impacts such as narrowing and loss.

Updating the shoreline change rates in North Kā‘anapali, Honokōwai, and Kahana provides data to assess the near shoreline in recent years. Coastal erosion has continued to happen in the study area and may be a representation of the same or worse level of severity in other parts of Hawai‘i. Erosion will continue to worsen as sea level rise acceleration grows. Without the necessary changes in Hawai‘i’s shoreline management system, the state will continue to head toward a future without beaches.

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