Environmental Modelling & Software 52 (2014) 111–120

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

A simplified approach for simulating changes in beach habitat due to the combined effects of long-term sea level rise, storm erosion, and nourishment

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ARTICLE INFO

Article history:
Received 16 October 2013
Accepted 20 October 2013
Available online 15 November 2013

Keywords:
SLAMM
Coastal erosion
Beach nourishment
Hurricanes
Risk contours

ABSTRACT

Better understanding of the vulnerability of coastal habitats to sea level rise and major storm events are aided by the use of simulation models. Since coastal habitats also undergo frequent nourishment restoration works in order to maintain their viability, vulnerability models must be able to assess the combined effects of sea level rise, storm surge, and beach nourishment. The Sea Level Affecting Marshes Model (SLAMM) was modified and applied to quantify the changes in the beach area in a 5-km stretch of beach in Santa Rosa Island, Florida due to these combined effects. A new methodology to estimate spatial erosion patterns was developed based on measured erosion during three historic storm events representing a wide range of storm intensities over the study area (named storms Ivan (H5), Dennis (H4), and Katrina (TS)). Future major storms over the 2012–2100 period were generated based on the frequency distribution of historic storms using 4000 simulations to account for uncertainty in the storms temporal distribution. Potential effects of individual, successive, and random storms occurring over the area under 0–1.5 m nourishment schemes were evaluated. The risk of losing the beach habitat in 90 years for different scenarios is studied based on probability distribution contours constructed with the model results. Simulation results suggest that without nourishment, a major storm with a category of tropical storm or higher will reduce the beach at the end of the period by 97–100%. This loss can be reduced to 60% by maintaining a 1-m beach elevation and can further be reduced to 34% with 1.5 m beach nourishment.

1. Introduction

Coastal habitats are some of the most dynamic and vulnerable habitats due to their proximity to water bodies and their inherently complex land/water dynamics. In addition, they are also vital for shoreline dependent organisms, tourism, port facilities, and military installations. Beaches in particular form the first line of defense against coastal storms for the communities located adjacent to them. Continuous sea level rise and seasonal storms can significantly alter these habitats resulting in habitat modification, habitat loss, and damage to structures. In order to maintain the viability of these shorelines for anthropogenic and ecological services, protection and restoration efforts are implemented in the form of beach nourishment (i.e., dredging off shore and depositing dredged materials on shore) which is the most common shore protection implemented in many countries (Anthony et al., 2011, Finkl, 1996; Leadon 2002; Hamm et al., 2002, Van der Wal, 2004). Predicting the potential state of coastal habitats in time is crucial as a foundation for comparing viable restoration and management alternatives. However, simulating changes in these habitats is a challenge due to the complex interaction between the different coastal processes (e.g. inundation, erosion, sedimentation, wetland conversions and shoreline modifications during long-term sea level rise) taking place at different temporal and spatial scales and the uncertainty associated with estimating these processes under future scenarios. Some processes occur over a longer period while others occur abruptly within a season. For example, sediments are constantly transported in and out of the habitat due to seasonal tidal movement and gradual sea level rise. Moreover, sudden and massive sediment movements can occur during major storm events (e.g., hurricanes and tropical depressions) which can drastically change

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http://dx.doi.org/10.1016/j.envsoft.2013.10.020

the habitat. These processes affect the capability of the habitat to perform its designated roles (Greening et al., 2006). A numerical model that can simulate the combined effects of all these coastal processes (i.e., sea level rise, erosion by seasonal major storm events, and nourishment) is an ideal tool to use to predict the fate of the habitat which can be used as basis for conservation and restoration endeavours. However, there are clear practical limitations when incorporating physically based coastal models for predicting beach erosion in long-term simulations such as those assessing the impact of sea level rise. Generally, predicting the morphological impacts of major storm events on coastal habitats always involves the use of physically based hydrodynamic models that require numerous parameters to be estimated by calibration (Larson et al., 2004; Leont'yev, 1996; Marsonet al., 2004; McCall et al., 2010; Roelvink et al., 2009; Van Rijn, 2009) as well as clearly defined boundary and initial conditions. Due to the spatial and temporal variability of the parameters governing near-shore sediment movements (Levin et al., 2006; Morton, 2010; Quartel et al., 2008) these models are usually applied to smaller areas and are also computationally demanding. Moreover, the combined effects of the short-term erosion from these storms and the long-term erosion from sea level rise are not evaluated in these models which add uncertainty to the results in long-term assessment cases where sea level rise is the dominant process.

The habitat model SLAMM version 6 (Sea Level Affecting Marshes Model) (Warren Pinnacle Consulting, Inc., Warren, VT), an open-source code software developed in the 1980s with the U.S. Environmental Protection Agency (EPA) funding, has been used to simulate changes in coastal habitats due to sea level rise in order to assess the future of numerous wetland areas in the United States (Chu-Agor et al., 2011a; Craft et al., 2009; Geselbracht et al., 2010; Galbraith et al., 2003, 2002; Lee et al., 1992, 1991; NWF, 2006; Park et al., 1993, 1991). It simulates the dominant processes involved in coastal wetland conversions and shoreline modifications during long-term sea level rise. Inundation (i.e. reduction in elevation due to sea level rise), gradual erosion, overwash, saturation, salinity, and accretion are the primary processes included in SLAMM with simplified rule-based and empirical algorithms. It has the advantage of being a simple model to use with minimal data requirements and yet it simulates all major processes pertinent to wetland and shoreline changes. It provides relevant information needed by policymakers and environmental managers at low cost. Currently, SLAMM does not have the capabilities to simulate abrupt changes in the elevation of the habitats due to erosion by major storm events or due to restoration activities such as beach nourishment. This limitation prevents the inclusion of time-specific events like hurricanes, which are inherent in these kinds of coastal habitats. The need to simulate the combined effects of sea level rise, erosion by seasonal major storm events, and nourishment prompted the modification of SLAMM in this study.

This study presents an alternative and simplified methodology to determine changes in the beach due to major storms that does not depend on rigorous hydrodynamic models but was based on the actual measured erosion following the occurrence of seasonal storm events. The approach followed here was to modify SLAMM, so that time-specific changes in the habitat can be included in the simulation and thus create a robust but simple model that can simulate both the long term and abrupt changes in the habitat. The actual measured erosion summarized the results of all the processes taking place during the event (e.g. erosion due to storm surge, wind erosion, scouring, etc.).

The objective of this study was to analyze the combined effects of future sea level rise (SLR), historic storms, and nourishment to a stretch of beach habitat in Santa Rosa Island, Florida. A new methodology with SLAMM was developed to simulate these changes over a large area based on measured erosion or deposition from historic storm events. The framework developed in this study was aimed at providing environmental managers a set of simplified tools to evaluate changes in coastal habitats due to these important processes.

2. Materials and methods

2.1. Study area

The study area was a 5-km length beach located at Santa Rosa Island (SRI), Florida (Fig. 1) which is part of Eglin Air Force Base (AFB). The SRI barrier complex is important in maintaining the regional biodiversity and protecting the mainland and bays from extreme storm events (Sutter et al., 2001). Since the SRI is an important region being the home of listed, tracked, and rare species of plants and animals like the Perforated reindeer lichen (*Cladonia perforata*), Snowy plover (*Charadrius alexandrines*), Green sea turtle (*Chelonia mydas*) and many others, its vulnerability to SLR (Chu-Agor et al., 2011b) and major storm events is an important concern. In addition, protecting military infrastructure in the area is of utmost importance to Eglin AFB (Sutter et al., 2001).

2.2. Simulating long-term land cover changes

Land cover changes in the area were simulated using SLAMM version 6.2.1. SLAMM simulates dominant processes (i.e., inundation, gradual erosion, over wash, saturation, salinity, and accretion) involved in coastal wetland conversions and shoreline modifications during long-term sea level rise. Each wetland type is associated with certain elevation boundaries (Fig. 2) and conditions (e.g. salinity, tidal ranges, etc.) required for that specific wetland type to exist. SLAMM divides the study domain into cells and computes the minimum elevation, ME, of each cell for every time step determining whether the cells remain in their original land cover categories or be converted to lower elevation categories. The ME is computed as follows:

$$\mathrm{ME}_t = \mathrm{ME}_{t-1} + \Delta t(\mathrm{AR}) - \mathrm{SLR}_t \tag{1}$$

where AR is the site-specific accretion and/or sedimentation rate, SLR is the sea level rise, and t is the time. Sea level rise (SLR) is estimated at each time step as:

$$\mathrm{SLR}_t = \mathrm{GSLR}_t + \left(t_n - t_0\right)\left(\mathrm{risetrend}_{\mathrm{local}} - \mathrm{risetrend}_{\mathrm{global}}\right) \tag{2}$$

where GSLR is the global average sea level rise predicted based on IPCC (2007) projections, t_n is the current model year, t_0 is the initial year, $\mathrm{risetrend}_{\mathrm{local}}$ is the local historic trend of sea level rise, and $\mathrm{risetrend}_{\mathrm{global}}$ is the global historic trend of sea level rise. In this study, GSLR was assumed to be 2.0 m by 2100 (Pfeffer et al., 2008; Vermeer and Rahmstorf, 2009), which was scaled every time step using the IPCC A1B (IPCC, 2007) scenario.

The main inputs in SLAMM are elevation and land cover maps, local tidal data, and site-specific information for accretion, erosion, sedimentation, and overwash. Initial digital elevation model (DEM) with cell size of 2 m was used from the existing 2-m resolution LiDAR DEM (NOAA, 2011a). The land cover map from NOAA (2011a) database with a resolution of 30 m × 30 m was re-scaled to a 2-m cell size without any additional processing. Tidal data from NOAA (2011c) for the nearby Pensacola station were used. Site-specific information like accretion, sedimentation, and erosion rates were collected from previous studies in the area (Callaway et al., 1997; Chu-Agor et al., 2011a,b; DeLaune et al., 1989; Scholl et al., 1969). The uncertainty and sensitivity of SLAMM applied to the study area were evaluated in Chu-Agor et al. (2011a,b).

2.3. Simulating time-specific changes

One of the limitations of the original version of SLAMM is that it only simulates gradual changes in the area due to sea level rise. Since it is not a hydrodynamic model, it does not take into account extreme sand mobilization caused by major storm events or manmade alterations such as beach restoration. In order to address these issues, the SLAMM code was modified to take into account time-specific changes in the land cover by adding another term to Eq. (1) as follows:

$$\mathrm{ME}_t = \mathrm{ME}_{t-1} + \Delta t(\mathrm{AR}) - \mathrm{SLR}_t \pm \Delta\mathrm{ME}_t \tag{3}$$

where $\Delta\mathrm{ME}_t$ is the change in elevation at time step t due to anthropogenic changes or major storm events. Using Eq. (3), the modified SLAMM can take additional maps reflecting changes in elevation, slope and cell category at specific time step for a selected group of cells. For example, if beach nourishment was carried out in a particular year, SLAMM can increase the ME of the cells for that particular year to take into account changes in elevation and slope due to beach nourishment. In cases where nourishment is implemented, the land cover category of the nourished cells has to be specified, otherwise, it is assumed to be beach. Similarly, if a major storm hits the area resulting in significant erosion, SLAMM can reduce the ME of the cells according to the decrease in elevation due to erosion following the procedure presented below.