Ocean and Coastal Management 163 (2018) 113–129

Contents lists available at ScienceDirect

Ocean and Coastal Management

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

Coastal exposure of the Hawaiian Islands using GIS-based index modeling

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ARTICLE INFO

Keywords:
Coastal vulnerability index
Sea level rise
Wave exposure
Beach erosion
InVEST
Natural capital
Decision-making
GIS

ABSTRACT

High energy wave environments intensify the impacts of sea level rise and create threats to island communities, which requires measures to prevent the loss of lives and assets. There is a need to identify hazard-prone sites in order to mitigate and reduce threats. In this study, the overall coastal exposure of Hawai'i's shoreline, accounting for topography, bathymetry, wave, surge, and sea level rise is estimated along with interactions with natural habitats, coastal defense structures, and human activities. We quantify coastal exposure using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model, which provides relative comparisons between shoreline segments to identify the most hazardous locations in the state. The study includes estimates of the probability of erosion and calculates exposure index metrics for at-risk areas. Although the average exposure index of the islands at the low to medium vulnerability level, an alarming 34% of the state has moderate to high vulnerability. Geomorphology and wave exposure cause the high levels of risk. Maui, O'ahu, and Kaua'i are the top three most vulnerable islands. While geomorphology is most important in influencing vulnerability on O'ahu, and Kaua'i, sea level rise, and surge potential are the most influential factors on Maui and Kaho'olawe, respectively. Although high wave energy affects all the Hawaiian Islands, Lana'i and Kaua'i are especially influenced by wave exposure while O'ahu has the most eroded shorelines. Natural habitats serve as barriers to the adverse effects of exposure and reduce vulnerabilities. The observed probability distribution of the exposure and erosion indices for islands is also provided. By understanding which shorelines are most sensitive and the dominant factors affecting their vulnerability, policymakers can promote public awareness and support planning, design, and implementation of adaptation strategies.

1. Introduction

Island communities, whose economies and livelihoods depend on coastal assets and opportunities, are highly susceptible to changes in climate. Consideration of the biophysical and socio-economic effects of climate change (Doukakis, 2005) enables island communities to develop hazard management strategies in response to their vulnerabilities (Kim et al., 2015; Torresan et al., 2008). Identifying and assessing highly vulnerable areas (Torresan et al., 2008) as well as the contributing factors to vulnerability are necessary groundwork in developing a strategy for surviving inundation, erosion, degradation, flooding, and salinization caused by sea level rise (SLR) (Tysban et al., 1990).

Recent studies on global mean surface temperature (Rahmstorf, 2007) and the polar ice sheet melt (Pfeffer et al., 2008) call attention to SLR rates and their impact on the shorelines. The studies also indicate a likely acceleration in SLR rates with increased global warming (Church and White 2006; Jevrejeva et al. , 2008; Merrifield et al. 2009). According to the IPCC AR5, the average global SLR rates increased to 0.47 m by Representative Concentration Pathways (RCP) 4.5 and 0.63 m by RCP 8.5 by 2100. However, recent studies (Kopp et al., 2016, 2015; Mengel et al., 2015; Slangen et al., 2014; Sweet et al., 2017) showed that the previously reported low probability distributions fail to capture uncertainties in future predictions (Sweet et al., 2017) and that global SLR rates are 0.3–0.5 m higher within the Hawaiian Islands under an intermediate-high scenario (1.5 m global mean SLR by the year 2100) due to static equilibrium effects (Sweet et al., 2017). On the other hand, Parker (2017, 2016) indicates that the impact of multidecadal oscillations and subsidence decelerate the SLR rates of the Hawaiian Islands. Despite the debate between future SLR scenarios, we need a better understanding of past conditions to allow for future planning. Therefore, we include the relative sea level recorded by the

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https://doi.org/10.1016/j.ocecoaman.2018.06.003
Received 3 March 2018; Received in revised form 30 May 2018; Accepted 1 June 2018

tide gauge measurements which capture past rates more reliably than model scenarios (Parker, 2016; Parker et al., 2013; Parker and Ollier, 2016a). These measurements should include the subsidence rates, record length and oscillations in the recording period (Baker and McGowan, 2015; Chambers et al., 2012; Mazzarella and Scafetta, 2012; Parker and Ollier, 2016b; Scafetta, 2014).

The coastal vulnerability index (CVI) is widely used to assess shoreline vulnerabilities (Cooper and McLaughlin, 1998; Gornitz, 1990; Thieler and Hammar-Klose, 1999) by identifying risk-prone areas undergoing physical changes and impacts due to SLR (Rangel-Buitrago and Anfuso, 2015; Thieler and Hammar-Klose, 1999). The CVI measures the exposure, sensitivity and adaptive capacity of a community (Core Writing Team et al., 2007 (IPCC AR4)). Different approaches summarized in Nguyen et al. (2016) comprise both the biophysical and social dimensions of vulnerability to assess complex coastal vulnerability determinants relative to SLR, such as climate forcing and socioeconomic factors (Boruff et al., 2005; Mclaughlin and Cooper, 2010; Szlafsztein and Sterr, 2007), and coastal sensitivity (Abuodha and Woodroffe, 2010). Defining the indicators which identify the vulnerability of a region is a challenge because different parameters protect the shoreline at different levels (Denner et al., 2015). Within the scientific community there is no commonly accepted validation for exposure results (Nguyen et al., 2016). Researchers integrate weighted index calculations with an analytic hierarchy process (AHP) (Duriyapong and Nakhapakorn, 2011; Le Cozannet et al., 2013; Mani Murali et al., 2013) and fuzzy AHP (Özyurt and Ergin, 2010; Tahri et al., 2017) to reduce the subjectivity of the indicator (Balica, 2012). Although these approaches are a good attempt at dealing with uncertainty in the decision-making (Tahri et al., 2017), it can be an overwhelming process in the preliminary stages of the CVI application. The CVI application proposed by Gornitz (1990) and Thieler and Hammar-Klose (1999) is a standardized measure for relative SLR vulnerability assessments and widely used. The method can be modified by using percentile ranges instead of actual values (Shaw et al., 1998). The GIS is an efficient tool used to measure the impact on hazard prone areas to flooding (Lawal et al., 2011) and erosion (Rizzo et al., 2017). The GIS application of the CVI displays the frequency distribution of the index variable. CVI mapping is also used to support planning and decision making in response to climate change (Kelly et al., 1994; Onat et al., 2018a) and to integrate ecological and social functions into ecosystem-based management (Mangubhai et al., 2015; Yoo et al., 2014) for the future (Denner et al., 2015; Musekiwa et al., 2015). Spatially explicit models like the Integrated Valuation of Ecosystem Services and Tradeoffs tool (InVEST) shows the impact of the changes in the ecosystem (Natural Capital Project, 2008). The overlapping analysis of the InVEST model is used to understand the interaction of coastal habitats with SLR (Arkema et al., 2013a; Onat et al., 2018a), modeling ecosystem services for coastal zone planning (Arkema et al., 2017, 2014; Guannel et al., 2016, 2015; Guerry et al., 2012) and protection against climate stressors (Cabral et al., 2017; Elliff and Kikuchi, 2015; Langridge et al., 2014; Vogl et al., 2016). A better understanding of the vulnerability of the shorelines from coastal stressors leads to improved climate change adaptation plans (Onat et al., 2018a).

The motivation for this study comes from the need to define the current vulnerabilities and quantify the change in vulnerabilities due to SLR and climate change. The exposure and sensitivity of the region to climate events can also be better estimated with more in-depth knowledge of coastal vulnerabilities. Another vital aspect is that the most exposed areas are identified from critical physical parameters that affect the vulnerability of the shoreline, which are needed for prioritizing different adaptation measures.

There are three main goals for this paper. The first goal is to identify which environmental parameters most affect Hawaii and understand the linkages between them. Even though coastal hazard risk and inundation maps display historical event impacts, more information is needed because the perception of risk may be inaccurate, especially in highly susceptible areas. Exaggerated risk causes public fear and desensitizes the community to likely scenarios (Bolter, 2013). This study also demonstrates the contribution of shoreline attributes to exposure. It addresses the gaps in inundation or hazard maps by considering natural and anthropogenic processes (Bolter, 2013), as well as their interactions with population and infrastructure to define vulnerability (Wu et al., 2002). The second goal of the study is to reduce uncertainty when prioritizing of vulnerable coastal systems and determine effective linkages between vulnerability assessment and development planning. The third goal is to show what factors reduce resilience in specific regions through inspection of the input values affecting exposure and vulnerability, which addresses the most critical underlying factors affecting vulnerability.

The next section explains the unique characteristics of the Hawaiian Islands and the SLR influence over the shorelines. The methods used in to define exposure metrics and conduct the statistical analysis are described in Section 3. The vulnerability of each shoreline segment is quantified using CVI. The research considers topography, bathymetry, wave and surge exposure, SLR, and the impact of natural habitats, coastal defense structures, and population by evaluating and illustrating the degree of change in exposure. Section 4 covers the results and discuss the characteristics of input vulnerability and exposure metrics are provided. The research presents assessments of vulnerability that policymakers can use to select appropriate adaptation and mitigation strategies. We investigate the characteristics of vulnerability and exposure metric distributions and comparing the differences between them. Also presented are the habitat, coastal defense structure and population density effects for island exposure, and typical characteristics of the most vulnerable locations for each island. In the final section, the results of the CVI analysis and the implications for research, planning, and development are presented.

2. Study area

The study area covers the shorelines of the seven main Hawaiian Islands – Kaua'i, O'ahu, Moloka'i, Lana'i, Maui, Kaho'olawe and Hawai'i (Big Island) (Fig. 1). The islands are the result of hotspot formations and include beaches formed from sandy, alluvial deposits, coral reefs and volcanic bedrocks (Romine and Fletcher, 2012). Surrounded by fringing reefs, the islands have diverse habitats due to the tropical environment. The Hawaiian Islands are under the influence of high energy waves (Moberly and Chamberlain, 1964; Vitousek and Fletcher, 2008) and tropical storms, and undergo shoreline changes due to erosion (Romine and Fletcher, 2012). Prediction of climate change effects is challenging due to the islands' complex natural and geographic formations (Eversole and Andrews, 2014). Coastal areas have been urbanized by tourism and housing development, and roads and utilities connecting these coastal communities.

The SLR projection for Hawai'i is highly variable due to local isostatic response (Caccamise, 2003; Church et al., 2004; Richmond et al., 2001; Romine and Fletcher, 2012) originating from the volcanic formation of the islands, which creates disparity in historic sea level across the state (Fletcher, 2000). Long-term trend measurements from tide measurements which include GPS station corrections show that the Big Island and Maui have higher rates of SLR (1.8 mm/yr and 2.02 mm/yr, respectively), while O'ahu and Kaua'i have a SLR rates of 1.43 and 1.47 mm/yr, respectively (Yang and Francis, 2018). The differences in SLR rates are from the sinking of Hawai'i and Maui due to the flex caused by the weight of geologically young volcanic material on the underlying crust, while O'ahu and Kaua'i are outside of the subsidence zone (Fletcher, 2000; Richmond et al., 2001; Romine et al., 2013).

Sea level rise adversely contributes to existing hazards in the state. Hawai'i faces risks of coastal erosion, SLR, tropical storms, flooding, high wave events, volcanic and seismic activity and tsunamis (Fletcher et al., 2012; Richmond et al., 2001). Fletcher et al. (2012) and Richmond et al. (2001) developed hazard intensity maps using