Tracking Shoreline Conditions to Protect Infrastructure

Center for Transportation, Environment, and Community Health
Final Report

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16. Abstract

Recognizing the massive values at stake along US shorelines from sea level rise, we are developing new approaches for tracking shoreline changes. We adapted newly emerging UAV-based elevation mapping to use on shorelines, in order to conduct high spatial and temporal resolution tracking of infrastructure and shoreline conditions. We combined this approach with RTK-GPS (real-time kinematic geo-positioning systems) field measurements to create a multi-scale picture of shoreline change due to sea level rise. Research products included: 1) a demonstration of high-resolution terrain-mapping methods for quantifying shoreline flooding event impacts on coastal infrastructure and adjacent ecosystems, and 2) description of how this information could be used to validate sea level rise models and inform coastal hazard-adaptation planning for shoreline infrastructure.

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Executive Summary

Recognizing the massive values at stake along US shorelines from sea level rise, we are developing new approaches for tracking shoreline changes. We adapted newly emerging UAV-based elevation mapping to use on shorelines, in order to conduct high spatial and temporal resolution tracking of infrastructure and shoreline conditions. We combined this approach with RTK-GPS (real-time kinematic geo-positioning systems) field measurements to create a multi-scale picture of shoreline change due to sea level rise. Research products included: 1) a demonstration of high-resolution terrain-mapping methods for quantifying shoreline flooding event impacts on coastal infrastructure and adjacent ecosystems, and 2) description of how this information could be used to validate sea level rise models and inform coastal hazard-adaptation planning for shoreline infrastructure.

Introduction

US shorelines are naturally affected by tidal changes and storm events. This dynamic and highly-productive environment is home to a wide range of ecosystems, diverse species and critical infrastructure. In the U.S., shoreline counties are home to 40% of the US population (http://oceanservice.noaa.gov/facts/population.html, accessed 3/1/2017). A longitudinal survey of coastal managers in California found sea level rise and related problems to be among the most challenging issues they face (Finzi Hart et al., 2011). Scientists have estimated that as many as 13 million people could be displaced by increased inundation due to sea level rise and coastal flooding. Because of both historical and current population pressures in the coastal zone, property values here are often higher than inland values. Estimates for the total property value exposed to the effects of storms, sea level rise and nuisance flooding range from $7.2 billion for Long Island, projected by 2080 (NYSERDA, 2011), >$100 billion for California (Heberger et al., 2009), to $17 trillion for the entire US coastline (http://www.air-worldwide.com/Publications/AIR-Currents/2015/The-Growing-Value-of-U-S--Coastal-Property-at-Risk/, accessed 3/1/2017). As sea level rise encroaches or seems to encroach on coastal properties, the value loss has been estimated to be $3-5 billion/year and the actual loss of property value to be $500 million/year (Evans, 2004). These property values and economic activities are not accounted for in the valuation of natural and constructed shoreline features that provide free or subsidized services to coastal communities and state economies (Pendleton, 2008). As marshes are impacted, they may be eroded/inundated and no longer front shoreline infrastructure, so that coastal managers will attempt to provide flood protection through other means, which will be complicated by coastal regulation. Coastal flooding potential and actual water levels stand at the intersection of most predictions of climate change impacts on CA shorelines (e.g., Cayan et al., 2008). Understanding the various contributions to instantaneous and potential future water levels at the shoreline is critical for integrated coastal planning that recognizes both green (e.g., tidal marsh) and grey (e.g., roadways and levees) infrastructure.

Although coastal counties increasingly rely on un-validated inundation models to predict where shorelines might be at risk, there is currently no standard method for coastal communities and states to use to reliably track actual risks and impacts to the built and green infrastructure of shoreline areas (see Woodruff and Stults, 2016). Identifying built and green infrastructure that is both exposed now or in the future to the ocean and vulnerable to sea level rise and increased storminess is a complicated and potentially expensive process for local and state transportation agencies (Rowan et al., 2014).

All coastal planning agencies seeking to adapt built-systems to coastal flooding use remote-sensing based elevation models and predictions, which have often inadequate or unknown estimates of accuracy and uncertain timeframes. Previous NCST-supported research by UC Davis team members has resulted in a bi-coastal, time-lapse camera network for monitoring actual changes in shoreline infrastructure and associated ecosystems (Shilling et al., 2017). During the current project, we proposed and partially-developed cutting-edge methods for shoreline terrain mapping. We used these methods to demonstrate both how to carry out shoreline tracking as well how findings from shoreline tracking programs could be used to foster community adaptation and resilience. Using emerging UAV-based terrain mapping approaches and RTK-GPS (real-time kinematic geographic-positioning system), we expanded the concept of real-time detection of degree, extent, and rate of shoreline change to inform adaptation and resilience programs of state and local governments. Essentially, we are proposing an approach to collect shoreline change data that both informs immediate needs of infrastructure agencies and provides data needed to validate the inundation models relied upon to anticipate future coastal risks.

Methods

We measured changes at both large and small spatial extents focusing on shorelines where these habitat areas involve sensitive habitats with threatened and endangered species or adjacent to developed areas with critical human infrastructure. We used both UAV-based terrain mapping and ground-based elevation measurements from real time kinematic geo-positioning systems (RTK-GPS). We compared the two approaches for their ability to estimate ground elevations with very fine grain (centimeters resolution).

RTK-GPS

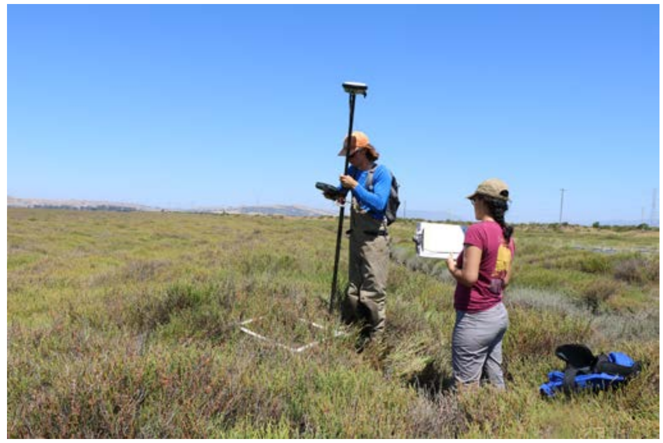

Figure 1. Using the RTK-GPS in a tidal marsh on the San Pablo Bay shoreline.

We borrowed an RTK-GPS from a UCD colleague (Dr. Greg Pasternack) and partnered with the USGS to collect ground measurements along transects carried out by USGS in 2008 (Figure 1). We adapted methods used in marshes and terrestrial systems (Rosso et al., 2006; Bearman et al., 2010; Casas et al., 2012) to capture actual ground elevation with cm-scale vertical and horizontal resolution (i.e., grid cell size). The theoretical accuracy of this instrument is +/- 3 cm. We used the new elevations (2018) to create a new elevation map for the study area and to create a "difference map" comparing elevations in 2018 and 2008. Elevation maps were created using interpolation in ArcGIS to estimate an elevation surface based on elevation measured at points. Specifically, we used the Spatial Analyst tool Interpolation with the Inverse Distance Weighted option and 5 m cell size to create the elevation raster file (Thorne et al., 2013).

UAV

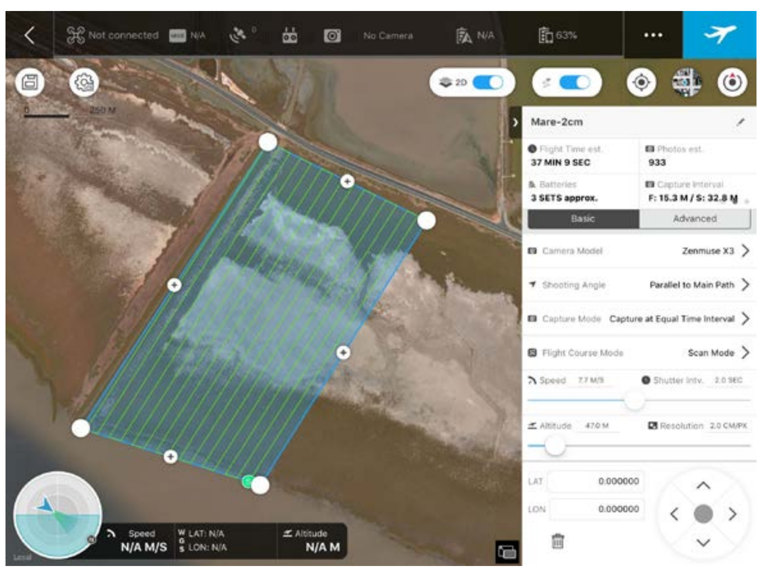

Figure 2. Flight area and flight lines used in the San Pablo Bay tidal marsh adjacent to SR 37.

Our original intention was fly a 1 km x 1 km transect along the developed and undeveloped shoreline between Novato and Vallejo, including marshes, berms/levees, highways/roadways, beaches, and other structures. Due to persistent issues with the UAV (i.e., sent back to manufacturer 3 times for repair), we flew an area of west UC Davis campus with test flights and one flight at the shoreline. We used a Matrice 100 quadcopter (DJI.com; FAA# FA3AYMRNFH) UAV with a high-resolution camera (ZenMuse X3) and onboard inertial measurement unit (IMU) to capture imagery. The theoretical instrument accuracy for this UAV is: Vertical: 0.5 m, Horizontal: 2.5 m. The flight-lines were created using the DJI Mission Planner and approved by UC Davis for research flights (Figure 2). We also used a fixed-wing UAV (FX-61 flying wing; 1550mm; FAA# FA3FFYLFC3) with a Canon Powershot SX 260 HS camera and flight-lines created using the open-source MissionPlanner by Ardupilot (http://ardupilot.org/planner/). Post-flight, images were processed using the Pix4D software, which results in a composite ortho-image of all images (Figure 3).

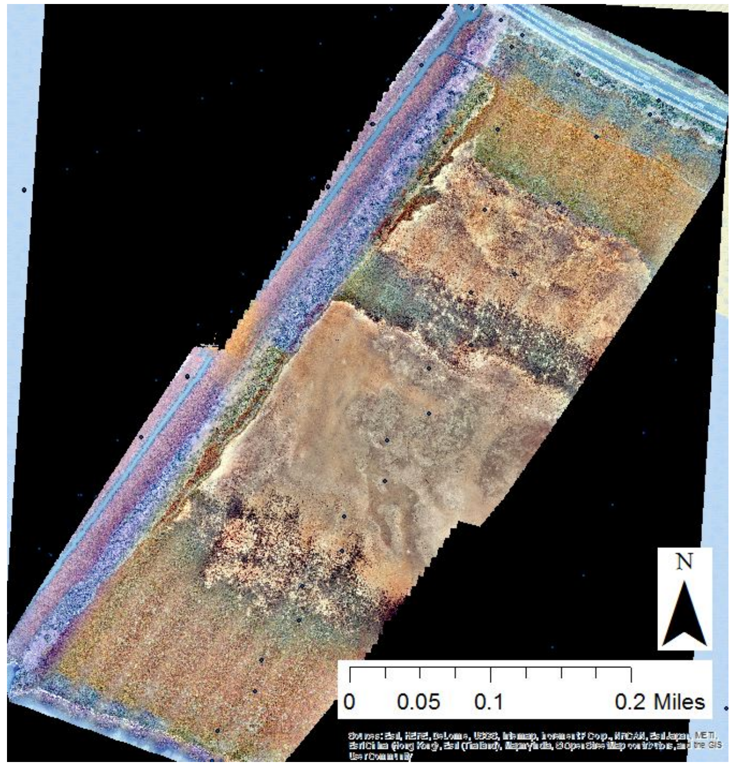

Figure 3. Composite image of all images taken by UAV on San Pablo Bay shoreline.

Results

The outputs of these mapping approaches included a series of high-resolution measurements of elevation, vegetation cover and height, images of the landscape and RTK-GPS and UAV-based raster maps of estimated elevations, for a shoreline adjacent to a state highway. Comparison with elevation measurements taken in 2008 also allowed detection of change in this area. These elevation maps can be compared with 2010 LiDAR-based elevation maps to determine if predictive modeling is likely to be accurate.

RTK-GPS

We generated a map of ground and vegetation surface elevation and change in elevation from 2008-2018 (Figure 4). We also estimated the change in volume corresponding to the change in elevation between 2008 and 2018.

There were dramatic losses in elevation for certain portions of the shoreline (up to 1.8 m) and gains in elevation in others (up to 1.9 m; Figure 4). Basically, the ground surface of the shoreline was rearranged over that decade, leaving some areas lower and devoid of vegetation and others higher and retaining vegetation. The net result of retaining vegetated areas above mean-high-high-water (MHHW) is that these areas are less prone to erosion during storms, king tides, or sea level rise. The result of lost vegetation and lost elevation makes areas more prone to erosion. As much as half of the shoreline abutting 8 miles of SR 37 lost elevation (0.1 to 1.8 m) between 2008-2018.

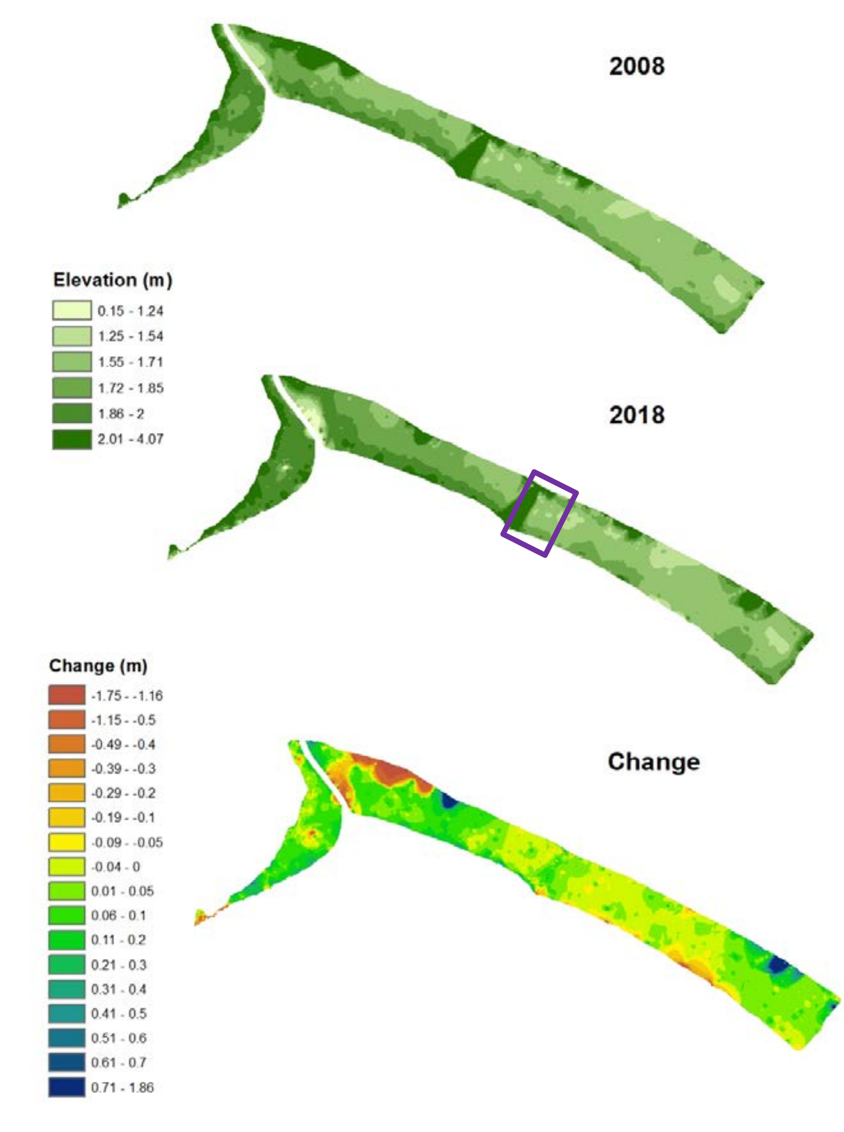

Figure 4. Elevation and change in elevation of the San Pablo Bay shoreline, 2008-2018. The grain/grid cell size is 5 m x 5 m. The purple box over a portion of the 2018 elevation map represents the area flown using the UAV.

We estimated the amount of sediment equivalent to the differences (increases and decreases) in elevation across the shoreline area. The shoreline gained 73,527 m^3 in ground volume between 2008 and 2018. We also estimated the change in vegetation volume, which is proportional to biomass and canopy cover. The change in volume was -394,145 m^3.

These findings suggest that there a minor gain in sediment along the shoreline and that the shoreline changed its overall morphology, including areas in contact with the Bay and the highway that lost elevation. These findings also indicate that there was extensive vegetation loss, which is both a loss of vegetative carbon and of vegetative cover, which can limit erosional and other changes in the shoreline.

UAV

In addition to using RTK-GPS to estimate landscape elevation, we also used UAV-photogrammetry to estimate elevation across a portion of the tidal marsh plain abutting SR 37 (Figure 3). We estimated vertical error for flat portions of the test area in the West Village, which included a roadway. For two 1-meter segments of roadway, which included ~60 measurements of elevation (~2.8 cm pixel size), the standard deviation was 0.8 and 1.1 cm. Assuming these areas are actually flat, this represents the error in the measurement in the field, including instrument (UAV-flying, IMU, camera) and image processing error. We conducted one flight in a portion of the San Pablo Bay shoreline (Figures 2 and 3, purple box in Figure 4). The estimated elevation from photogrammetry for this area ranged from 0.23 to 3.16 m relative to NAVD88 (Figure 5). The resulting UAV-based elevation map was much higher resolution than the equivalent elevation map derived from field RTK-GPS measurements. Both are much higher horizontal and vertical resolution than typical elevation maps from airplane-based LiDAR (typically 1 meter^2 horizontal and 10 cm vertical, RMSE).

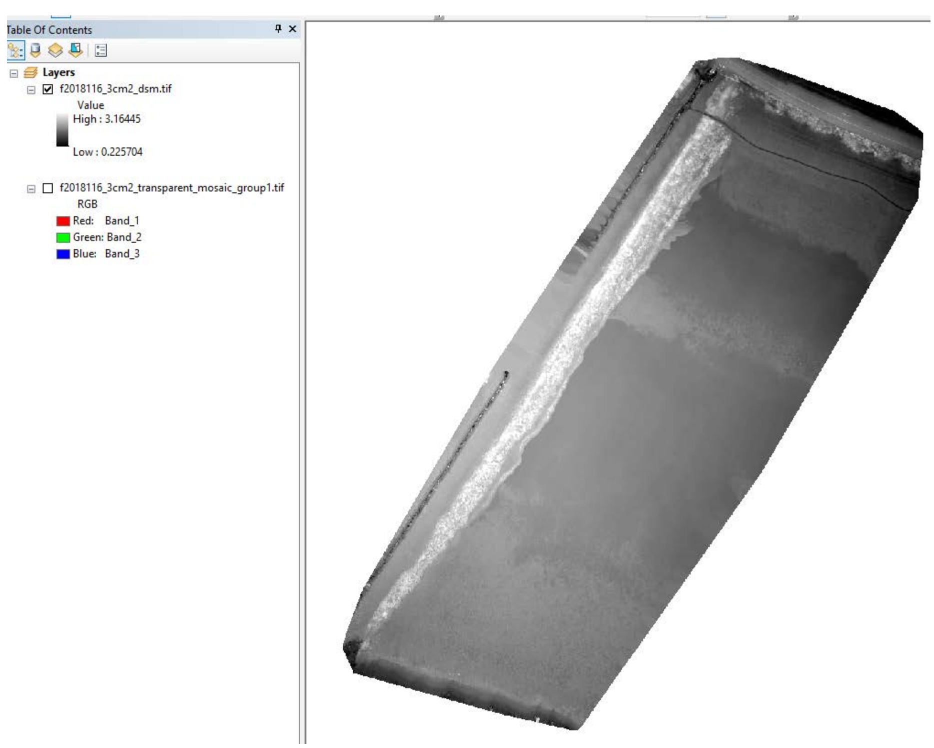

Figure 5. Elevation map derived from UAV-based photogrammetry for area indicated with a purple box in Figure 4.

COMPARISON WITH PREVIOUS ELEVATION MAP

Shoreline mapping to study and predict impacts from sea level rise and storm surge are almost exclusively based on airborne LiDAR data, most of which was collected in 2010. These data are generally lower resolution, have lower accuracy, and greater error associated with them than the combination of RTK-GPS and UAV-photogrammetry. The combination of methods provide greater likelihood that predictive models will be based upon accurate determination of ground elevation, and knowledge of the error associated with the measurements.

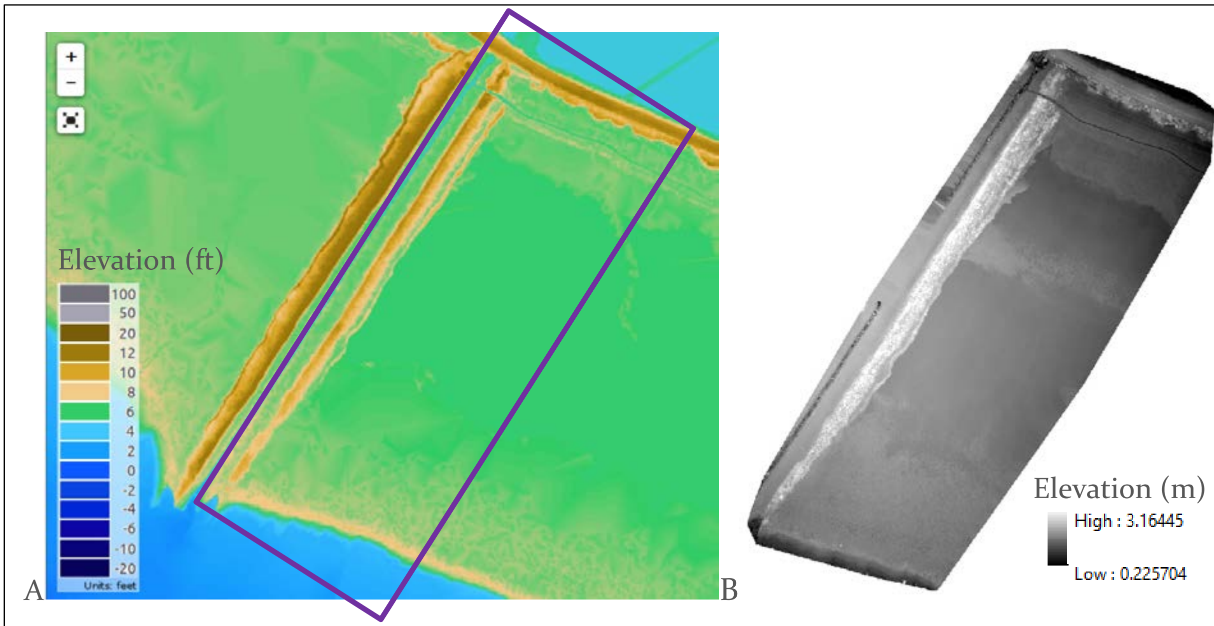

Figure 5. Comparison of previously-estimated elevation from (A) airborne LiDAR and (B) UAV photogrammetry. The photogrammetric measurements have ~100 times the spatial resolution and ~1/3 the error of the LiDAR.

The timeframe of change for the RTK-GPS study (10 years) was only slightly longer than the interval since collection of LiDAR data (8 years), which are the basis for all predictive modeling on the US coastline used in transportation planning. Our results for shoreline change suggests that the actual shoreline conditions now are quite different from when the LiDAR data were collected. In addition, the LiDAR data represent a high-resolution picture of bare ground, where it occurs and the top of dense vegetation on tidal marshes, whereas our RTK-GPS based elevation map represents ground elevations only.

Although the UAV data represent only one time period, they have finer spatial resolution than the LiDAR or RTK-GPS data. However, they also suffer from similar limitations to the LiDAR data, where the surfaces of dense vegetation can't be differentiated from the ground. This can potentially be corrected by subtracting the height of the canopy from the estimated elevation in vegetated areas.

Both the RTK-GPS and UAV-based elevation maps could be used to inform predictive modeling in two ways: 1) to develop a inundation prediction model based upon the data and compare rate and extent of flooding under each model with each approach; and 2) to compare actual inundation with a given sea elevation for each elevation map (i.e., RTK-GPS, UAV, and LiDAR) to see which correctly predicts inundation events.

Conclusions

Shoreline retreat poses a major risk to shoreline infrastructure and despite its potential for significant economic damage, is a relatively under-studied phenomenon. We demonstrated 2 methods for measuring shoreline position and elevation at very fine spatial resolution. In the case of shoreline retreat and loss, fine spatial resolution can translate into fine temporal resolution and can help inform coastal planners, managers, and policy-makers about the gradual or stochastic rate of threat expansion.

We found re-arrangement of the study area shoreline, but no significant sediment loss, over a 10-year period (2008-2018). Some areas that were lower elevation (relative to MHHW) became higher, while others remained high. More importantly, new areas of low elevation appeared, which also corresponded to areas of vegetation die-off. Overall, there was a large loss of vegetation volume on the shoreline landscape, which is likely to result in further and more rapid changes (e.g., erosion, retreat) due to the loss of the protective vegetative cover.

We propose that these methods should be deployed regularly in time and space because they allow determination of rates of shoreline change at fine spatial and temporal scales at relatively low cost. In addition, these methods can results in new elevation maps that can be used to update flood-prediction models which are critical to shoreline adaptive planning.

Citations

Bearman, J.A., C.T. Friedrichs, B.E. Jaffe, and A.C. Foxgrover. 2010. Spatial trends in tidal flat shape and associated environmental parameters in South San Francisco Bay. *Journal of Coastal Research*, 26: 342 – 349.

Casas, Á., D. Riaño, J. Greenberg and S. Ustin. 2012. Assessing levee stability with lidar imagers. *Remote Sensing of Environment*, 117:281-288.

Cayan, D.R., E.P. Maurer, M.D. Dettinger, M. Tyree, and K. Hayhoe. 2008. Climate change scenarios for the California region. Climatic Change Vol. 87 (Suppl 1): S21-S42.

Evans, R.L. 2004. Rising Sea Levels and Moving ShorelinesOceanus Magazine, 43(1), (https://www.whoi.edu/oceanus/feature/rising-sea-levels-and-moving-shorelines).

Finzi Hart, J. A., P. M. Grifman, S. C. Moser, A. Abeles, M. R. Myers, S. C. Schlosser, and J. A. Ekstrom. 2012. Rising to the Challenge: Results of the 2011 Coastal California Adaptation Needs Assessment. USCSG-TR-01-2012. University of Southern California Sea Grant Program.

Heberger, M., H. Cooley, P. Herrera, P.H. Gleick, and E. Moore. 2011. Potential impacts of increased coastal flooding in California due to sea level rise. *Climatic Change,* Vol. 109, (Suppl 1), 2011, pp. S229–S249.

New York State Energy Research and Development Authority (NYSERDA). 2011. Responding to Climate Change in New York State (ClimAID). Pp. 652.

Pendleton, L.H. 2008. The Economic and Market Value of Coasts and Estuaries: What's At Stake? Report of Restore America's Estuaries. Pp. 182Rosso, P.H., S.L. Ustin, and A. Hastings. 2006. Use of lidar to study changes associated with *Spartina* invasion in San Francisco Bay marshes. *Remote Sensing of Environment* 100 (3): 295-306.

Rowan E., C. Snow, A. Choate, B. Rodehorst, S. Asam, R. Hyman, R. Kafalenos, A. Gye. 2014. Indicator Approach for Assessing Climate Change Vulnerability in Transportation Infrastructure. Transportation Research Record: Journal of the Transportation Research Board, Volume 2459. DOI: 10.3141/2459-03.

Shilling, F.M., D. Waetjen, K. Taniguchi, T. Grosholz, E. Grijalva, C. Sur, K. Andrews, and A. Ballard. 2017. Using time lapse cameras to track shoreline change due to sea level rise. Report to National Center for Sustainable Transportation, Davis 16 pages

Thorne, KM, DL Elliott-Fisk, GD Wylie, WM Perry, and JY Takekawa. 2013. Importance of Biogeomorphic and Spatial Properties in Assessing a Tidal Salt Marsh Vulnerability to Sea-level Rise. Estuaries and Coasts, DOI 10.1007/s12237-013-9725-x.

Woodruff, S.C. and M. Stults. 2016. Numerous strategies but limited implementation guidance in U.S. local adaptation plans. *Nature Climate Change*. http://www.nature.com/nclimate/journal/vaop/ncurrent/full/nclimate3012.html