Using Time Lapse Cameras to Track Shoreline Change Due to Sea Level Rise

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A Research Report from the National Center for Sustainable Transportation

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Executive Summary

Shoreline habitats and infrastructure are currently being affected by sea level rise (SLR) and as global temperatures continue to rise, will continue to get worse for millennia. Governments' and individuals' decisions to adapt to SLR could have profound consequences for adjacent ecosystems, transportation systems, and urban settings. The cost for this adaptation will also increase over time. Natural systems often attenuate impacts of SLR and storms, providing a free and often unrecognized and under-appreciated protective service for shoreline infrastructures. There is no current information available to shoreline agencies on fine-scale and near-term/current changes in shoreline in response to SLR. We describe a method to monitor shoreline and infrastructure changes in response to SLR using a network of time-lapse cameras. We found that the method was sensitive to vertical changes in sea level of <1 cm, roughly equivalent to 1-2 years of SLR under the A1 scenario (i.e., high emissions/business-as-usual). SLR of >20 cm has occurred in the San Francisco Bay and other US coastal areas and is likely to rise by another 30-45 cm by mid-century. This rapid degree of rise means that it is imperative to include planning for infrastructural modifications in current regional and corridor plans. Accurate and timely information about the actual extent of SLR impacts to shorelines will be critical during highway adaptation. The method described is feasible for near-term (1 to 10 years) to long-term application, and can be used for measuring fine-resolution shoreline changes (e.g., degree of inundation, plant cover, and geomorphology) in response to SLR and associated wave action inundation of marshes and infrastructure. We demonstrate the method with networks of cameras in two coastal states (CA and GA), using web-informatics and services to organize photographs that could be combined with related external data (e.g., gauged water levels, moon phases) to create an information mashup. We discuss how outputs from these techniques could be used to validate models of SLR threats to coastal systems and inform transportation and regulatory decision-making. Finally, we discuss next steps, including using two other, complementary methods for monitoring shorelines: drone-based terrain-mapping and historical, opportunistic and satellite photographs.

Introduction

California's coastal communities face significant risks from storms in the form of flooding, erosion, and shoreline retreat. Climate change is expected to result in accelerated rates of sea level rise (*1*) and changing seasonal wave conditions (*2*), further exposing the California shoreline to impacts (*3*, *4*). A longitudinal survey of coastal managers in California found sea level rise (SLR) and related problems among the most challenging issues (*5*). The federal transportation authorization act, Safe Accountable Flexible Efficient Transportation Equity Act (SAFETEA-LU), lists 8 planning factors in developing sustainable transportation systems, most of which can be related to impacts of SLR on coastal systems. These factors include increasing driver safety and mobility, protecting the environment, linking transportation planning to local economic and development activities, maintaining the existing networked systems, and efficient system operation and management (http://www.fhwa.dot.gov/safetealu/, accessed 7/28/2016).

Sea level has already risen by 20 cm along the California coast and may be 1.5 m above present levels by 2100 (*6*). Ice sheet melting is accelerating in Antarctica, so it is likely that SLR will concomitantly increase (*7*). Increased wave energy has occurred and is expected to continue over the coming century. However, transportation system and coastal vegetation adaptive changes occur slowly and may not be rapid enough to keep up with increased SLR and storm-driven inundation. Adaptation of infrastructural and natural systems will need to occur to avoid a wholesale change in tidal marshes, estuarine systems, low-lying urban areas, and exposed highway infrastructure.

Tidal marshes provide many key ecosystem functions and services including nutrient absorption, carbon sequestration, flood and storm attenuation, water filtration, coastal recreation, and habitat for many species including several that are threatened or endangered (*8*, *9*, *10*, *11*). Coastal ecosystems, including tidal marsh habitats, are some of the most at-risk environments in an era of climate change, especially because of SLR projected for the coming decades and century (*12*). Because of the low elevation of tidal marshes, small changes in mean daily tidal elevations lead to large changes in the frequency, duration and intensity of inundation, which strongly affects plant and animal communities that inhabit the intertidal zone (*13*, *14*, *15*). Before human appropriation of tidal marshes for agriculture and urbanization, these habitats adapted to changing sea levels by changing configuration of the shoreline, advancing inland or retreating with higher or lower sea levels respectively (*16*, *17*).

In modern times, tidal marshes and estuaries have become centers of agriculture and human population. The confluence of fresh water, high levels of natural resources, and access to the sea has led to dense agricultural, urban, and industrial development of most temperate and tropical estuaries. Diking, dredging, filling, and poldering (separating marshlands from natural hydrology by diking) have greatly reduced the extent of tidal wetlands in California (*10*, *18*).

San Francisco Bay (SF Bay), CA on the west coast of North America, is a good case study for these issues. The human population of the greater SF Bay Area (which includes the 9 counties bordering SF Bay) exceeded 7 million in 2010 (*19*). Great efforts have been made over the last 20 years to quantify and coordinate habitat goals for restoration planning in SF Bay and its ecosystem. Part of this work involves the restoration of more than 100,000 acres of tidal marsh wetlands around the bay over the next 50-100 years (*10*, *17*). However, many of the remnant marsh patches around the SF Bay are bordered on the landward side with agriculture, or various types of infrastructure and development that cannot be easily or cheaply relocated. SF Bay contains many important ecological features; therefore restoration of tidal marsh habitat in SF Bay must incorporate measures to foster higher levels of ecosystem function, as well as assuring integrated planning with any required adaptations in infrastructure. Physical change is a reality for managers and residents throughout the California coast, yet we have little precise and systematic information about how that coastline is actually changing on useful temporal (annual to decadal) and spatial (meter to kilometer) scales.

Measuring and adapting to actual rates of shoreline change is a critical component of federal and state climate change policies. Measurement of sea level has historically been done using tide gauges and global satellite altimetry, which has been available since 1992. There is no consistent method or system for measuring and recording shoreline change over large areas and at fine resolution other than infrequent and expensive LiDAR overflights that do not capture more frequent seasonal fluctuations. The most recent coastal LiDAR data (2010) that has been used to inform the Federal Highway Administration (FHWA) and other studies have known sensitivity to vegetation height on coastal floodplains and marshes. Actual sediment surface elevations may be 6 to 12 inches lower than predicted by LiDAR data because of vegetation interference, which alter any LiDAR-based predictive modeling of SLR and affected area. In a recent Hydraulic Engineering Circular (*20*), FHWA recommends using these predictive models to inform adaptation planning for coastal highways and systems, and that model validation use hind-casting of elevations. There was no recommended method for directly monitoring shoreline change, or using change detection to validate and update the predictive models, which is possibly because no such methods have been developed and tested. Remote sensing does not occur frequently enough to measure important fine-scale changes and predictive models have unknown accuracy for measuring change. Using these methods, transportation planners and ecosystem restoration ecologists must propose expensive, long-term programs to decision-makers based on large-scale, predictive models (e.g., *21*) which have not been validated based upon field measurements of shoreline change in response to SLR.

Developing sustainable transportation systems involves conscious and deliberate acts of investigation of benefits for and impacts to transportation systems and implementation of programs and projects that will mitigate these impacts. SLR is a subtle process only detectable using instrumentation such as time-lapse cameras, unless detailed measurements of the process of SLR and coastal change are used to show the rate and extent of the process and impacts. We present here an approach to carry out fine-scale, short-term data collection needed to fill the current gap in understanding of shoreline change in response to SLR. The approach relies on time-lapse cameras to record changes at high temporal resolution (e.g., 10 minute intervals) and spatial resolution (0.1-100 m^2). Academic coastal camera monitoring systems were pioneered in the 1980s and have since been used to monitor beach and surf conditions (*22*, *23*, *24*). Ours is the first systematic application of this approach to the process of shoreline change in response to SLR. This method also provides visual evidence to decision-makers of the process of SLR and its impacts, and facilitates the prioritization of mitigation actions in the presence of limited funds.

Approach

Study Areas

Two networks of shoreline monitoring stations were developed in the United States, one on the west coast in the San Francisco Bay Area, California (Figure 1A) and the other on the south-east coast on Jekyll Island, Georgia (USA, Figure 1B). Permission of various kinds were required for deployment of the system in or near sensitive coastal ecosystems and infrastructure. The system is designed to be in place for years, up to decades, to measure shoreline change. Because of this, it was necessary to choose locations for mounting cameras that were unlikely to move or be lost in response to shoreline change, or were unlikely to be affected by ownership changes or theft. Forty time-lapse cameras (CA:25; GA:15) at 19 (CA) and 14 (GA) locations were directed toward a natural or artificial feature, or both. Sites were chosen in partnership with eventual users (based on meetings with managers of natural or built coastal features, members of educational institutions, and non-governmental organizations) of climate change impact and coastal change data. Sites were categorized based upon stakeholder input (numbers of each type per state): 1) shoreline levees, berms, or riprap providing flooding/inundation protection (CA:11: GA:2); 2) developed (residential/commercial) areas (CA:3); 3) transportation structures (local roads and state highways, CA:6 GA:4); 4) critical shoreline infrastructure (e.g., power station, GA:1); 4) natural or restored marshes, beaches and mudflats (CA19: GA:11); and 5) actively-managed areas (CA:4).

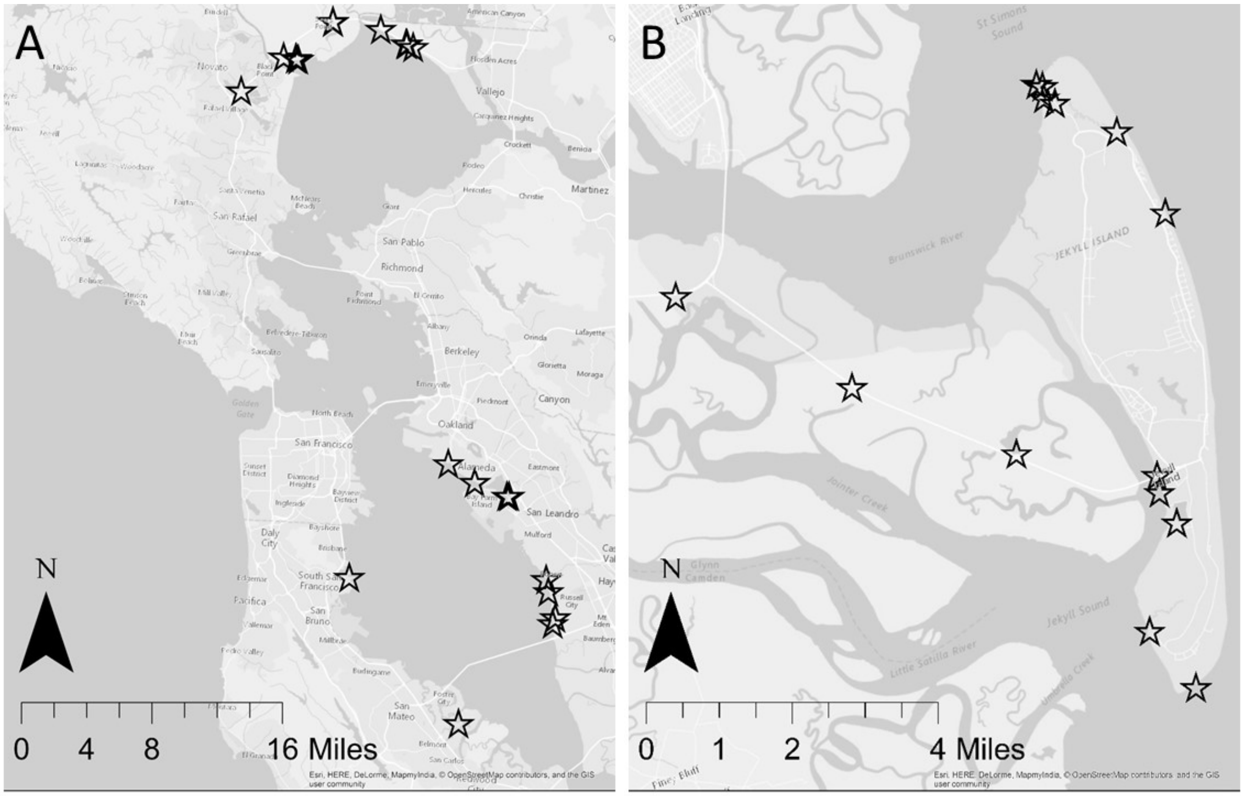

FIGURE 1. Locations (stars) of time-lapse cameras in (A) SF Bay Area, CA, and (B) Jekyll Island, GA.

Instruments

Two models of Bushnell trail cameras were used (Aggressor HD and Trophy Cam HD), collecting 14 mega-pixel and 8 mega-pixel images, respectively. Cameras were mounted in steel lock-boxes on existing or newly-erected posts and other structures, between 7' and 20' above dry ground/mean higher high water. Locations and structures were chosen so that disturbance of the camera was unlikely for several years. Camera lateral and forward pitch were measured and fixed so that lateral pitch was 0^{o} $\pm 0.1^{o}$ from horizontal, and forward pitch was known, recorded, and generally between 10^{o} and 15^{o} from vertical. Time interval between images was generally 5, 10 or 15 minutes, each image having an automatic time stamp embedded in the image file.

Web-Based Informatics

Data management was supported by a web-based informatics system which includes a large file system for storing images, a database for tracking metadata and integrated data components, and a Content Management System (CMS) to provide a method for human interaction with the data and the project level information, including the locations and placement of the cameras. We used open source tools to develop the system "stack", including the following: Ubuntu Linux server to manage the overall web system; Apache Web Server to provide web services; PostgreSQL Database Management System for data storage and retrieval needs; PostGIS to manage additional geospatial data and for performing other spatial queries; and Drupal 7 CMS as the public-facing web-system.

Novel web-services were created to carry out the following functions: 1) accept image files as data-points and store them according to pre-set protocols; 2) add metadata to the image file data-points using automated (e.g., time, date, location) and manual approaches (e.g., site identity); 3) store image files in a searchable/queryable database to support quality control and visualization and data use by oceanographers, coastal planners, community organizations, ecologists, and others (e.g., local agencies); and 4) develop simple automated summaries of image data for each camera-monitoring location, which could be composed of several cameras.

The system has a concept of a project where only its members have the ability to add and edit the data under its umbrella. Underneath a project are two spatial concepts, a monitoring location, and a camera position, both which are represented as spatial coordinates. We instituted the hierarchical relationship so that multiple cameras can be represented by the same location (not more than 100 meters apart), and hence, similar tidal attributes. A project can have many locations, and those locations can be far away from each other, and are assumed to have different tidal attributes.

Storage and Processing Requirements

There are a number of factors which determine the size of an image from a 14 megapixel camera, the primary type used here. If the photo is saved as JPG file type, a lossy format, the compression level, which can vary, will determine how much information is lost. For this project, we kept the image in the original format in which the camera stored the image. We estimated the storage requirements, which impacts web-system functioning for larger camera networks by calculating the annual storage needs for one camera based on frequency the images are taken during a day and an average file size.

Bulk Upload & Wireless Ingestion of Photographs

Time-lapse cameras photograph the land/waterscape at a set interval, such as every 10 or 15 minutes. Each image is stored on the camera's internal memory (such as a SD card), which, depending on the size of the card, frequency of photos, number of megapixels, and a sufficient power source, can store several months-worth of data. These data can be incorporated into the data portal by manually uploading a set of images or through an automated import mechanism which can ingest the photograph after it has been transmitted from the camera (via wifi or physical cable), across a network (such as 3G, 4G, and 802.11), and to the server where a web service manages the image queue. The images collected from each camera are included in a compressed file (.zip) of images and uploaded to a corresponding web-system position. An automated routine un-compresses the file, renames the photographs, and assigns them to the position. Remote transmission of data is more cost-effective, but loss of data might be higher due to the greater instability of the network connections. In the end, both methods associate a physical camera in the field to a camera position on the data portal, extract metadata from the image's Exif region to become part of the data record, and ultimately provide access to the photographs across the web. From the position page on the website, a user can view all of the corresponding photographs, and download sets of images in bulk, for other types of analysis.

Image Correction and Analysis

Perspective rectification was carried out for oblique images to mimic an overhead view by correcting for trapezoidal distortion using the "perspective" tool in GIMP. This method was necessary for calculating unit-area within oblique images and could be simultaneously applied to large sets of images. Inundation-quantification was based on vector quantization in order to automatically conduct basic tasks like quantify area and duration of shore inundation, or height and duration of contact with infrastructure from series of photographs. We quantified inundated area by changing color ranges in images to black and white using the "threshold" tool in GIMP and using GIMP's "histogram" tool to measure the white area within certain zones of the images particular to the camera view. The threshold tool converts a color or greyscale image to black and white, where white pixels are those within the threshold range determined by the user, ranging between X and 255. In this case, the threshold range was set so that water-covered area were separable from non-covered areas, where the value at the lower end of the range was given and the upper value was always 255. These zones were selected manually for each camera view and then used repeatedly for time series of images. The result of the measurement could be expressed as a percent of the study area, or as area if the dimensions of the study zone were measured.

Sensitivity to Changing Sea Elevation

We studied marsh inundation during the upward arm of single tide cycles as a way to mimic the effects of sea elevation rising. Inundation area and rate of tide rise was estimated for two separate types of marsh areas in the North San Francisco Bay. One was vegetated with dense cover of pickleweed (Salicornia spp.), which is typically associated with mid-high tidal brackish and salt marshes. The other was dominated by bulrush (Scirpus spp.), which is also typical of mid-tidal marshes. We measured changes in inundation, as indexed by change in light reflected from water surfaces, during half of a tidal cycle (29 January, 2014, bulrush marsh; 25 November, 2015, pickleweed marsh). We compared rate of change in sea elevation due to the tide rising to the increase in light reflectance from water surfaces inundating the shore. Water elevation data was retrieved from the National Oceanic and Atmospheric Administration (NOAA) Tides and Currents website (http://tidesandcurrents.noaa.gov/), for the Richmond station (http://tidesandcurrents.noaa.gov/stationhome.html?id=9414863). Rate of change was calculated as the slope of a linear regression analysis for water elevation or area of marsh inundation.

Correcting for Illumination Differences

Estimating inundation relies upon quantifying the water-surface areas in images using image processing and analytical tools. Under most light conditions and with the oblique angles used, the surface of water is often the brightest object in any given shoreline image. We tested how much light reflectance from non-water objects in images (e.g., vegetation) could affect conclusions about inundation. We used a single marsh area, changing the analyzed area and the thresholds used for converting a color range to a luminance range, where white indicates illumination and black no illumination.

Results

Deployment of the Systems

After 12 months we had retained 32 of 33 original camera locations, but lost access to one due to planned breach of a levee as part of a marsh restoration project. Stakeholder/partner interest stayed high throughout the deployment of cameras, suggesting that expansion of camera networks and use of data is likely to occur.

Web Informatics

For high-frequency time lapse (1 minute), we found the annual storage requirements for one camera was up to 2.1 TB based on ~526,000 images (depending on duration of daylight). For lower frequency (e.g., 30 minutes), the number of images and storage requirements would be correspondingly lower (~17,500 and 70 GB, respectively). Our project has deployed 40 cameras so far, and uses 5, 10, and 15 minute intervals, with the average being 10 minutes and the average file size just below 3 MB. Given these parameters, our current network will produce ~6.3 TB of image files per year. This is a consideration in expanding the camera system and querying the database.

Image Correction

We batch-corrected images for distortion due to perspective by applying a correction trapezoid (Figure 2A). We then batch-converted the images to a two-color threshold value that turned water surfaces into white pixels (Figure 2B). The pixels/m change predictably in the resulting rectangle 200 pixels/m at the lower end of the trapezoid to 21 pixels/m at the upper end (Figure 2A). This allows conversion of various pixel positions away from the camera to be converted to unit-area. Although we did this on small sets of images, this approach could be automated using darktable or GIMP.

FIGURE 2. Correction for perspective and conversion to image for quantification of water surface area. A) Trapezoidal area used to select sample area within image for correction. B) Resulting rectangular sample area, converted to 2-colors (black and white), where white corresponds to water surfaces.

Sensitivity to Changing Sea Elevation

The two North San Francisco Bay marshes (pickleweed, bulrush) demonstrated different patterns and rate of inundation, which was related to their composition (Figure 3). The rate of sea elevation change in response to the tide rising was 0.62 cm/min and 0.49 cm/min (brackets, Figure 3A & Figure 3B, respectively). The corresponding increase in inundated area per cm rise was 27,935 pixels/cm and 22.073 pixels/cm (brackets, Figure 3A & Figure 3B, respectively).

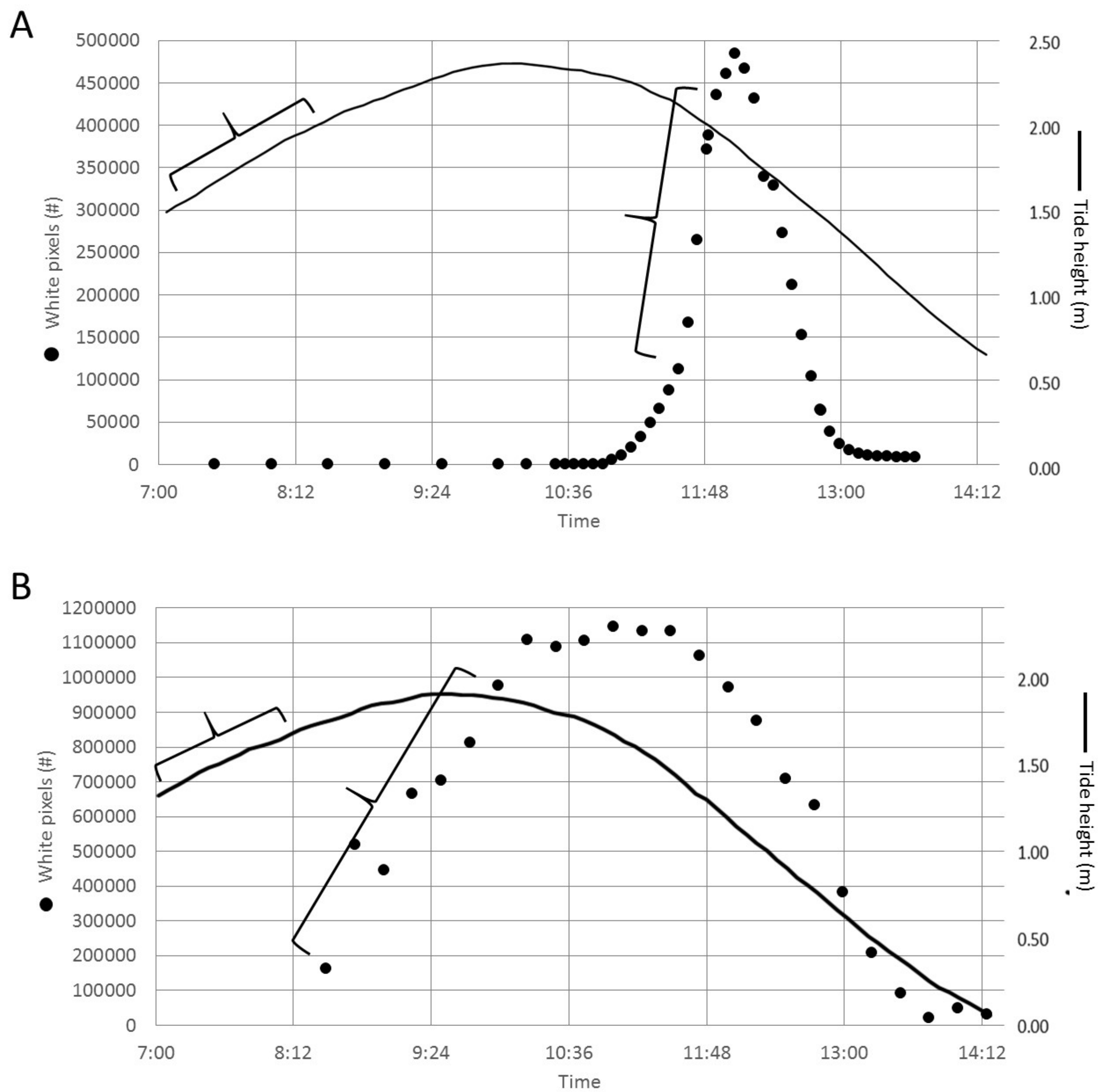

FIGURE 3. Estimated marsh inundation and tide-based change in sea elevation for one tide cycle. Change in reflected light (# white pixels) and sea elevation (tide) for: (A) a mid-high tidal, pickleweed-dominated marsh and B) a mid-tidal, bulrush-dominated marsh. Brackets indicate the range of tide heights and marsh area used to calculate rate of water elevation change and rate of inundation.

Correcting for Light Reflection Differences

We compared two analysis area conditions and two reflected light quantification conditions (Figure 4). In the first case, the analyzed marsh area included both vegetation and a dendritic channel network (Mixed) or primarily the dendritic channel network (Simple). In the second case, the threshold for conversion of the color image to black and white was low (Threshold 127) or high (Threshold 200), where the high threshold converts low-reflectance pixels to black and low threshold is more permissive. There was greater measured reflectance (# white pixels) from vegetation when threshold = 127, and none for threshold = 200 (Arrow 1, Figure 4). There was even more for the Mixed analysis area that included more vegetation (Arrow 2, Figure 4). The measured reflectance converged in the Simple analysis area for the low (gray circle) and high (open square) threshold values when the area was dominated by water surfaces. Although the Simple and Mixed analysis areas were the same size (# pixels), the total reflectance was greater in the Mixed area (Arrow 3, Figure 4), which also included more unsubmerged vegetation. The Simple analysis area was dominated by dendritic channels and reached a maximum reflectance value (~300,000) once the entire analysis area was filled with water surfaces.

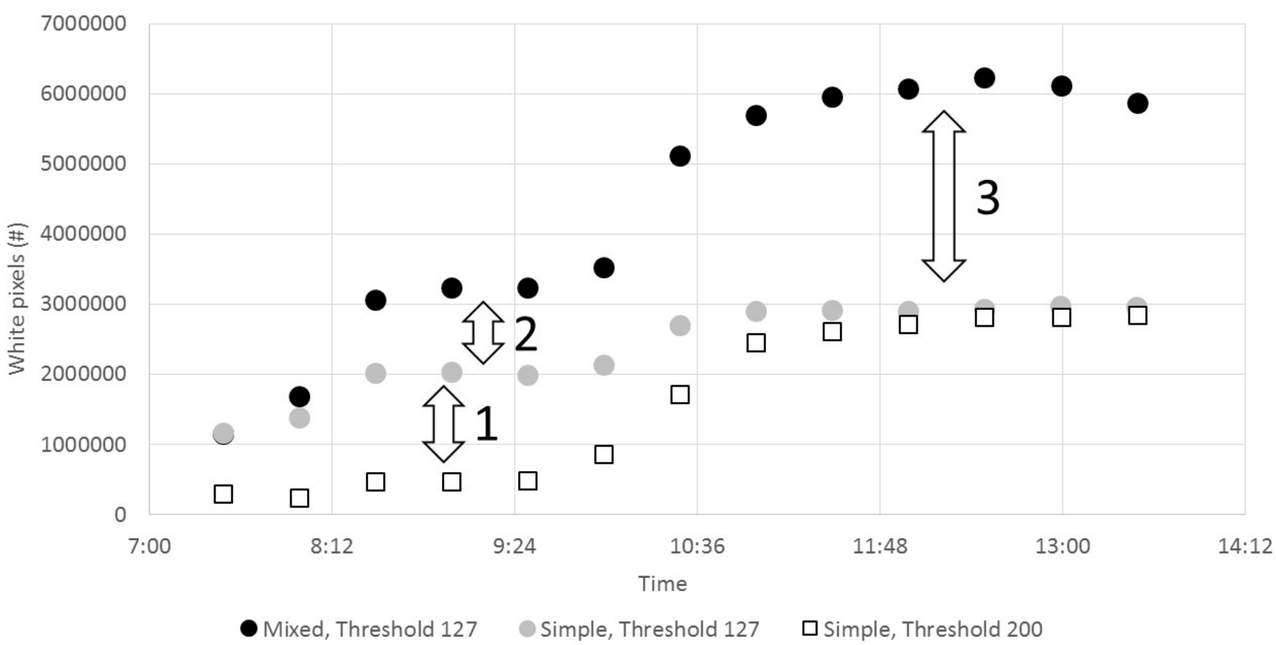

FIGURE 4. Effect of analysis area and threshold value for measuring light reflectance. The open squares correspond to reflected light (# white pixels) for the Simple analysis area with a threshold of 127. The gray circles correspond to reflected light for the Simple analysis area with a threshold of 200. The black circles correspond to reflected light for the Mixed analysis area with a threshold of 127. The arrows denote comparisons among values where light reflection from vegetation was common and controlled for through threshold settings and are numbered according to different types of comparison.

Discussion and Conclusions

We describe a novel method for better understanding the effects of SLR on shorelines by monitoring fine-resolution (spatially and temporally), multi-extent shoreline change over short to indefinite time intervals. The method is suitable for quantifying shoreline change in response to SLR, or any other rapid or slow cause of change. We found that the method was sensitive to vertical changes in sea level of <1 cm, roughly equivalent to 1-2 years of SLR under the A1 scenario. High-resolution (i.e., 14 MP) images also provide detailed spatial information (<1 cm^2) for objects near (10's of meters) the camera, including sediment, vegetation, and infrastructure. We propose that the data collected could be used for three primary purposes: 1) measuring actual shoreline changes in the places monitored; 2) validating regional change (e.g., inundation) models using local, high-resolution (spatial and temporal) imagery/image analyses; and 3) demonstrating rate and magnitude of SLR impacts to inform the public about relative urgency of adaptation.

Relevant Policies and Agency Activity

Federal guidance for climate change adaptation in coastal ecosystem and transportation systems relies on predictive models to guide planning (*10*, *20*). This includes planning for the recovery of endangered species in the face of SLR, which is mandated by the federal Endangered Species Act (ESA) (*11*, *25*). These needs are reflected in the approach that every coastal U.S. state has taken of either generating coastal inundation/threats maps based on elevation models and SLR projections, or adopting those of other organizations. At the same time, federal organizations, such as FHWA, and others have recognized that new monitoring methods, including involving private parties in data collection, will be needed to collect new kinds of data and at a finer scale and wider extent (*26*). California state policy (*27*, *28*) provides extensive step-wise guidance on how to plan for SLR, including the use of predictive models. It also suggests that monitoring (*27*, Step 6 of 6) is part of the adaptive management approach necessary to protect coastal natural and infrastructural features. Despite the recognized need for monitoring methods, no detailed guidance on implementation is given at the state level (*27*, *28*) or federal level (*26*) for how to do this.

Infrastructural and regulatory scientists and planners are struggling with both how to estimate potential impacts of SLR and increased wave run-up on natural ecosystems and human economies, and how to mitigate the impacts through adaptive actions. We have not found evidence in the literature of the type of data collection that we describe. Most approaches rely upon aerial photogrammetry, which has insufficient temporal and spatial resolution to understand SLR impacts on local scales. The vast majority of the discussion revolves around predictive models of how coastal systems will be affected with very little measurement of actual magnitude and type of change. This may be primarily because of the perception that the changes will be slow and thus hard to measure and that fixes will be expensive. With this project, we demonstrate how it is possible to monitor SLR on annual to decadal time frames and how this information could be used to inform adaptive planning and project development, especially in an environment where highly-regulated coastal systems are adjacent to the valuable infrastructure (e.g., highways) that must be adapted.

Our approach embraces the finding that new knowledge and technological systems are far more likely to be effective if “co-produced” with a wide range of actors who will be involved in their implementation, and in the use of resulting data (*29*, *30*). Beyond the many promising co-benefits of this approach (e.g., education, community engagement) it may reveal cost-effective pathways toward a statewide coastal change monitoring network with importance to local communities, researchers, and agencies.

Sustainable transportation necessitates acting at multiple scales, from project to region. The method described here could be used to inform the Regional Transportation Plan scale by validating predictive models of SLR and impacts at this scale and informing prioritization of action among highways and sub-regions. It could also be used to inform local-scale planning and implementation of adaptation goals, including placement of particular infrastructure and restoration of marsh resilience. In particular, if specific areas or types of shore ecosystems are particularly vulnerable to SLR, then transportation organizations planning for adaptation of coastal infrastructure could give consideration to possible future conditions of regulated ecosystems and species. Finally, the proposed study will be useful at the project scale, where design and funding of specific infrastructure takes place and regulatory interaction associated with coastal systems is most detailed and rigorous.

Next Steps

During the planning of the project and deployment of the cameras, we found that partner agencies thought of many other uses that could be made of the large quantities of high-resolution (spatial and temporal) imagery. We also began to explore using satellite images to retrospectively measure coarse levels of change in shorelines, over years or decades. Finally, we began investigating ways that we could use periodic drone flights with photographic and LiDAR detection of change to complement the method described here. Our planned next steps include:

1) Maintenance and expansion of the camera networks to include more built and natural system elements (e.g., coastal bluffs) and types of partners (e.g., local/municipal government);
2) Potentially reducing image resolution to reduce database management requirements, while retaining enough information to track change;
3) Incorporating satellite image analysis as a large extent, low-resolution way to complement our approach;
4) Using drone-based LiDAR and/or image analysis to periodically measure low-tide surface elevations and confirm estimates of inundation from our land-based cameras; and
5) Continue to share information about the system and data with interested parties.

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