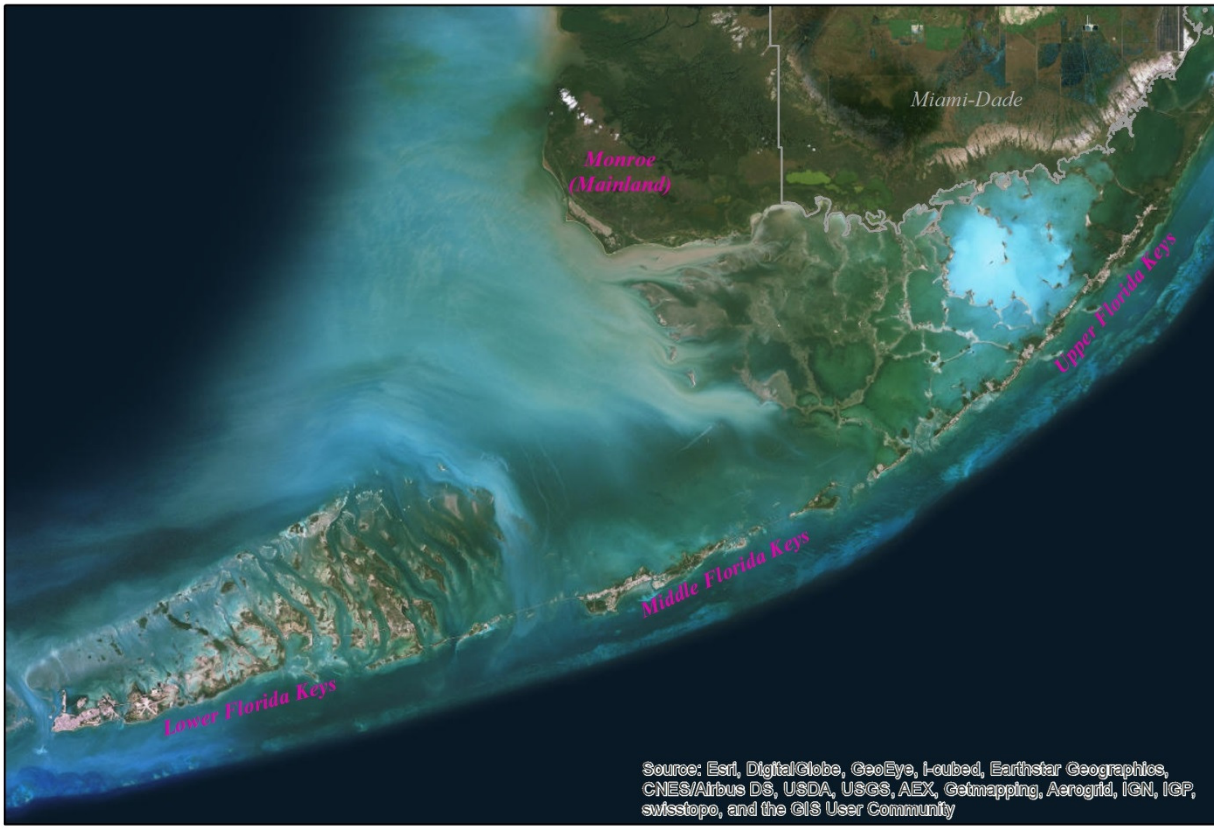
Sea Level Rise Vulnerability Assessment for Monroe County, Florida:

Technical Appendix in Support of the GreenKeys! Sustainability and Climate Action Plan



January 26, 2016

Final Report for Monroe County Sustainability Program

Rhonda Haag, Manager

Murray Nelson Center

102050 Overseas Highway

Key Largo, FL 33037

Authors: Jason M. Evans, PhD & Chris Bergh

Project Manager: Erin L. Deady, P.

Page intentionally left blank

Sea Level Rise Vulnerability Assessment for Monroe County, Florida:

Technical Appendix in Support of the GreenKeys! Sustainability and Climate Action Plan

Final Report for Monroe County Sustainability Program

Rhonda Haag, Manager

Murray Nelson Center

102050 Overseas Highway

Key Largo, FL 33037

January 26, 2016

Authors:

Jason M. Evans, PhD, Assistant Professor of Environmental Science, Stetson University

Chris Bergh, Director, Coastal and Marine Resilience Program, The Nature Conservancy

Project Manager:

Erin L. Deady, P.A.

Recommended Citation:

Evans, J.M. and C. Bergh. 2016. Sea Level Rise Vulnerability Assessment for Monroe County, Florida. Technical Appendix in Support of the GreenKeys! Sustainability and Climate Action Plan. Key Largo: Monroe County Sustainability Program.

Acknowledgments

The data and analyses developed for this report would not have been possible without the cooperation of many people and organizations. This list is our best attempt to thank everyone involved for their collaboration, patience, and assistance in making the project possible and providing inputs critical for successful completion. We apologize in advance for any unintentional omissions.

Erin Deady, P.A., the lead project manager for the GreenKeys! Sustainability and Climate Action Plan, tirelessly led a diverse team of researchers and consultants through a complex and multi-faceted 2-year project period. The project's overall success stems directly from Erin's leadership of the project team and close interface with Monroe County officials to work through a dizzying set of technical and policy issues. It was truly a privilege to work under her leadership in developing this report.

Rhonda Haag, Manager of the Monroe County Sustainability Program, ably guided the overall project through many public meetings, technical discussions, and document reviews. Her insistence on the highest quality visualizations and real world applicability from technical modeling was instrumental in the evolution of this document and is an enormous asset to the citizens of Monroe County.

Many other staff members from the Monroe County government provided guidance, data, and feedback throughout all or portions of the project period. These include: Roman Gastesi, County Administrator; Christine Hurley, Assistant County Administrator; Kevin Wilson, Assistant County Administrator; Michael Roberts, Senior Administrator/Environmental Resources; Judith Clarke, Director of Engineering Services; Bryan Davisson, GIS Administrator/Analyst; Wayne Whitley, GIS Server Administrator/Systems Analyst; Mary Wingate, Senior Floodplain Coordinator; and Robbie Shaw, Monroe County Property Appraiser's Office.

Additional datasets and assistance were provided by the following individuals and organizations: Tom Walker, Julie Cheon, Robert Bethel, Kerry Cromie, and Marnie Walterson – Florida Keys Aqueduct Authority; Paulette McNamara – Florida Keys Electric Cooperative; Kris Bremer, Frankie Garcia, and Dale Finnigan – Keys Energy Service; Maria Cahill – Florida Department of Transportation; David Strong, Paul Hearn, and Eric Swain – United States Geological Survey; Bob Glazer and Brian Beneke – Florida Fish and Wildlife Conservation Commission; Crystal Goodison – University of Florida GeoPlan; and Vivienne Handy – Quest Ecology.

Technical development of datasets was accomplished through the cooperative efforts of numerous research assistants. These technical contributors included:

Kathleen Freeman, GIS Specialist/GIS Coordinator, The Nature Conservancy, Florida Chapter. Assistance with Sea Level Affecting Marshes Model (SLAMM) dataset assembly; management and uploading of project data for The Nature Conservancy's Coastal Resilience 2.0 web portal.

Jimmy Nolan, Local Government Project Manager, Information Technology Outreach Services, Carl Vinson Institute of Government, University of Georgia. Provided critical assistance with parcel dataset acquisition, management, and interpretation for flood modeling.

J. Scott Pippin, Public Service Assistant, Planning and Environmental Services Division, Carl Vinson Institute of Government, University of Georgia. GIS dataset development and literature assembly.

Alex Clark, Undergraduate Intern, Department of Environmental Science and Studies, Stetson University. Digitization of building footprints.

Zella Conyers, Undergraduate Intern, Department of Environmental Science and Studies, Stetson University. Digitization of building footprints and assembled datasets for Sea Level Affecting Marshes Model (SLAMM).

Emily Niederman, Undergraduate Intern, Department of Environmental Science and Studies, Stetson University. Digitization of building footprints and assistance with elevation extraction.

Justin Baumann, Undergraduate Intern, Department of Environmental Science and Studies, Stetson University. Digitization of building footprints and assistance with elevation extraction.

Alexandra Horst, Undergraduate Intern, Department of Geography, University of Georgia. Assembled annotated bibliography utilized for final report development.

Three technical reviewers provided a formal list of in-depth comments and suggested edits on an earlier version of this document: Dr. Jennifer Jurado, Director, Broward County Environmental Planning and Community Resilience Division; Dr. Jayantha Obeysekera, Chief Modeler, South Florida Water Management District; and Nicholas Aumen, Regional Science Advisor – South Florida, United States Geological Survey. Comments from each of these technical reviewers greatly strengthened the analyses and overall presentation for the final report. Additional technical comments from Monroe County staff, particularly including Michael Roberts and Judith Clarke, also helped strengthen several elements within the final report.

Copy-editing and reference checks for the final report were kindly provided by Sidney P. Johnston, Grants and Contracts Manager, Stetson University.

Please note that the authors are solely responsible for the final contents in this report. No acknowledged individuals bear responsibility for any of the analyses, opinions, and recommendations presented within the final document.

Table of Contents

List of Tables

List of Figures

Monroe County, FL: GIS Vulnerability Assessment for Sea Level Rise Planning

Introduction

The GreenKeys! planning process included a comprehensive vulnerability assessment for sea level rise scenarios in the year 2030 and 2060. Components of this assessment included analysis of ground elevation relative to current and future tidal heights for all public roads and buildings owned by Monroe County, as well as critical infrastructure that includes emergency response, law enforcement, wastewater facilities, water supply, schools, and electrical utilities. Assessments of land cover change and habitat vulnerability to sea level rise were also performed using tidal inundation models and custom scenarios of the Sea Level Affecting Marshes Model (SLAMM). This Technical Appendix provides a thorough explanation of the datasets, modeling procedures, and results of this vulnerability assessment.

Sea Level Rise Scenarios

The Southeast Florida Regional Climate Change Compact (2011) developed a series of sea level rise scenarios recommended for use in vulnerability assessments conducted by local governments in Monroe, Miami-Dade, Broward, and Palm Beach counties. Using a baseline year of 2010, Southeast Florida Regional Climate Change Compact (2011) recommended a 2030 sea level rise planning scenario of 3 inches and a maximum 2030 sea level rise scenario of 7 inches. By 2060 the recommended minimum sea level rise scenario is 9 inches, while the maximum sea level rise scenario is 24 inches.

The Southeast Florida Regional Climate Change Compact (2011) sea level rise scenarios are based upon the low and high Modified Natural Research Center (1987) quadratic sea level rise equations, as more recently described by the US Army Corps of Engineers (2011).

The quadratic sea level rise equation, based upon a unit measure of inches, is defined as:

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

$E(t)$ = sea level rise (in) in year t

t = years since 1992 (yr)

a = historic local sea level rise trend in inches per year (in/yr), as determined from a tide gauge record; for SE Florida, a = 0.0913 (in/yr) based on the Key West tide gauge record.

b = sea level rise acceleration coefficient (in/yr^2); for low scenario, b_{low} = .001067; for high scenario, b_{high} = .004449

The low sea level rise curve (b = .001067) implies a gradual acceleration of sea level rise over the next several decades, primarily due to thermal expansion of ocean waters and polar ice sheet melt rates similar to what has been observed over the last fifty years. The low sea level rise curve recognizes the contributions of anthropogenic global warming and climate change to sea level rise, but generally assumes that global greenhouse gas emissions will slow and/or that near-term climate sensitivity to greenhouse gases is low.

The high sea level rise curve (b = .004449), by contrast, implies a rapid acceleration of sea level rise over the next several decades due to more rapid thermal expansion of ocean water and accelerated melting of ice sheets in Greenland and West Antarctica. The high sea level rise curve assumes that global greenhouse gas emissions continue to grow and that near-term climate sensitivity to greenhouse gases is high.

We do note that governmental reports and published literature indicate a much wider range of sea level rise scenarios than those developed by the Southeast Florida Regional Climate Change Compact (2011). For example, the National Climate Assessment (Parris et al. 2012) contains scenarios of “Lowest” and “Highest” sea level rise that are both outside of the scenario window adopted by the Southeast Florida Regional Climate Change Compact (2011).

The “Lowest” scenario from the National Climate Assessment (Parris et al. 2012) assumes continuation of a simple linear trend for global sea level rise (0.075 in/yr) as based upon a simple regression of historic tide gauge data. Translated into a 2010 baseline, this “Lowest” scenario would equate to approximately 1.5 inches of sea level rise by 2030 and 3.75 inches by 2060 at a global level. Using the slightly higher linear trend from the Key West tide gauge (0.0913 in/yr), this linear trend would be approximately 1.8 inches by 2030 and 4.6 inches by 2060. Parris et al. (2012) note that this low sea level rise scenario is appropriate for use as a minimum standard for relatively low value projects with high risk tolerance and subject to frequent replacement.

The “Highest” scenario from the National Climate Assessment (Parris et al. 2012) assumes the onset of catastrophic polar ice sheet melt that would raise sea levels at Key West by 9 inches at 2030 and 31 inches by 2060. The highest sea level rise scenario is most appropriate to use for extremely high value projects with very little risk tolerance (e.g., nuclear power plants) and extreme adverse consequences under a near-term inundation scenario.

Sea Level Rise Calculations

The base planning year, or the assumed zero elevation point, for sea level rise under the Southeast Florida Regional Climate Change Compact (2011) scenarios was 2010. Consistency with the US Army Corps of Engineers (2011) sea level rise curves requires establishment of unique zero points for the low and high scenarios curves at the year 2010. This is accomplished by calculating sea level rise with the quadratic function using the t value associated with the original 1992 tidal reference period, and then adjusting this value to a 2010 sea level based on the calculated sea level rise between 1992 and 2010.

For the **low sea level rise scenario**, the calculated sea level rise between 1992 and 2010 ($E(t)_{Low2010}$) using the quadratic sea level rise curve is approximately 2 inches:

$E(t)_{Low2010}$ = (.0913*(2010-1992)) + (.001067*$(2010-1992)^2$)

$E(t)_{Low2010}$ = (.0913*18) + (.001067*18^2)

$E(t)_{Low2010}$ = 1.989 inches (or ~2 inches)

To obtain the Southeast Florida Regional Climate Change Compact (2011) low sea level rise value for 2030 from a 2010 baseline ($E(t)_{LowCompact2030}$), the assumed sea level rise of 2 inches between 1992 and 2010 is then subtracted from the quadratic sea level rise calculated for the period between 1992 and 2030 ($E(t)_{Low2030}$):

$E(t)_{Low2030}$ = (.0913*(2030-1992)) + (.001067*$(2030-1992)^2$)

$E(t)_{Low2030}$ = (.0913*38) + (.001067*38^2)

$E(t)_{Low2030}$ = 5.0101 inches (or ~5 inches)

$E(t)_{LowCompact2030} = E(t)_{Low2030} - E(t)_{Low2010}$

$E(t)_{LowCompact2030}$ = (5 inches) – (2 inches)

$E(t)_{LowCompact2030}$ = 3 inches

To obtain the Southeast Florida Regional Climate Change Compact (2011) low sea level rise value for 2060 from a 2010 baseline ($E(t)_{LowCompact2030}$), the assumed sea level rise of 2 inches between 1992 and 2010 is similarly subtracted from the quadratic sea level rise calculated for the period between 1992 and 2060 ($E(t)_{Low2060}$):

$E(t)_{Low2060}$ = (.0913*(2060-1992)) + (.001067*$(2060-1992)^2$)

$E(t)_{Low2060}$ = (.0913*68) + (.001067*68^2)

$E(t)_{Low2060}$ = 11.142 inches (or ~11 inches)

$E(t)_{LowCompact2060} = E(t)_{Low2060} - E(t)_{Low2010}$

$E(t)_{LowCompact2060}$ = (11 inches) – (2 inches)

$E(t)_{LowCompact2060}$ = 9 inches

For the **high sea level rise scenario**, the calculated sea level rise between 1992 and 2010 ($E(t)_{Low2010}$) using the quadratic sea level rise curve is approximately 3 inches:

$E(t)_{High2010}$ = (.0913*(2010-1992)) + (.004449*(2010-1992)^2)

$E(t)_{High2010}$ = (.0913*18) + (.004449*18^2)

$E(t)_{High2010}$ = 3.08 inches (or ~3 inches)

To obtain the Southeast Florida Regional Climate Change Compact (2011) high sea level rise value for 2030 from a 2010 baseline ($E(t)_{LowCompact2030}$), the assumed sea level rise of 3 inches between 1992 and 2010 is then subtracted from the quadratic sea level rise calculated for the period between 1992 and 2030 ($E(t)_{Low2030}$):

$E(t)_{High2030}$ = (.0913*(2030-1992)) + (.004449*(2030-1992)^2)

$E(t)_{High2030}$ = (.0913*38) + (.004449*38^2)

$E(t)_{High2030}$ = 9.89 inches (or ~10 inches)

$E(t)_{HighCompact2030} = E(t)_{High2030} - E(t)_{High2010}$

$E(t)_{HighCompact2030}$ = (10 inches) – (3 inches)

$E(t)_{HighCompact2030}$ = 7 inches

To obtain the Southeast Florida Regional Climate Change Compact (2011) high sea level rise value for 2060 from a 2010 baseline ($E(t)_{LowCompact2030}$), the assumed sea level rise of 3 inches between 1992 and 2010 is similarly subtracted from the quadratic sea level rise calculated for the period between 1992 and 2060 ($E(t)_{Low2060}$):

$E(t)_{High2060}$ = (.0913*(2060-1992)) + (.004449*(2060-1992)^2)

$E(t)_{High2060}$ = (.0913*68) + (.004449*68^2)

$E(t)_{High2060}$ = 26.78 inches (or ~27 inches)

$E(t)_{HighCompact2060} = E(t)_{High2060} - E(t)_{High2010}$

$E(t)_{HighCompact2060}$ = (27 inches) – (3 inches)

$E(t)_{HighCompact2060}$ = 24 inches

Data and Methods

The first step in developing the vulnerability assessment for Monroe County was compilation of existing geo-spatial and tabular datasets from available sources. The full list of original datasets is provided in Table 1.

Table 1: Dataset Inventory

Original Dataset Description	Original File Name	Source
Digital Elevation Model (Raster)	FLLIDAR_MOSAIC_FT.gdb	UF GeoPlan (2013a)
Digital Flood Insurance Rate Map (DFIRM) in the State of Florida (Polygon)	Dfirm_nfhl_feb15.gdb	UF GeoPlan (2015)
Property parcels (Polygon)	PARCEL_PUBLIC.shp	Monroe County Property Appraiser (MCPA)
Monroe County sections (Vector polygon)	SECPOLY.shp	MCPA
Aerial photography (MrSID imagery)	20-1 MrSID Compressions (Folder)	MCPA
Land cover and habitats (Polygon)	Land_Cover_Habitat.shp	Monroe County GIS
Road centerlines (Polyline)	ROADCENTER.shp	Monroe County Property Appraiser
FDOT roads (Polyline)	Original_Infrastructure_Layers.gdb	UF GeoPlan (2013b)
Critical facilities (Point)	Critical_Facilities.shp	Monroe County GIS
Parcels with county facilities (Polygon)	County_Buildings.shp	Monroe County GIS
Government buildings (Point)	gc_govbuild_feb13.shp	UF GeoPlan (2013c)
Correctional facilities (Point)	gc_correctional_feb13.shp	UF GeoPlan (2013d)
Law enforcement (Point)	gc_lawenforce_dec12.shp	UF GeoPlan (2013e)
Schools (Point)	gc_schools_may12.shp	UF GeoPlan (2012)
Water tanks (Point)	wTank.shp	Florida Keys Aqueduct Authority (FKAA)
Cathodic rectifiers (Point)	wCathodicRect.shp	FKAA
System valves (Point	wSystemValve.shp	FKAA
Control valves (Point)	wControlValve.shp	FKAA
Sampling stations (Point)	wSamplingStation.shp	FKAA
Test stations (Point)	wTestStation.shp	FKAA
Wastewater treatment plants (Point)	WWTP_LOCATIONS.shp	FKAA

SLAMM Land cover categories (Raster)	sfl_slm_lc_rd.tif	Florida Fish and Wildlife Conservation Commission (FWC)

<u>LIDAR Digital Elevation Model (DEM)</u>

In 2007-2008 the Florida Division of Emergency Management collected raw elevation point cloud data throughout southeast Florida using airborne LIDAR (light detection and ranging) technology. Original technical specifications for this LIDAR collection are described by FDEM (2009). Bare earth accuracy of the LIDAR point cloud was reported at +/- 0.6 feet at the 95% confidence level (FDEM 2009), or a root mean square error of 0.3 feet. Using this LIDAR point data, the University of Florida's GeoPlan Center (2013) constructed a ground surface digital elevation model (DEM; File Name = FLIDAR_MOSAIC_FT; see Table 1) at a horizontal cell size resolution of 5 meters (~16 feet). The vertical datum of the UF GeoPlan LIDAR DEM is in NAVD88 and the original projection is in Albers Equal Area Conic HARN.

To facilitate efficient use of the dataset for advanced geoprocessing operations needed to conduct the vulnerability assessment, the original UF GeoPlan LIDAR DEM was clipped to only contain the geography of the Florida Keys portion of Monroe County, as encompassing the island chain from Key Largo to Key West. This clipped DEM was named UF_LIDAR.

The presence of buildings and heavy vegetation cover poses inherent challenges in gathering raw ground elevation data using aerial LIDAR technology. For this reason, the UF GeoPlan Center (2013) DEM was originally processed to provide that buildings and other areas lacking ground return values were assigned a "null," or unknown, ground elevation. This technique of assigning null values to raster cells with non-ground LIDAR returns is a standard process for development of base DEM layers (Dehvari and Heck 2012).

Because assessment of potential flood vulnerability to buildings is a key goal of a sea level rise vulnerability assessment, it is necessary to apply geographical interpolation techniques that replace null values with a continuous estimate of ground elevations near and underneath structures. For this project we utilized Inverse Distance Weighting (IDW) to interpolate, or quantitatively estimate using known ground elevation data from adjacent areas, ground elevation values for all cells defined as "null" within the Florida Keys. The IDW method is a standard procedure used for such applications (Aguilar et al. 2010; Achilleos 2011).

The following workflow in ArcGIS10.1 was used to perform this interpolation:

1. **Raster to Point**. Input raster: UF_LIDAR; Output point feature: UF_LIDAR_Points. *Purpose: Convert raster grid cells to point features*

2. **Inverse Distance Weighting**. Input point features: UF_LIDAR_Points; Z Value Field: GridCode; Output raster: IDW_LIDAR; Output cell size: 5 meters; Power: 2; Search Radius Setting, Number of Points: 12.

Purpose: Interpolate point values to continuous DEM

3. **Clip Raster.** Input Raster: IDW_LIDAR; Output extent: SecPoly (Monroe County Sections); Use Input Feature for Clipping Geometry (checked); Output Raster Dataset: MC_LIDAR
Purpose: Restrict interpolated DEM coverage to the geography covered by Monroe County property records within the Florida Keys, thus reducing file size for geoprocessing operations

The interpolated LIDAR DEM for Monroe County (File Name = MC_LIDAR) as referenced to NAVD88 was used as the basis for further geoprocessing to develop a DEM suitable for sea level rise and tidal flooding vulnerability assessments.

<u>Mean Higher High Water (MHHW) Surface</u>

Modeling of future sea level rise impacts is typically conducted using a local Mean Higher High Water (MHHW) tidal datum. The definition of MHHW is the average height of the highest high tide observed each day at a given location relative to an orthometric datum, usually NAVD88. Complex geomorphological, bathymetric, and climatological factors, particularly wind speed and direction, are known to produce significant differences in MHHW height across the Florida Keys (Lee and Smith 2002). For example, the height of MHHW differs by 1.5 feet across the entire Florida Keys island chain, and can differ as much as one foot between the Atlantic Ocean and Florida Bay sides of Key Largo and other areas of the upper keys (Yang et al. 2012).

Due to these known datum issues, the Southeast Florida Regional Climate Change Compact (2012) has recommended that all sea level rise analyses conducted in southeast Florida perform regional transformations of the MHHW surface as compared to NAVD88. The National Oceanic and Atmospheric Administration (NOAA) has developed a free software program called VDatum for the specific purpose of transforming DEM values between different orthometric and tidal datums (NOAA 2014). The VDatum transformations are based upon comparative analysis of tide heights relative to orthometric datums across numerous permanent and temporary tide gauges across the coastal U.S. The technical basis for the most recent VDatum transformations in the Florida Keys is described in detail by Yang et al. (2012).

Following the recommendations of the Southeast Florida Regional Climate Change Compact (2012), we developed a VDatum transformation surface from NAVD88 to MHHW for the entire Florida Keys portion of Monroe County. This surface was developed by first transforming all raster cells within the interpolated LIDAR DEM (File Name = MC_LIDAR) into a value of zero, which has the function of making all cells correspond to the NAVD88 datum (File Name = MASKNAVD). The MASKNAVD file was then loaded into VDatum to perform a transformation surface from NAVD88 to MHHW (Figure 1). This transformation surface file was renamed KEYSVDTM.

The geography of the VDatum transformation from NAVD88 to MHHW is based upon tidal readings and does not extend to upland areas where tidal incursion is infrequent. Because the purpose of a sea level rise vulnerability assessment is to project into future flood risk into areas that may not currently experience regular tidal flooding, it was necessary to interpolate the MHHW elevation surface (KEYSVDTM) onto all upland areas area covered by the vulnerability assessment.

Following the technical procedures outlined by the Southeast Florida Regional Climate Change Compact (2012), we applied an IDW procedure similar to the one described above for the revised LIDAR DEM to develop an interpolated MHHW surface relative to NAVD88 across the Florida Keys portion of Monroe County.

1. **Raster to Point**. Input raster: KEYSVDTM; Output point feature: KEYSVDTM.
   Purpose: Convert raster grid cells to point features

2. **Inverse Distance Weighting**. Input point features: KEYSVDTM; Z Value Field: GridCode; Output raster: IDW_VDTM; Output cell size: 5 meters; Power: 2; Search Radius Setting, Number of Points: 12.
   Purpose: Interpolate point values to continuous correction surface

3. **Clip Raster.** Input Raster: IDW_VDTM; Output extent: SecPoly (Monroe County Sections); Use Input Feature for Clipping Geometry (checked); Output Raster Dataset: MC_VDATUM

A final GIS processing step was then employed to adjust the MC_LIDAR DEM from the NAVD88 orthometric datum to a local tidal datum based upon MHHW. This step utilized the Raster Calculator function in ArcGIS10.1 to add the NAVD to MHHW correction surface to the Monroe County LIDAR DEM (Raster Calculator script: “MC_LIDAR” + “MC_VDATUM”). This final MHHW-based LIDAR DEM (File name = MHHW_DEM), as shown in Figures 2a-2f, provides the basis for the sea level rise flooding and inundation vulnerability assessments described throughout the remainder of this document.

Figure 1: NOAA VDatum 3.4 Software NAVD88 to MHHW Transformation

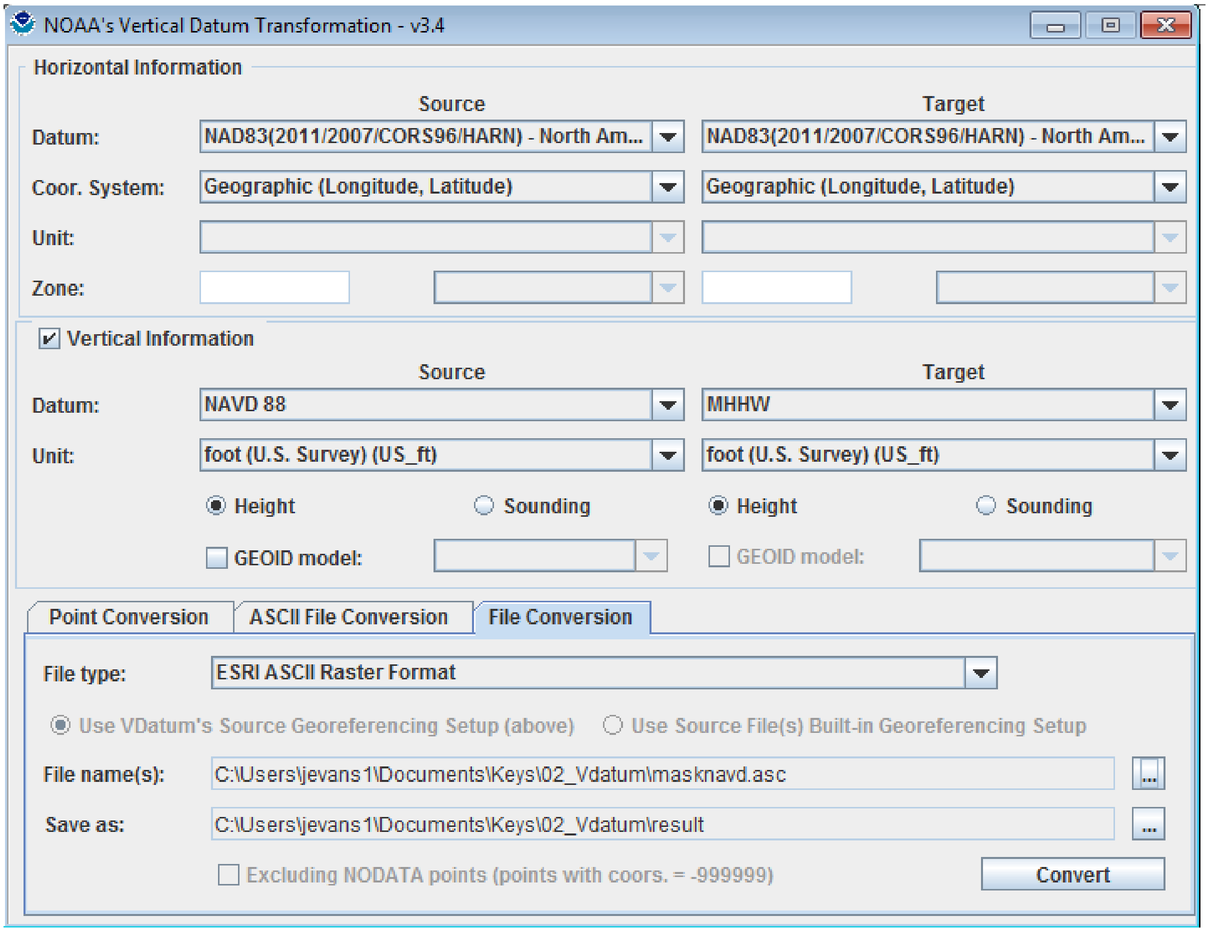


Figure 2a. MHHW Digital Elevation Model, Northern and Central Key Largo

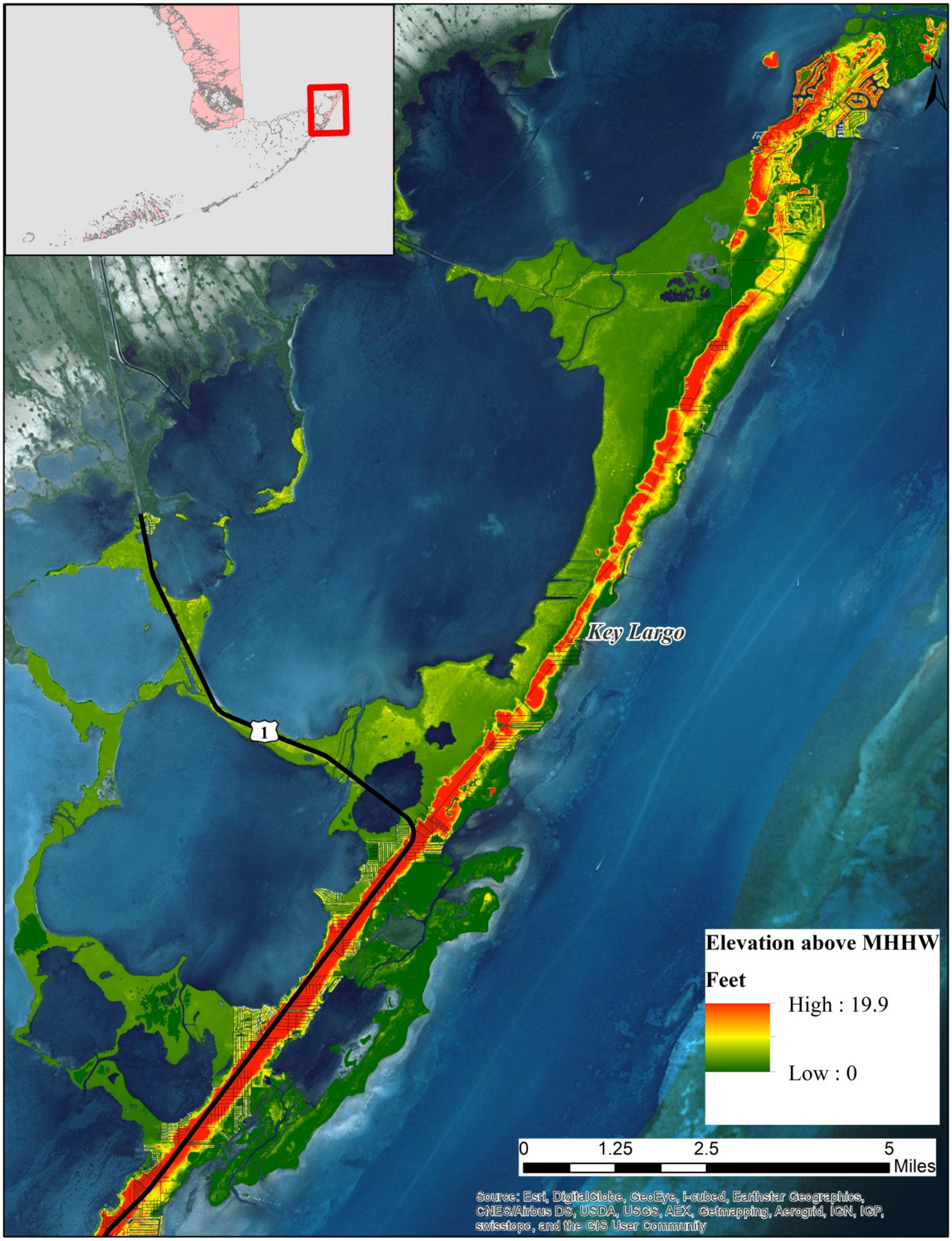


Figure 2b. MHHW Digital Elevation Model, Central Key Largo to Upper Matecumbe Key

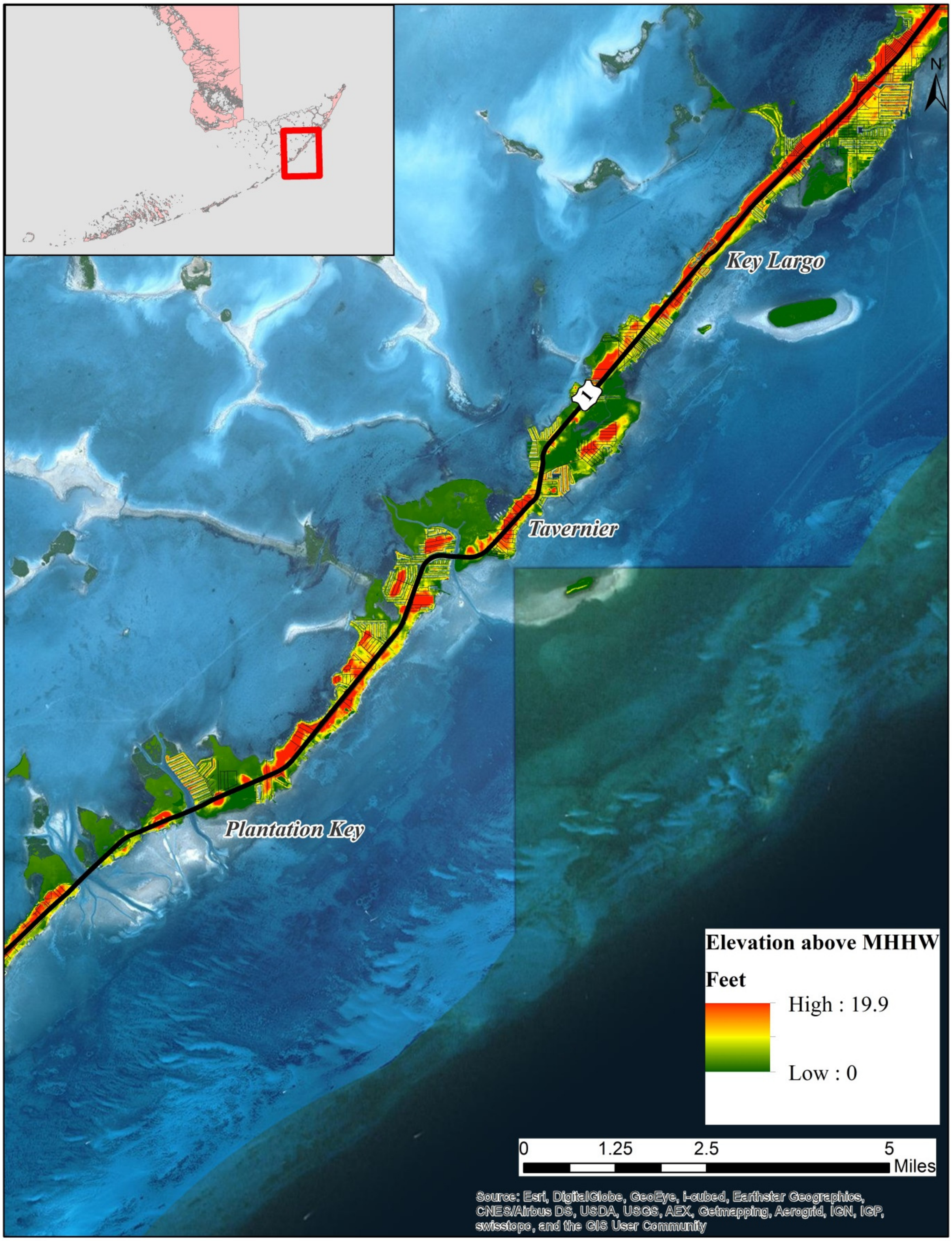


Figure 2c. MHHW Digital Elevation Model, Upper Matecumbe Key to Long Key

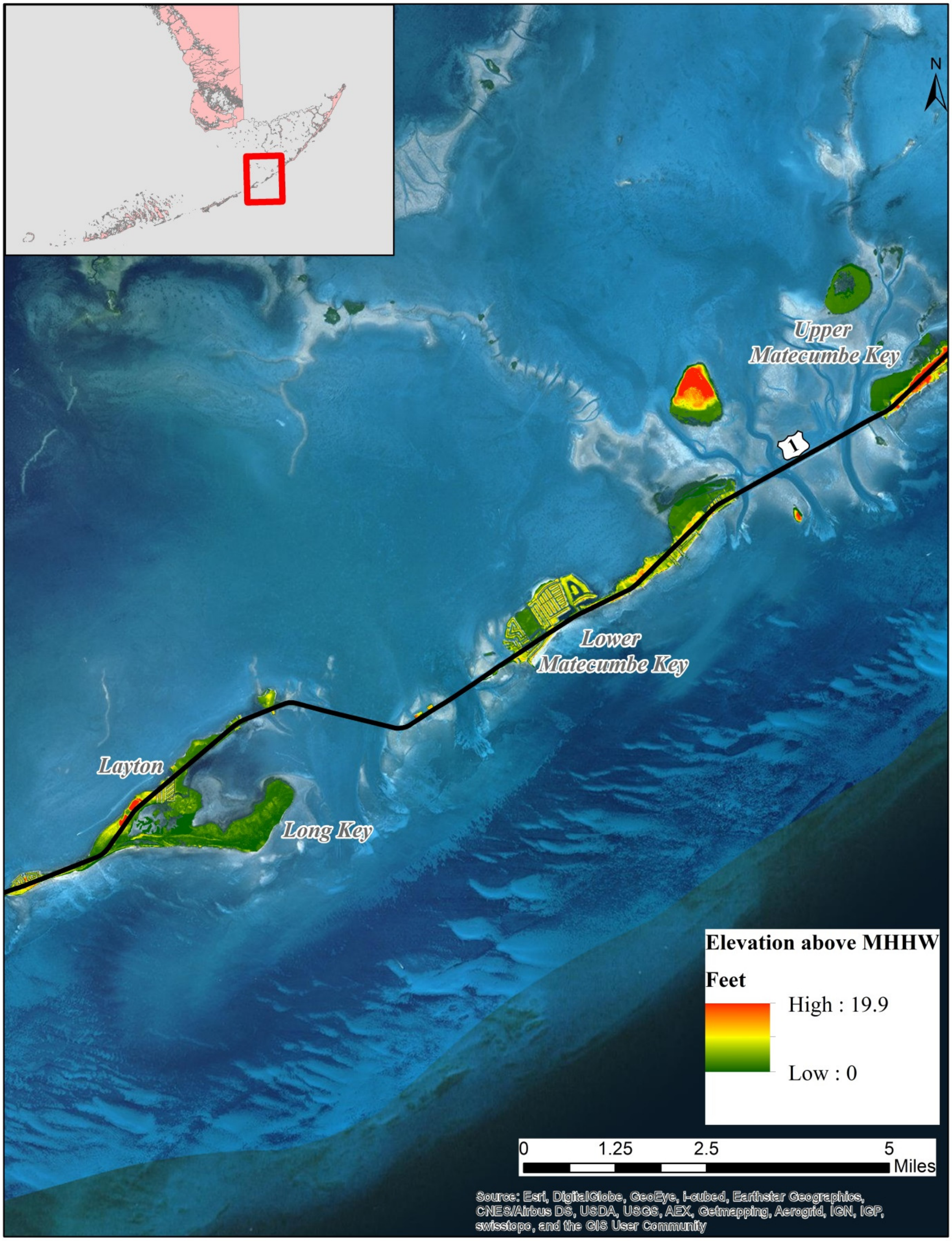


Figure 2d. MHHW Digital Elevation Model, Duck Key to Vaca Key

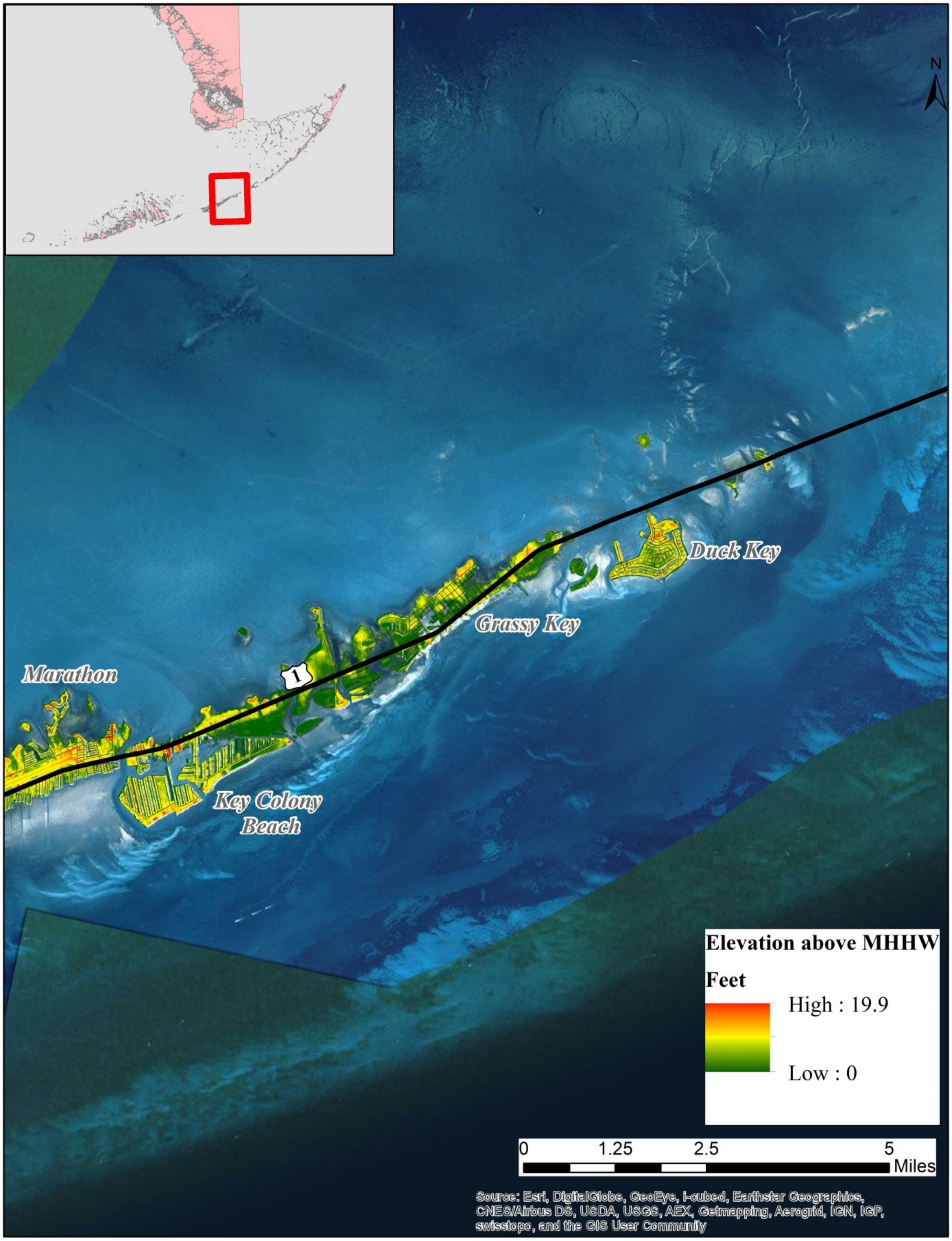


Figure 2e. MHHW Digital Elevation Model, Vaca Key to Bahia Honda Key

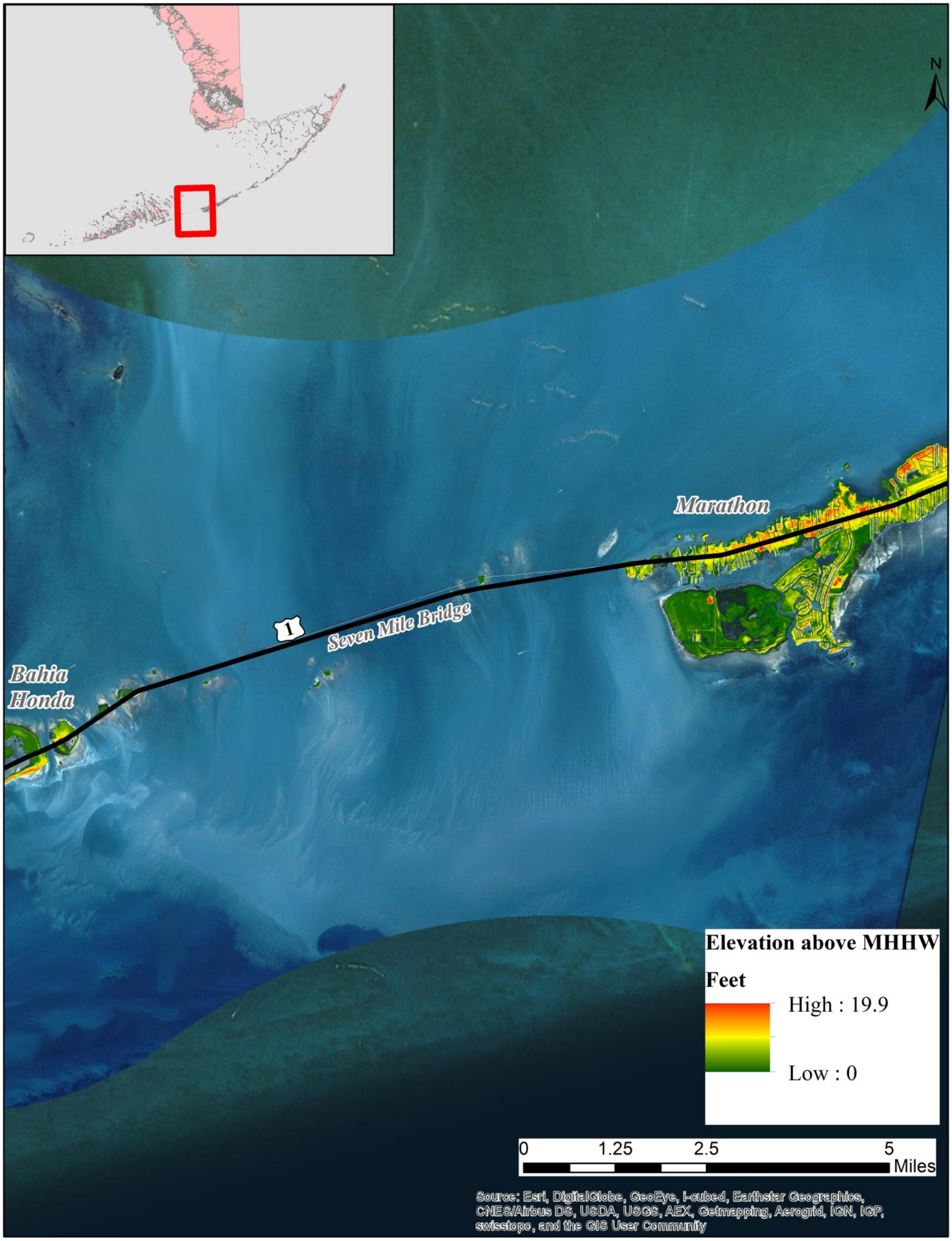


Figure 2f. MHHW Digital Elevation Model, Bahia Honday Key to Summerland Key

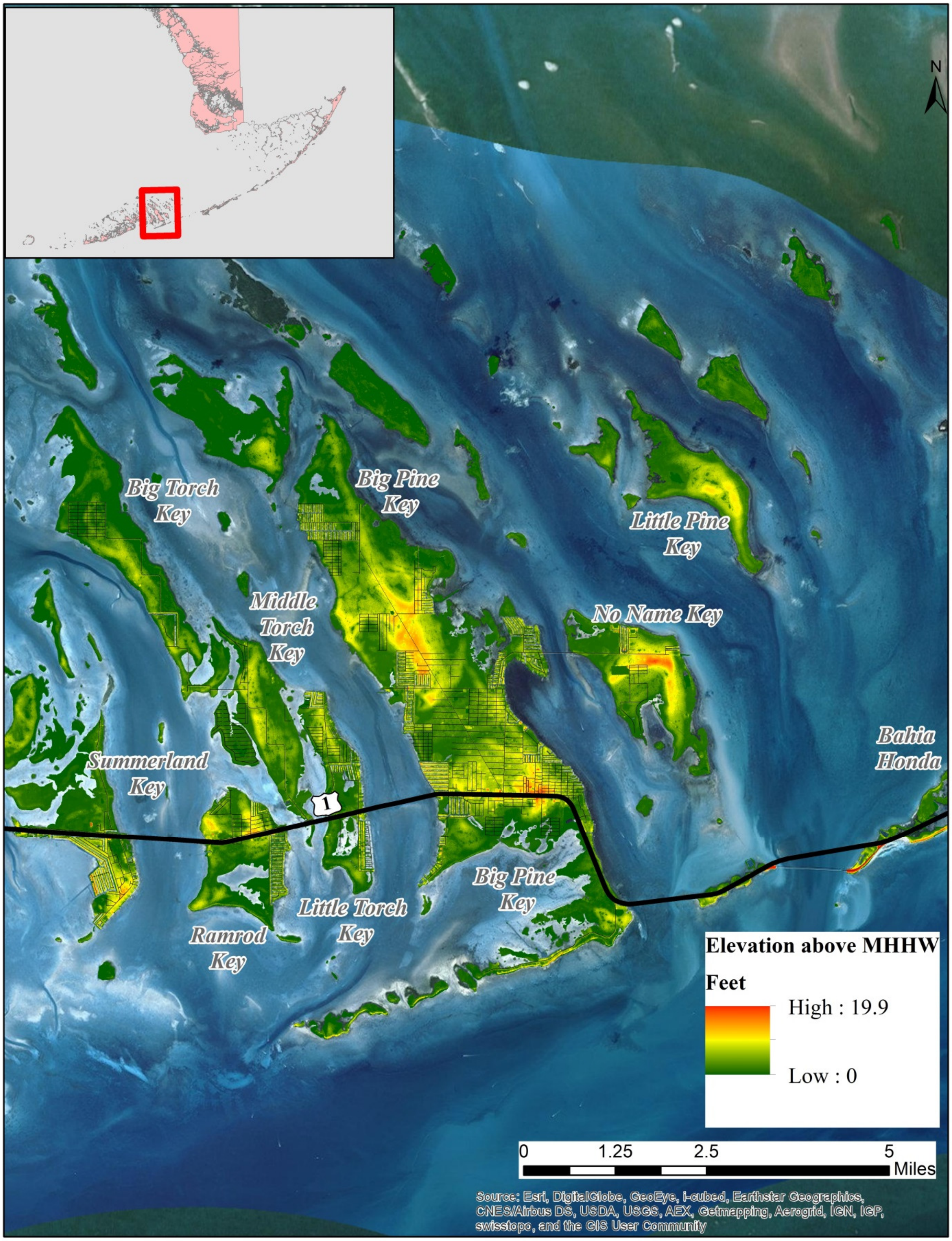


Figure 2g. MHHW Digital Elevation Model, Cudjoe Key to Big Coppitt Key

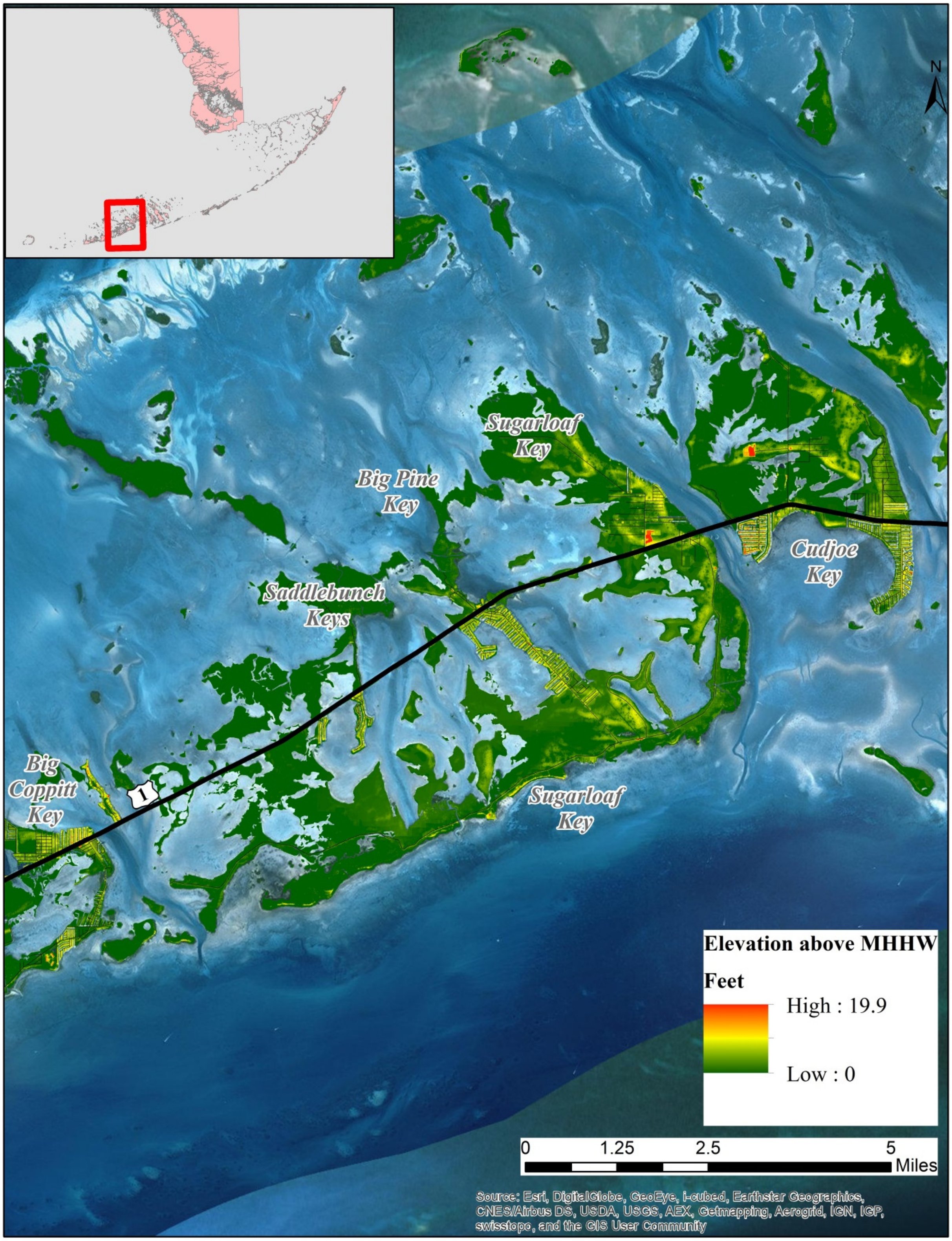
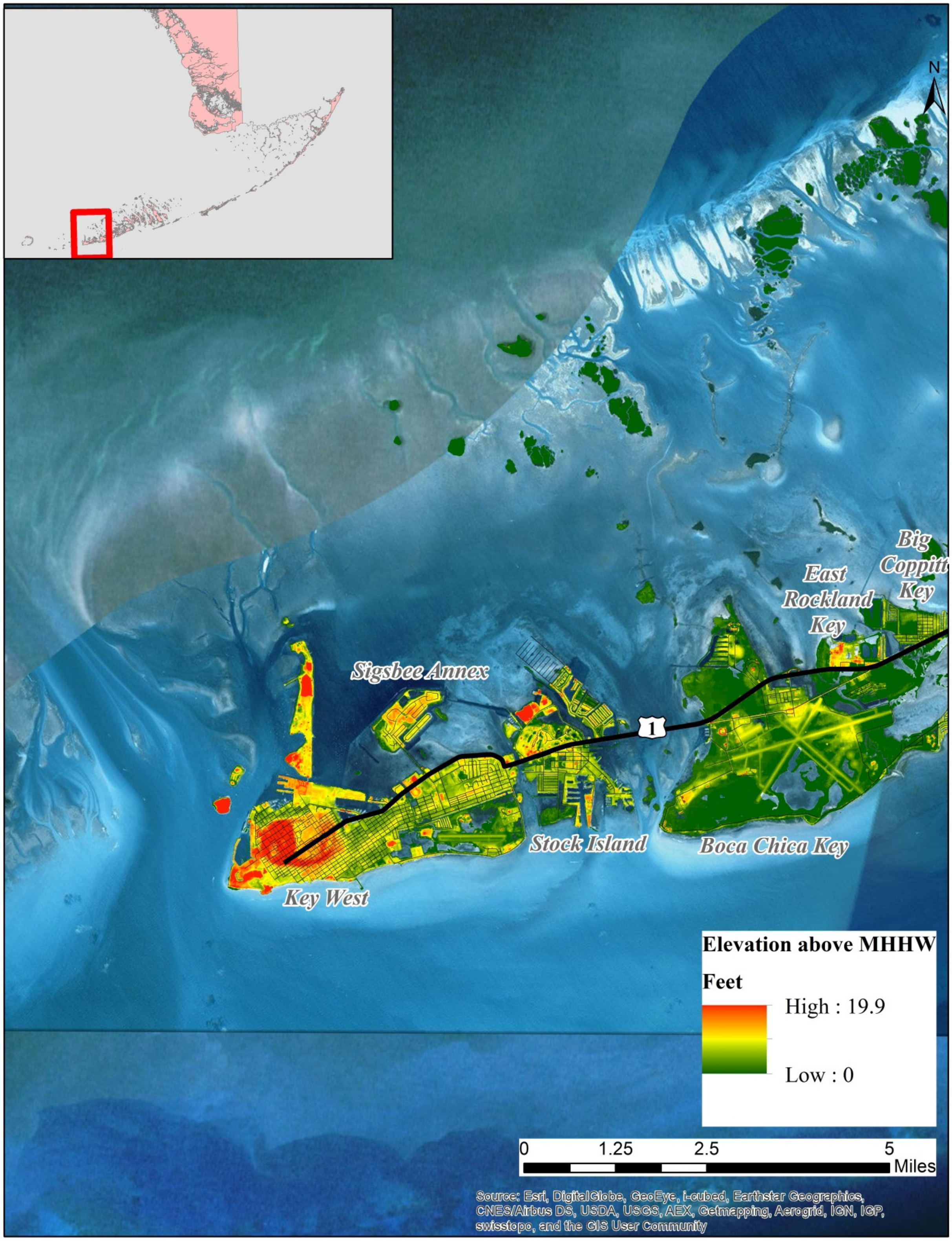


Figure 2h. MHHW Digital Elevation Model, Big Coppitt Key to Key West



Tidal Flooding Thresholds for Monroe County

NOAA maintains two permanent tide gauge installations in Monroe County. The Key West tide gauge, located near the Truman White House on the northwestern coast of Key West, has been in operation since 1913 (Figure 3). The Vaca Key tide gauge (Figure 4), located in Marathon on the Florida Bay side of Vaca Key, has been in operation since 1971. NOAA reports that the long-term linear trend of sea level rise over the full Key West tide gauge record amounts to approximately 0.77 feet, or 9.24 inches, across a 100-year period. The sea level rise trend across the shorter Vaca Key tide gauge record amounts to 1.10 feet, or 13.2 inches, if extrapolated across a similar 100-year period.

A recent report by NOAA (2014) describes how sea level rise is already resulting in increased occurrences of "minor" tidal flooding of streets, yards, and low-lying areas throughout the U.S. Such minor flooding events are often referred to as "nuisance floods," as they are typically associated with little or no permanent damage to human assets and recede quickly with the outgoing tide. Typical consequences of nuisance flooding are temporarily slowed or stopped traffic flow through low-lying roads and damage to saltwater intolerant landscaping plants in low-lying yards. However, such tidal flood events can also lead to temporary, but sometimes significant, loss of stormwater drainage potential. For this reason, co-occurrence of heavy rainfall events with a nuisance tidal flood can also result in more severe and potentially damaging floods.

Such high tides may occur unpredictably due to storm or high wind conditions, or more predictably due to the confluence of lunar and solar gravitational forces that increase tidal magnitude. The highest tidal amplitudes of each month, often referred to as "spring tides," generally occur on and near the days of full moons and new moons.[1] The colloquial term of "king tide" is often used to describe the highest spring tides observed each year. In the Florida Keys, king tides most often occur during spring tides in the months of September, October, and November, although king tides may also occasionally be observed in other months due to astronomical and climatological factors.

In Monroe County, the nuisance tidal flooding threshold is defined as a tide that reaches 1.08 feet above MHHW (NOAA 2014). To assess nuisance flooding occurrences in Monroe County, two five-year records of daily high tides, one covering January 1, 1980 – December 31, 1984 and the other covering January 1, 2010 – December 31, 2014, were obtained for the Key West tide gauge (NOAA 2015a). This record shows that only two tides exceeded nuisance flood conditions during the period of 1980-1984, or an average annual occurrence of less than once per year (0.4 per year). The relative rarity of nuisance flood events from 1980-1984 is highlighted by the fact

[1] We note that the term spring tide does not relate to the season of spring, but instead is derived from an image of a tide that "springs forth" (National Ocean Service 2014).

that both of the recorded events occurred within the span of three days: 1) 1.14’ above MHHW tide on November 14, 1981; and 2) 1.22’ above MHHW on November 16, 1981.

The 2010-2014 period, by contrast, shows a total of twelve nuisance flood events, or an average of 2.4 events per year. This includes three events in 2010 (1.08’ above MMHW on September 6; 1.12’ above MHHW on October 8; and 1.25 above MHHW on October 10), five events in 2012 (1.17’ above MHHW on October 17; 1.24’ above MHHW on October 30; 1.16’ above MHHW on November 14; and 1.08’ above MHHW on November 15), two events in 2013 (1.14’ above MHHW on December 3 and 1.09’ above MHHW on December 4), and three events in 2014 (1.15’ above MHHW on October 11; 1.28’ above MHHW on November 24; and 1.14’ above MHHW on November 25).

Using this recent and historic tide gauge assessment, we applied two tidal flood exposure thresholds for assessing infrastructure vulnerability to sea level rise in the Monroe County: 1) nuisance flooding, which may be expected to occur at elevations less than or equal to 1.08 feet above MHHW; and 2) inundation flooding, which occurs at elevations less than MHHW. These values are summarized by each sea level rise scenario in Table 2.

The highest tidal water height across the full Key West tide gauge record is 3.13’ above MHHW, which occurred on October 24, 2005 as a storm surge associated with Hurricane Wilma. The Vaca Key tide gauge recorded a significantly higher storm surge of 5.79’ above MHHW during Hurricane Wilma; this storm surge is also the highest observed over the record of the Vaca Key tide gauge.

Because sea level rise can be expected to correspondingly raise the flood levels for storm surges such as those experienced with Hurricane Wilma, there was interest among Monroe County officials and stakeholder in developing analyses and visualizations of a “Wilma-sized” extreme event under the two future sea level rise scenarios. Rounding up from the observed height of the Hurricane Wilma surge at Vaca Key, this extreme event was uniformly defined as 6 feet above MHHW across the Florida Keys for the purpose of this analysis. More specific analyses of exposure to enhanced surge height, as based upon currently defined FEMA flood zones (UF GeoPlan 2015), were undertaken for structures with Elevation Certificate information.

Table 2: Monroe County Tidal Flooding Thresholds. Values based upon the Southeast Florida Regional Climate Change Compact (2011) "Low" and "High" sea level rise projections. All elevation values are as feet above MHHW, as referenced to the 1983-2001 National Tidal Datum Epoch. All areas with elevations less than the listed value are assumed to have vulnerability to the respective flooding category under each sea level rise scenario.

Flood threshold	Sea Level Rise			
	2030 – Low (3 inches)	**2030 – High (7 inches)**	**2060 – Low (9 inches)**	**2060 – High (24 inches)**
Inundation	*0.42'*	*0.83'*	*0.92'*	*2.25'*
Nuisance	*1.50'*	*1.91'*	*2.00'*	*3.33'*
Extreme	*6.42'*	*6.83'*	*6.92'*	*8.25'*

Figure 3: NOAA Tide Gauge at Key West, FL. Image obtained from http://tidesandcurrents.noaa.gov/stationhome.html?id=8724580, accessed November 19, 2015.

Figure 4: NOAA Tide Gauge at Vaca Key, FL. Image obtained from http://tidesandcurrents.noaa.gov/stationphotos.html?id=8723970#, accessed November 19, 2015.

Building Footprints

A building footprint layer is a GIS polygon file, typically in shapefile format, that outlines the land area occupied by buildings. Early in the project period it was learned that Monroe County, like many communities in Florida, currently lacks a GIS building footprint layer. Due to this dataset limitation, a previous sea level rise assessment for Monroe County, as conducted by the Southeast Florida Regional Climate Change Compact (2012), utilized parcel-scale geographies to conduct analyses of future flood risk. However, as noted in this previous study (Southeast Florida Regional Climate Change Compact 2012), parcel-scale analyses of flood vulnerability have an important disadvantage: they often do not provide information directly relevant to assessing flood risk to buildings located within the parcel. This is because parcels can contain large percentages of property that are naturally more low-lying than the ground on which a building is located. Furthermore, buildings often are constructed on ground that has been significantly elevated above natural grade through the deposit of fill.

Development of a building footprint layer, which can be manually drawn from high quality aerial photographs or in some cases through more automated methods that provide indication of the land area occupied by buildings, is a common methodology used to improve the geographic precision of flood vulnerability assessments within the built environment. For this project, we developed a building footprints layer that includes the visible rooftop outlines of structures that various sources (see Table 1) have listed as public and critical infrastructure located within Monroe County. This critical infrastructure includes schools, law enforcement, fire stations, other government buildings, electric and water utilities, hospitals, and disaster response staging areas.

To develop this building footprint layer, we used a query function to select parcels from the original Monroe County Property Appraiser dataset (PARCEL_PUBLIC.shp) that contained the point, address, or polygon locations of public and critical infrastructure (as found in Critical_Facilities.shp, County_Buildings.shp, gc_govbuild_feb13.shp, gc_correctional_feb13.shp, and gc_lawenforce_dec12.shp). These infrastructure parcels were then exported into a new file (INFRASTRUCTURE_PARCELS.shp). High resolution 2012 aerial MrSID orthophotography supplied by the Monroe County Property Appraiser was then used as the basis for manual digitization of all building footprints seen within the boundaries of each parcel in the INFRASTRUCTURE_PARCELS.shp file. A total of 1,316 buildings and structures in Monroe County, including 386 on parcels that the Property Appraiser dataset identifies as owned by Monroe County, were digitized into building footprints through this procedure. The building footprint digitization of the Murray E. Nelson Government Center in Key Largo is shown as an example in Figure 5. The building footprints layer for Monroe County was named MONROECOUNTY_FOOTPRINTS.shp.

Figure 5: Building Footprint of the Murray E. Nelson Government Center. Building located at 102050 Overseas Highway, Key Largo. Building footprint overlaid onto parcel boundary from the Monroe County Property Appraiser and aerial photography.

Flood Probabilities from LIDAR Elevations

The Southeast Florida Regional Climate Change Compact (2012) presented a methodology that takes into account the statistical uncertainties in both the aerial LIDAR and MHHW VDatum transformation surface to produce two categories of future flood risk from sea level rise: 1) Possible, which is defined as a 25% - 75% probability of flooding under a given sea level rise scenario; and 2) Likely, which is defined as a greater than 75% probability of flooding under a given sea level rise scenario.

This is calculated based upon standard Z-score methodology:

$$Standard\ Z - score = \frac{Flood\ threshold\ (2010\ MHHW) - Land\ Elevation\ (LIDAR)}{RMSE_{(Total)}}$$; where

$$RMSE_{(Total)} = \sqrt{RMSE^2_{(LIDAR)} + RMSE^2_{(VDatum)}}$$ = 0.46, as defined by

$RMSE_{(LIDAR)}$ = 0.3 (FDEM 2009) and $RMSE_{(VDatum)}$ = 0.35 (NOAA 2014)

A standard Z-score for a LIDAR elevation with 25% probability of being exceeded under a given flood threshold is equal to -0.67, whereas a Z-score for a LIDAR elevation with a 75% exceedance probability is 0.67. Rearrangement of terms gives the following equation for solving LIDAR elevations that correspond to each Z-score probability term:

$$Land\ elevation\ (LIDAR) = \ Flood\ threshold\ (2010\ MHHW) - (RMSE_{(Total)} * Z - score_p)$$

As shown in Table 3, we applied this methodology to define a series of LIDAR elevation thresholds for flood risk in Monroe County at the 2030 and 2060 sea level rise scenarios that takes into the account the uncertainties in both the LIDAR DEM and VDatum transformation.

Table 3: LIDAR Elevation Ranges by Flood Threshold and Sea Level Rise Scenario. All values are in feet above MHHW, as referenced to the 1983-2001 National Tidal Datum Epoch.

Flood Threshold	Sea Level Rise Scenario			
	2030 – Low (3 inches)	**2030 – High (7 inches)**	**2060 – Low (9 inches)**	**2060 – High (24 inches)**
Likely Inundation	*< 0.11’*	*< 0.44’*	*< 0.69’*	*< 1.84’*
Possible Inundation	*0.11’ – 0.73’*	*0.44’ – 1.06’*	*0.69’ – 1.31’*	*1.94’ – 2.56’*
Likely Nuisance	*< 1.19’*	*< 1.52’*	*< 1.77’*	*< 3.02’*
Possible Nuisance	*1.19’ – 1.81’*	*1.52’ –2.14’*	*1.77’ – 2.39’*	*3.02’ – 3.64’*
Likely Extreme	*< 6.11’*	*< 6.44’*	*< 6.69’*	*< 7.94’*
Possible Extreme	*6.11’ – 6.73’*	*6.44’ – 7.06’*	*6.69’ – 7.31’*	*7.94’ – 8.56’*

Infrastructure that falls into the “Likely Inundation” category shows high risk of complete loss under the given sea level rise scenario unless significant adaptation actions are taken. Infrastructure that falls into the “Possible Inundation” category can may also have high risk of future flooding with the possibility of complete loss under the given sea level rise scenario. Although the bounds of uncertainty prevent a confident conclusion that the lands containing infrastructure in the “Possible Inundation” category will be inundated under a given sea level rise scenario, the risk is high enough to imply a need for additional site investigation and higher precision elevation surveys to better resolve the timing and extent of risks.

Infrastructure in the “Likely Nuisance” category shows very high risk of exposure to annual nuisance flooding events under the given sea level rise scenario. While tolerance for such annual nuisance flooding exposure is dependent on infrastructure type, identification in this category indicates a high priority to further assess the vulnerability of the infrastructure through site investigations and/or careful tracking of conditions at the site during future king tide events. Although there is less confidence in the future nuisance flood vulnerability of infrastructure in the “Possible Nuisance” category, near-term employment of additional site investigations to better resolve elevations and careful tracking of conditions at these sites during future king tide events are warranted.

Infrastructure in the “Likely Extreme” category shows very high risk of exposure to flooding from a “Wilma-sized” event under the given sea level rise category. The “Possible Extreme” category indicates that there is some concern that the given infrastructure could be exposed to flooding during an extreme event. The primary importance of these categories is that sea level rise can be expected to open up new flood risks for infrastructure that historically would have been undamaged by a storm surge of Hurricane Wilma’s size and intensity. Although detailed site investigations and consultation with applicable FEMA floodplain designations are recommended to better resolve the extreme event flood risks of all critical infrastructure within defined special flood hazard areas, near-term prioritization of such investigations is recommended for critical infrastructure with LIDAR elevation estimates below 6.89’ above MHHW (i.e., the threshold for Possible Extreme event flood risk under 7” of sea level rise, or the maximum sea level rise expected by 2030).

Flood Risk Assessment for Public Buildings and Critical Infrastructure

Using ArcGIS10.1, we employed a Zonal Statistics procedure to define four ground elevation values within the bounds of all building footprint polygons for identified public facilities and critical infrastructure within Monroe County: 1) maximum elevation, as referenced to MHHW (source DEM data, MHHW_DEM); 2) minimum elevation, as referenced to MHHW (source DEM data, MHHW_DEM); 3) maximum elevation, as referenced to NAVD88 (source DEM data, MC_LIDAR); and 4) minimum elevation, as referenced to NAVD88. The maximum elevation value, whether using MHHW or NAVD88, corresponds to the highest DEM cell value found within the bounds of the building footprint polygon. Similarly, the minimum elevation values correspond to the lowest DEM cell value found within the bounds of the building footprint polygon. For the sake of brevity, data tables for buildings included in this report only contain the maximum MHHW-based elevation obtained through the Zonal Statistics calculation.

A summary of structures owned by Monroe County that show a maximum MHHW-based ground elevation below the “Possible Nuisance” flooding threshold for the high 2060 sea level rise scenario, as defined by the Southeast Florida Climate Change Compact (2011), is given in Table 4. Flood risks for these building footprints are defined according to the highest risk category reached at the earliest date among the Inundation and Nuisance flood risk categories listed in Table 3. For example, a structure that shows a ground elevation of 0.80’ would be ranked under the “Possible Inundation” 2030 category for the high sea level scenario, as this category also implies all beneath it (i.e., “Likely Nuisance” and “Possible Nuisance”) in 2030. A structure that shows a ground elevation of 1.68’ would be ranked as “Possible Nuisance” by 2030 under the high sea level rise scenario. Although the category of “Likely Inundation” by 2060 also applies, the categorization scheme indicates that a more near-term possibility of nuisance flooding has been identified.

It should also be reiterated that the ground elevation methodology used to develop the flood vulnerability results in Table 4 does not contain any information regarding the finished first floor elevation of the individual structures. Many buildings in Monroe County are built on foundations that have been elevated through fill or other materials to be higher than the surrounding grade, or are elevated well above grade through piling, pier, or stilt construction to minimize the exposure of the structure to storm surge flooding. Therefore, it must be stressed that assessments of tidal flood damage risk to structures cannot be confidently projected through the results in Table 4 alone. But even for structures elevated above grade, the prospects of future tidal flooding beneath the structure and/or on access roads leading to the structure poses a clear set of concerns, including the usability of floor space at grade, vehicle accessibility, and maintenance of electrical equipment serving the structure.

Buildings in this list that show 2030 tidal flood risk are clear candidates for enhanced monitoring to detect potential access and structural issues associated with increased tidal flooding exposure, as well as development of site-specific elevation data for finished first floors and sensitive building equipment. Adaptation decisions will be highly specific to each structure and include considerations such as condition and age of building, how critical the building is to County operations, and the “true” vulnerability of the structure to tidal flooding exposure once finished floor elevations and other site-specific information is characterized.

Table 4: **LIDAR-Based Flood Risk Assessment for Monroe County Buildings**. The list is ordered from lowest to highest MHHW elevation, as determined by the maximum LIDAR DEM value within each building footprint. Includes buildings owned by Monroe County, the Monroe County Sherriff's Office, and the Monroe County School Board with ground elevations that show inundation or tidal flooding risk under 2030 or 2060 sea level rise scenarios. Duplicate facility names indicate different buildings within a single government-owned parcel or infrastructure complex.

FACILITY NAME	ADDRESS	FT ABOVE MHHW	TIDAL FLOOD RISK, HIGH SEA LEVEL RISE SCENARIO	TIDAL FLOOD RISK, LOW SEA LEVEL RISE SCENARIO
TOWER 31 CRAIN ST	TOWER 31 CRAIN ST	1.04	Possible Inundation, 2030	Likely Nuisance, 2030
HARRY HARRIS OCEAN PARK	DOVE CREEK	1.11	Likely Nuisance, 2030	Likely Nuisance, 2030
MURRAY NELSON GOVERNMENT COMPLEX	102050 OVERSEAS HWY	1.17	Likely Nuisance, 2030	Likely Nuisance, 2030
SUGARLOAF SCHOOL	255 CRANE BLVD	1.24	Likely Nuisance, 2030	Possible Nuisance, 2030
310 AVENUE B	310 AVENUE B	1.26	Likely Nuisance, 2030	Possible Nuisance, 2030
BERNSTEIN PARK	6751 5TH ST	1.33	Likely Nuisance, 2030	Possible Nuisance, 2030
320 AVENUE B	320 AVENUE B	1.42	Likely Nuisance, 2030	Possible Nuisance, 2030
SALT PONDS BUNKER AREA	SOUTH OF LINDA AVE	1.46	Likely Nuisance, 2030	Possible Nuisance, 2030
AIR CARGO AMERICA/FEDERAL EXPRESS	3491 S ROOSEVELT BLVD	1.54	Possible Nuisance, 2030	Possible Nuisance, 2030
DRIVE-IN THEATER	5030 5TH AVE	1.56	Possible Nuisance, 2030	Possible Nuisance, 2030
BERNSTEIN PARK	6751 5TH ST	1.57	Possible Nuisance, 2030	Possible Nuisance, 2030
POINCIANA ELEMENTARY SCHOOL	1212 14TH ST	1.65	Possible Nuisance, 2030	Possible Nuisance, 2030
MURRAY NELSON GOVERNMENT COMPLEX	102050 OVERSEAS HWY	1.68	Possible Nuisance, 2030	Possible Nuisance, 2030
330 AVENUE B	330 AVENUE B	1.77	Possible Nuisance, 2030	Possible Nuisance, 2030
MURRAY NELSON GOVERNMENT COMPLEX	102050 OVERSEAS HWY	1.84	Possible Nuisance, 2030	Possible Nuisance, 2060
KEY WEST INTERNATIONAL AIRPORT	3491 S ROOSEVELT BLVD	1.88	Possible Nuisance, 2030	Possible Nuisance, 2060
KEY WEST INTERNATIONAL AIRPORT	3491 S ROOSEVELT BLVD	1.88	Possible Nuisance, 2030	Possible Nuisance, 2060
KEY WEST INTERNATIONAL AIRPORT	3501 S ROOSEVELT BLVD	1.88	Possible Nuisance, 2030	Possible Nuisance, 2060
OVERSEAS HWY	OVERSEAS HWY	1.88	Possible Nuisance, 2030	Possible Nuisance, 2060
340 AVENUE B	340 AVENUE B	1.92	Possible Nuisance, 2030	Possible Nuisance, 2060
POINCIANA ELEMENTARY SCHOOL	1212 14TH ST	1.99	Possible Nuisance, 2030	Possible Nuisance, 2060

KEY WEST INTERNATIONAL AIRPORT	3491 S ROOSEVELT BLVD	2.05	Possible Nuisance, 2030	Possible Nuisance, 2060
DRIVE-IN THEATER	5030 5TH AVE	2.06	Possible Nuisance, 2030	Possible Nuisance, 2060
KEY WEST HIGH SCHOOL	2100 FLAGLER AVE	2.09	Possible Nuisance, 2030	Possible Nuisance, 2060
31009 ATLANTIS DR	31009 ATLANTIS DR	2.10	Possible Nuisance, 2030	Possible Nuisance, 2060
ANIMAL SHELTER OFFICE	5427 COLLEGE RD	2.18	Possible Inundation, 2060	Possible Nuisance, 2060
OVERSEAS HWY	OVERSEAS HWY	2.18	Possible Inundation, 2060	Possible Nuisance, 2060
SALT PONDS BUNKER AREA	PT OF SALT PONDS SOUTH OF LINDA AVE	2.21	Possible Inundation, 2060	Possible Nuisance, 2060
HORACE O'BRYANT MIDDLE SCHOOL	1105 LEON ST	2.21	Possible Inundation, 2060	Possible Nuisance, 2060
KEY WEST INTERNATIONAL AIRPORT	3491 S ROOSEVELT BLVD	2.21	Possible Inundation, 2060	Possible Nuisance, 2060
DRIVE-IN THEATER	5030 5TH AVE	2.22	Possible Inundation, 2060	Possible Nuisance, 2060
HEALTH CLINIC	3375 OVERSEAS HIGHWAY	2.23	Possible Inundation, 2060	Possible Nuisance, 2060
KEY WEST INTERNATIONAL AIRPORT	3491 S ROOSEVELT BLVD	2.23	Possible Inundation, 2060	Possible Nuisance, 2060
5948 PENINSULAR AVE	5948 PENINSULAR AVE	2.24	Possible Inundation, 2060	Possible Nuisance, 2060
KEY WEST INTERNATIONAL AIRPORT	3491 S ROOSEVELT BLVD	2.29	Possible Inundation, 2060	Possible Nuisance, 2060
DRIVE-IN THEATER	5030 5TH AVE	2.32	Possible Inundation, 2060	Possible Nuisance, 2060
DRIVE-IN THEATER	5030 5TH AVE	2.32	Possible Inundation, 2060	Possible Nuisance, 2060
31009 ATLANTIS DR	31009 ATLANTIS DR	2.35	Possible Inundation, 2060	Possible Nuisance, 2060
31009 ATLANTIS DR	31009 ATLANTIS DR	2.35	Possible Inundation, 2060	Possible Nuisance, 2060
DRIVE-IN THEATER	5030 5TH AVE	2.39	Possible Inundation, 2060	Possible Nuisance, 2060
DRIVE-IN THEATER	5030 5TH AVE	2.39	Possible Inundation, 2060	Possible Nuisance, 2060
DRIVE-IN THEATER	5030 5TH AVE	2.40	Possible Inundation, 2060	N/A
DRIVE-IN THEATER	5030 5TH AVE	2.40	Possible Inundation, 2060	N/A
MARATHON AIRPORT EAST	10600 AVIATION BLVD	2.43	Possible Inundation, 2060	N/A
KEY WEST DRIVER LICENSE OFFICE	3491 S ROOSEVELT BLVD	2.45	Possible Inundation, 2060	N/A
DRIVE-IN THEATER	5030 5TH AVE	2.47	Possible Inundation, 2060	N/A
DRIVE-IN THEATER	5030 5TH AVE	2.48	Possible Inundation, 2060	N/A
DRIVE-IN THEATER	5030 5TH AVE	2.48	Possible Inundation, 2060	N/A
MARATHON AIRPORT EAST	10600 AVIATION BLVD	2.52	Possible Inundation, 2060	N/A

31009 ATLANTIS DR	31009 ATLANTIS DR	2.52	Possible Inundation, 2060	N/A
30150 SOUTH ST	30150 SOUTH ST	2.52	Possible Inundation, 2060	N/A
DRIVE-IN THEATER	5030 5TH AVE	2.56	Possible Inundation, 2060	N/A
DRIVE-IN THEATER	5030 5TH AVE	2.56	Possible Inundation, 2060	N/A
DRIVE-IN THEATER	5030 5TH AVE	2.56	Possible Inundation, 2060	N/A
DRIVE-IN THEATER	5030 5TH AVE	2.57	Likely Nuisance, 2060	N/A
BIG PINE VOLUNTEER FIRE STATION/EMS 13	390 KEY DEER BLVD	2.58	Likely Nuisance, 2060	N/A
31009 ATLANTIS DR	31009 ATLANTIS DR	2.60	Likely Nuisance, 2060	N/A
PUBLIC SERVICE BUILDING	30415 LYTTONS WAY	2.61	Likely Nuisance, 2060	N/A
OVERSEAS HWY	OVERSEAS HWY	2.62	Likely Nuisance, 2060	N/A
KEY WEST INTERNATIONAL AIRPORT	3501 S ROOSEVELT BLVD	2.62	Likely Nuisance, 2060	N/A
KEY WEST INTERNATIONAL AIRPORT	3501 S ROOSEVELT BLVD	2.63	Likely Nuisance, 2060	N/A
HORACE O'BRYANT MIDDLE SCHOOL	1105 LEON ST	2.63	Likely Nuisance, 2060	N/A
DRIVE-IN THEATER	5030 5TH AVE	2.64	Likely Nuisance, 2060	N/A
DRIVE-IN THEATER	5030 5TH AVE	2.64	Likely Nuisance, 2060	N/A
DRIVE-IN THEATER	5030 5TH AVE	2.65	Likely Nuisance, 2060	N/A
5530 3RD AVE	5530 3RD AVE	2.67	Likely Nuisance, 2060	N/A
MARATHON AIRPORT EAST	10600 AVIATION BLVD	2.69	Likely Nuisance, 2060	N/A
MARATHON AIRPORT EAST	10600 AVIATION BLVD	2.69	Likely Nuisance, 2060	N/A
31009 ATLANTIS DR	31009 ATLANTIS DR	2.69	Likely Nuisance, 2060	N/A
31009 ATLANTIS DR	31009 ATLANTIS DR	2.69	Likely Nuisance, 2060	N/A
PUBLIC SERVICE BUILDING	30415 LYTTONS WAY	2.69	Likely Nuisance, 2060	N/A
BIG PINE SCHOOL	MM 30.5 OVERSEAS HWY	2.72	Likely Nuisance, 2060	N/A
5530 3RD AVE	5530 3RD AVE	2.76	Likely Nuisance, 2060	N/A
31009 ATLANTIS DR	31009 ATLANTIS DR	2.77	Likely Nuisance, 2060	N/A
31009 ATLANTIS DR	31009 ATLANTIS DR	2.77	Likely Nuisance, 2060	N/A
DRIVE-IN THEATER	5030 5TH AVE	2.81	Likely Nuisance, 2060	N/A
BIG PINE VOLUNTEER FIRE STATION/EMS 13	390 KEY DEER BLVD	2.83	Likely Nuisance, 2060	N/A
BIG PINE VOLUNTEER FIRE STATION/EMS 13	390 KEY DEER BLVD	2.83	Likely Nuisance, 2060	N/A

31009 ATLANTIS DR	31009 ATLANTIS DR	2.85	Likely Nuisance, 2060	N/A
TEEN CENTER	3491 S ROOSEVELT BLVD	2.87	Likely Nuisance, 2060	N/A
KEY WEST INTERNATIONAL AIRPORT	3501 S ROOSEVELT BLVD	2.88	Likely Nuisance, 2060	N/A
5300 MACDONALD AVE	5300 MACDONALD AVE	2.89	Likely Nuisance, 2060	N/A
31009 ATLANTIS DR	31009 ATLANTIS DR	2.93	Likely Nuisance, 2060	N/A
MARATHON AIRPORT EAST	10600 AVIATION BLVD	2.94	Likely Nuisance, 2060	N/A
31009 ATLANTIS DR	31009 ATLANTIS DR	2.94	Likely Nuisance, 2060	N/A
MONROE COUNTY HOUSING CORPORATION	240 SOMBRERO BCH RD	2.95	Likely Nuisance, 2060	N/A
SCHOOL BOARD/TRANSPORTATION FACILITY	201 TRUMBO RD	3.00	Likely Nuisance, 2060	N/A
BIG PINE VOLUNTEER FIRE STATION/EMS 13	390 KEY DEER BLVD	3.00	Likely Nuisance, 2060	N/A
HARRY HARRIS COUNTY PARK	E BEACH RD	3.03	Possible Nuisance, 2060	N/A
CUDJOE REGIONAL WASTEWATER TREATMENT PLANT	780 BLIMP RD	3.05	Possible Nuisance, 2060	N/A
240 SOMBRERO BCH RD	240 SOMBRERO BCH RD	3.06	Possible Nuisance, 2060	N/A
5300 MACDONALD AVE	5300 MACDONALD AVE	3.08	Possible Nuisance, 2060	N/A
5530 3RD AVE	5530 3RD AVE	3.09	Possible Nuisance, 2060	N/A
31009 ATLANTIS DR	31009 ATLANTIS DR	3.10	Possible Nuisance, 2060	N/A
ANIMAL SHELTER KENNELS	5427 COLLEGE RD	3.10	Possible Nuisance, 2060	N/A
MARATHON AIRPORT EAST	10600 AVIATION BLVD	3.10	Possible Nuisance, 2060	N/A
LAYTON WASTEWATER TREATMENT PLANT	67900 OVERSEAS HWY	3.11	Possible Nuisance, 2060	N/A
MONROE COUNTY HOUSING CORPORATION	240 SOMBRERO BCH RD	3.12	Possible Nuisance, 2060	N/A
MONROE COUNTY SHERIFF'S OFFICE – STOCK ISLAND	5525 COLLEGE RD	3.13	Possible Nuisance, 2060	N/A
BIG PINE SCHOOL	MM 30.5 OVERSEAS HWY	3.14	Possible Nuisance, 2060	N/A
BIG PINE SCHOOL	MM 30.5 OVERSEAS HWY	3.14	Possible Nuisance, 2060	N/A
CHICKLETS ON THE BEACH	CLARENCE HIGGINS BEACH	3.14	Possible Nuisance, 2060	N/A
1000 ATLANTIC BLVD	1000 ATLANTIC BLVD	3.14	Possible Nuisance, 2060	N/A
31009 ATLANTIS DR	31009 ATLANTIS DR	3.18	Possible Nuisance, 2060	N/A
31009 ATLANTIS DR	31009 ATLANTIS DR	3.18	Possible Nuisance, 2060	N/A

31009 ATLANTIS DR	31009 ATLANTIS DR	3.19	Possible Nuisance, 2060	N/A
BIG PINE SCHOOL	MM 30.5 OVERSEAS HWY	3.19	Possible Nuisance, 2060	N/A
KEY WEST INTERNATIONAL AIRPORT FIRE/RESCUE #4	3501 S ROOSEVELT BLVD	3.21	Possible Nuisance, 2060	N/A
SALUTE! ON THE BEACH	1000 ATLANTIC BLVD	3.23	Possible Nuisance, 2060	N/A
31009 ATLANTIS DR	31009 ATLANTIS DR	3.27	Possible Nuisance, 2060	N/A
5300 MACDONALD AVE	5300 MACDONALD AVE	3.30	Possible Nuisance, 2060	N/A
BIG PINE SCHOOL	MM 30.5 OVERSEAS HWY	3.30	Possible Nuisance, 2060	N/A
MONROE COUNTY HOUSING CORPORATION	240 SOMBRERO BCH RD	3.31	Possible Nuisance, 2060	N/A
MARATHON AIRPORT WEST	9400 OVERSEAS HWY	3.34	Possible Nuisance, 2060	N/A
COUNTY MORG	56633 OVERSEAS HWY	3.36	Possible Nuisance, 2060	N/A
BIG PINE SCHOOL	MM 30.5 OVERSEAS HWY	3.39	Possible Nuisance, 2060	N/A
5300 MACDONALD AVE	5300 MACDONALD AVE	3.41	Possible Nuisance, 2060	N/A
BIG PINE VOLUNTEER FIRE STATION/EMS 13	390 KEY DEER BLVD	3.41	Possible Nuisance, 2060	N/A
MARATHON AIRPORT WEST	9400 OVERSEAS HWY	3.43	Possible Nuisance, 2060	N/A
MARATHON AIRPORT WEST	9400 OVERSEAS HWY	3.44	Possible Nuisance, 2060	N/A
MARATHON AIRPORT WEST	9400 OVERSEAS HWY	3.49	Possible Nuisance, 2060	N/A
MARATHON AIRPORT EAST	10600 AVIATION BLVD	3.50	Possible Nuisance, 2060	N/A
MARATHON AIRPORT WEST	9400 OVERSEAS HWY	3.51	Possible Nuisance, 2060	N/A
KEY WEST INTERNATIONAL AIRPORT	3501 S ROOSEVELT BLVD	3.55	Possible Nuisance, 2060	N/A
MONROE COUNTY HOUSING CORPORATION	240 SOMBRERO BCH RD	3.55	Possible Nuisance, 2060	N/A
BIG PINE SCHOOL	MM 30.5 OVERSEAS HWY	3.55	Possible Nuisance, 2060	N/A
MARATHON AIRPORT WEST	9400 OVERSEAS HWY	3.60	Possible Nuisance, 2060	N/A
COUNTY MORG	56633 OVERSEAS HWY	3.61	Possible Nuisance, 2060	N/A
HARRY HARRIS OCEAN PARK	DOVE CREEK	3.61	Possible Nuisance, 2060	N/A
MONROE COUNTY HOUSING CORPORATION	240 SOMBRERO BCH RD	3.62	Possible Nuisance, 2060	N/A
MONROE COUNTY HOUSING CORPORATION	240 SOMBRERO BCH RD	3.64	Possible Nuisance, 2060	N/A
MONROE COUNTY HOUSING CORPORATION	240 SOMBRERO BCH RD	3.64	Possible Nuisance, 2060	N/A

Flood Risk Assessment for Public Buildings with Elevation Certificates

Survey data that provide a finished first floor elevation are generally regarded as the most definitive basis for evaluating a structure's vulnerability to flood damage, particularly from extreme flood events. The most accurate public information regarding the finished first floor elevations for many buildings can be found on Elevation Certificates, which are developed by licensed surveyors for many properties as a requirement of the National Flood Insurance Program. Archives of Elevation Certificates developed for public buildings in Monroe County are maintained by Monroe County's Floodplain Coordinators or the Floodplain Coordinators of municipalities in which the structures are located.

Through public records searches conducted in collaboration with the Floodplain Coordinators in Monroe County, we obtained the print or scanned Elevation Certificate records for a total of thirty-five structures owned by Monroe County. Using address or building names provided on these Elevation Certificates, we appended a new set of attributes within the building footprint layer (MONROECOUNTY_FOOTPRINTS.shp) to include first floor elevation, lowest adjacent grade, and, where available, highest adjacent grade for all buildings with Elevation Certificates. In most cases, the elevation heights from Elevation Certificate surveys were referenced to the National Geodetic Vertical Datum of 1929 (NGVD29), rather than the NAVD88 datum used for LIDAR-based elevations. Because the NGVD29 to NAVD88 vertical datum conversion varies significantly across the Florida Keys, it is critically important to perform geographically precise transformations between these datums to ensure maintenance of elevation accuracy for each individual structure. To do this, we utilized NOAA's (2015b) orthometric height to transform elevations from NGVD29 to NAVD88 for each Elevation Certificate record. For buildings with an Elevation Certificate, the final building footprint layer contains the original NGVD29 finished first floor elevation data, the orthometric conversion from NOAA (2015b), the adjusted NAVD88-based finished first floor elevation value obtained through orthometric conversion, and available adjacent grade (low and/or high) as adjusted to NAVD88.

A summary of finished first elevation data for the thirty-five buildings owned by Monroe County with digitized Elevation Certificate information, along with sea level rise tidal flooding risk, is provided in Table 5. Notably, all but two buildings with potential future exposure of finished first floors to regular tidal flooding due to sea level rise, and most facilities that show potential future access issues due to low adjacent grade elevation, are located within the Pigeon Key Historic District, which was listed on the National Register of Historic Places in 1990 (http://www.nationalregisterofhistoricplaces.com/fl/monroe/districts.html). Due to the sensitive historic character of these buildings and structures, consultation with the Pigeon Key Foundation, which manages the Pigeon Key site under a long-term lease from Monroe County, and utilization of FEMA's (2008) National Flood Insurance Program Floodplain Management Bulletin for Historic Structures is recommended to determine appropriate sea level rise adaptation and flooding resilience strategies on Pigeon Key.

Two Monroe County structures outside of the Pigeon Key Historic District show potential future exposure of finished floors to regular tidal flooding under the considered sea level rise scenarios: 1) the Monroe County Animal Shelter in Key West; and 2) the West Martello Tower in Key West. Of most immediate concern from a government services perspective is the Animal Shelter, which shows a finished first floor elevation of 2.97' above local MHHW. This indicates potential exposure to nuisance tidal flooding by 2060 under the high sea level rise scenario. It is also notable that the adjacently located Monroe County Animal Shelter office building shows 2060 access concerns from nuisance flooding under the high sea level rise scenario. Because the low elevation of these buildings also places them at high vulnerability of damage from a storm surge, potential relocation to a more elevated site or other flood adaptation measures may be an important additional criterion to consider under any future plans to renovate the Animal Shelter facility.

The historic West Martello Tower, which was listed on the National Register of Historic Places in 1976 (Griffin and Longiaru 2012), shows a first floor elevation of 3.22' above local MHHW. This floor elevation suggests potential exposure to nuisance flooding by 2060 under the high sea level rise scenario. The historic nature and hardened construction materials that comprise the West Martello Tower likely pose significant challenges for near-term sea-level rise adaptation measures. Consultation of historic preservation specialists in Monroe County, the Florida Department of State, Division of Historical Resources in Tallahassee, and FEMA (2008) guidelines for retrofitting and stabilizing historic structures in floodplain areas is recommended for the West Martello Tower.

Three buildings located within the Key West International Airport (KWIA) complex, located at 3491 S. Roosevelt Boulevard, show potential access concerns due to future sea level rise. Two buildings show adjacent grade elevations of less than 2' above MHHW (one at 1.58' and the other at 1.65'). These elevations indicate vulnerability to nuisance flooding by 2060 under a low sea level rise scenario, or complete inundation by 2060 under a high sea level rise scenario. The KWIA terminal, with a low surrounding grade elevation of 2.86' above MHHW, shows potential exposure to nuisance flooding access concerns by 2060 under a high sea level rise scenario.

Several Monroe County buildings with digitized Elevation Certificates show potential exposure to an extreme flood event similar to Hurricane Wilma as amplified by up to two feet of sea level rise at 2060. Of most immediate concern due to the social vulnerability of facility residents is the Bay Manor assisted-living retirement home, which has an Elevation Certification that shows a finished first floor elevation of 4.20' above NAVD88, or 4.19' above local MHHW. For the near-term, procedures for rapid evacuation in the case of an approaching storm surge event are likely the most feasible adaptation option for this facility. Longer term consideration may be given to relocation to a more elevated site, or retrofit construction to a higher grade on the current site.

Also of high to moderate concern are two Monroe County Sheriff's Office structures. First, the Freeman substation on Cudjoe Key, which has a finished floor elevation of 6.54' above NAVD88 (6.25' as adjusted to local MHHW) shows a first floor elevation just below the current 100-year floodplain. This risk profile makes relocation or retrofit elevation of the Freeman substation a likely priority for flood mitigation and emergency preparedness. The Marathon substation, which has a first floor elevation of 7.40' above NAVD88 (7.53' as adjusted to local MHHW), could potentially be vulnerable to an extreme event storm surge by 2060 under a high sea level rise scenario. Medium-term relocation or retrofit elevation of the Marathon substation is likely to become a priority if sea level rise takes a high trajectory over the next two decades.

Of moderate future concern are the Roth Building and two nearby structures (listed as Radio Transmission Shop and County Offices) that are owned by Monroe County on Plantation Key in the Village of Islamorada. Although all structures show finished floor elevations above the current FEMA 100-year floodplain height, a high rate of sea level rise would be expected to put the structures at potential risk of extreme event flooding by 2060. Decisions regarding possible flood adaptation for these structures should take into account both the rate of sea level rise observed over the next two decades, as well as the overall life cycle of the buildings.

Other structures with Elevation Certificates that show risk of current or future flooding from a "Wilma-sized" event are two recreation structures at Clarence Higgs Beach, including a vendor and public restroom structure, and the historic East Martello Tower Museum. While the Clarence Higgs Beach structures may be of relatively low priority for adaptation measures due to the recreational nature of the facilities, any retrofit or upgrade projects may wish to incorporate appropriate hazard mitigation design features. Appropriate sea level rise adaptation measures for the East Martello Tower, which was listed on the National Register of Historic Places in 1972 (Griffin and Logiaru 2012) will require significant study due to both the fort construction materials and the historic nature of the site.

.

Table 5: Tidal Flood Risk Assessment for Public Facilities Based on Elevation Certificate Records. Finished first floor and lowest grade elevations digitized from Elevation Certificates. NAVD88 to MHHW (1983 – 2001 National Tidal Datum Epoch) calculated by VDatum adjustment.

BUILDING SITE NAME	ADDRESS	FINISHED FIRST FLOOR (NAVD88)	FINISHED FIRST FLOOR (MHHW)	LOWEST GRADE ELEVATION (MHHW)	TIDAL FLOOD RISK, HIGH SLR SCENARIO	TIDAL FLOOD RISK, LOW SLR SCENARIO
BRIDGE TENDER'S DORM	PIGEON KEY US HIGHWAY 1	0.72	1.22	0.22	Nuisance 2030 (Structure)	Nuisance 2030 (Structure)
COMMISSARY/DORM	PIGEON KEY US HIGHWAY 1	1.02	1.52	0.52	Nuisance 2030 (Structure)	Nuisance 2060 (Structure)
GENERATOR BUILDING	PIGEON KEY US HIGHWAY 1	1.17	1.67	-0.33	Nuisance 2030 (Structure)	Nuisance 2060 (Structure)
KITCHEN/DINING AREA	PIGEON KEY US HIGHWAY 1	2.67	3.17	1.17	Nuisance 2060 (Structure)	Nuisance 2030 (Access)
GNOGE FOREMAN'S/GUEST HOUSE	PIGEON KEY US HIGHWAY 1	2.82	3.32	2.32	Nuisance 2060 (Structure)	N/A
SECTION GANG CLASSROOMS AND OFFICES	PIGEON KEY US HIGHWAY 1	2.82	3.32	2.32	Nuisance 2060 (Access)	N/A
ANIMAL SHELTER KENNELS	5427 COLLEGE ROAD	3.03	2.97	2.97	Nuisance 2060 (Structure)	N/A
HONEYMOON COTTAGE/STAFF HOUSING	PIGEON KEY US HIGHWAY 1	3.15	3.65	1.65	Inundation 2060 (Access)	Nuisance 2060 (Access)
WEST MARTELLO TOWERS	1100 ATLANTIC BLVD	3.42	3.22	3.22	Nuisance 2060 (Structure)	N/A
AIRPORT BUILDING	3491 SOUTH ROOSEVELT BLVD	3.71	3.58	1.58	Nuisance 2030 (Access)	Nuisance 2060 (Access)
AIRPORT BUILDING	3491 SOUTH ROOSEVELT BLVD	3.79	3.65	1.65	Inundation 2060 (Access)	Nuisance 2060 (Access)
ANIMAL SHELTER OFFICE	5427 COLLEGE ROAD	3.82	3.76	2.76	Nuisance 2060 (Access)	N/A
AIRPORT TERMINAL	3491 S. ROOSEVELT BLVD	4.06	3.86	2.86	Nuisance 2060 (Access)	N/A
PUBLIC REST ROOM	CLARENCE HIGGS BEACH	4.06	3.93	3.93	N/A	N/A
BAY SHORE MANOR	5200 COLLEGE ROAD	4.20	4.19	3.19	Nuisance 2060 (Access)	N/A

CHICKLETS ON THE BEACH	CLARENCE HIGGS BEACH	4.40	4.20	3.20	Nuisance 2060 (Access)	N/A
ASST. PAINT FOREMAN'S STAFF HOUSING	PIGEON KEY US HIGHWAY 1	5.22	5.72	0.72	Inundation 2030 (Access)	Nuisance 2030 (Access)
ASST. BRIDGE TENDER'S MUSEUM	PIGEON KEY US HIGHWAY 1	5.42	5.92	0.92	Nuisance 2030 (Access)	Nuisance 2030 (Access)
EAST MARTELLO TOWERS/MUSEUM	3501 S. ROOSEVELT BLVD	6.13	5.99	3.99	N/A	N/A
SHERIFF'S OFFICE FREEMAN SUBSTATION	20950 OVERSEAS HIGHWAY	6.54	6.25	4.55	N/A	N/A
SHERIFF'S SUBSTATION	3103 OVERSEAS HIGHWAY	7.40	7.53	6.53	N/A	N/A
ROTH BUILDING	50 HIGH POINT RD	7.66	8.35	6.46	N/A	N/A
66 RADIO TRANSMISSION ROOM/SHOP	88770 OVERSEAS HIGHWAY	8.11	8.39	8.39	N/A	N/A
#65 COUNTY OFFICES	MM 88.5 US 1	8.38	8.63	7.63	N/A	N/A
COUNTY GARAGE	88770 OVERSEAS HIGHWAY	8.50	8.78	8.78	N/A	N/A
ANIMAL SHELTER	10550 AVIATION BLVD	9.00	9.37	5.37	N/A	N/A
STORAGE ROOMS	938 WHITEHEAD ST	10.01	9.84	9.84	N/A	N/A
PUBLIC LIBRARY	101485 OVERSEAS HIGHWAY	10.44	10.45	9.45	N/A	N/A
GOVERNMENTAL CENTER	HIGHPOINT ROAD	10.61	11.14	7.10	N/A	N/A
SHERIFF'S SUB STATION	88770 OVERSEAS HIGHWAY	11.14	11.31	10.31	N/A	N/A
SHERIFF'S SUB STATION	88770 OVERSEAS HIGHWAY	11.14	11.38	10.38	N/A	N/A
LIBRARY	81830 OVERSEAS HIGHWAY	11.99	11.73	8.73	N/A	N/A
MONROE COUNTY CIVIL/PROPERTY DIVISION	500 WHITEHEAD STREET	13.19	13.06	11.06	N/A	N/A
LIGHTHOUSE MUSEUM/CURATOR'S QUARTERS	938 WHITEHEAD ST	14.16	13.99	8.99	N/A	N/A
MONROE COUNTY SUPERVISOR OF ELECTIONS	530 WHITEHEAD ST	14.66	14.54	11.54	N/A	N/A

Table 6: Extreme Event Flood Risk Assessment for Public Facilities Based on Elevation Certificate Records. Finished first floor elevations were digitized from Elevation Certificates. Flood zones and base flood elevations (BFE) determined from FEMA Digital Flood Insurance Rate Map (UF Geoplan 2015)

BUILDING SITE NAME	ADDRESS	FINISHED FIRST FLOOR (NAVD88)	FLOOD ZONE	STATIC BFE (NAVD88)	EXTREME FLOOD RISK, HIGH SLR SCENARIO	EXTREME FLOOD RISK, LOW SLR SCENARIO
BRIDGE TENDER'S DORM	PIGEON KEY US HIGHWAY 1	0.72	AE	6.6	In current floodplain	In current floodplain
COMMISSARY/DORM	PIGEON KEY US HIGHWAY 1	1.02	AE	7.6	In current floodplain	In current floodplain
GENERATOR BUILDING	PIGEON KEY US HIGHWAY 1	1.17	VE	8.6	In current floodplain	In current floodplain
KITCHEN/DINING AREA	PIGEON KEY US HIGHWAY 1	2.67	AE	6.6	In current floodplain	In current floodplain
GNOGE FOREMAN'S/GUEST HOUSE	PIGEON KEY US HIGHWAY 1	2.82	AE	6.6	In current floodplain	In current floodplain
SECTION GANG CLASSROOMS AND OFFICES	PIGEON KEY US HIGHWAY 1	2.82	AE	6.6	In current floodplain	In current floodplain
ANIMAL SHELTER KENNELS	5427 COLLEGE ROAD	3.03	AE	7.7	In current floodplain	In current floodplain
HONEYMOON COTTAGE/STAFF HOUSING	PIGEON KEY US HIGHWAY 1	3.15	AE	7.6	In current floodplain	In current floodplain
WEST MARTELLO TOWERS	1100 ATLANTIC BLVD	3.42	VE	8.7	In current floodplain	In current floodplain
AIRPORT BUILDING	3491 SOUTH ROOSEVELT BLVD	3.71	VE	9.7	In current floodplain	In current floodplain
AIRPORT BUILDING	3491 SOUTH ROOSEVELT BLVD	3.79	VE	9.7	In current floodplain	In current floodplain
ANIMAL SHELTER OFFICE	5427 COLLEGE ROAD	3.82	VE	9.7	In current floodplain	In current floodplain
AIRPORT TERMINAL	3491 S. ROOSEVELT BLVD	4.06	VE	9.7	In current floodplain	In current floodplain
PUBLIC REST ROOM	CLARENCE HIGGS BEACH	4.06	VE	8.7	In current floodplain	In current floodplain
BAY SHORE MANOR	5200 COLLEGE ROAD	4.20	AE	7.7	In current floodplain	In current floodplain
CHICKLETS ON THE BEACH	CLARENCE HIGGS BEACH	4.40	VE	8.7	In current floodplain	In current floodplain

ASST. PAINT FOREMAN'S STAFF HOUSING	PIGEON KEY US HIGHWAY 1	5.22	VE	8.6	In current floodplain	In current floodplain
ASST. BRIDGE TENDER'S MUSEUM	PIGEON KEY US HIGHWAY 1	5.42	AE	6.6	In current floodplain	In current floodplain
EAST MARTELLO TOWERS/MUSEUM	3501 S. ROOSEVELT BLVD	6.13	VE	9.7	In current floodplain	In current floodplain
SHERIFF'S OFFICE FREEMAN SUBSTATION	20950 OVERSEAS HIGHWAY	6.54	AE	6.6	In current floodplain	In current floodplain
SHERIFF'S OFFICE MARATHON SUBSTATION	3103 OVERSEAS HIGHWAY	7.40	AE	5.6	2060	N/A
ROTH BUILDING	50 HIGH POINT RD	7.66	AE	6.5	2060	N/A
RADIO TRANSMISSION SHOP	88770 OVERSEAS HIGHWAY	8.11	AE	6.5	2060	N/A
COUNTY OFFICES	MM 88.5 US 1	8.38	AE	6.5	2060	N/A
COUNTY GARAGE	88770 OVERSEAS HIGHWAY	8.50	X	N/A	N/A	N/A
ANIMAL SHELTER	10550 AVIATION BLVD	9.00	AE	6.6	N/A	N/A
STORAGE ROOMS	938 WHITEHEAD ST	10.01	X	N/A	N/A	N/A
PUBLIC LIBRARY	101485 OVERSEAS HIGHWAY	10.44	X	N/A	N/A	N/A
GOVERNMENTAL CENTER	HIGHPOINT ROAD	10.61	AE	6.5	N/A	N/A
SHERIFF'S SUB STATION	88770 OVERSEAS HIGHWAY	11.14	AE	6.5	N/A	N/A
SHERIFF'S SUB STATION	88770 OVERSEAS HIGHWAY	11.14	X	N/A	N/A	N/A
LIBRARY	81830 OVERSEAS HIGHWAY	11.99	X	N/A	N/A	N/A
MONROE COUNTY CIVIL/PROPERTY DIVISION	500 WHITEHEAD STREET	13.19	X	N/A	N/A	N/A
LIGHTHOUSE MUSEUM/CURATOR'S QUARTERS	938 WHITEHEAD ST	14.16	X	N/A	N/A	N/A
MONROE COUNTY SUPERVISOR OF ELECTIONS	530 WHITEHEAD ST	14.66	X	N/A	N/A	N/A

Recommendations for Monroe County Buildings

The building footprints dataset developed for this project provides detailed guidance as to where public structures and critical infrastructure may be at risk of future flooding from sea level rise.

Digitized Elevation Certificates suggest high vulnerability for buildings at several historic sites owned by Monroe County, including the Pigeon Key Historic District, the East Martello Tower, and the West Martello Tower. Sea level rise adaptation and flooding resilience actions for these sites will require detailed consultation with historic preservation specialists, facility managers, and other officials and stakeholders. Utilization of the FEMA (2008) guidance for retrofit and stabilization of historic structures with flood vulnerability is recommended as a basis for initiation of any near-term adaptation action at these sites.

Facilities with current extreme event flood risk, as based upon current FEMA floodplain designations and Elevation Certificate information, include the Monroe County Animal Shelter, the Bay Manor assisted living facility, the Monroe County Sheriff's Office Freeman Substation, and several buildings at the Key West International Airport. Moreover, the analysis suggests that the Animal Shelter and Key West International Airport buildings would face exposure to flooding of structures during king tide events by 2060 under a high sea level rise scenario. Specific engineering and design assessments to identify appropriate on-site adaptation measures or relocation alternatives for each of these buildings is recommended for these identified facilities.

It is also recommended that future flood vulnerability assessments in Monroe County build upon the work in the GreenKeys! project and continue efforts to develop a more complete digital record of Elevation Certificates or other survey quality elevation data for public facilities. Use, integration, and improvement of this record will promote higher confidence in flood risk assessments, thereby providing a basis for development of a building-by-building prioritization for flood retrofit and/or rebuilding as conditions warrant. Additional criteria such as facility importance, building age/condition, and grade-level flood vulnerability assessments (as listed in Table 4) may also be used to prioritize the development of enhanced elevation data for specific sites, as well as development of appropriate adaptation strategies.

Because tidal flooding from sea level rise is a hazard that develops progressively, issues such as unacceptable loss of access and the eventual vulnerability of an individual structure due to tidal flooding will be preceded by many minor, but visible, nuisance flooding events. For this reason, we also recommend the development and implementation of a geographic database for Monroe County employees (and interested residents) to document the time and location of nuisance flood events that affect parking lots, access roads, and landscapes of public facilities. Coupled with the building footprint layer and associated vulnerability assessment, such a geographically explicit and temporally documented nuisance flood record will provide a strong basis for implementation of targeted and justified public investments to mitigate tidal flooding vulnerabilities

Wastewater Treatment Plants

In recent years, Monroe County and its municipalities have invested hundreds of millions of dollars to provide advanced wastewater treatment services throughout the Florida Keys. The driving force for these investments was the recognition that onsite wastewater treatment facilities (i.e., septic tanks) and small wastewater package plant facilities in use for many years in much of the Florida Keys were adversely effecting local water quality and coastal ecosystems (Lapointe et al. 1990; Lipp et al. 2002). Due to the magnitude of local investment in the development of centralized wastewater treatment plants and the low tolerance for flood-induced failures within these systems (Rose et al. 2001), there is clear public interest in assessing the future risks to these facilities due to sea-level rise.

Through consultations with Monroe County staff, a total of nine wastewater treatment plants were identified for inclusion in this sea level rise vulnerability assessment. Five of these facilities are currently operated by the Florida Keys Aqueduct Authority (FKAA): Key Haven, Big Coppitt Regional, Bay Point, and Duck Key. A sixth FKAA facility, the Cudjoe Regional Wastewater Treatment Plant, is currently under construction and scheduled to begin service in December 2015 (http://www.cudjoewastewater.com/). Other facilities included in our analysis include the K W Resort Utilities Corporation's wastewater treatment plant located on South Stock Island; the Key Largo Wastewater Treatment District's wastewater treatment plant located in Key Largo; and the North Key Largo Utility Corporation's wastewater treatment plant located in Ocean Reef. Because this study was conducted for unincorporated Monroe County, additional wastewater treatment facilities operated by the municipalities of Key West, Key Colony Beach, Marathon, and Islamorada were not included in the vulnerability assessment. An overview map of all assessed facilities is shown as Figure 6.

For this vulnerability assessment, all visible structures on property parcels associated with these nine wastewater treatment plants were digitized into building footprints. The digitization method was identical to the one described in the above "Building Footprints" section. A Zonal Statistics analysis for each digitized structure, with elevations referenced to both MHHW and NAVD88, was also performed for each wastewater treatment plant site.

A complete summary of maximum LIDAR DEM ground elevations (as referenced to local MHHW) and the respective sea level rise flood risk for all structures associated with the nine wastewater treatment plants is shown in Table 7. These results suggest that none of the evaluated wastewater treatment plant structures show risk for regular tidal flooding by 2030, and also show no risk to regular tidal flooding at 2060 under a low sea level rise scenario. Results for the 2060 high sea level rise scenario do indicate potential ground level flooding to some structures. Visualizations that identify specific structures with ground level flood risk under the 2060 high sea level rise scenario are provided in Figure 7 (K W Resort Utilities WWTP), Figure 8 (Key Haven WWTP), Figure 9 (Bay Point WWTP), Figure 10 (Duck Key WWTP), Figure 11 (Cudjoe WWTP), Figure 12 (Layton WWTP), and Figure 13 (North Key Largo WWTP).

Figure 6: **Wastewater Treatment Plant Locations**

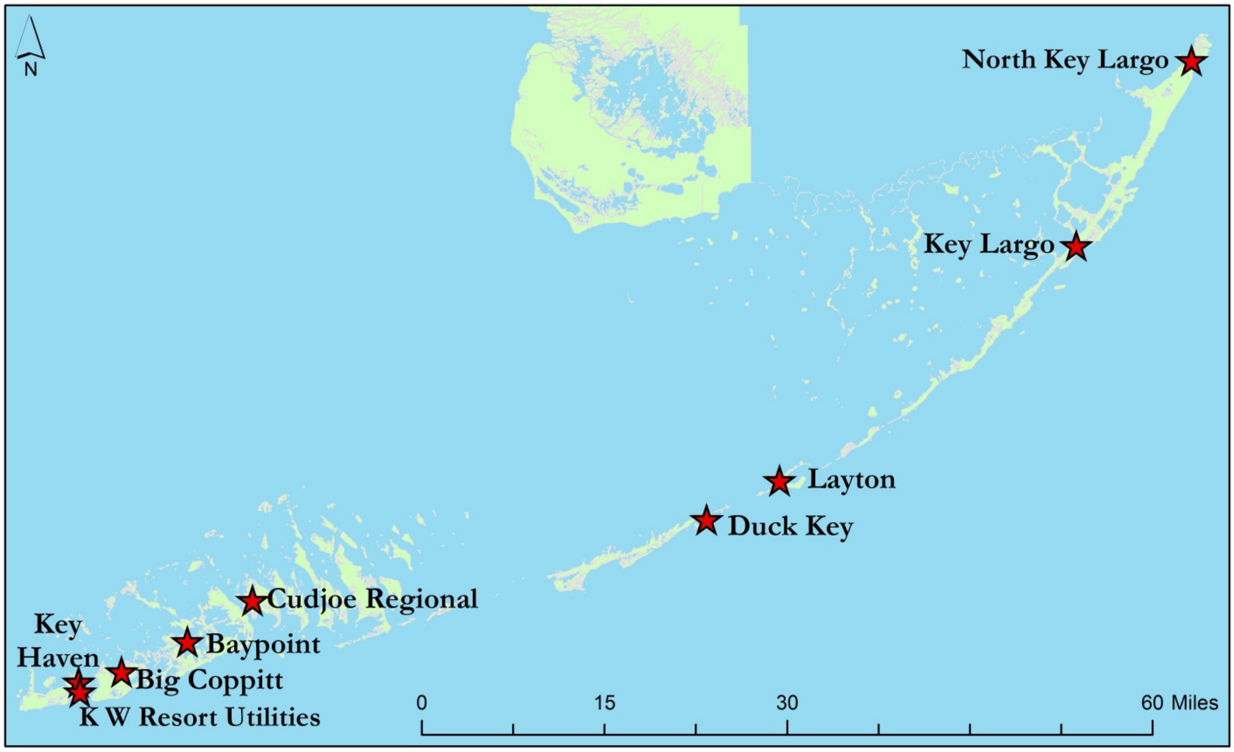


Table 7: **LIDAR-Based Flood Risk Assessment for Wastewater Treatment Plants**. The list is ordered from lowest to highest MHHW elevation, as determined by the maximum LIDAR DEM value within each building footprint. Value of N/A indicates little to no identified risk of regular tidal flooding.

	FT ABOVE MHHW	2060 TIDAL FLOOD RISK, HIGH SEA LEVEL RISE SCENARIO
K W RESORT UTILITES WASTEWATER TREATMENT PLANT	2.21	Possible Inundation
KEY HAVEN WASTEWATER TREATMENT PLANT	2.35	Likely Nuisance
BAY POINT WASTEWATER TREATMENT PLANT	2.41	Likely Nuisance
DUCK KEY WASTEWATER TREATMENT PLANT	2.89	Likely Nuisance
DUCK KEY WASTEWATER TREATMENT PLANT	2.89	Likely Nuisance
NORTH KEY LARGO WASTEWATER TREATMENT PLANT	2.97	Likely Nuisance
CUDJOE REGIONAL WASTEWATER TREATMENT PLANT	3.05	Possible Nuisance
LAYTON WASTEWATER TREATMENT PLANT	3.11	Possible Nuisance
NORTH KEY LARGO WASTEWATER TREATMENT PLANT	3.16	Possible Nuisance
BAY POINT WASTEWATER TREATMENT PLANT	3.57	Possible Nuisance
NORTH KEY LARGO WASTEWATER TREATMENT PLANT	3.73	N/A
KEY LARGO WASTE WATER PLANT	3.86	N/A
KEY LARGO WASTE WATER PLANT	3.86	N/A
KEY LARGO WASTE WATER PLANT	3.91	N/A
BIG COPPITT WASTEWATER TREATMENT PLANT	3.99	N/A
DUCK KEY WASTEWATER TREATMENT PLANT	4.21	N/A
KEY LARGO WASTE WATER PLANT	4.23	N/A
KEY LARGO WASTE WATER PLANT	4.28	N/A
KEY LARGO WASTE WATER PLANT	4.33	N/A
KEY LARGO WASTE WATER PLANT	4.33	N/A
KEY LARGO WASTE WATER PLANT	4.40	N/A
KEY HAVEN WASTEWATER TREATMENT PLANT	4.52	N/A
DUCK KEY WASTEWATER TREATMENT PLANT	4.54	N/A

KEY LARGO WASTEWATER TREATMENT PLANT	4.58	N/A
KEY LARGO WASTE WATER PLANT	4.63	N/A
NORTH KEY LARGO WASTEWATER TREATMENT PLANT	4.64	N/A
K W RESORT UTILITES WASTEWATER TREATMENT PLANT	4.66	N/A
KEY LARGO WASTEWATER TREATMENT PLANT	4.68	N/A
DUCK KEY WASTEWATER TREATMENT PLANT	4.71	N/A
DUCK KEY WASTEWATER TREATMENT PLANT	4.71	N/A
KEY LARGO WASTE WATER PLANT	4.71	N/A
K W RESORT UTILITES WASTEWATER TREATMENT PLANT	4.75	N/A
KEY LARGO WASTE WATER PLANT	4.83	N/A
DUCK KEY WASTEWATER TREATMENT PLANT	4.96	N/A
K W RESORT UTILITES WASTEWATER TREATMENT PLANT	4.99	N/A
K W RESORT UTILITES WASTEWATER TREATMENT PLANT	5.16	N/A
DUCK KEY WASTEWATER TREATMENT PLANT	5.30	N/A
CUDJOE REGIONAL WASTEWATER TREATMENT PLANT	5.42	N/A
CUDJOE REGIONAL WASTEWATER TREATMENT PLANT	5.48	N/A
KEY LARGO WASTE WATER PLANT	5.62	N/A
LAYTON WASTEWATER TREATMENT PLANT	5.90	N/A
NORTH KEY LARGO WASTEWATER TREATMENT PLANT	6.07	N/A
CUDJOE REGIONAL WASTEWATER TREATMENT PLANT	6.15	N/A
CUDJOE REGIONAL WASTEWATER TREATMENT PLANT	6.32	N/A

Figure 7: **KW Resort Utilities Wastewater Treatment Plant**. Aerial photograph (top) and 2060 high sea level rise assessment (bottom). Yellow star indicates structure with flood risk.

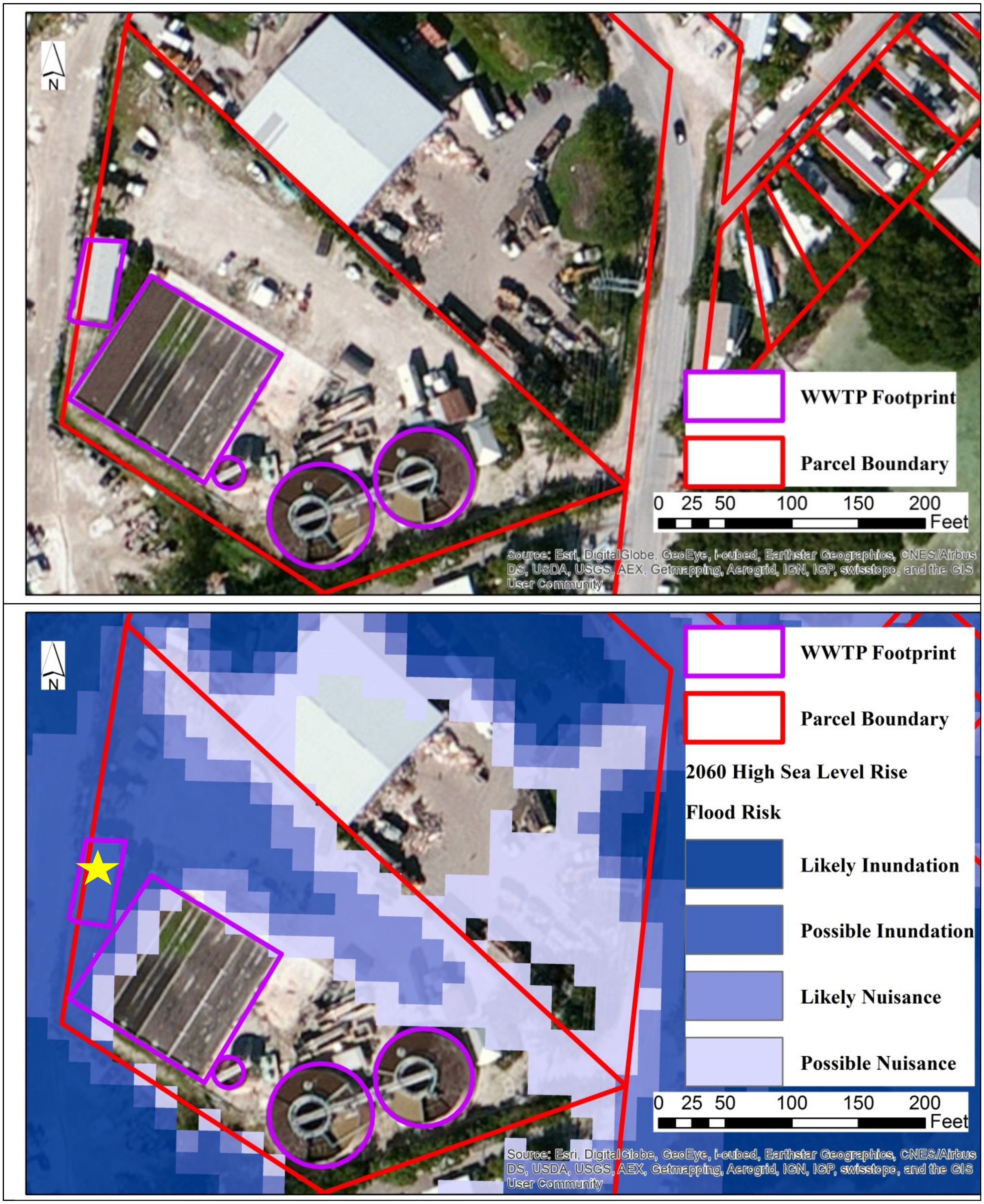


Figure 8: **Key Haven Wastewater Treatment Plant.** Aerial photograph (top) and 2060 high sea level rise assessment (bottom). Yellow star indicates structure with flood risk.

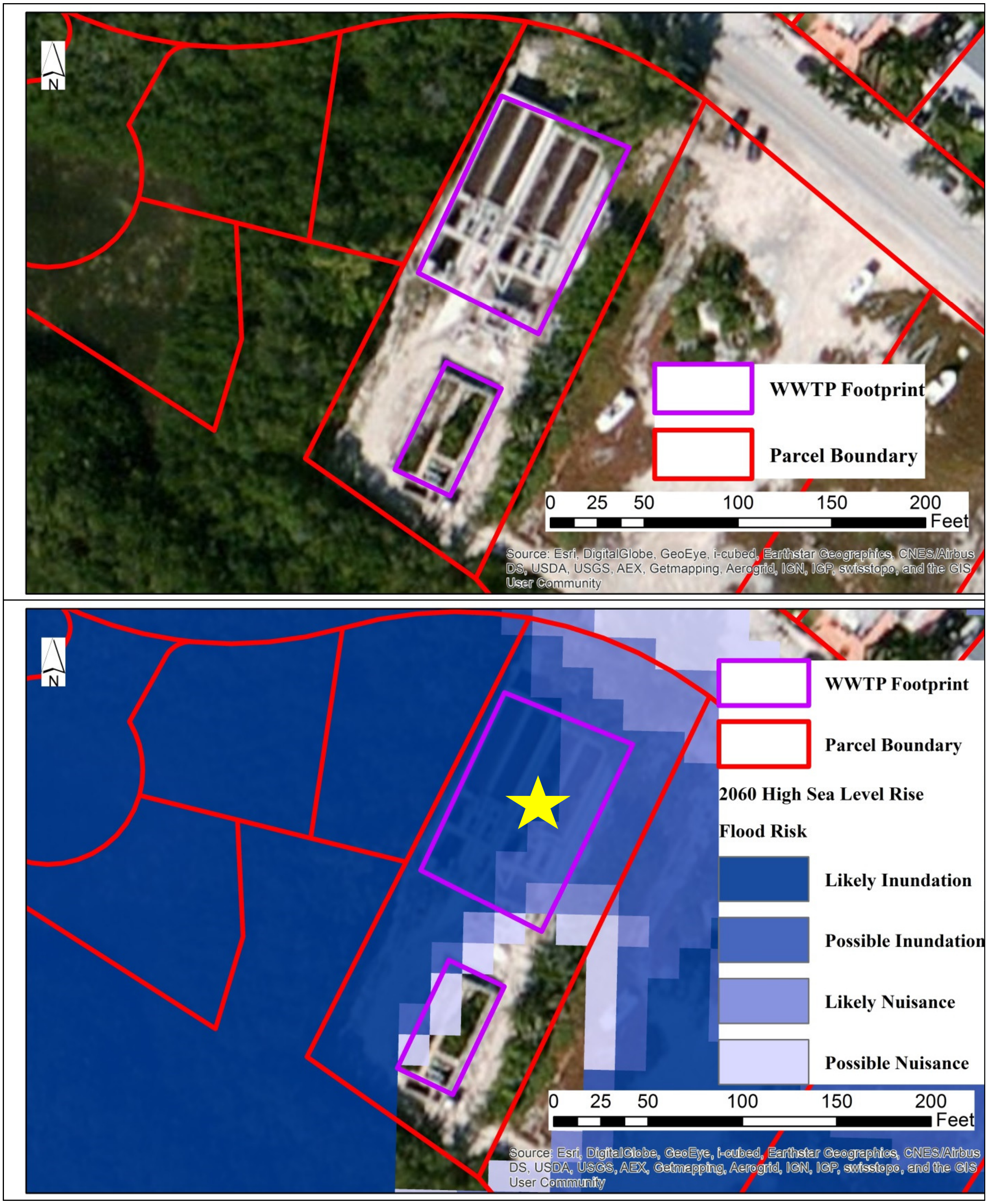


Figure 9: **Bay Point Wastewater Treatment Plant.** Aerial photograph (top) and 2060 high sea level rise assessment (bottom). Yellow star indicates structure with flood risk.

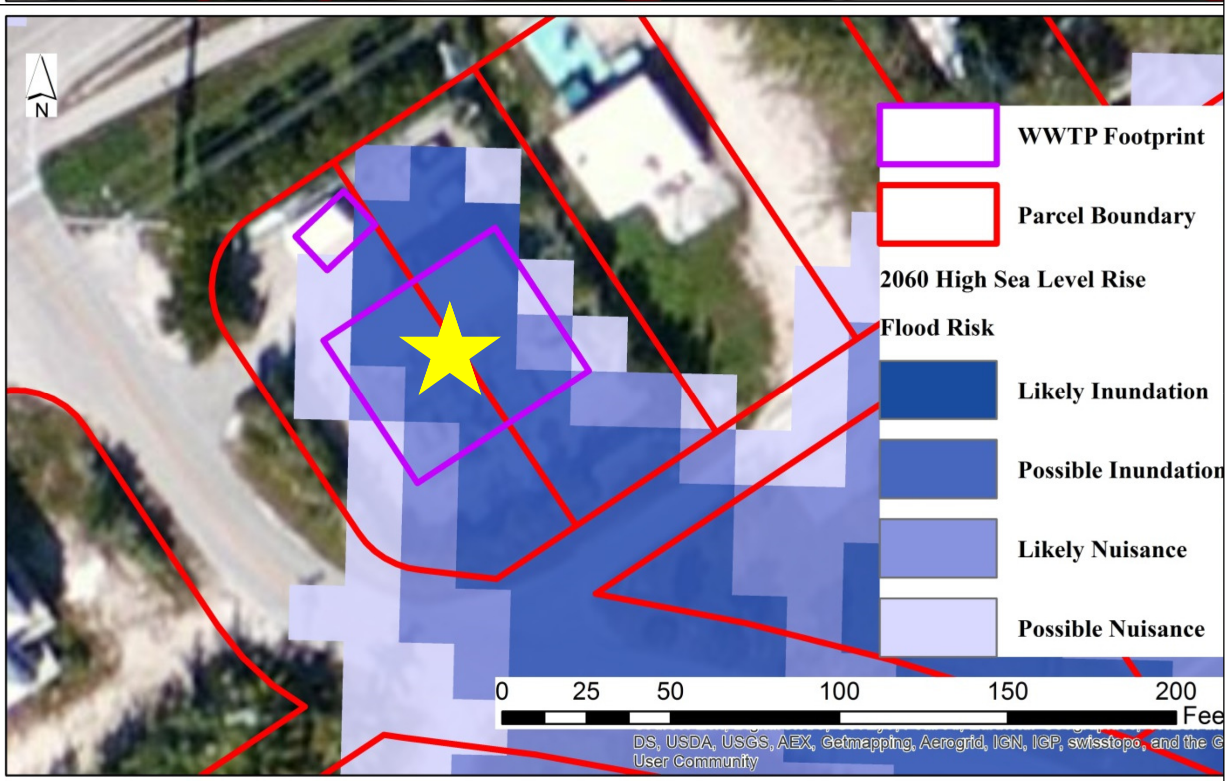
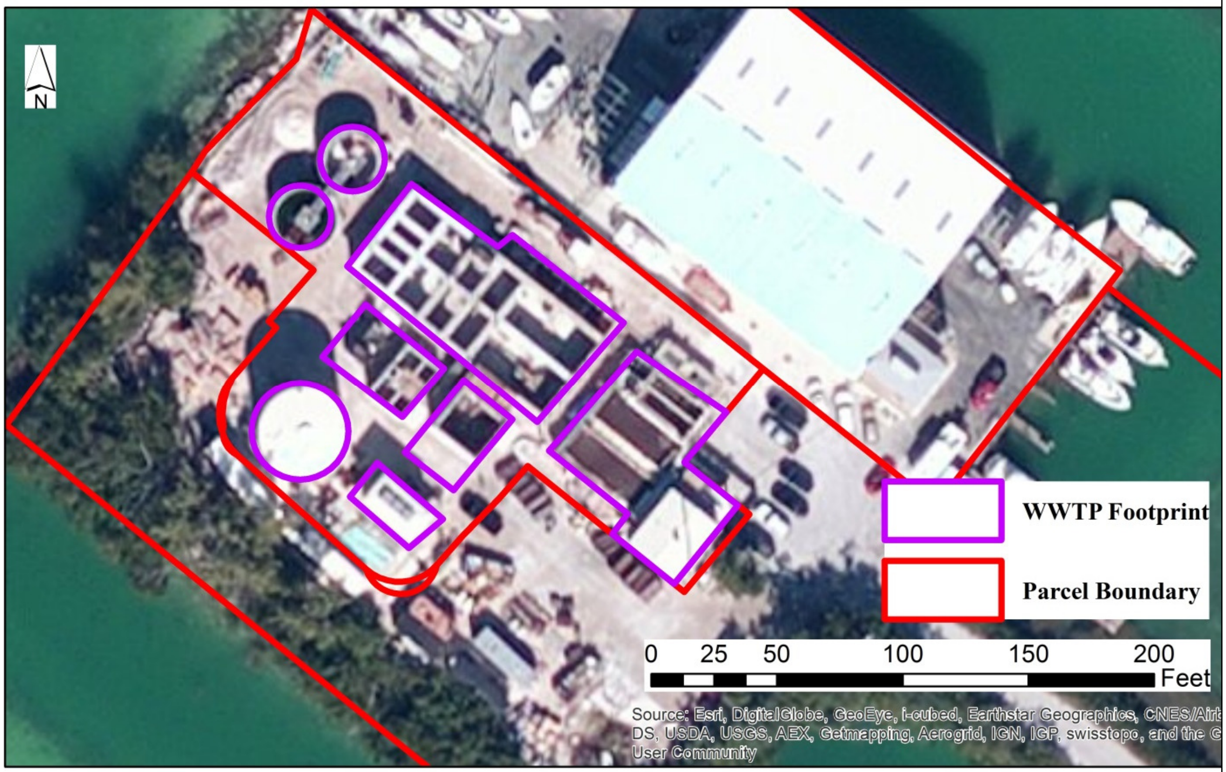


Figure 10: **Duck Key Wastewater Treatment Plant**. Aerial photograph (top) and 2060 high sea level rise assessment (bottom). Yellow star indicates structure with flood risk.



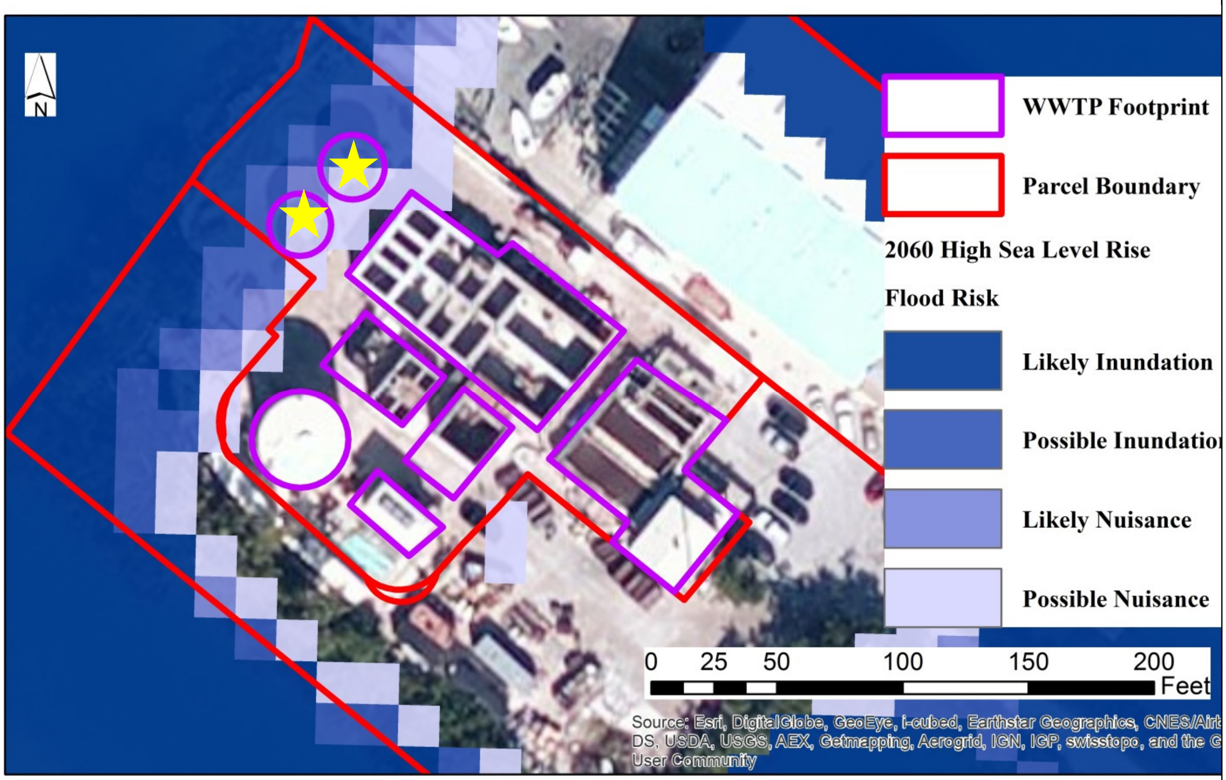


Figure 11: **Cudjoe Regional Wastewater Treatment Plant.** Aerial photograph (top) and 2060 high sea level rise assessment (bottom). Yellow star indicates structure with flood risk.

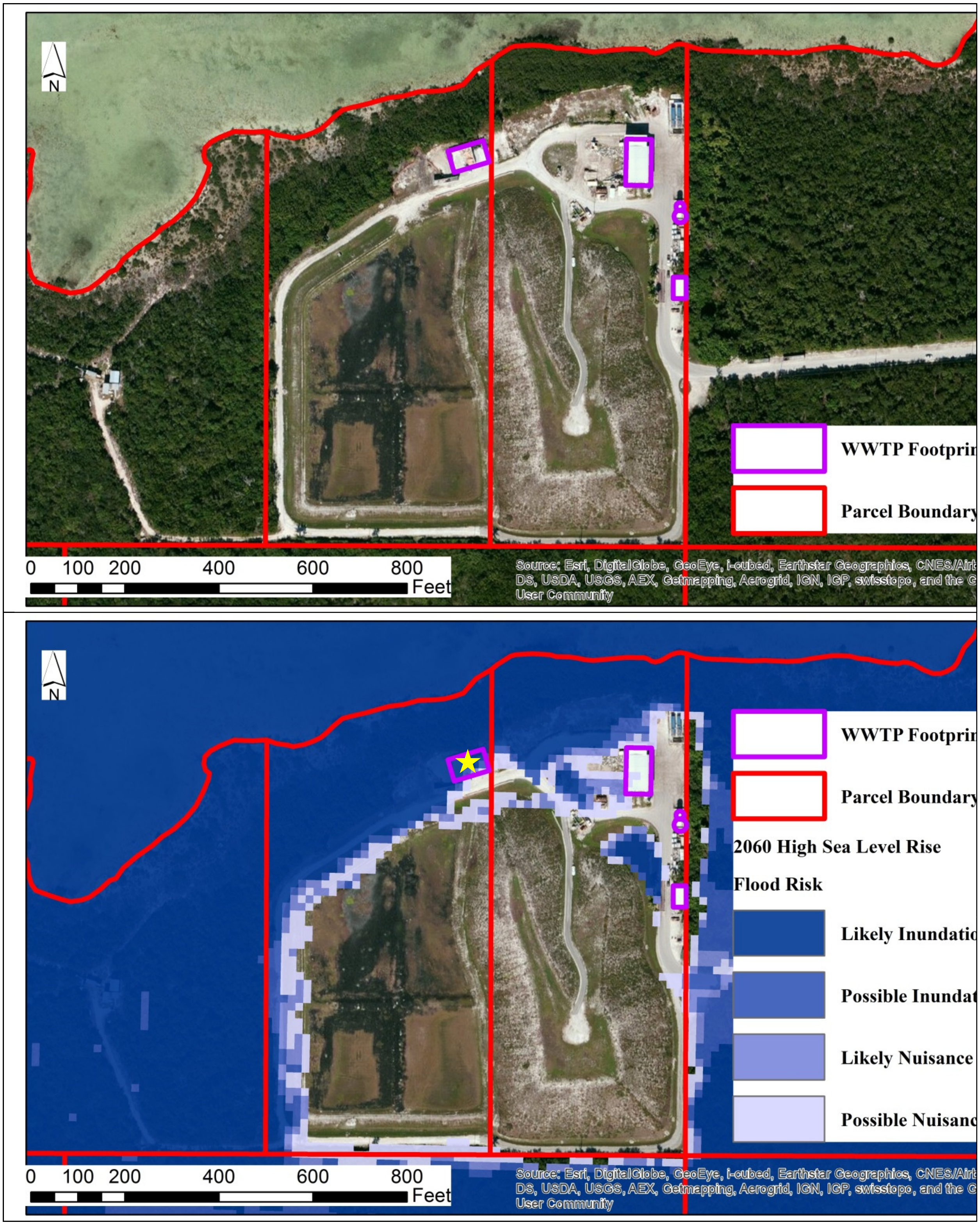


Figure 12: **Layton Wastewater Treatment Plant**. Aerial photograph (top) and 2060 high sea level rise assessment (bottom). Yellow star indicates structure with flood risk.

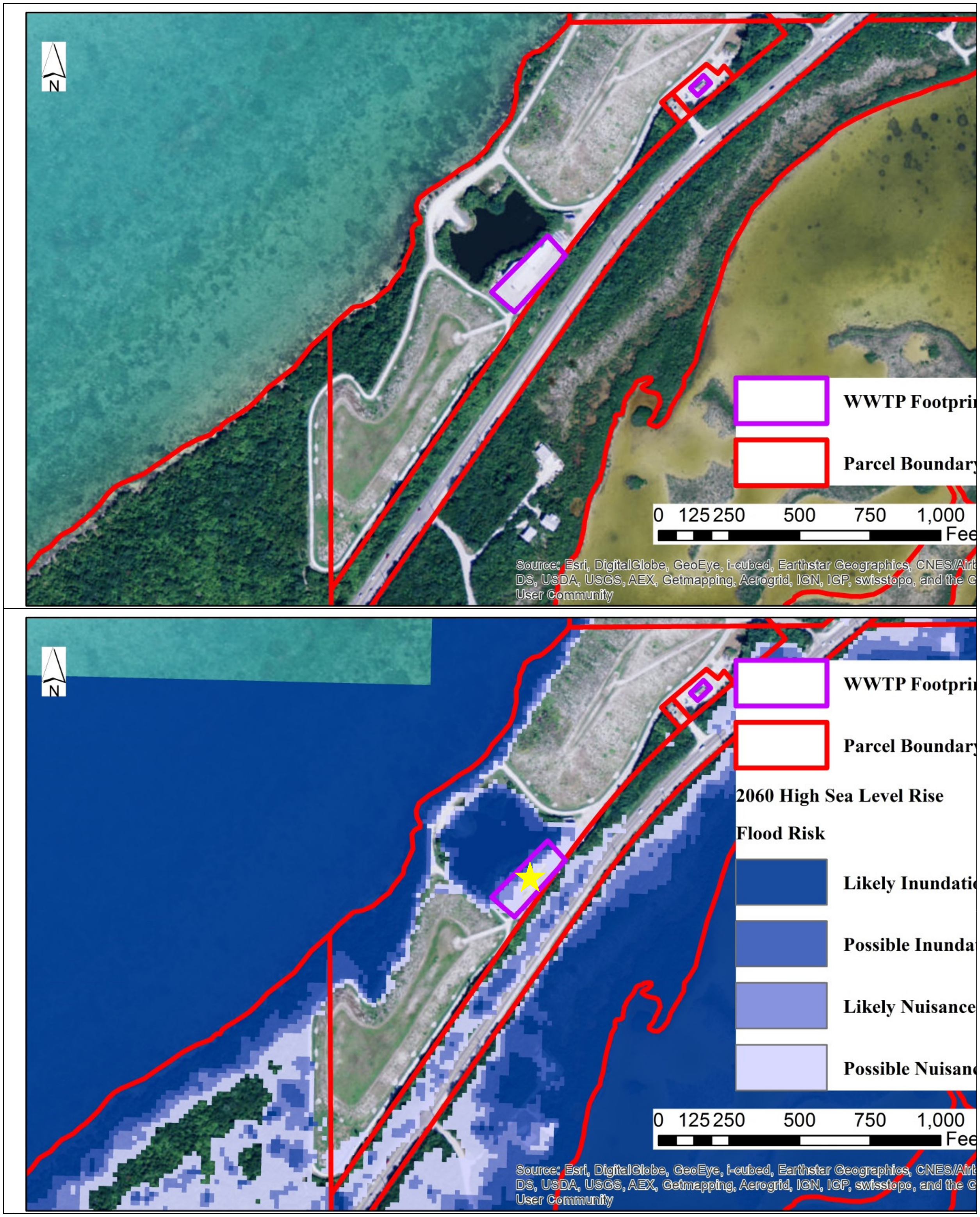
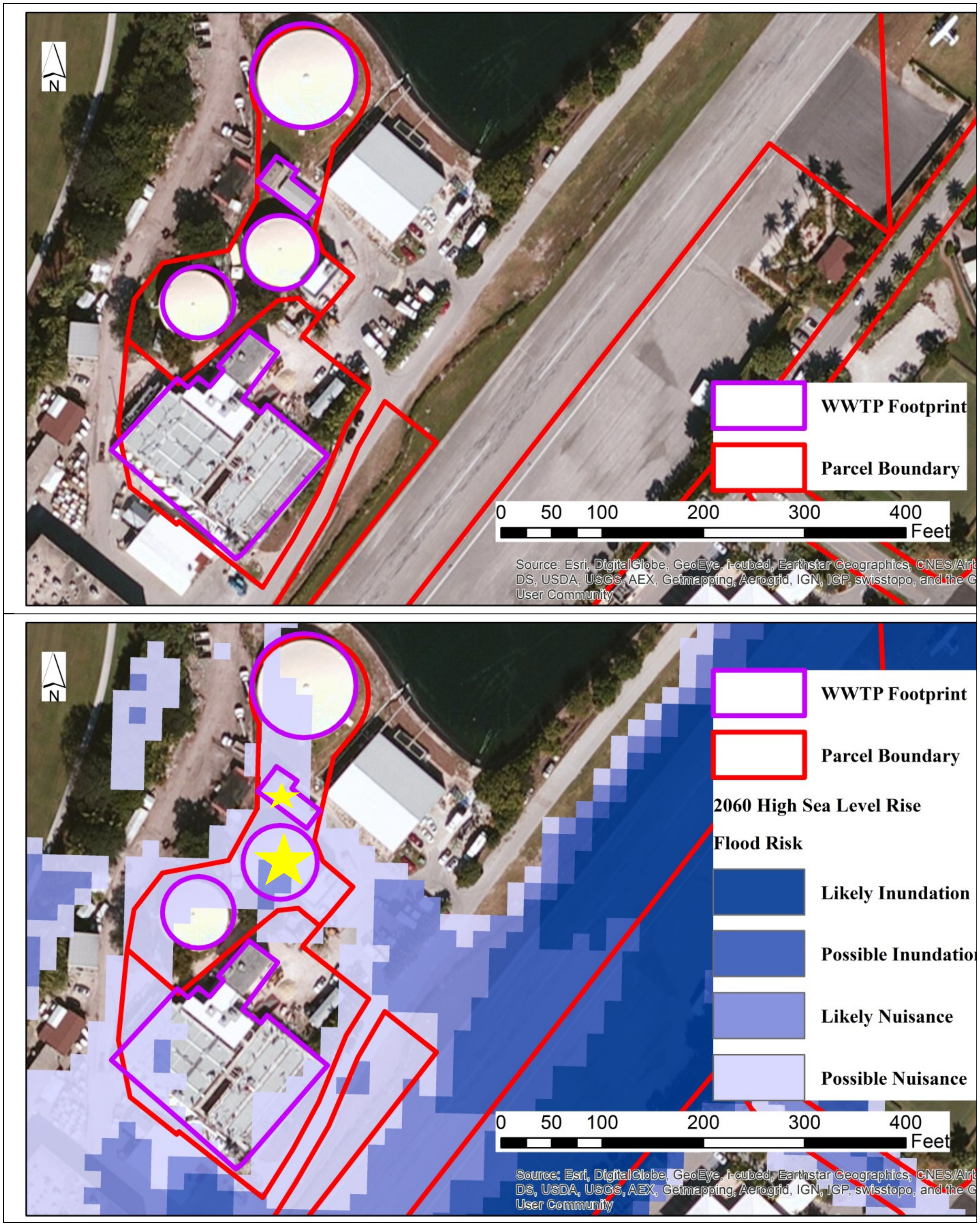


Figure 13: **North Key Largo Wastewater Treatment Plant**. Aerial photograph (top) and 2060 high sea level rise assessment (bottom). Yellow star indicates structure with flood risk.



Recommendations for Wastewater Treatment Infrastructure

It is important to note that ground level elevations within building footprints do not necessarily correspond to flood height tolerances, particularly during extreme event scenarios, for wastewater treatment facilities. For this reason, the current analysis alone does not provide sufficient information for development of infrastructure upgrades or other specific constructions actions that may be needed to address flood risks at any of the assessed wastewater treatment facilities. Site-specific analyses that include survey quality elevation data of sensitive components and engineering assessments of infrastructure resistance to floodwaters are recommended as a critical next step to determine the present and future vulnerability of wastewater treatment facilities to extreme flood events.

Visual assessment of each facility's overlay map does, however, suggest that structures and surrounding parcels associated with the Key Haven (Figure 8) and Bay Point (Figure 9) could be exposed to widespread tidal flood risk under the 2060 high sea-level rise scenario. Consultations with Monroe County and FKAA staff indicate that the Key Haven facility is scheduled for decommission soon after the Cudjoe Regional Wastewater Treatment Plant enters into service. This decommissioning action can be expected to mitigate any long-term sea-level rise concerns associated with the Key Haven site. The relatively low elevation of the Bay Point Wastewater Treatment Plant suggests that large-scale infrastructure maintenance and upgrade decisions for this facility should likely include potential stressors from future sea-level rise as a priority design criterion. This recommendation is particularly important to consider if future tide gauge monitoring indicates that a high end sea-level rise trajectory is being realized.

Given Monroe County's unique history of centralized wastewater treatment development and known vulnerability to sea-level rise, it is likely appropriate for the County to require that site planning and design of any new wastewater treatment facilities should include resilience to future sea-level rise as a primary engineering consideration. It is likely also appropriate to require that significant maintenance, upgrade, or expansion of any existing wastewater treatment facilities consider stressors from sea-level rise within the life-cycle design framework.

The EPA (2014) has recently released a guidance document for auditing site-level flood resilience of wastewater infrastructure. Following this guide, we specifically recommend that the Monroe County's Floodplain Coordinators be supplied with site-level assessments that characterize resistance of above-ground structures and associated electrical components to damages from extreme event flooding. Development of maintenance recording protocols and, as necessary, engineering assessment to assess resilience of below-grade wastewater pipes and pump infrastructure to increased saltwater incursion associated with sea-level rise is also recommended.

From a long-term planning perspective, flood hazards from a high sea-level rise scenario would be expected to alter current patterns of resident population settlement and the magnitude of visitor travel within the Florida Keys (Mozumder et al. 2011; Zhang et al. 2011; Flugman et al. 2012). We therefore recommend that future siting and capacity decisions for Monroe County's wastewater treatment facilities under a high sea-level rise scenario therefore should not only account for the flood risks at the site of wastewater treatment facilities themselves, but also associated changes in the resident population and economic activity of wastewater service areas. Although the high range of uncertainty associated with future sea-level rise projections currently prevents confident assessment in the timing of any such population shifts, accumulation of additional knowledge about the trajectory of sea-level rise is expected to narrow the bounds of projection uncertainty over the next two decades. With the benefit of such additional knowledge it likely will be appropriate to revisit the specific future flood vulnerabilities for each wastewater treatment plants, as well as holistically evaluate the range of expected changes in service population over the life cycle of these facilities.

Flood Risk Assessment for Electric Utility Infrastructure

Electrical power in the Florida Keys is provided by two utilities: 1) Keys Energy Services (KES), which serves Key West and the Lower Keys south of the Seven Mile Bridge; and 2) Florida Keys Electric Cooperative Association (FKEC), which serves the Upper and Middle Keys north of the Seven Mile Bridge.

As part of this sea level rise vulnerability assessment, point geography information was obtained for the following seven electric utility sites deemed as critical infrastructure by Monroe County: 1) KES South Stock Island generating plant; 2) KES South Stock Island substation; 3) KES Big Coppitt facility; 4) FKEC Marathon substation; 5) FKEC James T. Ellis facility; 6) FKEC Rock Harbor station; and 7) FKEC Tavernier Operations Center. Infrastructure footprint layers were digitized for each of these facilities, resulting in a total of 34 separate footprint polygons. Ground level elevations within these footprints were calculated using the Zonal Statistics methodology described above for public buildings and wastewater treatment plants.

Results of these analyses, as summarized in Table 8, indicate that ground elevations for all assessed electrical utility infrastructure are higher than the threshold associated with regular (non-storm) tidal flood risk at 2060 under the high sea level rise scenario. It is well-known that flooding of electrical infrastructure poses very high danger to human health, can result in catastrophic system failure, and generally requires significant expense to make post-flooding repairs. As such, the low vulnerability of assessed electric utility infrastructure to sea-level rise through at least 2060 can be viewed as a direct consequence of these facilities being sited and designed to ensure low exposure to flood risks.

<u>Recommendations for Electric Utility Infrastructure</u>

Although the footprint analysis shows no risk from regular tidal flooding to assessed electrical utility facilities through 2060 under the high sea level rise scenario, ground elevations within several footprints do indicate potential exposure to extreme event flooding. Additional site-level evaluations are, however, needed to determine above-ground elevations of sensitive components and associated extreme event flood risk for these facilities.

Information was not presently available to assess exposure of more localized electrical equipment, particularly within the context of private homes and businesses, to future tidal flooding associated with sea-level rise. Large-scale digitization of Elevation Certificates that contain specific information about the siting and elevation of electrical equipment is a suggested future step to develop comprehensive information about the scale of this risk. Such assessments are needed as a basis for determining the appropriateness of policy options for preventing and mitigating future tidal flooding risks to electrical infrastructure across Monroe County.

Table 8: **LIDAR-Based Ground Elevations for Electric Infrastructure**. No regular tidal flooding risk is identified under any sea level rise scenario for these facilities.

FACILITY NAME	FT ABOVE MHHW	2060 TIDAL FLOOD RISK, HIGH SEA LEVEL RISE SCENARIO
KEYS ENERGY SERVICES SUBSTATION	4.27	N/A
KEYS ENERGY SERVICES SUBSTATION	4.27	N/A
KEYS ENERGY SERVICES GENERATING PLANT	4.79	N/A
FKEC - MARATHON SUBSTATION	4.85	N/A
FKEC - MARATHON SUBSTATION	5.02	N/A
KEYS ENERGY SERVICES GENERATING PLANT	5.04	N/A
FKEC - MARATHON SUBSTATION	5.04	N/A
FKEC - MARATHON SUBSTATION	5.09	N/A
FKEC - MARATHON SUBSTATION	5.10	N/A
KEYS ENERGY SERVICES GENERATING PLANT	5.25	N/A
FKEC - MARATHON SUBSTATION	5.35	N/A
FKEC - MARATHON SUBSTATION	5.35	N/A
FKEC - TAVERNIER OPERATIONS CENTER	5.37	N/A
KEYS ENERGY SERVICES GENERATING PLANT	5.51	N/A
FKEC - MARATHON SUBSTATION	5.51	N/A
FKEC - MARATHON SUBSTATION	5.57	N/A
KEYS ENERGY SERVICES GENERATING PLANT	5.58	N/A
KEYS ENERGY SERVICES GENERATING PLANT	5.59	N/A
KEYS ENERGY SERVICES GENERATING PLANT	5.84	N/A
KEYS ENERGY SERVICES FACILITY BIG COPPITT	5.92	N/A
FKEC - MARATHON SUBSTATION	6.01	N/A
FKEC - MARATHON SUBSTATION	6.09	N/A
KEYS ENERGY SERVICES GENERATING PLANT	6.51	N/A
FKEC - MARATHON SUBSTATION	6.58	N/A

FKEC - MARATHON SUBSTATION	6.61	N/A
KEYS ENERGY SERVICES GENERATING PLANT	6.83	N/A
FKEC - MARATHON SUBSTATION	6.83	N/A
KEYS ENERGY SERVICES FACILITY BIG COPPITT	6.93	N/A
KEYS ENERGY SERVICES FACILITY BIG COPPITT	6.93	N/A
KEYS ENERGY SERVICES GENERATING PLANT	7.00	N/A
FKEC - TAVERNIER OPERATIONS CENTER	8.05	N/A
FKEC - ROCK HARBOR STATION	9.15	N/A
FKEC - JAMES T ELLIS FACILITY	9.35	N/A
FKEC - TAVERNIER OPERATIONS CENTER	9.47	N/A

Climate Change Risks for Water Supply

Public water throughout Monroe County is provided by the Florida Keys Aqueduct Authority (FKAA; http://www.fkaa.com/our_water_source.htm). The majority of FKAA's water supply is obtained from a freshwater Biscayne Aquifer well-field in southern Dade County near Florida City. This freshwater is treated prior to public distribution at the J. Robert Dean Water Treatment Plant, and then pumped through a 130-mile transmission line that stretches to Key West.

During dry climate conditions and high demand periods, FKAA has the capacity to utilize limited amount of brackish groundwater from the Floridan aquifer. This brackish water is treated through a reverse osmosis desalination process at the J. Robert Dean Water Treatment Plant. Additional seawater desalination facilities located in Stock Island and Marathon are utilized by FKAA for public water supply in the case of emergency disruptions to the main pipeline source.

Climate change and saltwater intrusion of the Biscayne Aquifer

The Biscayne Aquifer is characterized by limestone and sands with extremely high porosity, as well as close hydrologic connectivity with regional surface water resources, particularly the Everglades ecosystem. The aquifer is known to produce large amounts of high quality freshwater and recharge rapidly with rainfall events. For these reasons, hydrogeologists generally list the Biscayne Aquifer among the most productive groundwater resources in the world (Stringfield et al. 1979; Andersen et al. 1988; Prinos et al. 2014).

However, saltwater intrusion into the Biscayne Aquifer has long been known as a serious public water supply concern for southeast Florida (e.g., Parker et al. 1955; Leach et al. 1972; Klein and Waller 1985; Andersen et al. 1988; Sonenshein 1996; Prinos et al. 2014). A variety of local human-disturbance factors have historically contributed to saltwater intrusion into the Biscayne Aquifer. These include construction of drainage canals that directly connect inland freshwater surface waters to coastal water bodies, lowered surface headwater pressures in the Everglades due to regional flood control and agricultural drainage, large-scale groundwater pumping for municipal and agricultural supply, and development of impervious urban surfaces that reduce local recharge (Andersen et al. 1988; Dausman et al. 2005; Prinos et al. 2014).

Notably, the most severe saltwater intrusion issues in southeast Florida have been documented to occur either in wells located along the eastern reaches of the Biscayne Aquifer near the Atlantic Ocean, or in wells located near drainage canals that facilitate linear transport of saltwater into more inland areas. By contrast, wells in more western area of the Biscayne Aquifer and located at some distance from large drainage canals have generally shown lower historic risk to saltwater intrusion. Increased monitoring of saltwater movement in the Biscayne Aquifer, decreases of groundwater withdrawals from high-risk well-fields, abandonment and westward relocation of highly affected well-fields, and large-scale regional hydrologic interventions associated with the multi-decade Comprehensive Everglades Restoration Plan (CERP) have all been implemented for the purpose of mitigating regional saltwater intrusion throughout southeast Florida (Prinos et al 2014).

Even with benefit of these management strategies, there is increasing recognition that climate change poses an additional set of stressors that further threaten the long-term viability of Biscayne Aquifer well-fields as a source of high quality freshwater supply. Joint studies by the United States Geological Survey, South Florida Water Management District, and local water suppliers have specifically documented historic sea level rise as an important contributing factor in regional landward movement of the saltwater interface across the Biscayne Aquifer over the past several decades (Dausman et al. 2005; Prinos et al. 2014). Areas near well-fields with water tables that have been lowered by freshwater pumping are especially vulnerable to rapid contamination from rising seas (Langevin and Zygnerski 2013), as the high porosity of the aquifer permits ocean waters to readily infiltrate through and beneath cones of depression created by well-fields.

It is also widely documented that severe droughts can quickly lower the freshwater lens and in some cases result in both landward and upward movement of the saltwater interface within the Biscayne Aquifer (Peters and Reynolds 2008). This saltwater movement is associated with decreases in interconnected regional surface water levels. The decreases occur due to evaporation and lack of groundwater recharge through rainfall replenishment, as well as increased human demand for freshwater supply from surface and groundwater surfaces for agricultural and urban landscape uses during drought periods (Bloetscher et al. 2010). Some climate change models suggest that increasingly severe drought conditions and higher dry season temperatures are more likely to occur within southeast Florida over the next several decades, further stressing regional freshwater resources and providing conditions that promote the landward encroachment of saltwater lenses (Bloetscher et al. 2011). Thus, there is great regional concern that the interacting stressors of sea level rise, increased water demand, drainage canals that promote landward movement of sea water, and anomalously severe droughts could together precipitate significant regional saltwater contamination of freshwater wells within the Biscayne Aquifer over the next decades (Obeysekera et al. 2011; Aumen et al. 2015).

Climate Change and Future FKAA Water Sources

The FKAA well-field is among the most southern and western of the public supply well-fields within the Biscayne Aquifer system. This location, along with the relatively low water demands of Monroe County as compared to much larger Miami-Dade and Broward counties, has generally made the FKAA well-field show less near-term vulnerability to sea level rise and associated saltwater intrusion than larger Biscayne Aquifer well-fields located to the north and east (Hearn et al. 2013). However, long-term monitoring and updated hydrologic modeling has indicated that a wedge of saltwater intrusion has penetrated into the Biscayne Aquifer along the Card Sound Road Canal toward the FKAA well-field (Prinos et al. 2014; Figure 14). Although Prinos et al. (2014) note that recently installed saltwater control structures in the Card Sound Road Canal systems are expected to provide important mitigation of this saltwater intrusion, water managers and planners at FKAA (2011) have recognized that the cumulative impacts of sea-level rise, drought stress, and regional population growth may limit Monroe County's future capacity for freshwater withdrawals from the current Biscayne Aquifer wellfield.

Clearly, a rate of future sea level rise that trends toward the high end climate change scenario (i.e., 24 inches by 2060) would pose significantly greater near-term and long-term saltwater intrusion concerns to the FKAA well-field (and all Biscayne Aquifer well-fields) than the low end scenario (i.e., 9 inches by 2060). However, uncertainties among the complex and multi-variate factors – such as drought, regional population changes, Everglades restoration, and major storm surges – that affect saltwater intrusion currently preclude confident temporal forecasts as to the sustainable yield of the FKAA well-field under any sea level rise scenario through 2060.

Due to these inherent uncertainties, continuation and expansion of regional saltwater intrusion monitoring efforts by the South Florida Water Management District (SFWMD), United States Geological Survey (USGS), FKAA, and other regional water suppliers that utilize the Biscayne Aquifer are critical to identify emerging salinity intrusion issues quickly and implement appropriate near-term mitigation measures. Over the longer term, it is recognized that development of greater desalination capacity, increased reuse of wastewater resources, deployment of local rainfall capture devices (e.g., cisterns), local and regional conservation, and other regional alternative supply mechanisms (e.g., surface water reservoirs and aquifer storage and recovery) will be required to ensure sustainable water supply for future residents and visitors to Monroe County (FKAA 2011; Borisova et al. 2013; SFWMD 2013). The compounding impacts of climate change provide additional impetus for continued investigation and appropriate deployment of these alternatives by FKAA, SFWMD, and other managers and water providers.

Sea Level Rise and Water Supply Infrastructure

In cooperation with this sea level rise vulnerability assessment for Monroe County and in accordance with FKAA's (2011) ongoing goal to assess "impact thresholds for sea level rise and needed infrastructure," FKAA officials provided our project team with a series of point locations for various types of water supply distribution infrastructure within Monroe County. These files included water storage tanks, system valves, control valves, and cathodic rectifiers associated with the water distribution network, as well as a series of test stations and sampling stations maintained by FKAA. Values for MHHW-based LIDAR elevation were extracted for all points associated with this infrastructure. These elevation values were then used to assign a future flood vulnerability score for each individual infrastructure point. Cumulative results of these assessments are provided in Tables 9a-9d.

Importantly, the vulnerability assessment for each individual infrastructure point is based solely upon the extracted ground elevation associated with each point, and therefore does not account for any additional above-ground elevation of components that may be especially vulnerable to saltwater flooding. While ground-level exposure to tidal flooding generally provides some increased risk of materials corrosion and periodic loss of maintenance access, interpretation of specific long-term risks and vulnerability thresholds will require additional site-level information (i.e., above ground elevations, presence and condition of saltwater flood-proofing materials, and overall saltwater resistance of components). To support the ongoing climate adaptation planning efforts at FKAA (2011), field and maintenance technicians can utilize the extracted MHHW elevations as an important objective criterion for enhanced monitoring of saltwater corrosion of individual infrastructure pieces. As appropriate, such monitoring can identify needs for retrofit maintenance and/or prioritization for replacing infrastructure to avoid or resist future saltwater exposure.

Recommendations for Water Supply Infrastructure

The complex factors that contribute to saltwater intrusion require sustained cooperation between Monroe County, FKAA, SFWMD, USGS, and other agencies to monitor groundwater conditions in the south Dade wellfield area. Continuation of water conservation measures to reduce consumer demand for freshwater, development of alternative supply sources, and hydrologic restoration of the greater Everglades ecosystem are all recommended to reduce longterm saltwater intrusion risks into the FKAA wellfield.

Potential saltwater corrosion of water supply infrastructure due to increased tidal exposure is another risk that may be of increasing maintenance concern over the next decades. We recommend that FKAA technicians consult elevation data for water supply infrastructure, as developed through this project, to inform field monitoring and inspection of individual equipment. In particular, equipment with low-lying elevations may be flagged for closer inspection of potential saltwater corrosion, as well as site-collection of above ground elevations of any components that are sensitive to tidal flooding. Replacement of aging or vulnerable water supply infrastructure with designs that maximize resilience to future tidal flood exposure is also recommended.

Figure 14: Saltwater Intrusion in Biscayne Aquifer. Graphic extracted from Prinos et al. (2014, http://pubs.usgs.gov/sir/2014/5025/downloads/sir2014-5025_figure17large.pdf).

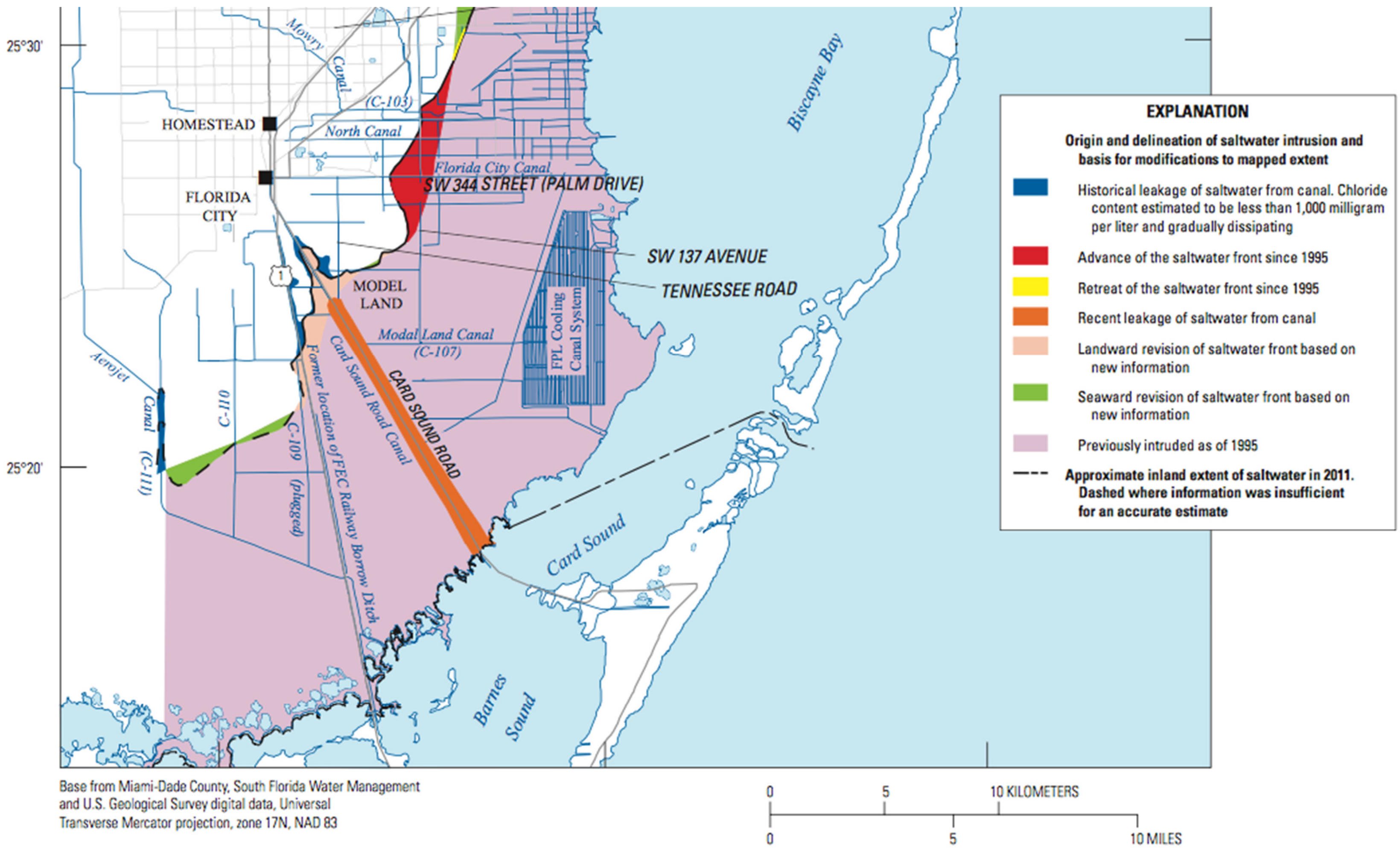


Table 9a: Flood Risk Assessment for FKAA Infrastructure, 3" Sea Level Rise. Flood risk thresholds are at ground level. Further site-level information is required to assess specific vulnerabilities of components to tidal flooding damage.

Infrastructure Type (Total Number)	2030 Flood Threshold: Low Sea Level Rise			
	Likely Inundation	Possible Inundation	Likely Nuisance	Possible Nuisance
Water Tanks (25)	N/A	N/A	N/A	N/A
Cathodic Rectifiers (55)	N/A	N/A	N/A	N/A
Control Valves (1,230)	N/A	88	118	109
System Valves (5,888)	N/A	87	175	436
Sampling Stations (184)	N/A	6	9	7
Test Stations (170)	N/A	2	5	4

Table 9b: Flood Risk Assessment for FKAA Infrastructure, 7" Sea Level Rise Flood risk thresholds are at ground level. Further site-level information is required to assess specific vulnerabilities of components to tidal flooding damage.

Infrastructure Type (Total Number)	2030 Flood Threshold: High Sea Level Rise			
	Likely Inundation	Possible Inundation	Likely Nuisance	Possible Nuisance
Water Tanks (25)	N/A	N/A	N/A	1
Cathodic Rectifiers (55)	N/A	N/A	2	2
Control Valves (1,230)	56	56	271	143
System Valves (5,888)	39	121	414	580
Sampling Stations (184)	6	3	24	13
Test Stations (170)	1	3	7	2

Table 9c: Flood Risk Assessment for FKAA Infrastructure, 9" Sea Level Rise Flood risk thresholds are at ground level. Further site-level information is required to assess specific vulnerabilities of components to tidal flooding damage.

Infrastructure Type (Total Number)	2060 Flood Threshold: Low Sea Level Rise			
	Likely Inundation	Possible Inundation	Likely Nuisance	Possible Nuisance
Water Tanks (25)	N/A	N/A	N/A	1
Cathodic Rectifiers (55)	N/A	N/A	2	2
Control Valves (1,230)	75	56	299	150
System Valves (5,888)	60	151	562	630
Sampling Stations (184)	6	4	27	13
Test Stations (170)	2	4	9	2

Table 9d: Flood Risk Assessment for FKAA Infrastructure, 24" Sea Level Rise Flood risk thresholds are at ground level. Further site-level information is required to assess specific vulnerabilities of components to tidal flooding damage.

Infrastructure Type (Total Number)	2060 Flood Threshold: High Sea Level Rise			
	Likely Inundation	Possible Inundation	Likely Nuisance	Possible Nuisance
Water Tanks (25)	N/A	2	7	1
Cathodic Rectifiers (55)	2	3	7	1
Control Valves (1,230)	264	183	602	165
System Valves (5,888)	695	795	2,173	863
Sampling Stations (184)	17	19	50	23
Test Stations (170)	9	6	19	11

Flood Risk Assessment for Roads

Increased tidal inundation of road beds and road surfaces is generally one of the earliest impacts of sea level rise observed in low lying coastal communities. Although saltwater infiltration into road surfaces may begin as an infrequent and temporary nuisance, repeated and severe inundation of road beds and road surfaces can cause a wide range of significant problems and expensive damages. The most readily apparent of these issues is blockage or restriction of traffic lanes due to flooding conditions and increased corrosion of metals on vehicles that may frequently pass through shallow saltwater puddles. Because roads often serve as conduits for stormwater, tidal flooding of roadways during heavy rains may in some cases result in loss of drainage potential that causes more widespread local flooding. Repeated tidal saturation of road bed soils and scour action across road surfaces may also in some cases result in wash out or partial collapse of road surfaces (Titus 2002).

Through funding provided by the Florida Department of Transportation (FDOT), the University of Florida GeoPlan Center has recently developed and publicly released a series of geographic information system (GIS) files that provide preliminary assessments of sea level rise inundation vulnerability for roads and other transportation systems (Thomas and Watkins 2013). The UF GeoPlan Center describes this GIS database in online links and project documentation as the "Sea Level Scenario Sketch Planning Tool" (http://sls.geoplan.ufl.edu/documents-links/), which we hereafter refer to as the "Sketch Planning Tool."

The Sketch Planning Tool is based upon a 5-meter horizontal resolution LIDAR DEM and is designed for landscape-level vulnerability assessments of road infrastructure. The Sketch Planning Tool project documentation (Thomas and Watkins 2013) notes that the 5-meter cell granularity of the DEM combined with the vertical uncertainty bounds in the underlying LIDAR data used to construct the DEM prevent warn against use of Sketch Planning Tool results at a site-level scale. This means that while generally high confidence can be put in the summation of results (e.g., road miles vulnerable to future flooding impacts) and the likelihood of general flood risks across Monroe County as indicted by the Sketch Planning Tool, less confidence can be placed in the geographic precision of results at the level of an individual road segment. Instead, the results from the Sketch Planning Tool provide a preliminary, but objective, assessment of potential vulnerabilities, which must then be further corroborated through site-specific information (e.g., existing reports of nuisance flooding, or site surveys that indicate road grade surfaces below elevation thresholds associated with future flood risks).

For this project, we modified the original Sketch Planning Tool datasets in two ways:

1) Incorporation of additional road segments contained with the Monroe County Property Appraiser's GIS archive, but not originally contained within the Sketch Planning Tool dataset. This provides for a more complete assessment of local roads not included within the Sketch Planning Tool.

2) Assessment of 2030 and 2060 flood vulnerability at possible nuisance flood thresholds (i.e., 1.08 above MHHW) in addition to inundation-level flooding for both the low and high sea level rise scenarios. This accounts for the fact that the onset of multiple nuisance flooding events a year will cause significant road maintenance and access issues well before the severe loss of services associated with inundation-level (i.e., daily) flooding.

Conservatively taking into account the uncertainty bounds of the LIDAR dataset, we defined the possible nuisance flood thresholds of road segments as: A) 2030 Low Sea Level Rise: 1.57 feet (19 inches); B) 2030 High Sea Level Rise: 1.90 feet (23 inches); C) 2060 Low Sea Level Rise: 2.07 feet (25 inches); and D) 2060 High Sea Level Rise: 3.32 feet (40 inches).

A summary of road miles within Monroe County that the Sketch Planning Tool indicates as vulnerable to nuisance flooding during king tide events (i.e., 1.08 feet above MHHW) with each sea level rise scenario is provided in Table 10. The road miles subject to potential inundation (i.e., tidal flooding on a daily basis) by each sea level rise scenario are provided in Table 11. A series of 1:50,000 scale visualizations from the Sketch Planning Tool for 2030 low and high sea level rise scenarios across the Florida Keys portion of Monroe County is provided as Figures 15a.1 – 15q.2.

In Figures 16a & 16b, we provide close-up visualizations of US Highway 1 on Lower Matecumbe Key (near Mile Marker 74) that the Sketch Planning tools indicate as potentially susceptibility to nuisance flooding under future king tide scenarios. Field visits to this site during king tide conditions (including November 24-25, 2014 & September 29, 2015) indicated evidence of significant tidal incursion into the shallow roadside swale on the northwest side of US Highway 1. These observations are congruent with the apparent susceptibility of this segment of US Highway 1 to near-term nuisance tidal flood risks, particularly during heavy rainfall events that may occur during high tides. Mitigation of this and other future nuisance flood risks on the US Highway 1 corridor is clearly a priority due to the critical importance of this highway as the sole transportation and emergency evacuation route in the Florida Keys portion of Monroe County.

Table 10: **Road Miles Vulnerable to Nuisance Flooding by Sea Level Rise Scenario**. Road segments in Monroe County identified using the Sketch Planning Tool (Thomas and Watkins 2013).

	Original Road Miles	2030 Low	2030 High	2060 Low	2060 High
US Highway 1	112.5	2.3	3.2	4.0	14.3
All Roads	830.0	143.6	188.0	217.6	449.9

Table 11: Road Miles Vulnerable to Inundation Flooding by Sea Level Rise Scenario. Road segments in Monroe County identified using the Sketch Planning Tool (Thomas and Watkins 2013).

	Original Road Miles	2030 Low	2030 High	2060 Low	2060 High
US Highway 1	112.5	0.1	0.4	0.7	4.0
All Roads	830.0	14.8	23.5	54.5	217.6

Figure 15a.1: **FDOT Sea Level Rise Sketch Planning Tool, 2030 Low Sea Level Rise, Northern Key Largo**

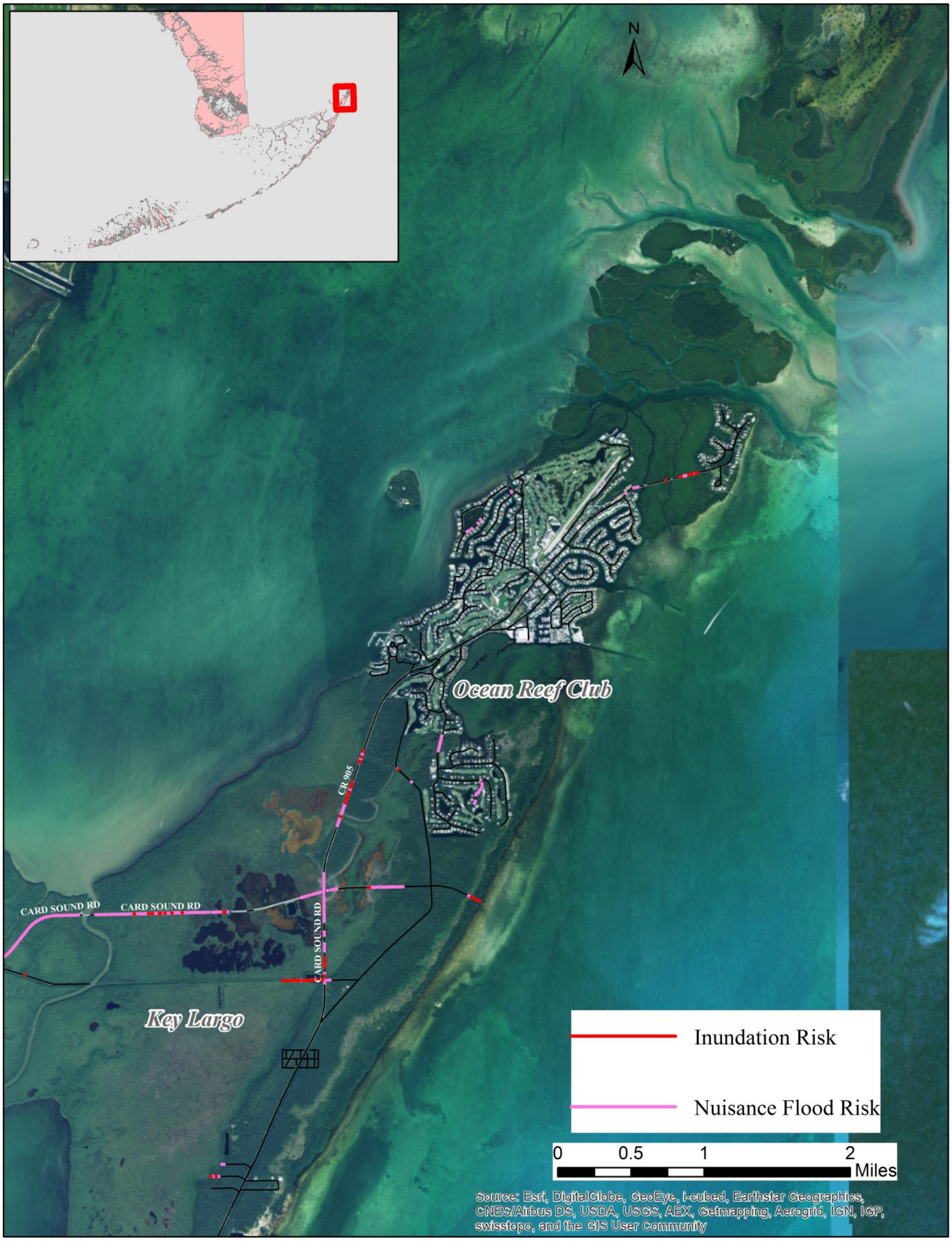


Figure 15a.2: **FDOT Sea Level Rise Sketch Planning Tool, 2030 High Sea Level Rise, Northern Key Largo**

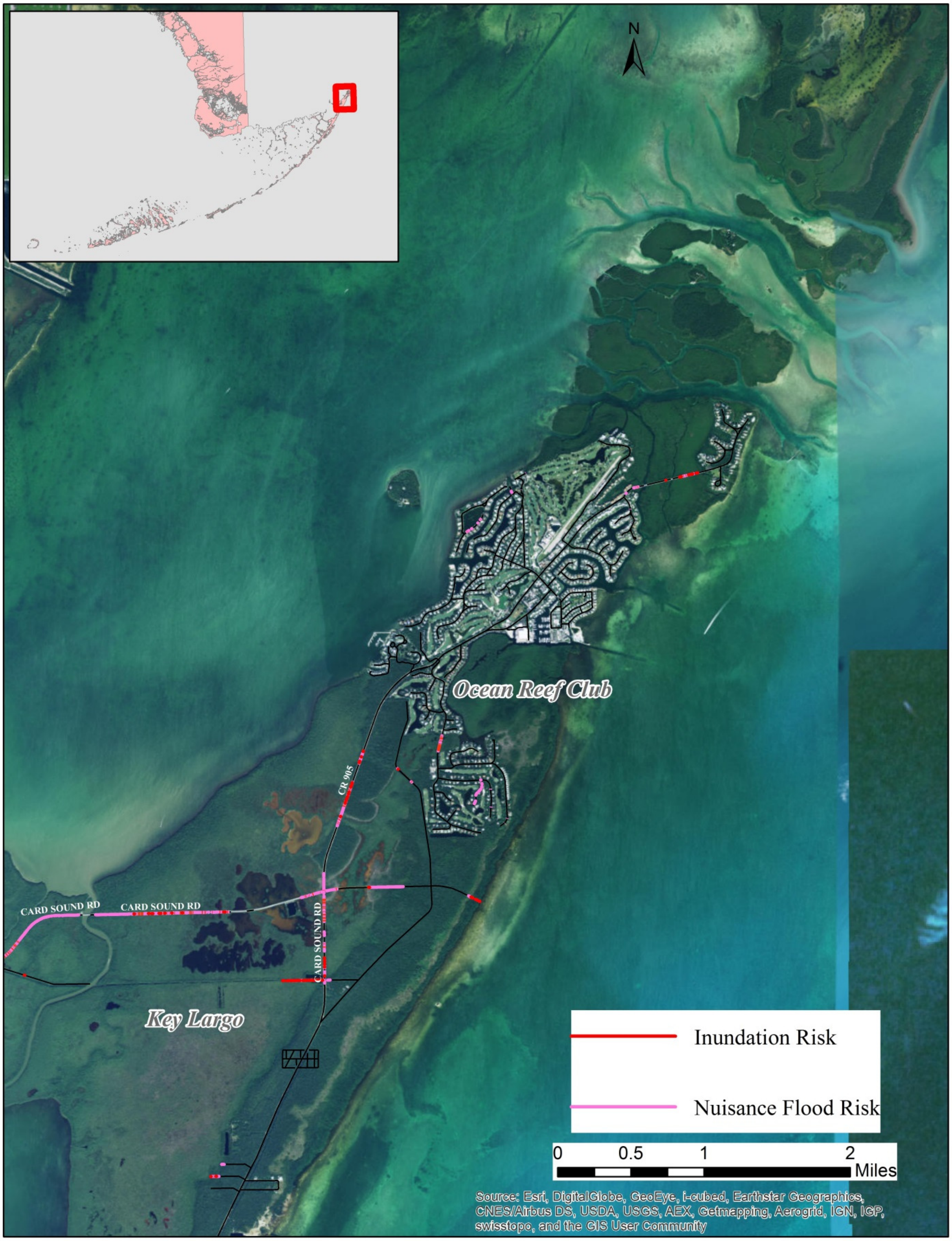


Figure 15b.1: **FDOT Sea Level Rise Sketch Planning Tool, 2030 Low Sea Level Rise, North Central Key Largo**

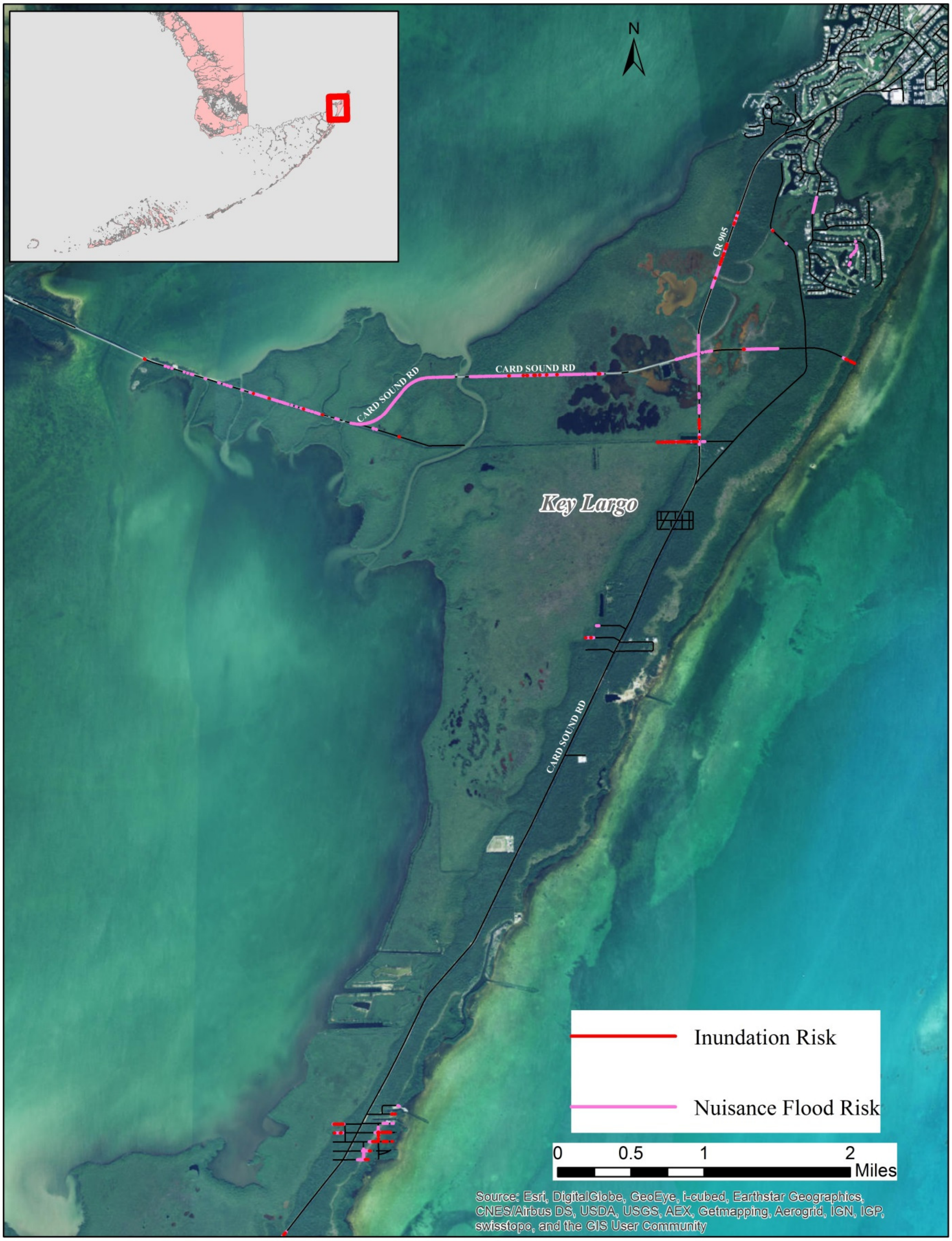


Figure 15b.2: **FDOT Sea Level Rise Sketch Planning Tool, 2030 High Sea Level Rise, North Central Key Largo**

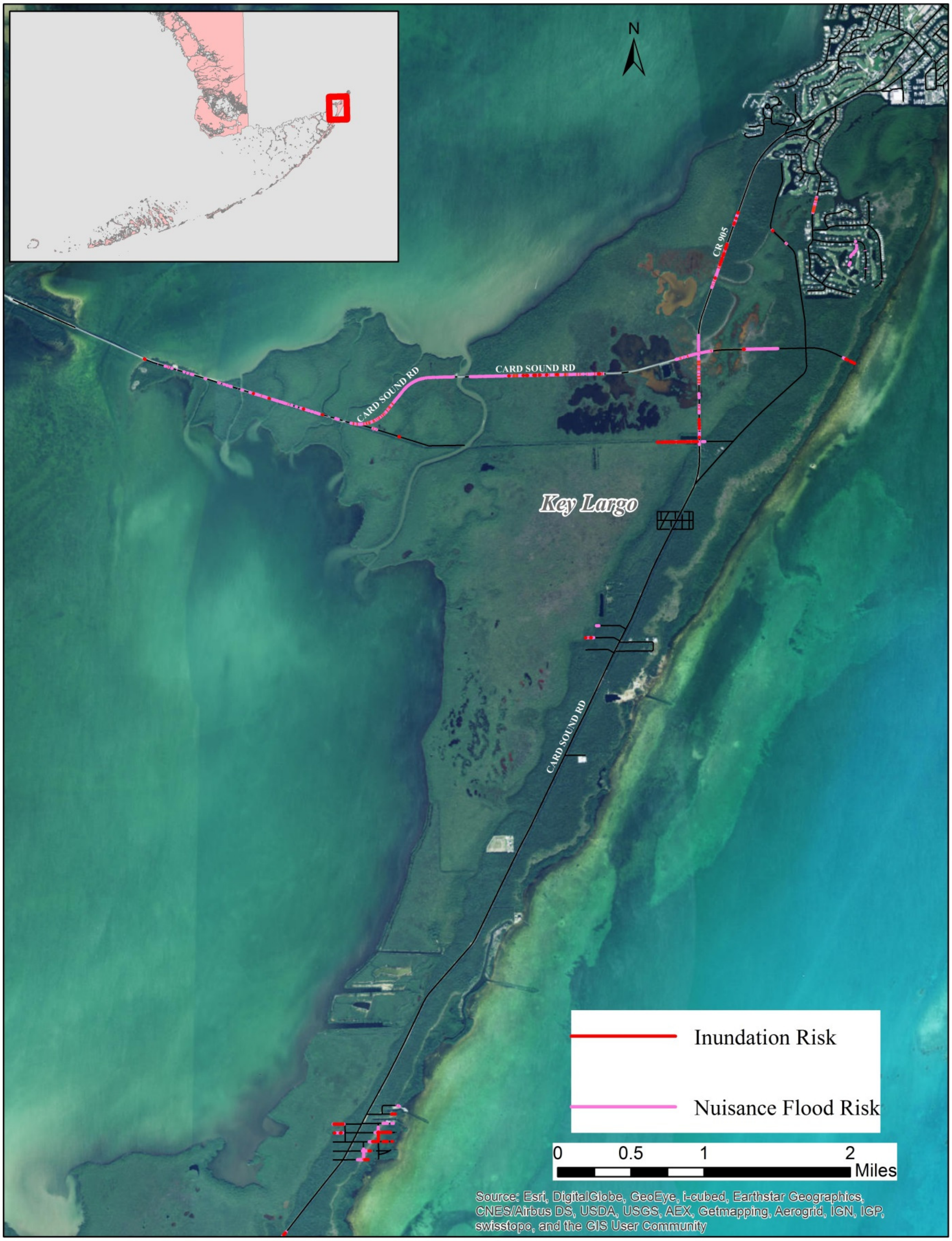


Figure 15c.1: **FDOT Sea Level Rise Sketch Planning Tool, 2030 Low Sea Level Rise, South Central Key Largo**

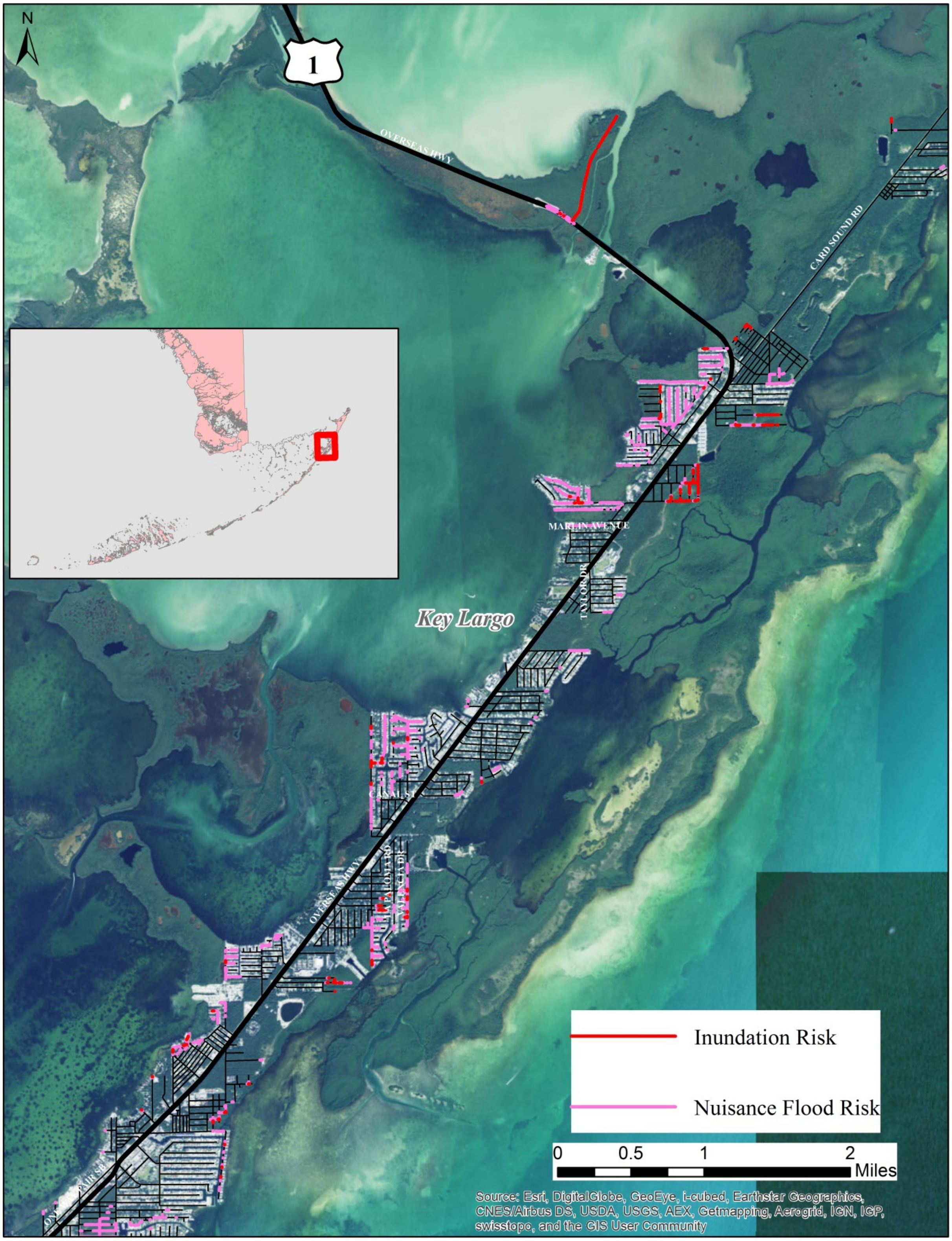


Figure 15c.2: **FDOT Sea Level Rise Sketch Planning Tool, 2030 High Sea Level Rise, South Central Key Largo**

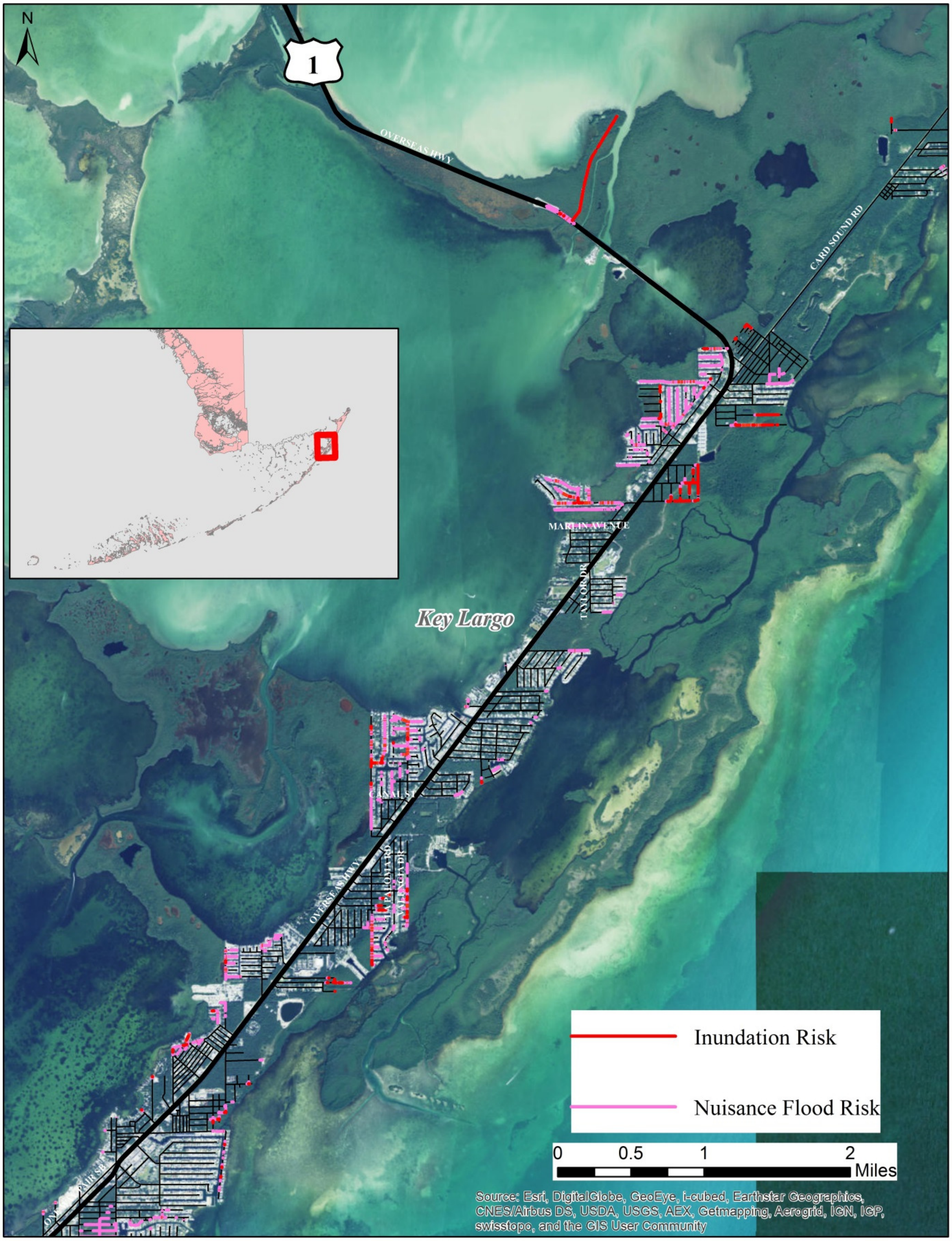


Figure 15d.1: **FDOT Sea Level Rise Sketch Planning Tool, 2030 Low Sea Level Rise, South Key Largo to Plantation Key**

Figure 15d.2: **FDOT Sea Level Rise Sketch Planning Tool, 2030 High Sea Level Rise, South Key Largo to Plantation Key**

Figure 15e.1: **FDOT Sea Level Rise Sketch Planning Tool, 2030 Low Sea Level Rise, South Plantation Key to Upper Matecumbe Key**

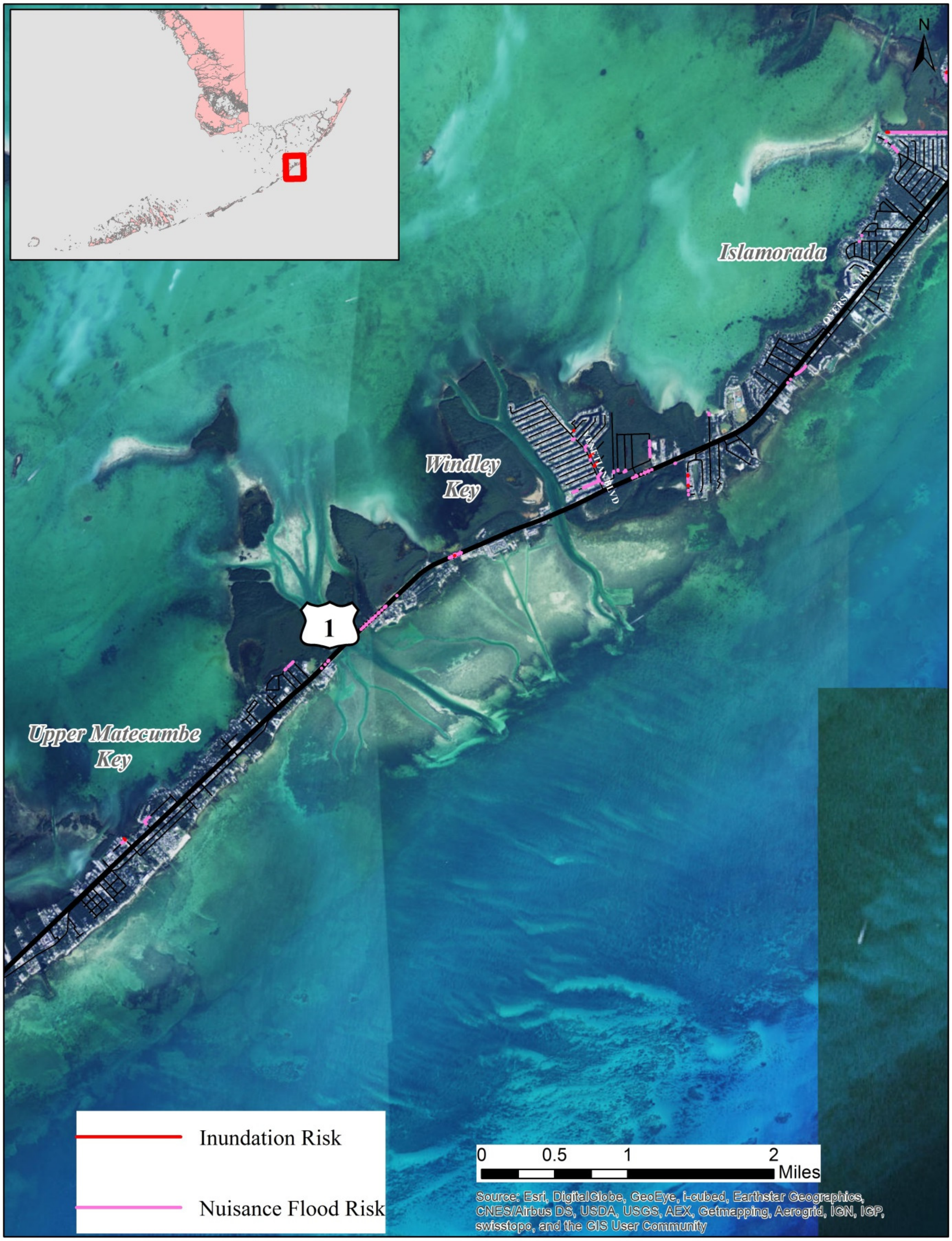


Figure 15e.2: **FDOT Sea Level Rise Sketch Planning Tool, 2030 High Sea Level Rise, South Plantation Key to Upper Matecumbe Key**

Figure 15f.1: **FDOT Sea Level Rise Sketch Planning Tool, 2030 Low Sea Level Rise, Upper Matecumbe Key to Lower Matecumbe Key**

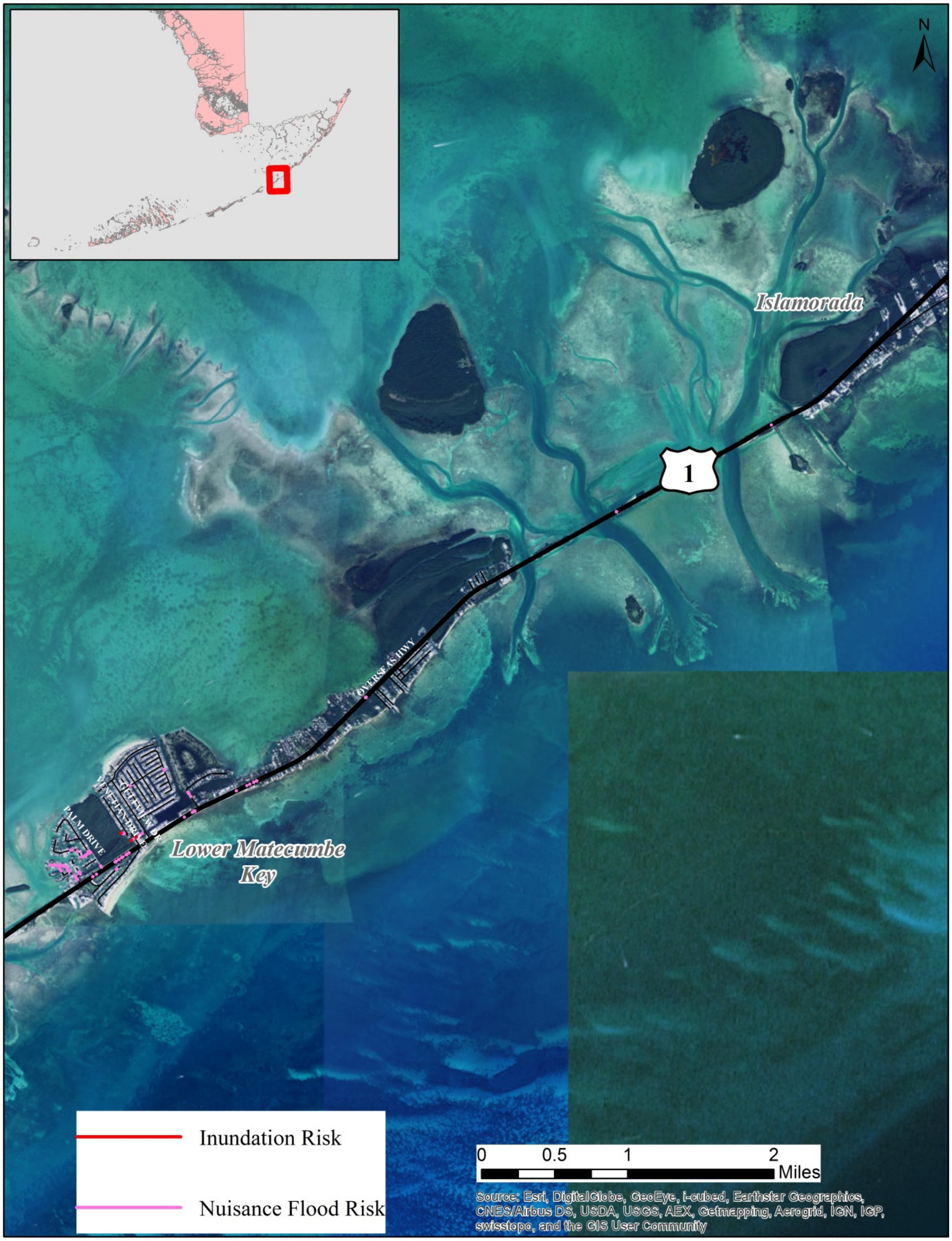


Figure 15f.2: **FDOT Sea Level Rise Sketch Planning Tool, 2030 High Sea Level Rise, Upper Matecumbe Key to Lower Matecumbe Key**

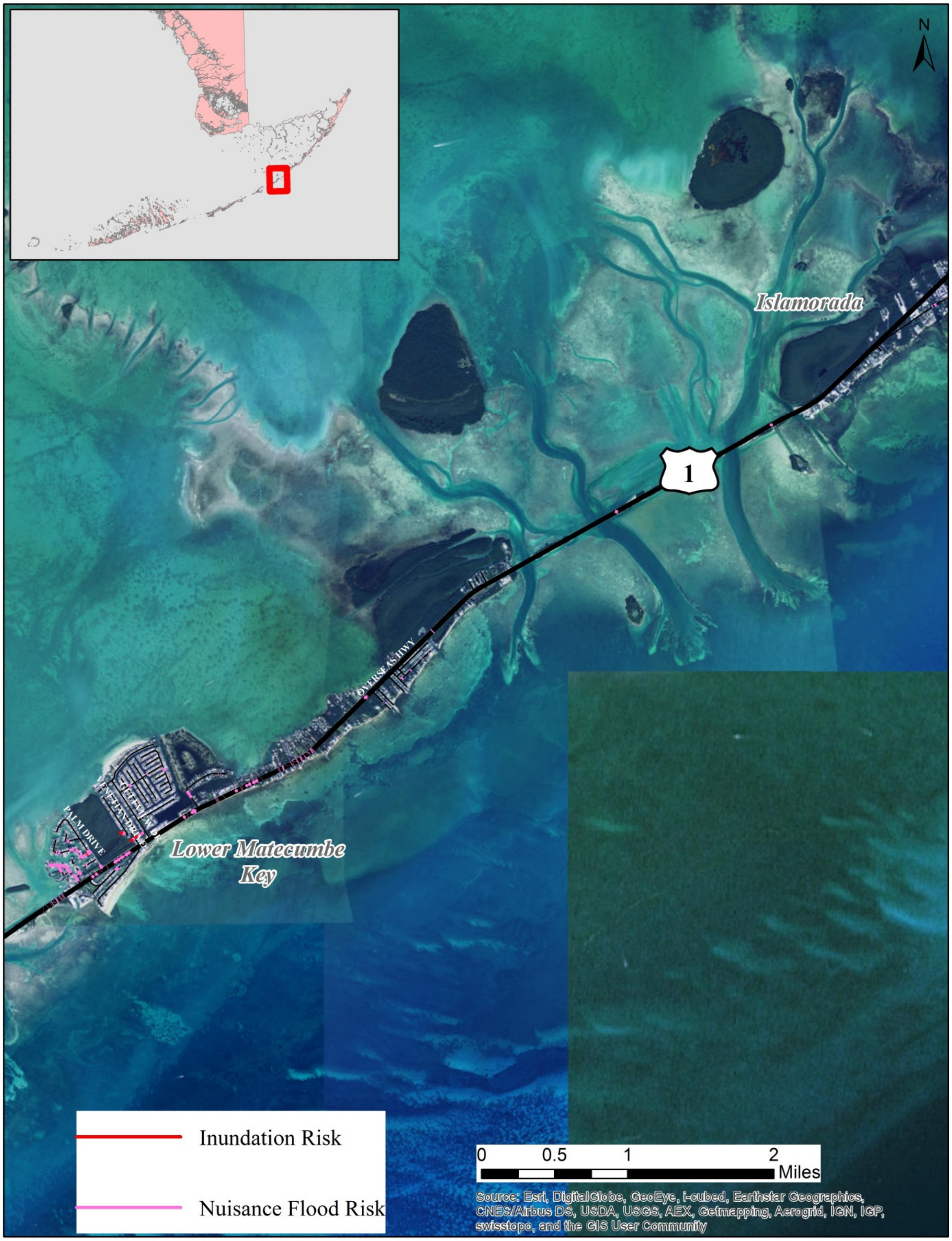


Figure 15g.1: **FDOT Sea Level Rise Sketch Planning Tool, 2030 Low Sea Level Rise, Layton**

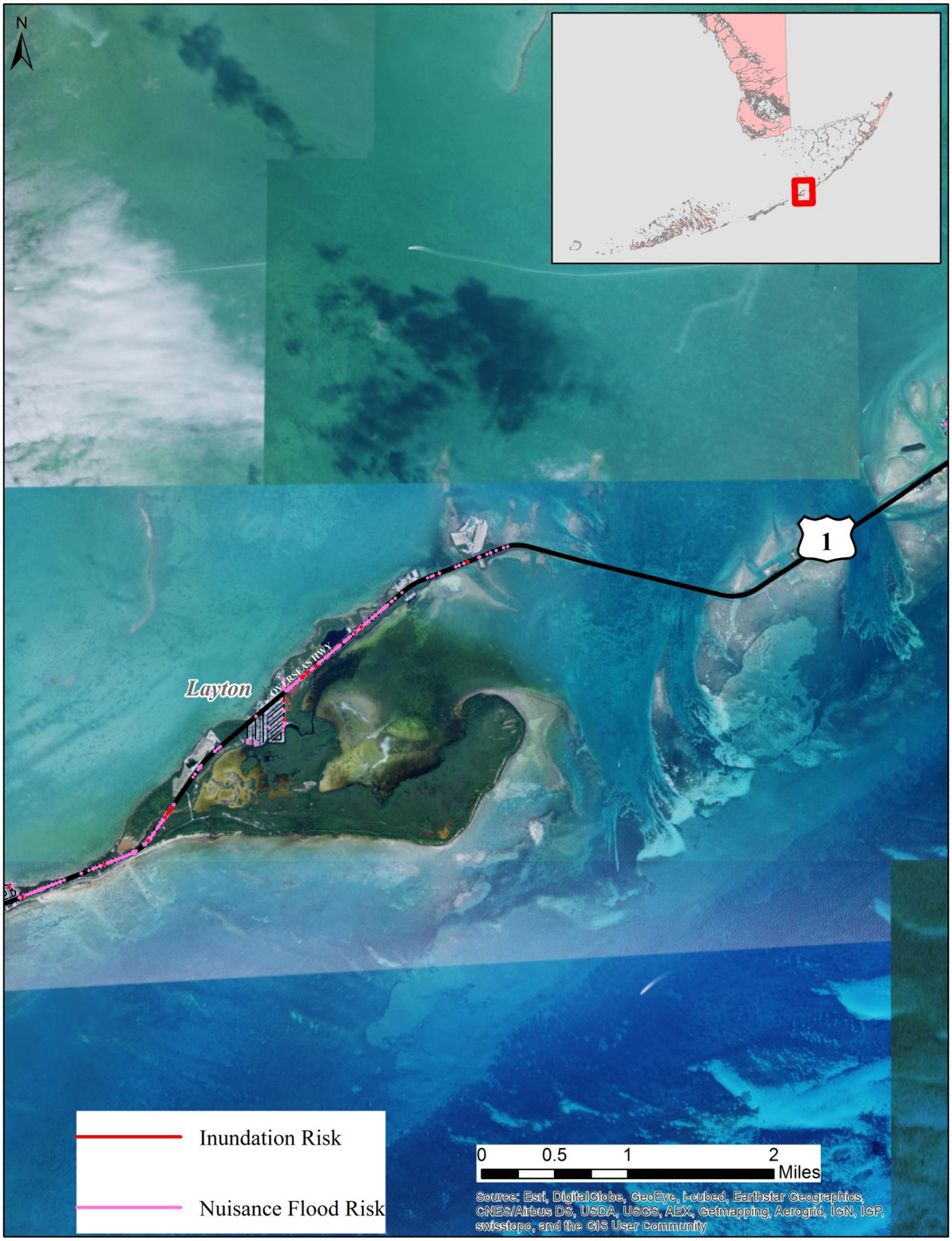


Figure 15g.2: **FDOT Sea Level Rise Sketch Planning Tool, 2030 High Sea Level Rise, Layton**

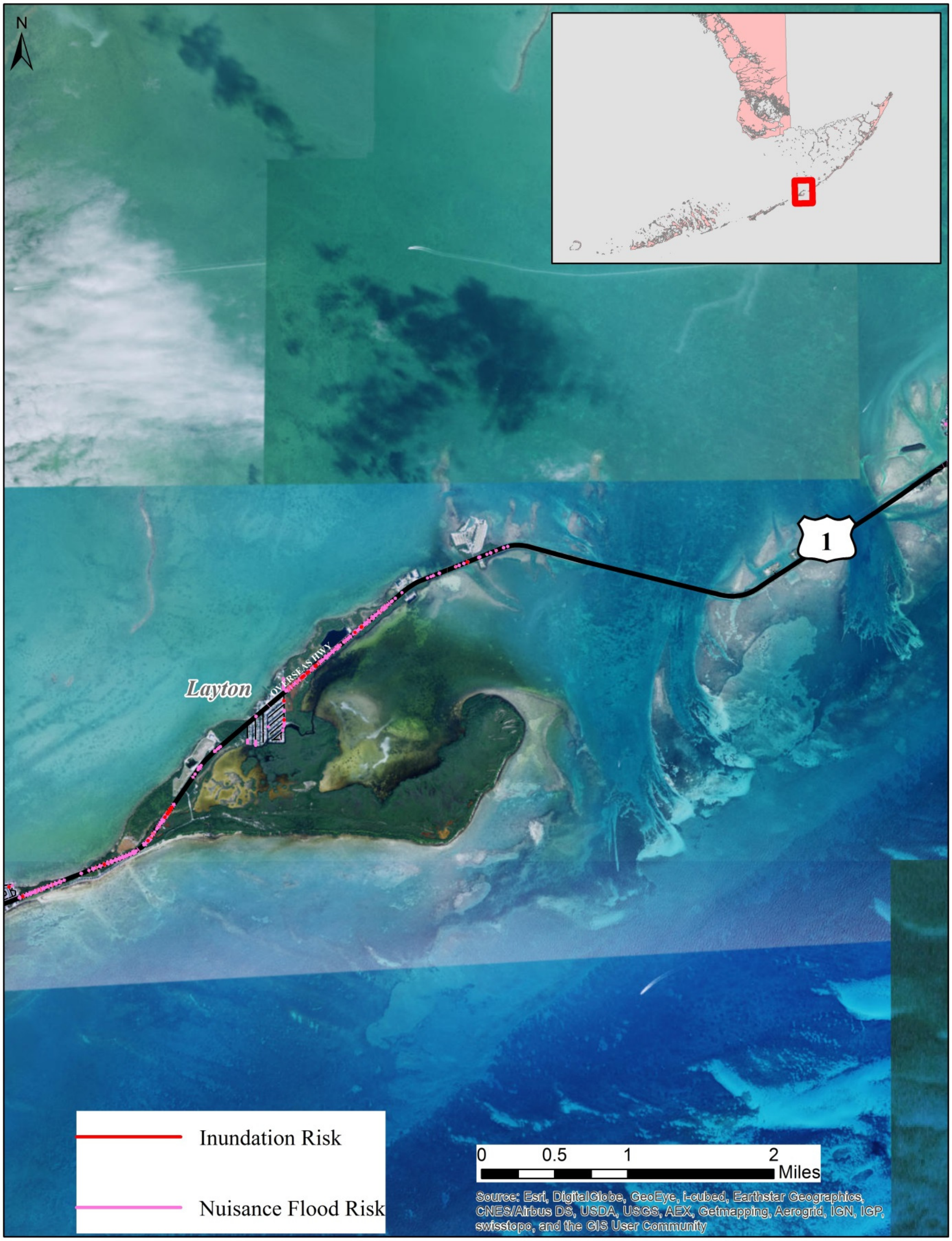


Figure 15h.1: **FDOT Sea Level Rise Sketch Planning Tool, 2030 Low Sea Level Rise, Duck Key**

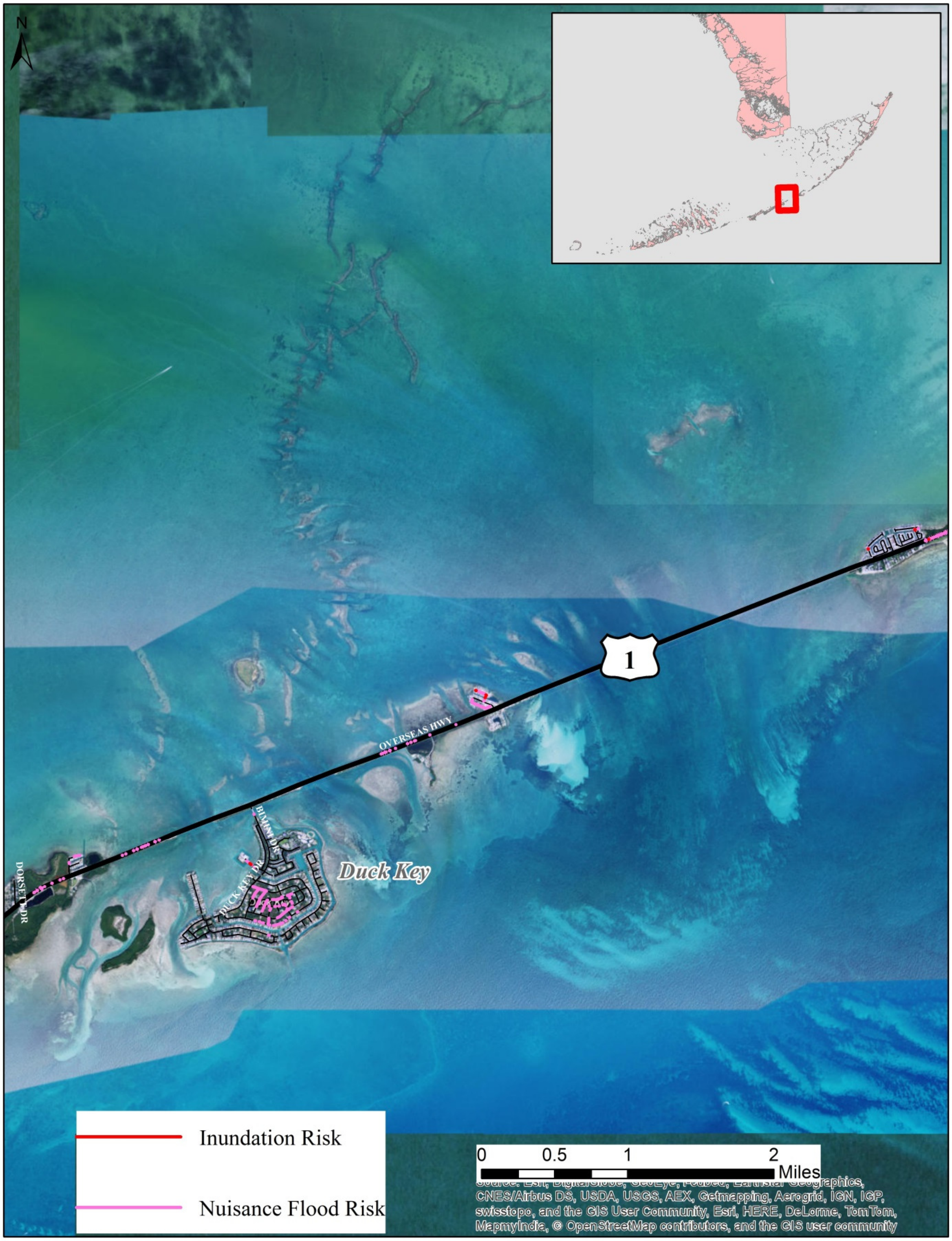


Figure 15h.2: **FDOT Sea Level Rise Sketch Planning Tool, 2030 High Sea Level Rise, Duck Key**

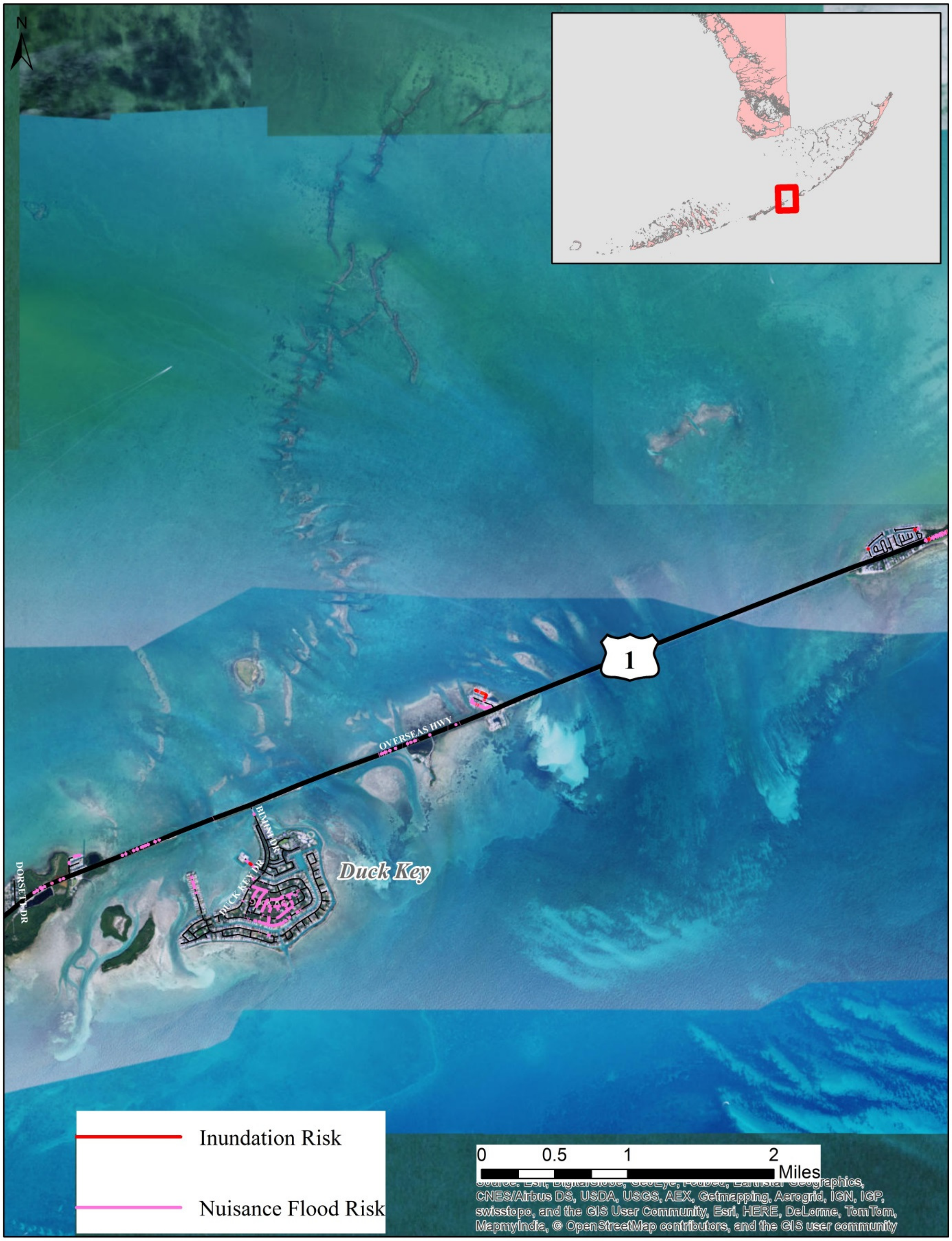


Figure 15i.1: **FDOT Sea Level Rise Sketch Planning Tool, 2030 Low Sea Level Rise, Grassy Key to Vaca Key**

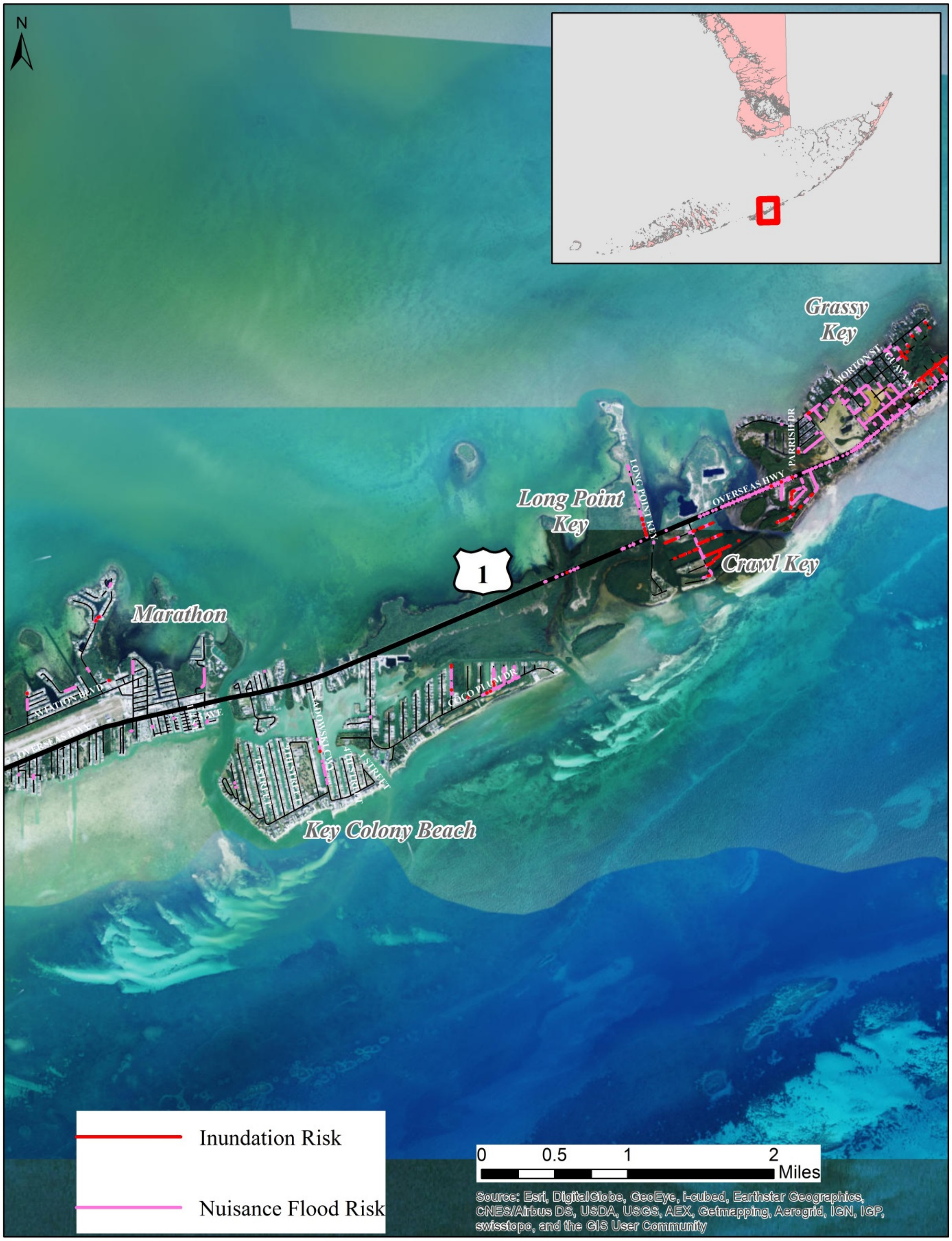


Figure 15i.2: **FDOT Sea Level Rise Sketch Planning Tool, 2030 High Sea Level Rise, Grassy Key to Vaca Key**

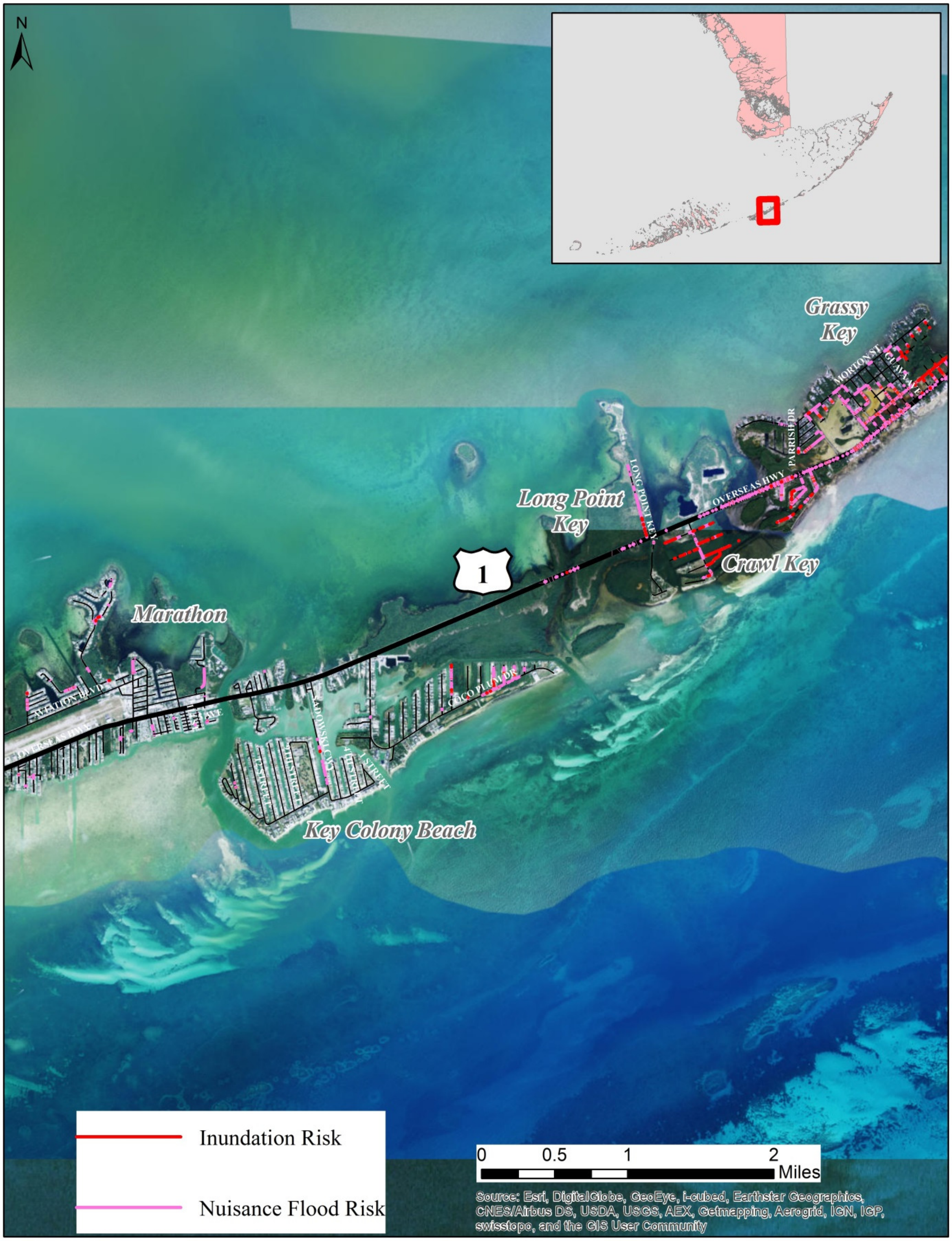


Figure 15j.1: **FDOT Sea Level Rise Sketch Planning Tool, 2030 Low Sea Level Rise, Vaca Key to Seven Mile Bridge**

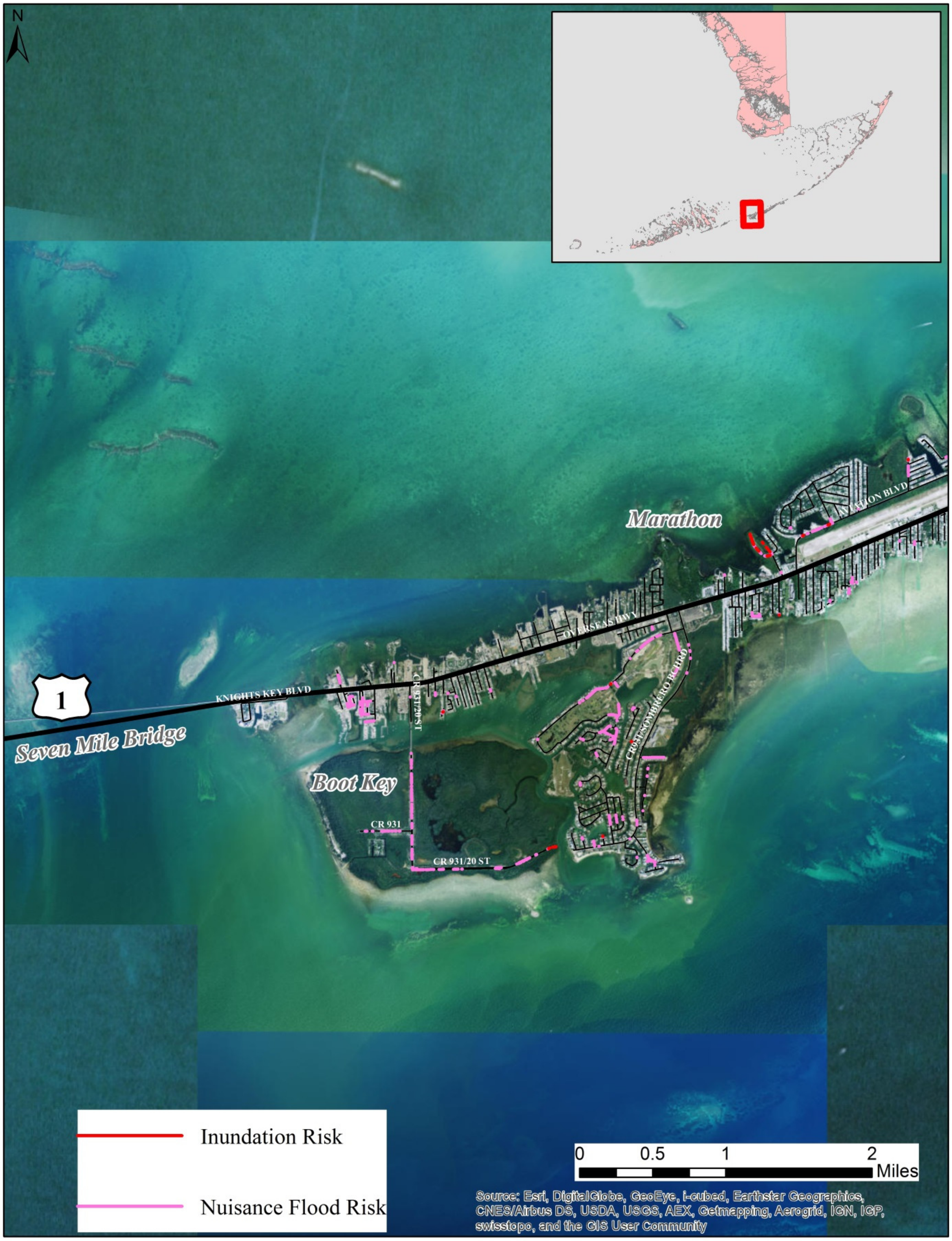


Figure 15j.2: **FDOT Sea Level Rise Sketch Planning Tool, 2030 High Sea Level Rise, Vaca Key to Seven Mile Bridge**

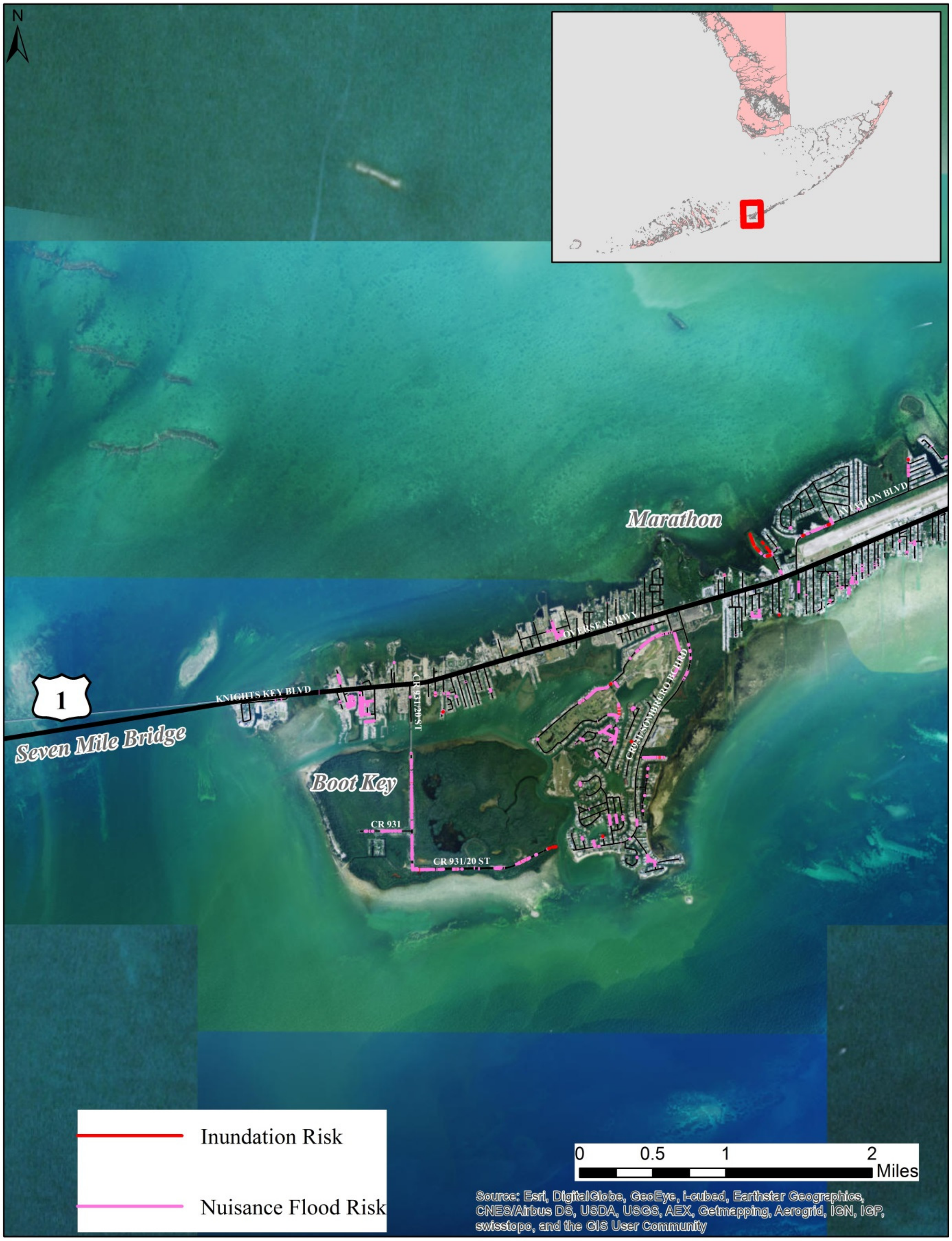


Figure 15k.1: **FDOT Sea Level Rise Sketch Planning Tool, 2030 Low Sea Level Rise, Seven Mile Bridge**

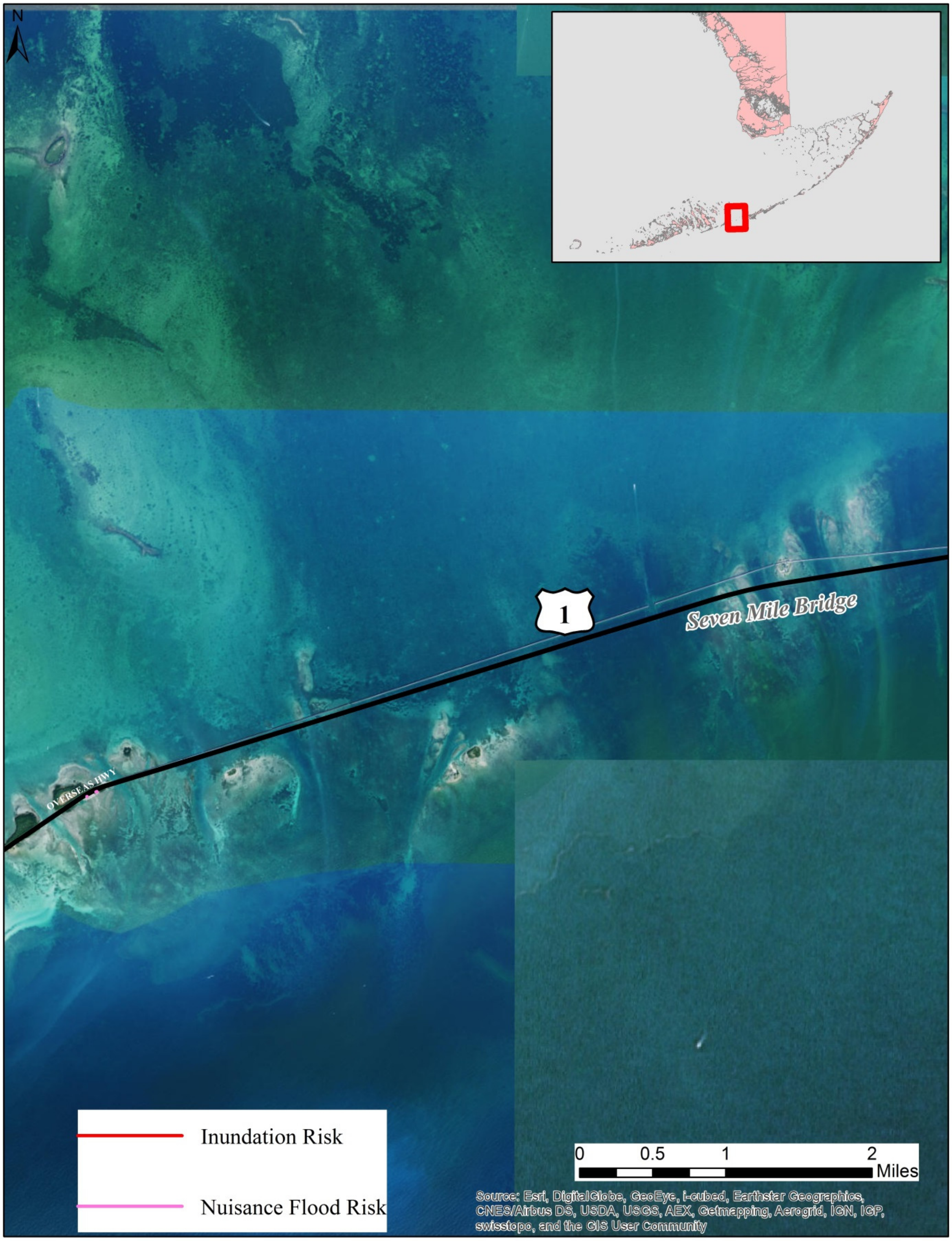


Figure 15k.2: **FDOT Sea Level Rise Sketch Planning Tool, 2030 High Sea Level Rise, Seven Mile Bridge**

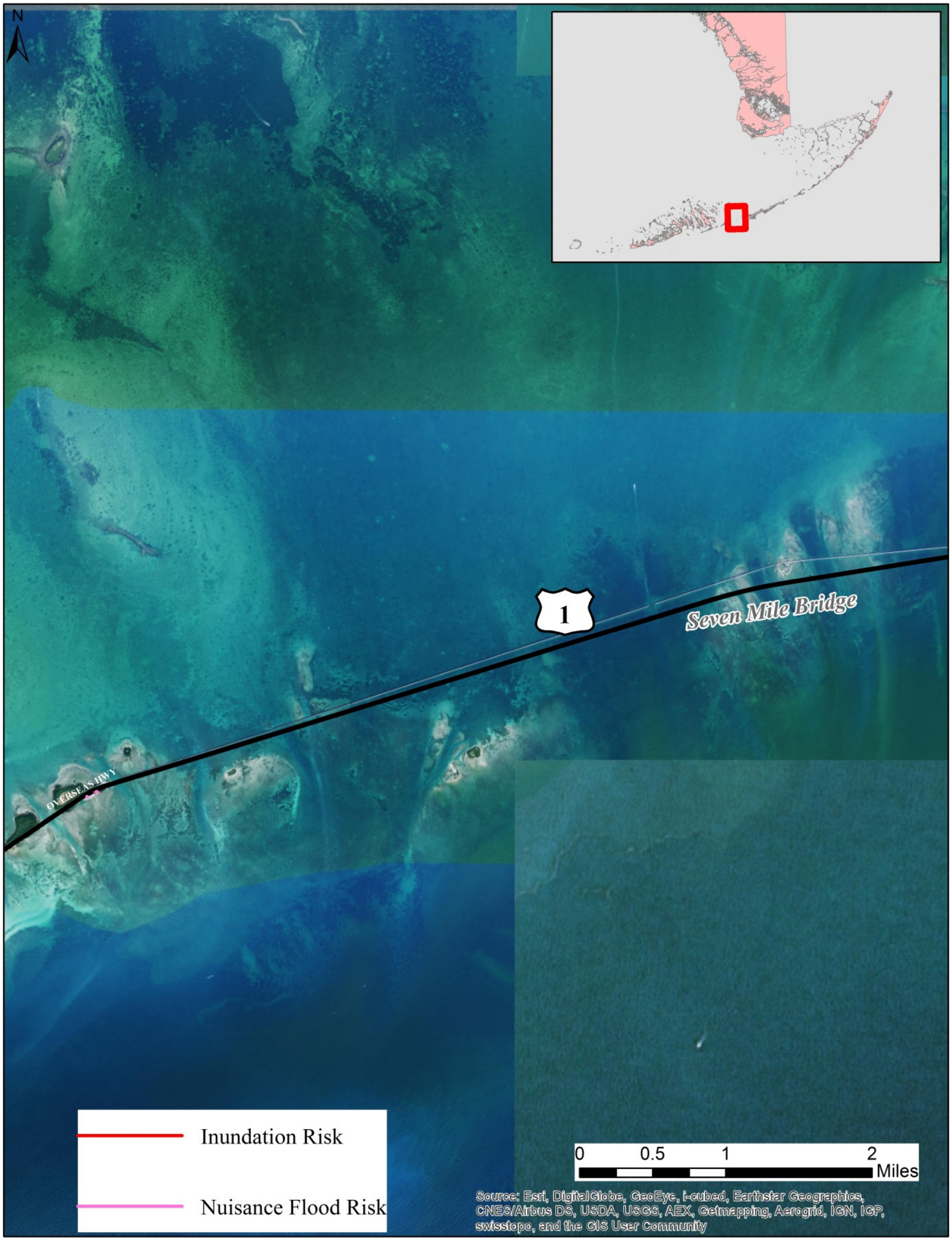


Figure 15l.1: **FDOT Sea Level Rise Sketch Planning Tool, 2030 Low Sea Level Rise, Ohio Key to Big Pine Key**

Figure 15l.2: **FDOT Sea Level Rise Sketch Planning Tool, 2030 High Sea Level Rise, Ohio Key to Big Pine Key**

Figure 15m.1: **FDOT Sea Level Rise Sketch Planning Tool, 2030 Low Sea Level Rise, Big Pine Key to Ramrod Key**

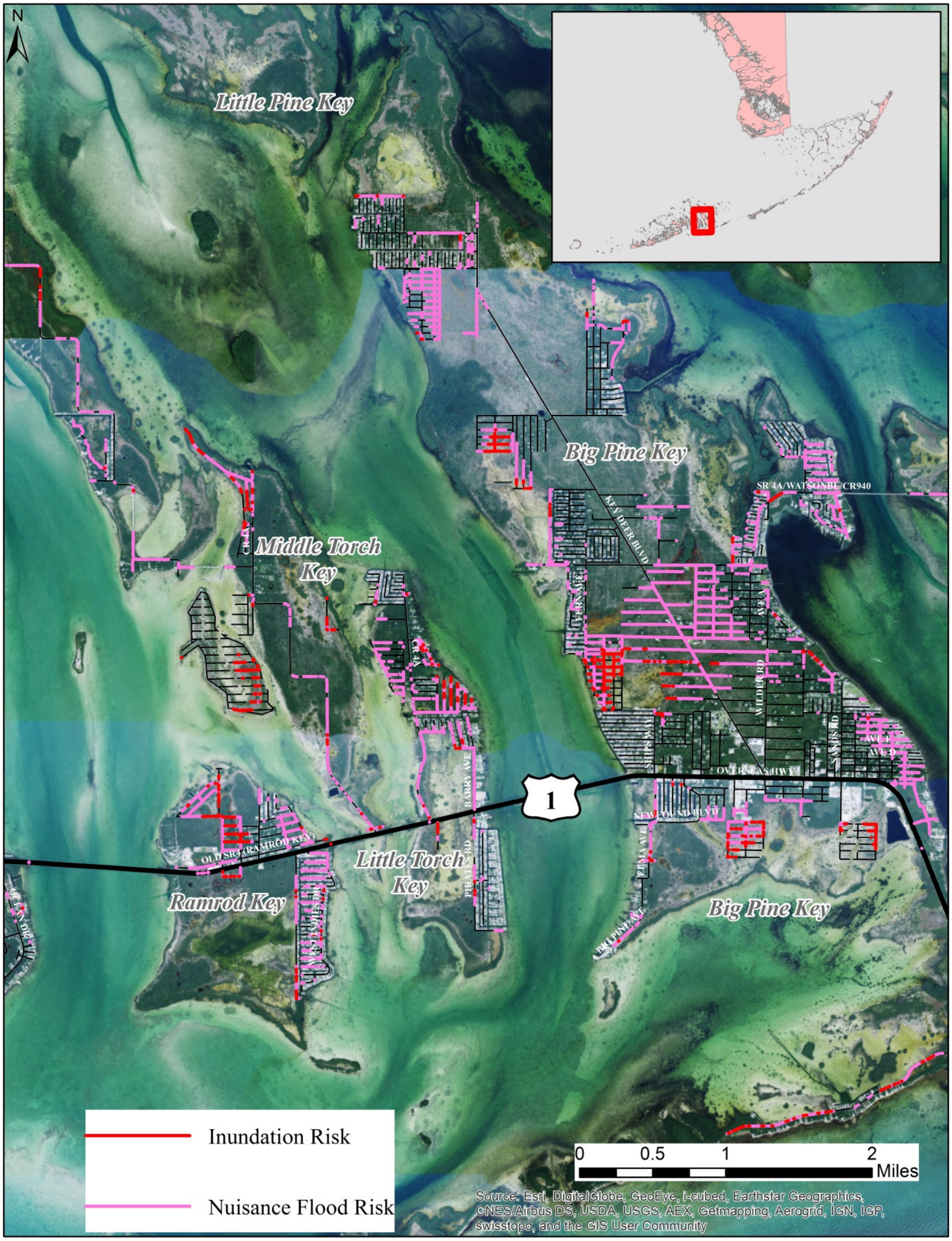


Figure 15m.2: **FDOT Sea Level Rise Sketch Planning Tool, 2030 High Sea Level Rise, Big Pine Key to Ramrod Key**

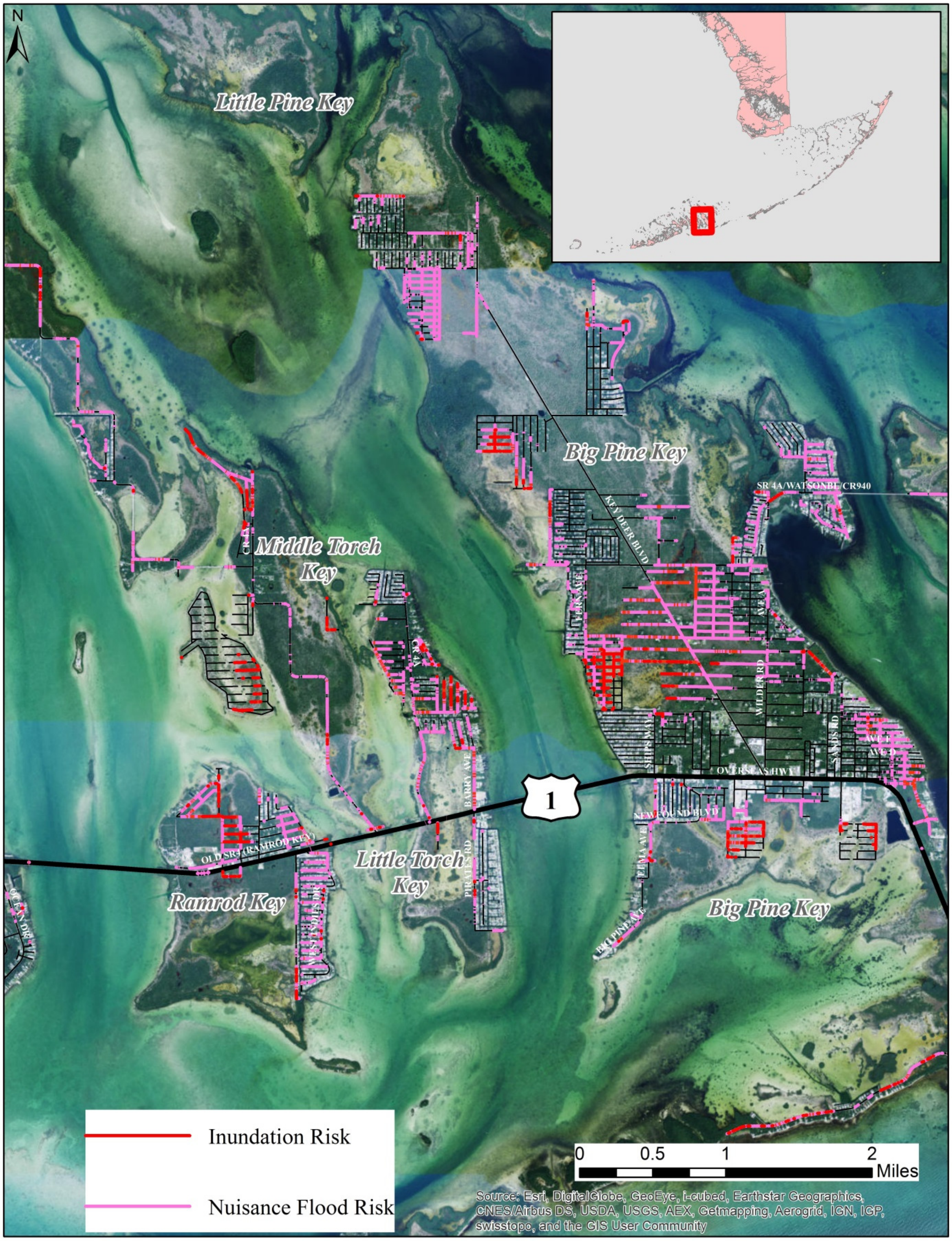


Figure 15n.1: **FDOT Sea Level Rise Sketch Planning Tool, 2030 Low Sea Level Rise, Summerland Key to Sugarloaf Key**

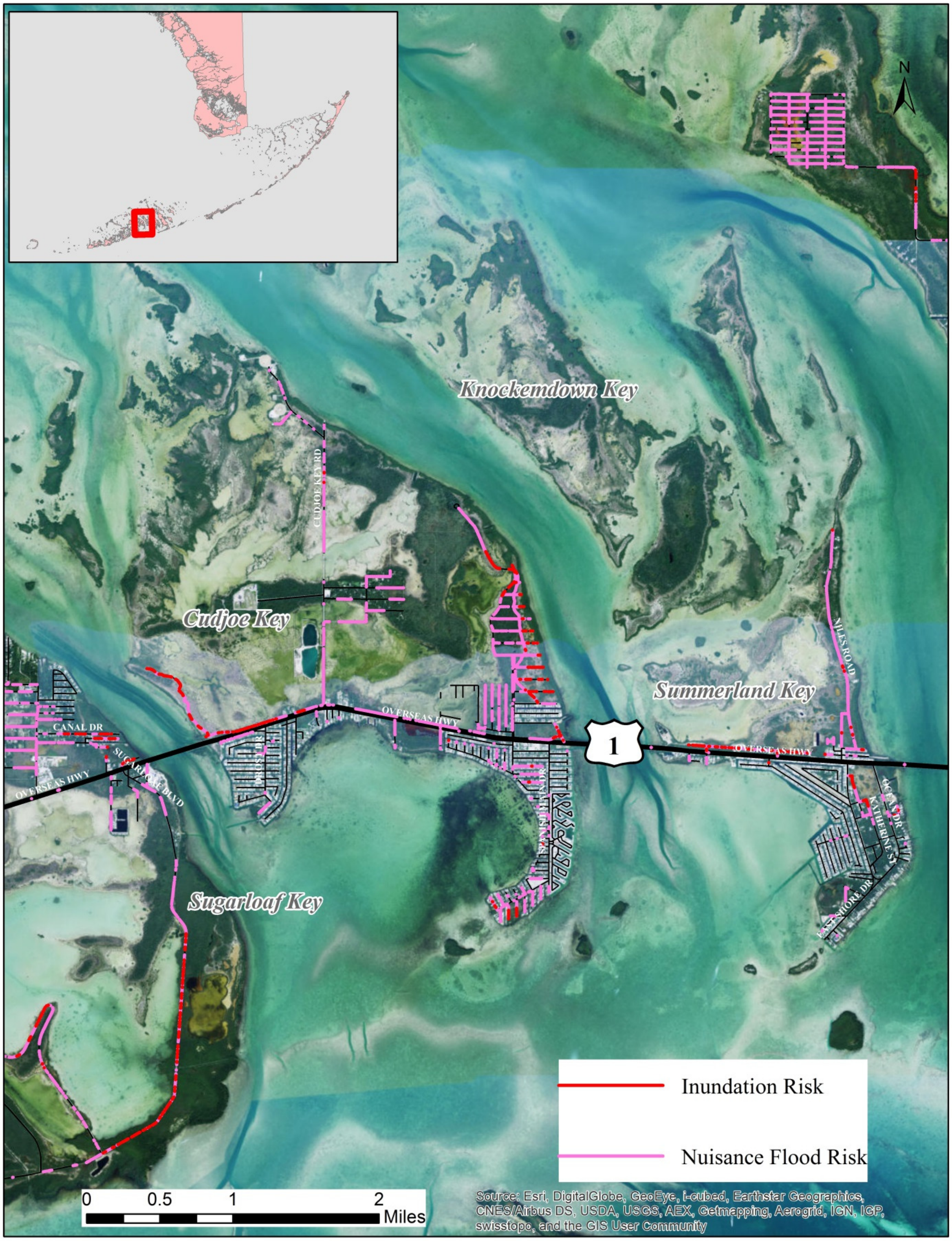


Figure 15n.2: **FDOT Sea Level Rise Sketch Planning Tool, 2030 High Sea Level Rise, Summerland Key to Sugarloaf Key**

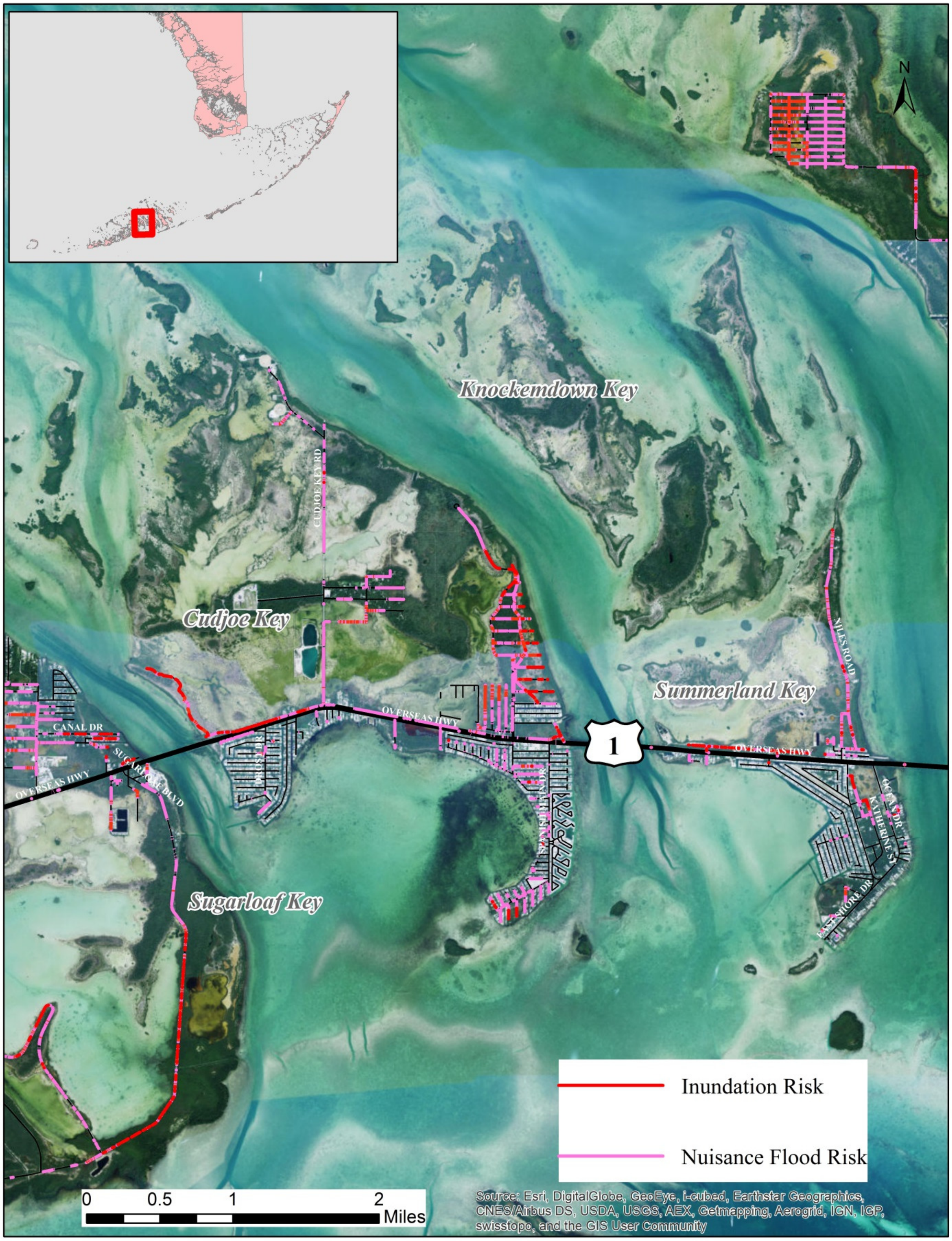


Figure 15o.1: **FDOT Sea Level Rise Sketch Planning Tool, 2030 Low Sea Level Rise, Sugarloaf Key to Saddlebunch Keys**

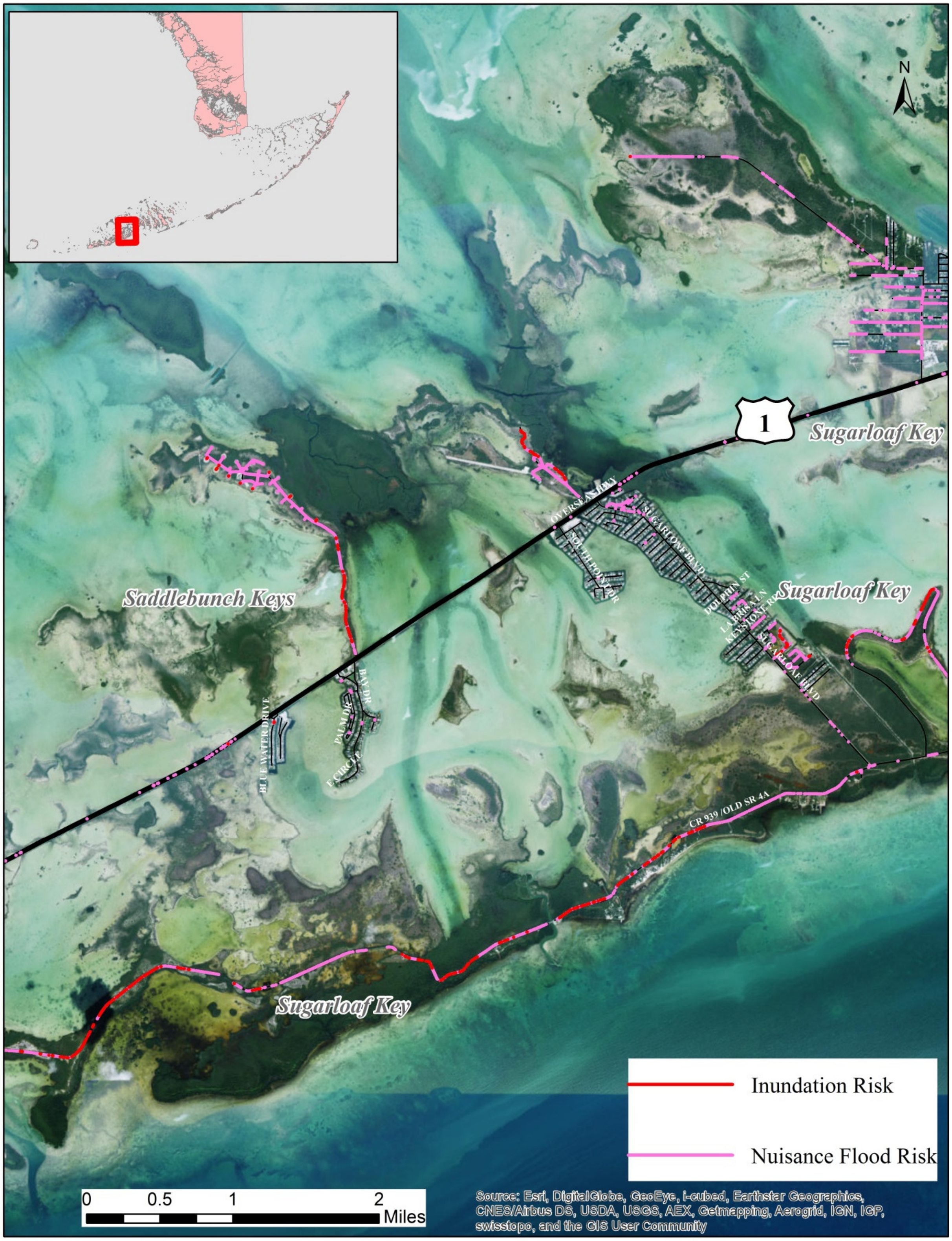


Figure 15o.2: **FDOT Sea Level Rise Sketch Planning Tool, 2030 High Sea Level Rise, Sugarloaf Key to Saddlebunch Keys**

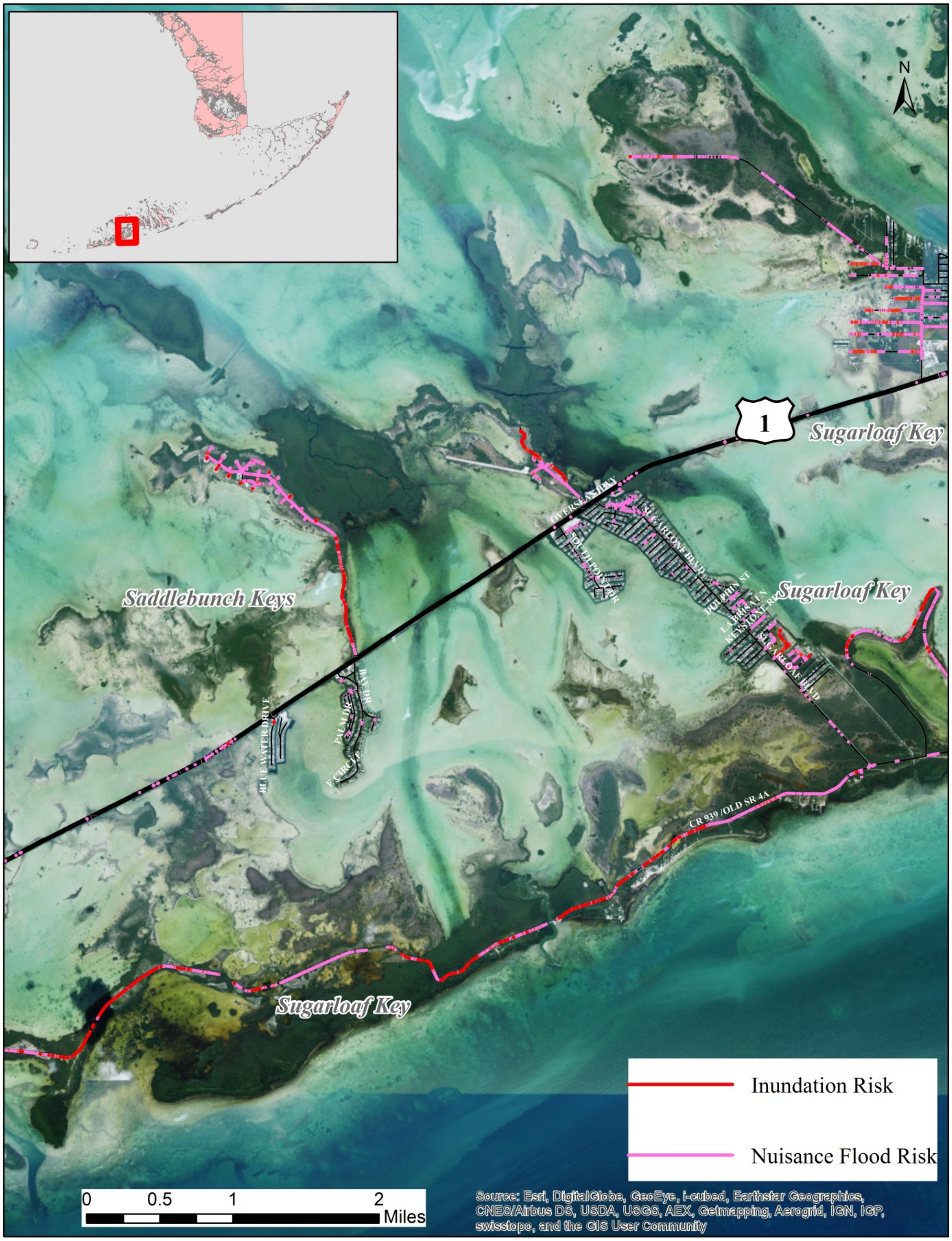


Figure 15p.1: **FDOT Sea Level Rise Sketch Planning Tool, 2030 Low Sea Level Rise, Big Coppitt Key to Boca Chica Key**

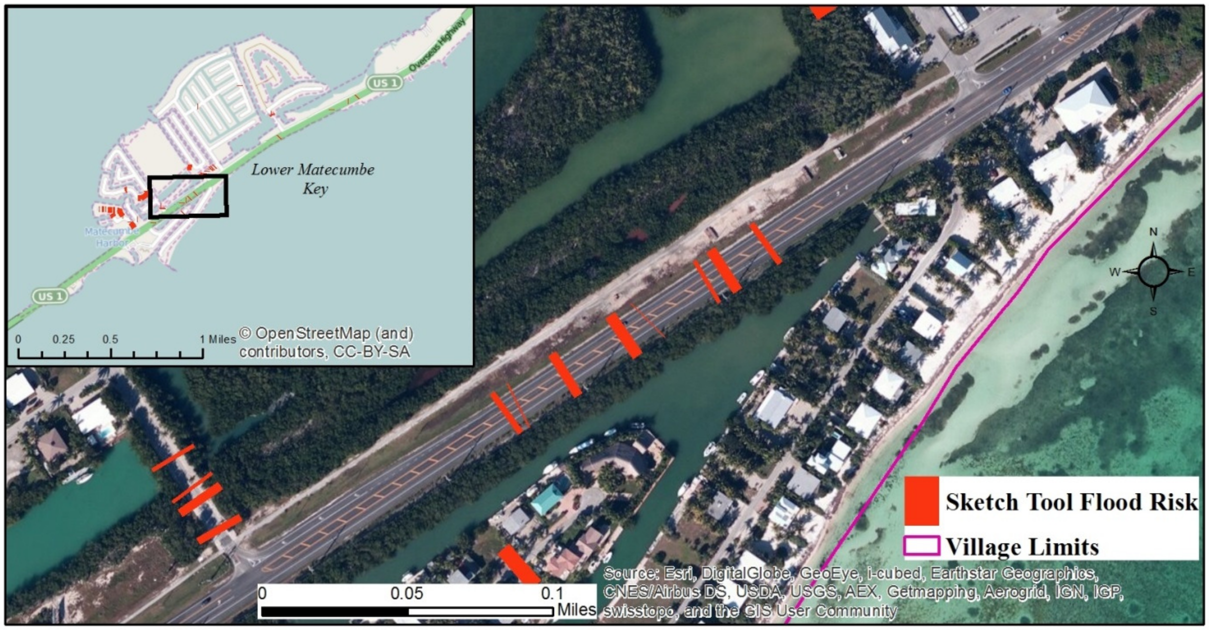
Figure 15p.2: **FDOT Sea Level Rise Sketch Planning Tool, 2030 High Sea Level Rise, Big Coppitt Key to Boca Chica Key**

Figure 15q.1: **FDOT Sea Level Rise Sketch Planning Tool, 2030 Low Sea Level Rise, Stock Island to Key West**

Figure 15q.2: **FDOT Sea Level Rise Sketch Planning Tool, 2030 High Sea Level Rise, Stock Island to Key West**

Figure 16a: **FDOT Sea Level Rise Sketch Planning Tool Close-Up for US1, Lower Matecumbe Key, 2030 Sea Level Rise Scenarios**. Picture A) shows road segments predicted as vulnerable to nuisance flooding with 3 inches of sea level rise (2030, Low Scenario). Picture B) shows road segments predicted as vulnerable to nuisance flooding with 7 inches of sea level rise (2030, High Scenario).

A)



B)

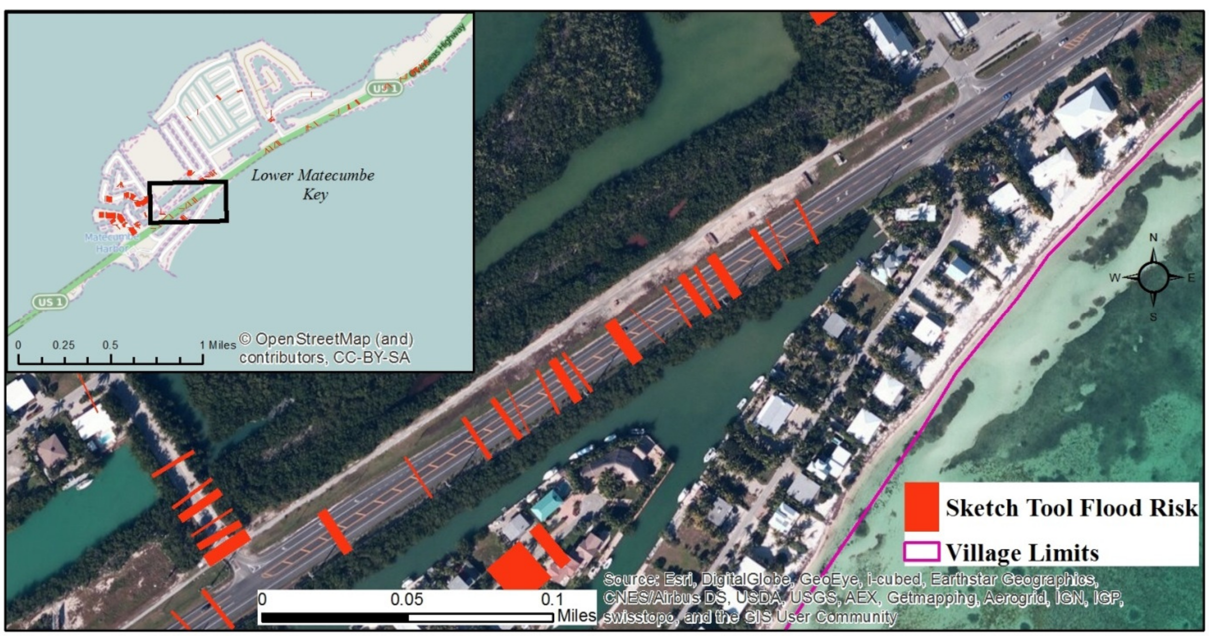
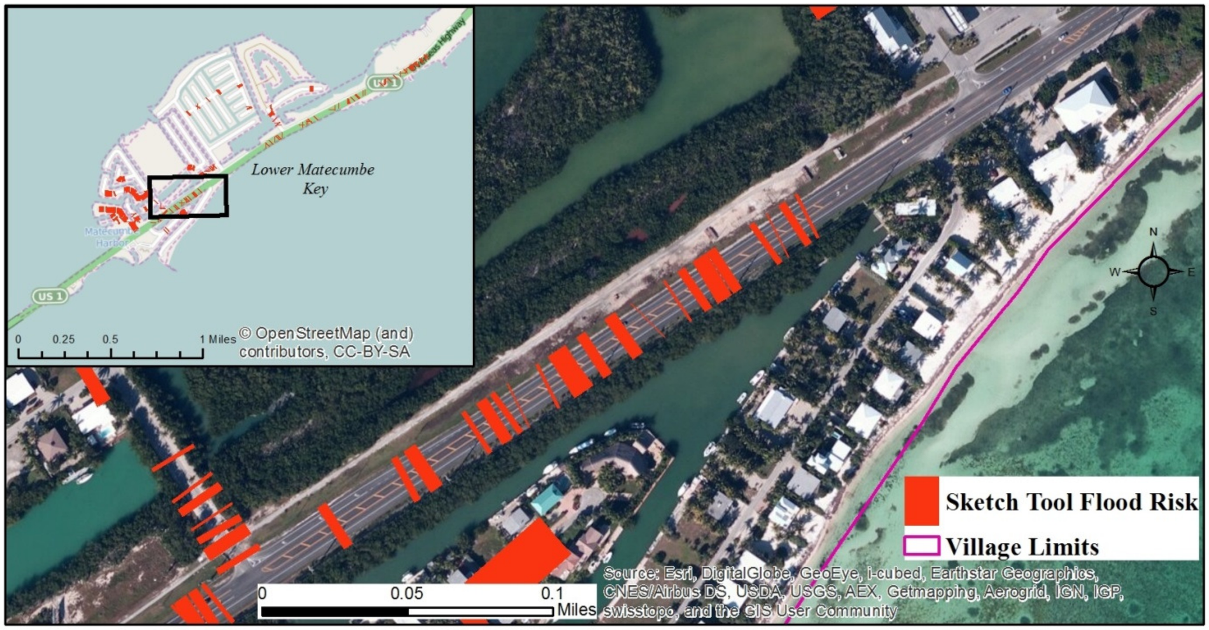
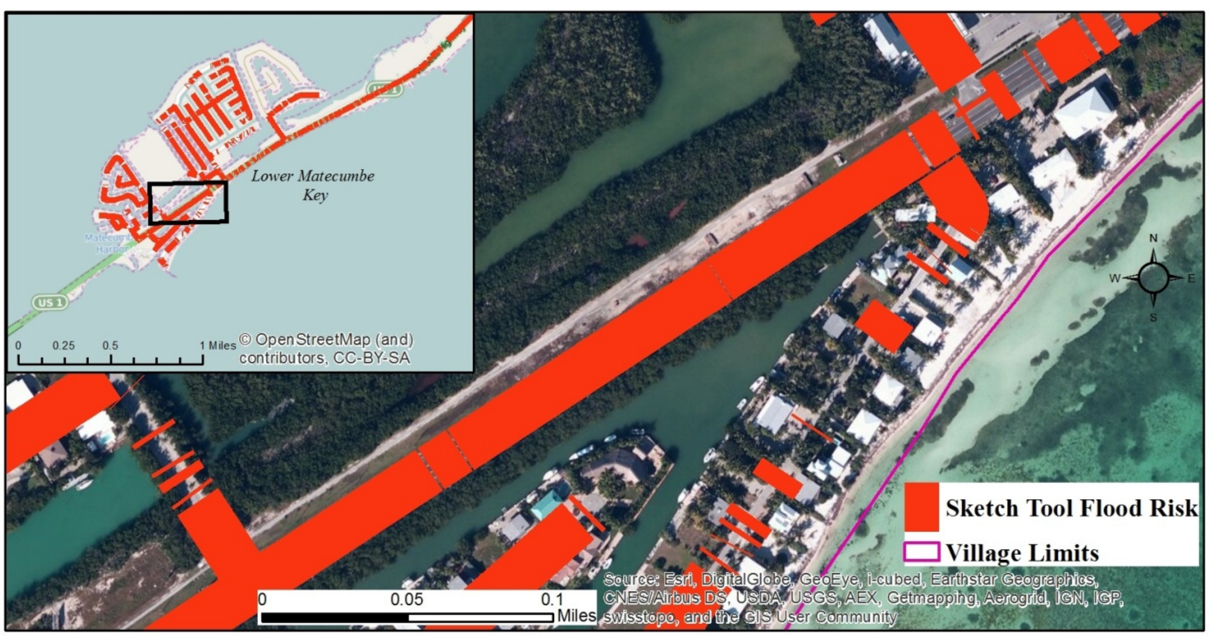


Figure 16b: **FDOT Sea Level Rise Sketch Planning Tool Close-Up for US1, Lower Matecumbe Key, 2060 Sea Level Rise Scenarios**. Picture A) shows road segments predicted as vulnerable to nuisance flooding with 9 inches of sea level rise (2060, Low Scenario). Picture B) shows road segments predicted as vulnerable to nuisance flooding with 24 inches of sea level rise (2060, High Scenario).

A)



B)



Recommendations for Roads

Tolerance for nuisance road flooding is dependent on the amount of traffic served by the road being impacted. Nuisance tidal flooding conditions on major highways, even if infrequent, pose clear concerns for public safety, health, and welfare, while also impacting the local economy through the temporary loss of primary transportation routes. Such consequences justify near-term and preventive action to mitigate existing or potential flood risks on primary highway transportation routes. For this reason, we strongly recommend near-term action to address potential flood hazards identified on US Highway 1 near Mile Marker 74.

For less-traveled neighborhood roads, onset of shallow nuisance road flooding that occurs several times each year may not necessarily impose severe traffic constraints, although access to individual homes may be temporarily restricted. Actions to address tidal flooding, such as elevation of road beds, necessarily imply additional engineering interventions to provide adequate stormwater drainage and avoid subsequent run-off impacts to low-lying buildings. Such interventions also imply significantly increased costs for road upgrade as compared to repaving at current grade. For these reasons, we recommend development of level of service and cost-benefit criteria to determine the suitability of flood resistance interventions for County-maintained roads with sea level rise vulnerability.

Due to the complexity and significant cost associated with road upgrade decisions, we also recommend collection of enhanced elevation data along road surfaces in Monroe County that can significantly reduce the error margin inherent to the current aerial LIDAR DEM (+/- 0.6’). As recently described by FDOT (2013), use of terrestrial mobile LIDAR along road bed surfaces can provide survey-grade elevation data with vertical accuracy of 0.1’ (~1.2 inches). Such enhanced elevation data would provide significantly higher confidence in future flood vulnerability assessments of road segments, as well as a robust technical basis for design of new road surfaces and enhanced stormwater drainage features (FDOT 2013).

Habitat Risk Assessment

Monroe County is world-renowned for its wide diversity of marine and terrestrial habitats, many of which are unlike those found anywhere else in the United States. These resources include an extensive living coral barrier reef system off the Atlantic coast, highly productive submersed sea grass and intertidal mangrove communities, vast subtropical wetlands in Everglades National Park, and rare tropical upland vegetation communities found throughout the Florida Keys archipelago. These habitats are critical to a variety of endemic, endangered, threatened, and otherwise rare species. They also serve as the base of a regional ecosystem that sustains a number of commercially and recreationally important fisheries, as well as other wildlife-dependent industries and activities such as diving and snorkeling. For these reasons, there has been a long-term recognition that the health and sustainability of natural ecosystems is central to the economy, lifestyle, and overall heritage of Monroe County (Park et al. 2002; Bhat 2003; Mozumder et al. 2011).

The federal government controls a number of large conservation areas in or including portions of Monroe County. These include Everglades National Park, Big Cypress National Preserve, Key Deer National Wildlife Refuge, Crocodile Lake National Wildlife Refuge, Great White Heron National Wildlife Refuge, and the Key West National Wildlife Refuge. Boca Chica Naval Air Station, although it is not primarily a conservation area, provides vital habitat and habitat protection for a number of protected species.

Major state-owned conservation areas in Monroe County include John Pennekamp Coral Reef State Park, Dagny Johnson Key Largo Hammock Botanical State Park, Long Key State Park, Lignumvitae Key Botanical State Park, Curry Hammock State Park, Bahia Honda State Park, and the Florida Keys Wildlife and Environmental Area which includes portions of islands from the Saddlebunch Keys to Key Largo. A number of other smaller conservation tracts held by federal, state, county, municipal, and private entities are also found throughout Monroe County. Summed together, approximately 96% of Monroe County's land area is set aside for conservation purposes. Jurisdiction of many protected areas also extends into near-shore marine waters on both the Florida Bay and Atlantic Ocean sides of Monroe County, and joint federal and state management of all near-shore waters in the Florida Keys is encompassed under the auspices of Florida Keys National Marine Sanctuary.

Although the natural habitats of Monroe County are among the most highly protected and strictly managed in Florida, there is great concern that various aspects of climate change pose a significant long-term peril to the future health and sustainability of many ecosystems. In fact, numerous scientific studies and previous assessments have noted that Monroe County's marine and terrestrial habitats are likely among the most vulnerable in the United States to climate change impacts (Scavia et al. 2002; Bergh 2011; Noss 2011; Reece et al. 2013). Perhaps the most generally predictable of these projected impacts is long-term disappearance of upland ecosystems and associated species that become inundated by rising seas (Ross et al. 2008;

Menon et al. 2010; Saha et al. 2011). However, there is also significant potential for large-scale changes in the composition and productivity of marine ecosystems due to the combined stressors of ocean acidification (as associated with increased atmospheric carbon dioxide), increased ocean temperatures, and rapid sea level rise (Duarte 2002; Orth et al. 2006; Hoegh-Guldberg et al. 2007; De'ath et al. 2012; Cunning and Baker 2013). Impacts of climate change on intertidal mangrove wetland communities are perhaps among the least predictable, as such communities could potentially decline or expand depending on multiple factors that include rate of sea level rise, changes in regional sedimentation patterns, and the future extent of human engineering interventions within the intertidal zone (Krauss et al. 2014).

This habitat vulnerability assessment is arranged into three sections. The first section provides a general overview of potential climate change impacts for the barrier coral reef and sea grass marine ecosystems. The second section of the vulnerability assessment utilizes an inundation analysis and updated series of sea level rise scenario runs from the Sea Level Affecting Marshes Model (SLAMM) to identify long-term ecosystem conversion risk potential to upland and intertidal land covers within Monroe County. The third section, as written by Chris Bergh of The Nature Conservancy, provides a summary of management interventions with potential to assist with long-term habitat resilience, adaptation, and dispersal of habitats under accelerated future climate change conditions.

Marine Ecosystems

Coral Barrier Reef

The Atlantic marine waters off of Monroe County are internationally recognized as the site of world's third largest living coral barrier reef system. The full coral reef ecosystem, which is mostly located on a shallow shelf off the Atlantic coast of the Florida Keys, is known to contain over fifty species of coral, 500 species of fish, and numerous other marine organisms. Seven coral types found within the Florida Keys, including the once common staghorn (*Acropora cervicornis*) and elkhorn (*Acropora palmata*) corals, are federally listed as threatened species (NOAA 2015c).

The clear water conditions, colorful coral structures, and abundant marine life within the Florida Keys coral reef system together make it the base of an exceptionally productive suite of commercial fisheries and a highly popular destination for divers, snorkelers, and recreational fishers. The living coral reef system also provides other important physical functions such as attenuation of damaging wave energy from coastal storms and decreased tidal erosion of oceanfront lands.

Over the past several decades, a number of major stressors are known to have caused substantial degradation to the coral reef system and other near shore waters in the Florida Keys. These stressors primarily include high nutrient inputs and pathogen contamination from septic tanks (Lapointe et al. 1990; Sutherland et al. 2011), sediment loading from development activities

(Lapointe et al. 1994), regional hydrologic impacts to the greater Everglades ecosystem (Lapointe et al. 2004), overfishing of large predator species (Roberts 1995), and habitat destruction from ship groundings, anchor damage and other direct impacts.

For all these reasons, there has been longstanding effort to implement management interventions and governmental policies that support the improvement of water quality and ecosystem health within the Florida Keys coral reef ecosystem. Such efforts have resulted in large-scale replacement of septic tanks with centralized sewerage throughout Monroe County, local load reduction of nutrients and sediments into the near-shore environment (Rehr et al. 2012), reduced fishing pressures on apex predators and other slowly reproducing species (Bohnsack et al. 1994; Suman et al. 1999), regulations designed to limiting direct habitat damage from vessel groundings and anchoring, and a system of mooring buoys to minimize anchor damage on many of the most visited reefs. Improvement of the coral reef system is also one of the broader ecosystem recovery goals associated with the long-term Comprehensive Everglades Restoration Plan (Keller and Causey 2005; Caraco and Drescher 2011).

Scientific research in recent years has raised a wide range of concerns about the cumulative impacts of increasing ocean temperatures and ocean acidification on the long-term worldwide survival of extant coral barrier reefs, including those in the Florida Keys (Eakin et al. 2010; Pandolfi et al. 2011). Numerous studies, for example, suggest that major coral bleaching episodes, which are characterized by rapid whitening of coral colonies, very often coincide with warmer than normal ocean water conditions (Wagner et al. 2010; Eakin et al. 2010; Hoegh-Guldberg 2011). Such bleaching events, which were first reported globally and throughout the Florida Keys in 1979 (Jaap 1979; Hoegh-Guldberg 2011), often are followed by coral death and macro-algae overgrowth that precipitates complete loss of the previous coral reef habitat (Pandolfi et al. 2005). Coral reef researchers generally agree that long-term global warming of ocean waters due to greenhouse gas emissions is a dominant factor in the historical emergence of coral bleaching as a worldwide phenomenon (Hoegh-Guldberg et al. 2007; De'ath et al. 2012; Cunning and Baker 2013).

A number of scientific researchers have more recently discovered that ocean acidification poses another major persistent threat to coral reefs on a global scale (Hoegh-Guldberg et al. 2007). Ocean acidification is directly caused by increased concentrations of atmospheric carbon dioxide. This is because carbon dioxide gas readily dissolves into carbonic acid within marine and other aquatic systems, and higher atmospheric concentration of carbon dioxide has the straightforward chemical effect of raising the equilibrium point for the concentration of carbonic acid in the marine environment. This uptake of atmospheric carbon dioxide and transformation into dissolved carbonic acid that effectively displaces calcium carbonate in solution, thus resulting in a lowered pH (i.e., higher acidity) of the water.

Because calcium carbonate is a mineral that all hard, reef-making corals require to build their exterior structure, there is wide concern that many coral species may be unable to adapt to the rapid reduction of available calcium carbonate that is associated with ongoing ocean acidification (Carpenter et al. 2008). For example, experiments with the threatened elkhorn coral suggest that reproduction and growth of this species are substantially reduced by levels of ocean acidification that are expected to occur within the next several decades (Albright et al. 2010). Similar results of declining reproduction and growth due to ocean acidification were also reported by Albright and Langdon (2011) for the common Caribbean coral (*Porites astreoides*).

It is well-known that the coral reefs of the Florida Keys have suffered from several extensive bleaching outbreaks in recent decades, including major events in 1979, 1987, 1990, 1997-1998, 2005, 2010, and 2014. While the 2010 bleaching event is notably unusual in that it was associated with anomalously cold water (Colella et al. 2012), the other bleaching events have been widely associated with warm water anomalies (Porter et al. 1999; Eakin et al. 2010). Many of the bleached coral reefs in the Florida Keys have been documented to shift into macro-algae dominated systems that subsequently lack many of the original coral species assemblages (Somerfield et al. 2008; Eakin et al. 2010).

Current scientific research unfortunately provides no definitive answers as to what species composition of corals may be most recoverable and/or sustainable in the Caribbean region over the next several decades of expected climate change. However, scientific research does strongly indicate that factors such as nutrient enrichment, overfishing, and physical disturbance all significantly reduce the resilience of coral reefs to climate change and acidification stressors. For this reason, continued implementation of traditional coral reef management actions are widely recommended as strategies for supporting the maintenance of functional coral reef systems under rapid climate change (Wagner et al. 2010).

Such traditional reef restoration actions include decreasing loads of nutrients and sediments, continued restoration of apex predator populations and minimization of direct habitat destruction and damage. Ongoing efforts by NOAA, The Nature Conservancy, Mote Marine Laboratory, Florida Fish and Wildlife Conservation Commission, and the Coral Reef Restoration Foundation to reseed staghorn and boulder corals into degraded areas have shown some promise, although research to improve propagation and planting techniques is ongoing (Johnson et al. 2011). Monroe County's continued cooperation with federal, state, and private partners in support of such conservation and restoration initiatives is critical to support the discovery and implementation of strategies that may promote long-term recovery and resilience of the Florida Keys coral barrier reef system in the face of future climate change.

Sea Grass Meadows

Much of the shallow near-shore waters of the Florida Keys contain extensive submersed seagrass meadows. Principally composed of turtle grass (*Thalassia testudium*) and manatee grass (*Syringodium filiforme*), these seagrass communities form a highly productive habitat critical to economically important fisheries and large seabird populations found in the Florida Keys. Large numbers of pink shrimp (*Farfantepenaeus duorarum*), stone crab (*Menippe mercenaria*), spiny lobster (*Panuliris argus*), and juvenile sport fishes are known to rely upon seagrass communities as a critical nursery habitat. Endangered species that include the Florida manatee (*Trichechus mantus*), American crocodile (*Crocodylus acutus*), and green sea turtle (*Chelonia mydas*) are also found within the seagrass habitats. The Florida Bay ecosystem, which forms at the southern end of the Everglades ecosystem and extends to the coast of the Upper Florida Keys, is widely regarded as one of the most extensive and productive seagrass meadows in the world (Hall et al. 2007).

Similar to the coral reef ecosystems on the Atlantic Ocean side of the island chain, the seagrass communities of the Florida Keys have historically become degraded due to widespread declines in marine water quality (Kruszynski and McManus 2002). Large levels of anthropogenic nutrient loading from local (primarily septic tanks within the Florida Keys) and regional (primarily agricultural and urban loading from southern mainland Florida) sources (LaPointe and Clark 1992) have been a significant source of water quality degradation. Elevated nutrients in Florida Bay have been directly associated with large-scale algal blooms that reduce water clarity and, in some cases, cause the decline or even disappearance of seagrasses from affected areas (LaPointe et al. 1994). The other major water quality issue in Florida Bay is a long-term increase in the bay's salinity. These salinity increases have been largely caused by losses of regional freshwater inputs from the Everglades (Hall et al. 2007). However, blockages of tidal exchange between Florida Bay and the Atlantic Ocean, particularly as associated with construction of Henry Flagler's Florida East Coast Railway viaduct-and-causeway system in the early 20th century, have also resulted in increased residence times and onset of hypersaline conditions in low flush areas (Rudnick et al. 2005). These long-term salinity increases are thought to be another major contributing factor in the decline of many seagrass patches and associated aquatic organisms observed in the Florida Keys region over the past several decades (Boyer et al. 2009).

Climate change, particularly the long-term warming and rising marine waters, is thought to be another large-scale stressor that will generally decrease the resilience of seagrass ecosystems worldwide. Because seagrass die-offs in Florida Bay and other areas of the world have been associated with elevated water temperatures (Boesch et al. 1993), there is concern among scientists that the local and worldwide frequency and extent of such events may increase as marine waters continue to warm over the next several decades (Orth et al. 2006; Paerl and Paul 2012). There are also concerns that accelerated sea level rise may in some cases increase water depths beyond critical light penetration thresholds, thus resulting in die-back of seagrasses from deeper water areas (Short and Neckles 1999). While all seagrass species have the evolutionary capacity to colonize areas that become newly submerged due to rising sea levels, most seagrass researchers believe that rapid sea level rise in conjunction with other human disturbances such as eutrophication and coastal development will most likely result in significant net losses of seagrass area for the foreseeable future (Duarte 2002; Orth et al. 2006).

Unlike many of the hard corals in the Florida Keys barrier reef, issues associated with ocean acidification are not thought to pose a direct concern for the biological survival of seagrass species. While there is some concern that seagrass meadows could indirectly decline due to changes in algal species composition or decreases of hard-shelled algal grazer species associated with ocean acidification (Kroeker et al. 2010), there is strong evidence that seagrass species are resilient to acidifying ocean conditions likely to occur into the foreseeable future (Koch et al. 2013). In fact, studies indicate that elevated atmospheric carbon dioxide and dissolved carbonic acid could have a mild fertilization effect that promotes increased growth of seagrasses (Guinotte and Fabry 2008). Due to this carbon uptake function, a number of researchers have argued that direct planting, cultivation, and maintenance of seagrass communities should be encouraged as a key global climate change mitigation strategy (Mcleod et al. 2011; Fourqurean et al. 2012).

Under conditions of rapidly warming and rising seas, conservation of seagrass communities will clearly require a multi-pronged strategy. The fundamental piece of this strategy is reduction of phosphorus, nitrogen, and other anthropogenic pollutant loads into shallow marine waters that have historically supported seagrass communities. Algal blooms fueled by nutrient loading remain as the primary global stressor to seagrass communities, and there is high consensus among scientists that seagrass areas with low anthropogenic nutrient burdens will tend to show the highest resilience to both sea-level rise and warming of marine waters (Orth et al. 2006; Bricker et al. 2008; Paerl and Paul 2012). Continued nutrient mitigation in Florida Bay through advanced wastewater treatment, stormwater management, and other water quality improvement practices can therefore be expected to increase the resilience of the sea grass community to climate change stressors. Efforts to improve water quality through restoration of regional freshwater inputs and increased tidal flushing are also considered critical to the long-term recovery and future resilience of sea grass communities within the Florida Bay ecosystem (Rudnick et al. 2005).

A second piece of this strategy is to provide undeveloped migration corridors for seagrasses to colonize as sea levels rise over time. It is clear that construction of engineered bulkheads or other hardened structures to stabilize shorelines will significantly impede movement of seagrasses into newly submerged areas (Gilman 2004; Bulleri and Chapman 2010). Because continuous areas of low-lying land adjacent are critical for future migration of shallow marine ecosystems, future land buying and conservation zoning initiatives in Monroe County could feasibly include marine ecosystem migration under accelerated sea level rise as a possible overlay component. It is also recommended that Monroe County promote living shorelines and mangrove restoration as an alternative to traditional bulkheads for near-term stabilization of eroding coastal areas, while also allowing for long-term marine ecosystem migration (Bulleri and Chapman 2010; Spalding et al. 2014).

Finally, aggressive replanting of seagrasses has in some cases been shown to result in long-term and sustained reduction of algal bloom cycles and recovery of seagrass communities, especially when performed in conjunction with large-scale nutrient reductions (van Katwijk et al. 2009;

Greening et al. 2011). Continued cooperation with federal, state, and private efforts to research, implement, and improve seagrass replanting efforts is a clear near-term recommendation for Monroe County. Over a longer time horizon, Monroe County may wish to pursue "blue carbon" payments for conserved and restored seagrass areas through international carbon mitigation markets that may begin emerging over the next decade (Ullman et al. 2013). Such payments could serve as a possible revenue source for adaptive management and, as necessary, assisted migration/colonization of seagrass communities under accelerated climate change scenarios.

Habitat Change Analysis

A detailed upland and intertidal habitat impacts analysis was conducted for the entirety of the Florida Keys portion of Monroe County. The analysis utilized the Sea Level Affecting Marshes Model (SLAMM), which is an advanced land cover and ecosystem change tool (Warren Pinnacle Consulting, Inc., 2012), The utility of SLAMM is that, unlike other flood vulnerability assessment methods, it integrates long-term hydrologic functions and ecosystem parameters to give projections about future changes to tidal habitat types, such as saltwater marshes, mangroves, and other coastal wetlands, that are already subjected to regular tidal flooding.

As the southernmost area of the continental United States, Monroe County and the Florida Keys contain a distinct set of tropical forest and herbaceous vegetation communities. The following is a set of main ecosystem descriptions in the Florida Keys, as based upon original community profiles provided by the Florida Natural Areas Inventory (2010).

Mangroves

Natural marine shorelines and low-lying islands throughout Monroe County contain vast areas of tidal mangrove and buttonwood forest communities. Mangrove forests are typically located on elevations that are below the MHHW line but higher than mean sea level. Dominant canopy trees are the red mangrove (*Rhizophora mangle*), black mangrove (*Avicennia germinans*), and white mangrove (*Lagyncularia racemosa*), with an understory that can include glasswort (*Salicornia* sp.), salt grass (*Distichlis spicata*), and sea daisy (*Borrichia aborescens*).

Mangrove forests are generally quite productive nursery areas for the marine ecosystem, while mangroves and buttonwood communities both provide critical nesting habitat for large flocks of wading and seabirds. In addition to the high habitat value of these systems, intact mangrove and buttonwood communities both provide important functions such as filtering upland pollution, mitigating chronic wave erosion of shorelines, and absorbing destructive wave energy associated with coastal storm events.

Buttonwood Forest

Buttonwood forests typically form directly up-gradient from mangroves in the supratidal zone, which has a ground elevation higher than the MHWW line, but is subject to regular saltwater flooding during spring tides and other high tide events. Typical plants in the buttonwood community include the buttonwood (*Conocarpus erectus*), joewood (*Jacquinnia keyensis*), wild dilly (*Manilkara bahamensis*), blacktorch (*Erithalis fruticose*), and saffron plum (*Bumelia celastrina*).

Freshwater Marshes

The Florida Keys support low-lying freshwater marshes, with the largest coverages of such systems found in and near the National Key Deer Refuge on Big Pine Key and No Name Key. These freshwater marshes are flooded for long periods of the year by narrow lenses of freshwater that sit on top of underlying salty groundwater or above the freshwater lenses of the larger Lower Keys islands, but they can become temporarily saline during droughts or high tidal events. Typical plant species found in freshwater marshes of the Florida Keys include sawgrass (*Cladium jamaicense*), spike rush (*Eleocharis* sp.), saw sedge (*Cyperus ligularis*), white-top sedge (*Dichromen floridensis*), and broom sedge (*Andropogon glomeratus*). The freshwater marshes and even rarer freshwater ponds and solution holes, while small in areal coverage within the Florida Keys, provide critical drinking water resources and foraging habitat for federally endangered species that include the key deer (*Oodocoileus virginianus clavium*) and marsh rabbit (*Sylvilagus palustris hefneri*) (Lopez et al. 2004; LaFever et al. 2007).

Upland Forests

The major natural upland forest types in the Florida Keys are tropical hammocks and pine rocklands. Tropical hammocks are characterized by a closed canopy of hardwood trees and shade-tolerant understory species similar to those found on tropical islands in the West Indies. Typical tropical hammock plants in the Florida Keys include gumbo limbo (*Bursera simaruba*), Jamaican dogwood (*Piscidia piscipula*), poisonwood (*Metopium toxiferum*), pigeon plum (*Coccoloba diversifolia*), and seagrape (*Coccoloba uvivera*). Tropical hammocks on Key Largo serve as critical habitat for the endangered Key Largo woodrat (*Neotama floridana smalli*) and the Key Largo cotton mouse (*Peromyscus gossypinus allapaticolola*) (Barbour and Humphrey 1982; McCleery et al. 2006). The white-crowned pigeon (*Columba leucocephala*), listed as threatened by the State of Florida, relies heavily upon intact tropical hammocks in the Florida Keys to forage poisonwood fruits (Bancroft et al. 2000).

Pine rocklands in the Florida Keys are characterized by an open canopy of slash pine (*Pinus elliottii*) trees and a diverse understory of shrubs and herbaceous plants with high tolerance to drought and dependence on periodic fires to prevent succession to tropical hammock. In addition to slash pine trees, typical plants on a Florida Keys pine rockland include Keys thatch palm (*Thrinax morissii*), silver palm (*Coccothrinax agrentata*), locustberry (*Bursonima lucida*), and blackbead (*Pithecellobium keyense*). Federally endangered key deer and marsh rabbits utilize pine rocklands as critical forage and breeding habitat.

Beach Berm

Beach berms, or coastal berms, are scrubby shrub thickets or short forests that form on ridges of loose marine sediments deposited by coastal storm surge events. Older and higher beach berms can contain trees similar to those found on tropical hammocks, with trees that include gumbo limbo (*Bursera simaruba*), seagrape (*Coccoloba uvifera*), silver palm (*Coccothrinax argentata*), seven year apple (*Genipa clusifolia*), and poisonwood (*Metopium toxiferum*). Common tall shrubs include Spanish stopper (*Eugenia foetida*), hog plum (*Ximenia americana*), white indigoberry (*Randia aculeata*), Florida Keys blackbead (*Pithecellobium keyense*), and saffron plum (*Sideroxylon celastrinum*). Perfumed spiderlily (*Hymenocallis latifolia),* bayleaf capertree (*Capparis flexuosa*), buttonsage (*Lantana involucrata*), and rougeplant (*Rivina humilis*) are among the more common short shrubs and herbs within beach berm communities. Rare plants such as pride-of-big-pine (*Stumpfia maritima*), joewood (*Jacquinia keyensis*), and wild dilly (*Manilkara jaimiqui*) are often found on beach berms.

SLAMM Analysis

SLAMM utilizes a series of algorithms to integrate future climate change scenarios and ecosystem parameters to make predictions about the transition of different land covers due to sea level rise. For coastal wetlands, sea level rise in some cases is expected to increase the area of tidal wetland due to upland areas becoming subject to tidal flooding, which may then promote colonization by tidal wetland vegetation (Kirwan and Megonigal 2013). In other cases, coastal wetlands may be expected to decline and transition to open water or non-vegetated mud-flats due to the inability of wetland plants to adapt to rising tides and/or coastal erosion pressures (Ellison and Stoddart 1990; Gilman et al 2008). For mangrove ecosystems, the primary physical mechanism behind different transition scenarios is the ability of mangroves roots to capture sediment flux. In low sea level rise scenarios or areas with high sediment loads, mangrove ecosystems may capture sufficient sediment flux to outpace the effects of sea level rise (Parkinson et al. 1994). By contrast, higher rates of sea level rise and/or low sediment fluxes may outpace the sediment capture ability, thus leading to mangrove mortality and subsequent transition to a subtidal or open water ecosystem. The high value of SLAMM as a tool for making such complex assessments is well-recognized by many coastal researchers (e.g., Linhoss et al. 2014; Hauer et al. 2015), state agencies (Glazer 2013), and federal agencies (Lee et al. 2014).

Our SLAMM analysis builds upon a previous iteration of SLAMM runs (see Glazer 2013) performed by the Florida Fish and Wildlife Conservation Commission (FWC). The previous FWC analysis utilized an earlier version of SLAMM (version 6.01) and sea level rise curves developed by the 2001 Intergovernmental Panel on Climate Change (IPCC). Our analysis updates this prior FWC work by using a later version of SLAMM (version 6.2) and revised sea level rise curves that conform precisely to the lower and upper bounds of the Southeast Florida Regional Climate Change Compact (2011).

Runs of SLAMM 6.2 require geospatial inputs for land cover, elevation, and slope, as well as a series of ecosystem input parameters that include direction of offshore wind, historic trends of sea level rise, great diurnal tide range, elevation of the boundary where saltwater wetlands end, and estimated values of erosion and accretion for freshwater and saltwater wetlands. Brian Beneke of FWC provided the project team with a land cover file based originally upon the Florida Cooperative Land Cover Map (FNAI 2010), which an expert panel assembled by FWC crosswalked into land cover categories required by SLAMM (Glazer 2013; Table 12). As noted by Glazer (2013), areas designated in SLAMM as "brackish marsh" and "shrub-scrub marsh" were determined to have no direct analogue from the FNAI (2010) land covers, and thus instead were manually identified and edited by the expert panel using aerial photography.

All ecosystem parameter inputs for SLAMM analyses, as described in detail by Glazer (2013), were provided to the project team by FWC. Elevation and slope parameters were derived from the same LIDAR-based DEM, as referenced to NAVD88 (NAVD_LIDAR), used as the basis for other project analyses. Consistent with the original FWC analyses (Glazer 2013) and the resolution of the crosswalked SLAMM land cover map provided by FWC, all SLAMM runs for this project were performed at a 10m raster cell size. Summary results for the 2030 and 2060 SLAMM land cover change analyses in Monroe County are provided in Table 13.

As expected, the general trend of the SLAMM results is that a higher rate of sea level rise is associated with an increased conversion of upland and freshwater dependent land covers into tidal wetlands and open water habitats over time. However, an idiosyncratic result is that undeveloped dry land ecosystems show an increase in area by 2030 under the low sea level rise scenario (i.e., three inches total sea level rise), while developed dry land ecosystems show a decrease in area. A likely explanation for this discrepancy is that LIDAR elevations are often biased upward in areas of high coastal vegetation cover (Wang et al. 2009; Hladik and Alber 2012). This upward elevation bias may result in ground elevation data points within intertidal ecosystems being (erroneously) recorded as higher than MHHW or, in some cases, even higher than annual high water levels. Such an upward bias could, in turn, lead SLAMM to convert some extant coastal wetland areas into undeveloped dry land under a low sea level rise scenario. This is because tidal vegetation communities that erroneously show underlying elevations in exceedance of annual high water levels would be assumed to support successional growth into non-tidal, upland vegetation communities. To address these issues for future habitat modeling, we suggest detailed field collection of high resolution elevation data within vegetated wetlands and subsequent development of DEM correction surfaces (see Hladik and Alber 2012).

Mangrove ecosystems in Monroe County show a highly divergent response under the two sea level rise scenarios. Under the low sea level rise scenario, mangrove area shows a slight increase (4%) by 2030, with a progressive decrease (-6%) occurring by 2060. By contrast, the high sea level rise scenario shows a slight (3%) decline in area by 2030, followed by a very significant decline (47%) in area by 2060. These results are consistent with research suggesting that mangrove ecosystems have some capacity for collecting sediments and "keeping up" with low levels of sea level rise, as well as colonizing into upland areas that become more regularly inundated by tidal influx (Kirwan and Megonigal 2013). However, existing research also suggests that high rates of sea level rise can overwhelm the adaptive and colonization capacity of mangroves, resulting in major die-backs and significant reduction in areal coverage (Gilman et al 2008).

Another SLAMM result that warrants discussion is the significant decline (53% - 76% by 2030 scenario; 66% - 93% by 2060 scenario) in inland fresh marshes. Such freshwater marshes, while covering a very small land area in the Florida Keys, are known as highly important habitat and drinking water source for critically endangered species, including the key deer and Lower Keys marsh rabbit. Conversion of large acreages of these freshwater marshes into saltwater ecosystems are widely expected to result in further population declines, and thus pose enhanced extinction risks, for these dependent endangered species (LaFever et al. 2007; Ross et al. 2008; Maschinski et al. 2011).

Although SLAMM is an advanced ecosystem and land cover change model, we do note that caution is warranted in terms of how the results of SLAMM should be interpreted within the Florida Keys. Underlying elevation errors within the LIDAR DEM, classification errors within the land cover file, and geographic transformations necessary for the model to function all introduce uncertainty about the results, particularly at lower levels of sea level rise. In addition, careful calibration of the model with historic land cover change and field observations (Gilman et al. 2007) would provide helpful guidance for further updates and revisions of the modeling input parameters to better fit the specific ecological nuances of the Florida Keys.

Even with these caveats, the current results for Monroe County are broadly consistent with the view that coverage, expansion, and/or die-back within mangrove ecosystems may be one of the most crucial near-term indicators of the sea-level rise trajectory that takes shape over the next several decades (Blasco et al. 1996). Notably, statistical confidence intervals of sea level rise trends may make it analytically difficult to discriminate clearly between a rate of sea-level rise of three inches or a rate of seven inches that may occur by 2030 using tide gauge data alone (see, e.g., Holgate 2007). However, responses of intertidal ecosystems, such as mangroves, may show high sensitivity to near-term sea level rise shifts. For this reason, it is plausible that a mangrove response through 2030 that is characterized by shoreward invasion into upland areas with general maintenance of extant populations may provide near-term indication that a lower rate of sea level rise is occurring. By contrast, a net loss (i.e., die-back rate exceeds colonization rate) of mangrove coverage from natural areas in Monroe County through 2030 may provide some indication that sea level rise is trending toward a higher scenario.

It is critical to reiterate that a variety of other factors - such as hurricane disturbance, coastal hardening with sea walls or other bulkheads, and hydrologic alterations that change regional sediment balances - can have impacts on future mangrove distribution that may exacerbate, or even exceed those, associated with sea level rise (Smoak et al. 2013). Therefore, maintenance of natural habitat corridors in low-lying areas that allow for up-gradient colonization of tidal wetlands is the most commonly recommended strategy for promoting future coverage of mangroves and other tidal wetland ecosystems, including under accelerated sea level rise trends (Gilman et al. 2007). Construction of hardened bulkheads and impervious surfaces in low-lying areas can be expected to slow or even entirely prevent colonization of wetland vegetation, even as the hardened surfaces become more regularly subjected to tidal inundation (Titus et al. 1991).

Due to the critically important coastal habitat and storm surge protection (Gedan et al. 2011) functions provided by mangrove habitats, identification of intact corridors for future tidal wetland migration corridors is recommended as a potential overlay criterion for future land purchase and flood mitigation initiatives within Monroe County. In addition to these local values, the extremely high productivity and carbon sequestration potential of mangrove forests is increasingly being recognized as a potentially important climate change mitigation strategy (see, e.g., Alongi 2012). Similar to the discussion above for seagrass communities, Monroe County may therefore wish to pursue future revenue opportunities from "blue carbon" payments associated with conservation and assisted migration of local mangrove habitats.

Habitat Inundation Analysis

A complementary habitat vulnerability assessment was conducted using a tidal inundation approach overlaid onto land cover categories defined by Monroe County's internal habitat mapping effort (original file Land_Cover_Habitat.shp, as listed in Table 1). Discussions with Monroe County staff indicated that several vegetation and land cover categories in the Monroe County habitat map were in some cases more detailed and potentially accurate than those provided by the FNAI (2010) mapping effort. Because the SLAMM algorithm required further compression of the FNAI (2010) categories, it was determined that a separate vulnerability analysis that maintains original freshwater wetland and upland vegetation communities would therefore be helpful for planning purposes. The disadvantage of the inundation approach, however, is that it does not support a confident assessment of risks to mangrove or other intertidal and supratidal wetland ecosystems within the coastal zone. The advantage of the inundation approach is that it provides more direct information about potential impacts to specific upland habitat types (i.e., tropical hammock and pineland) in a way that the SLAMM results do not. Cross-comparison of the separate analyses also provides additional information in terms of all overall impact trends and potential insight into future research efforts to resolve uncertainties.

The inundation analysis was developed through an area summation analysis of each habitat type with extracted elevation from the LIDAR DEM. The initial area for each upland habitat and land cover type represents the summed area of DEM cells above MHHW (>0 feet above MHHW) within the respective habitat polygons at the condition of 2010 sea level. The same calculation was then performed for each 2030 and 2060 sea level rise scenario, with the MHHW elevations in the LIDAR DEM adjusted downward for each scenario using the range of possible and likely flood inundation thresholds (as defined in Table 3). The logic for this calculation is that any upland habitat exposed to daily tidal flooding will be inundated and transformed into a tidal ecosystem (Saha et al. 2011). The possible and likely categories are calculated separately (i.e., possible inundation is not additive to likely inundation) and follow the explicit elevation ranges defined in Table 3.

Full results of the inundation analysis by habitat type are provided in Table 14a for 2030 sea level rise scenarios and in Table 14b for 2060 sea level rise scenarios. While gross area calculations in Tables 14a & 14b are not directly comparable with the SLAMM results due to differences in the source land cover data layers, cross-comparison of percent changes show similar trends of future loss for developed, freshwater and upland forest ecosystems under higher sea level rise scenarios. Freshwater wetlands show high vulnerability by 2030 at even a low sea level rise scenario (27.8% possibly lost) and large-scale disappearance (89% likely lost) under a high sea level rise scenario at 2060. Pineland forests show moderately higher resilience than tropical hammock forests across all the sea level rise scenarios, although the high sea level rise scenario indicates possible to likely loss for over 40% of total upland forest area in the Florida Keys by 2060.

Under a high sea level rise scenario, there is a growing view among conservation scientists that long-term future existence of endangered species, such as the key deer, marsh rabbit, Key Largo cotton mouse, and Key Largo woodrat, may imply assisted migration to alternative habitat areas (Ross et al. 1994; Lopez et al. 2004; LaFever et al. 2007; Maschinski et al. 2011; Greenberg et al. 2013). However, the key deer and marsh rabbit each show higher near-term vulnerability to sea level rise due to the very low-lying nature of freshwater wetlands in the Lower Keys, while the relatively higher elevations of some hammock forests on Key Largo provide somewhat less near-term threat from sea-level rise to the cotton mouse and woodrat. Close cooperation with the United States Fish and Wildlife Service (USFWS), FWC, and conservation organizations to monitor populations of endangered species, track habitat trends, and, as necessary, implement relocation experiments under conditions of drastic habitat loss for endangered species due to sea level rise is recommended as a near-term and long-term climate adaptation strategy for Monroe County.

Table 12: Crosswalk to SLAMM Land Cover Categories. Original FNAI (2010) land cover categories and associated SLAMM land cover classification, as adapted from Glazer (2013). Note – not all SLAMM or FNAI land covers from this list are found in the Florida Keys.

SLAMM Land Cover	FNAI Code and Land Cover Class
Developed Dry Land	1800 - Cultural 1821 - Low Intensity Urban 1822 - High Intensity Urban 1840 - Transportation 1841 - Roads 1842 - Rails 1850 - Communication 1860 - Utilities 1870 - Extractive 1872 - Sand & Gravel Pits 1873 - Rock Quarries 1875 - Reclaimed Lands 1877 - Spoil Area 3240 - Sewage Treatment Pond 3260 - Industrial Cooling Pond 18211 - Urban Open Land 18212 - Low Structure Density 18221 - Residential, Med. Density 18222 - Residential, High Density 18223 - Commercial & Services 18224 - Industrial 18225 - Institutional 182131 - Parks 182132 - Golf courses 182134 - Zoos
Undeveloped Dry Land	1110 - Upland Hardwood Forest 1123 - Live Oak 1125 - Cabbage Palm 1130 - Rockland Hammock 1131 - Thorn Scrub 1210 - Scrub 1214 - Coastal Scrub 1220 - Upland Mixed Woodland 1300 - Pine Flatwoods and Dry Prairie 1311 - Mesic Flatwoods 1320 - Pine Rockland 1330 - Dry Prairie 1340 - Palmetto Prairie 1400 - Mixed Hardwood-Coniferous 1500 - Shrub and Brushland 1610 - Beach Dune 1620 - Coastal Berm 1630 - Coastal Grassland 1640 - Coastal Strand

Undeveloped Dry Land	1650 - Maritime Hammock 1740 - Keys Cactus Barren 1831 - Rural Open 1832- Agriculture 1880 - Bare Soil/Clear Cut 7000 - Exotic Plants 7100 - Australian Pine 7200 - Melaleuca 7300 - Brazilian Pepper 18331 - Cropland/Pasture 18332 - Orchards/Groves 18323 - Tree Plantations 182111 - Urban Open Forested 183111 - Oak - Cabbage Palm Forests 183311 - Row Crops 183312 - Field Crops 183313 - Improved Pasture 183314 - Unimproved/Woodland Pasture 183321 - Citrus 183324 - Fallow Orchards 183331 - Hardwood Plantations 183341 - Tree Nurseries 183342 - Sod Farms 183343 - Ornamentals 183352 - Specialty Farms 1833151 - Fallow Cropland
Swamp	2112 - Mixed Scrub-Shrub Wetland 2200 - Freshwater Forested Wetlands 2230 - Other Hardwood Wetlands 2233 - Mixed Wetland Hardwoods 2240 - Other Wetland Forested Mixed 2242 - Cypress/Pine/Cabbage Palm 7400 - Exotic Wetland Hardwoods 22211 - Hydric Pine Flatwoods 22212 - Hydric Pine Savanna 22311 - Bay Swamp 22312 - South Florida Bayhead
Cypress Swamp	2210 - Cypress/Tupelo(incl Cy/Tu mixed) 2211 - Cypress 2213 - Isolated Freshwater Swamp 2214 - Strand Swamp
Inland Fresh Marsh	2111 - Wet Prairie 2120 - Freshwater Marshes 2125 - Glades Marsh 2131 - Sawgrass 2140 - Floating/Emergent Aquatic Vegetation 2300 - Non-vegetated Wetland 5251 – Buttonwood Forest 21211 - Depression Marsh

Brackish Marsh	*Expert Input
Scrub-Shrub Marsh	*Expert Input
Salt Marsh	5240 - Saltwater Marsh
Mangrove	5250 - Mangrove Swamp
Tidal Flat	5220 - Tidal Flat 9100 - Unconsolidated Substrate
Ocean Beach	1670 - Sand Beach (Dry)
Rocky Intertidal	52111 - Keys Tidal Rock Barren
Inland Open Water	3000 - Lacustrine 3100 - Natural Lakes & Ponds 3200 - Artificial Lakes & Ponds 3211 - Aquacultural Ponds 3220 - Artificial Impoundment/Reservoir 3230 - Quarry Pond 4200 - Canal/Ditch 4210 - Canal 8000 - Open Water
Estuarine Open Water	5000 - Estuarine
Tidal Creek	4000 - Riverine 4100 - Natural Rivers & Streams
Open Ocean	6000 - Marine

Table 13: **SLAMM 6.2 Habitat Change Results for the Florida Keys**. Runs are based upon the 2030 and 2060 Southeast Florida Regional Climate Change Compact (2011) sea level rise scenarios. All area units are in acres.

	Year (Sea Level Rise Scenario)								
Habitat	**2010**	**2030 (Low)**	**% Change**	**2030 (High)**	**% Change**	**2060 (Low)**	**% Change**	**2060 (High)**	**% Change**
Developed Dry Land	19,045	17,507	**-8%**	16,888	**-11%**	16,075	**-16%**	11,642	**-39%**
Inland Fresh Marsh	148	70	**-53%**	35	**-76%**	50	**-66%**	10	**-93%**
Brackish Marsh	4,498	3,960	**-12%**	2,589	**-42%**	3,421	**-24%**	161	**-96%**
Mangrove	39,277	40,968	**4%**	38,142	**-3%**	36,855	**-6%**	20,665	**-47%**
Open Ocean/Estuarine	21,593	23,688	**10%**	30,481	**41%**	33,787	**56%**	63,192	**193%**
Salt Marsh	1,510	1,240	**-18%**	1,137	**-25%**	1,123	**-26%**	207	**-86%**
Swamp	535	279	**-48%**	154	**-71%**	105	**-80%**	12	**-98%**
Scrub-Shrub Marsh	3,344	2,914	**-13%**	2,249	**-33%**	2,663	**-20%**	561	**-83%**
Undeveloped Dry Land	11,705	12,361	**6%**	11,312	**-3%**	8,908	**-24%**	6,537	**-44%**

Table 14a: **Habitat Inundation Analysis, 2030 Sea Level Rise Scenarios**. Area (in acres) of upland, freshwater, and anthropogenic land cover types in Monroe County with possible and likely exposure to sea level rise inundation under the given scenario.

		2030 Low Scenario 3 Inches Sea Level Rise				2030 High Scenario 7 Inches Sea Level Rise			
Land Cover	**2010 Acres**	**Possibly Lost**	**%**	**Likely Lost**	**%**	**Possibly Lost**	**%**	**Likely Lost**	**%**
Beach Berm	143.9	14.6	-10.2%	N/A	N/A	11.8	-8.2%	9.0	-6.3%
Developed Land	12,870.5	702.5	-5.5%	N/A	N/A	695.1	-5.4%	333.8	-2.6%
Exotic	470.0	47.2	-10.0%	N/A	N/A	61.4	-13.1%	18.7	-4.0%
Freshwater Wetland	999.8	277.5	-27.8%	N/A	N/A	422.0	-42.2%	69.5	-6.9%
Hammock	8,726.5	470.3	-5.4%	N/A	N/A	814.8	-9.3%	172.3	-2.0%
Impervious Surface	3,052.6	83.0	-2.7%	N/A	N/A	115.1	-3.8%	37.7	-1.2%
Pineland	1,753.7	31.6	-1.8%	N/A	N/A	61.7	-3.5%	9.5	-0.5%
Undeveloped Land	2,429.2	258.9	-10.7%	N/A	N/A	319.0	-13.1%	104.8	-4.3%

Table 14b: **Habitat Inundation Analysis, 2060 Sea Level Rise Scenarios**. Area (in acres) of upland, freshwater, and anthropogenic land cover types in Monroe County with possible and likely exposure to sea level rise inundation under the given scenario.

		2060 Low Scenario 9 Inches Sea Level Rise				2060 High Scenario 24 Inches Sea Level Rise			
Land Cover	**2010 Acres**	**Possibly Lost**	**%**	**Likely Lost**	**%**	**Possibly Lost**	**%**	**Likely Lost**	**%**
Beach Berm	143.9	10.9	-7.6%	12.7	-8.9%	13.6	-9.5%	33.6	-23.3%
Developed Land	12,870.5	641.9	-5.0%	563.8	-4.4%	1,684.0	-13.1%	2,292.4	-17.8%
Exotic	470.0	61.4	-13.1%	34.7	-7.4%	77.1	-16.4%	179.8	-38.3%
Freshwater Wetland	999.8	426.9	-42.7%	186.0	-18.6%	66.0	-6.6%	889.7	-89.0%
Hammock	8,726.5	982.3	-11.3%	332.6	-3.8%	1,229.6	-14.1%	2,688.6	-30.8%
Impervious Surface	3,052.6	144.7	-4.7%	62.0	-2.0%	363.8	-11.9%	466.3	-15.3%
Pineland	1,753.7	83.3	-4.8%	20.9	-1.2%	397.1	-22.6%	376.2	-21.5%
Undeveloped Land	2,429.2	315.4	-13.0%	198.0	-8.2%	321.5	-13.2%	856.5	-35.3%

Managing and Conserving Habitat with Sea Level Rise

Just as the development paradigm in Monroe County changed dramatically from initial settlement through rapid modernization to today's nearly built-out phase, the nature conservation paradigm has also undergone transformations. Early conservation efforts focused on curtailing unsustainable harvest practices via regulation and law enforcement.

As the pace of development quickened, the need for habitat protection became apparent. Federal designations (e.g., Key West National Wildlife Refuge's establishment in 1908), the purchase of private property through public and private efforts, and the establishment of regulations limited habitat destruction and degradation. Active management of natural areas to maintain, or in some cases restore, their habitat values for native flora and fauna has grown in importance over the years as a result of increased understanding of what species need to persist and the threats to their persistence. Rare and imperiled species conservation concerns and the desire for sustainable commercial and recreational uses of many natural areas have further refined these conservation strategies over the years. The intensity and complexity of conservation efforts in Monroe County is remarkable and the positive results that have been achieved are undeniable, but these efforts have labored under an illusion that has only recently become apparent. That illusion is one of stationarity, or the assumption that things will be the same in the future as they are today or have been in recent memory. In the case of natural areas this leads to the expectation that protection and effective management of today's habitat will ensure the persistence of that habitat and the species it supports into the foreseeable future. The observed and predicted impacts of sea level rise compel natural area managers and regulators in the low-lying Florida Keys to reevaluate this assumption and to foresee a different future; one in which the goal of conservation becomes much more nuanced and complex.

A traditional conservation goal such as, "Prevent the loss of natural areas and native species populations," might become, "Guide natural areas and native species populations through change; staving off losses for as long as possible; maximizing opportunities for them to adapt and; ensuring that future conditions are as productive as possible for both nature and the people who depend on it for their livelihoods and quality of life."

Far from invalidating past conservation efforts or undermining the value of tried and true conservation approaches, sea level rise accentuates their importance. Past land protection efforts provide room for adaptation to occur, or to be actively shepherded, with minimal constraints. Invasive species prevention and control efforts, fire management in the Lower Florida Keys pine rocklands and other traditional conservation strategies take on new importance as they may also increase the resilience of natural systems and populations coping with chronic stress from sea level rise or acute impacts from storms, droughts and other climate-influenced phenomena.

A local example of resilience-based management may be found in the realm of coral reef conservation. Coral reefs are particularly vulnerable to climate change-induced stresses, such as elevated seawater temperature, which triggers coral bleaching and diseases, and ocean acidification, which weakens existing coral skeletons and makes it more difficult for new coral structure to grow. In the Keys and southeast Florida, the Florida Reef Resilience Program has been utilizing the concept of ecological resilience since 2005 to identify coral reefs that will be best able to withstand climate change impacts and develop resilience-based reef management and reef use strategies that will maximize protection of resilient reefs and enhance the viability of those that are less resilient. Like sea level rise, ocean warming and acidification cannot be effectively addressed at the local level alone. However, by minimizing local stresses such as degraded water quality, boat groundings, anchor damage and destructive fishing practices, reef managers and reef users can help make Florida coral reefs and the people and industries that depend upon them more resilient to climate change-related stresses.

See http://frrp.org/ and the "Climate Change Action Plan for the Florid Coral Reef System 2010-2015" http://frrp.org/wp-content/uploads/2013/07/Final-FL-Reef-Action-Plan-WEB.pdf

Conservation Land Acquisition Considerations

In the 2009 publication, "Disturbance and the Rising Tide: The Challenge of Biodiversity Conservation in Low-island Ecosystems," Ross et al. (2009) lay out a compelling argument for helping natural areas and ecosystems adapt to both the incremental long-term effects of sea level rise and acute disturbances such as storm surges. Their approach calls for identification and protection of "core areas" with the best chances of persistence during sea level rise, intensive management of core areas and, ex-situ conservation strategies including species relocation.

Proponents of conservation in the Florida Keys have been focused on identification and protection of core areas for conservation for many years. In the early 1990s this took the form of establishment of the Florida Keys boundaries for the state's land acquisition program, now known as Florida Forever. Subsequent changes to Florida Forever resulted in the Keys projects being classified as "climate change lands" due to their vulnerability to sea level rise. Monroe County recently completed a land acquisition prioritization process that factored sea level rise into its recommendations.

Identifying core areas for sea level rise adaptation is not as simple as choosing the highest ground, although elevation is a critical component of any such analysis. Four other important components include:

(1) Representation: All habitat types and species should be included in protected core areas to the extent possible.

(2) Replication: There should be more than one core area for each habitat type and/or species so the impacts of a single unmanageable event, such as a severe storm surge, are less likely to damage all habitat or species occurrences.

(3) Connectivity: Gene flow among core areas is ensured by maintaining biological corridors or, in extreme cases, via direct human intervention (i.e. translocations of organisms or their gametes within the historic range of the species or subspecies). Connectivity also comes into play in assessing the ability of a given habitat patch within a core area to migrate from lower to higher ground during the course of sea level rise.

(4) Effective management: Synonymous with "intensive management" (Ross et al. 2009), it is imperative that core areas are not only identified and protected in a legal sense but that they are also managed to reduce threats and maintain the natural processes that shape the ecosystem.

"No Regrets" Strategies

Several common natural resource management strategies that have been practiced in the Keys for decades increase the resilience of natural areas and native species to climate stress. These practices still stand on their own merits, but in light of sea level rise, storms, floods and droughts, their importance is further amplified.

Invasive Exotic Species Management

Invasive exotic species degrade natural areas by directly competing with native species that have life history requirements similar to those of the invader and by degrading habitat of native species that rely on native prey or forage that is displaced by the invader. Invasive exotic plants, most notably Australian pine (several *Casuarina* species), are known to destabilize dunes and other coastal habitats that are the front line of natural defense against storm surges and coastal erosion which will be exacerbated by sea level rise. At present, prevention, early detection of, and rapid response to new invasive species and long-term control of established invasive species in the Florida Keys is as advanced and effective as almost any place in the world thanks to the efforts of the Florida Keys Invasive Exotics Task Force and its member organizations, including Monroe County. Invasive exotic species management must continue to take place in order for natural areas to maintain high habitat values regardless of sea level rise.

Sea level rise may favor some salt tolerant invasive exotics such as Australian pine, Asiatic colubrina (*Colubrina asiatica*) and scaevola (*Scaevola sericea*), while disfavoring those that are less salt-tolerant. Melaleuca (*Melaleuca quinqueneriva*) and Old World climbing fern (*Lygodium microphyllum*) are examples of extremely problematic invasive exotic species that plague South Florida's mainland but have had very little impact in the Keys due at least in part to their inability to tolerate salt. If the more rapid rates of projected sea level rise become evident, soil salinization and salt spray will provide some measure of control for some species and this may be taken into account when prioritizing control efforts.

Wildland Fire Management

Pine rockland forests, found only in the Lower Keys, southern Miami-Dade County and the Bahamas Archipelago, are a fire-dependent forest community that sustains a rich diversity of flora and fauna. By maintaining a mosaic of pine rockland and hardwood hammock patches, upland biological diversity is conserved across the larger landscape. In the absence of periodic fires, fire-sensitive broadleaf plant species invade the pine forest and hardwood hammock becomes established through ecological succession. Fire is a natural process that counteracts succession in pine rocklands. Sea level rise is expected to accelerate forest succession from the highly salt-sensitive pine forest to the slightly less salt-sensitive hammock forest and the careful application of controlled burns is an economically viable and ecologically appropriate antidote to that succession. If sea level rise were not a consideration, controlled burns would still be necessary to prevent succession to hammock. Improving fire management in Lower Keys pine rocklands should be brought to the forefront of the USFWS's habitat management agenda because the USFWS is the dominant player in pine rockland fire management and the lead entity charged with conserving a number of fire-dependent species.

Special care will need to be taken when planning and conducting controlled burns on the low elevation fringes of fire-dependent forests where stress from saltwater intrusion may interact with stress from fire and result in unwanted fire effects such as old-growth pine mortality. In this case the illusion of stationarity may be particularly troublesome and dangerous. Controlled burn prescriptions and operations that led to desirable fire effects in the 1970's or even more recently may not result in the same fire effects today or as the sea rises. Habitat managers should be on the lookout for indications that fire is no longer an effective habitat management tool for some forest or wetland blocks due to sea level rise and at some point accept that succession to hammock or wetland conditions is inevitable. Under some circumstances fire may be used to favor herbaceous marshes over swamps dominated by woody species but field observations and SLAMM modelling conducted for this project suggest that fire-sensitive mangroves and open water habitat types are more likely to result from sea level rise than marsh habitat types. The value of an adaptive management approach and application of the precautionary principle will become even more imperative to fire management planning and operations as the sea rises.

Wetland Restoration

The inherently limited area of the islands and naturally unfavorable geological conditions for freshwater retention in the middle and upper Keys soils make freshwater wetlands one of the rarest habitat types in the archipelago. Mangroves and saltmarshes are comparatively common, but all wetland types have suffered from habitat destruction via outright filling of wetlands and degradation via drainage and fragmentation by roads. Remaining wetlands are critically important to many wildlife species including several that are listed as threatened or endangered.

Removing fill from historic wetlands and restoring connectivity in degraded wetlands by strategically filling some ditches, removing obsolete roadbeds and installing culverts under actively-used roads are tried and true methods for recovering lost wetland habitat and improving habitat quality. Wetland mitigation requirements of the Army Corps of Engineers, Florida Department of Environmental Protection and South Florida Water Management District have been used to restore significant areas of wetland habitat on public conservation lands throughout the Keys and other wetland restoration projects have been conducted through a variety of mechanisms. In recent years sea level rise projections have been factored into some wetland restoration projects and this must become the norm given the present and projected rates for rise.

Filling or plugging some ditches may be essential to prevent unnaturally rapid infiltration of interior wetlands and upland habitats by saltwater as the sea rises. Restoring hydrological connectivity by removing obsolete roadbeds and installing culverts under functional roads to improve habitat condition takes on added importance because it enables storm surges to drain off the land in places where they have historically become impounded by roads, causing unnecessary damage to freshwater-dependent habitats and species as they slowly sink into the ground and groundwater. These actions should also slow the shrinkage and salinization of the fresh groundwater lenses present on Big Pine Key and other islands of the Lower Keys.

Managing Today for Tomorrow’s Marine Ecosystem

There are no credible predictions suggesting that sea level will reverse its multi-millennial trend of rise. At some point, hopefully long in the future, the Florida Keys will become marine habitat and they are likely to remain marine habitat for many millennia thereafter. Given this fact, conservation measures and other modern day decisions about land use and development should be evaluated with an eye to their future impact on marine habitat quality. As a hypothetical example, erecting a dike around critical habitat for a rare species may slow the advance of sea level rise temporarily, but once sea level rise overcomes both the habitat and the dike itself, the presence of the submerged dike may disrupt movement or other aspects of some marine organisms’ life cycles.

While it is difficult to conceive of many terrestrial habitat conservation activities that would compromise future marine habitat quality, it is much easier to predict potential negative impacts of the modern built environment on the future marine environment. Landfills, underground storage tanks for petroleum products, soil contaminated by past pollution spills and a multitude of other, less discrete sources of pollutants that could prove toxic to marine life are present in the Florida Keys today. Some forms of pavement and other artificial surfaces may prove inhospitable to the establishment of mangroves, seagrass, or settlement of coral larvae. Seawalls and other forms of shoreline hardening may disrupt movement or other aspects of marine species’ life cycles. The question, “Will the short-term solution to today’s problem impact the future marine environment,” is one well worth asking. The faster the sea rises the more seriously this issue must be factored into decision making.

Species Translocations and Ex-Situ Conservation Measures

If retention of viable populations of all Florida Keys' terrestrial endemic species continues to be a goal of natural resource managers, then protection, effective management and restoration of these species habitats will eventually need to be supplemented with and eventually supplanted by more manipulative measures. At one end of the spectrum of these measures is assisted migration of salt-sensitive species from lower to higher areas on the island or habitat patch on or in which they are already present. This might take the form of gathering a plant's seeds and sowing them inland and upslope, or growing small plants in a nursery before planting them to help reduce uncertainty about the species dispersing on its own. Vulnerable individual plants or individual animals that may not readily disperse on their own (e.g. tree snails) might even be translocated inland and upslope on a given island. More mobile species may be translocated among islands within their historic ranges. This has already been done with mixed success in the cases of the key deer and the Lower Keys marsh rabbit although not explicitly as a sea level rise adaptation strategy.

Most biologists and natural resource managers are relatively comfortable with these measures, if more traditional conservation approaches lose efficacy as the pace of sea level rise quickens. However, as soon as the conversation changes to one of moving individuals, or their genes, to places where they have never been or where they would not have been likely to disperse on their own, consensus begins to fray. Some are proponents of biodiversity conservation in the absolute sense, that is, every species must be preserved in perpetuity. Others, while regretting any anthropogenic contributions to the acceleration of extinctions, support the extinction of species without any intervention. Between these two extremes lies a vast middle ground.

Ex-situ conservation measures, those that take place outside of the natural ranges of the species in question, may take a variety of forms. Using a rare plant as one example, the Florida semaphore cactus (*Consolea corallicola*) is federally listed as an endangered species. The only natural populations of this species are on two islands in the Florida Keys. Ex-situ propagation of genetic clones (i.e., individuals derived from tissue cultivation as opposed to sexual reproduction) of one population has already taken place, with clones cultivated at several locations on the mainland and returned to the site of genetic origin, as well as to natural areas on nearby islands. Clones have also been retained at the sites of propagation. The clones returned to the wild provide an example of what is often called "captive breeding" in animal conservation terms while the clones maintained on the mainland are examples of genetic banking. Seed banks, along with conservation-focused botanical gardens and zoological parks, are other common forms of genetic banking. In all of these approaches, the goal is not to create new, self-maintaining populations at the production location, but to provide a reservoir of genetic material that may be used to augment or reestablish populations in their native ranges.

Using a hypothetical key deer conservation strategy as the focus of another example of ex-situ conservation, one can see the complexities involved when the goal is to create new populations outside of the natural range of a species. The key deer herd has been physically and genetically isolated in the Lower Keys for millennia and it is that isolation that led to the genetic and morphological differences that distinguish these animals from the common whitetail deer on the mainland. The rarity of the key deer led to their listing as endangered species under federal law, while their common cousins on the mainland are legally hunted for sport and often considered a nuisance due to their large populations. When sea level rise makes the Florida Keys uninhabitable for the key deer, moving them to the mainland would lead to their rare genes mixing with the whitetail genes and becoming lost over the generations. Confining the key deer to an enclosure would prevent them from breeding with the whitetails, but would be perpetually costly, vulnerable to failure, and not provide any reasonable hope of eventually returning the key deer to the island ecosystem which, in genetic terms, created them.

Moving key deer to another island or any ecosystem where there are no whitetail deer – the Bahamas for example – would lead to an altered ecosystem. Negative consequences for the native species that the deer would forage on and the native animals that depended on those forage species prior to introduction of the deer are predictable. Novel interactions between the deer and other elements of the ecosystem are much more difficult to predict. From the perspective of its new home, this key deer conservation strategy would amount to an intentional introduction of an invasive exotics species, the pros and cons of which would not be fully known for generations and whose negative consequences could be very difficult to undo.

For some species, the risks of ex-situ conservation in the wild might be worth taking. For others genetic banking in zoos and botanical gardens may be the only practical, long-term solution, if extinction is an unacceptable outcome. If not the present generation, future generations of natural resource managers will be faced with making these challenging choices and decisions. Monroe County is likely to be a party to these discussions, although it is likely to take a back seat to the state and federal agencies, which have the primary responsibilities for any species in need of ex-situ conservation.

Summary of Dataset Deliverables

All final GIS datasets for this vulnerability assessment are to be delivered to Monroe County in ESRI File Geodatabase format with supporting metadata upon project completion. The files within these geodatabases are summarized in Table 15.

Table 15: **Final Dataset Deliverables.** All Geographic Information Systems (GIS) files projected to an Albers Conical Equal Area as used by the Florida Geographic Data Library.

Dataset Description	File Name	Dataset Type
MHHW-based Digital Elevation Model	MHHW_LIDAR	Raster (5 meter cell size)
NAVD88-based Digital Elevation Model	NAVD_LIDAR	Raster (5 meter cell size)
Building Footprints of Public Facilities and Critical Infrastructure Parcels	MONROECOUNTY_FOOTPRINTS	Polygon Features
Complete Road Segments	Original_Roads	Polyline Features
Road Segments with Sketch Planning Tool Nuisance Flooding Vulnerability, 2030 Low Sea Level Rise Scenario	Low_2030_Nuisance	Polyline Features
Road Segments with Sketch Planning Tool Inundation Flooding Vulnerability, 2030 Low Sea Level Rise Scenario	Low_2030_Inundation	Polyline Features
Road Segments with Sketch Planning Tool Nuisance Flooding Vulnerability, 2030 High Sea Level Rise Scenario	High_2030_Nuisance	Polyline Features
Road Segments with Sketch Planning Tool Inundation Flooding Vulnerability, 2030 High Sea Level Rise Scenario	High_2030_Inundation	Polyline Features

Road Segments with Sketch Planning Tool Nuisance Flooding Vulnerability, 2060 Low Sea Level Rise Scenario	Low_2060_Nuisance	Polyline Features
Road Segments with Sketch Planning Tool Inundation Flooding Vulnerability, 2060 Low Sea Level Rise Scenario	Low_2060_Inundation	Polyline Features
Road Segments with Sketch Planning Tool Nuisance Flooding Vulnerability, 2060 High Sea Level Rise Scenario	High_2060_Nuisance	Polyline Features
Road Segments with Sketch Planning Tool Inundation Flooding Vulnerability, 2060 High Sea Level Rise Scenario	High_2060_Inundation	Polyline Features
FKAA water tanks	wTank	Point Features
FKAA cathodic rectifiers	wCathodicRect	Point Features
FKAA system valves	wSystemValve	Point Features
FKAA control valves	wControlValve	Point Features
FKAA sampling stations	wSamplingStation	Point Features
FKAA test stations	wTestStation	Point Features
SLAMM Initial Condition, 2030, and 2060 High and Low Sea Level Rise Scenarios for Monroe County	MonroeCountySAP_SLAMM_Webmerc.gdb	Geodatabase

References

Achilleos, G.A. 2011. The inverse distance weighted interpolation method and error propagation mechanism – creating a DEM from an analogue topographical map. Journal of Spatial Science 56:283-304.

Aguilar, F.J., J.P. Mills, J. Delgado, M.A. Aguilar, J.G. Negreiros and J.L. Perez. 2010. Modeling vertical error in LiDAR-derived digital elevation models. ISPRS Journal of Photogrammetry and Remote Sensing 65:103-111.

Albright, R. B. Mason, M. Miller, and C. Langdon. 2010. Ocean acidification compromises recruitment success of the threatened Caribbean coral Acropora palmata. Proceedings of the National Academy of Sciences USA 107:20400-20404.

Albright, R. and C. Langdon. 2011. Ocean acidification impacts multiple early life history processes of the Caribbean coral *Porites astreoide*s. Global Change Biology 17:2478-2487.

Alongi, D.M. 2012. Carbon sequestration in mangrove forests. Carbon Management 3:313-322.

Andersen, P.F., J.W. Mercer, and H.O. White. 1988. Numerical modeling of salt-water intrusion at Hallandale, Florida. Groundwater 26:619-630.

Aumen, N.G., K.E. Havens, G.R. Best, and L. Berry. 2015. Predicting ecological responses of the Florida Everglades to possible future climate scenarios: Introduction. Environmental Management 55:741-748.

Bancroft, G.T., R. Bowman, and R.J. Sawicki. 2000. Rainfall, fruiting phenology, and the nesting season of white-crowned pigeons in the Upper Florida Keys. The Auk 117:416-426.

Barbour, D.B. and S.R. Humphrey. 1982. Status and habitat of the Key Largo woodrat and cotton mouse (*Neotoma floridana smalli* and *Peromyscus gossypinus allapaticola*). Journal of Mammalogy 63:144-148.

Bergh, C. 2011. Initial estimates of the ecological and economic consequences of sea level rise on the Florida Keys. The Nature Conservancy. http://www.georgetownclimate.org/resources/initial-estimates-of-the-ecological-and-economic-consequences-of-sea-level-rise-on-the-flo. Accessed July 27, 2015.

Bergh, C. and A. Morkill. 2012. Sea Level Rise Adaptation in the Florida Keys: Conserving Terrestrial and Intertidal Natural Areas and Native Species. http://www.frrp.org/SLR%20documents/Sea%20level%20rise%20adaptation%20in%20the%20Florida%20Keys_workshop%20synthesis%20FINAL.pdf. Accessed August 31, 2015.

Bhat, M. 2003. Application of non-market valuation to the Florida Keys marine reserve management. Journal of Environmental Management 56:315-325.

Blasco, F., P. Saenger, and E. Janodel. 1996. Mangroves and indicators of coastal change. Catena 27:167-178.

Bloetscher, F., D.E. Meeroff, B.N. Heimlich, A.R. Brown, D. Bayler, and M. Loucraft. 2010. Improving resilience against the effects of climate change. American Water Works Association 102:36-46.

Bloetscher, F., B.N. Heimlich, and T. Romah. 2011. Counteracting the effects of sea level rise in southeast Florida. Journal of Environmental Science and Engineering 5:1507-1525.

Boesch, D. F., N.E. Armstrong, C.F. D'Elia, N.G. Maynard, H.W. Paerl, and S.L. Williams. 1993. Deterioration of the Florida Bay ecosystem: An evaluation of the scientific evidence. Interagency Working Group report to National Fish and Wildlife Foundation. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.22.8350&rep=rep1&type=pdf. Accessed September 4, 2015.

Bohnsack, J.A., D.E. Harper, and D.B. McClellan. 1994. Fisheries trends from Monroe County, Florida. Bulletin of Marine Science 54:982-1018.

Borisova, T., C. Rawls, and D. Adams. 2013. Balancing urban water demand and supply in Florida: Overview of tools available to water managers. EDIS Document FE811. University of Florida IFAS Extension. https://edis.ifas.ufl.edu/pdffiles/FE/FE81100.pdf. Accessed September 24, 2015.

Boyer, J.N., C.R. Kelble, P.B. Ortner, and D.T. Rudnick. 2009. Phytoplankton bloom status: Chlorophyll a biomass as an indicator of water quality condition in the southern estuaries of Florida, USA. Ecological Indicators 6:S56-S67.

Bricker, S.B., B. Longstaff, W. Dennison, A. Jones, K. Boicurt, C. Wicks, and J. Woerner. 2008. Effects of nutrient enrichment in the nation's estuaries: A decade of change. Harmful Algae 8:21-32.

Bulleri, F. and M.G. Chapman. 2010. The introduction of coastal infrastructure as a driver of change in marine ecosystems. Journal of Applied Ecology 47:26-35.

Caraco, D. and S. Drescher. 2011. Review of programs to protect southeast Florida's coral reefs. Ellicott City, MD: Center for Watershed Protection. ftp://docs.lib.noaa.gov/pub/data.nodc/coris/library/NOAA/CRCP/other/grants/LBSP_Project_21_Overview_of_Programs_in_SE_FL_to_Reduce_LBSP.pdf. Accessed September 4, 2015.

Carpenter, K.E., M. Abrar, G. Aeby, R.B. Aronson, et al. 2008. One-third of reef-building corals face elevated extinction risk from climate change and local impacts. Science 321:560-563.

Colella, M.A., R.R. Ruzicka, J.A. Kidney, J.M. Morrison, and V.B. Brinkhuis. 2012. Cold-water event of January 2010 results in catastrophic benthic mortality on patch reefs in the Florida Keys. Coral Reefs 31:621-632.

Dausman, A. and C.D. Langevin. 2005. Movement of the saltwater interface in the surficial aquifer system in response to hydrologic stresses and water-management practices, Broward County, Florida. U.S. Geological Survey. Scientific Investigations Report 2004-5256. http://lake.wateratlas.usf.edu/upload/documents/sir20045256.pdf. Accessed September 4, 2015.

De'ath, G., K.E. Fabricius, H. Sweatman, and M. Puotinen. 2012. The 27-year decline of coral cover on the Great Barrier Reef and its causes. Proceedings of the National Academy of Sciences USA 109:17995-17999.

Dehvari, A. and R.J. Heck. 2012. Removing non-ground points from automated photo-based DEM and evaluation of its accuracy with LiDAR DEM. Computers & Geosciences 43:108-117.

Duarte, C.M. 2002. The future of seagrass meadows. Environmental Conservation 2:192-206.

Eakin, C.M., J.A. Morgan, S.F. Heron, T.B. Smith, G. Liu, L. Alvarez-Filip, B. Baca, E. Bartels, C. Bastidas, C. Bouchon, M. Brandt, A.W. Bruckner, et al. 2010. Caribbean corals in crisis: Record thermal stress, bleaching, and mortality in 2005. PLOS One. DOI:10.1371/journal.pone.0013969.

Ellison, J.C. and D.R. Stoddart. 1990. Mangrove ecosystem collapse during predicted sea-level rise: Holocene analogues and implications. Journal of Coastal Research 7:151-165.

EPA. 2014. Flood resilience: A basic guide for water and wastewater utilities. http://water.epa.gov/infrastructure/watersecurity/emerplan/upload/epa817b14006.pdf. Accessed July 22, 2015.

FDEM. 2009. 2007-2008 Florida Division of Emergency Management (FDEM) Lidar Project: Blocks 1-10 (Southeast Florida and Keys). https://catalog.data.gov/harvest/object/0ece0e91-c1ec-4bcf-8b76-b33ab209c695/html/original. Accessed September 17, 2015.

FDOT. 2013. Terrestrial Mobile LiDAR Surveying & Mapping Guidelines. http://www.dot.state.fl.us/surveyingandmapping/documentsandpubs/20131007_tml_guidelines.pdf. Accessed November 19, 2015.

FEMA. 2008. National Flood Insurance Program (NFIP) Floodplain Management Bulletin: Historic Structures. FEMA-467-2. http://www.fema.gov/media-library-data/20130726-1628-20490-7857/tb_p_467_2_historic_structures_05_08_web.pdf. Accessed June 23, 2015.

Florida Keys Aqueduct Authority (FKAA). 2011. 2011 Strategic Plan. http://www.fkaa.com/Strategic%20Plan%202011.2.pdf.

Flugman, E., P. Mozumder, and T. Randhir. 2012. Facilitating adaptation to global climate change: Perspectives from experts and decision-makers serving the Florida Keys. Climatic Change 112:1015-1035.

FNAI. 2010. Guide to the natural communities of Florida: 2010 edition. Tallahassee: Florida Natural Areas Inventory.

Fourqurean, J.W., C.M. Duarte, H. Kennedy, N. Marbà, M. Holmer, M.A. Mateo, E.T. Apostolaki et al. 2012. Seagrass ecosystems as a globally significant carbon stock. Nature Geoscience 5:505-509.

Gedan, K.B., M.L. Kirwan, E. Wolanski, E.B. Barbier, and B.R. Silliman. 2011. The present and future role of coastal wetland vegetation in protecting shorelines: Answering recent challenges to the paradigm. Climatic Change 106:7-29.

Gilman, E.L. 2004. Assessing and managing coastal ecosystem response to projected sea-level rise and climate change. International Research Foundation for Development Forum on Small Island States: Challenges, Prospects, and International Cooperation. https://www.researchgate.net/profile/Eric_Gilman2/publication/228694123_Assessing_and_managing_coastal_ecosystem_response_to_projected_relative_sea-level_rise_and_climate_change/links/09e4150d622f2f044b000000.pdf.

Gilman, E.L., J. Ellison, N.C. Duke, and C. Field. 2008. Threats to mangroves from climate change and adaptation options: A review. Aquatic Botany 89:237-250.

Glazer, R. 2013. Alternative futures under climate change for the Florida Key's benthic and coral systems. Marathon: Florida Fish and Wildlife Conservation Commission. http://www.car-spaw-rac.org/IMG/pdf/Final_Report-_Glazer_-_KeysMAP-1.pdf. Accessed June 23, 2015.

Greenberg, C.H., R.W. Perry, K.E. Franzreb, S.C. Loeb, D. Saenz, et al. 2013. Climate change and wildlife in the southern United States. *In* Climate Change Adaptation and Mitigation Management Options: A Guide for Natural Resource Managers in Southern Forest Ecosystem, pp. 379-420. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.451.5212&rep=rep1&type=pdf.

Greening, H.S., L.M. Cross, and E.T. Sherwood. 2011. A multiscale approach to seagrass recovery in Tampa Bay, Florida. Ecological Restoration 29:82-93.

Griffin, S.L. and C.M. Longiaru. 2012. Key West Historic Resources Survey 2011. Prepared by PanAmerican Consultants, Inc. for the City of Key West Planning Department. http://www.cityofkeywest-fl.gov/egov/documents/1345059719_688751.pdf. Accessed November 19, 2015.

Guinotte, J.M. and V.J. Fabry. 2008. Ocean acidification and its potential effects on marine ecosystems. Annals of the New York Academy of Sciences 1134:320-342.

Hall, M.O., K. Madley, M.J. Durako, J.C. Zieman, and M.B. Roblee. 2007. Florida Bay. *In* Seagrass Status and Trends in the Northern Gulf of Mexico: 1940-2002. United States Geological Survey Scientific Investigations Report 2006-5287. Eds. L. Handley et al., pp. 243-254. http://pubs.usgs.gov/sir/2006/5287/pdf/FloridaBay.pdf.

Hauer, M.E., J.M. Evans, and C.R. Alexander. 2015. Sea-level rise and sub-county population projections in coastal Georgia. Population and Environment 37:44-62.

Hearn, P., D. Strong, E. Swain, and J. Decker. 2013. Internet-based modeling, mapping, and analysis for the Greater Everglades (IMMAGE; Version 1.0): Web-based tools to assess the impact of sea level rise in South Florida. U.S. Geological Survey Open-File Report 2013-1185.

Hladik, C. and M. Alber. 2012. Accuracy assessment and correction of a LIDAR-derived salt marsh digital elevation model. Remote Sensing of Environment 121:224-235.

Hoegh-Guldberg, O. 2011. Coral reef ecosystems and anthropogenic climate change. Regional Environmental Change 11:S215-S227.

Hoegh-Guldberg, O., P.J. Mumby, A.J. Hooten, R.S. Steneck, et al. 2007. Coral reefs under rapid climate change and ocean acidification. Science 318:1737-1742.

Holgate, S.J. On the decadal rates of sea level change during the twentieth century. Geophysical Research Letters 34: DOI:1029/2006GL028492.

Jaap, W.C. 1979. Observations on Zooxanthella expulsion at Middle Sambo Reef, Florida Keys. Bulletin of Marine Science 29:414-422.

Johnson M.E., C. Lustic, E. Bartels, I.B. Baums , D.S. Gilliam, et al. 2011. Caribbean *Acropora* restoration guide: Best practices for propagation and population enhancement. The Nature Conservancy, Arlington, VA.

Keller, B.D. and B.D. Causey. 2005. Linkages between the Florida Keys National Marine Sanctuary and the South Florida Ecosystem Restoration Initiative. Ocean and Coastal Management 48:869-900.

Kirwan, M.L. and J.P. Megonigal. 2013. Tidal wetland stability in the face of human impacts and sea-level rise. Nature 504:53-60.

Klein, H. and B.G. Waller. 1985. Synopsis of saltwater intrusion in Dade County, Florida, through 1984. U.S. Geological Survey Water-Resources Investigations Report 85-4104. Washington, D.C.

Koch, M. G. Bowes, C. Ross, and X.H. Zhang. 2013. Climate change and ocean acidification effects on seagrasses and marine macroalgae. Global Change Biology 19:103-132.

Krauss, K.W., K.L. McKee, C.E. Lovelock, D.R. Cahoon, N. Saintilan, R. Reef, and L. Chen. 2014. How mangrove forests adjust to rising sea level. New Phytologist 202:19-34.

Krusczynski, W.L. and F. McManus. 2002. Water quality concerns in the Florida Keys: Sources, effects and solutions. In The Everglades, Florida Bay, and Coral Reefs of the Florida Keys: An Ecosystem Sourcebook. Eds., J.W. Porter and K.G. Porter, pp. 827-882. CRC Press: Boca Raton.

LaFever, D.H., R.R. Lopez, R.A. Feagin, and N.J. Silvy. 2007. Predicting the impacts of future sea-level rise on and endangered lagomorph. Environmental Management 40:430-437.

Langevin, C.D. and M. Zygnerski. 2013. Effect of sea-level rise on salt water intrusion near a coastal well field in southeastern Florida. Groundwater 51:781-803.

Lapointe, B.E., J.D. O'Connell, and G.S. Garrett. 1990. Nutrient couplings between on-site sewage disposal systems, groundwaters, and nearshore surface waters of the Florida Keys. Biogeochemistry 10:289-307.

LaPointe B.E. and M.W. Clark. 1992. Nutrient inputs from the watershed and coastal eutrophication in the Florida Keys. Estuaries 15:465-476.

Lapointe, B.E., D.A. Tomasko, W.R., Matzie. 1994. Eutrophication and tropic state classification of seagrass communities in the Florida Keys. Bulletin of Marine Science 54:696-717.

Lapointe, B.E., P.J. Barile, and W.R. Matzie. 2004. Anthropogenic nutrient enrichment of seagrass and coral reef communities in the Lower Florida Keys: Discrimination of local versus regional nitrogen sources. Journal of Experimental Marine Biology and Ecology 308:23-58.

Leach, S.D., H. Klein, and E.R. Hampton. 1972. Hydrologic effects of water control and management of southeastern Florida. Tallahassee: Florida Bureau of Geology Report of Investigations no. 60.

Lee, H., D.A. Reusser, M.R. Frazier, L.M. McCoy, P.J. Clinton, and J.S. Clough. 2014. Sea level affecting marshes model (SLAMM) – new functionality for predicting changes in distribution of submerged aquatic vegetation in response to sea level rise. Version 1.0. Newport, OR: United States Environmental Protection Agency. http://warrenpinnacle.com/prof/SLAMM6/SLAMM_6.3_final_release.pdf. Accessed June 23, 2015.

Lee, T.N. and N. Smith. 2002. Volume transport variability through the Florida Keys tidal channels. Continental Shelf Research 22:1361-1377.

Linhoss, A.C., G. Kiker, M. Shirley, and K. Frank. 2014. Sea-level rise, inundation, and marsh migration: Simulating impacts on developed lands and environmental systems. Journal of Coastal Research 31:36-46.

Lipp, E.K., J.J. Jarrell, D.W. Griffin, J. Lukasik, J. Jacukiewicz, and J.B. Rose. 2002. Preliminary evidence for human fecal contamination in coral of the Florida Keys, USA. Marine Pollution Bulletin 44:666-670.

Lopez, R.R., N.J. Silvy, R.N. Wilkins, P.A. Frank, M.J. Peterson, and M.N. Peterson. 2004. Habitat-use patterns of Florida Key Deer: Implications of urban development. The Journal of Wildlife Management 68:900-908.

Maschinski, J. M.S. Ross, H. Liu, J. O'Brien, E.J. von Wettberg, and K.E. Haskins. 2011. Sinking ships: Conservation options for endemic taxa threatened by sea level rise. Climatic Change 107:147-167.

McCleery, R.A., R.R. Lopez, N.J. Silvy, P.A. Frank, and S.B. Klett. 2006. Population status and habitat selection of the endangered Key Largo woodrat. The American Midland Naturalist 155:197-209.

Mcleod, E. G.L. Chmura, S. Bouillon, R. Salm, M. Björk, C.M. Duarte, C.E. Lovelock, W.H. Schlesinger and B.R. Silliman. 2011. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. Frontiers in Ecology and the Environment 9: 552-560.

Menon, S., J. Soberon, X. Li, A.T. Peterson. 2010. Preliminary assessment of terrestrial biodiversity consequences of sea-level rise mediated by climate change. Biodiversity and Conservation 19:1599-1609.

Mozumder, P. E. Flugman, and T. Randhir. 2011. Adaptation behavior in the face of global climate change: Survey responses from experts and decision-makers serving the Florida Keys. Ocean and Coastal Management 54:37-44.

National Ocean Service. 2014. Why do we have spring tides in the fall? http://oceanservice.noaa.gov/facts/springtide.html. Accessed November 19, 2015.

NOAA. 2014. Vertical Datum Transformation. http://vdatum.noaa.gov/. Accessed April 12, 2015.

NOAA. 2015a. Key West, FL – Station ID: 8724580. http://tidesandcurrents.noaa.gov/stationhome.html?id=8724580. Accessed April 12, 2015.

NOAA. 2015b. Orthometric Height Conversion. http://www.ngs.noaa.gov/cgi-bin/VERTCON/vert_con.prl. Accessed April 12, 2015.

NOAA. 2015c. Corals. http://www.nmfs.noaa.gov/pr/species/invertebrates/corals.htm. Accessed November 19, 2015.

Noss, R. 2011 .Between the devil and the deep blue sea: Florida's unenviable position with respect to sea level rise. Climatic Change 107:1-16.

Obeysekera, J., M. Irirzzary, J. Park, J. Barnes, and T. Desssalegne. 2011. Climate change and its implications for water resources management in south Florida. Stochastic Environmental Research and Risk Assessment 25:495-516.

Orth, R.J., T.J.B. Carruthers, W.C. Dennison, C.M. Duarte, J.W. Fourqurean, K.L. Heck, A.R.Hughes et al. 2006. A global crisis for seagrass ecosystems. Bioscience 56:987-996.

Paerl, H.W. and V.J. Paul. 2012. Climate change: Links to global expansion of harmful cyanobacteria. Water Research 46:1349:1363.

Pandolfi, J.M., J.B.C. Jackson, N. Baron, R.H. Bradbury, H.M. Guzman, T.P. Hughes, C.V. Kappel, F. Micheli, J.C. Ogden, H.P. Possingham, and E. Sala. 2005. Are U.S. coral reefs on the slippery slope to slime? Science 307:1725-1726.

Pandolfi, J.M., S.R. Connolly, D.J. Marshall, and A.L. Cohen. 2011. Projecting coral reef futures under global warming and ocean acidification. Science 333:418-422.

Park, T., J.M. Bowker, and V.R. Leeworthy. 2002. Valuing snorkeling visits to the Florida Keys with stated and revealed preference models. Journal of Environmental Management 65:301-312.

Parker, G.G., G.E. Ferguson, and S.K. Love. 1955. Water Resources of Southeastern Florida. U.S. Geological Survey Water-Supply Paper 1255. Washington, D.C. http://sofia.usgs.gov/publications/papers/wsp1255/PDF/wrsf_1255.htm.

Parkinson, R.W., R.D. DeLaune, and J.R. White. 1994. Holocene sea-level rise and the fate of mangrove forests within the wider Caribbean region. Journal of Coastal Research 10:1077-1086.

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.

Peters, C.J. and J. Reynolds. 2008. Saltwater intrusion monitoring in the Biscayne Aquifer near Florida City, Miami-Dade County, Florida: 1996-2007. 20th Saltwater Intrusion Meeting, pp. 195-198. http://www.swim-site.nl/pdf/swim20/file214-217.pdf.

Porter, J.W., S.K. Lewis, and K.G. Porter. 1999. The effect of multiple stressors on the Florida Keys coral reef system: A landscape hypothesis and physiological test. Limnology and Oceanography 44:941-949.

Prinos, S.T., M.A. Wacker, K.J. Cunningham, and D.V. Fitterman. 2014. Origins and delineations of saltwater intrusion in the Biscayne Aquifer and changes in the distribution of saltwater in Miami-Dade County, Florida. U.S. Geological Survey Scientific Investigations Report 2014-5025. http://dx.doi.org/10.3133/sir20145025.

Reece, J.S., R.F. Noss, J. Oetting, T. Hoctor, and M. Volk. 2013. A vulnerability assessment of 300 species in Florida: Threats from sea level rise, land use, and climate change. PLOS One DOI:10.1371/journal.pone.0080658.

Rehr, A.P., M.J. Small, P. Bradley, W.S. Fisher, A. Vega, K. Black, and T. Stockton. 2012. A decision support framework for science-based, multi-stakeholder deliberation: A coral reef example. Environmental Management 50:1204-1218.

Roberts, C.M. 1995. Effects of fishing on the ecosystem structure of coral reefs. Conservation Biology 9:988-995.

Rose, J.B., P.R. Epstein, E.K. Lipp, B.H. Sherman, S.M. Bernard, and J.A. Patz. 2001. Climate variability and change in the United States: Potential impacts on water- and foodborne diseases caused by microbiologic agents. Environmental Health Perspectives 109:211-221.

Ross, M.S., J.J. O'Brien, L.S.L. Sternberg. 1994. Sea-level rise and the reduction in pine forests in the Florida Keys. Ecological Applications 4:144-156.

Ross, M.S., J.J. O'Brien, R.G. Ford, K. Zhang, and A. Morkill. 2008. Disturbance and the rising tide: The challenge of biodiversity management on low-island ecosystems. Frontier in Ecology and the Environment 7:471-478.

Rudnick, D.T., P.B. Ortner, J.A. Browder, and S.M. Davis. 2005. A conceptual model of Florida Bay. Wetlands 25:870-883.

Saha, A.K, S. Saha, J. Sadle, J. Jiang, M.S. Ross, et al. 2011. Sea level rise and south Florida coastal forests. Climatic Change 107:81-108.

Scavia, D., J.C. Field, D.F. Boesch, R.W. Buddemeir, V. Burkett, D.R. Cayan, et al. 2002. Climate change impacts on coastal and marine ecosystems. Estuaries 25:149-164.

SFWMD. 2013. Lower East Coast Water Supply Plan Update. South Florida Water Management District. http://www.sfwmd.gov/portal/page/portal/xrepository/sfwmd_repository_pdf/2013_lec_plan.pdf. Accessed September 24, 2015.

Short, F.T. and H.A. Neckles. 1999. The effects of global climate change on seagrasses. Aquatic Botany 63:169-196.

Smoak, J.M., J.L. Breithaupt, T.J. Smith, and C.J. Sanders. 2013. Sediment accretion and organic carbon burial relative to sea-level rise and storm events in two mangrove forests in Everglades National Park. Catena 104:58-66.

Somerfield, P.J., W.C. Jaap, K.R. Clarke, M. Callahan, K. Hackett, J. Porter, M. Lybolt, C. Tsokos, and G. Yanev. 2008. Changes in coral reef communities among the Florida Keys, 1996-2003. Coral Reefs 27:951-965.

Sonenshein, R.S. 1996. Delineation of saltwater intrusion in the Biscayne Aquifer, Eastern Dade County, Florida 1995. U.S. Geological Survey Water-Resources Investigations Report 96-4285. http://fl.water.usgs.gov/Miami/online_reports/wri964285/. Accessed August 3, 2015.

Southeast Florida Regional Climate Change Compact. 2011. A Unified Sea Level Rise Projection for Southeast Florida. https://southeastfloridaclimatecompact.files.wordpress.com/2014/05/sea-level-rise.pdf. Accessed April 12, 2015.

Southeast Florida Regional Climate Change Compact. 2012. Analysis of the Vulnerability of Southeast Florida to Sea Level Rise. http://www.southeastfloridaclimatecompact.org/wp-content/uploads/2014/09/vulnerability-assessment.pdf. Accessed April 12, 2015.

Spalding, M.D., A.L. McIvor, M.W. Beck, E.W. Koch, I. Moller, D.J. Reed, P. Rubinoff, T. Spencer, T.J. Tolhurst, T.V. Wamsley, B.K. van Wesenbeeck, E. Wolanski, and C.D. Woodruff. 2014. Coastal ecosystems: A critical element of risk reduction. Conservation Letters 7: 293-301.

Stringfield, V.T., J.R. Rapp, and R.B. Anders. 1979. Effects of karst and geologic structure on the circulation of water and permeability in carbonate aquifers. Developments in Water Science 12:313-332.

Suman, D., M. Shivlani, and J.W. Milon. 1999. Perceptions and attitudes regarding marine reserves. A comparison of stakeholder groups in the Florida Keys National Marine Sanctuary. Ocean & Coastal Management 42:1019-1040.

Sutherland, K.P., S. Shaban, J.L. Joyner, J.W. Porter, and E.K. Lipp 2011. Human pathogen shown to cause disease in the threatened elkhorn coral Acropora palmate. PLOS One. DOI:10.1371/journal.pone.0023468.

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.

Thomas, A. and R. Watkins. 2013. Development of a Geographic Information System (GIS) tool for the preliminary assessment of the effects of predicted sea level and tidal change on transportation infrastructure. FDOT Contract #BDK75 977-63. University of Florida, GeoPlan Center. ftp://ftp.sls.geoplan.ufl.edu/pub/sls/docs/FDOT_BDK75_977-63_Final_Technical_Report.pdf. Accessed May 17, 2015.

Titus, J.G., R.A. Park, S.P. Leatherman, J.R. Weggel, M.S. Greene et al. 1991. Greenhouse effect and sea level rise: The cost of holding back the sea. Coastal Management 19:171-204.

Titus, J. 2002. Does sea level rise matter to transportation along the Atlantic Coast? In *The Potential Impacts of Climate Change on Transportation.* DOT Center for Climate and Environmental Forecasting, pp. 135-150. http://2climate.dot.gov/documents/workshop1002/workshop.pdf#page=142. Accessed August 30, 2015.

UF GeoPlan Center. 2012. Florida Public and Private Schools. http://www.fgdl.org/metadataexplorer/full_metadata.jsp?docId=%7B6D62CEF6-9809-4FB3-8703-5C6B98C4C378%7D&loggedIn=false. Accessed April 12, 2015.

UF GeoPlan Center. 2013a. Florida Digital Elevation Model (DEM) Mosaic. http://www.fgdl.org/metadata/fgdl_html/flidar_mosaic_ft.htm. Accessed April 12, 2015.

UF GeoPlan Center. 2013b. Sea Level Scenario Sketch Planning Tool. http://sls.geoplan.ufl.edu/download-data/. Accessed April 12, 2015.

UF GeoPlan Center. 2013c. Local, State, and Government buildings in Florida – 2013. http://www.fgdl.org/metadataexplorer/full_metadata.jsp?docId=%7B3F4414F8-409F-43FF-BB71-A0501443A224%7D&loggedIn=false. Accessed April 12, 2015.

UF GeoPlan Center. 2013d. Correctional Facilities in Florida – 2013. http://www.fgdl.org/metadataexplorer/full_metadata.jsp?docId=%7B4CA86144-20DA-4119-A755-74D2F9F5B66F%7D&loggedIn=false. Accessed April 12, 2015.

UF GeoPlan Center. 2013e. Law Enforcement Facilities in Florida – 2012. http://www.fgdl.org/metadataexplorer/full_metadata.jsp?docId=%7BDC1D5A35-C117-4964-BEE8-44F964AFFA61%7D&loggedIn=false. Accessed April 12, 2015.

UF GeoPlan Center. 2015. National Flood Hazard Layer (NFHL) – Florida Extent. http://www.fgdl.org/metadata/fgdc_xml/dfirm_fldhaz_feb15.shp.xml. Accessed June 22, 2015.

Ullman, R. V. Bilbao-Bastida, and G. Grimsditch. 2013. Including blue carbon in climate market mechanisms. Ocean & Coastal Management 83:15-18.

Van Katwijk, M.M., A.R. Bos, V.N. de Jonge, L.S.A.M. Hanssen, D.C.R. Hermus, and D.J. de Jong. 2009. Guidelines for seagrass restoration: Importance of habitat selection and donor population, spreading of risks, and ecosystem engineering effects. Marine Pollution Bulletin 58:179-188.

Wagner, D.E., P.Kramer, and R. van Woesik. 2010. Species composition, habitat, and water quality influence coral bleaching in southern Florida. Marine Ecology Progress Series 408:65-78.

Walker, R., B. Bendell, and L. Wallendorf. 2011. Defining engineering guidance for living shoreline projects: Coastal Engineering Practice 1064-1077.

Wang, C., M. Menenti, M.P. Stoll, A. Feola, E. Belluco, and M. Marani. 2009. Separation of ground and low vegetation signatures in LiDAR measurements of salt-marsh environments. Geoscience and Remote Sensing 47:2014-2023.

Warren Pinnacle Consulting, Inc. 2012. SLAMM 6.2 Technical Documentation. Sea Level Affecting Marshes Model, Version 6.2 beta. http://warrenpinnacle.com/prof/SLAMM6/SLAMM6.2_Technical_Documentation.pdf. Accessed Junes 22, 2015.

Yang, Z., E.P. Myers, I. Jeong, and S.A. White. 2012. VDatum for coastal waters from the Florida shelf to the South Atlantic Bight. Tidal datums, marine grids, and sea surface topography. NOAA Technical Memorandum NOS CS 27. http://vdatum.noaa.gov/download/publications/TM_NOS-CS27_FY12-14_VDatum_FL_SA_zyang.pdf. Accessed September 10, 2015.

Zhang, K., J. Dittman, M. Ross, and C. Bergh. 2011. Assessment of sea level rise impacts on human population and real property in the Florida Keys. Climatic Change 107:129-146.