

Quantifying storm surge and risk reduction costs: a case study for Lafitte, Louisiana

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Abstract

Rising sea levels have increased flood risk in coastal communities on both the east and west coasts of the USA. The goal of this analysis is to approximate flood defense costs from cyclonic flooding as a partial means to evaluate the resilience of coastal communities. Storm surge models were previously constructed via an established approach to represent historical and future coastal Louisiana landscapes and associated flood patterns. Coastal flooding was also previously simulated via a suite of 14 hurricanes. Approximate levee heights surrounding Lafitte, Louisiana, are calculated from the surge and wave output of Hurricane Isaac, the predominated hurricane in the Lafitte area for all years examined (NAVD88, m): 1.68 (1930), 2.92 (1970), 3.30 (1990), 4.82 (2010), 5.93 (2030), 6.57 (2050), 7.16 (2070), 7.70 (2090), and 8.22 (2110). Approximate costs per person are also calculated (2010 USD): \$49,500 (1930), \$41,400 (1970), \$37,500 (1990), \$181,600 (2010), \$223,600 (2030), \$247,800 (2050), \$269,900 (2070), \$290,100 (2090), and \$309,800 (2110). The Gulf of Mexico (GOM) migrated 7.4 km inland within the Louisiana Barataria coastal basin between 1973 and 2010. For each person in Lafitte, flood defense costs increased approximately (2010 USD) \$19,000 per person per kilometer inland migration of the GOM from 1973 to 2010. The methodology developed in this case study effectively connects wetland loss with increased flood defense costs and can be applied to communities with similar challenges.

Keywords Coastal wetland loss · Flood risk · Land water ratio · Coastal resilience · Hurricane storm surge · Flood defense costs

1 Introduction

Coastal communities of the contiguous USA are experiencing increased flood risk due to rising sea levels (Kulp and Strauss 2017). Among other factors, changes in management of the

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Mississippi River have increased flood risk for Louisiana coastal communities (Boesch et al. 1994; Louisiana Coastal Wetlands Conservation and Restoration Task Force 1993; Siverd et al. 2019a; Twilley et al. 2016; Twilley et al. 2008). A widely adopted definition of flood risk is the probability of flooding multiplied by the consequence of flooding (Jonkman et al. 2003; Vrijling 2001). To maintain the same level of flood risk, the probability of flooding must decrease as the consequence of flooding increases (i.e., increased flood damage costs due to a larger population and greater economic development in a flood prone area) (Filatova et al. 2011; Nicholls et al. 2007). Probability of flooding increases due to wetland loss, relative sea level rise, an increase in the frequency of hurricane landfalls, and/or increase in storm intensity (Bilskie et al. 2019; Fischbach et al. 2017; Irish et al. 2013; Needham and Keim 2012; Needham and Keim 2014; Siverd et al. 2019a; Twilley et al. 2016). Investments in flood defenses such as dikes (i.e., levees), floodgates, dunes, and wetland restoration reduce the probability of flooding, and therefore flood risk (Barbier 2015; Jonkman et al. 2009; Kulp and Strauss 2017; Wong et al. 2017) and can be expressed in terms of per person costs. For example, the total cost to construct the New Orleans hurricane storm damage and risk reduction system (HSDRRS) (Fig. 1b) was (2010 USD) \$14.6 billion. The 2010 HSDRRS-protected population was 924,000 (US Army Corps of Engineers 2009; US Army Corps of Engineers 2018a; US Army Corps of Engineers 2018b). Therefore, HSDRRS costs were approximately USD \$15,800 per person.

Coastal wetlands provide many benefits, including flood protection via reduced storm surge and wave heights (Barbier et al. 2013; Barbier et al. 2011; Reguero et al. 2018; Spalding et al. 2014). Flood risk reduction attributable to wetlands has been quantified as a component of wetland ecosystem services (Batker et al. 2010; Costanza et al. 2008). An estimate of the wetland ecosystem service of hurricane storm surge protection along the Louisiana coast is approximately \$1700/(ha*year) (2004 USD) when considering wetland area, GDP, and historical hurricane tracks. Storm surge protection value of hectares of wetland lost by the 2005 hurricane season was approximately \$29.4 billion (Costanza et al. 2008). A more recent and extensive study estimated that Mississippi River Delta wetlands annually generate \$12 to \$47 billion in “goods and ecosystem services” for a minimum asset value of \$330 billion to \$1.3 trillion over a 100-year period (3.5% discount rate) (2007 USD) (Batker et al. 2010). “Goods and ecosystem services” include hurricane and flood protection, water supply, water quality, recreation, and fisheries. Investing nothing in ecosystem services leads to losses of \$41 billion over the same 100-year period (3.5% discount rate) not including losses from levee failures, disrupted shipping, or disrupted oil and gas flow. Restoring the Mississippi River Delta via managed diversions of the Mississippi River avoids the \$41 billion loss and adds \$21 billion (3.5% discount rate) in economic value not including benefits from added levee protection, fewer displaced residents, lower recovery costs, lower national oil and gas prices, and overall expanding the south Louisiana economy (Batker et al. 2010).

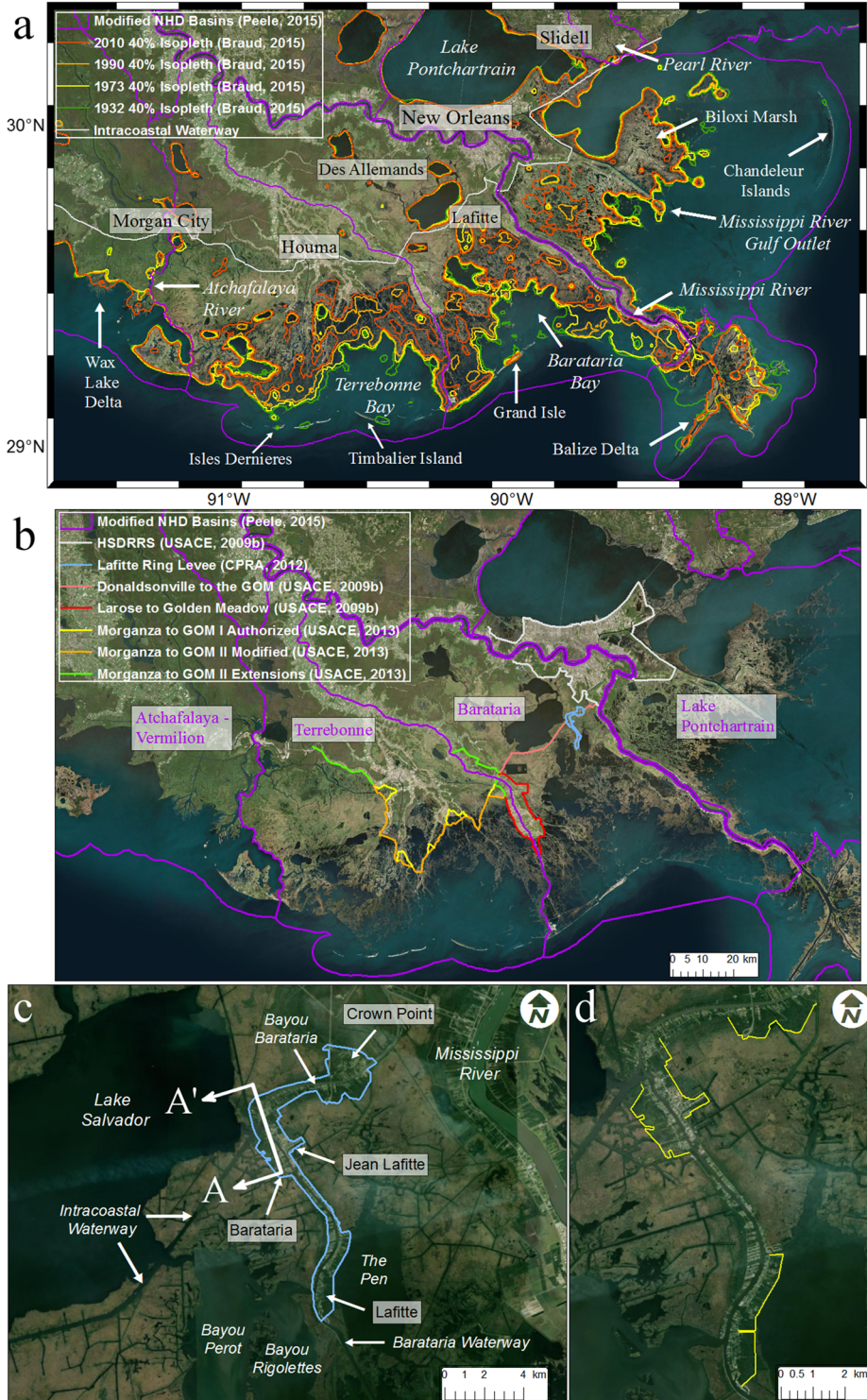
The goal of this analysis is to quantify and partially assess the resilience of a coastal community via examination of historical changes in storm surge heights and associated flood defense costs per person per kilometer of inland migration of the GOM. Specifically, the co-evolution of flood defense costs and wetland loss between the GOM and the four historic communities of Crown Point, Barataria, Jean Lafitte, and Lafitte (collectively called “Lafitte” in this analysis) are examined. This analysis utilizes a levee construction cost factor per unit length and height derived from a cost estimate of a proposed ring levee that would have surrounded the four communities of Lafitte (Coastal Protection and Restoration Authority 2012). A similar cost factor was previously derived to compute a rough estimated cost of a

dike raising project adjacent to the River Waal in The Netherlands (Van der Toorn 2010). Additionally, a unitary cost per measure was utilized to calculate the total cost effectiveness of nature-based measures (e.g., wetland restoration) versus gray infrastructure (e.g., levee construction, home elevation,) to adapt to future sea level rise (Reguero et al. 2018). The most recent and prior Louisiana coastal master plans provide 50-year projections of the Louisiana coastal landscape and detailed projects to reduce the rate of wetland loss (Coastal Protection and Restoration Authority 2007; Coastal Protection and Restoration Authority 2012; Coastal Protection and Restoration Authority 2017). A recently published regional plan provides a set of seven adaptation strategies to prepare the Louisiana coast for relative sea level rise over the next 50 years (LA SAFE 2019). We contribute to existing literature by establishing a methodology to calculate the evolution in flood defense costs for a coastal community as a result of wetland loss over the past 80 years and through the next 100 years.

2 Background summary

Storm surge models with comparable mesh representations of the Louisiana coastal landscape circa 1930, 1970, 1990, and 2010 were previously constructed to examine the impact of negligible sediment input (i.e., sediment-starvation) in the Terrebonne and Barataria coastal basins and substantial sediment input (i.e., sediment-abundance) in the Atchafalaya-Vermilion coastal basins (Fig. 1b) (Siverd et al. 2019a). Constructing comparable historical coastal landscapes with contemporary data was not possible because lidar, for example, has only been widely applied since the early 2000s. Therefore, the method of Siverd et al. (2018) was utilized. Land to water (L:W) isopleths, which indicate areas of constant percentage of land versus water across coastal Louisiana (Fig. 1) (Gagliano et al. 1970; Siverd et al. 2018; Twilley et al. 2016), were derived and provided boundaries for coastal zones labeled high, intermediate, and submersed. Each coastal zone featured a singular elevation and roughness value (Siverd et al. 2018). From 1970 to 2010, mean surge elevations increased by 0.250 m and 0.282 m, or triple the applied global mean sea level (GMSL) rise of 0.08 m, within sediment-starved Terrebonne and Barataria coastal basins, respectively. In contrast, the mean surge elevation increase was only 0.096 m, or the same order of magnitude of GMSL rise, within sediment-abundant Atchafalaya-Vermilion between 1970 and 2010 (Siverd et al. 2019a). Storm surge model mesh representations of future Louisiana coastal landscapes circa 2030, 2050, 2070, 2090, and 2110 were also previously constructed via L:W isopleths (Fig. 2) (Siverd et al. 2019b). For consistency, the same 14 hurricane wind and pressure fields were simulated with all nine models, and storm surge water surface elevations were output for each mesh year. In the present analysis, these water levels are used to approximate Lafitte levee heights, lengths, and costs (Section 4.5) from 1930 to 2110.

Resilience can be defined as “the ability to prepare and plan for, absorb, recover from, and more successfully adapt to actual or potential adverse events” and refers to all measures a community takes to reduce the impact of storm surge events (National Research Council 2012). The communities of Lafitte provide a compelling case study to assess the resilience of a coastal community. Established in 1730, the communities of Lafitte historically did not require flood defenses due to the surge-reducing wetlands between Lafitte and the GOM (Siverd et al. 2019a; Siverd et al. 2018; The Town of Jean Lafitte 2018). However, riverine sediment deposition was substantially reduced in the Barataria coastal basin following the damming of Bayou Lafourche at Donaldsonville in 1906 (Fig. 1b) (Morgan 1979). As a result, wetlands



◀ **Fig. 1** 2015 and 2016 satellite images. **a** Location of 40% L:W isopleths for 1932 (green), 1973 (yellow), 1990 (orange), 2010 (red), and hydrologic unit code 6 (HUC6) coastal basins (purple). **b** Hurricane and flood risk reduction projects and studies in southeast Louisiana (U.S. Army Corps of Engineers 2013). **c** Proposed 2012 CPRA Lafitte ring levee (Coastal Protection and Restoration Authority 2012). **d** Existing levees constructed in Lafitte area as of 2015 (yellow)

south of Lafitte subsided and converted from coastal zone high in 1930 to intermediate in 1970 and 1990 and to submersed (i.e., open water) in 2010 (Siverd et al. 2019a). By 2010, the inland migration of the GOM in the Barataria coastal basin south of Lafitte led to higher storm surge and wave heights near Lafitte and therefore, greater flood risk. Because inland migration of the GOM and increased flood risk are connected, a metric is established to describe this relationship (e.g., increase in flood defense costs per kilometer of inland migration of the GOM). From 1932 to 2010, the 40% L:W isopleth, the interface of wetland and water migrated approximately 8.6 km inland within the Barataria coastal basin (Siverd et al. 2019a). Additionally, between 2010 and 2110, the 40% L:W isopleth is projected to continue migrating toward Lafitte (Fig. 2) (Siverd et al. 2019b).

3 Case study

The study area is the Barataria coastal basin bound by the Bayou Lafourche ridge to the west, west bank of the Mississippi River to the north and east, and Barataria Bay to the south (Fig. 1b). The focus of this case study is the rural coastal communities of Crown Point, Barataria, Jean Lafitte, and Lafitte (collectively called “Lafitte” in this paper) located on Bayou Barataria within the Barataria coastal basin (Fig. 1). These four culturally significant communities were established on the natural levees of Bayou Barataria similarly as New Orleans first developed on the natural levee of the Mississippi River (Rogers 2008). They collectively had a 2010 population of approximately 4734, an average elevation of 1.0 m above mean sea level (MSL), and are prone to flooding from high tides, tropical storms, and hurricanes (Sack and Schwartz 2018; The Town of Jean Lafitte 2018; U.S. Census Bureau 2016; U.S. Geological Survey 2018). As of 2019, 14.50 km of unconnected levees, approximately the height of the Bayou Barataria natural levee, provided limited flood protection to these four communities. A plan to construct a 4.88-m high, 14.50-km ring levee around the four communities of Lafitte was included in the 2012 Louisiana Coastal Master Plan (Coastal Protection and Restoration Authority 2012) (Fig. 1c) but was discarded before publishing of the 2017 Louisiana Coastal Master Plan due to unfavorable results of a benefit-cost analysis (Coastal Protection and Restoration Authority 2017; Schleifstein 2012).

4 Methods

4.1 Historical hydrodynamic model development

The storm surge model developed for the Louisiana Coastal Protection and Restoration Authority of Louisiana (CPRA)’s 2017 Coastal Master Plan (CPRA2017) (Fischbach et al. 2017) was previously applied as a base mesh for the development of comparable storm surge model meshes for the years circa 1930, 1970, 1990, 2010, 2030, 2050, 2070, 2090, and 2110 (Siverd et al. 2019a; Siverd et al. 2019b). The CPRA2017 base mesh comprises approximately 1.4 million nodes and

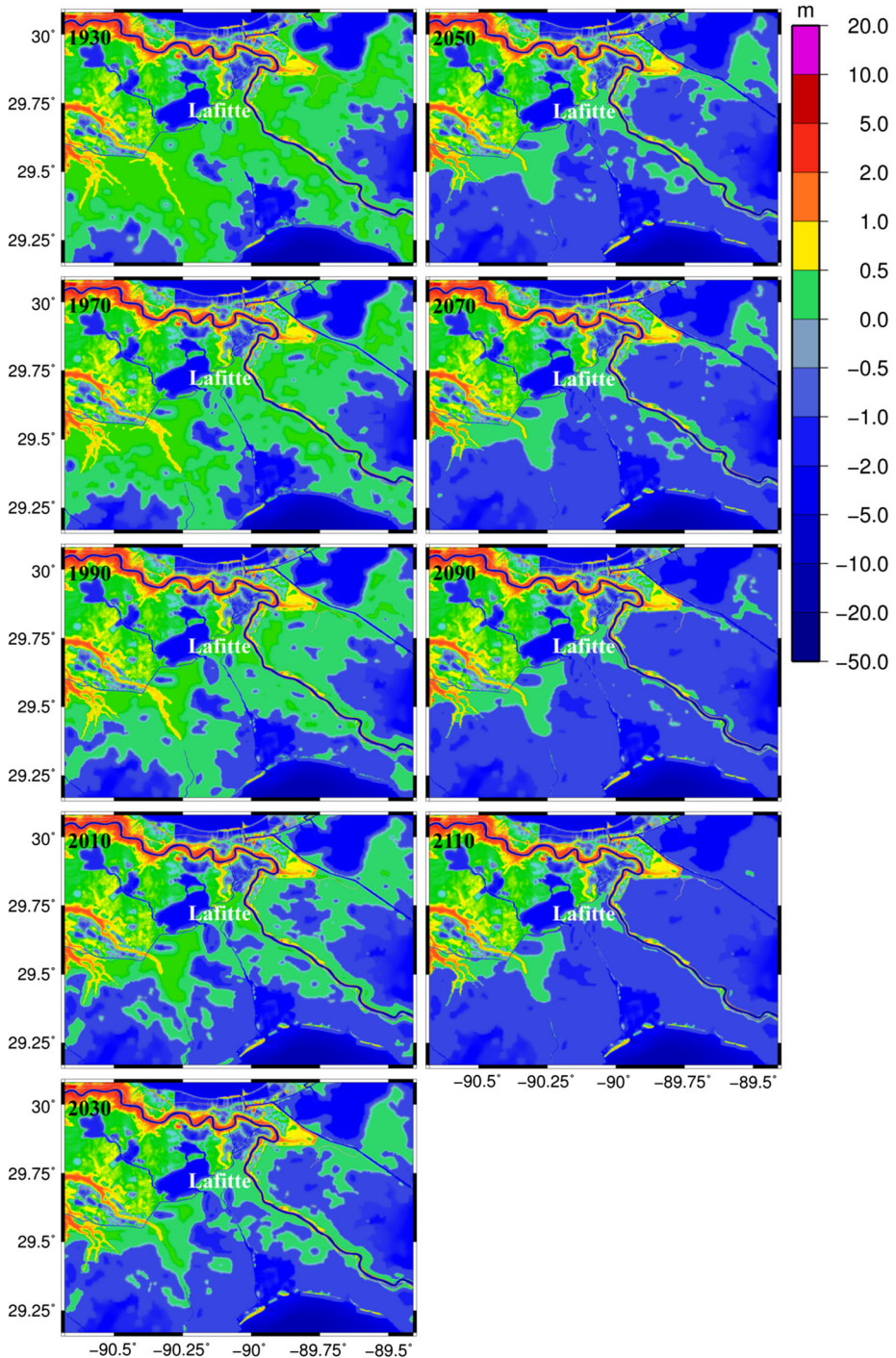


Fig. 2 Historical and future topo-bathymetric landscapes with respect to NAVD88 in the Barataria coastal basin for 1930, 1970, 1990, 2010, 2030, 2050, 2070, 2090, and 2110

2.7 million elements which characterizes the western north Atlantic Ocean west of the 60°W meridian, Caribbean Sea, and GOM. With 93% of nodes placed between Mobile Bay; Alabama; and the Bolivar Peninsula, Texas, the base mesh emphasizes the northern GOM. Wind, pressure and wave forcings were simulated, while tides and Mississippi River discharges were not included. For historical eras, tidal phasing and river discharge assumptions would be required and add complexity to the overall analysis, while future tidal phasing and river discharges are not known. The local tide amplitude is included as a post-processing step of this analysis by including an additional 0.31 m in the levee freeboard height calculation (National Oceanic and Atmospheric Administration 2018).

The construction of manmade navigation canals, weirs, and levees began before 1930, continued after 1930 and through 2010 in the coastal basins south and west of the Mississippi River. To construct comparable meshes for the years 1930, 1970, 1990, 2010, 2030, 2050, 2070, 2090, and 2110 and to focus on changes in morphology, all weirs and levees were removed from the CPRA2017 base mesh in this area (Siverd et al. 2018). Lafitte case study results are unaffected by levee omission due to the non-existence of major storm surge-reducing levees in this area from 1930 to 2010 and the assumption that none are built through 2110. Mesh resolution was also increased seaward of the modern (2017) barrier islands to accurately describe barrier islands in southeast Louisiana for 1930, 1970, 1990, and 2010. This modified CPRA2017 storm surge model mesh is called the “detailed” storm surge model mesh through the remainder of this paper.

The coupled ADvanced CIRCUlation two-dimensional depth integrated (ADCIRC-2DDI) code (Luettich Jr. et al. 1992) and the third-generation wave model, Simulating WAVes Nearshore (SWAN) (Booij et al. 1999; Dietrich et al. 2011; Zijlema 2010), was employed to simulate storm surge and wind waves along the Louisiana coast. Each model mesh featured comparable simplified representations of the Louisiana coastal landscape circa 1930, 1970, 1990, 2010, 2030, 2050, 2070, 2090, and 2110 respectively. Coastal zones were established for each year between the Intracoastal Waterway (ICWW) and GOM with the extent of each zone determined by the position of the 90%, 40%, and 1% L:W isopleths, which are lines indicating areas of constant percentage of land versus water across coastal Louisiana (Siverd et al. 2018). Coastal zones were assigned one value for elevation (with respect to NAVD88): high (0.47 m), intermediate (0.27 m), and submersed (−0.98 m) and Manning’s n bottom roughness: high (0.070), intermediate (0.045), and submersed (0.025) (Siverd et al. 2018). In addition, GOM water levels were set for each storm surge model via a constant GMSL rise rate of 2 mm/year from 1930 to 2010 (Church et al. 2013) and an average 5.1 mm/year of the Intermediate-Low scenario of Sweet et al. (2017) for 2010 to 2110. A negative linear sea level rise was applied for historical eras to reduce complexity. Conservative values were applied for future GMSL rise to demonstrate conservative changes in Lafitte levee implementation costs. GOM initial water levels were derived from the 2010 starting point of 0.23 m NAVD88, which considers the average seasonal variation of mean sea level during months of the highest hurricane activity (U.S. Army Corps of Engineers 2008). See Table 1 for the GOM initial water levels for each model year.

4.2 1930, 1970, 1990, and 2010 storm surge model meshes

L:W isopleths (1%, 40%, 90%) were derived for 1932, 1973, 1990, and 2010 (Fig. 1a) and applied to the detailed model mesh from Lake Sabine to the Pearl River. USGS quad sheets

Table 1 Storm surge model descriptions for mesh years 1930 through 2110

#	Storm surge model mesh year	GOM initial water level (m)	Navigation waterways year
1	1930	0.07	1930
2	1970	0.15	1970–2110
3	1990	0.19	1970–2110
4	2010	0.23	1970–2110
5	2030	0.32	1970–2110
6	2050	0.43	1970–2110
7	2070	0.54	1970–2110
8	2090	0.64	1970–2110
9	2110	0.74	1970–2110

and/or National Oceanic and Atmospheric Administration (NOAA) T-sheets were utilized to input barrier islands, ridges, and navigation waterways as they existed in each mesh year. For more details see Siverd et al. (2019a) and Siverd et al. (2019b).

4.3 2030, 2050, 2070, 2090, and 2110 storm surge models

A trend was identified in inland L:W isopleth migration from 1973 to 2010. The land to water ratio decreased by approximately 10% every 20 years in any given area south of the ICWW. Specifically, the location of the 1973 40% L:W isopleth corresponded with the 2010 20% L:W isopleth and the 1990 40% L:W isopleth corresponded with the 2010 30% L:W isopleth. This trend was extrapolated into the future, utilizing the 2010 L:W isopleths: 2010 50% = 2030 40%; 2010 60% = 2050 40%; 2010 70% = 2070 40%, 2010 80% = 2090 40%, and 2010 90% = 2110 40%. Similarly, 2010 99% = 2030 90%. Because the state of Louisiana has committed to maintaining barrier islands, the 2010 barrier islands were unchanged through 2110 (Coastal Protection and Restoration Authority 2018). For more details, see Siverd et al. (2019b).

4.4 Storm surge model simulations

Meteorological wind and pressure fields developed from 14 historical hurricanes (Cox et al. 1995; Powell et al. 1998) were previously utilized to execute simulations with all nine storm surge models. The 14 hurricanes included Isaac (2012), Gustav (2008), Ike (2008), Dennis (2005), Katrina (2005), Rita (2005), Ivan (2004), Georges (1998), Earl (1998), Opal (1995), Andrew (1992), Kate (1985), Elena (1985), and Agnes (1972). Each of these 14 hurricanes reached a category 1 status while in the GOM and made landfall between Galveston and Apalachicola Bay. Of these historical hurricanes, Isaac contributed the highest water surface elevations for all eras from 1930 to 2110 in the Lafitte area. Therefore, Isaac storm surge is utilized to design historical and future flood defenses for Lafitte. Future hurricane intensification is not included in this analysis due to relatively minimal impact on surge and waves compared with future subsidence and GMSL rise (Irish et al. 2013). Designing flood defenses to resist storm surge from a singular historical hurricane provides greater perspective of the evolution of costs for community residents because they are able to use flood damage caused by Isaac in 2012 as a reference for the severity of damage that may have occurred if Isaac struck Lafitte in 1930 or 2110, for instance. Simulation output included (per mesh node) maximum water surface elevation,

inundation time, current velocity, and wave statistics (Dietrich et al. 2011). Per node maximum of maximums (MOM) water surface elevation was computed from the simulation output of all 14 hurricanes.

4.5 Dike (levee) design height and cost methods

The purpose of this analysis is to calculate an approximate cost per person to protect Lafitte from flooding for each mesh year and to quantify the increase in cost per kilometer inland migration of the GOM. As of 2019, unconnected levees with an approximate elevation of 1.0m NAVD88 and 14.50 km cumulative length (Fig. 1d) provided limited flood protection to the communities of Lafitte (Fig. 1d). For mesh years 1930, 1970, and 1990, the cumulative levee length as of 2019 is used to calculate levee construction costs if Isaac were to make landfall for each mesh year. For mesh years 2010 through 2110, the 47.55 km levee alignment proposed by the CPRA in the 2012 Coastal Master Plan is utilized to calculate future flood defense costs. Required levee elevations are derived from Isaac surge and wave simulation output for each mesh year. A cost factor can be utilized to calculate a rough estimate of levee costs for each storm surge model mesh year (Siverd et al. 2014; Van der Toorn 2010). Because Isaac surge and wave output from previous analyses (Siverd et al. 2019a; Siverd et al. 2019b) for the year 2010 yields a levee height of 4.82 m (see Section 5), similar to that of the levee ring design by the Coastal Protection and Restoration Authority (2012) (4.88 m), the CPRA levee ring is utilized to obtain a cost factor per vertical meter and per linear meter (m^2). To calculate the cost factor, the estimated total cost of the ring levee, including nine floodgates, around Lafitte for hurricane storm surge risk reduction (USD 870 million) is divided by the horizontal length (47.55 km) and vertical height (4.88 m) to yield an approximate factor of USD $\$3752.00/\text{m}^2$. The costs to manufacture and install floodgates per m^2 is greater than the cost to install earthen levees per m^2 (Siverd et al. 2014; Van der Toorn 2010). However, due to the considerably greater length of levees (47.55 km) than floodgates (209 m), floodgate costs are assumed to have only minimal influence on the total cost. This assumption results in a conservative cost factor for 1930, 1970, and 1990 because only low grass levees were constructed during these eras.

The cost per person for each mesh year is based on population of all four communities from census data: 1850 (1930), 3838 (1970), 4791 (1990), and 4734 (2010–2110) (U.S. Census Bureau 2018). The 1930 estimate is derived from 1930 census data of ward 6 of Jefferson Parish with the population of Grand Isle subtracted. Decennial population data from 1980 to 2010 for Barataria, Jean Lafitte, and Lafitte is provided by the U.S. Census Bureau (2018). The 1970 collective population of these three communities is estimated by assuming the same growth rate as that of the entire ward from 1970 to 1980. For Crown Point, the 2010 estimated population is the product of the number of households (250) that would be protected and the 2014 Jean Lafitte average household number (3) (Center for Planning Excellence 2014). For 1970 and 1990, the Crown Point population is assumed the same percentage of the total as that of 2010. The 2010 population of 4734 is first assumed for 2030, 2050, 2070, 2090, and 2110 for all four communities to focus on the cost increases due to wetland loss and because the future population is presently unknown. A second analysis utilizes the population decline trajectory of Isles de Jean Charles from 1955, approximately 400 residents, to today, approximately 100 residents, or a 75% decline (Varney 2018; Zanolli 2016).

A USD 870 million levee ring (Coastal Protection and Restoration Authority 2012) is required to protect 4734 residents of Lafitte (U.S. Census Bureau 2018) from Isaac surge and waves in mesh year 2010 for a cost per person of approximately USD $\$183,800$. Levee height

is needed to calculate this cost per person for 1930, 1970, 1990, 2030, 2050, 2070, 2090, and 2110. Water surface elevation and the wave run-up are required to calculate levee height (EurOtop 2016; Vrijling et al. 2011). In this case study, the water surface elevations and maximum significant wave heights are derived from Isaac storm surge simulation output. Wave run-up is calculated from $R_{u2\%max}$ in EurOtop (2016) (Eq. 2). $R_{u2\%}$ (Eq. 1) is provided for reference.

$$R_{u2\%} = 1.65 \times \gamma_b \times \gamma_f \times \gamma_\beta \times \xi_{m-1,0} \times H_{m0} \quad (1)$$

$$R_{u2\%max} = 1.0 \times \gamma_b \times \gamma_f \times \left(4 - \frac{1.5}{\sqrt{\gamma_b \times \xi_{m-1,0}}} \right) \times H_{m0} \quad (2)$$

where γ_b is the berm influence factor, γ_f is the roughness factor, γ_β is the angle of incidence factor, $\xi_{m-1,0}$ is the breaker parameter, and H_{m0} is the zero moment wave height at the toe of the structure (EurOtop 2016). Because exact levee design specifications are not known at this early stage in design, conservative values for the berm influence factor, roughness factor, and breaker parameters are input to calculate $R_{u2\%max}$ for each mesh year (Table 2). For example, for mesh year 2010, $\gamma_b = 1$, $\gamma_f = 1$, and $\xi_{m-1,0} = 4$. For a wave height at the toe of the levee (H_{m0}) of 0.9 m, a $R_{u2\%max}$ of 2.93 m is calculated and added to the simulated output water surface elevation of 1.59m NAVD88 for a levee elevation of 4.52m NAVD88. Next, 0.31 m is added to the levee elevation height to account for water surface fluctuations due to tides for a final levee elevation of 4.82m NAVD88. For this analysis, waves are assumed only to impact the back levees and are not generated within Bayou Barataria for mesh years 1930, 1970, and 1990. Therefore, flooding from Bayou Barataria bank overtopping is assumed to not occur in mesh years 1930, 1970, or 1990 because water surface elevations are on average at or below the natural levee elevation for these mesh years. Lastly, all levees are assumed not to breach.

5 Results

5.1 Hurricane Isaac water surface elevations and significant wave heights

Maximum of maximums (MOM) water surface elevations and MOM significant wave heights were previously calculated via maximum water surface elevations and significant wave heights simulation output, respectively, from all 14 hurricanes (Siverd et al. 2019a; Siverd et al. 2019b). The dominant hurricane storm surge in Lafitte for all nine storm surge model mesh years was generated by Isaac (navy blue, Fig. 3). Therefore, Isaac surge and wave heights are utilized in this analysis. For mesh year 1930, Isaac water surface elevations were between 0 and 1 m near Lafitte (Siverd et al. 2019a). For 1970 and 1990, Isaac water surface elevations were between 0 and 2 m (Siverd et al. 2019b). For 2010, Isaac water surface elevations rose to between 1.0 and 2.5 m. Isaac significant wave heights averaged approximately 0.2 m (1930), 0.5 m (1970), 0.6 m (1990), and 0.9 m (2010) (arrow, Fig. 4) and 1.1 m (2030), 1.2 m (2050), 1.3 m (2070), 1.4 m (2090), and 1.5 m (2110) (arrow, Fig. 5).

For a better representation of Isaac water surface elevations, transect A–A' (Fig. 1c) is taken of Isaac simulation surge results across Jean Lafitte for all storm surge model mesh years (1930, 1970, 1990, 2010, 2030, 2050, 2070, 2090, and 2110) and averages are calculated (box

Table 2 Levee design and approximate cost calculations to resist storm surge water surface elevations (WSE) if Hurricane Isaac were to make landfall for Lafitte, Louisiana 1930, 1970, 1990, 2010, 2030, 2050, 2070, 2090, and 2110, assuming a constant population from 2010 to 2110

	1930	1970	1990	2010	2030	2050	2070	2090	2110
WSE (h, m) (Fig. 6)	0.73	0.99	1.05	1.59	2.05	2.37	2.63	2.84	3.04
Hmo (m) (Figs. 4 and 5)	0.2	0.5	0.6	0.9	1.1	1.2	1.3	1.4	1.5
γ_b	1	1	1	1	1	1	1	1	1
γ_f	1	1	1	1	1	1	1	1	1
γ_β	1	1	1	1	1	1	1	1	1
$\xi_{m-1,0}$	4	4	4	4	4	4	4	4	4
Rt2% (m) (EurOtop)	1.32	3.30	3.96	5.94	7.26	7.92	8.58	9.24	9.90
Rt2%max (m) (EurOtop)	0.65	1.63	1.95	2.93	3.58	3.90	4.23	4.55	4.88
Levee height (m)	1.38	2.62	3.00	4.52	5.63	6.27	6.86	7.39	7.92
Rc (freeboard, m)	1.68	2.92	3.30	4.82	5.93	6.57	7.16	7.70	8.22
Levee length (km)	14.50	14.50	14.50	47.55	47.55	47.55	47.55	47.55	47.55
Total cost (2010 Mil USD)	91.7	158.8	179.8	859.9	1059	1173	1278	1374	1467
Protected population	1850	3838	4791	4734	4734	4734	4734	4734	4734
Cost per person (2010 USD)	49,546	41,388	37,528	181,633	223,644	247,764	269,890	290,141	309,792

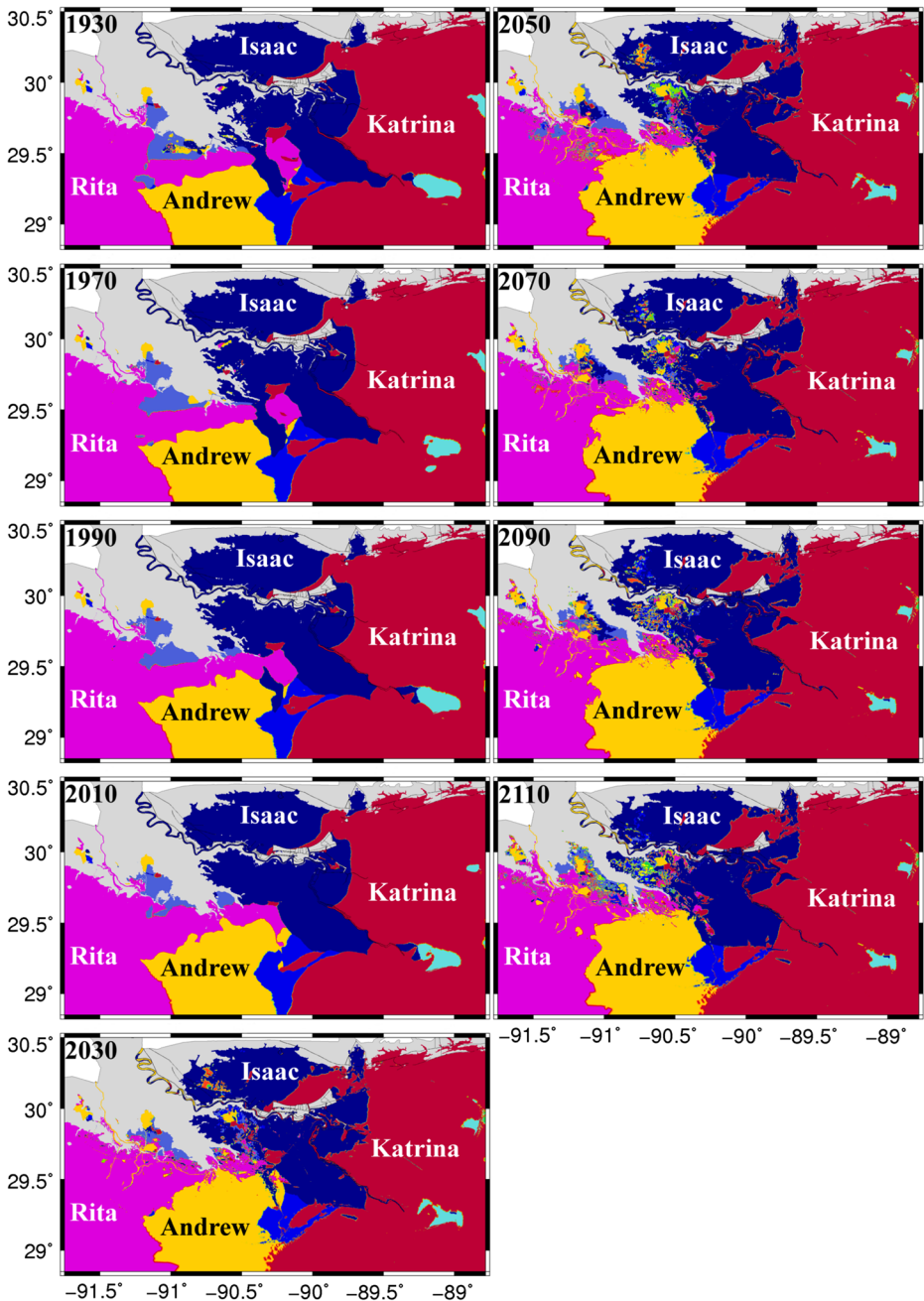


Fig. 3 Areas where simulated peak water levels from each of the 14 hurricanes were largest. Isaac (navy blue, center) water surface elevations were the highest in the study area (Barataria HUC6 coastal basin) and Lake Pontchartrain. Katrina (red) water surface elevations dominate east and south of the Mississippi River. Andrew (yellow) dominates south of Houma. Rita (pink) water surface elevations dominate south of Morgan City and the Wax Lake-Atchafalaya Deltas

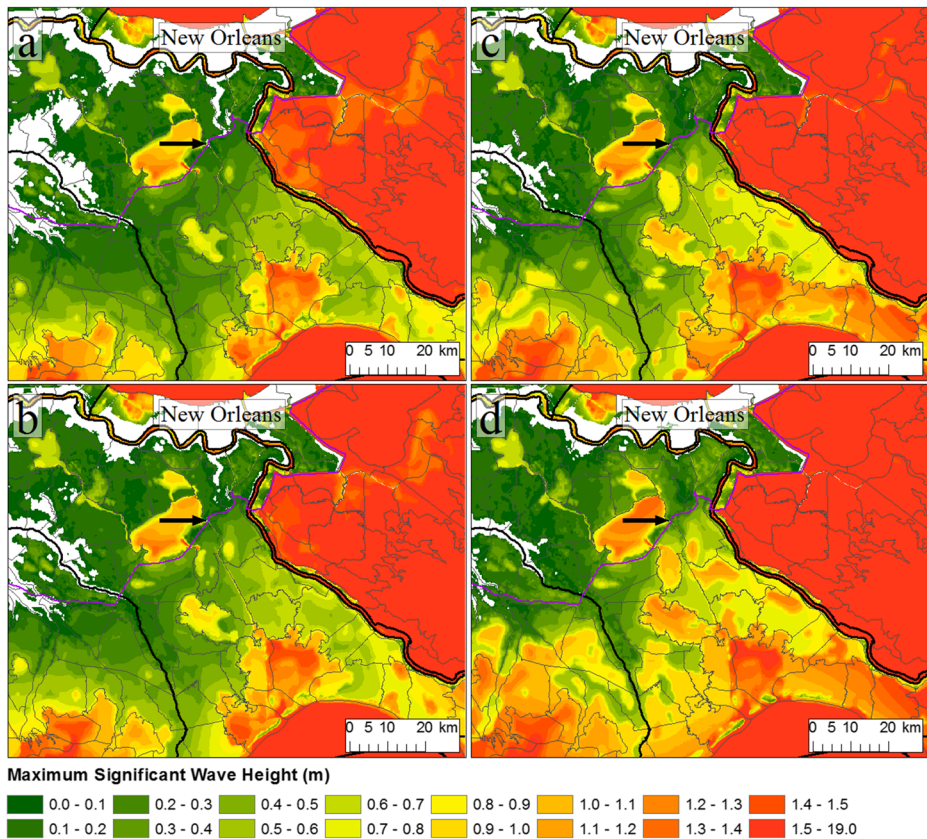


Fig. 4 Maximum of maximums (MOM) significant wave heights (m, NAVD88) computed from all 14 historical hurricanes for a 1930, b 1970, c 1990, and d 2010. HUC6 basins (bold lines) and HUC12 sub-watersheds (gray lines) are included for spatial reference. GMSL rise of 2 mm/year 1930–2010 was included. Purple line is the Intracoastal Waterway (ICWW) and northern most boundary of the study area. Arrow points to intersection of ICWW and Bayou Barataria and the communities of Barataria and Jean Lafitte

Fig. 6a; Table 2, row 1). For mesh year 1930, the average Isaac surge elevations calculated from non-zero values across transect A–A' is 0.73 m. For mesh year 1930, simulation results also indicate that Isaac surge elevations are 1.35 m in south Lafitte and 0.85 m in Barataria. Crown Point remained dry throughout the 1930 mesh year simulation. The average of the water surface elevations of 1.35 m and 0.85 m and 0.0 m equates the average found across transect A–A'. Results further demonstrate that Jean Lafitte begins to flood in 1990 and experiences an approximate 0.5m average flood depth in 2010. Actual Hurricane Isaac high water marks measured in Jean Lafitte by the National Hurricane Center (Berg 2013) are similar to the water surface elevations simulated for mesh year 2010. Uniform Isaac water surface elevations begin to occur in 2030 and by 2110 Isaac surge inundates the entire study area with a uniform 3.0 m depth, as indicated by the flat line in Fig. 6a.

5.2 Lafitte levee design and cost calculation 1930–2110

To calculate wave run-up, EurOtop (2016) (Eq. 2) is utilized for gentle, impenetrable slopes. Because the maximum values for the factors are assumed, the $R_{u2\%max}$ formula yields a lower

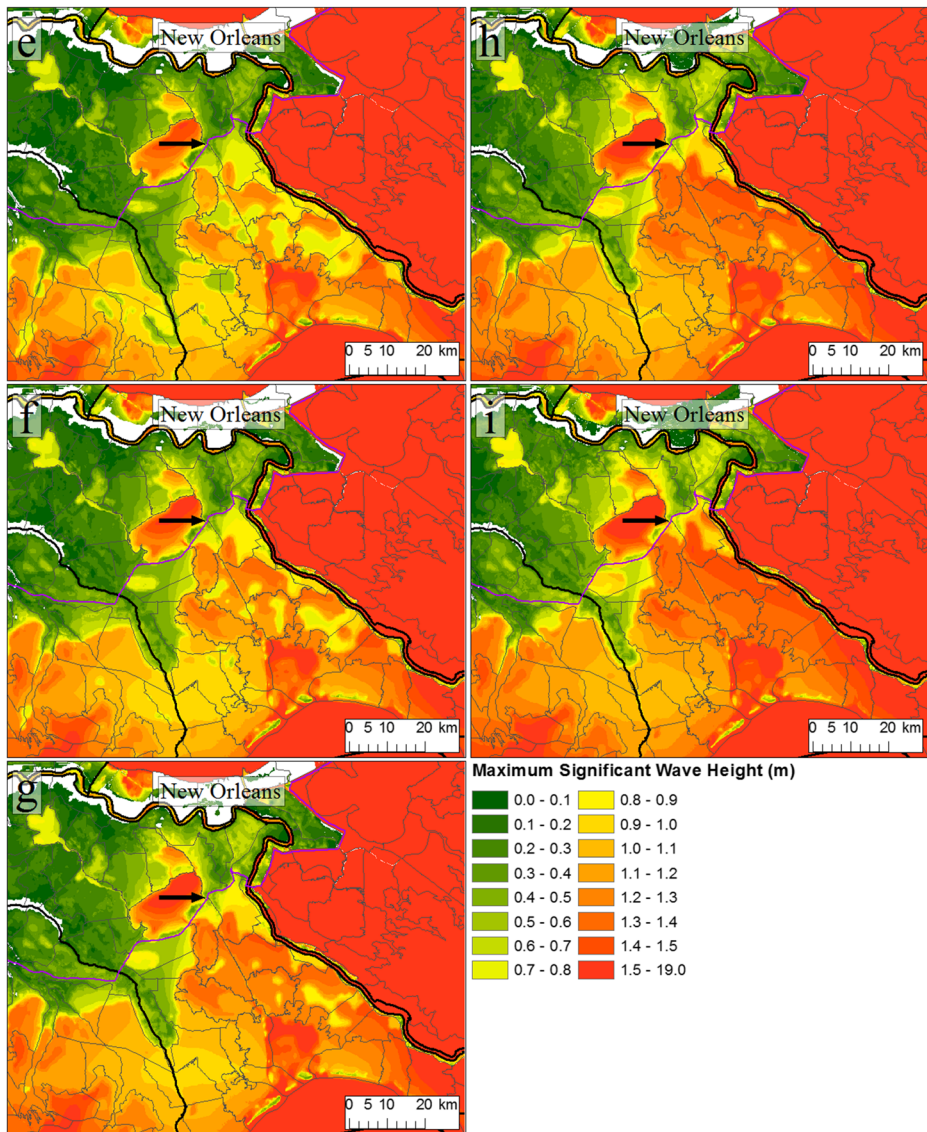


Fig. 5 Maximum of maximums (MOM) significant wave heights (m, NAVD88) computed from all 14 historical hurricanes for e 2030, f 2050, g 2070, h 2090, and i 2110. HUC6 basins (bold lines) and HUC12 sub-watersheds (gray lines) are included for spatial reference. GMSL rise of 2 mm/year 1930–2010 was included. Purple line is the Intracoastal Waterway (ICWW) and northern most boundary of the study area. Arrow points to intersection of ICWW and Bayou Barataria and the communities of Barataria and Jean Lafitte

wave run-up than $R_{u2\%}$. Therefore, $R_{u2\%max}$ is used to calculate levee design height. For freeboard, 0.31 m in additional levee height is assumed for each storm surge model mesh year to account for the tide amplitude (Table 2). The cost factor of USD \$3752.00/m² (Coastal Protection and Restoration Authority 2012) is multiplied by the levee design height including freeboard and the levee length to calculate total levee costs. Costs per person are calculated by dividing the total cost for each mesh year by the protected population (Table 2). For example,

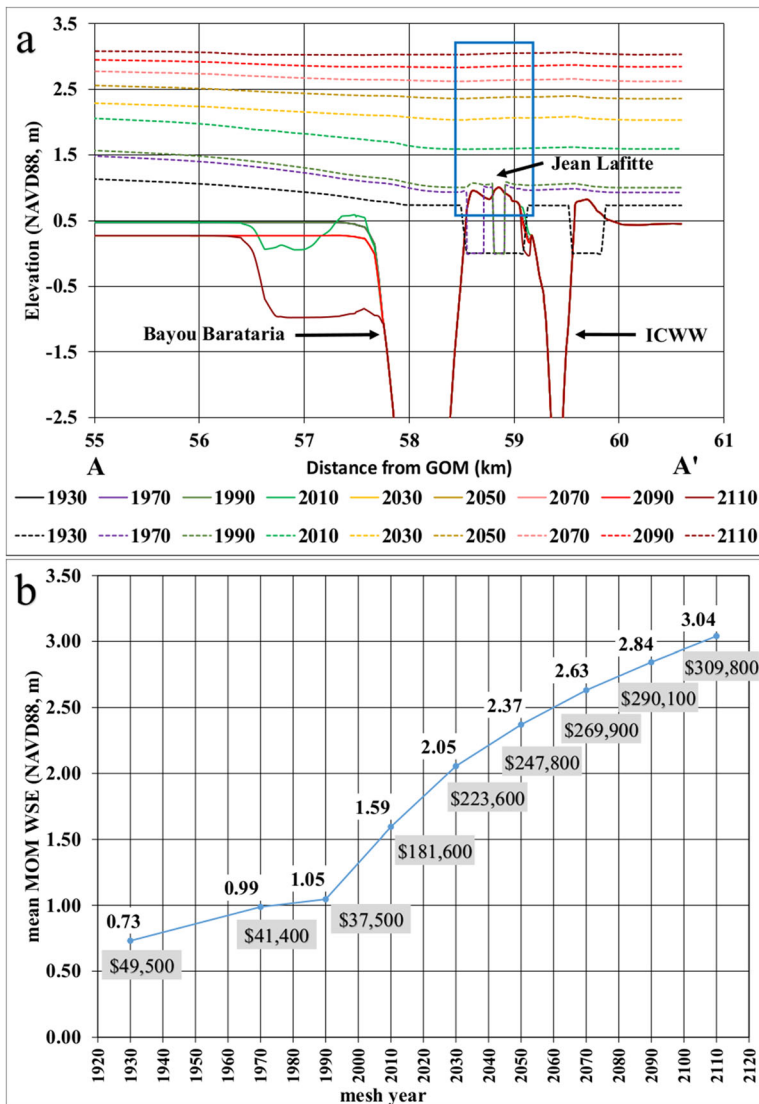


Fig. 6 **a** Elevation (solid lines, NAVD88) and Hurricane Isaac water surface elevations (dashed lines) from A–A' (Fig. 1) for storm surge model mesh years 1930, 1970, 1990, 2010, 2030, 2050, 2070, 2090, and 2110. **b** Mean non-zero Isaac water surface elevations from blue box in (a). Gray boxes average cost per person in 2010 USD for protection from Isaac storm surge for each storm surge model mesh year 1930–2110. GMSL rise of 2 mm/year 1930–2010 and GMSL rise of 5.1 mm/year 2010–2110 were included

for mesh year 2010 the freeboard levee height of 4.82 m is multiplied by the levee length of 47.55 km and the cost factor of \$3752.00/m² (Coastal Protection and Restoration Authority 2012) to yield a total cost of \$859.9 million in 2010 US dollars (Table 2). To calculate cost per person, the total cost is divided by the Lafitte protected population of 4734 to obtain \$181,633 per person.

Rough estimates of Lafitte flood defense costs for each mesh year are included in Table 2. For populations of 1850 (1930), 3838 (1970), 4791 (1990), and 4734 (2010–

2110), costs per person (2010 USD) range from \$45,500 in 1930 to \$309,800 in 2110 (Fig. 6b, Table 2). The progressively larger population from 1930 to 1990 has greater influence on the costs per person metric than the progressively rising water surface elevations and, therefore, causing the costs per person to decrease from 1930 to 1990. Therefore, costs per person are also calculated for a population decline of 75% from 2010 to 2110, the same rate as that of Isles de Jean Charles from 1955 to present. By 2110, the costs per person (2010 USD) increases to \$1,238,600 to implement flood defenses adequate to resist an Isaac storm surge (Table 3).

From 1932 to 2010 the GOM migrated approximately 8.6 km toward Lafitte within the Barataria coastal basin with 7.4 km of the inland migration occurring from 1973 to 2010. From storm surge model mesh year 1930 to 2010, flood defense costs increased approximately (2010 USD) \$89.3 million per kilometer of GOM inland migration. And, from 1970 to 2010, costs increased (2010 USD) \$94.7 million per kilometer of GOM inland migration. When accounting for population change from 1930 to 2010, Lafitte flood protection costs increased approximately (2010 USD) \$15,000 per person per kilometer inland migration of the GOM. From 1970 to 2010, the increase in Lafitte flood defense costs rise to approximately (2010 USD) \$19,000 per person per kilometer inland migration of the GOM.

6 Discussion

The four coastal communities of Lafitte are located on the west side of the Mississippi River levees approximately 58 to 60 km inland from Grand Isle and 37 km from the 1930 north shore of Barataria Bay. This area was therefore historically protected by wetlands from hurricane storm surge and waves. The counter-clockwise rotation of hurricane winds resulted in higher water surface elevations on the GOM side of the Mississippi River east bank levee. The collective population of these four communities increased 1930 to 1970 from 1850 to 3838 (107% increase) and 1970 to 2010 from 3838 to 4734 (23% increase). In addition, 7.4 km of the 8.6-km 1932 to 2010 GOM inland migration occurred from 1973 to 2010. Therefore, the increase in Lafitte flood defense costs from mesh year 1970 to 2010 (2010 USD) of \$19,000 per person per kilometer inland migration of the GOM is calculated via a fixed probability of flooding through the dominance of Hurricane Isaac in this area for all storm surge model mesh years, near constant population and constant rate of historical global mean sea level (GMSL) rise.

The four coastal communities of Lafitte provide a compelling case study which demonstrates the impact of wetland loss and ocean inland migration on storm surge for a historically unprotected coastal community. Proximity to the GOM and constant vulnerability to storm surges from 1930 to 2010 allow for a theoretical design of historical flood defenses for Lafitte for each storm surge model mesh year. From 1930 to 2010, a constant GMSL rise of 2 mm/year is applied to reduce analysis complexity and to provide conservative estimates of historical water surface elevations. The future GMSL rise scenario Intermediate-Low of Sweet et al. (2017) is applied to provide conservative estimates of future water surface elevations. In addition, the non-linear relationship of GMSL rise and increase in storm surge heights (Atkinson et al. 2012; Bilskie et al. 2016; Siverd et al. 2019b; Smith et al. 2010; Wamsley et al. 2010) is accounted for in the surge output via storm surge model meshes representative of each historical and future year.

Table 3 Levee design and approximate cost calculations to resist storm surge water surface elevations (WSE) if Hurricane Isaac were to make landfall for Lafitte, Louisiana 1930, 1970, 1990, 2010, 2030, 2050, 2070, 2090, and 2110, assuming the protected population reduces by 75% from 2010 to 2110

	1930	1970	1990	2010	2030	2050	2070	2090	2110
WSE (h, m) (Fig. 6)	0.73	0.99	1.05	1.59	2.05	2.37	2.63	2.84	3.04
Hmo (m) (Figs. 4 and 5)	0.2	0.5	0.6	0.9	1.1	1.2	1.3	1.4	1.5
γ_b	1	1	1	1	1	1	1	1	1
γ_f	1	1	1	1	1	1	1	1	1
γ_β	1	1	1	1	1	1	1	1	1
$\xi_{m-1,0}$	4	4	4	4	4	4	4	4	4
Ru2% (m) (EurOtop)	1.32	3.30	3.96	5.94	7.26	7.92	8.58	9.24	9.90
Ru2%max (m) (EurOtop)	0.65	1.63	1.95	2.93	3.58	3.90	4.23	4.55	4.88
Levee height (m)	1.38	2.62	3.00	4.52	5.63	6.27	6.86	7.39	7.92
Rc (freeboard, m)	1.68	2.92	3.30	4.82	5.93	6.57	7.16	7.70	8.22
Levee length (km)	14.50	14.50	14.50	47.55	47.55	47.55	47.55	47.55	47.55
Total cost (2010 Mil USD)	91.7	158.8	179.8	859.9	1059	1173	1278	1374	1467
Protected population	1850	3838	4791	4734	4024	3314	2604	1894	1184
Cost per person (2010 USD)	49,546	41,388	37,528	181,633	263,104	353,927	490,652	725,199	1,238,644

Four distinct phases are established in the evolution of flooding for Lafitte, Louisiana: 1. 1730–1930: no flood defenses required because surge did not propagate far enough inland; 2. 1930–1990: Barataria Waterway dredged for navigation, which added a new pathway for surge to Lafitte; 3. 1990–2010: wetland collapse between Lafitte and the Gulf of Mexico (GOM) due to damming of Bayou Lafourche in Donaldsonville in 1906; 4. 2010–2110: periodic drowning due to conversion of all wetlands to open water between Lafitte and the GOM. Hurricane Isaac water surface elevations increase approximately a half meter from 1990 to 2010 due to wetland collapse. By 2010, the length of required levees increases to a 47.55-km ring levee from 14.50 km of unconnected levees because Bayou Barataria began to overflow its banks after 1990. The required levee costs increase from (2010 USD) \$37,500 in 1990 to \$181,600 in 2010. By 2110, the costs to implement Hurricane Isaac flood defenses increases to (2010 USD) \$309,800 per person due to continued wetland loss and GMSL rise.

The methodology established to quantify the evolution of flood defense costs can be applied beyond Louisiana as a partial means to evaluating the resilience of coastal communities. The methodology is especially applicable to communities located on deltaic coasts impacted by relative sea level rise. Pre- and post-storm surge resilience activities include development and implementation of a long-term plan to address future flood risks. A suite of hurricane storm surges could be simulated to calculate the cost per person per kilometer ocean inland migration, which would establish past cost trends. The results of historical costs analyses assist policy makers in identifying possible resilience measures to reduce impact from future floods especially considering the type of community being protected. For example, measures such as elevating homes in rural Lafitte could prove more cost effective than in urban New Orleans where the costs per person are substantially lower to maintain a hardened flood defense system consisting of levees and flood gates (Louisiana Recovery Authority 2007). Wetland restoration between both rural and urban communities and the ocean also provides a cost-effective means to lower flood defense costs (Reguero et al. 2018).

7 Conclusions

Results demonstrate the substantial challenge rural coastal communities face due to future relative sea level rise. Communities such as Lafitte that have existed for nearly 300 years will confront ever increasing flood defense costs. For Lafitte, calculating the impact of wetland loss and relative sea level rise on flood defense costs is possible because the probability of flooding, population, rate of GMSL rise, and hurricane forcings are held constant or near constant from 1970 to 2010. A rough estimate of costs reveals protecting Lafitte from Hurricane Isaac-induced flooding becomes unsustainable due to cost acceleration following the collapse of wetlands between this community and the Gulf of Mexico from 1990 to 2010. The costs to implement flood protection that resists storm surge from Hurricane Isaac increases from (2010 USD) \$37,500/person in 1990 to \$181,000/person in 2010. By 2110, the costs increase to (2010 USD) \$309,800/person. In contrast, the cost to protect the more densely populated New Orleans area was \$15,800/person in 2010, an order of magnitude less than the \$181,000/person to provide flood protection for Lafitte. Using a slightly different metric, Lafitte flood defense costs increase from storm surge model mesh year 1970 to 2010 approximately (2010 USD) \$19,000 per person per kilometer inland migration of the GOM.

A similar analysis of quantifying historical storm surge and flood defense costs while maintaining flood protection from a specific level of hurricane forcing could be conducted for other unprotected Louisiana coastal communities including Des Allemands, Delacroix, Shell Beach, Venice, and coastal communities in southwest Louisiana as well as communities with similar challenges across the world. Costs per person per kilometer of inland ocean migration would demonstrate the rate of change in flood defense costs across coastal regions and identify coastal communities with higher future flood defense costs. Results would be a component of an overall resilience evaluation and aid residents and policy makers when designing long-term flood risk reduction plans. Possible resilience measures to incorporate in a long-term risk reduction plan include elevating business and residential structures in rural communities, increasing robustness of hardened flood defenses protecting urban communities, and implementing nature based measures such as marsh/dune maintenance and restoration.

Additional considerations should be incorporated in an overall community flood risk reduction plan. Benefit-cost analyses should be conducted concerning both local and national interests. For example, an energy port could be both prone to flooding and of high national economic importance (e.g., Port Fourchon). Therefore, benefits of implementing flood defenses may greatly exceed costs even though the population of permanent residents at the port is very small. Cultural value of both local and national importance may also play a role in flood risk reduction planning. The communities of Barataria and Jean Lafitte, for example, possess unique and irreplaceable culinary, historical, musical, and architectural qualities that are part of the south Louisiana culture known worldwide (Center for Planning Excellence 2014). Community relocation costs are also an important factor to consider. For example, the community of Isles de Jean Charles, located within the Terrebonne coastal basin, was awarded a \$48.3 million grant by the Department of Housing and Urban Development to relocate further inland (Dannenbergh et al. 2019; Varney 2018). As a community of 100 people, the relocation cost per person is approximately \$483,000. Although future relocations are expected to require less funding per resident, total relocation costs for a larger community would likely be substantially greater than those for Isles de Jean Charles and therefore must be included in a flood risk reduction plan. Future costs due to the continuing trends in wetland loss, GMSL rise, and increasing cyclonic intensity should also be included in the net present value costs of flood defenses. Risk perception and local inhabitants' willingness to relocate should also be considered (Kelman et al. 2019).

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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