COASTAL RISK CONSULTING

Village of Key Biscayne

Flood Vulnerability Assessment & Adaptation Report

April 2017

Table of Contents

Introduction

Coastal Risk Consulting, LLC (Coastal Risk) was retained by the Village of Key Biscayne (VKB or the Community), located in Miami-Dade County, Florida to perform a Flood Vulnerability and Risk Assessment, specifically focused on the effects of Sea Level Rise (SLR) and tidal flooding. Additionally, the assessment examines storm surge associated with hurricanes, and areas at risk for flooding due to groundwater. This report is the culmination of the assessment, which included a comprehensive analysis, community survey, and two community forums. VKB faces unique challenges, as the community is located on an island off the eastern coast of Miami-Dade county with only one ingress and egress, the Rickenbacker Causeway. These unique challenges are explored in this assessment.

Coastal Risk utilized its state-of-the-art technology, the Coastal Risk Rapid Assessment (CRRA™), to model current and future flood risks due to: (1) tides; (2) storm surge; and, (3) groundwater, as compounded by local sea-level rise rates through the year 2045. The CRRA™ uses as a centerpiece of its flood modeling the spatial extent of non-storm or nuisance flooding, which is related to factors such as sea level rise, tidal forcing, groundwater depth, and local subsidence. In addition to where on the community flooding will occur, the CRRA™ projects when (how many days per year) and how deep tidally-related flooding will be. This provides a unique visual communication tool within the vulnerability assessment.

In addition to the Flood Vulnerability and Risk Assessment (Phase 1), Coastal Risk is providing VKB with Adaption Strategies (Phase 2), which generally examines the effectiveness of certain adaptation options and the results of the community outreach.

Background

Key Biscayne is located within the southernmost barrier island of the Atlantic coast in Miami-Dade County, Florida. Its unique location between the Atlantic Ocean and the Biscayne Bay gives the Village direct exposure to the Atlantic Ocean; a factor, which coupled with Key Biscayne's very low elevation (average of 3.4 feet above the Mean Sea Level), makes Key Biscayne especially vulnerable to sea level rise and associated increases in storm surges. Moreover, the only access to Key Biscayne is through the Rickenbacker Causeway and its three bridges: the West Bridge, the William Powell Bridge and Bear Cut Bridge. And, even though Bear Cut Bridge was recently renovated in 2014, more exposure of these structures to the corrosive effects of seawater is to be expected with sea level rise, and, thus, leaves not only the two structures yet to be renovated vulnerable, but, the recently renovated bridge, as well (Smith and Tirpak, 1989).

The lack of natural beach nourishment from littoral drift processes that would normally transport sand from north to south along the Florida coastline is also a major challenge. This sand nourishment has been impaired by deep artificial inlets such as the Government Cut, and has led to various beach stabilization and re-nourishment efforts for over four decades. A further complication is the lack of mangroves to serve as barriers to sea level rise in three-quarters of the beaches on Key Biscayne. The ocean-side beach, which does have some mangroves, also has a host of other structures, which increases the cost, and complexity of beach re-nourishment or replacement where necessary.

Tides on Key Biscayne can vary throughout the year by up to 2 feet or more due to the effect of lunar orbital cycles, thermal expansion of water as it reaches its peak warmth during late summer and early fall, and seasonal changes in onshore winds and atmospheric pressure. The "king tides." the highest of all annual high tides, occur during the fall when these factors act to enhance tidal levels and can lead to flooding in areas that do not normally experience flooding during other parts of the year. As described below, Coastal Risk's modeling framework analyzes tidal patterns and projections of future sea level rise in order to determine the highest potential water level for the upcoming years. In our analysis, we quantify tidally-influenced flooding in order to show the regions that will be affected, as well as how often the flooding will occur.

As is the case over much of South Florida, the Village of Key Biscayne sits above bedrock that is primarily limestone. Limestone is highly porous compared to other substrates, with an exceptional ability to store and conduct water. Additionally, South Florida's drinking water comes from its limestone aquifers. The permeable nature of limestone has two consequences relevant to sea level rise. The first is that rising sea levels allow saltwater form the ocean to push further inland, contaminating the freshwater aquifer used for drinking wells (HighWaterLine Organization 2017). Currently, rising sea levels pose threats to fresh drinking water across South Florida, although fortunately there are no drinking wells located on Key Biscayne. The second consequence is that rising sea levels will also cause the inland water table to rise, reducing the available water storage capacity of the ground. As the water tables rise, the ground is able to absorb less water in the event of heavy rainfall, increasing the risk of rainfall-induced flooding. When sea level rise reaches even greater heights in the coming decades, the limestone bedrock will allow the water table to seep up from the ground itself, making seawalls and other protective external barriers less effective for low-lying areas

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Methodology

Coastal Risk Consulting, LLC has developed advanced geospatial modeling capabilities designed to analyze and predict current and future climate impacts (flooding, tidal changes, storm surge, sea-level rise, groundwater conditions, etc.) at the parcel-level for coastal communities throughout the United States. Our proprietary modeling framework forecasts the probability of both tidal flooding and storm surge inundation on individual property parcels over the next 30-years. The model uses publicly-available databases and best practices from National Oceanic and Atmospheric Administration (NOAA) and the United States Army Corps of Engineers (USACE), which are integrated with Coastal Risk's geospatial analysis tools to forecast current flood risk and future change flooding due to sea level rise (Sweet and Park, 2014; Sweet et al., 2014).

Key components of Coastal Risk's modeling include high-resolution LiDAR measurements of surface topography. The LiDAR measurements provide elevation information with unprecedented resolution, areal coverage, and accuracy for the entire Village. Figure 1 displays a map of the LiDAR elevations for the Village. Note the higher elevations towards the eastern (windward) side of the island, the low elevations towards the southeastern portion of the Village, and the clear outline of roadways by their relatively low elevation. Such information provides a simple graphical visualization to identify the location and extent of low-lying areas. It also gives context to the Coastal Risk modeling results and assists with evaluation and prioritization of adaption strategies.

The Coastal Risk modeling framework integrates this information with local tidal records, simulations of hurricane storm surge using the NOAA Sea Lake Overland Surge from Hurricanes (SLOSH), and community-based, scientific projections of future sea level rise to predict future current and future changes in flood risk. The storm surge model is a proprietary application of the SLOSH model developed by the National Oceanic and Atmospheric Administration (NOAA, 2017), which is widely used to quantify storm surge risk (Frazier et al, 2010; Shepard et al., 2012).

Three types of flood risk are examined in this document: 1) tidal or non-storm flooding (often referred to as “sunny day flooding” because it can occur under clear skies when no rain is present, and also “fair-weather flooding” and “nuisance flooding”) which arises from sea water rising above existing land elevations; 2) storm surge flooding, which occurs from hurricanes (or tropical cyclones) making landfall on or near the Village; and, 3) heavy rainfall flooding, which results when rainfall exceeds the drainage and ground storage capacity. The sections below outline the flood risks for the Village under current conditions and highlights how these flood risks will change in the future due to sea level rise.

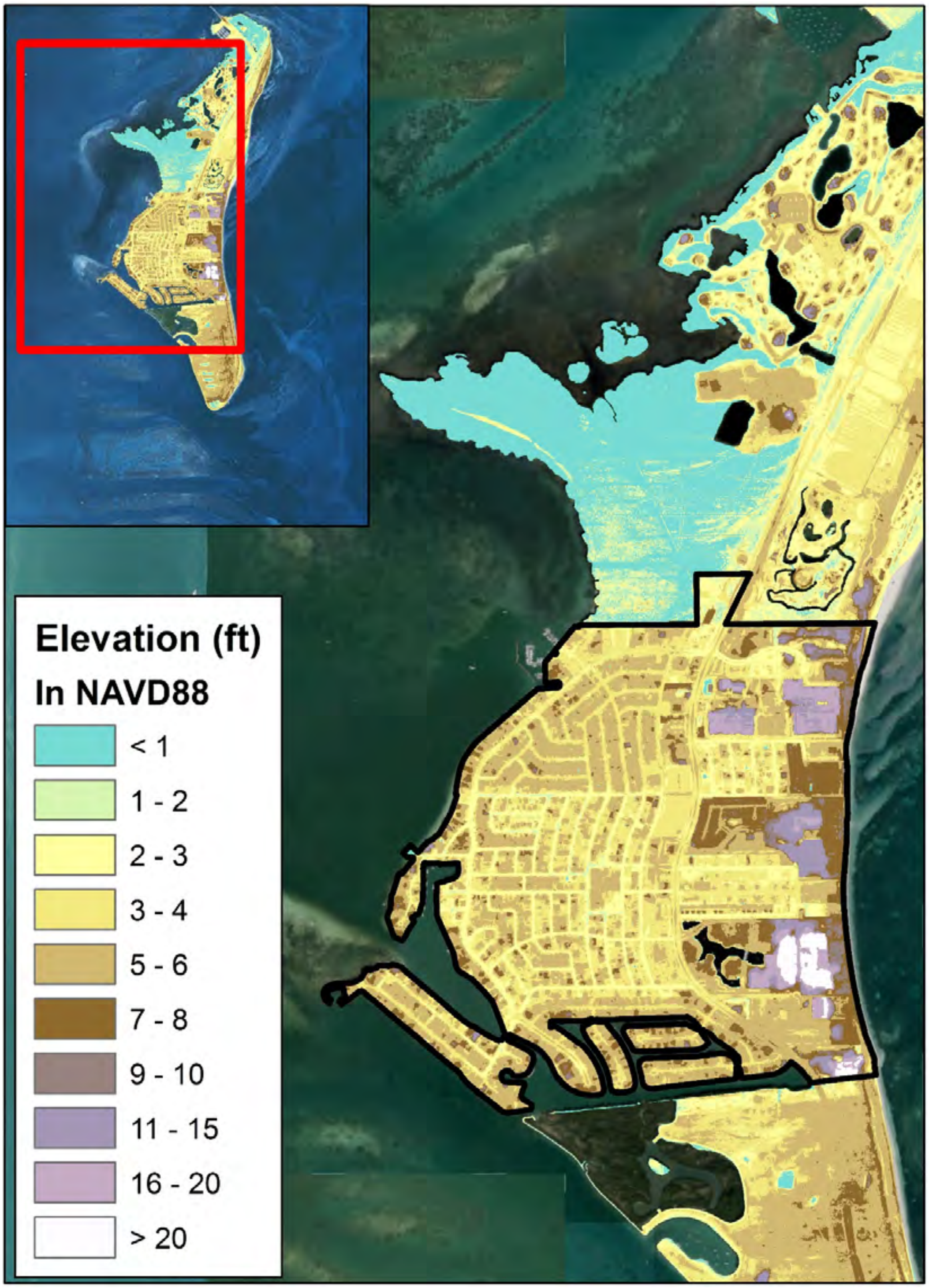


Fig. 1. High-resolution LiDAR map depicts the range of elevation in Village of Key Biscayne. All elevations are relative to the NAVD88 vertical datum – a global benchmark used to provide a common reference for measuring elevation.

Phase 1: Vulnerability Assessment

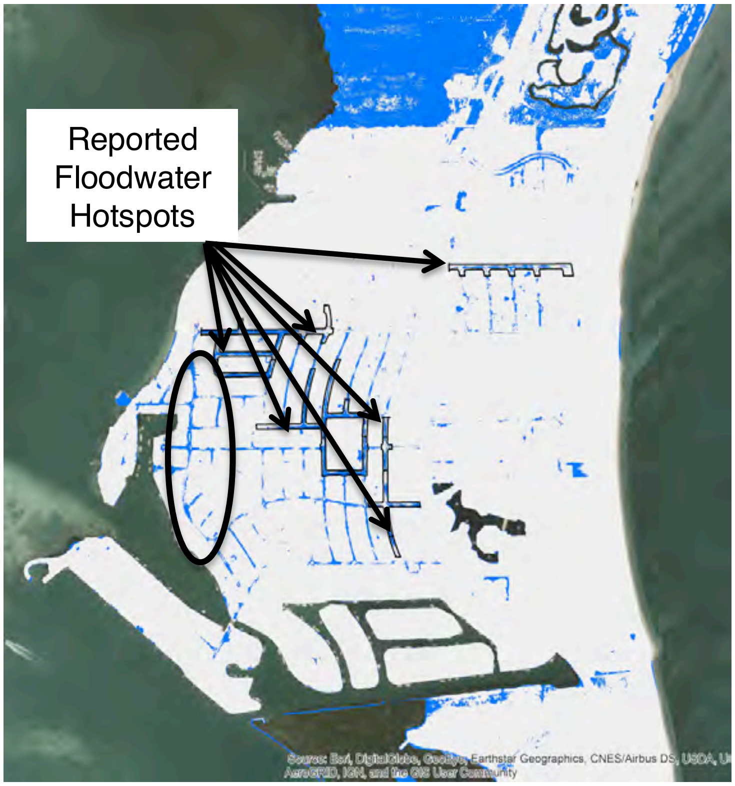
Phase 1 of this report examines current and future flood risks to provide credible and actionable information on the vulnerability of the Village of Key Biscayne to sea level rise. Three types of flooding are considered: Tidal flooding, storm surge flooding, and heavy rainfall flooding.

1.1 Tidal Flooding

This section summarizes the current and future flood risks due to tidal or “sunny day” flooding that will be faced by the Village of Key Biscayne. Tidal flooding is the temporary inundation of low-lying areas by sea water during high tide events, such as king tides. It is not a result of rainfall.

The blue shading in Figure 2 highlights those regions in Key Biscayne where the Coastal Risk model predicts that flooding should already be occurring during king tides. Note that, within the Village, current flooding is predicted to be limited to roadways, especially those on the southwestern portion of the Village. Extensive flooding is also predicted to occur in low-lying undeveloped areas immediately to the north of the Village. The black outlines on Figure 2 indicate those regions that are currently recognized as tidal floodwater hotspots based upon observational reports to the Village engineer from residents and Village staff (Jose G. Lopez, Village of Key Biscayne, personal communication). These flood hotspots agree well with the Coastal Risk model predictions. Note, however, that there are some roadways, for example in the far western portion of the Village (black oval in Figure 2), in which flooding is predicted to be imminent or is currently un-reported to the Village.

Next, we extend the tidal flood analysis illustrated above into the future using projections of sea level rise created by the United States Army Corps of Engineers and have been recommended for use by the South Florida Climate Compact (South Florida Regional Compact, 2016). Figures 3a-d show the Coastal Risk model predictions of tidal flooding for the Village for 10-year increments into the future based upon these sea level rise projections: 2016 (top left), 2025 (top right), (2035 (bottom left), 2045 (bottom right). By 2025, the area affected by tidal flooding has increased due to rising sea levels. The primary areas affected are low-lying roadways in the central and western parts of the Village of Key Biscayne, as well as low-lying areas in Crandon Park and Bill Baggs Cape Florida State Park. Over the next three decades, the tidal flooding is projected to affect ever-increasing areas and, by 2045, virtually every road will within the Village will experience tidal flooding, as well as a significant number of individual properties. The portion of the Village that will be most significantly affected is the area west of Crandon Blvd between Heather and Mashta Drives, as well as east of Crandon Blvd between Heather and Sonesta Drives, and Galen and Enid Drives.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, U
AeroGRID, IGN, and the GIS User Community

Fig. 2. **Current Tidal Flooding**: The blue regions in this map depict areas **currently** susceptible to tidal flooding. Black outlines indicate those regions that have been reported to the Village as tidal floodwater hotspots based upon observational reports.

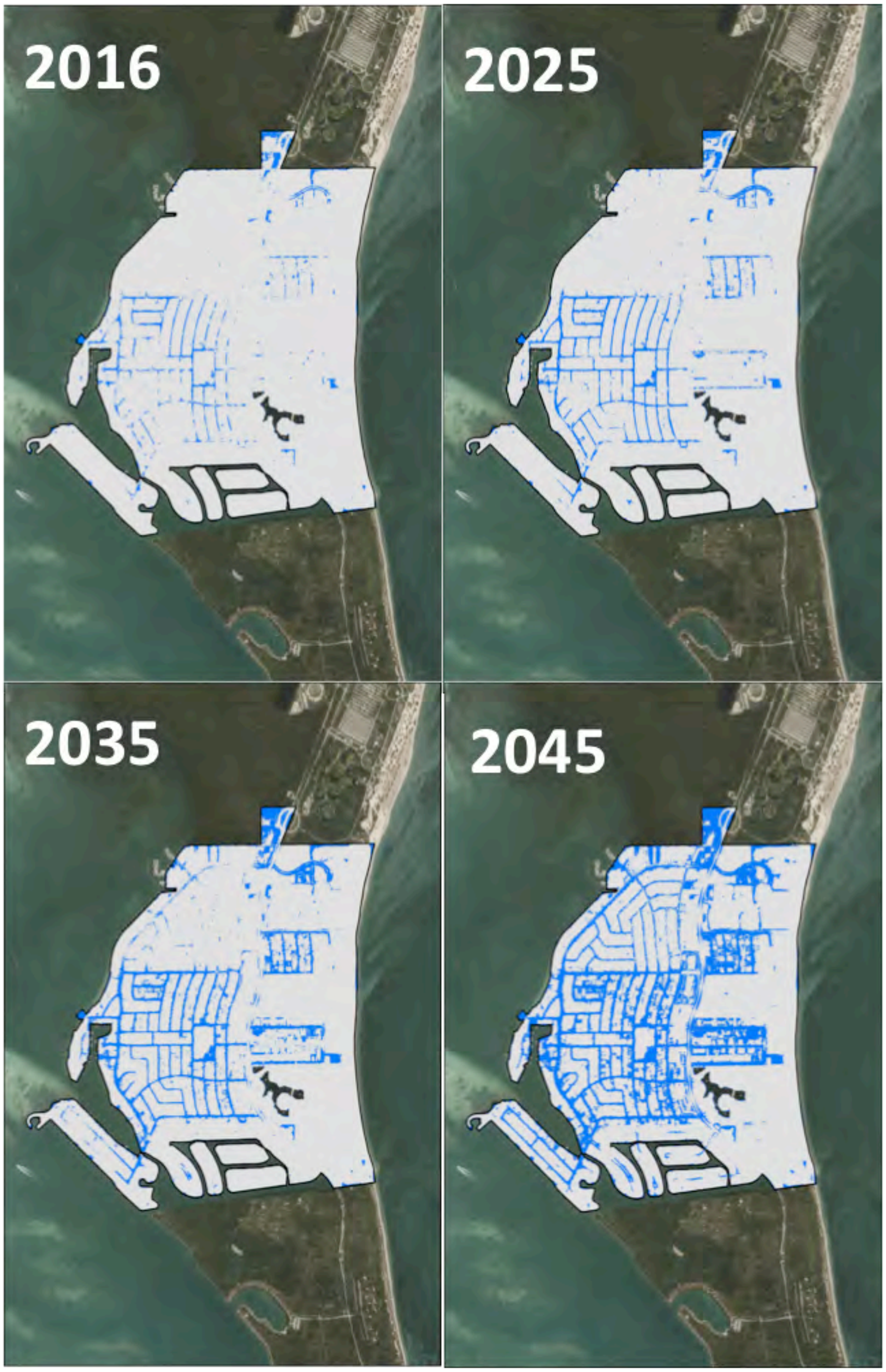


Fig. 3. **Projected Tidal Flooding for 2016-2045**: The blue regions in this map depict areas that will be susceptible to tidal flooding based on Coastal Risk model projections. No adaption efforts are included in this projection. Maps are presented for 2016 (top left), 2025 (top right), 2035 (bottom left), and 2045 (bottom right).

To get a better understanding of the frequency of inundation, Fig. 4 depicts the percentage of days that each parcel within the Village will experience at least some tidal inundation on their property. There is a large variation in the frequency of flooding throughout, with some properties experiencing tidal flooding almost daily while others experience no tidal flooding. Once again, the most vulnerable regions are west of Crandon Blvd between Heather and Mashta Drives, as well as east of Crandon Blvd between Heather and Sonesta Drives, and Galen and Enid Drives.

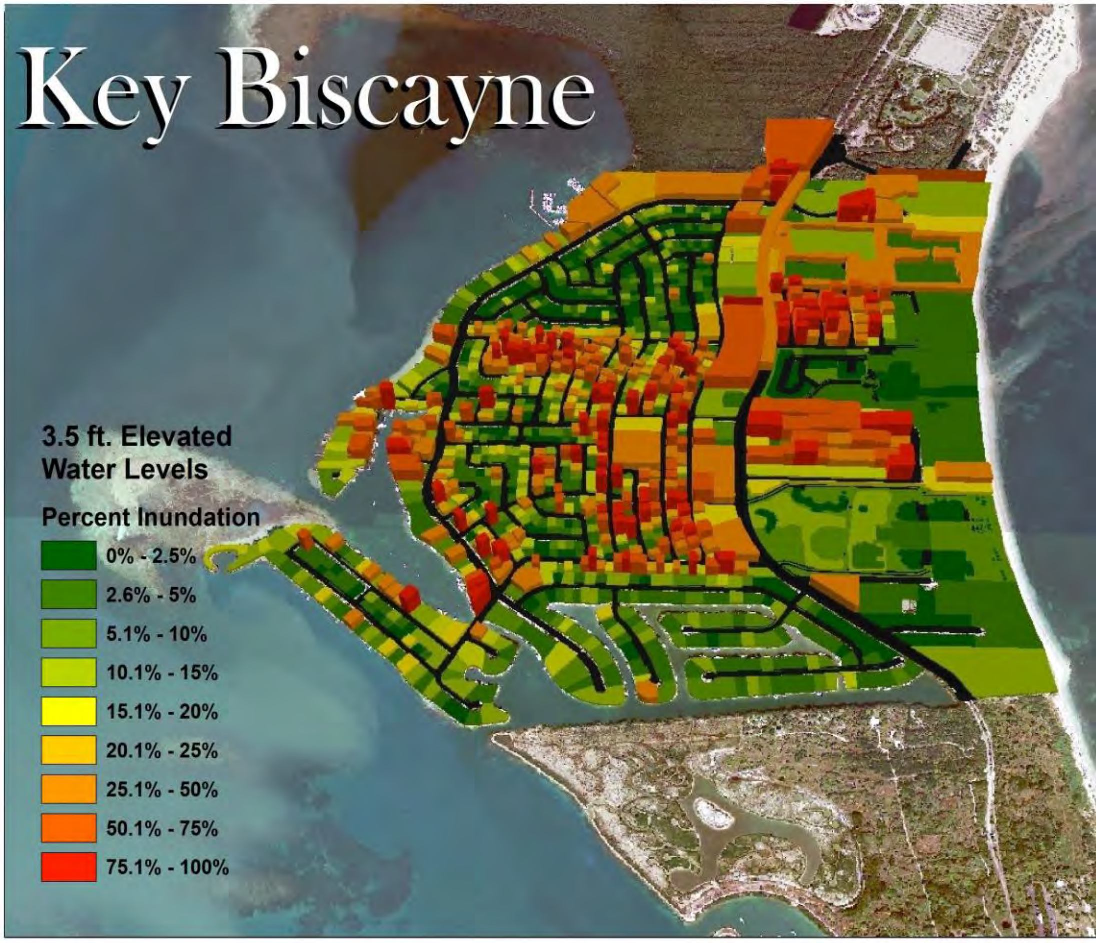


Fig.4. Percentage of Days with Tidal Floodwater: This map shows the percentage of days during the year where each parcel will experience tidal inundation over some part of their property for tidal levels that are 3.5 feet above the NAVD88 datum. That water height is equivalent to the projected highest water level that will be reached during "King tides" by the middle of this century. This scenario assumes that no adaptation measures are taken.

1.2 Storm Surge Flooding

This section summarizes the current and future flood risks due to storm surge flooding. Storm surge refers to the increased water levels generated by a tropical cyclone due to the strong winds and lower atmospheric pressure. Storm surges occur for all categories of tropical cyclones, from a tropical storm up to a Category 5 hurricane. While the surge generally increases with the intensity of the storm, there are a number of additional factors that affect storm surge. These include the size of the storm, its proximity, the path of the storm prior to landfall, the coastal topography and offshore ocean bathymetry, and the timing of the storms arrival with local tides. Because of its location between the Atlantic Ocean and Biscayne Bay and low elevation, the Village of Key Biscayne is extremely vulnerable to storm surge even for current sea levels.

To illustrate the general vulnerability of the island and how this risk changes with rising sea levels, the analysis below presents the maximum surge that would result from a Category 3 hurricane under both current and future sea level conditions. Major Hurricane (Category 3 or higher) strike rates for Miami-Dade County are approximately once every 8 years based on historical records (NHC).

Figure 5 depicts the depth of the storm surge (above ground) that will be experienced under current sea level conditions from a hypothetical Category 3 hurricane that makes landfall on or near Key Biscayne. Note that, even for current sea levels, virtually the entire Village will be inundated by the surge with some regions experiencing water depths of up to 8 feet. It is worth noting that the Village is in the Florida Department of Emergency Management's evacuation Zone A, meaning evacuation is mandatory for a Category 1 or higher storm.

As the sea level rises, the storm surge increases proportionately and by 2045 (Fig. 6) the storm surge exceeds 8 feet in certain parts of the Village, with largest water depths occurring primarily over the lowest lying roadways.

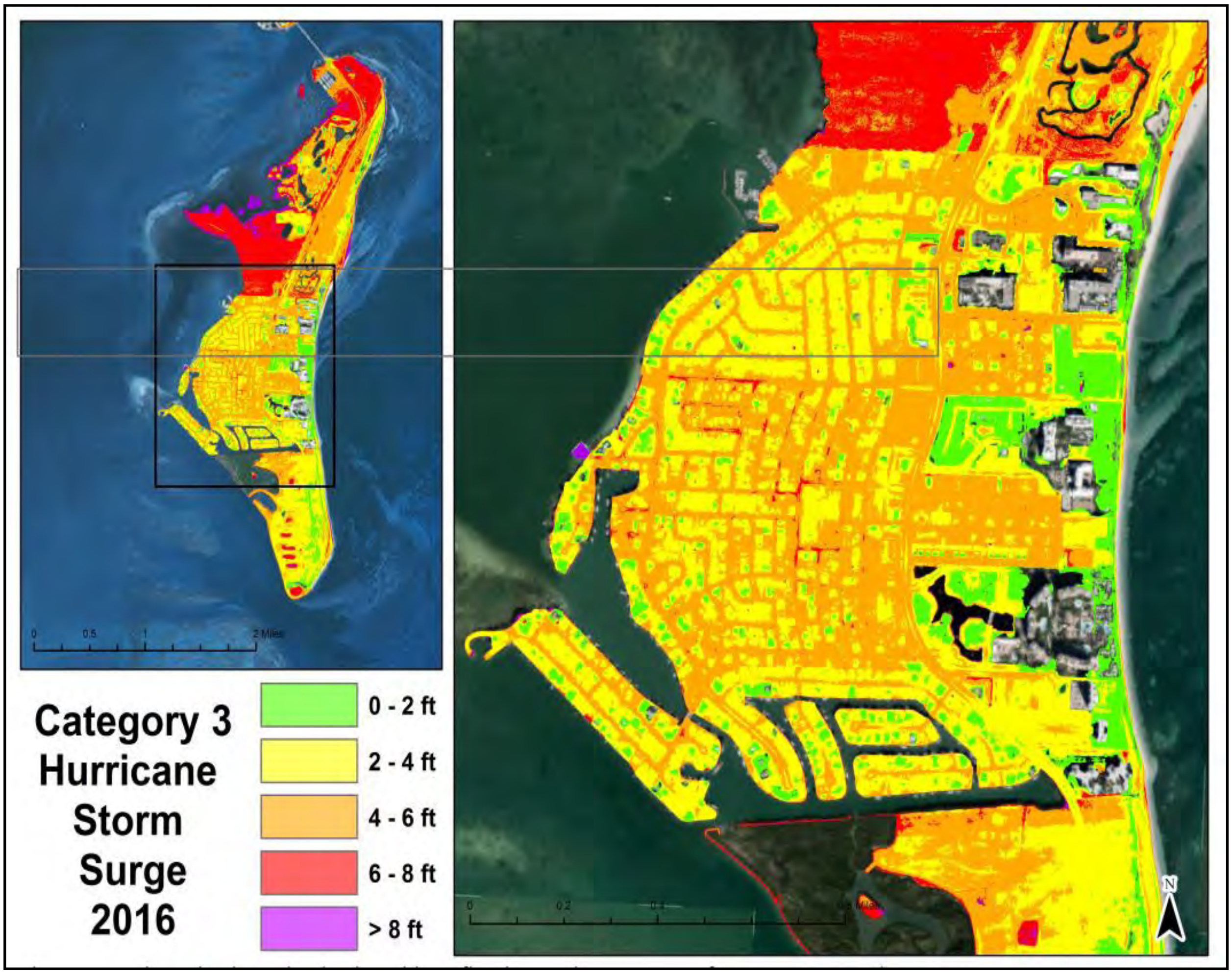


Fig. 5. Current Storm Surge Flooding: This map shows the maximum height of a storm surge (above the ground elevation) from a Category 3 hurricane at current sea level based on the NOAA SLOSH model simulations and LiDAR topography measurements.

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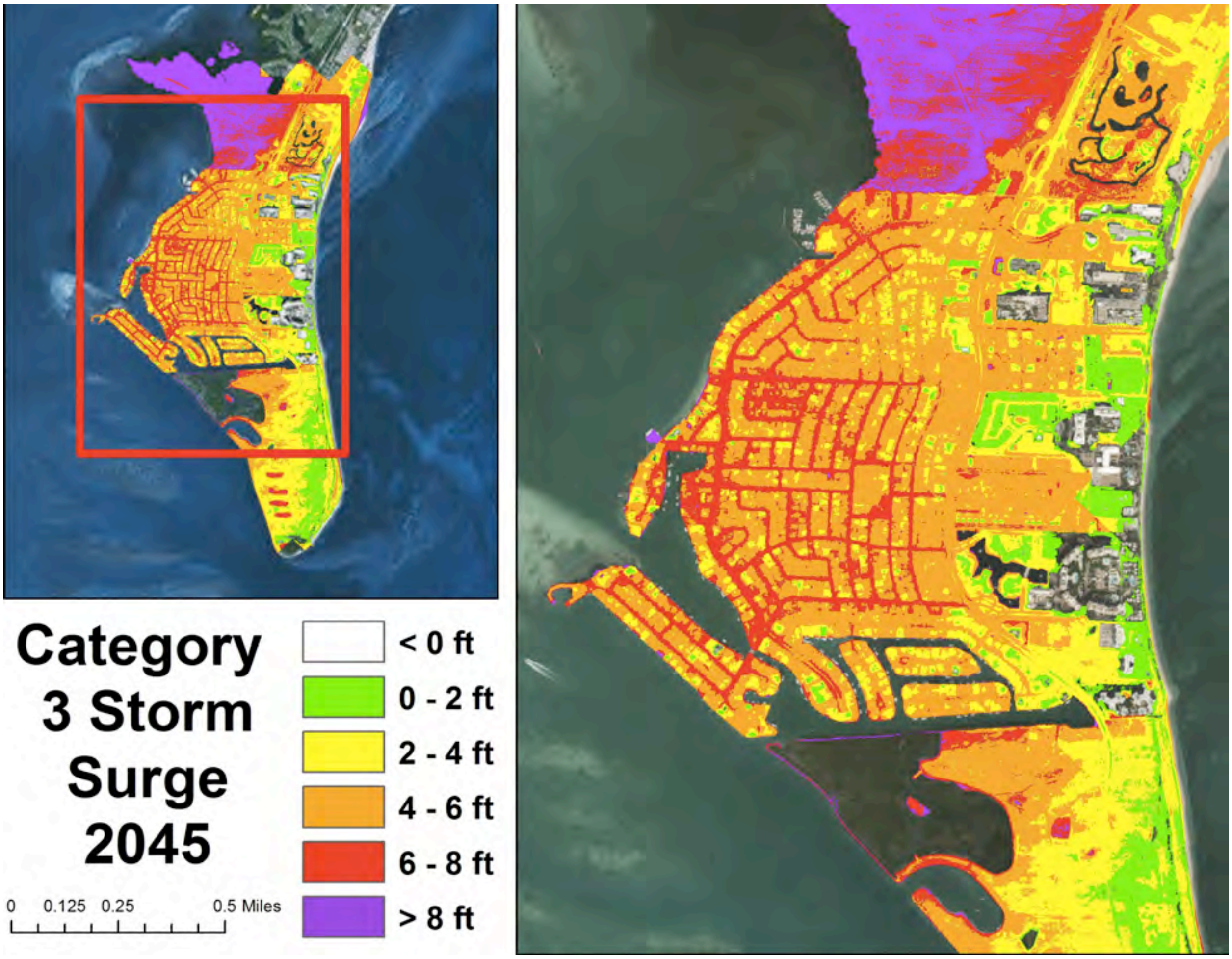

Fig. 6. Projected Storm Surge Flooding for 2045: This map shows the maximum height of a storm surge (above the ground elevation) from a Category 3 hurricane based on the NOAA SLOSH model simulations using projected sea levels for 2045.

1.3 Rainfall Flooding

Due to Key Biscayne's low mean elevation, the water table lies relatively close to the surface resulting in a limited capacity for the storage of rainfall. Groundwater flooding can occur when precipitation infiltrates into the ground and causes the water table to rise above normal levels. Poor drainage can lead to large areas of standing water after even small rainstorms. As the mean sea level rises, heavy rainfall flooding will become more and more frequent as the average water table height rises in the limestone bedrock underneath, and the ground becomes less absorbent in heavy rain events (HighWaterLine, 2017).

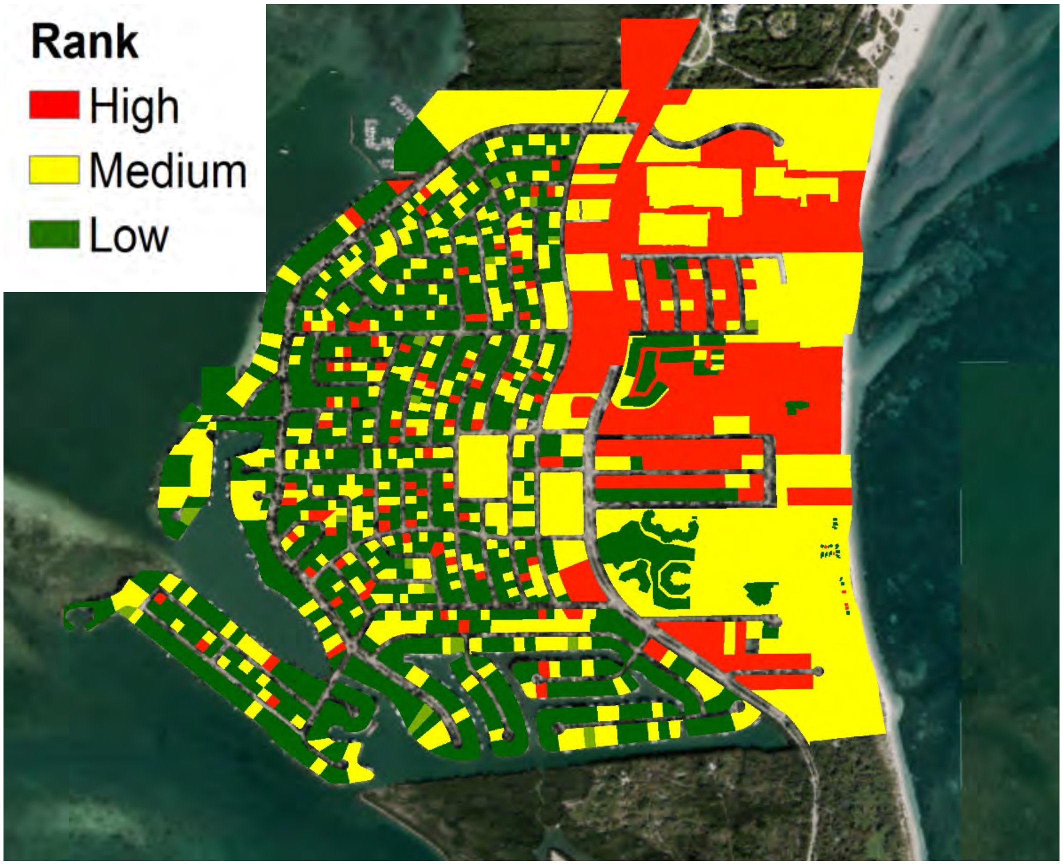

Fig. 7. Heavy rainfall flooding risk from low risk (green) to high (red).

The vulnerability to rainfall flooding (Fig. 7) varies substantially throughout the Village of Key Biscayne. Most of the Village has low (green) to medium (yellow) risk, while areas east of Crandon Blvd generally have a medium to high (red) risk of heavy rainfall accumulation and groundwater flooding. The large differences from parcel to parcel reflect spatial variations in elevation, water table height, and drainage capacity.

Phase 2: Adaptation Strategies

The second phase of this report outlines potential adaptation strategies that are available to the Village of Key Biscayne to lessen the impacts of sea level rise. Other municipalities, such as Boston and Miami, are developing common strategies for adaptation planning that involve 3 basic components (Ruvin 2010, Walsh 2016): 1) Community Engagement; 2) Policy Review; and, 3) Infrastructure Improvement. The town hall meetings and community surveys that were jointly organized by the Key Biscayne Community Foundation and Coastal Risk provide examples of effective outreach activities to engage, educate, and receive feedback from the community on the subject of sea level rise.

This section outlines the information presented at the 2nd town hall meeting that focused specifically on how infrastructure improvements can moderate the vulnerability of the Village of Key Biscayne to the impacts of sea level rise. All improvements presented here are idealized and hypothetical in nature. They are designed to provide insight into the benefits of various adaptation measures relative to a “no adaptation” scenario. Our results are based on the same modeling framework developed for the **Phase 1 Vulnerability Assessment**. Three categories of infrastructure improvements are presented here: 1) Storm Drainage Improvements; 2) Elevating Sea Walls; and, 3) Raising Roads and Property. We focus primarily on tidal flooding, but also include projections of how rainfall flooding can be mitigated due to certain adaptation measures. Although there is no viable adaptation strategy to prevent storm surge flooding, as the property and roadway elevations increase and reduce tidal flooding, this will have a proportionally similar reduction in the depth of storm surge flooding.

2.1 Storm Drainage and Sea Walls

During heavy rain events, storm drainage systems are designed to allow the excess rainfall runoff to drain into the ocean, rather than accumulate in low-lying areas.

However, as sea level rises, the outflow pipes of the drainage systems can become submerged during high tides, allowing ocean water to flow back through the pipes and up from the storm drains. A standard remedy for prevent this problem is to place "backflow valves" which allow rainwater to run out towards the ocean, but prevent ocean water from flowing back into the drainage pipes under high tides. In the fall of 2016, the Village of Key Biscayne began installing backflow preventers on all municipally owned outflow pipes. The installation of these valves began in the fall of 2016. Sea walls, on the other hand, provide a defense against the overland encroachment of ocean water during high tides. Thus, most strategies for limiting tidal flooding include both the installation of backflow valves and the elevation of sea walls.

Fig. 8. The extent of tidal flooding (blue) in the Village of Key Biscayne projected to occur by 2045 under two scenarios: No Adaptation (left), With Backflow Valves (right). Note that the No Adaptation scenario (Figure 10, left) is identical to Figure 5 of Phase 1.

To demonstrate the benefit of raising sea walls and installing backflow valves, Fig. 8 compares the extent of tidal flooding projected to occur in 2045 under a No Adaptation scenario (left) and with backflow valves and sea walls constructed to a minimum of 5 feet NAVD88 (right). Note how the installation on backflow valves and elevation of sea walls reduces the severity of tidal flooding throughout the Village, however, the tidally induced is not eliminated. The reason the flooding is not eliminated stems from the porous nature of the limestone bedrock on which Key Biscayne and much of South Florida rests. Tidal flooding not only occurs from the overland flow of water and the reverse flow through drainage pipes, but it also comes from underneath through the ground. As the sea level rises, the water table underneath the ground also rises. This causes water to seep up through the ground during high tides.

2.2 Roadway and Property Elevation

As seen in Figure 8, even with the installation of backflow valves and elevation of sea walls, many of the roads within the Village of Key Biscayne will be inundated during king tides by 2045. Such extensive flooding can have a significant impact on commerce and daily life, as well as emergency services and other critical functions of the municipality. Because roads are typically designed to be lower than surrounding properties, they are generally the most vulnerable to flooding. Many municipalities, such as Miami Beach, are beginning to elevate roads in order to prevent such flooding. In contrast to sea wall and drainage system improvements, roadway and property elevation increases are costly, complicated, impose significant short-term disruptions and concomitant obligations on private property owners (residential and commercial).

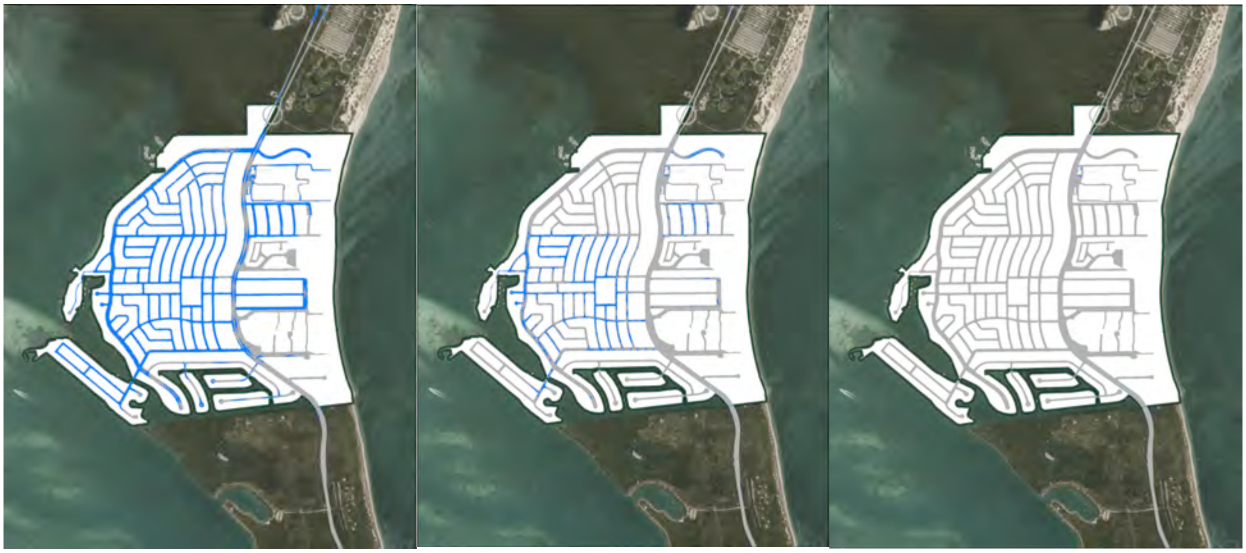

Fig. 9. The extent of inundated roads (blue) in the Village of Key Biscayne projected to occur by 2045 due to tidal flooding under three scenarios: No Adaptation (left), Elevated Roads by 1 foot (middle), Elevated Roads by 2 feet (right). Note that, for clarity, only

roadway flooding is depicted in these maps. The inundation of adjacent properties due to tidal flooding (as seen in Figures 10, 12) is not included here.

Figure 9 depicts the roads that would be flooded within the Village by 2045 under 3 different scenarios: No Adaption (left), elevating roads by 1 foot (middle), and elevating roads by 2 feet (right). Note that a 1-foot roadway elevation reduces flooding considerably and a 2-foot roadway elevation completely eliminates flooding of all roads within the Village.

Note that Fig. 9 focuses solely on roadway flooding. In contrast, Figure 10 shows the inundation of both roads and property (i.e., non-roadways) due to tidal flooding in 2045. Three different scenarios are presented: No Adaptation (left); elevation of flooded regions (both roads and properties) by 1 foot (middle); elevation of flooded regions (both roads and properties) by 2 feet (right). Elevation by 1 foot (middle) significantly reduces the flooding in most areas of the Village with the exception of some roads primarily in the southwestern portion of the Village. Increasing the elevation by 2 feet (right) virtually eliminates flooding throughout the Village.

Fig. 10. The extent of tidal flooding (blue) in the Village of Key Biscayne projected to occur by 2045 due to tidal flooding under three scenarios: No Adaptation (left), elevation of flooded properties 1 foot (middle), elevation of flooded properties 2 feet (right).

The most efficient adaption planning combines multiple strategies. Figure 11 shows projections for the extent of flooding by 2045 under a No Adaptation Scenario (left) and a combined adaptation scenario which accounts for the installation of backflow valves, elevation of sea walls and increasing the elevation of all roads by 1 foot. Not that this eliminates most roadway flooding and partially reduces property (i.e., non-roadway) flooding throughout the Village. However, there still are significant areas of the Village that remain vulnerable to tidal flooding. These regions would require elevation of the ground to prevent flooding on those properties (e.g., as modeled in Figure 10).

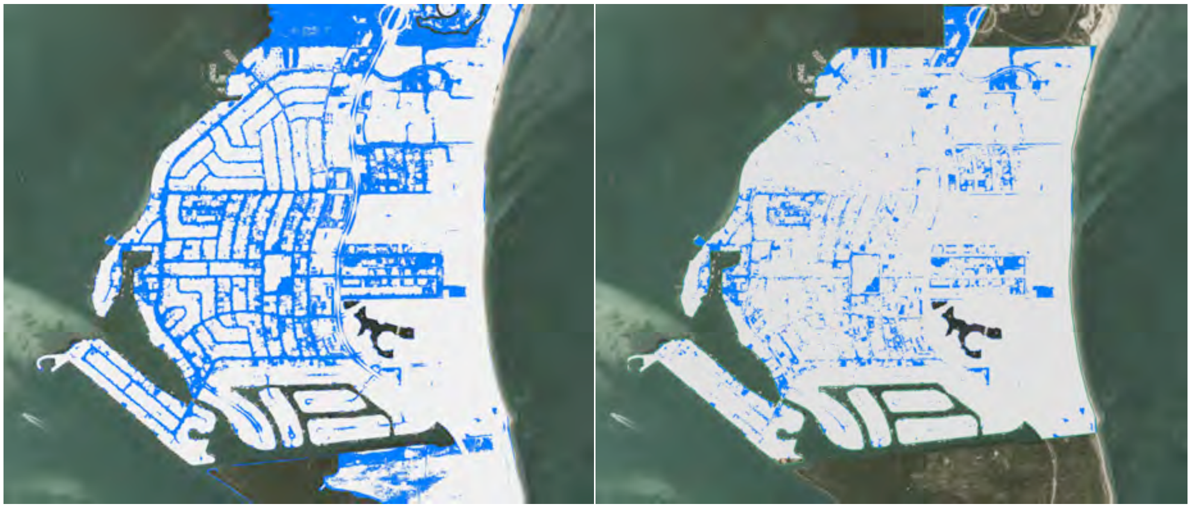

Fig. 11. The extent of tidal flooding (blue) in the Village of Key Biscayne projected to occur by 2045 under two scenarios: No Adaptation (left), With Backflow Valves, Elevated Sea Walls and 1 Foot Roadway Elevation (right).

Conclusion

This reports outlines the vulnerability of the Village of Key to sea level rise over the next 30 years. The Village currently experiences tidal flooding and rainfall flooding over limited areas, particularly along low lying roads west of Crandon Blvd. The regions vulnerable to tidal flooding will increase substantially over the next 30 years as sea levels continue to rise. By 2045, if no adaptation steps are taken, most roads within the Village will experience tidal flooding during king tides, as will many low-lying residential and commercial properties. Increasing sea levels will also increase the likelihood of rainfall-induced flooding as the water table rises thereby reducing the water holding capacity of the ground. As the difference between mean sea level and elevation of the land decreases, the ability for the land to gravitationally drain into the ocean will also decrease.

Even at current sea levels, the entire island is vulnerable to storm surge flooding. For this reason, the Village is in the Florida Department of Emergency Management's evacuation Zone A, meaning evacuation is mandatory for a Category 1 or higher storm. Over the next 30 years, the threat of storm surge will increase; with the depth of storm surge inundation increasing roughly in proportion to the rate of local sea level rise.

The second phase of this report outlines idealized adaptation strategies that the Village can implement to lessen the impacts of sea level rise. Drainage and Seawall improvements offer a cost-effective, fast and efficient option for reducing the vulnerability of the Village to tidal flooding. Elevating roads and low-lying properties can further reduce or completely eliminate the occurrence of tidal flooding if the increase in elevation is significant enough. However, such adaption measures are costly and require extensive coordination and planning with other infrastructure measures (e.g., drainage improvements, walkway improvements, burying power lines, etc.) and with local residents. Any adaptation plan requires commitment from both the local government and private property owners (both residential and commercial). Many residents are unaware of the obligations that may be required of them in order to adapt their property to sea level rise. Continued outreach and communication by local governments is thus also a critical component any adaptation plan.

The adaptation efforts presented here are highly idealized and designed to begin the process of adaptation planning. Future adaptation efforts will require more specific scenarios using the Coastal Risk modeling framework to investigate specific adaption plans. Such plans should be community-based and engage residents, business owners, and policy makers through continued communication and outreach activities.

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