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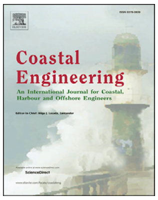

Hydrodynamic storm surge model simplification via application of land to water isopleths in coastal Louisiana

Christopher G. Siverd[a,*], Scott C. Hagen[a,b,c,d], Matthew V. Bilskie[b], DeWitt H. Braud[d], R. Hampton Peele[e], Robert R. Twilley[d,f]

[a] Department of Civil and Environmental Engineering, Louisiana State University, 257 Military Science Building, Baton Rouge, LA, 70803, United States
[b] Center for Coastal Resiliency, Louisiana State University, 124C Sea Grant Building, Baton Rouge, LA, 70803, United States
[c] Center for Computation and Technology, Louisiana State University, 340 E. Parker Blvd., Baton Rouge, LA, 70803, United States
[d] Coastal Studies Institute, Louisiana State University, Howe-Russell Geoscience Complex, Room 331, Baton Rouge, LA, 70803, United States
[e] Louisiana Geological Survey, Louisiana State University, 3079 Energy, Coast and Environment Building, Baton Rouge, LA, 70803, United States
[f] College of Coast and Environment, Louisiana State University, 1002-Q Energy, Coast and Environment Building, Baton Rouge, LA, 70803, United States

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ABSTRACT

The Mississippi River Delta ranks the seventh largest delta in the world. It provides a habitat for the Louisiana seafood industry, navigation canals and rivers that support five of the 15 largest cargo ports by volume in the United States, and hurricane storm surge protection for coastal cities and oil and gas industry infrastructure that facilitates 90% of the outer continental oil and gas extraction. Due to substantial coastal wetland loss since 1900, the risk of damage to these industries and infrastructure has increased through time. The goal of this research is to develop a methodology to analyze the historical and future evolution of coastal hazards, such as hurricane storm surge, across a complex, low-lying coastal landscape. To accomplish this task, the change in coastal hazards is analyzed through historical changes in coastal wetlands. Specifically, isopleths, defined as lines on a map indicating a constant value of a given variable, are developed to describe areas of constant values of the ratio of land to water (L:W) across coastal Louisiana.

In this analysis, a methodology is developed that utilizes land to water (L:W) isopleths to simplify the modern day Louisiana coastal landscape as represented in a state-of-the-art high resolution storm surge model. L:W isopleths are derived for the year 2010 and used to construct 36 storm surge models, each featuring variations of three distinct coastal zones: “High” (i.e. high wetland), “Intermediate” (i.e. wetland), and “Submersed” (i.e. region between open water and wetland). The ADvanced CIRCulation (ADCIRC) code is used to compute water surface elevations and depth-averaged currents forced by hurricane wind and pressures from Hurricanes Rita, Gustav, and Katrina for each model. Peak water levels and volume of inundation are quantified within hydrologic unit code watersheds (HUC12) in order to compare storm surge models featuring high resolution and simplified coastal landscapes.

A L:W isopleth permutation of 99%–90%–40%–1% with areas labeled “High” (99%–90%), “Intermediate” (90%–40%) and “Submersed” (40%–1%) is found to best represent simulated storm surge that most closely reproduces the high resolution storm surge model. Simulation results reveal the methodology developed in this analysis is effective in identifying an isopleth permutation that accurately simplifies a high resolution storm surge model. This result may lead to future analyses of the historical evolution of storm surge attenuation in the Mississippi River Delta (MRD) as well as other complex, low-lying deltas. These possibilities include developing storm surge models for the years 1930 and 1970, for instance, with the same isopleth permutation to examine the changes in storm surge attenuation through time. This analysis could also be applied in other similar low-lying coastal regions to conduct past and future analyses of the evolution of coastal hazards.

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* Corresponding author.
E-mail addresses: csiver3@lsu.edu (C.G. Siverd), shagen@lsu.edu (S.C. Hagen), mbilsk3@lsu.edu (M.V. Bilskie), dbraud1@lsu.edu (D.H. Braud), hampton@lsu.edu (R.H. Peele), rtwilley@lsu.edu (R.R. Twilley).

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1. Introduction

The wetlands of the Mississippi River Delta (MRD) comprise the seventh largest delta in the world (Couvillion et al., 2011) and create a habitat for the (approximately) USD 3 billion/year Louisiana seafood industry (Restore the Mississippi Delta Coalition, 2012). The river dominated delta (Coleman et al., 1998; Galloway, 1975) draws runoff from 31 U.S. States and two Canadian provinces (U.S. Army Corps of Engineers, 2016) and features five of the 15 largest ports (by cargo volume) in the U.S. accounting for 20% of all waterborne transport in the country (Restore the Mississippi Delta Coalition, 2012). In addition, wetlands of the MRD and of the Chenier Plain collectively comprise the Louisiana coastal landscape and provide hurricane storm surge protection for coastal cities from New Orleans to Lake Charles and oil and gas industry infrastructure that produces 90% of the U.S.'s outer continental oil and gas (Coastal Protection & Restoration Authority of Louisiana, 2017).

Unfortunately since 1900 and prior to the landfall of Hurricane Katrina in 2005, according to Costanza et al. (2008), the surface area of the MRD wetlands was reduced by 480,000 ha (1850 sq mi) and Katrina temporarily reduced the wetlands by an additional 20,000 ha (77 sq mi). This resulted in a total wetland storm protection value loss of USD 28.3 billion and USD 1.1 billion, respectively (Costanza et al., 2008). With recent studies predicting high future global and relative sea level rise (RSLR) along the Louisiana coast (Jevrejeva et al., 2016; Parris et al., 2012; Stocker et al., 2013; Sweet et al., 2017), understanding the historic response of coastal storm surge to wetland loss could provide insight into future storm surge characteristics. This understanding may also further affirm the dynamic and non-linear relationship in both space and time of RSLR and storm surge (Atkinson et al., 2012; Bilskie et al., 2014, 2016a).

In 1963, the United States Army Corps of Engineers (USACE) investigated the response of coastal storm surge to the presence of wetlands and found through observing seven storms that made landfall across coastal Louisiana that storm surge can be attenuated by approximately one vertical meter for every 14.5 horizontal kilometers of coastal wetlands (U.S. Army Corps of Engineers, 1963). However, this “rule of thumb” was derived from data with substantial scatter due to the difficulty in accounting for complex landscapes or varying hurricane characteristics (Lawler et al., 2016; Lovelace, 1994; McGee et al., 2006; Wamsley et al., 2010). Since the 1963 research by the USACE, numerous studies have employed hydrodynamic models to examine hydrodynamic coastal processes including the effect of storm parameters and local topo-bathymetry on storm surge attenuation (Barbier et al., 2013; Bunya et al., 2010; Chen et al., 2005, 2008; Chen and Zhao, 2011; Dietrich et al., 2010; Karim and Mimura, 2008; Lesser et al., 2004; Möller et al., 2014; Resio and Westerink, 2008; Shepard et al., 2011; Suzuki et al., 2012; van Rijn et al., 2007; Wamsley et al., 2010; Westerink et al., 2008). Storm parameters such as landfall location, wind velocity, size and duration have been shown to influence coastal storm surge propagation (Irish et al., 2008; Lawler et al., 2016; Loder et al., 2009; Resio and Westerink, 2008; Wamsley et al., 2010; Zhang et al., 2012). Furthermore, recent hydrodynamic model development studies have emphasized increasing model resolution to improve the accuracy of simulated hydrodynamic processes by better representation of coastal landscapes (Ali, 1999; Bilskie et al., 2015; Bilskie and Hagen, 2013; Blain et al., 1998; Dietrich et al., 2011; Lawler et al., 2016; Luettich and Westerink, 2004; Massey et al., 2011, 2015; Walstra et al., 2012; Westerink et al., 2008). These studies suggest that storm surge depends on the geometry of the local coastal landscape, including elevation (topography and bathymetry) and structural characteristics of the coastal vegetation (bottom roughness). Specifically, studies focused on coastal Louisiana (Loder et al., 2009; Wamsley et al., 2010) and the mid-Atlantic coastal region of the U.S. (Lawler et al., 2016) indicate that the influence of fragmented wetlands on storm surge diminishes with increased surge depth.

Finer storm surge model mesh resolution (i.e. shorter element lengths and smaller distances between mesh nodes), the application of lidar to improve topographic mapping, and advancements in high performance computing (HPC) have clearly improved the knowledge of storm surge propagation across the coastal landscape (Bilskie et al., 2015, 2016b; Bilskie and Hagen, 2013; Bunya et al., 2010; Dietrich et al., 2010; Kashiyama et al., 1997; Massey et al., 2011; Mederios et al., 2011; Mori et al., 2014; Sanders et al., 2010). However, modern remote sensing technology, such as lidar, has only been in existence since the early 1970s. The emergence of lidar coincided with the rapid advance in computing capabilities, digital and analog electronics and later the development of global positioning systems (GPS) in the 1980s (Brock and Purkis, 2009; Krabill et al., 1984). By the 1990s, lidar technology advancement and cost reduction allowed this new technology to be deployed in the field and by the 2000s it was extensively used to map topographic features of coastal zones (Brock et al., 1999; Brock and Purkis, 2009; Sallenger et al., 1999, 2003, 2007). Lack of high-resolution elevation data for coastal wetlands and a lack of common data collection methods (i.e. airborne lidar-derived elevations versus traditional field surveys) for past decades (e.g. pre-1990) poses a challenge when attempting to model and examine storm surge response to historical coastal landscapes for historic eras (i.e. how coastal Louisiana's wetland loss over recent decades has altered storm surge attenuation and protection). Therefore, a storm surge model of the modern Louisiana coast featuring high mesh resolution and a detailed topo-bathymetric landscape cannot be compared to storm surge models developed from antiquated data (and data collection methods).

To compare storm surge response to modern and historic landscapes, an equivalent model development methodology must be employed. This can be accomplished with isopleths describing the ratio of land to water (L:W). Isopleths have been used in fields of study such as meteorology (Sawyer, 1956) and are defined as “a line on a map connecting points at which a given variable has a specified constant value” (Merriam-Webster, 2017). In this analysis, the points of specified constant value that create a line describe the percent of land with respect to water. Presently (2017), these points can be derived from a satellite image or aerial photography to yield the constant value of the ratio of land to water along the Louisiana coast. Alternatively, the same procedure can be applied to digitized historical maps. In the present analysis, the major goal is to develop a methodology that utilizes L:W isopleths to simplify the modern day Louisiana coastal landscape as represented in a state-of-the-art high resolution storm surge model. It is hypothesized that simulated peak water levels and inundation volume from the L:W isopleth derived storm surge model will be comparable to that of the high resolution model. The following sections present the methodology developed to apply the L:W isopleths to a high resolution model of coastal Louisiana, simplify it, and validate this simplified coastal landscape model by comparing it to the high resolution model.

2. Study area

The study area is the coastal Louisiana landscape bounded by the Sabine River (west), Pearl River (east), Intracoastal Waterway (ICWW) (north) and the Gulf of Mexico (south) (Fig. 1a). Within this region exists two distinct coastal landscapes; the retrograding Mississippi River Delta (MRD) (Bentley et al., 2016; Blum and Roberts, 2009) east of the Atchafalaya Delta (Fig. 1a) and the prograding Chenier Plain west of the Atchafalaya Delta (Bentley et al., 2016; Huh et al., 2001). MRD formation began approximately 7500 years before present (BP) with the substantial reduction in the rate of sea level rise (SLR) and the building of the Maringouin-Sale-Cypremort Delta southeast of the modern-day city of Lafayette. Approximately 5500 years BP the Mississippi River avulsed to begin the formation of the Teche Delta, next the St. Bernard Delta 4000 years BP, the Lafourche Delta 2500 years BP, Balize Delta 1000 years BP and the Atchafalaya-Wax Lake Deltas 400 years BP. The Balize and Atchafalaya-Wax Lake Deltas are the only two deltas still active (Bentley et al., 2016; Blum and Roberts, 2009; Roberts, 1997). The landscape formed by this process of river avulsion and delta creation is