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Tybee Island Sea Level Rise Adaptation Plan

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Administered by the National Oceanic and Atmospheric Administration (NOAA), Sea Grant conducts research, outreach and education in 33 coastal and Great Lakes states.

FINAL REPORT APRIL 2016



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TYBEE ISLAND Sea Level Rise ADAPTATION PLAN

FINAL REPORT
April 2016

Authors:
Jason M. Evans, Jill Gambill, Robin J. McDowell, P. Warwick Prichard, and Charles S. Hopkinson

FUNDED BY THE NATIONAL SEA GRANT COLLEGE PROGRAM

Administered by the National Oceanic and Atmospheric Administration (NOAA), Sea Grant conducts research, outreach and education in 33 coastal and Great Lakes states.

Executive Summary

Through an award provided by the National Oceanographic and Atmospheric Administration's (NOAA) National Sea Grant College Program, the City of Tybee Island partnered with researchers and outreach professionals from Georgia Sea Grant, the University of Georgia, and Stetson University to develop this sea-level rise adaptation plan. Using a participatory approach, this project assessed how coastal flooding risks in the City of Tybee Island are being exacerbated by sea-level rise and also explored potential adaptation actions for making the City more resilient over time.

Sea Level Rise Impacts

Long-term data from the National Oceanographic and Atmospheric Administration (NOAA) tide gauge at Fort Pulaski, located within a few miles of Tybee Island, document 10 inches of local sea-level rise since 1935. This study summarizes and documents several ways in which the City of Tybee Island is already being impacted by rising seas. The most visible of these impacts include:

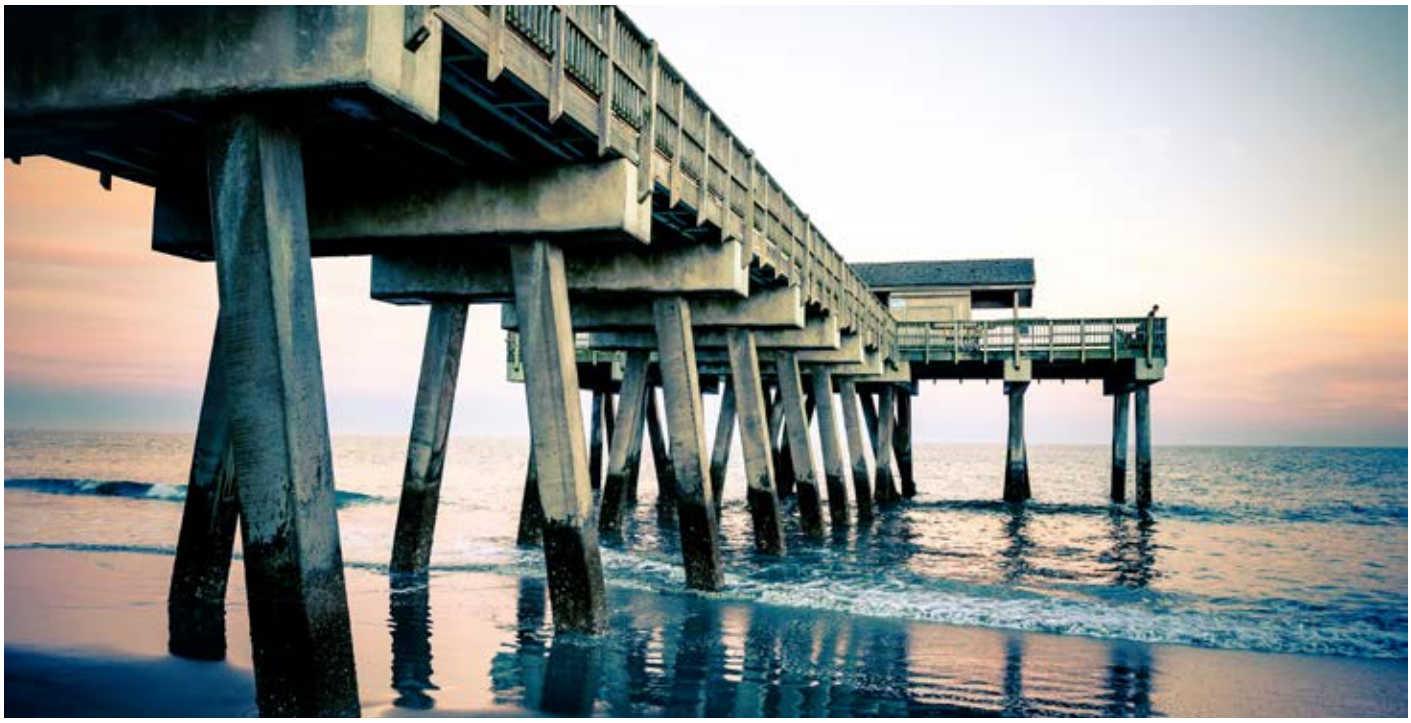
1. More frequent closures of US Highway 80, the sole road access connecting the City of Tybee Island to mainland Chatham County, due to periodic tidal flooding.
2. Tidal backup of stormwater drainage systems in low-lying areas of Tybee Island, resulting in periodic saltwater flooding of neighborhood roads and yards.
3. Increased coastal erosion, particularly on Tybee Island's Atlantic beaches.

Adaptation Options

Project researchers worked with citizens and public officials to identify a series of five adaptation actions for their potential to make the City of Tybee Island more resilient to sea-level rise and coastal flooding. While it is acknowledged that other kinds of sea-level rise adaptation approaches may be required in the future, identification and consideration of these five actions is regarded as an initial step for long-term sea-level rise planning.

Elevating Well Pump Houses

The City of Tybee Island utilizes three well pump houses for public water supply from the Upper Floridan Aquifer. Two of these well pump houses, one located on Butler Ave. and one located on 14th St., show high risk of damages from coastal flooding. A third well pump house, located at Van Horne Ave., is located on relatively high ground with less coastal flooding risk.



Benefit-cost analyses indicate very high justification for near-term elevation and flood-proofing of the Butler Ave. and 14th St. well pump house facilities. Further technical evaluation of the Van Horne Ave. pump house facility is also recommended to ensure the highest level of protection for this public water supply source.

Elevating US Highway 80

Tidal flooding of US Highway 80, the sole road access to Tybee Island, occurs on a low-lying causeway located between the Lazaretto Creek and Bull River bridges. Local tide gauge data suggest that this corridor of US Highway 80 experienced approximately 23 tidal flooding events in 2015, which is significantly more than in any year since the tide gauge was installed in 1935. The full tide gauge record at Fort Pulaski indicates that long-term sea-level rise is largely responsible for the increased number of tidal flood events on US Highway 80.

This highway flooding is known to restrict accessibility to Tybee Island and poses clear risks to public safety, particularly through loss of emergency vehicle access and blockage of the City's sole evacuation route. Due to these public safety concerns, it is recommended that current plans to modernize US Highway 80, including the replacement of the Lazaretto Creek and Bull River bridges, consider the flood risk impacts from future sea-level rise as a primary design criterion.

It is recommended that current plans to modernize US Highway 80 consider the flood risk impacts from future sea-level rise as a primary design criterion.

Stormwater Retrofits

The City of Tybee Island has recently undertaken significant efforts to retrofit stormwater systems in low-lying areas known to experience tidal flooding. Investments undertaken by the City include construction of larger underground pipe conveyances and installation of tidal backflow preventers on low-lying stormwater discharge points. Benefit-cost analysis indicates that these stormwater system investments are highly justified as an approach for avoiding damage to property and economic activity under any sea-level rise scenario over a 50-year time frame.

Image: 'The Tybee Island Pier', http://flic.kr/m01229/16613725822_37d18ab4c1_o. License at http://creativecommons.org/licenses/by/2.0.



The Tybee Island Sea-Level Rise Plan received NOAA Sea Grant's 2014 highest national outreach award and was included as a case study for sea-level rise adaptation by the U.S. Climate Resilience Toolkit.

Enhanced Sea Wall

Due to concerns about future flood risk, the project team was asked to evaluate potential benefits and costs for construction of an enhanced sea wall along a low-lying section of Tybee Island. Technical analyses indicated that the enhanced sea wall would provide little tidal flood protection benefit for several decades and, due to high construction costs, would only provide net benefits under a very high sea-level rise scenario. Follow-up discussions with City of Tybee Island officials and stakeholders indicated that pursuit of an enhanced sea wall for sea-level rise adaptation should not be recommended at this time.

Beach Renourishment

The Atlantic beaches of Tybee Island, which provide significant flood protection to the City and are a primary driver for the local tourism economy, are subject to high rates of erosion. Much of this coastal erosion is directly attributable to federal construction of the Savannah Harbor channel, which is located directly north of Tybee Island. However, sea-level rise is also increasing long-term beach erosion at Tybee Island and many other coastal communities.

Periodic sand renourishment projects by the U.S. Army Corps of Engineers, as authorized through a federal agreement called the Tybee Island Shoreline Protection Plan, have proven critical to the maintenance of Tybee Island's beaches over the past several decades. Large-scale beach dune restoration activities by the City of Tybee Island and the Georgia Department of Natural Resources have also produced substantial shoreline protection benefits.

The current Tybee Island Shoreline Protection Plan is scheduled to expire in 2024. Early discussions to re-authorize and renew the Tybee Island Shoreline Protection Plan provide an opportunity to include future sea-level rise scenarios and enhanced dune-field construction in the design of future beach renourishment projects implemented within the City of Tybee Island.

A Regional and National Model

In recognition of the wide-reaching impacts of this project, the Tybee Island Sea-Level Rise Plan received NOAA Sea Grant's highest national outreach award in 2014. The project has also been included as a case study for sea-level rise adaptation by the U.S. Climate Resilience Toolkit, the Union for Concerned Scientists, and U.S. Senator Sheldon Whitehouse of Rhode Island. Methodologies and approaches for sea-level rise planning originally developed in cooperation with the City of Tybee Island are currently being utilized in several other U.S. southeast communities, including St. Marys, Georgia; Hyde County, North Carolina; and Monroe County, Florida.

CHAPTER 1:

Introduction

Sea-level rise is one of the most pressing long-term concerns for coastal communities throughout the world. Whether through more frequent and widespread flooding or devastating destruction due to intensified storm surges, sea-level rise has the potential to dramatically affect the economic, infrastructural, and environmental bases of communities within the coastal zone.



Local observations and scientific knowledge have confirmed that rising seas are already affecting communities in the United States. Diverse impacts that include loss of road access during high-tides, increased flood damage to low-lying buildings, and documented shifts in coastal ecosystems necessitate new kinds of planning and resource mobilization. To meet this challenge, private citizens, businesses, non-governmental organizations, and governments at the local, state, and federal level are engaging in innovative partnerships that mark critical initial steps toward long-term sea-level rise adaptation.

Tybee Island is one of the first communities in Georgia to formally plan for sea-level rise. As a low-lying barrier island and beach community, Tybee Island is particularly vulnerable. The island has already experienced approximately 10 inches of sea-level rise since 1935, and this trend is expected to accelerate in the future. A major tourism hub of the Georgia coast, Tybee Island also is a significant driver of the state's coastal economy. Both in leadership and risk, the island is at the front lines of sea-level rise adaptation.

Through an innovative partnership with Georgia Sea Grant and the University of Georgia, with funding from the National Oceanographic and Atmospheric Administration's (NOAA) National Sea Grant College Program, Tybee Island has taken its first steps in planning for and adapting to sea-level rise. Pairing local knowledge with academic expertise, this effort has analyzed how the island might be affected by sea-level rise over the next 50 years. The study documents how the island is being impacted and discusses how infrastructure such as roads, water supply wells, and stormwater drainage might be made less vulnerable to sea-level rise and more resilient to sea-level rise. Through a community-driven process, an interdisciplinary team assisted the City of Tybee Island in identifying and prioritizing vulnerable areas and assets, as well as analyzing the costs and benefits of potential adaptation options.

This project has been held up as a model for other coastal governments throughout the country, via the U.S. Climate Resilience Toolkit and on the U.S. Senate Floor, and has inspired similar planning efforts in communities throughout the southeastern United States. Recipient of Sea Grant's 2014 National Superior Outreach Programming Award, the project has reached over 4,000 citizens, students, government officials, and scientists in its development.



US80 DURING A KING TIDE EVENT, OCTOBER 2015

AN INNOVATIVE PARTNERSHIP

In November 2011, officials from the City of Tybee Island began discussing local concerns about sea-level rise with faculty and staff from Georgia Sea Grant and the University of Georgia's Carl Vinson Institute of Government. Citizens were reporting an increase in flooding during large spring tide events and expressed particular concern about the flooding of U.S. Highway 80, the sole road on and off the island. This regular tidal flooding was occurring independently of rain or storm events, and community members worried that rising sea-levels were increasing the frequency and severity of flooding over time. Implications of sea-level rise on evacuation and emergency management plans, public health, property values, and the overall economic vitality of the community were also discussed.

In February 2012, Georgia Sea Grant and the Institute of Government were awarded a Community Climate Adaptation Initiative (CCAI) grant from the NOAA National Sea Grant College Program to work with the City of Tybee Island on a sea-level rise adaptation plan. The explicit intent of the CCAI program was to enhance planning in coastal communities, such as Tybee Island, being impacted by sea-level rise and other climate stressors. Partners in this grant application included the Georgia Department of Natural Resources Coastal Resources Division (DNR-CRD), the Chatham-Savannah Metropolitan Planning Commission (MPC) and Catalysis Adaptation Partners, LLC (CAP). Other entities that provided data and technical assistance with the planning process included the Georgia Coastal Regional Commission (CRC), Georgia Department of Transportation (GDOT), Skidaway Institute of Oceanography (SKIO), the United States Army Corps of Engineers (USACE), and the Ecological Planning Group.

The purpose of the project was to lay a foundation for climate adaptation on Tybee Island by:

1. Identifying impacts due to current and future tidal flooding;
2. Educating community members about their vulnerability to flooding and sea-level rise
3. Assessing the financial feasibility of potential adaptation responses
4. Informing decisions about how to avoid or mitigate impacts, and thus minimize expected vulnerabilities and economic losses over time





PAUL WOLFF, DR. ROBIN MCDOWELL AND DR. JASON EVANS OUTSIDE TYBEE ISLAND CITY HALL

This report is the capstone of the Tybee Island Coastal Communities Climate Adaptation Initiative project. It provides a synthesis of the public engagement processes, technical research, and sea-level rise adaptation strategies identified in partnership with the City of Tybee Island. An overall philosophy behind the report is that thorough consideration of future sea-level rise scenarios is critical for developing appropriate public policies and initiating sound infrastructural investments. There is also recognition that reduction of flood risks should be balanced by costs of adaptation action and the sustainable maintenance of a community's character, supporting ecosystems, and economic vitality.

It is important to note that this plan does not provide a complete accounting of all future risks on Tybee Island due to sea-level rise, or contain an exhaustive list of potential actions that may be taken in response to these risks. Instead, the plan is an initial effort to characterize vulnerabilities, explore potential adaptation actions, and, as appropriate, recommend implementation of those identified actions that show clear benefit. Ideally, these initial steps can become a foundation for future planning iterations informed by greater experience, better knowledge, and improved technologies. Such a continuous and adaptive process that actively incorporates new information into future decision-making is the essence of resilience planning.

ADAPTATION FOCUS AREAS

In a series of facilitated public input sessions, Tybee Island residents and government officials worked with the project team to characterize risks and vulnerabilities, identify potential adaptation actions, and explore policy measures. It was recognized that one of the earliest impacts of rising sea-levels on Tybee Island is decreased stormwater drainage as higher tides push into swales, ditches, and underground pipe conveyances. Back-up of stormwater systems during high tides was identified as a source of increased flooding within the local community during major rainfall events.[1] During very high tides, some stormwater systems had been observed to flow backwards on days without rainfall, potentially resulting in the conveyance of saltwater onto roads, yards, and low-lying structures. Increased occurrence of such tidal flooding events, sometimes called "sunny day flooding," was identified as a primary concern from sea-level rise.[2] There was also recognition that rising seas can result in the replacement of upland ecosystems with intertidal marsh and estuarine mudflats systems, while also increasing saltwater contamination risks for drinking water wells and underground aquifers.[3]

1 Parkinson, R.W. and T. McCue. 2011. Assessing municipal vulnerability to predicted sea-level rise: City of Satellite Beach, Florida.

2 Davenport, C. 2014. Miami finds itself ankle-deep in climate change debate. *The New York Times*, May 7. http://www.nytimes.com/2014/05/08/us/florida-finds-itself-in-the-eye-of-the-storm-on-climate-change.html?_r=0. Accessed December 29, 2015.

3 Passeri, D.L., S.C. Hagen, S.C. Medeiros, M.V. Bilskie, K. Alizad, and D. Wang. 2015. The dynamic effects of sea-level rise on low-gradient coastal landscapes: A review. *Earth's Future* 3:159–181.

Image top left: "View South from the Tybee Island (GA) Pier & Pavilion July 2012" by Ron Cogswell, http:// flic.kr/22711505@N05/7808031678. License at http://creativecommons.org/licenses/by/2.0.

Through this engagement process, the following "Focus Areas" emerged as the basis for framing and evaluating the community's sea-level rise adaptation options.

A. **MUNICIPAL INFRASTRUCTURE:** Since Tybee Island is a low-lying barrier island, much of the City's infrastructure and private property is vulnerable to flooding. Sea-level rise can be expected to exacerbate these vulnerabilities over time. Identifying these vulnerabilities, evaluating the relative costs and benefits of infrastructure improvement options, and recommending specific adaptation actions for municipal implementation were defined as key goals for sea-level rise planning.

B. **ACCESS AND CONNECTIVITY:** Tybee Island's sole road to the mainland, linking it with the Savannah Metropolitan area, is US Highway 80. Sections of this highway are very low lying and currently flood during large spring tide events. Sea-level rise can be expected to increase the frequency and severity of these flood events over the next several decades. Development of data and analyses that characterize future sea-level rise impacts on US80 and contribute to evaluation of improvement projects for the highway was identified as a key goal of the planning effort.

C. **COASTAL DYNAMICS:** Barrier islands like Tybee Island are the visible portion of a much larger and highly dynamic coastal sediment system. Coastal erosion problems on Tybee Island can be expected to worsen with sea-level rise and dredging impacts from the Savannah Harbor deepening, and therefore will need to be managed through a variety of management interventions. Some approaches include beach renourishment, dune restoration, living shorelines, coastal armoring, and relocation of vulnerable infrastructure.

D. **MANAGEMENT AND STEWARDSHIP:** Preservation of Tybee Island's rich history and proactive management promoting future sustainability are core values of the community. Careful planning, coordination across jurisdictional boundaries, and adaptation to unanticipated changes will all be required for Tybee Island to maintain its heritage and remain a thriving community over the next several decades.









PLAN OVERVIEW

Following this introduction, the remainder of the plan is organized into four chapters. Chapter 2 provides a general overview of coastal hazards on Tybee Island and how these hazards are exacerbated by sea-level rise. Chapter 3, *Community Outreach and Engagement*, provides a specific history of the public participation processes used to inform the planning effort on Tybee Island. Key to this public participation process was identification of specific actions that could be evaluated using future flood risk calculations and associated benefit-cost analyses. Chapter 4, *Analysis*, describes the flood risk calculations and benefit-cost modeling results for the adaptation actions chosen through the public participation process. These results provide an important starting point for further discussion of the suitability of the specific actions evaluated, and provide a basis for exploring other sets of adaptation actions that may emerge in continued planning. The report concludes with Chapter 5, *Project Impacts*, which discusses the broader impacts of this project to the City of Tybee Island, other coastal communities, higher education, and national discussions about climate change adaptation.

Image: 'Tybee Island' by Grant Dawson, http://flic.kr/grantdaws/17476748923. License at http://creativecommons.org/licenses/by/2.0.



FIGURE 2.1: TYBEE ISLAND, GEORGIA

CHAPTER 2:

Coastal Hazards at Tybee Island

Tybee Island is the northernmost barrier island on the Georgia coastline (FIGURE 2.1). Located in Chatham County about 15 miles due east of Savannah, the incorporated City of Tybee Island covers an area of about 2.7 square miles (~1,712 acres) and is home to approximately 3,000 permanent residents

Although the most densely developed of Georgia's barrier islands, Tybee Island maintains a quaint "beach town" character that features many historic sites, thriving local businesses, and productive coastal ecosystems. These unique attributes contribute to Tybee Island's increasing popularity with visitors from around the state, nation, and world. During the summer season, the resident population of Tybee Island approximately doubles due to an influx of seasonal residents and long-term vacationers. In addition, a significant number of daily visitors come to the island from surrounding coastal communities. Some reports indicate that, on busy summer weekends, the number of visitors to Tybee Island can exceed 30,000,[4] resulting in significant benefits to the local and state economy.

The City of Tybee Island has an average upland elevation of approximately 7.5 feet, as referenced to the North American Vertical Datum of 1988 (NAVD88). The island's highest elevations, which in a few isolated locations exceed 20 feet above NAVD88, occur on vegetated beach dunes adjacent to the Atlantic Ocean coastline (Figure 2.2). The western shoreline of the island is bordered by extensive saltmarshes dominated by Spartina alterniflora and other salt tolerant vegetation.

FORT PULASKI TIDE GAUGE

A long-term NOAA tide gauge station, originally installed in 1935, is located within several miles of the City of Tybee Island at the Fort Pulaski National Monument. Records from the Fort Pulaski tide gauge shows that waters in and around Tybee Island experience a daily tide range of 7.5 feet.[5] The daily tide range on Tybee Island can exceed nine feet during bi-monthly "spring tides" that occur during full and new moon phases.

Flooding of streets and yards has long been a concern in Tybee Island, particularly during heavy rainfall events that occur at high tide.[6] In addition to such stormwater flooding, Tybee Island also has historically experienced occasional saltwater flooding

4 Senate Research Office. 2007. Final Report of the Senate Tybee Island Beach Renourishment Study Committee. Atlanta: Georgia State Senate. http://www.senate.ga.gov/sro/Documents/StudyCommRpts/07TybeeIslandRpt.pdf. Accessed January 5, 2016.

5 NOAA. 2016. Datums for 8670870, Fort Pulaski, GA. http://tidesandcurrents.noaa.gov/datums.html?id=8670870. Accessed January 5, 2016.

6 Allred, K. 2011. Flash flood warning continues: Chatham & Jasper Counties. June 29. http://www.wsav.com/story/20697103/flash-flood-warning-continues-chatham-jasper-counties. Accessed June 12, 2015.

Historical data from the Ft. Pulaski tide gauge indicates that the frequency of nuisance flooding events is steadily increasing over time.

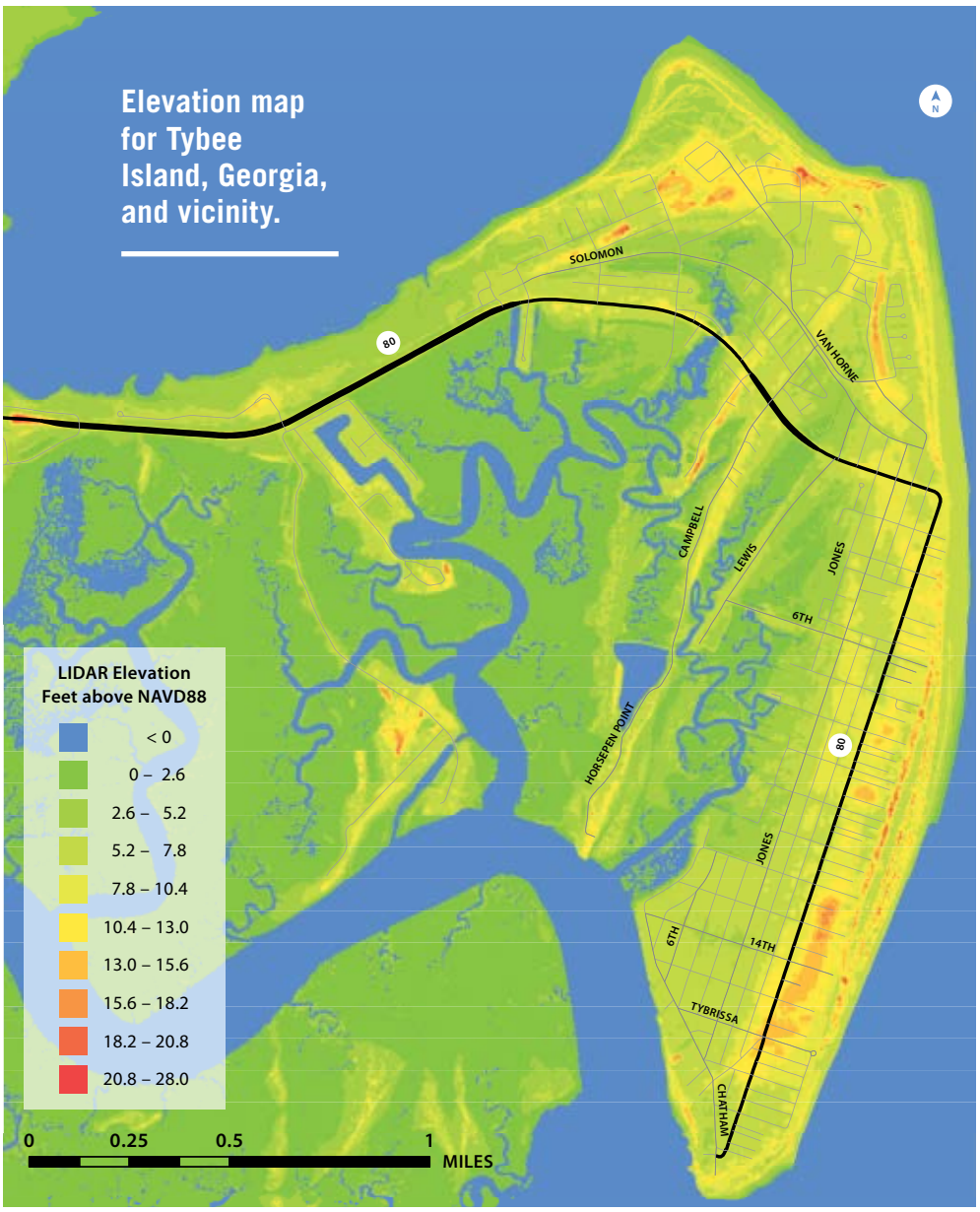


FIGURE 2.2: ELEVATION MAP FOR TYBEE ISLAND, GEORGIA, AND VICINITY. ELEVATION DATA ORIGINATED FROM THE 2009 CHATHAM COUNTY GEORGIA LIDAR PROJECT (HTTP://WWW.NGDC.NOAA.GOV/DOCUCOMP/PAGE?XML=NOAA/NESDIS/NGDC/MGG/LIDAR/ISO/XML/2009_CHATHAM_LIDAR_M1121.XML&VIEW=GETDATAVIEW&HEADER=NONE). LIDAR POINT CLOUD WAS PROCESSED INTO 5' RESOLUTION DIGITAL ELEVATION MODEL (DEM) TILES THROUGH NOAA DIGITAL COAST (HTTPS://COAST.NOAA.GOV/DIGITALCOAST/ABOUT).

during "king tide" events (Figure 2.3), which are colloquially defined as the highest spring tides that naturally occur each year. Although strong onshore winds can aperiodically raise the height of any tide, large king tides are highly predictable occurrences caused by the position of the moon and sun in relation to the earth.

A king tide that causes minor saltwater flooding of roads and yards is often referred to as a source of "nuisance" tidal flooding. For the Savannah and Tybee Island region, NOAA defines a nuisance tidal flood as water that reaches at least 5.2 feet above NAVD88 at the





FIGURE 2.3: LOCAL TIDAL FLOODING DURING A KING TIDE EVENT NOVEMBER 14, 2012 *(Photos by Jason Evans)*

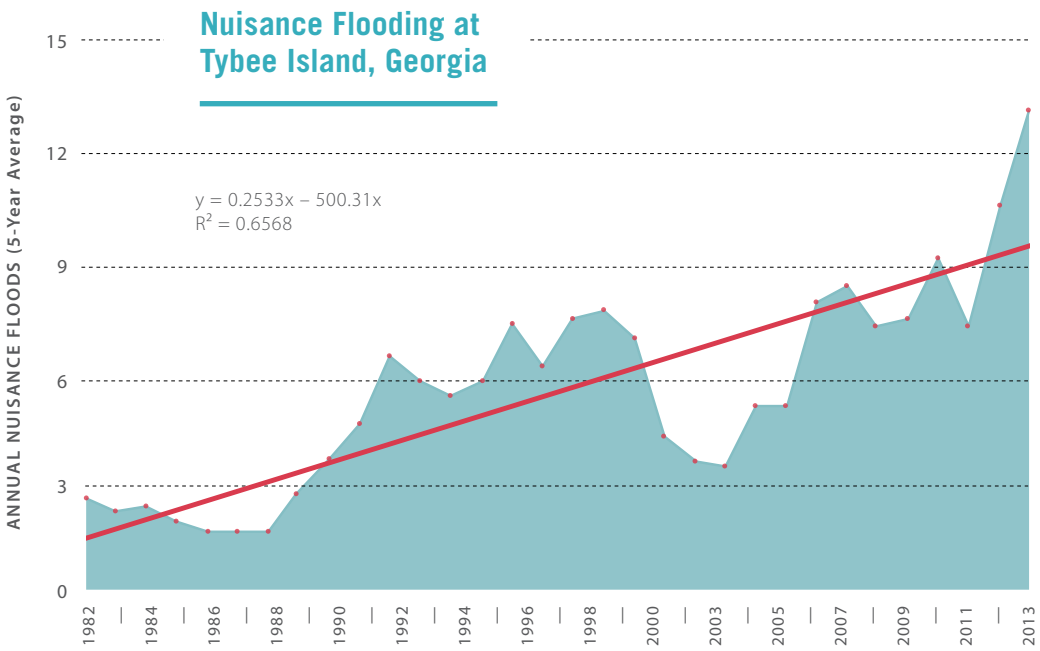


FIGURE 2.4:
NUISANCE FLOODING AT TYBEE ISLAND, GEORGIA FROM 1980–2015. VALUES REPRESENT THE ANNUALIZED AVERAGE OF TIDE EVENTS THAT EXCEED 9.2 FEET ABOVE MEAN LOWER-LOW WATER (MLLW), OR 1.7 FEET ABOVE MEAN HIGHER-HIGH WATER (MHHW), OVER A ROLLING FIVE-YEAR PERIOD AT NOAA'S FORT PULASKI TIDE GAUGE. LISTED YEARS REPRESENT THE MID-POINT OF A GIVEN FIVE-YEAR PERIOD. FOR EXAMPLE, 1982 COVERS THE 5-YEAR PERIOD FROM 1980–1984, WHILE 2013 COVERS THE FIVE-YEAR PERIOD FROM 2011–2015.

Ft. Pulaski tide gauge.[7] The Ft. Pulaski tide gauge record indicates that the frequency of nuisance flood events has steadily increased at Tybee Island over the past several decades (Figure 2.4). A total of 23 separate nuisance flood events were recorded at Ft. Pulaski in 2015 alone, which is the most of any year within the 80-year tide gauge record. Although the frequency of nuisance tidal floods fluctuates each year due to variations in weather and astronomical tide cycles, the long-term trend of increased nuisance flooding on Tybee Island is a clear consequence of rising sea-level.

7 NOAA. 2015. Fort Pulaski Tide Gage. National Weather Service, Advanced Hydrologic Prediction Service. http://water.weather.gov/ahps2/hydrograph.php?gage=fpkg1&wfo=chs. Accessed June 12, 2015.

SEA-LEVELS AND GLOBAL CLIMATE CHANGE

Recent sea level rise is likely the highest that has been experienced on earth for several thousand years.

Global sea-level is controlled by two primary factors: 1) the average temperature of the oceans; and 2) the amount of water held within the earth's continental ice sheets. Ocean temperature affects sea-level due to the basic physical property of warmer water having more volume than cooler water. In other words, because warmer water takes up more space than cooler water, warming of the oceans causes a rise in sea-level. Continental ice sheets are another important control on sea-level because they store large amounts of the earth's water outside of the ocean basin. Much like adding ice cubes will raise the level of water in a cup, melting ice sheets have the effect of raising global sea-level due to the increased amount of water being put into the ocean system.[8]

It is well-known that major changes in sea level have occurred throughout earth's geologic ages. For example, global sea level during the warmest portion of earth's last major interglacial period, or approximately 119,000 years before present, reached approximately 20 feet higher than today.[9] Most of the landmasses that make up Georgia's current barrier islands (Figure 2.5), including what is now Tybee Island, were either submerged or not yet formed during this ancient stand of higher sea-level (Figure 2.6). By contrast, sea



FIGURE 2.5: OVERVIEW MAP OF GEORGIA'S COASTAL REGION



FIGURE 2.6: VISUALIZATION OF GEORGIA'S COASTAL REGION AT PLEISTOCENE HIGH STAND SEA-LEVEL (~118,000 BP)

8 USGS. 2016. Ice, Snow, and Glaciers: The Water Cycle. http://water.usgs.gov/edu/watercycleice.html. Accessed January 5, 2016.

9 Markewich, H.W. and W. Markewich. 1991. An Overview of Pleistocene and Holocene Island Dunes in Georgia and the Carolinas — Morphology, Distribution, Age, and Paleoclimate. U.S. Geological Survey Bulletin 2069. Washington: United States Government Printing Office. http://pubs.usgs.gov/bul/2069/report.pdf. Accessed January 6, 2016.

level during the height of the last ice age, or approximately 21,000 years before present, was about 400 feet lower than today. This low sea-level was caused by the very large volumes of water being held in continental ice sheets across the northern hemisphere, as well as lower global ocean temperatures that were present during the glaciation. During this lower sea-level stand, the Atlantic coastline of Georgia was located approximately 100 miles eastward of today's coastal barrier islands (Figure 2.7).

Beginning about 19,000 years ago, rapid melting of ice sheets in North American and northern Europe brought about several thousand years of very rapid sea-level rise, which at times may have exceeded over 10 feet of rise per 100 years. After several melt cycles, ice sheets then stabilized at about 6,000 years before present. The ice sheet stabilization brought about a long period of time, notably encompassing all of written human history, in which sea level has remained relatively constant.[10]

A large body of tide gauge and, since 1992, satellite measurements indicates that global sea-level rose by about seven to eight inches over the 20th century. While this rate of recent sea-level rise is low compared to the rise at the end of the last ice age, it is likely the

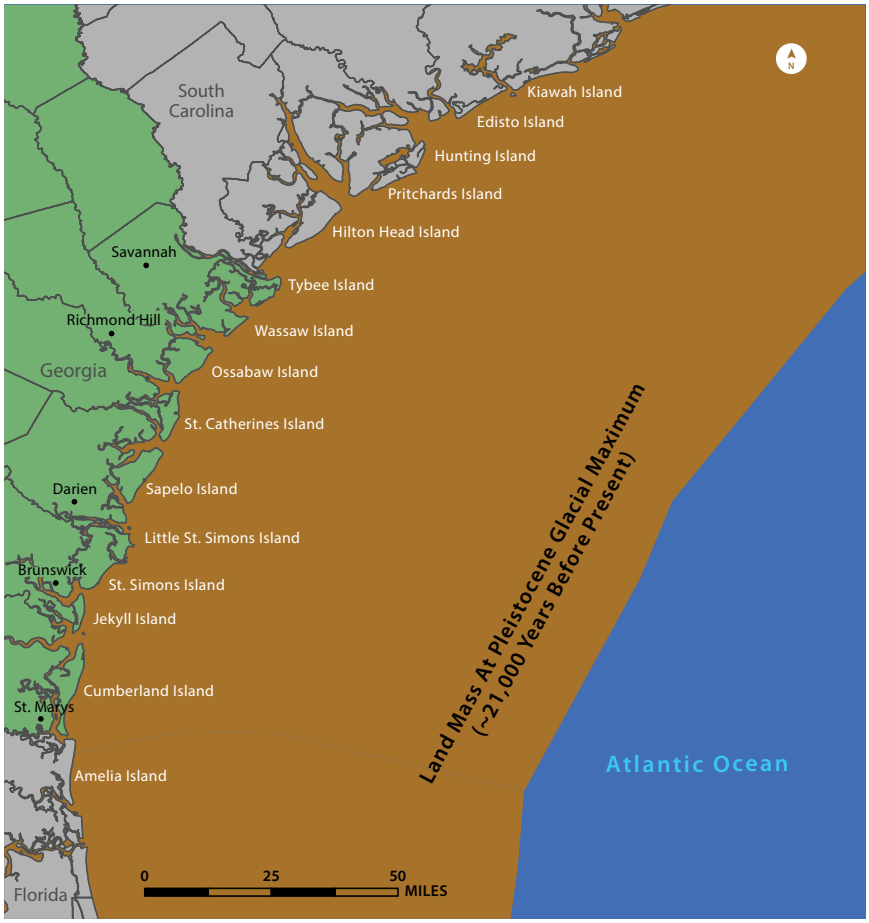


FIGURE 2.7: VISUALIZATION OF THE GEORGIA BIGHT REGION AT PLEISTOCENE LOW STAND SEA-LEVEL (~21,000 BP)

10 Gornitz, V. 2012. The great ice meltdown and rising seas: Lessons for tomorrow. NASA, Goddard Institute for Space Studies. http://www.giss.nasa.gov/research/briefs/gornitz_10. Accessed January 6, 2016.

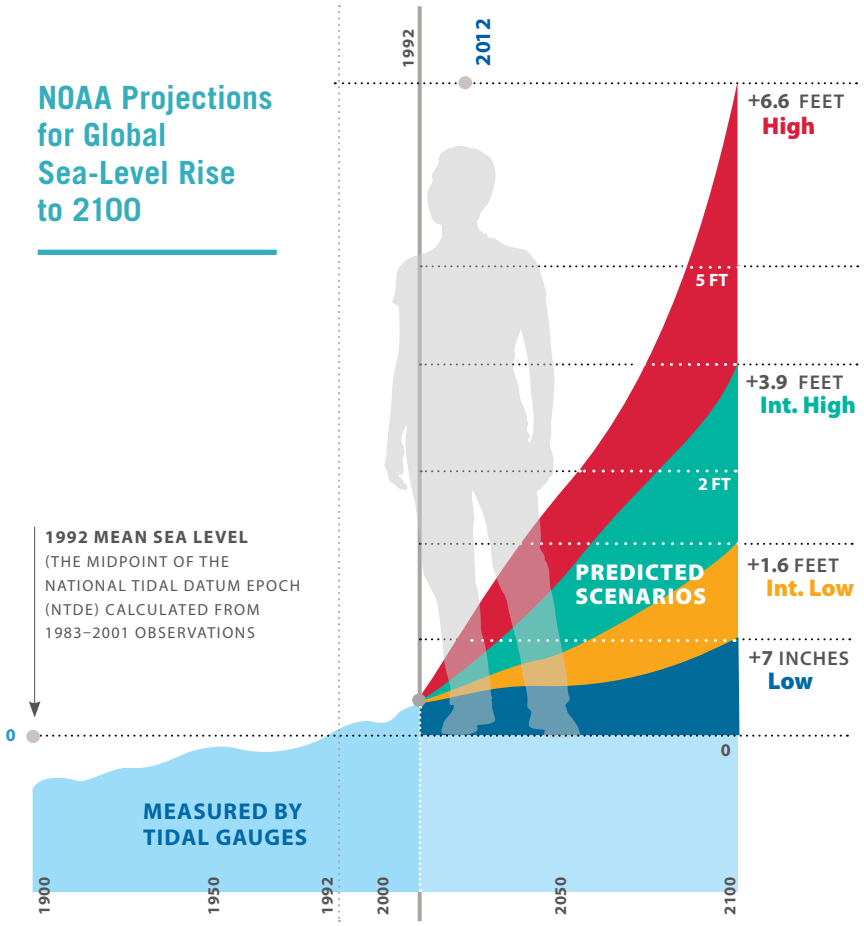


FIGURE 2.9: NOAA PROJECTIONS FOR GLOBAL SEA-LEVEL RISE TO 2100. THE LOWEST SCENARIO ASSUMES VERY MODERATE GLOBAL CLIMATE CHANGE AND A GENERAL CONTINUATION OF THE SEA-LEVEL RISE TREND OBSERVED IN THE 20TH CENTURY TIDE GAUGE RECORD. THE HIGHEST SCENARIO ASSUMES SIGNIFICANT GLOBAL CLIMATE CHANGE THAT INDUCES LARGE-SCALE MELTING OF THE GREENLAND AND ANTARCTIC ICE SHEETS.

highest rise in sea-level that has been experienced on earth for several thousand years.[11] The documented local sea-level rise at Fort Pulaski is approximately 10 inches since 1935, or about 12 inches if averaged over a 100-year period (Figure 2.8). Geologists have identified regional land subsidence, or local sinking of the land surface, as the most likely cause for the higher rate of sea-level rise observed at Fort Pulaski as compared to the recent global average.[12]

There is wide agreement among scientists that the increased sea-level rise observed over the past century is a consequence of rising ocean temperatures and glacial melting associated with anthropogenic global warming. For this reason, scientists are concerned that sea-levels have the potential to rise at a much faster pace over the 21st century due to the high likelihood of accelerated climate change. A recent report by NOAA suggests that global sea-levels in the year 2100 will almost certainly be at least eight inches higher than present, but could potentially rise by up to 6.6 feet (Figure 2.9).[13] The most recent report from the Intergovernmental Panel on Climate Change (IPCC) suggests that 2100 sea-level rise is most likely to be between about one to three feet, although the possibility of higher sea-level rise is not ruled out.[14]

11 Hay, C.C., E. Morrow, R.E. Kopp, and J.X. Mitrovica. 2015. Probabilistic reanalysis of twentieth-century sea-level rise. *Nature* 517:481-484.

12 Davis, G.H. 1987. Land subsidence and sea level rise on the Atlantic coastal plain of the United States. Environmental Geology and Water Sciences 10:67–80.

13 Parris, A., P. Bromirski, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, K. Knuuti, R. Moss, J. Obeysekera, A. Sallenger, and J. Weiss. 2012. Global sea level rise scenarios for the National Climate Assessment. NOAA Tech Memo OAR CPO. http://scenarios.globalchange.gov/sites/default/files/NOAA_SLR_r3_0.pdf.

14 IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. Geneva: IPCC.

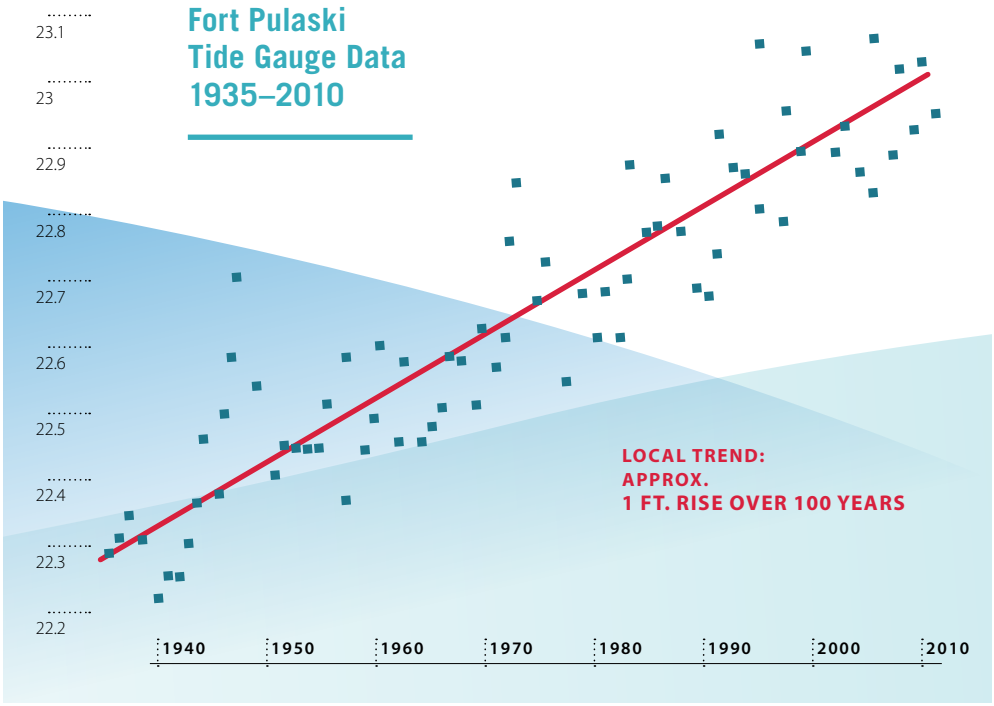


FIGURE 2.8: THE NOAA TIDE GAUGE AT FORT PULASKI HAS RECORDED APPROXIMATELY 10 INCHES OF SEA-LEVEL RISE SINCE 1935.

HURRICANES AND STORM SURGES

Like most other barrier islands in Georgia and the US Atlantic coast, Tybee Island is at significant risk of tidal surge flooding from hurricanes and other large storms. Reflecting this storm surge risk, all of Tybee Island has been designated as a Special Flood Hazard Area (SFHA) by the Federal Emergency Management Agency (FEMA).[15]

The most recent direct landfall from a hurricane-strength storm in Georgia was Hurricane David in September 1979. David was a massive storm that left tremendous destruction and thousands dead in the Caribbean, but weakened significantly before reaching the Georgia coast as a minimal Category 1 storm. Fortunately, the largest portion of Hurricane David's storm surge in Tybee Island occurred near low tide, and therefore local tidal flooding was relatively minor. More recently, Hurricane Floyd was projected to strike the Georgia coast at major hurricane strength, prompting large-scale evacuations in September 1999. However, the hurricane changed course and instead made a highly destructive landfall in coastal North Carolina. Georgia's coastal communities experienced almost no damage from the near miss of Hurricane Floyd.

Because Georgia has not experienced a direct landfall from a major hurricane[16] in over a century, there is some public perception that hurricanes are unlikely to strike Georgia's coast,[17] or that Georgia's coast is somehow immune to hurricanes altogether. It is very important to stress that such perceptions are quite mistaken. In fact, the geologic record

FEMA has designated the entirety of Tybee Island a Special Flood Hazard Area (SFHA).

15 http://www.cityoftybee.org/EmergencyMgmt.aspx?CNID=139. Accessed June 15, 2015.

16 The National Hurricane Center (http://www.nhc.noaa.gov/aboutsshws.php, accessed January 5, 2016) defines a major hurricane as having winds of at least 111 miles per hour, or a Category 3 storm or higher on the Saffir-Simpson hurricane wind scale.

17 Pavey, R. 2010. Georgia rarely gets hit by hurricanes: here's why. The Augusta Chronicle. September 1. http://chronicle.augusta.com/content/blog-post/rob-pavey/2010-09-01/georgia-rarely-gets-hit-hurricanes-here-s-why.



US80 DURING A KING TIDE EVENT, OCTOBER 2015 *Credit: Tybee Island Police Department*

Perceptions that Georgia's coast is somehow immune to hurricanes are quite mistaken.

shows that the Georgia coast has been frequently impacted by large hurricanes over the past millennia.[18] This indicates that future hurricanes, including very powerful and destructive storms, can and should be expected to affect the region.

During the 19th century alone, six major hurricanes made direct landfalls on the Georgia coast, including the years of 1804, 1813, 1824, 1854, 1893 and 1898.[19] The most severe of these was the 1893 Sea Islands Hurricane, estimated to have been at Category 3 strength when it made landfall on August 27 near Tybee Island. Approximately 2,000 U.S. fatalities were caused by this hurricane, leading the Savannah Morning News to dub it the "Cyclone of Death". Many of the fatalities were associated with a massive storm surge, estimated at 16 feet above predicted tidal conditions at Tybee Island. Records from the time indicate that almost all structures on Tybee Island were destroyed by the powerful storm surge and fierce winds associated with this hurricane.[20]

The City of Tybee Island is well-recognized for its extensive efforts to promote storm surge awareness and hurricane preparedness among its citizens and visitors. For example, the City has installed several storm surge displays that show the potential flood heights associated with hurricanes of variable intensity, including a prominent display at the entrance of City Hall. The City also has a one-foot freeboard requirement, which mandates the elevation of first floors for new or substantially improved homes at one foot above the designated 100-year floodplain height. Further examples of hurricane and storm surge flood protection activities undertaken by the City of Tybee Island can be found at the City's Emergency Management website (http://www.cityoftybee.org/emergencymgmt.aspx).

In a 2010 planning effort, hazard planners in the City of Tybee Island, Chatham County, and other local governments identified the need to better understand how sea-level rise is changing flood risks from storm surges and potential impacts to the built environment.[21]

18 Kiage, L.M., D. Deocampo, T.A. McCloskey, T.A. Bianchette, and M. Hursey. 2011. A 1900-year Paleohurricane Record from Wassaw Island, Georgia, USA. Journal of Quarternary Science 26:714–722.

19 Fraser, W.J. 2006. Lowcountry Hurricanes: Three Centuries of Storms at Sea and Ashore. Athens: University of Georgia Press.

20 Ciucevitch, R.A. 2005. *Tybee Island: The Long Branch of the South*. Charleston: Arcadia Publishing.

21 Chatham Emergency Management Agency. 2010. Chatham County Multi-Jurisdictional Pre-Disaster Hazard Mitigation Plan. Developed in cooperation with the governments of: Chatham County, City of Bloomingdale, City of Garden City, City of Pooler, City of Port Wentworth, Town of Thunderbolt, City of Savannah, City of Tybee Island. http://www.chathamemergency.org/!Chatham%20Base%20HMP_CFA_102110.pdf. Accessed June 15, 2015.



A GEORGIA SEA GRANT MARINE EDUCATION INTERN COLLECTING FLOOD DATA ON TYBEE ISLAND, OCTOBER 5, 2015

The large-scale flooding associated with Superstorm Sandy, which devastated portions of the northeast US Atlantic coast in October 2012, raised broader national attention to the problem of sea-level rise resulting in larger storm surge events that overwhelm the capacity of existing coastal defense infrastructure.[22, 23] Although the magnitude of recent sea-level rise on Tybee Island (~10 inches since 1935, or ~12 inches over the past 100 years) is relatively small compared to a major hurricane storm surge, it is well-understood that a higher base sea-level inexorably increases the potential damages from a given storm surge event.[24]

BEACH EROSION AND SHORELINE PROTECTION

The beaches and shorelines of Tybee Island are subject to the natural forces of erosion (removal of sediments that leads to loss of land) and accretion (deposit of sediments that leads to the building of land). The beaches of Tybee Island, like most barrier islands of the southeast US Atlantic coast, tend to erode sands from the island's northern end, while sands tend to deposit and accrete on the southern end of the island.[25] Much of this natural sand movement process, known as the longshore drift, is driven by prevailing winds and associated wave angles. Hurricanes and other large storms can also have very large, and sometimes quite different, impacts on the local erosion and accretion of beach sediments.

Natural beach erosion and accretion processes on Tybee Island have been substantially altered by human activities for well over a century. For example, a 2008 technical report by the US Army Corps of Engineers found that historic dredging of the Savannah Harbor channel, which connects from the Savannah River to the Atlantic Ocean just north of Tybee Island, is responsible for between 73.6–78.5 percent of the net beach erosion that has occurred on Tybee Island since 1897.[26] This impact is caused by the deepened channel significantly reducing the velocity of the longshore drift current, which then results in

22 Miller, K.G., R.E. Kopp, B.P. Horton, J.V. Browning, and A.C. Kemp. 2013. A geological perspective on sea-level rise and its impacts along the U.S. mid-Atlantic coast. Earth's Future 1:3–18.

23 Neumann, J.E., K. Emanuel, S. Ravela, L. Ludwig, P. Kirshen, K. Bosma, and J. Martinich. 2015. Joint effects of storm surge and sea-level rise on US coasts: New economic impacts, adaptation, and benefits of mitigation policy. Climatic Change 129:337–349.

24 Tebaldi, C., B.H. Strauss, and C.E. Zervas. 2012. Modelling sea level rise impacts on storm surges along US coasts. Environmental Research Letters 7:021001.

25 Griffin, M.M. and V.J. Henry. 1984. Historical Changes in the Mean High Water Shoreline of Georgia. Bulletin 98. Atlanta: Georgia Geologic Survey. https://epd.georgia.gov/sites/epd.georgia.gov/files/related_files/site_page/B-98.pdf. Accessed January 5, 2016.

26 McKee Smith, J. D.K. Stauble, B.P. Williams, and M.J. Wutkowski. 2008. Impact of Savannah Harbor Deep Draft Navigation Project on Tybee Island Shelf and Shoreline. ERDC/CHL TR-08-5. Savannah: U.S. Army Corps of Engineers.



TYBEE ISLAND BEACH RENOURISHMENT, NOVEMBER 4, 2014
(U.S. Army Corps of Engineers photo by Billy Birdwell)

beach sediments falling out of suspension into the channel bottom. Consequently, beach sediments that would have reached Tybee Island under natural conditions instead become trapped in the Savannah Harbor channel.

Increased shoreline erosion was apparent on Tybee Island soon after the Savannah Harbor channel project was initiated in the 19th century. These erosion issues then prompted a long history of additional coastal engineering interventions that have attempted to abate and reverse beach erosion effects on Tybee Island. Perhaps the most notable early (circa 1938–1941) project was construction of a large concrete sea wall, with a top height approximately 12 feet above mean low water, on the Atlantic beach side of Tybee Island. This sea wall, constructed largely by the federal government through the Depression-era Works Project Administration (WPA), successfully halted most westward erosion on Tybee Island. However, wave scour erosion was significantly worsened on the east (beach) side of the sea wall. As a result, many high tides from the 1940s to early 1970s directly submerged much of Tybee Island's Atlantic beach, allowing waves to crash directly onto the WPA sea wall. This then progressively eroded the beach even further over time.[27]

In a decades-long series of attempts to reverse this erosion cycle, coastal engineers at the federal, state, and local level designed and installed a variety of beach groins and sand berm structures east of the WPA sea wall on Tybee Island. These structural interventions largely failed, however, and rapid beach erosion continued almost unabated on Tybee

27 The City of Tybee Island. 2014. Tybee Island Beach Management Plan. http://weblink.cityoftybee.org/weblink/0/edoc/15641/070_050_Tybee%20Island%20Beach%20Management%20plan%200ctober%2027%202014.pdf. Accessed January 6, 2016.

Island through the early 1970s. A comprehensive 1985 report by the US Army Corps of Engineers identified loss of beach sediment supply due to the Savannah Harbor channel, continued wave scouring due to the WPA sea wall, and long-term sea-level rise—as documented locally at the Fort Pulaski tide gauge—as the primary contributing causes of this chronic beach erosion problem at Tybee Island.[28]

Since the mid-1970s the beaches of Tybee Island, like many eroding US beaches, have been maintained through large-scale sand renourishment projects. Sand renourishment involves the use of mechanical dredges to capture suitable sediments from offshore areas and subsequent deposit of these sediments onto the beach and nearshore coastal waters. The agreement between local, state, and federal authorities that covers the renourishment of Tybee Island's beaches, called the "Tybee Island Shore Protection Project," is authorized by the Federal Shore Protection provisions of the Water Resources Development Act of 1976. The provisions of the Tybee Island Shore Protection Project make the beaches of Tybee Island eligible for federally assisted renourishment every seven years through 2024.[24,25]

Large-scale sand renourishment under the Tybee Island Shore Protection Project began in 1975–1976. Other renourishment projects were completed on Tybee Island in 1986-1987, 1999–2000, 2008, and 2014–2015.[29] Over time, these renourishment projects have almost completely covered the WPA sea wall with beach sands, thus effectively removing the enhanced wave scour and accelerated beach erosion effects once associated with this structure. The renourishment projects are generally regarded as essential to the creation and maintenance of large areas of recreational beach on Tybee Island, which has served as a primary driver in the growth of the City's tourist economy over the past several decades.[30] These significant economic benefits provide a primary justification for the local, state, and federal expenditures required to complete the renourishment projects on Tybee Island.

Another fundamental goal of the Tybee Island Shore Protection project is to manage and renourish the City's beaches in a way that provides "flood control protection from hurricanes and storm damage". Consistent with this goal, a long-term partnership between the City of Tybee Island and the Georgia Department of Natural Resources has resulted in the restoration of large expanses of vegetated sand dunes along most of Tybee Island's beaches. These dune restoration activities have provided significant flood protection benefits for Tybee Island residents, while also further reducing the impacts of beach erosion and improving habitat conditions for several shore-dependent wildlife species. In recognition of these important ecosystem services, the most recent Tybee Island Beach Management Plan, developed by the City of Tybee Island, calls for increasing effort to expand and strengthen dune-building activities across all of the City's beaches.[31]

Restoration of vegetated sand dunes along Tybee Island's beaches has provided significant flood protection benefits.

28 Oertel, G.F., J.E. Fowler, and J. Pope. 1985. History of Erosion and Erosion Control Efforts at Tybee Island, Georgia. AD–A156 163. Vicksburg: U.S. Army Corps of Engineers.

29 US Army Corps of Engineers. 2014. Final Environmental Assessment and Finding of No Significant Impact: Tybee Island, Georgia Shore Protection Project 2014-2015 Renourishment. Savannah: US Army Corps of Engineers. http://www.sas.usace.army.mil/Portals/61/docs/Planning/Plansandreports/TybeeFinalEA/FinalEA.pdf. Accessed January 6, 2016.

30 Toma, M. and A. Brewer. 2007. The Economic Impact of Tybee Island Beach Renourishment on Georgia's Economy. Savannah: Center for Regional Analysis, Armstrong Atlantic University. http://www.cityoftybee.org/Assets/Files/BeachTaskForce/BeachEconomicImpact.pdf.

31 The City of Tybee Island. 2014. Tybee Island Beach Management Plan. http://weblink.cityoftybee.org/weblink/0/edoc/15641/070_050_Tybee%20Island%20Beach%20Management%20plan%20October%2027%202014.pdf. Accessed January 6, 2016.



US80 DURING A KING TIDE EVENT, NOVEMBER 2012

CHAPTER 3:

Community Outreach and Engagement

Recent research documents the extent to which rising sea-levels are already impacting property, infrastructure, and ecosystems in many US coastal communities, including Tybee Island.[32] Focusing on a 50-year time frame, the Tybee Island Sea-level Rise Adaptation Plan was developed through a multi-tiered community-driven planning approach.

This effort entailed:

- Analyzing local vulnerability to sea-level rise;
- Identifying possible solutions to problems associated with flooding; and
- Weighing the cost and benefits of adaptation actions.

The project was developed and implemented using a trans-disciplinary approach that integrated expert knowledge, stakeholder engagement, and a participatory decision-making process.[33] This promoted a planning process that was more consistent with existing local infrastructure, relevant laws and ordinances, and cultural preferences.[34]

A series of three town hall meetings, all open to the public and held at the Tybee Island City Hall, were a central component of the project. Press releases, local media coverage, flyers, email announcements, social media and advertisements on the City of Tybee Island website, a local access television station, and the electric marquee outside of the City Hall Building were used to inform stakeholders about the meetings and invite their participation. An in-depth log of the town hall meeting content is provided in Appendix I.

Making Data Accessible

The first town hall meeting, held in May 2012, featured a series of expert presentations on sea-level rise science and adaptation, and also solicited input from public officials and local citizens about unique issues faced by Tybee Island. In discussing future projections of sea-level rise, the project team worked with the community to explain and compare

32 Sweet, W., J. Park, J. Marra, C. Zervas, and C. Gill. 2014. Sea Level Rise and Nuisance Flood Frequency Changes around the United States. NOAA Technical Report NOS CO-OPS 073. http://tidesandcurrents.noaa.gov/publications/NOAA_Technical_Report_NOS_COOPS_073.pdf. Accessed September 17, 2015

33 Angelstam, P. K. Anderson. M. Annerstedt, R. Axelsson, M. Elbadidze, P. Garrido, I. Stjernquist, et al. 2013. Solving problems in socio-ecological systems: Definition, practice and barriers of transdisciplinary research. Ambio – A Journal of the Human Environment 42:254–265.

34 Thompson Klein, J. 2013. The transdisciplinary moment(um). Integral Review: A Transdisciplinary & Transcultural Journal for New Thought, Research, and Praxis 9:189–199.

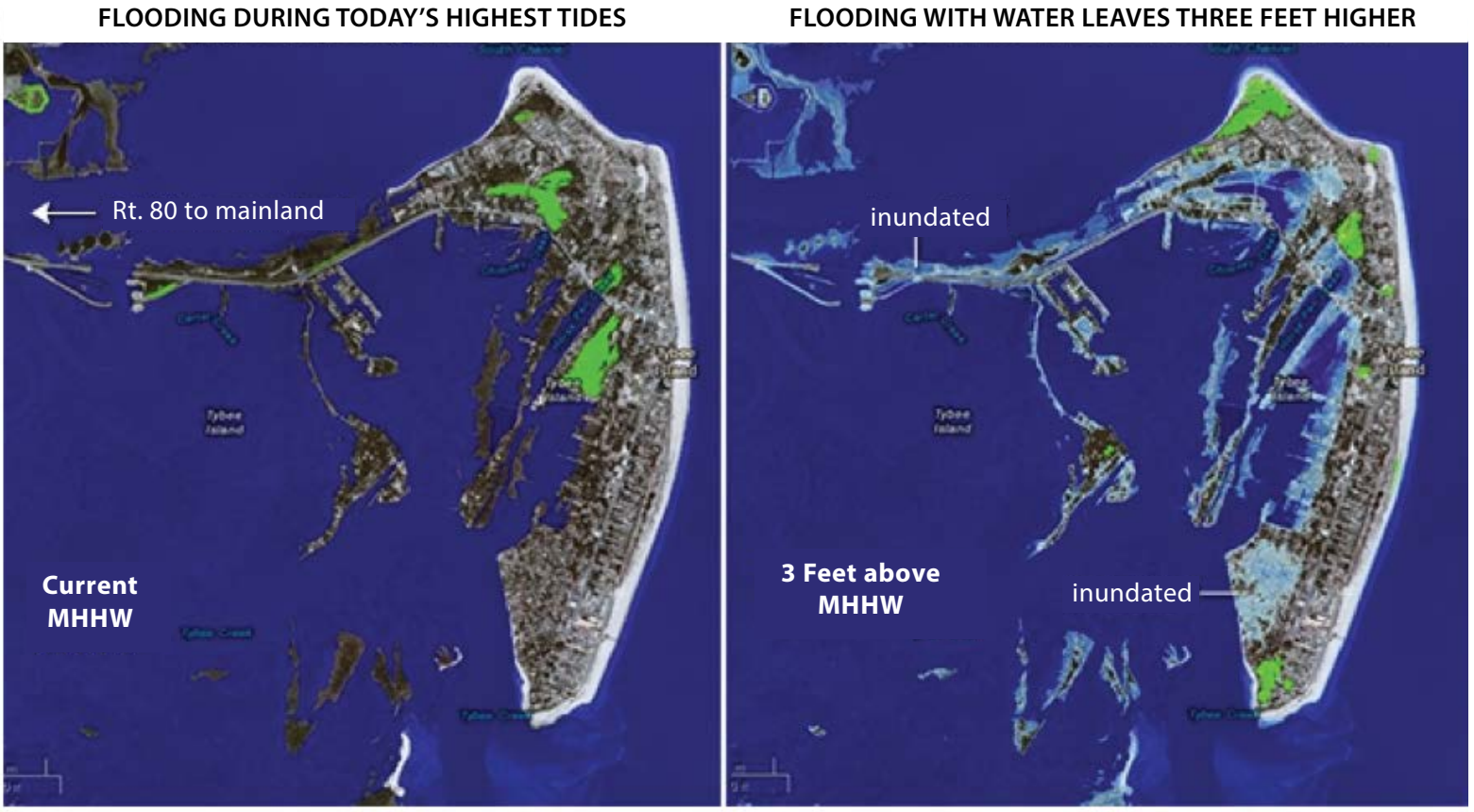


FIGURE 3.1. SEA-LEVEL RISE AND COASTAL FLOODING IMPACTS VIEWER MAPS OF TYBEE ISLAND TODAY (LEFT) AND WITH THREE FEET OF SEA-LEVEL RISE (RIGHT).[39]

different models and scenarios. Particular effort was made to acknowledge uncertainties in future projections and communicate hazards on a human time-scale.

The project team employed a variety of visualization and facilitation tools in support of this objective. For example, the Sea-level Rise and Coastal Flooding Impacts Viewer (https://coast.noaa.gov/digitalcoast/tools/slr), launched in 2011 by NOAA's Office for Coastal Management, allows website visitors to simulate different rates of sea-level rise in locations around the country. It uses a modified "bathtub" approach to sea-level rise, taking into account elevation, tidal variability, and hydro-connectivity to map coastal inundation under different sea-level rise scenarios.[35] By using the Viewer to display Tybee Island with three-feet of sea-level rise (Figure 3.1), the project team showed Tybee Island's vulnerability in a way that was concrete, relatable, and accessible to stakeholders.

Identifying Vulnerabilities

A second series of town hall meetings, held in August 2012, worked with local officials and citizens to identify local assets at-risk from sea-level rise, review sea-level rise adaptation strategies, and choose the rates of sea-level rise to be used in the adaptation planning process.

Utilizing a modified version of the Vulnerability, Consequences, and Adaptation Planning Scenarios (VCAPS) facilitation process, meeting participants were encouraged

35 NOAA. 2015. Frequent Questions: Digital Coast Sea Level Rise and Coastal Flooding Impacts Viewer. http://coast.noaa.gov/digitalcoast/_/pdf/SLRViewerFAQ.pdf. Accessed January 5, 2016.

39 Greenhalgh, E. 2014. On Georgia seashore, visualizing sea level rise to set planning priorities. https://www.climate.gov/news-features/climate-case-studies/georgia-seashore-visualizing-sea-level-rise-set-planning. Accessed January 5, 2016



to offer their institutional knowledge on vulnerable areas and anecdotal information on historic flooding events. Through this process, the project team gathered critical feedback and on-the-ground insights from local residents and community leaders. As summarized in Figure 3.2, meeting participants identified the following concerns related to sea-level rise:

- **FAILURES OF THE LOCAL STORMWATER MANAGEMENT SYSTEM**
- **FLOODING OF ROADS, PARTICULARLY US HIGHWAY 80**
- **INCREASED BEACH EROSION**
- **SALTWATER INTRUSION**
- **HIGHER AND STRONGER STORM SURGES**

Choosing Sea-Level Rise Scenarios

Meeting participants also worked with the project team to decide upon the projected height of sea-level rise to use in planning for the future. A wide range of published sea-level rise scenarios were discussed through facilitated discussion, with present members of the Tybee Island City Council providing final determination of model parameters through majority votes. Through this process, it was decided that widely cited sea-level rise curves published by climate scientists Martin Vermeer and Stefan Ramhstorf would be used for the ***High*** and ***Intermediate*** sea-level rise scenarios in the City's adaptation planning through the year 2060.[36] The ***Low*** sea-level rise value would be based on linear extrapolation of the Ft. Pulaski tide gauge record. A summary of these sea-level rise scenarios is provided in Table 3.1

SCENARIO	PROJECTED SEA-LEVEL RISE BY 2060*
High	31 inches
Intermediate	14 inches
Low	6 inches

TABLE 3.1: 2060 SEA-LEVEL RISE SCENARIOS FOR THE TYBEE ISLAND SEA-LEVEL RISE ADAPTATION PLAN. THE ASSUMED BASE YEAR FOR SEA-LEVEL IS 2010.[38]

36 Vermeer, M. and S. Rahmstorf. 2009. Global sea level linked to global temperature. Proceedings of the National Academy of Sciences of the United States of America.106:21527-21532.

38 Technical description of the methods to derive sea-level rise scenarios is provided in Appendix II.

Image: U.S. Army Corps of Engineers Savannah District by Billy Birdwell, http://flic.kr/savannahcorps/15534084458. License at http://creativecommons.org/licenses/by/2.0.

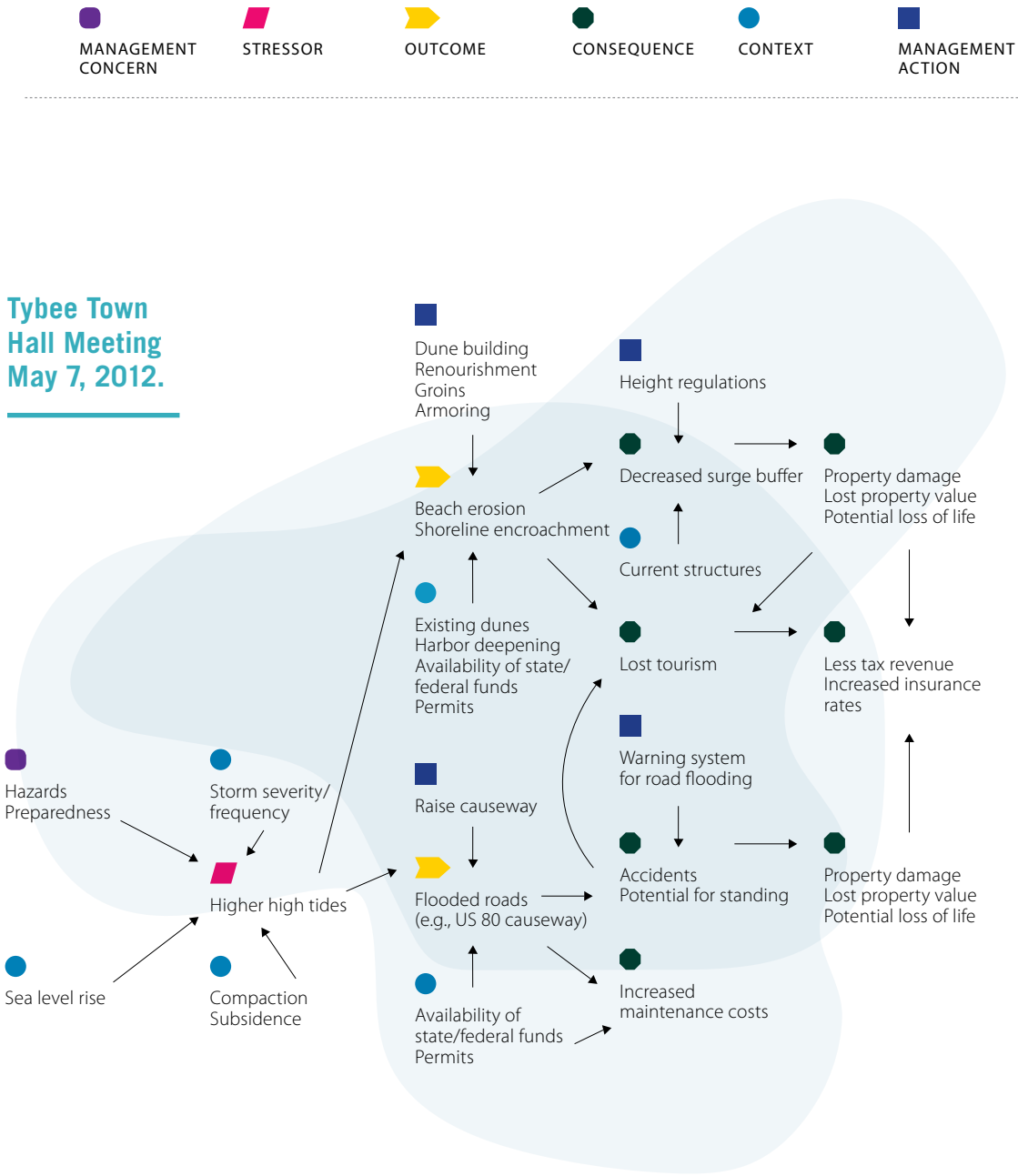


FIGURE 3.2. DIAGRAM OF DISCUSSIONS ON SEA-LEVEL RISE VULNERABILITIES AND ADAPTATION OPTIONS FROM TYBEE TOWN HALL MEETING ON MAY 7, 2012.





Choosing Adaptation Options

The project team presented a wide range of adaptation options and examples of sea-level rise planning practices from other communities. Some of these options and practices included infrastructure elevation, wet flood-proofing, dry flood-proofing, rolling easements, fee simple acquisition of vulnerable property, beach renourishment, and shoreline armoring. Based upon the specific sea-level rise vulnerabilities facing Tybee Island, five potential local adaptation actions were selected by the community for more detailed consideration:

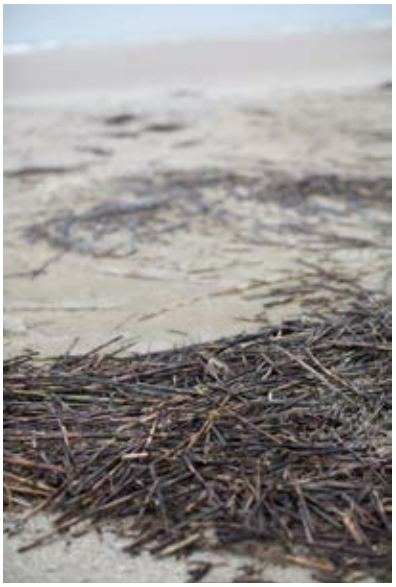
ACTION 1: ELEVATION OF MUNICIPAL WELL PUMPS:
Elevating the first floor of the City's well houses and electronic components to three feet above the 100-year floodplain.

ACTION 2: ELEVATION OF US 80:
Elevating the US 80 causeway between Wilmington Island and Tybee Island to three feet above current grade.

ACTION 3: STORMWATER RETROFITS:
Retrofits of low-lying stormwater infrastructure to prevent flooding from tidewater backflow.

ACTION 4: BUILDING A SEAWALL:
Construction of a back-island seawall, at a height of three feet over the current nuisance tidal flooding level, to prevent bank overflow in low-lying areas.

ACTION 5: ENHANCED BEACH NOURISHMENT:
Increased frequency of beach renourishment relative to increased sea-level rise out to 2060.



Choosing Benefit-Cost Criteria

The final component of the August 2012 town hall meetings was determination of the technical criteria that would be used to develop dollar-based inputs for adaptation modeling. The two criteria chosen through participant consensus were the tax-assessed values of buildings and the annual economic activity generated by the City's hotel-motel tax receipts. Assessed values of buildings were to be obtained from Chatham County's property parcel GIS database, while the spatial component of economic activity was to be developed by linking hotel-motel tax receipts to property addresses. The revenues would then be adjusted by a standard multiplier to account for economic activity from tourism. An annualized discount rate of 3 percent was chosen for modeling future flooding damage to both buildings and economic activity.

Weighing Results and Refining the Approach

A series of two town hall meetings, held in March 2013, presented a suite of technical evaluations and benefit-cost analyses for selected adaptation actions identified in the August 2012 meetings. Upon reviewing the results, members of the Tybee Island City Council directed the project team to further refine project analyses and recommendations in conjunction with the City of Tybee Island's Community Resources Committee and the Beach Task Force Committee.

Follow-up meetings with the Community Resources Committee provided feedback on LIDAR-based maps showing predicted extents of local king tides and offered guidance into additional areas where regular tidal flooding has been observed. Following these discussions, members of the Community Resources Committee initiated the Tybee Island King Tide Project,[37] which provides an online repository of photographs that document local tidal flooding events.

Meetings with the Beach Task Force Committee provided clear direction that formal benefit-cost modeling of sea-level rise and enhanced beach renourishment was beyond the resources available for this project. While current Congressional authorizations and schedules being followed by the US Army Corps of Engineers did not allow for additional dune elevation to be included as a design parameter in the 2014–2015 renourishment cycle, the Committee expressed interest in pursuing other avenues for promoting enhanced dune development as a storm buffer, sea-level rise adaptation, and overall flood mitigation strategy.

Additional Input and Outreach

This planning process involved extensive public outreach to Tybee Island residents, business leaders, elected officials, and government staff in making decisions about the scope and focus of the plan. In addition to public town hall-style meetings, regular communication took place with government staff, city committees, and other stakeholders. These conversations and collaborations provided additional data and insights that were included in the planning process. Additional technical and logistical support was provided by personnel from the Department of Natural Resources Coastal Resources Division (DNR-CRD), the Chatham County Metropolitan Planning Commission (MPC), and Catalysis Adaptation Partners LLC (CAP). Other entities that provided data and technical assistance through this process included the Georgia Coastal Regional Commission (CRC), Georgia Department of Transportation (GDOT), Skidaway Institute of Oceanography (SKIO), and the United States Army Corps of Engineers (USACE).

37 Tybee Island King Tide Project. 2015. https://www.flickr.com/groups/tybeekingtide. Accessed January 5, 2016.

CHAPTER 4:

Assessment of Adaptation Actions

To facilitate local decision-making, the project team developed a series of analyses to assess the relative benefits and costs of four selected adaptation options. This chapter summarizes the technical approaches used to develop these benefit-cost analyses and discusses the results.

ACTION 1: ELEVATION OF MUNICIPAL WELL PUMPS

Safe and sustainable sources of drinking water are a clear requirement for the health and welfare of any community. Tybee Island currently relies on three groundwater wells, all located within the City, to obtain its drinking water. During town hall meetings and follow-up discussions, City officials expressed a high degree of concern about the potential flooding of these wells as a result of a major storm surge or other high water event.



City staff reported on a recent visit to nearby Hilton Head, SC, where pump houses had been retrofitted such that electronic components were elevated above the 100-year base flood elevation, and preliminary cost estimates had been obtained for conducting a similar project at Tybee Island's three well houses. For these reasons, City officials and stakeholders requested assistance in characterizing benefits of elevating well pumps as a component of the sea-level rise adaptation plan. Elevating the pump houses to a height above the projected 1% probability flood area (100-year floodplain) was selected as an adaptation option to address this identified vulnerability.



Current Well House Elevations

Floor elevation for each of the well pump houses was measured using two approaches: 1) LIDAR ground level elevations extracted from the well-pump locations; and 2) onsite ground elevations of the pump house sites, as obtained from a precision three-dimensional Online Position User Service (OPUS) GPS unit.[40] Table 4.2 provides a comparison of the estimated ground elevations at each of the City's well pump houses. The OPUS GPS measurements were presumed to provide a higher point elevation accuracy and were used for all subsequent calculations.

Table 4.2 also provides a summary of the flood height probabilities heights, as based on a floodplain study completed by FEMA.[41] These flood heights include the 10 percent annual flood probability area (often referred to as the 10-year floodplain), 2 percent annual flood probability area (50-year floodplain), 1 percent annual flood probability area (100-year floodplain), and the 0.2 percent annual flood probability area (500-year floodplain). The 1 percent probability area, or the 100-year floodplain, is the regulatory floodplain for which the "base flood elevation" (BFE) is calculated (Figure 4.1).

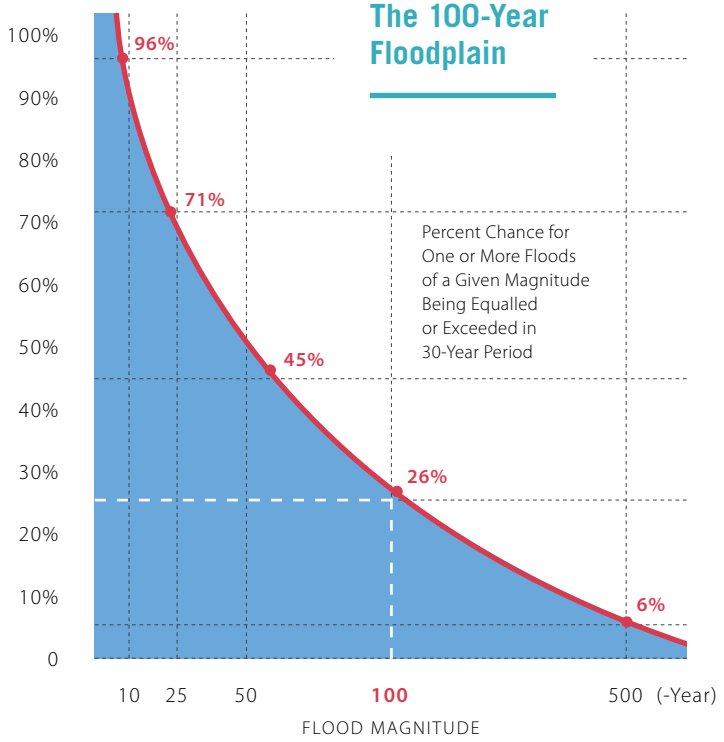


FIGURE 4.1: THE 100-YEAR FLOODPLAIN EXPLAINED

THE 100-YEAR FLOODPLAIN EXPLAINED.

The term "100-year floodplain" is an often misunderstood term of art in floodplain management that leads many people to misconceive the level of threat that building in the 100-year floodplain presents. The 100-year floodplain refers to the area that computer models show has a 1 percent chance of flooding in any given year. This means that theoretically, the return interval for such an event happening is 100 years. This leads many people to believe that these types of floods only happen once every century. In reality, there is a 1 percent chance of that level of flooding every year regardless of when the last flood occurred. This means that over 30 years, there is a 26 percent chance that a structure located in the 100-year floodplain (also known as the 1 percent annual flood probability area) will flood.[42]

40 The device used was an iGage X90-OPUS L1L2 Precision Static Occupation GPS. Results were processed through rapid static algorithms provided by the NOAA Online Position User Service (OPUS) (http://www.ngs.noaa.gov/OPUS/about.jsp#accuracy).

41 FEMA. 2009. Digital Flood Insurance Rate Map (DFIRM) Database (Chatham). Georgia GIS Clearinghouse. Retrieved from https://data.georgiaspatial.org/index.asp?body=preview&dataId=43928

42 Graphic adapted from, Frost-Tift, S., A. Mahadevia, D. Mills, A. Reeder, A. Sheldon, and J. Squerciati. 2014. Homeowner's Guide to Retrofitting: Six Ways to Protect Your Home From Flooding. FEMA P-312. http://www.fema.gov/media-library-data/1404148604102-f210b5e43aba0fb393443fe7ae9cd953/FEMA_P-312.pdf. Accessed January 6, 2016.

PUMP HOUSE	LIDAR ELEVATION	OPUS ELEVATION	10% PROBABILITY FLOOD	2% PROBABILITY FLOOD	1% PROBABILITY FLOOD (BFE)	0.2% PROBABILITY FLOOD
Van Horne Ave.	11.3 ft.	12.2 ft.	8.3 ft.	10.5 ft.	12 ft.	13.2 ft.
Butler Ave.	8.0 ft.	8.5 ft.	10.5 ft.	12.4 ft.	13 ft.	14.7 ft.
14th St.	9.3 ft.	9.2 ft.	8.3 ft.	10.5 ft.	12 ft.	13.2 ft.

TABLE 4.1: ESTIMATED GROUND ELEVATIONS FOR CITY OF TYBEE ISLAND WELL PUMP HOUSES[43]

Capital Damage Assessment

Capital damages to these three pumps from potential flood damage were calculated on the assumption of a $150,000 value and depth-damage relationships for municipal wells. The depth-damage equations used for this analysis are provided as Appendix III. Importantly, these damage assessments assume no permanent contamination of wells from floodwaters, but instead only estimate damages to well equipment associated with flood waters. Damages are also maximized at 30 percent of value for flood depths of six feet and higher.[44]

To account for sea-level rise in these calculations, the flood heights all flood eventswere adjusted upwards on an annual basis using the selected ***Low***, ***Intermediate***, and ***High*** sea-level rise scenarios. These adjusted flood depths were factored into the damage estimates for the years following 2010. Details of this calculation, including an assumed 3 percent annualized discount rate, are presented as Appendix IV. The results of the cumulative 50-year damage assessment for the City of Tybee Island's municipal well pump houses under each sea-level rise scenario are shown in Table 4.1.

PUMP HOUSE	LOW	INTERMEDIATE	HIGH
Van Horne Ave.	$129	$197	$498
Butler Ave.	$37,091	$38,264	$71,464
14th St.	$7,738	$8,936	$13,548

TABLE 4.2: CUMULATIVE 50-YEAR CAPITAL DAMAGE ASSESSMENT FOR CITY OF TYBEE ISLAND WELL PUMP HOUSES BY SEA-LEVEL RISE SCENARIO



43 Ground elevations are subject to the limitations of the techniques used, and should not be regarded as survey quality. Further site investigations by a licensed surveyor would provide the basis for more robust assessment.

44 FEMA. 2013. Multi-hazard loss estimation methodology, HAZUS-MH, Flood Model. Technical Manual. http://www.fema.gov/media-library-data/20130726-1820-25045-8292/hzmh2_1_fl_tm.pdf. Accessed June 15, 2015.

Economic Loss Assessment

Capital damage assessments were appended with a cumulative economic loss assessment to account for the economic losses that would result from a reduced water supply due to the shortages or rationing in the aftermath of a flood event. It was assumed that six feet of flooding in the pump house structure would cause loss of operation for two weeks, while lower flood level damages were reduced proportionately to flood height from six feet.[45]

A loss of $97 per capita per day was used as a conservative estimate of the economic impact of the loss of the water.[46] The economic losses were then divided by three to apportion the losses between the three wells. These single event losses were then extrapolated out to a cumulative 50-year damage assessment and discounted to present value. Full equations for this method are provided as Appendix V. The modeled economic loss results for each well pump are shown in Table 4.2.

Combined Loss Assessment and Benefit-Cost Ratio

Combining the capital damage and economic loss impacts, the total cumulative modeled flood risk cost for each of the City of Tybee Island's well pump facilities is shown in Table 4.3.

The estimated price of elevating the pump-house structures was $150,000 per structure. Using this estimate, the benefit-cost ratio for elevating each of the pump-houses was calculated as:

R = D/E

R = benefit-cost ratio;

D = cumulative 50-Year Damage Assessment;

E = estimated cost to elevate($150,000).

Results of these benefit-cost estimates over a 50-year period are summarized in Table 4.4.

PUMP HOUSE	LOW	INTERMEDIATE	HIGH
Van Horne Ave.	$16,905	$29,516	$65,053
Butler Ave.	$2,088,646	$2,291,663	$2,903,376
14th St.	$451,002	$525,118	$814,633

TABLE 4.3: CUMULATIVE 50-YEAR ECONOMIC LOSS DAMAGE ASSESSMENT FOR CITY OF TYBEE ISLAND WELL PUMP HOUSES BY SEA-LEVEL RISE SCENARIO

PUMP HOUSE	LOW	INTERMEDIATE	HIGH
Van Horne Ave.	$17,034	$29,713	$65,551
Butler Ave.	$2,125,737	$2,329,927	$2,974,840
14th St.	$458,740	$534,054	$828,181

TABLE 4.4: CUMULATIVE 50-YEAR TOTAL LOSS DAMAGE ASSESSMENT FOR CITY OF TYBEE ISLAND WELL PUMP HOUSES BY SEA-LEVEL RISE SCENARIO

PUMP HOUSE	LOW	INTERMEDIATE	HIGH
Van Horne Ave.	0.11	0.2	0.44
Butler Ave.	14.17	15.53	19.83
14th St.	3.06	3.56	5.52

TABLE 4.5: TABLE 4.4: 50-YEAR BENEFIT COST RATIO FOR PUMP HOUSE ELEVATION TO 3 FEET ABOVE BASE FLOOD ELEVATION

45 FEMA. 2009. BCA Reference Guide. June 2009. https://www.fema.gov/media-library/assets/documents/18870. Accessed January 5, 2016.

46 Aubuchon, C.P. and K.M. Morley. 2013. The economic value of water: Providing confidence and context to FEMA's methodology. Journal of Homeland Security and Emergency Management 10:245-25.

Discussion and Recommendations

The benefit-cost ratios from this analysis indicate that the Butler Avenue pump house is at high risk of flooding and should be elevated as soon as is practical. This conclusion can be derived completely independent of the sea-level rise scenario due to the very high benefit-cost ratios (14.17–19.83). The 14th St. pump house also shows a benefit-cost significantly greater than one under all scenarios, which suggests that near-term elevation of this pump house is also justified.

The Van Horne pump house, by contrast, is located at a somewhat higher elevation with significantly lower identified flood risk. For this reason, the benefit-cost results do not indicate a need for immediate adaptation action under any sea-level rise scenario. However, we do note that these arguably are conservative estimates of water supply disruption following a catastrophic flood event, as the results do not account for possible contamination of the water source associated with storm surge flooding. Further assessments are likely justified to determine the suitability of the Van Horne pump house for future elevation or other improvements to improve flooding resilience.

The sole road access to Tybee Island is a 5.5 mile section of US Highway 80 that connects the island to the City of Savannah and the mainland.

ACTION 2: ELEVATION OF US HIGHWAY 80

The sole road access to Tybee Island is a 5.5 mile section of US Highway 80 that connects the island to the City of Savannah and the mainland. This portion of US 80 begins at a bridge from Wilmington Island that crosses the Bull River, runs along several miles of an earthen causeway surrounded by tidal marsh, and leads into the City of Tybee Island over a bridge crossing Lazaretto Creek (Figure 4.2).

The public input for this project raised several well-known issues with the current configuration of this stretch of US 80:

1. The highway lacks emergency lanes across both the Lazaretto Creek and Bull River bridges. Traffic accidents and other obstructions have resulted in a complete loss of ground transportation access to and from Tybee Island for hours at a time.
2. Low grade at several sections along the earthen causeway allows for periodic flooding in high tide situations. This flooding results in highway closures that prevent traffic flow on and off of Tybee Island. This situation could also significantly restrict evacuation times during the approach of a hurricane or other large coastal storm event.
3. Narrow right of way shoulders present general safety concerns for motorists, bicyclists, and pedestrians, while also constricting traffic flow options following accident events and in emergency evacuation situations.



FLOODING ON US 80

The recommended alternative plan for US 80 calls for replacement of the Bull River and Lazaretto Creek bridges and 10-foot shoulders suitable for biking.

At the time of this project, the Georgia Department of Transportation (GDOT), the Coastal Region Metropolitan Planning Organization (CORE MPO), and the Chatham-Savannah Metropolitan Planning Commission (MPC), had long been considering options to redesign and reconstruct US 80 to address many of these issues. Plans developed by GDOT in the early to mid-2000s involved widening the entire road section and the Bull River bridge to four lanes, replacing the Lazaretto Creek bridge with a four-lane structure, creating a 24-foot raised grass median, and constructing two 10-foot outside shoulders with 6.5 foot wide bike paths. The GDOT plan also called for raising the entire road grade by three feet over the tidal flood stage to provide a margin of safety for pre-hurricane evacuations.[47] This plan, however, was not implemented by GDOT, largely due to its expense, environmental impacts, and concerns expressed by local and state stakeholders regarding potential for increased congestion within the City of Tybee Island.

In December 2012, the CORE MPO released a comprehensive study outlining options for replacing the Bull River and Lazaretto Creek bridges, as well making other improvements to the US 80 corridor. This study describes several new design options for improving the US 80 corridor into Tybee Island and outlines a participatory process used to select a preferred alternative. The recommended alternative calls for replacement of the Bull River and Lazaretto Creek bridges, maintenance of two-lane traffic but with addition of 10-foot shoulders suitable for biking, and improved access to the existing McQueen's Island pedestrian trail. Tidal flooding problems would be addressed by elevating the low-lying areas of the road to an elevation above minimal flood stage and uniform with the remainder of the road bed.[48] The local flood elevation is minimally defined by NOAA as 5.2 feet above NAVD 88.[49]



FIGURE 4.2: US HIGHWAY 80 TO TYBEE ISLAND. HIGHLIGHTED RED PORTION SHOWS STRETCH FROM BULL RIVER TO LAZARETTO CREEK BRIDGES.

47 Lewis and Zimmerman Associates. 2003. SR 26/US 80 Widening from Bull River to the Lazaretto Creek, Chatham County, Georgia, Value Engineering Study Report. Atlanta: Georgia Department of Transportation.

48 CDM Smith. 2012. US 80 Bridges Replacement Study: GDOT P.I. No. 0009379. CORE Coastal Region MPO. Savannah, GA. http://www.thempc.org/documents/Transportation/US 80 Bridges Study/US 80 Final Report/US 80 Final Report_NoAppendices.pdf. Accessed June 15, 2015.

49 NOAA. 2014. National Weather Service Advanced Hydrologic Prediction Service, Fort Pulaski Tide Gage. http://water.weather.gov/ahps2/hydrograph.php?gage=fpkg1&wfo=chs. Accessed January 5, 2016.

Future Flood Analysis for US 80

Using the NOAA minimum tidal flooding threshold of 5.2 ft NOAA 88 (~9.2 ft above MLLW) for the Savannah and Tybee Island region, we performed a flood threshold exceedance analysis using 2,822 high tide readings covering the four-year period from January 1, 2009– December 31, 2012 at the Fort Pulaski tide gauge. A total of 32 tide height values in excess of 5.2 feet above NAVD88 were recorded over the 2009–2012 period, giving an initial average of eight flood events per year. We note that this is a conservative initial estimate, as more recent tide records indicate an increase in nuisance flood events recorded at Fort Pulaski subsequent to our analysis period (as shown in Figure 2.4).

A comparison of annual tide events projected to exceed the flood stage at Ft. Pulaski through 2060 under different sea-level rise scenarios is provided in Figure 4.3. The ***Low*** sea-level rise is expected to result in at least 30 annual tidal flooding events by 2060, which is well over a three-fold increase over the average number of annual tidal flooding events observed from 2009–2012. Flood events from the ***Intermediate*** sea-level rise scenario (14 inches) would be well approximately 125 per year, while the ***High*** sea-level rise scenario (31 inches) would result in 540 flood events per year. Because Fort Pulaski typically has two separate high tide peaks per day, the occurrence of more than one flood per day indicates that on many days the road would flood on both high tides.

It is important to note that sea-level rise will not only increase the frequency of tidal flooding events, but will also increase both the height of high tides and the duration of time in which tidal flooding conditions are likely to result in road closures of US 80. Using a sinusoidal analysis described in Appendix VI, the tide gauge at Fort Pulaski showed an annual average of about 5.5 annual hours in excess of flood stage from 2009–2012. As shown in Figure 4.4, a scenario of ***Low*** sea-level rise would be expected to result in almost 37 annual hours flooding on US 80 by 2060, or approximately 6.7 times more hours of closure per year as compared to 2009–2012. The ***Intermediate*** sea-level rise projection would result in approximately 200 hours per year of tidal flooding on US 80 at 2060, while ***High*** sea-level rise would result in approximately 1,250 hours of tidal flooding per year.

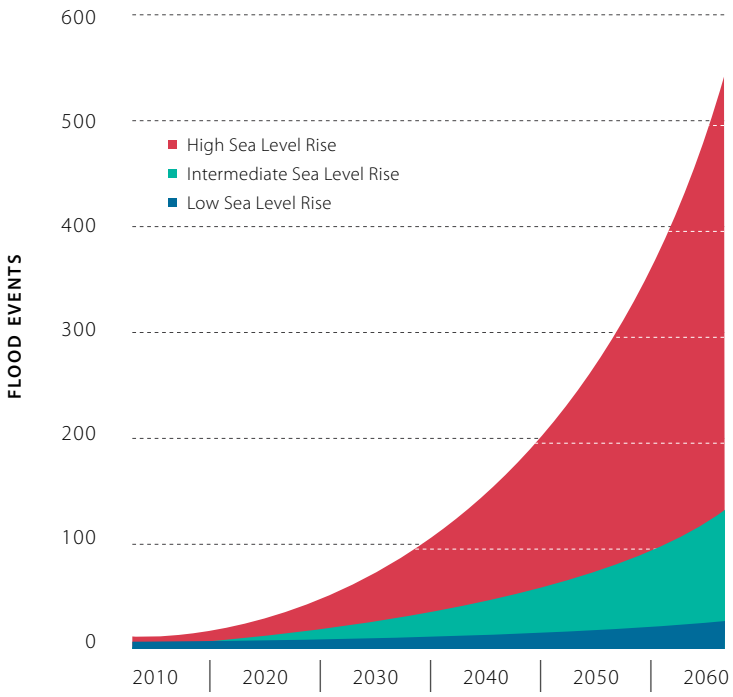


FIGURE 4.3: ANNUAL US 80 TIDAL FLOODING EVENTS WITH SEA LEVEL RISE SCENARIOS

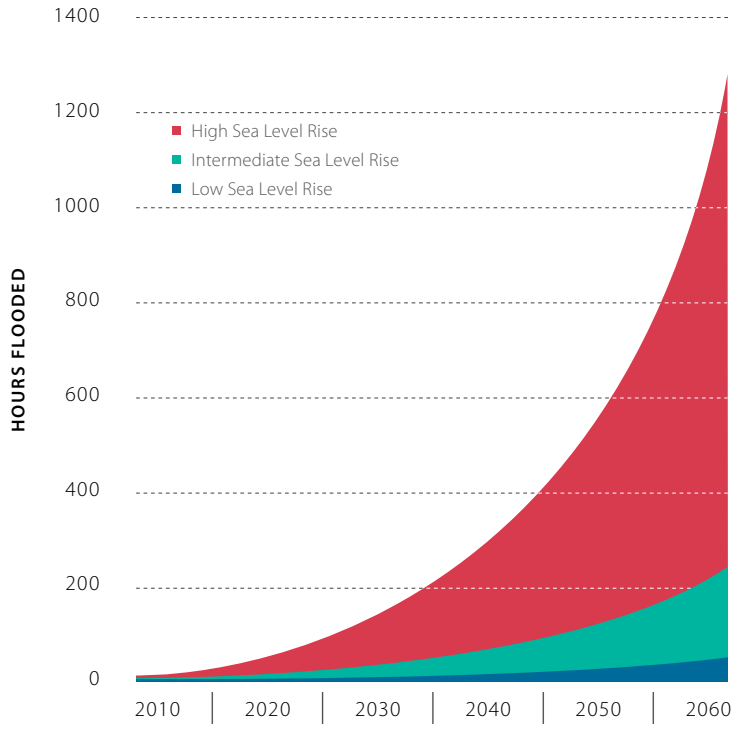


FIGURE 4.4: ANNUAL US 80 TIDAL FLOODING HOURS WITH SEA LEVEL RISE SCENARIOS

Benefit-Cost Modeling Exercise

Through the auspices of the public engagement process, a preliminary benefit-cost exercise for adaptation of US 80 was performed for the City of Tybee Island. Using facilitated participatory and stakeholder input, the dollar loss value (i.e., cost) of US 80 flooding was pegged to the loss of economic activity on the City of Tybee Island due to loss of accessibility.

The at-risk economic activity was further derived through analysis of hotel/motel tax receipts collected by the City of Tybee Island in 2011-2012. These tax receipts totaled $2.2 million, which approximated $36.7 in private hotel revenue. A multiplier of 1.7 was then used to transform hotel/motel tax revenue into a total estimate of $62.3 million in tourism-based economic activity for the City of Tybee Island.[51] This amounts to $7,112/hour of economic activity in the City of Tybee Island presumed to be at risk from tidal flooding of US 80. The analysis then assumed a one-to-one correspondence between hours of tidal flooding of US 80 and lost economic activity in the City of Tybee Island, with a 3 percent discount function applied annually for each year through 2060.

51 Toma, M. and A. Brewer. 2007. The Economic Impact of Tybee Island Beach Renourishment on Georgia's Economy. Savannah: Center for Regional Analysis, Armstrong Atlantic University. http://www.cityoftybee.org/Assets/Files/BeachTaskForce/BeachEconomicImpact.pdf.

Results of this preliminary benefit-cost analysis were presented in public forums and included in a review copy of this report. While the analysis was a useful exercise for conceptualizing risk from road flooding, comments by technical reviewers convincingly indicate that the assumptions are too simplifying and the results do not provide a sufficient assessment of benefits and costs associated with road elevation. For example, the analysis and results explicitly did not include numerous other damage and risk factors associated with tidal flooding of a major road. Such other factors include:

1. Overwash and groundwater damages to the roadbed and road surface
2. Public safety and emergency management hazards associated with loss of road access
3. Potential for increased vehicle accidents when the road is flooded
4. Potential for increased under-carriage corrosion to cars that travel through saltwater
5. Vulnerability to major storm surges and the potential for premature loss of US 80 before landfall of a hurricane.

Due to concerns about publication of a limited benefit-cost analysis, and with explicit acknowledgment that the present project lacked the resources and scope to perform such an engineering scale benefit-cost assessment of a major highway corridor, we have removed the results of this benefit-cost analysis from the final report. Instead, we recommend that our methodology for assessing the extent and duration of future tidal road flooding risks under different sea-level rise scenarios be incorporated into an alternative designs framework for roadway elevation within the ongoing US 80 bridge replacement and road bed improvement project. The substantial tidal flooding of US 80 in 2015 clearly underscores the substantial vulnerabilities of the existing roadway elevation and provides renewed impetus for ensuring that significant concerns about long-term public safety, infrastructure maintenance, and disaster resilience are incorporating into the final US 80 bridge replacement and road bed improvement project.



ACTIONS 3 & 4:
STORMWATER RETROFITS AND BUILDING A SEA WALL

Discussions at townhall meetings indicated that tidal flooding during king tide conditions is regularly observed within several areas of the City of Tybee Island. However, the most extensive issues were described to occur within the southwest quadrant of the island (Figures 4.5–4.8). City official reported that much of the property in the southwest corner of Tybee Island is composed of lands created during the early 20th century by the deposition of dredge and fill material onto low-lying marshlands. The likely combination of low native topography and accelerated soil subsidence has subsequently resulted in a low elevation profile for the built environment now located on these former marshland areas.

Flooding concerns associated with this low elevation profile are illustrated by observations of saltwater *discharge* from several stormwater drains onto adjacent streets and yards during extreme spring tide events (Figures 4.6–4.7), particularly along the 14th St. corridor. Such tidal penetration into the stormwater system is of high concern not only because of the direct flood risks from saltwater overflow into the built environment, but also because the influx of tidewaters into stormwater pipes is associated with a significant loss of drainage capacity. Heavy rainfall events that occur concurrently with high tides, therefore, have the potential to create significant flooding due to the lack of stormwater drainage potential within pipes flooded by tidewater.

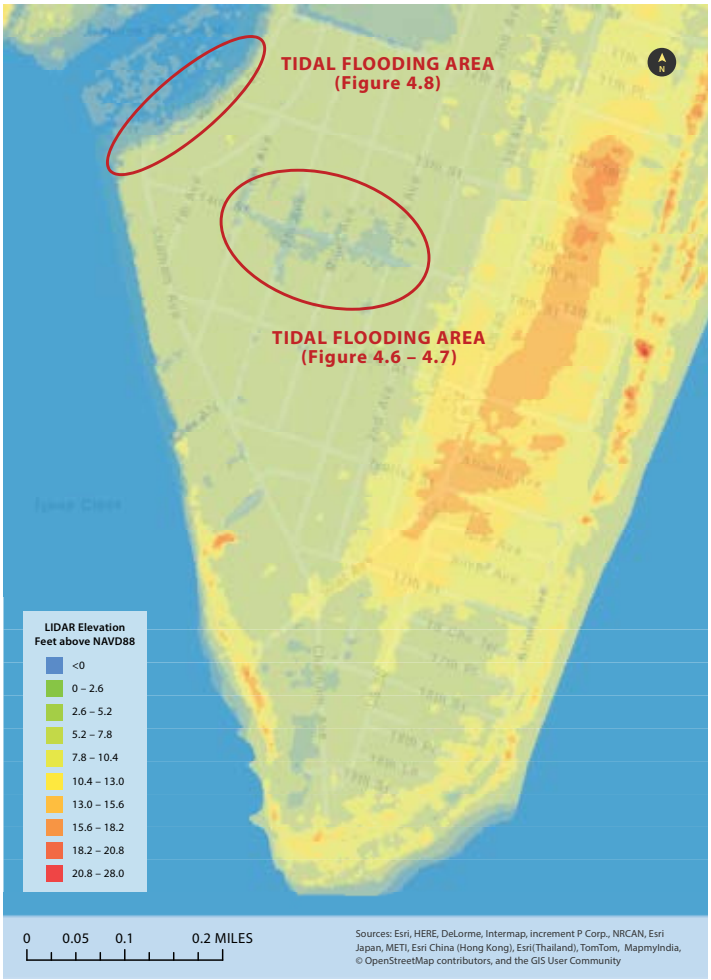


FIGURE 4.5: LIDAR ELEVATION PROFILE FOR CITY OF TYBEE ISLAND, SOUTHWEST QUADRANT

These existing flood concerns have already prompted significant action by the City of Tybee Island, including a major upgrade of stormwater pipes and installation of backflow preventers at the stormwater discharge point near the intersection of 14th St. and Venetian Dr. (Figure 4.9). Due to the additional concerns associated with sea-level rise, public officials and local stakeholders expressed interest in further evaluation of two adaptation actions: 1) installation of tidal backflow preventers on additional stormwater discharge points throughout the low-lying southwest island; and 2) construction of an engineered sea wall at three feet above the current tidal flooding stage (top of wall height at 8.2 feet NAVD) to protect low-lying properties. Figure 4.10 provides a map visualization overview of these suggested adaptation actions.



FIGURE 4.6: STORMWATER DRAIN WITH SALTWATER DISCHARGE DURING KING TIDE, NOVEMBER 14, 2012



FIGURE 4.7: SALTWATER FLOODING OF YARDS AND STREETS FROM STORMWATER DRAIN DISCHARGE DURING KING TIDE, NOVEMBER 14, 2012



FIGURE 4.8: SALTWATER FLOODING OF YARDS AND STREETS FROM BANK OVERFLOW DURING KING TIDE, NOVEMBER 14, 2012



FIGURE 4.9: STORMWATER TIDAL BACKFLOW PREVENTERS, NEAR INTERSECTION OF 14TH ST. AND VENETIAN DR.

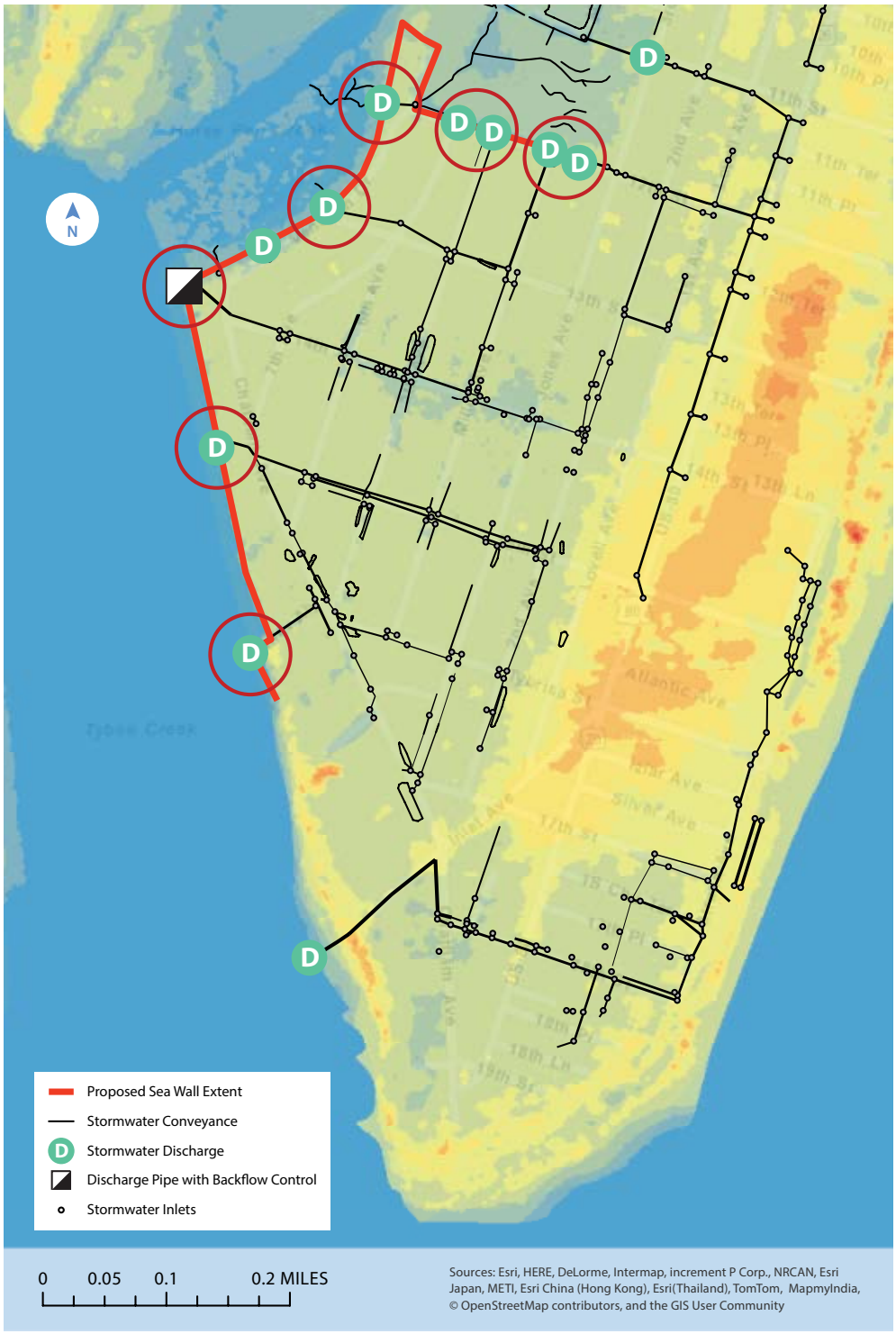


FIGURE 4.10: VISUALIZATION OF STORMWATER BACKFLOW AND SEA WALL ACTIONS FOR CITY OF TYBEE ISLAND, SOUTHWEST QUADRANT. RED CIRCLES INDICATE DISCHARGE POINTS THAT SHOW CONNECTIVITY TO LOW-LYING AREAS VULNERABLE TO TIDAL BACKFLOW FLOODING.

Approach

A building-based assessment, using values obtained through the 2011 property tax assessment dataset from Chatham County and hotel-motel tax receipts collected by the City of Tybee Island, was utilized as the basis for analyzing the stormwater retrofit and sea wall actions. LIDAR return elevation points processed to a five-square-foot cell size digital elevation model (DEM) were used as the basis for determining flood vulnerability in each building. A four-year tidal record (2009–2012) from the Fort Pulaski NOAA tide gauge was used to develop decadal tidal event exceedance predictions for each sea-level rise scenario. These methods are defined in Appendix VII.

Avoided loss functions were determined by each sea-level rise scenario and adaptation action. A hydrologic connectivity analysis indicated that significant floodwater penetration would be prevented for tides up to 6.2 feet above NAVD88 through use of backflow preventers alone, as existing bank elevation and bulkhead structures are sufficient to block overland tide flows under 6.2 feet tides. Avoided damage functions were therefore allocated solely to stormwater backflow preventers for all tides below 6.2 feet.

Bank overflow would, however, presumably cause overland flooding into low-lying areas beyond 6.2 feet tidal elevations, rendering the backflow preventers ineffective as a standalone flood prevention strategy. Avoided damages for tides above 6.2 feet were therefore allocated solely to the sea wall. However, it is important to note that sea wall effectiveness assumes that pipe flow stormwater penetration and groundwater are also averted through backflow preventers or other means. Cost of stormwater backflow preventers and additional upgrades to the stormwater system, including the recent expansion of pipe capacity along the 14th St. corridor, were assumed as $3 million. The cost of an engineered concrete sea wall at a height of 8.2 feet above NAVD88 was estimated at $35 million.

Avoided damages for tides above 6.2 feet were allocated solely to the sea wall; however, it is important to note that sea wall effectiveness assumes that pipe flow stormwater penetration and groundwater is also averted through backflow preventers or other means.

SEA-LEVEL RISE SCENARIO	DAMAGE AVOIDED BY TIDE GATE (NET PRESENT VALUE)	BENEFIT-COST RATIO
Low	$15,400,000	5.13
Intermediate	$36,200,000	12.07
High	$39,200,000	13.07

TABLE 4.6: AVOIDED DAMAGE AND BENEFIT COST CALCULATIONS FOR STORMWATER BACKFLOW PRE-VENTERS, SOUTHWEST TYBEE ISLAND

SEA-LEVEL RISE SCENARIO	DAMAGE AVOIDED BY SEA WALL (NET PRESENT VALUE)	BENEFIT-COST RATIO
Low	$700,000	0.02
Intermediate	$3,600,000	0.10
High	$60,800,000	1.74

TABLE 4.7: AVOIDED DAMAGE CALCULATIONS FOR SEA WALL 8.2 FT. ABOVE NAVD88, SOUTHWEST TYBEE ISLAND



RESULTS

A summary table of avoided damages for stormwater backflow preventers is provided in Table 4.6. These results indicate that stormwater retrofits with backflow preventers represent a good investment under all sea-level rise scenarios and likely are a "no-regret" action. However, it is also notable that stormwater retrofits, even if maintained in perfect working condition, would begin to fail as a standalone investment under the high sea-level rise scenario well before 2060. This assumed failure is due to the occurrence of bank overflow flooding that bypasses the stormwater system as tides begin to exceed the 6.2 feet bank height on a regular basis.

Avoided damages for the sea wall are provided in Table 4.7. These results indicate that the sea wall is a poor investment under the ***Low*** and ***Intermediate*** sea-level rise scenarios, but shows marginal benefit (1.74) under ***High*** sea-level rise. This latter result reflects the accrual of flood reduction benefits from the sea-wall after tides begin to exceed 6.2 feet on a regular basis. However, the ***High*** sea-level rise scenario ultimately leads to tides that exceed 8.2 feet before 2060, thus presumably overtopping the sea wall and causing extensive flood damage. Discussions with Tybee Island officials indicate that the additional stressors associated with a high rate of sea-level rise, poor benefit-cost results for other sea-level rise scenarios, and high ancillary environmental costs associated with construction of such a project all argue against further pursuit of the sea wall adaptation option at this time.

ACTIONS 5: ENHANCED BEACH RENOURISHMENT

As noted in Chapter 3, the resources and scope of this project prevented formal analysis of enhanced beach renourishment action (Action 5) as a strategy for sea-level rise adaptation and storm surge protection on Tybee Island. However, the importance of beach renourishment for the local tourism economy and flood protection at Tybee Island is well-documented in other studies, as summarized in Chapter 2.

Even with the reduced beach erosion impacts at Tybee Island due to burial of the WPA sea wall and intensive dune-field revegetation efforts, it is widely assumed that maintenance of Tybee Island's existing beach profile — and associated flood protection benefits — is completely dependent on the continuation of periodic renourishment activities. Deepening of the Savannah Harbor channel to accommodate larger "Post-Panamax" cargo ships and ongoing sea-level rise only strengthen this assumption, as both processes can be expected to increase the long-term beach erosion forces on Tybee Island. With the current Tybee Island Shore Protection Project scheduled to expire in 2024, the early stages of the re-authorization process provide an opportunity for local, state, and federal officials to incorporate sea-level rise as a central design and management parameter within a revised renourishment and shoreline protection plan.[52]

Deepening of the Savannah Harbor channel to accommodate larger 'Post-Panamax' cargo ships along with ongoing sea-level rise can be expected to increase the long-term beach erosion forces on Tybee Island.



52 See, for example, Leatherman, S.P. 1989. National Assessment of Beach Renourishment Requirements Associated with Accelerated Sea Level Rise. College Park, MD: U.S. EPA Office of Policy, Planning, and Evaluation. http://www.papers.risingsea.net/federal_reports/rtc_leatherman_nourishment.pdf.

CHAPTER 5:

Summary and Conclusion

The City of Tybee Island is one of the first communities in Georgia to formally address sea-level rise. Throughout the span of this planning project, city officials and the general public engaged with the project team to confront challenges and evaluate actions for helping the community adapt and thrive over the coming decades.

ELEVATING CITY WELL HOUSES

The City of Tybee Island operates three well pump houses that are the sole source of public water supply for the community. If these well houses are disabled by a flood, drinking water and waste disposal could be limited for several days or even weeks. Technical analyses indicate that the City's Butler Ave. well house is at very high risk of flooding and that action should likely be taken to elevate or otherwise floodproof this facility as soon as possible. The 14th St. well house also shows high risk of flooding and benefit-cost analyses indicate that elevation or other floodproofing of this facility is immediately justified. The Van Horne Ave. well house shows lower flood risk and benefit-cost analysis does not indicate the need for immediate action for elevating or floodproofing this facility. However, future study and assessments are warranted to ensure the long-term safety of the Van Horne Ave. facility.

ADAPTING U.S. 80

US Highway 80, the sole road access to Tybee Island, currently floods several times a year during high tide conditions. In 2015, Tybee Island experienced a total of 23 tides that were high enough to cause minor to moderate flooding conditions on US 80, by far the largest number that has been observed in any year on record. These flooding conditions cut Tybee Island off from the mainland for hours at a time, causing significant safety and evacuation concerns, as well as economic impacts. Sea-level rise will worsen these road flooding and accessibility issues unless US80 is elevated significantly above its current grade. Cooperation between the City of Tybee Island, the Coastal Region Metropolitan Planning Organization, the Georgia Department of Transportation, and other agencies is needed to ensure that sea-level rise is factored into ongoing engineering plans to replace two bridges and otherwise modernize the US80 corridor.

STORMWATER RETROFITS AND SEA WALL PROTECTION

Several areas in the southwest section of Tybee Island have low-lying stormwater drainage systems that become inundated and can even flow backwards during exceptionally high tides. This backflow causes saltwater flooding of streets and yards, while also increasing flood risks during rainfall events.

If no action is taken, sea-level rise can only be expected to worsen these conditions over time. The City of Tybee Island has already installed three tidal backflow preventers on stormwater pipe outfalls that drain the most vulnerable areas. Benefit-cost modeling indicates that these and other retrofits that prevent tidal backflow into southwest Tybee Island would be expected to accrue $15–39 million in avoided economic damages over a 50-year period. Continuation of such stormwater retrofits therefore appears to be a highly cost-effective, no-regrets adaptation strategy.

Additional modeling suggested that construction of a large engineered sea wall on the southwest portion of the island is likely not an appropriate adaptation strategy to pursue at this time. The benefit-cost ratio for the sea wall is positive only under the High sea-level rise scenario, and most flood protection benefits from the structure would not accrue until at least 25–30 years into the future.

The new CRS rating will translate into a 25 percent discount in flood insurance for each resident in the Special Flood Hazard Area.

BEACH RENOURISHMENT

Beginning in 2014, the US Army Corps of Engineers added approximately 1.3 million cubic yards of sand onto Tybee Island beaches.[53] This effort marks one of the final renourishments of Tybee Island through the US Army Corps of Engineer's current authorization from Congress, which expires in 2024. A priority for future beach renourishment projects and negotiation of a new authorization should be maintenance of flood protection under a condition of accelerating sea-level rise. Additionally, inspired by communities in the Northeast that suffered comparatively low damages during Superstorm Sandy, the City of Tybee is investigating the possibility of augmenting their sand dune system to help protect the island from storm surge during hurricanes.

COMMUNITY RATING SYSTEM

The City of Tybee Island recently underwent a review for FEMA's Community Rating System (CRS). A federal incentive program designed to incentivize flood resiliency, CRS rewards communities for adopting floodplain management ordinances, adhering to minimum standards for new construction and educating citizens about their flood risk. Due to the extensive public investments, outreach, and regulation that the City of Tybee has pursued over recent years, the City improved its CRS rating to a score of five. This rating translated into a 25 percent discount in flood insurance for each resident in the Special Flood Hazard Area.

53 Savannah Morning News. 2014. Tybee beach renourishment kicks off. http://savannahnow.com/news/2014-10-22/tybee-beach-renourishment-kicks. Accessed January 5, 2016.

A NATIONAL LEADER

Due to the hard work and vision of Tybee Island's City Council, government staff, and community members, the City has emerged as national leader in climate adaptation planning and coastal resilience. In addition to planning for sea-level rise, Tybee Island has focused on decreasing its carbon footprint through renewable energy production.[54]

The City is also widely recognized for its successful efforts to reduce stormwater pollution and improve local water quality through innovative filtration techniques.[55] With funding from National Fish and Wildlife Foundation's Five Star Urban Waters Restoration Grant Program, Tybee Island has recently partnered with UGA Marine Extension, Georgia Sea Grant, UGA's Carl Vinson Institute of Government, and other partners to construct a living shoreline along a tidal creek at the Burton 4-H Center. This living shoreline project, which is being constructed out of oyster shells and marsh vegetation, is expected to enhance fisheries habitat and improve local water quality.

In recognition of the outreach and educational efforts undertaken through this project, in 2014 the Tybee Island Sea-Level Rise Plan received NOAA Sea Grant's highest national outreach award. The project has also been featured as a case study in the U.S. Climate Resiliency Toolkit[56] and in a 2014 report by the Union of Concerned Scientists.[57] Senator Sheldon Whitehouse from Rhode Island visited Tybee Island during his Southeast Climate Road Trip and praised the island's climate adaptation efforts on the floor of the U.S. Senate.[58] Technical methodologies originally developed in Tybee Island have been subsequently utilized for resilience planning projects in several other coastal communities, including St. Marys, Georgia; Hyde County, North Carolina; the City of Islamorada, Florida and Monroe County, Florida.



54 Landers, M. 2015. As Solarize Tybee gains popularity, price drops. Savannah Morning News. http://savannahnow.com/news/2015-02-25/solarize-tybee-gains-popularity-price-drops. Accessed January 6, 2016.

55 Landers, M. 2011. Tybee gets good grades for beach water quality. Savannah Morning News. http://savannahnow.com/news/2011-07-02/tybee-gets-good-grades-beach-water-quality. Accessed January 6, 2016.

56 U.S. Climate Resilience Toolkit. 2015. Show Don't Tell: Visualizing Sea Level Rise to Set Planning Priorities," Taking Action: Case Studies of Resilience in Action. https://toolkit.climate.gov/taking-action/show-dont-tell-visualizing-sea-level-rise-set-planning-priorities. Accessed January 6, 2016.

57 Spanger-Siegfried, E., M. Fitzpatrick, and K. Dahl. 2014. Encroaching tides: How sea level rise and tidal flooding threaten US east and gulf coast communities over the next 30 years. Cambridge: Union of Concerned Scientists.

58 Landers, M. 2014. Update: Senator posts video of tour of Ga. climate change hot spots. Savannah Morning News. http://savannahnow.com/news/2014-04-24/senator-tours-ga-hot-spots-climate-change. Accessed January 6, 2016.

CLOSING THOUGHTS

This final report is intended as an initial step that will assist the City of Tybee Island with its efforts to include sea-level rise within local flood preparedness policies and environmental sustainability initiatives. For this reason, this report is intended to serve as a living document that can be freely appended and updated by City officials over time as new information and conditions may merit.

One of the biggest lessons learned through this project is that sea-level rise and climate adaptation is a complex endeavor with many challenges and uncertainties. The project team sincerely thanks Tybee Island's elected officials, municipal staff, and local residents for their partnership and patience in working through this planning process.

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Appendix

I: PUBLIC ENGAGEMENT AND OUTREACH LOG

Town Hall Meetings

A series of formal town hall meetings, all open to the public and held at the Tybee Island City Hall, were a central component of the project. These meetings featured expert presentations on sea-level rise science and adaptation, as well as solicited public input for considering adaptation options appropriate to the unique conditions faced by Tybee Island.

Public Meeting I

INTRODUCTION TO THE PROJECT AND CONNECTIONS WITH EXISTING HAZARD PROGRAMS // MAY 7, 2012

Tybee Island is a complex, multifaceted environment, with a host of overlapping issues and challenges. To kick off the public outreach process, the project's first public meeting focused on presenting the threats of sea-level rise to the island, as well as adaptation options for Tybee Island to consider. Speakers:

- Dr. Charles S. Hopkinson, Georgia Sea Grant Director. *Project Introduction.*
- Dr. Robin J. McDowell, Environmental Policy Program Director, Carl Vinson Institute of Government. *Meeting Overview and Facilitation Ground Rules.*
- Dr. Jason M. Evans, Environmental Sustainability Analyst, Carl Vinson Institute of Government. *City of Tybee Island Climate Adaptation Planning: Project Timeline and Technical Overview.*
- Jennifer Kline, Coastal Hazards Specialist, Coastal Resources Division, Georgia Department of Natural Resources. *Georgia DNR Coastal Hazards Program Efforts.*
- Jackie Jackson Teel, Director of Comprehensive Planning, Chatham County—Savannah Metropolitan Planning Commission. *The Next Steps after Chatham County's Coastal Risk Workshop.*

Facilitated session: Perceived and known vulnerabilities to flooding and sea-level rise in the City of Tybee Island.

McDowell and Evans led an open discussion with meeting attendees to gather detailed information about perceived current and future impacts of sea-level rise for the City of Tybee Island. As shown in Figure 1, a flowchart summary of this discussion was developed using diagram protocols from the Vulnerability, Consequences, and Adaptation Planning Scenarios (VCAPS) methodology and as implemented through the Open Source Visual Understanding Environment (VUE) software.[59] Key issues identified through this discussion included:

1. **Periodic over wash flooding of US Highway 80, the sole road access route to Tybee Island, during high tide events.** Identified consequences of this flooding include road closings that cause severe traffic backups, cutoff from emergency services, and loss of evacuation route during storm events; hazards to drivers when flooding occurs with little warning and no associated road closure; and long-term damage to the road bed from repeated over wash events.
2. **Periodic yard and street flooding within the City of Tybee Island during extreme high tide events.** Consequences of this flooding include damage to landscaping from saltwater intrusion; potential threats to low-lying structures, particularly if high tides are accompanied by rainfall events; and potential loss of property values in areas impacted by repetitive flooding.
3. **Increased beachfront and marsh front erosion due to the force of higher tides, as well as loss of near shore sediment transport due to the dredged shipping channel in the Savannah River.** Consequences of erosion include loss of private property, physical threats to waterfront structures, increased need for beach renourishment, reduced recreational values as beaches retreat, and higher risk from storm surge events if dune fields are compromised.



59 Tufts University. 2013. Visual Understanding Environment. http://vue.tufts.edu/. Accessed January 5, 2016.

Public Meeting II

VULNERABILITY ASSESSMENT AND DEFINITION OF ADAPTATION OPTIONS
AUGUST 6–7, 2012

A key element of the plan's strategy was to test a wide range of adaptation options and explore their tradeoffs over a long time period. Dr. Sam Merrill, Director of the New England Environmental Finance Center, walked participants through sea-level rise adaptation options for Tybee Island. Dr. Merrill also presented examples of sea-level rise planning currently being practiced in other communities.

Sea-level rise adaptation options depend heavily on a projected height of sea-level rise. Through facilitated discussion and straw poll votes, meeting participants decided to consider a range of sea-level rise scenarios for Tybee Island. These included a low scenario of 7 inches, an intermediate scenario of 1.3 feet and a high scenario of 2.3 feet by the year 2060. These scenarios closely match recommendations made by NOAA and other federal agencies for sea-level rise adaptation planning.

Local adaptation options identified for further evaluation included raising the city's well pump houses, making local storm water improvements, marsh-side armoring of the shoreline, increasing the height of future beach renourishment to accommodate sea-level rise and elevating US 80 four feet above current grade. Speakers:

- Dr. Chuck Hopkinson, Georgia Sea Grant Director. *Meeting Introduction*.
- Dr. Robin J. McDowell, Environmental Policy Program Director, Carl Vinson Institute of Government. *Meeting Overview and Facilitation Ground Rules*.
- Dr. Jason M. Evans, Environmental Sustainability Analyst, Carl Vinson Institute of Government. *Review and Recap of Meeting 1 Vulnerability Discussions*.
- Dr. Sam Merrill, New England Environmental Finance Center and Catalysis Adaptation Partners, LLC. *Benefit-Cost Modeling through the Coastal Adaptation to Sea level rise Tool (COAST)*.

Facilitated session 1: Discuss and define sea-level rise scenarios and vulnerable assets to be used for the adaptation planning exercise

Sea-level rise scenarios

Merrill and Evans led an open discussion with meeting attendees to define the sea-level rise scenarios to be used for the City's planning exercise, as well as to define the at-risk assets of concern that would be modeled for dollar values out to the year 2060. The scenarios were discussed in an open public forum, with present members of the Tybee Island City Council providing final determination of model parameters through majority votes. Through this process it was decided that the ***High*** and ***Intermediate*** sea-level rise values used for the City's adaptation planning would be based upon semi-empirical 2009 sea-level rise curves published by Martin Vermeer and Stefan Ramhstorf.[60] The ***Low*** sea-level rise value would be based upon linear extrapolation of the Ft. Pulaski tide gauge record.

The Ft. Pulaski tide gauge has maintained an almost continual record of tide heights since its original installation in 1935. The slope of the straight line regression for sea-level over this record provides an average rise of approximately 0.12 inches per year. Simple extrapolation of this linear trend through was used as the basis for the City of Tybee Island's ***Low*** sea-level rise scenario. By the year 2060, the tide gauge linear trend amounts to approximately 6 inches of sea-level rise over a 2010 baseline at Tybee Island.

The ***Intermediate*** sea-level rise curve, as defined by the work of Vermeer and Rahmstorf, is based upon lowered greenhouse emissions that minimize future warming of oceans and polar ice sheet melt, but nevertheless still result in an acceleration of sea-level rise over that observed during the 20th century. By the year 2100, this results in a sea-level rise of approximately 30 inches (75 cm) over a 1990 baseline.

The ***High*** sea-level rise curve, as defined by the work of Vermeer and Rahmstorf, is based upon a scenario of high greenhouse gas emissions and accelerated climate change that induces rapid thermal expansion of oceans and enhanced polar ice sheet melt. By the year 2100, this results in a sea-level rise of approximately 75 inches (190 cm) over a 1990 baseline.

Benefit-cost inputs

Merrill led a discussion with meeting attendees to decide upon the assets that would be used to develop dollar-based inputs for benefit-cost modeling. The following two assets were chosen: 1) tax assessed values of buildings; and 2) annual economic activity, as extrapolated from the City's hotel-motel tax receipts. Assessed values of buildings were to be obtained from Chatham County's property parcel GIS database, while the spatial component of economic activity would be developed by linking hotel-motel tax receipts to parcels on an annualized basis. An annualized discount rate of 3 percent was chosen for modeling future flooding damage to both buildings and economic activity.

***Facilitated session 2*:** Discuss and define adaptation actions for benefit-cost modeling

Merrill and Evans led a technical discussion with meeting attendees to define several adaptation actions that would be assessed in detail through the auspices of this project. A series of general adaptation action types were presented and discussed. These included infrastructural elevation, wet flood-proofing, dry flood-proofing, rolling easements, fee simple acquisition, beach renourishment, and shoreline armoring.

60 Vermeer, M. and S. Rahmstorf. 2009. Global sea level linked to global temperature. Proceedings of the National Academy of Sciences of the United States of America. 106:21527-21532.

Through these discussions, the following five locally specific adaptation options were chosen for more detailed analyses.

1. Retrofit elevation of the first floor of city well houses and electronic components to heights above the 100 year floodplain.
2. Elevation of the US 80 causeway between Wilmington Island and Tybee Island to 3 feet above current minimum grade.
3. Increased rates of beach renourishment relative to increased sea-level rise out to 2060.
4. Retrofits of stormwater infrastructure to prevent flooding from tidewater backflow, particularly within low-lying areas of the southwest island.
5. Construction of a back island seawall at 3 feet over mean higher high water (MHHW) to prevent flooding from bank overflow, particularly within low-lying areas of the southwest island.

Public Meeting III

PRESENTATION OF BENEFIT-COST MODELING RESULTS
MARCH 4–5, 2013

Dr. Jason Evans presented a series of benefit-cost evaluations for identified adaptation actions. Several actions, such as beach renourishment, elevation of well pumps and construction of tide valve gates on stormwater outlets that drain low-lying areas of the island, showed clear net economic benefits for all scenarios. Elevation of US 80 requires further analysis, but was judged to have high benefits with consideration of increased evacuation times before hurricanes and continuous access to the island during future high tide events. Speakers:

- Dr. Robin J. McDowell, Environmental Policy Program Director, Carl Vinson Institute of Government. *Meeting Introduction and Facilitation Ground Rules.*
- Dr. Jason M. Evans, Environmental Sustainability Analyst, Carl Vinson Institute of Government. *Tybee Island Sea-level Rise Planning: Benefit-Cost Evaluation Results for Adaptation Action Scenarios.*

***Facilitated session* (March 5):** Feedback from City Department Heads on modeling results and identification of other critical priorities

Evans and McDowell presented a suite of technical evaluations and benefit-cost analyses for adaptation actions defined in the August 6 and 7, 2012 townhall meetings. In summary, the evaluations indicated a very likelihood of significant economic benefit from use of backflow preventers on stormwater discharge pipes. Although not easily quantifiable through economic analyses tied to property and economic activity, very high flood resilience benefits were identified for the well pump and road elevation actions. Back island sea wall construction, however, was found to be a poor investment for flood protection at current dollar values.

II: SEA-LEVEL RISE EQUATIONS

Deterministic sea-level rise curves based on the ***Low***, ***Intermediate***, and ***High*** sea-level rise scenarios provide the baseline for the technical assessment of adaptation action presented in Chapter 4. As adapted from methods recommended by NOAA[61], sea-level rise projections were calculated through the following quadratic equation:

$E(t) = at + bt^2$; where

$E(t)$ = eustatic sea-level rise (inches)

t = years since 2010 baseline

a = annual local linear trend sea-level rise (inches)

b = sea-level rise acceleration coefficient (inches).

The Fort Pulaski tide gauge the record[62] provides a local value (i.e., integrating local subsidence and global sea-level rise) of a = 0.117 for all scenarios. Values for b are as follows:

b_{High}= 0.00557

$b_{Intermediate}$= 0.00203

b_{Low} =0.

The curves defined by Vermeer and Rahmstorf [63] begin at a 1990 sea-level. For this reason, a correction factor unique to each scenario was required to maintain a consistent 2010 baseline among all scenarios for the City of Tybee Island. This correction factor involves subtracting the amount of rise suggested by each respective scenario from 1990–2010 for the projected sea-level rise in all years from 2010–2060. For the Low scenario, the correction factor is 2.34 inches (0.195 feet). For the Intermediate scenario, the correction factor is 3.16 inches (0.263 feet). For the High scenario, the correction factor is 4.57 inches (0.381 feet).

TABLE III.1: SINGLE EVENT DEPTH DAMAGE EQUATIONS FOR MUNICIPAL WELL, CAPITAL COST (ADAPTED FROM FEMA 2013)

FLOOD HEIGHT (FT.)	DEPTH DAMAGE FUNCTION EQUATION
0 – 2	*D = 0.01F*V*
2 – 3	*D = (0.03F – 0.04)*V*
3 – 4	*D = (0.15F – 0.40)*V*
4 – 6	*D = (0.05F)*V*
> 6	*D = 0.3*V*

61 Eastern Research Group. 2013. What Will Adaptation Cost? An Economic Framework for Coastal Community Infrastructure. Charleston: NOAA Coastal Services Center. http://seagrant.noaa.gov/Portals/0/Documents/what_we_do/climate/NOAA_What_Will_Adaptation_Cost_Report.pdf. Accessed January 5, 2016.

62 NOAA. 2014. Mean Sea Level Trend, 8670870 Ft. Pulaski, Georgia. http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8670870. Accessed January 5, 2016.

63 Vermeer, M. and S. Rahmstorf. 2009. Global sea level linked to global temperature. Proceedings of the National Academy of Sciences of the United States of America. 106:21527-21532.

III: SINGLE-EVENT DEPTH DAMAGE EQUATIONS FOR MUNICIPAL WELL (CAPITAL COST)

The basis for single event losses to the capital infrastructure was depth damage thresholds for municipal wells developed by FEMA (2013), which were converted into continuous depth damage functions (Table III.1).

IV: SEA-LEVEL RISE ADJUSTMENT TO DEPTH-DAMAGE FUNCTION

Beginning from a 2010 baseline of sea-level, the flood heights (F) for 10 year, 50 year, 100 year, and 500 year storm surges were adjusted upwards on an annual basis using low, intermediate, and high sea-level rise scenarios. Therefore,

$F(t)_{SLRS} = F + E(t)_{SLRS}$; where

$F(t)_{SLRS}$ = Adjusted flood height at time period t (i.e., years since 2010) under given sea-level rise scenario

F = Flood height at 2010 baseline

$E(t)$ = eustatic sea-level rise at t under given sea-level rise scenario.

Using these adjustments, a cumulative damage estimate for each well covering all years and associated sea-level rise scenario adjustments from 2010 (t = 0) to 2060 (t = 50) was then calculated as:

$C_{SLRS} = \Sigma\ ((D(t)_{500} * P_{500} + D(t)_{100} * P_{100} + D(t)_{50} * P_{50} + D(t)_{10} * P_{10}) / (1 + i)^t)$; where

C_{SLRS} = Cumulative damage estimate ($) to well pump for given sea-level rise scenario

$D(t)_{500}$ = depth damage from Table III.1 under $F(t)$ as adjusted to 500 year flood height at year t

$D(t)_{100}$ = depth damage from Table III.1 under $F(t)$ as adjusted to 100 year flood height at year t

$D(t)_{50}$ = depth damage from Table III.1 under $F(t)$ as adjusted to 50 year flood height at year t

$D(t)_{10}$ = depth damage from Table III.1 under $F(t)$ as adjusted to 10 year flood height at year t

P_{500} = 0.002 (Probability of 500 year flood event)

P_{100} = 0.01 (Probability of 100 year flood event)

P_{50} = 0.01 (Probability of 50 year flood event)

P_{10} = 0.1 (Probability of 10 year flood event)

i = 0.03 (Discount rate)

V: CUMULATIVE ECONOMIC LOSS DAMAGE ASSESSMENT OF MUNICIPAL WELLS

Equation for well pump time down:

T (Time down) = [Max (F /6 (feet), 1)] * 14 (Days), Where F = Flood height

Rationale: Any flood above 6 feet will cause a maximum loss of 14 days. Flood depths below 6 feet are adjusted to cause less time out proportional to the flood height.

Single event economic flood loss equation:

L = (T * $97 (per person per day) * 2,990 (people on Tybee)) / 3 (Well pumps).

L = Economic loss per flood event

Cumulative 50-year projected economic loss from loss of well pumps, with flood heights adjusted by sea-level rise scenario as defined in Appendix IV.

$$L_{SLRS} \Sigma ((L(t)_{500} {}^{*}P_{500} + L(t)_{100} {}^{*}P_{100} + L(t)_{50} {}^{*}P_{50} + L(t)_{10} {}^{*}P_{10}) / (1+i)^{t});$$

VI: SINUSOIDAL TIDAL FLOODING EXCEEDANCE FOR US HIGHWAY 80

The flood exceedance time-period analysis is based upon the assumption of sinusoidal tide with a set period (p) of 742 minutes, which is the approximate average period between peak high tides (H_t) observed at the Fort Pulaski tide gauge. The initial sinusoidal equation form is:

$y_t = A \sin (2\pi x_t/p)$, where

y_t = height of tide at minute x_t

H_t = peak high tide during the given tidal cycle

A_t = elevation of the high tide peak above mean sea-level, which was assumed as $H_t/2$

x_t = minutes since beginning of tidal cycle

p = period (742 minutes)

All minutes (m) where y_t > 5.2 feet above navd88 were tracked across the full set of tide records (n=2,822) for 2009–2012, and then normalized to an annual value of exceedance minutes using the following function:

$\Sigma m/4$

Estimates of future event and time exceedances were developed through decadal calculations of eustatic sea-level rise, defined as *E(t)* in Appendix II, at the years 2020, 2030, 2040, 2050, and 2060 for each sea-level rise scenario. All initial tide heights (n=2,822) were adjusted for each decadal increment under each sea-level rise scenario as:

$y_{tSLR} = E(t)_I + y_t$, where

y_{tSLR} = Revised tide height (at minute x_t) under the given sea-level rise scenario

$E(t)$ = Eustatic sea-level rise at given year (t), as defined in Appendix II

y_t = Original tide height

All minutes (m_{SLR}) where y_t > 5.2 feet above NAVD88 were again tracked across the full set of tide records (n=2,822) for 2009–2012, and then annualized as:

$\Sigma\, m_{SLR}/4$

VII: DAMAGE AVOIDANCE ASSESSMENT FOR STORMWATER RETROFIT AND SEA WALL ACTIONS

A building-based sea-level rise vulnerability assessment for stormwater and sea wall actions was performed using a multi-step analytic process. First, ground elevation LIDAR return points[64] were processed to a 5ft² cell size digital elevation model (DEM) through the NOAA Digital Coast (http://coast.noaa.gov/digitalcoast/) website. Original raster tile datasets provided through Digital Coast were then mosaicked using ArcGIS 10.1 into a seamless digital elevation model dataset covering the City of Tybee Island. Because the original DEM contained null values for cells dominated by non-ground (e.g., building rooftops) returns, an inverse distance weighting (IDW) procedure was then utilized in ArcGIS 10.1 to interpolate elevation values such that estimated ground elevations were defined within the DEM for all areas of the City of Tybee Island. A Zonal Statistics procedure was then used in ArcGIS 10.1 to solve for minimum, mean, and maximum DEM values within the boundaries of building footprint polygons. These interpolated ground elevations underneath building footprints were used as the basis for flood risk analyses on a structure by structure basis.

A spatial join procedure in ArcGIS 10.1 was used to place tax assessed values for buildings from the 2011 property tax assessment dataset into each defined building footprint. On parcels containing numerous buildings in the footprint layer, the total assessed values at the parcel value were divided according to relative polygon area among the individual buildings.

YEAR	5.2' – 5.7' (NAVD)	5.7' – 6.2' (NAVD)	6.2' – 7.2' (NAVD)
2010	7.00	1.00	
2020	8.25	1.50	
2030	9.50	2.50	0.25
2040	11.50	3.50	0.50
2050	15.75	4.50	1.00
2060	20.25	6.75	1.25

TABLE VII.1: DECADAL FT. PULASKI PROJECTED TIDAL EVENT OCCURENCES WITH LOW SEA-LEVEL RISE

64 Chatham County, GA. 2012. 2009 Chatham County, Georgia Lidar. Charleston: NOAA Coastal Services Center. http://www.csc.noaa.gov/dataviewer/index.html?action=advsearch&qType=in&qFld=ID&qVal=1121. Accessed January 5, 2016.

Tide gauge data: All daily high tides from the 2009–2012 Ft. Pulaski tide gauge record were additively adjusted at decadal increments (2020, 2030, 2040, 2050, and 2060) to simulate each scenario of sea-level rise (Low, Medium, and High) using the equations in Appendix II. Annualized tide events for high tides corresponding from 5.2 ft.–5.7 ft., 5.7–6.2 ft., 6.2– 7.2 ft., and 7.2ft.–8.2 ft. above NAVD88 were then recorded for each decadal interval from 2010-2060 and as based upon each sea-level rise scenario. These values are summarized in Tables VI.1–VI.3. A generic depth-damage relationship adapted from the United States Army Corps of Engineers (Table VII.4) was then applied for each building in southwest Tybee Island at decadal increments for each sea-level rise scenario. To be conservative with damage assessment, the lower range of each tidal flooding increment was used as the basis for calculating flood depths at each structure. For example, in the range 5.2–5.7 feet, the tidal depth was set to 5.2 feet NAVD for all analyses.

Decadal point estimates of damage losses (L_B) by building value (V_B) were calculated across each sea-level rise scenario through a relationship with exceedance frequencies in Tables VII.1–VII.3 and depth damage relationships in Table VII.4:

$$L_B = DDF_{Tide} * F_{Tide} * V_B, \text{ as constrained to } L_B = Min(DDF_{Tide} * F_{Tide} * V_B, V_B)$$

A discounted damage function across all buildings (B) by decadal period (2010, 2020, 2030, 2040, 2050, and 2060) and sea-level rise scenario (Low, Intermediate, and High) was then calculated as:

$$L_t = \sum (L_B/(1.03)^t, \text{ where t = years since 2010}$$

These decadal estimates were then used to fit discounted damage curves over time. Cumulative damage values for taking no action under each scenario were then calculated through definite integrals to solve for area under damage curves across years 2011–2060 (Figures VI.1–VI.6).

YEAR	5.2' – 5.7' (NAVD)	5.7' – 6.2' (NAVD)	6.2' – 7.2' (NAVD)
2010	7.00	1.00	
2020	8.25	2.75	
2030	15.00	4.25	1.25
2040	29.50	7.75	2.00
2050	55.25	15.00	5.25
2060	79.25	36.75	11.25

TABLE VII.2: DECADAL FT. PULASKI PROJECTED TIDAL EVENT OCCURRENCES WITH INTERMEDIATE SEA-LEVEL RISE

YEAR	5.2' – 5.7' (NAVD)	5.7' – 6.2' (NAVD)	6.2' – 7.2' (NAVD)	7.2' – 8.2' (NAVD)	> 8.2' (NAVD)
2010	7.00	1.00			
2020	13.75	3.50	0.50		
2030	48.00	11.25	3.25		
2040	83.00	48.50	14.75	0.50	
2050	154.50	96.25	70.50	5.50	
2060	143.50	166.00	190.75	35.25	1.50

TABLE VII.3: DECADAL FT. PULASKI PROJECTED TIDAL EVENT OCCURRENCES WITH HIGH SEA-LEVEL RISE

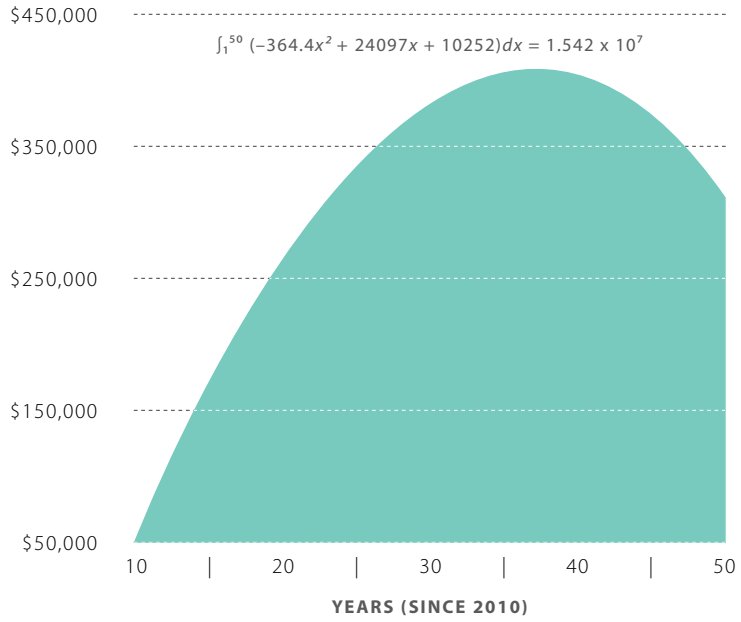


FIGURE VII.1: AVOIDED DAMAGES FOR PIPE BACKFLOW PREVENTERS, *LOW* SEA-LEVEL RISE

TABLE VII.4: TIDAL FLOODING DEPTH-DAMAGE RELATIONSHIP USED FOR CITY OF TYBEE ISLAND STRUCTURES, AS ADOPTED FROM THE UNITED STATES ARMY CORPS OF ENGINEERS[65]

FLOOD DEPTH	DAMAGE*
0	0%
1	2.5%
2	13.4%
3	23.3%
4	32.1%

$DDF = -0.008d^3 + 0.0567d^2 - 0.0182d - 0.0013$;
Where DDF = Percent damage

d = depth of flood, calculated as T – E, where T = tide increment; E = Maximum Lidar ground elevation within building footprint

*The original depth damage curves were adjusted upward by 2 feet to approximate actual building floor elevations, which are unknown at a building level, above interpolated Lidar ground elevation.

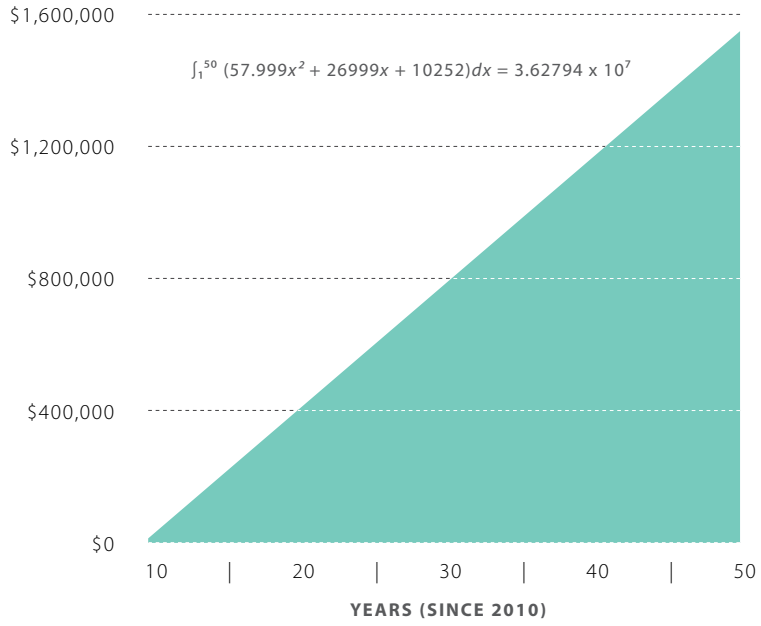


FIGURE VII.2: AVOIDED DAMAGES FOR PIPE BACKFLOW PREVENTERS, *INTERMEDIATE* SEA-LEVEL RISE

65 United States Army Corps of Engineers. 2000. Economic Guidance Memorandum (EGM) 01-03, Generic Depth-Damage Relationships. http://planning.usace.army.mil/toolbox/library/EGMs/egm01-03.pdf. Accessed June 15, 2015.

FIGURE VII.3: AVOIDED DAMAGES FOR PIPE BACKFLOW PREVENTERS, HIGH SEA-LEVEL RISE

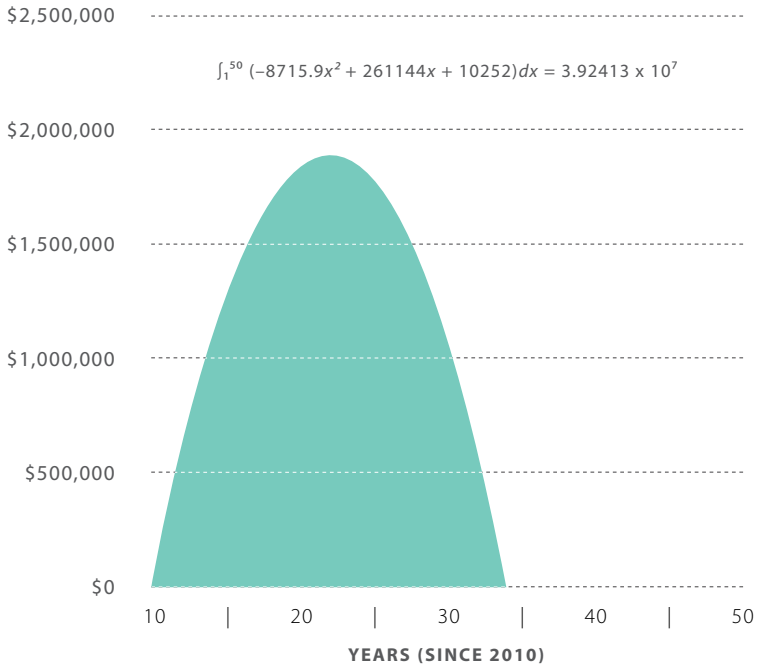
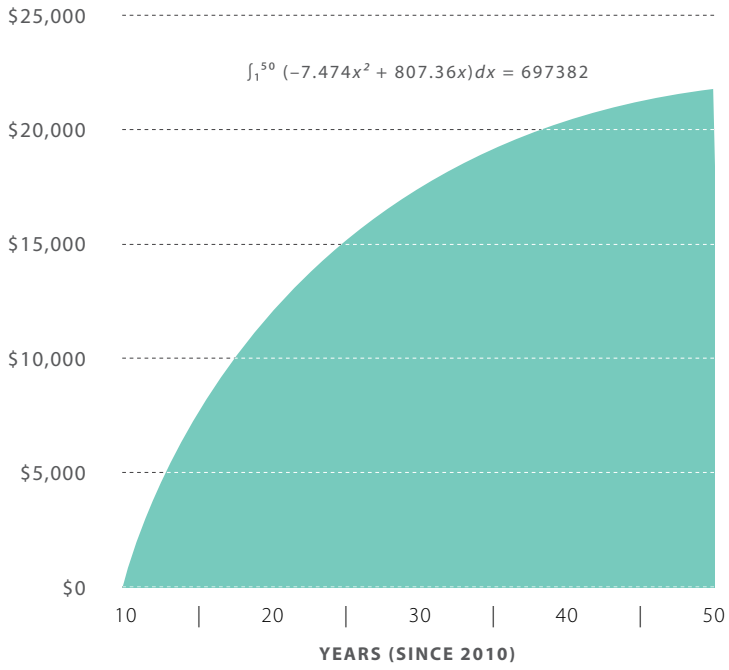


FIGURE VII.4: AVOIDED DAMAGES WITH SEA WALL, LOW SEA-LEVEL RISE



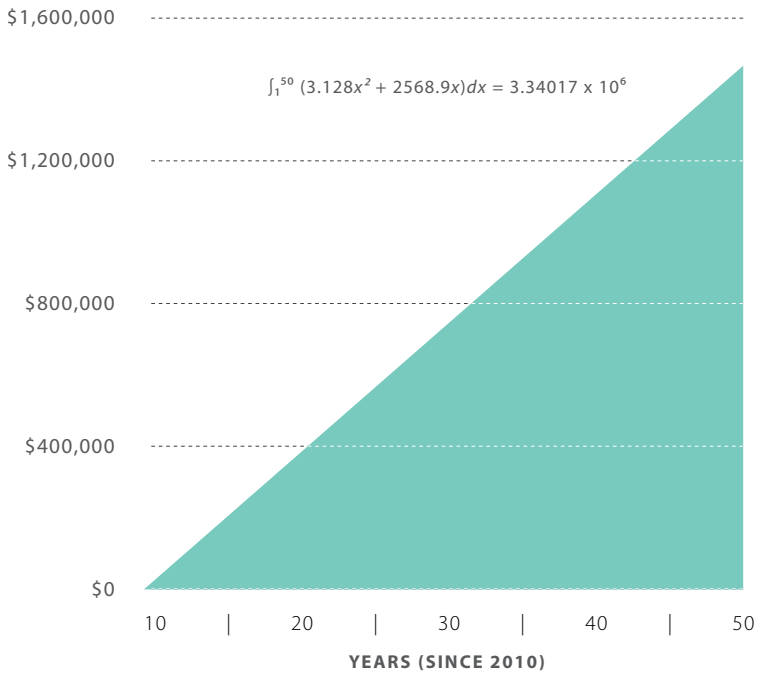


FIGURE VII.5: AVOIDED DAMAGE WITH SEA WALL, INTERMEDIATE SEA-LEVEL RISE

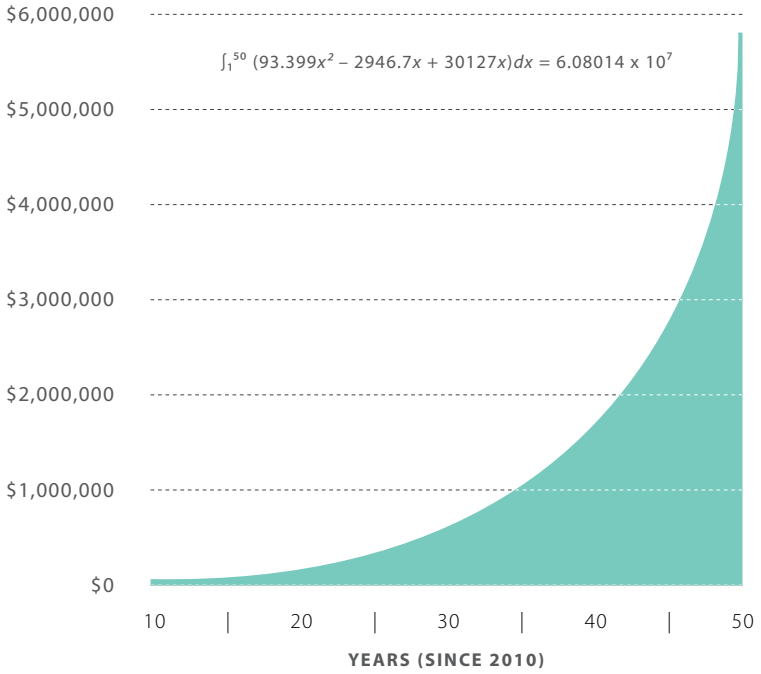


FIGURE VII.6: AVOIDED DAMAGES WITH SEA WALL, HIGH SEA-LEVEL RISE

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