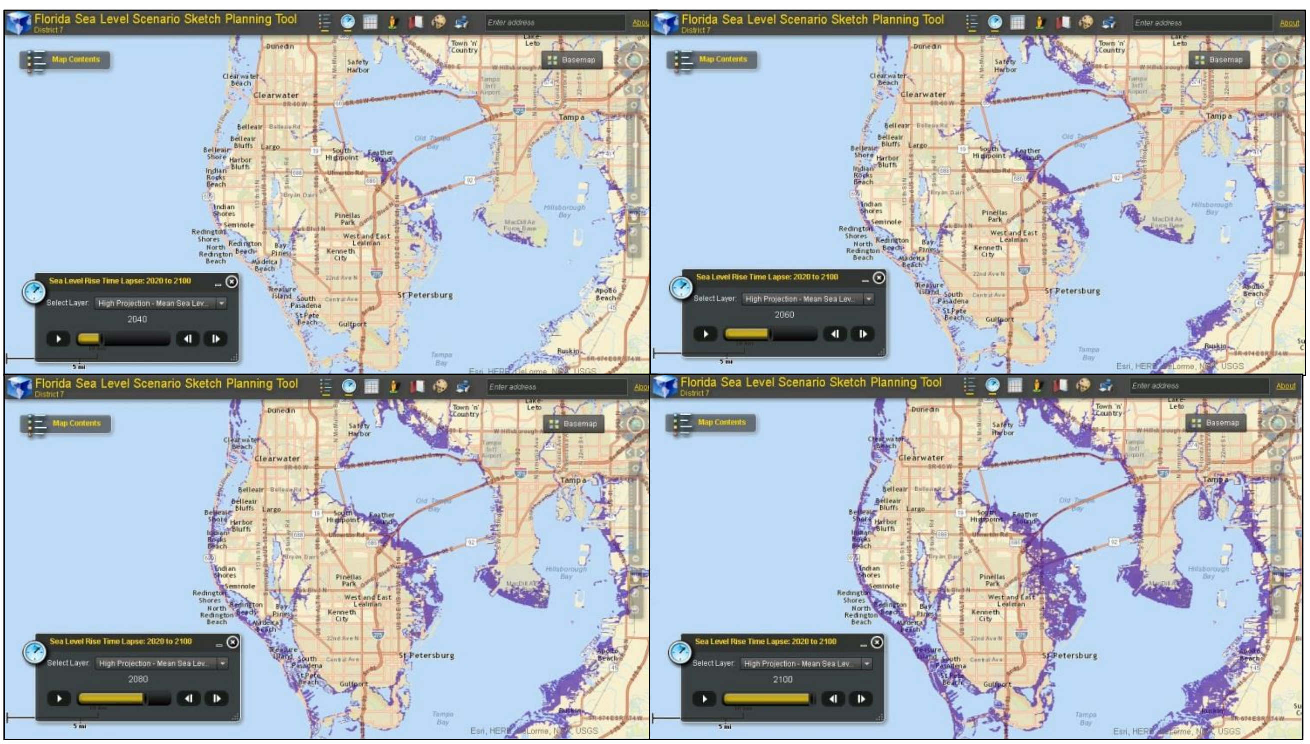
Testing and Enhancement of the Florida Sea Level Scenario Sketch Planning Tool

Contract BDV31-932-1
Final Report
October 2015

Prepared for Florida Department of Transportation
Office of Policy Planning

Prepared by
University of Florida GeoPlan Center



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Prepared for:
Florida Department of Transportation Office of Policy Planning
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Executive Summary

This project continued the work completed under FDOT Research Contract BDK75-977-63 entitled "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". In the prior work ("Phase 1"), researchers from the University of Florida (UF) GeoPlan Center developed the Florida Sea Level Scenario Sketch Planning Tool (SLS Sketch Planning Tool) to facilitate the identification of transportation infrastructure potentially at risk from projected sea level changes. The purpose of the tool is to visualize various sea level scenarios at future time periods in an effort to inform transportation planners and highlight infrastructure for potential avoidance, minimization, or mitigation. Continuing this work in "Phase 2", the UF GeoPlan Center tested and made enhancements to the SLS Sketch Planning Tool to increase its efficacy as a decision support tool.

In Phase 1, the tools and data were developed at the state and regional scale. In Phase 2, the data and tools were evaluated at the local or Metropolitan Planning Organization (MPO) scale. Partnerships with the Hillsborough MPO and Broward MPO (serving as the lead agency for the southeast Florida four-county region of Broward, Miami-Dade, Palm Beach, and Monroe Counties) offered testing opportunities through pilot projects. Both MPOs were awarded grants through the Federal Highway Administration (FHWA) Climate Change Resilience Pilot Program, which has funded partners to assess infrastructure vulnerability to the impacts of sea level changes and extreme weather events, determine adaptation options, and improve resiliency of infrastructure. This unique opportunity allowed the GeoPlan team to test the use of the SLS Sketch Planning Tool in a real-world context, while learning about data gaps and technical issues encountered when assessing vulnerability. The pilot projects utilized FHWA's Climate Change and Extreme Weather Vulnerability Assessment Framework for assessing transportation infrastructure vulnerable to the effects of climate change and extreme weather events and for developing recommendations on how to integrate this information into the decision-making process. In addition, other testing partnerships arose with the City of Satellite Beach and Monroe County, who were engaged in community resiliency and adaptation planning efforts.

During the work with the pilots, issues of data accuracy and resolution were examined. First, a known data issue involving areas around bridge approaches being incorrectly identified as inundated under sea level rise (SLR) scenarios was addressed. Methods to accurately represent bridge elevations were developed and tested in five counties (MPO pilot areas) and future work should include application of these methods to correct false positive inundation areas statewide. Next, the resolution of digital elevation models (DEMs) was evaluated to determine the difference in inundated areas derived from varying resolution DEMs. DEMs with higher horizontal resolution (less than 5.4 meter) were used to create GIS layers of inundation under various SLR scenarios. The results indicated that the horizontal resolution of 5.4-meter used in the SLS Sketch Planning Tool is appropriate for use at the regional and state planning scale and achieves a balance of file size and processing time, while not grossly over or under estimating the areas inundated. If adequate resources exist, then higher resolution elevation data can be used for analysis, but will take considerably more computing resources, time, and storage space to compute and store data outputs. The Sea Level Rise (SLR) Inundation Surface Calculator supports the input a DEM of any resolution from which inundation layers can be created.

Working with the FHWA pilots also offered an opportunity to learn about how other communities are assessing storm surge and inland flooding impacts to the transportation system. Currently, the SLS Sketch Planning Tool only includes information on potential impacts due to inundation from SLR. A more comprehensive approach to planning for transportation resiliency would include assessment of multiple inundation risks (SLR, storm surge, and inland flooding). Rising sea levels are estimated increase storm surge flood depths and the frequency of coastal flooding due to the higher "launch point" or water level for the surge to push onto the land (Kirshen, 2008a, Neumann, et al. 2015, Sweet and Park, 2014, Tebaldi et al. 2012). Storm surge models, methods, and current literature were researched to determine whether best practices are emerging for modeling storm surge in the context of SLR. Modeling approaches vary widely from simple additive models to complex hydrodynamic models typically used for engineering scale applications, and depend on factors of analysis scale, geographic extent, and resources available (financial, temporal, and expertise).

Test model runs were conducted in an effort to create a proof of concept for modeling future storm surge with SLR. The Multi-Hazard Loss Estimation Methodology (Hazus-MH) and the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) models were utilized for modeling future coastal flood risk areas. Created by the Federal Emergency Management Administration (FEMA), Hazus-MH is a standardized methodology used to estimate potential losses from earthquakes, hurricane winds, and floods. The Hazus-MH Flood Model was used to analyze future coastal flood hazard areas by adding increments of SLR to the Stillwater elevation of the base 100-year storm surge. This flood model follows FEMA's methodology for developing the Flood Insurance Rate Maps (FIRMs), where flood frequency and flood magnitude (or depth) are used to define flood hazard. Additionally, SLOSH model runs were conducted within the Hazus-MH Coastal Surge Model using a historic storm for the Tampa Bay area.

Estimating the effects of SLR on storm surge and inland flooding is a complex issue; with no one size fits all solution for modeling these effects. FHWA's 2014 Hydraulic Engineering Circular No. 25 - Volume 2, *Highways in the Coastal Environment: Assessing Extreme Events* outlines a framework for modeling storm surge and coastal flooding in the context of SLR. The framework is a tiered, level of effort approach that offers a gradient of modeling methods based on the geographic region, scale of analysis, technical expertise, and available resources. The subsequent levels of effort can be leveraged as the need for more refined analyses arises. From the research and testing completed in this phase of work, a tiered approach is recommended for assessing transportation vulnerability to storm surge and coastal flooding. First, transportation infrastructure at risk to current flood hazard areas should be incorporated into the SLS Sketch Planning Tool using the best available 100-year floodplain data from FEMA. Next, future coastal flood risk areas should be evaluated using the 500-year floodplain as a simple proxy to estimate future flood hazard areas (and in accordance with FEMA's updated Federal Flood Risk Management Standard). A more detailed approach for assessing future coastal flood risk would involve further evaluation of the Hazus-MH Coastal Flood Model. Incorporation of future storm surge risk (accounting for the effects of SLR) is a more complex topic that needs further investigation. While hydrodynamic models offer the most robust analyses, they are too time and computationally intensive for planning level analyses. One suggested approach for planning level analyses is the utilization of the Hazus-MH Coastal Surge Model with SLOSH to run historic storms, which could represent a more realistic surge risk than the Maximum of Maximums (MOMs) outputs which are typically used for hurricane evacuation studies. If the historic storms can be validated, then SLR can be added and modeled.

Working with the FHWA pilot projects also offered an opportunity to learn about the broader adaptation planning process outlined by FHWA for promoting resiliency in the Nation's transportation systems. While quality data is essential for successful vulnerability assessments, building public support for these assessments through community outreach and public education are also critical components to the planning process. Equally important is the integration of vulnerability and risk information into the transportation planning process as another variable to consider when making infrastructure investment decisions. An iterative process for evaluating risks and prioritizing investments based on vulnerability and risk will be crucial for increasing the resiliency of transportation systems.

Feedback and suggestions from the FHWA pilots and other communities regarding the SLS Sketch Planning Tool were utilized to make improvements and prioritize future enhancements to the map viewer and calculator components of the tool. Suggestions for the map viewer included a simplified table of contents for ease of use and summary generation tools to facilitate analysis of transportation facilities. In response, development of a new map viewer based on a different software platform was begun in order to achieve better functionality and a more modern software framework. In addition, improvements have been made to the SLR Inundation Surface Calculator based on feedback and an updated version of the calculator is available on the project website.

The involvement with the FHWA pilots and other communities demonstrated the demand and need for planning level tools to assess inundation risks and incorporate risk information into the planning process to ensure resilient infrastructure and protect public investments. While the available functionality in the SLS Sketch Planning Tool has proved useful, additional work remains to maintain its relevancy and increase its utility. First, the GIS layers of inundation should be modified to reflect the corrected bridge elevations and the analysis of at-risk infrastructure should be re-analyzed with the most current GIS infrastructure layers. Next, the map viewer interface should continue to be redesigned for ease of use and reporting. Finally, current and future coastal flood hazard areas should be incorporated per recommendations and findings in this report. Moving forward with these changes would address the feedback received from users and improve the applicability of the tool for planning-level infrastructure assessments.

Contents

Table of Figures and Tables

Background

This project “Testing and Enhancement of the Florida Sea Level Scenario Sketch Planning Tool” continued the work completed under FDOT Research Contract BDK75-977-63 entitled “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”. In the prior work “Phase 1” (February 2012 – December 2013), researchers from the University of Florida (UF) GeoPlan Center developed the Florida Sea Level Scenario Sketch Planning Tool (SLS Sketch Planning Tool) to facilitate the identification of transportation infrastructure potentially at risk from projected sea level changes. The purpose of the tool is to visualize various sea level scenarios at future time periods in an effort to inform transportation planners and highlight infrastructure for potential avoidance, minimization, or mitigation. Continuing this work in “Phase 2” (December 2013 – June 2015), the UF GeoPlan Center tested and made enhancements to the SLS Sketch Planning Tool to increase its’ efficacy as a decision support tool.

A primary focus of the Phase 1 work included the development of sea level change scenario tools and data at the state and regional scale. A primary focus of the Phase 2 work included the scaling down of data and tools for usefulness at the Metropolitan Planning Organization (MPO) or local scale. Efforts to scale down the tools involved testing of the tools by the Federal Highway Administration (FHWA)’s Climate Resiliency Adaptation Pilots, which were engaged in community resiliency and adaptation planning at a regional and local level. The FHWA has been funding adaptation pilots to assess infrastructure vulnerability to the impacts of trends such as sea level changes and extreme weather events and to determine adaptation options. This was a unique opportunity to test the use of the SLS Sketch Planning Tool with regional partners in Florida, who could benefit from the Tools, while providing critical feedback on usability enhancements.

Working with the FHWA pilots also offered an opportunity to learn about how other communities were assessing storm surge and inland flooding impacts to the transportation system. Currently, the SLS Sketch Planning Tool only includes information on potential impacts due to future sea level inundation. A comprehensive approach to planning for transportation resiliency would include assessment of inundation from multiple climate risks, namely storm surge and inland flooding. Storm surge and flooding models were also researched and explored in this scope of work in an effort to better model and estimate future infrastructure vulnerabilities from multiple inundation risks.

Additional work in this Phase included enhancements to the SLS Sketch Planning Tool map viewer; improvements to the ArcMap calculator for creating custom layers of sea level inundation; and creation of training materials and user guides. This report documents the work completed in Phase 2; detailed descriptions are listed by Task as outlined in the Scope of Work.

Task 1 – Data Enhancements

The primary objective of this task was to examine the resolution and accuracy of the data inputs used in the SLS Sketch Planning Tool. In Phase 1, sea level change scenario tools and data were developed at the state and regional scale and may not be appropriate for more granular level analyses. Phase 2 focused on scaling down the tools for usefulness at the MPO or local scale. In particular, the accuracy and resolution of bridge data and elevation data were examined. In addition, GIS data layers of infrastructure were evaluated for appropriateness at the MPO or local scale.

Bridge Elevation Data

In this task, GeoPlan developed a GIS methodology to extract bridge elevations from Lidar data in order to correct false positive inundation areas around bridge approaches. The Lidar-derived Digital Elevation Model (DEM) used for creation of the SLS Sketch Planning Tool inundation layers was sourced from NOAA (National Oceanic and Atmospheric Administration) and FDEM (Florida Division of Emergency Management). Because this DEM was created using a bare-earth model, the elevations of bridge approaches and bridge decks is sometimes incorrectly represented as a lower elevation (most likely the ground elevation below the bridge). The incorrect elevations result in the bridge approaches being incorrectly identified as inundated in the SLS Sketch Planning Tool inundation layers (see Figure 1). As seen in Figure 1, the blue areas represent 42 inches of inundation under the following future sea level scenario: 2060, U.S. Army Corps of Engineers (USACE) high projection, at mean higher high water (MHHW). Figure 1 shows false inundation of the Selmon Expressway bridge approaches over Hillsborough River, Tampa, FL. In Figure 2, the Google Street View tool (in the SLS Sketch Planning Tool Map Viewer) shows the view underneath one of the Selmon Expressway approaches that was identified as inundated in Figure 1. Inundation at 42 inches is not likely for this elevated section.

In order to correct this problem, GeoPlan developed a method to extract the correct bridge elevations from the Lidar data and create a raster GIS layer of bridge deck elevations. Lidar technology, or Light Detection and Ranging, is a remote sensing technique used for collecting high accuracy elevation data. Lidar transmits laser light pulses and records the time it takes for the sensor to detect the reflection. The time is then used as measurement of distance. The final data layer from the Bridge methods developed in this task is a DSM of "first return" elevations, or the first reflection from the Lidar laser pulse, which is the highest elevation recorded.

Figure 1. Map Viewer for FDOT District 7 showing inundation of bridge approaches.

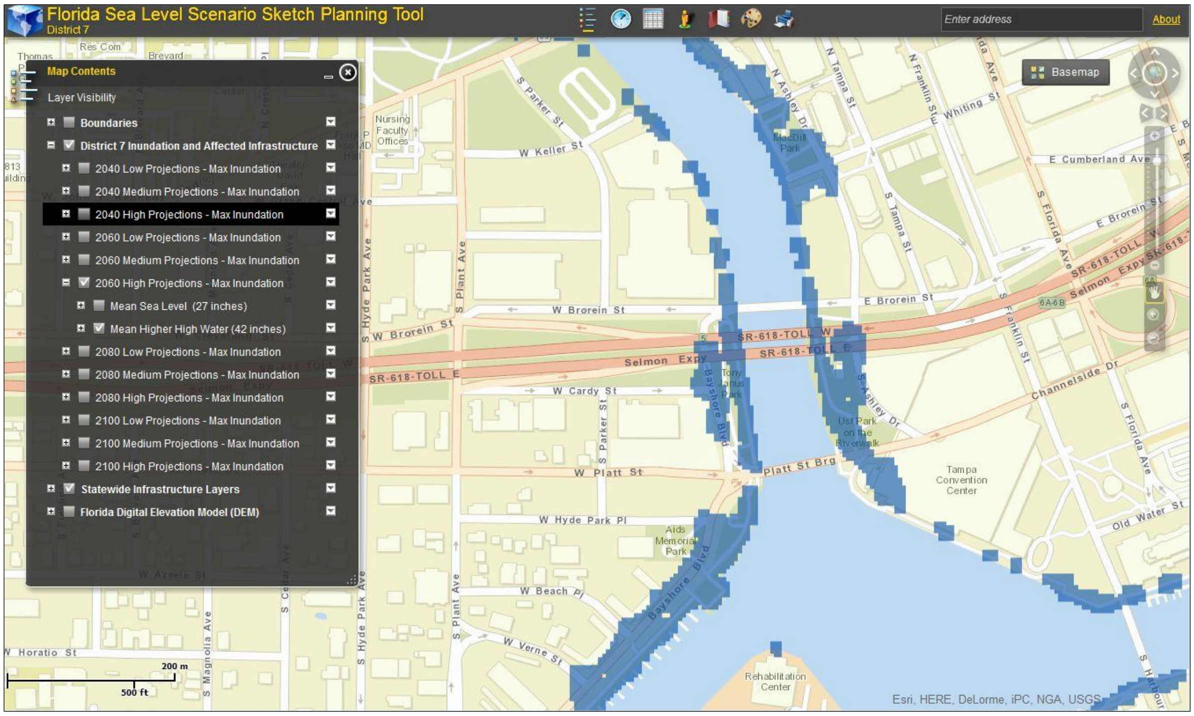
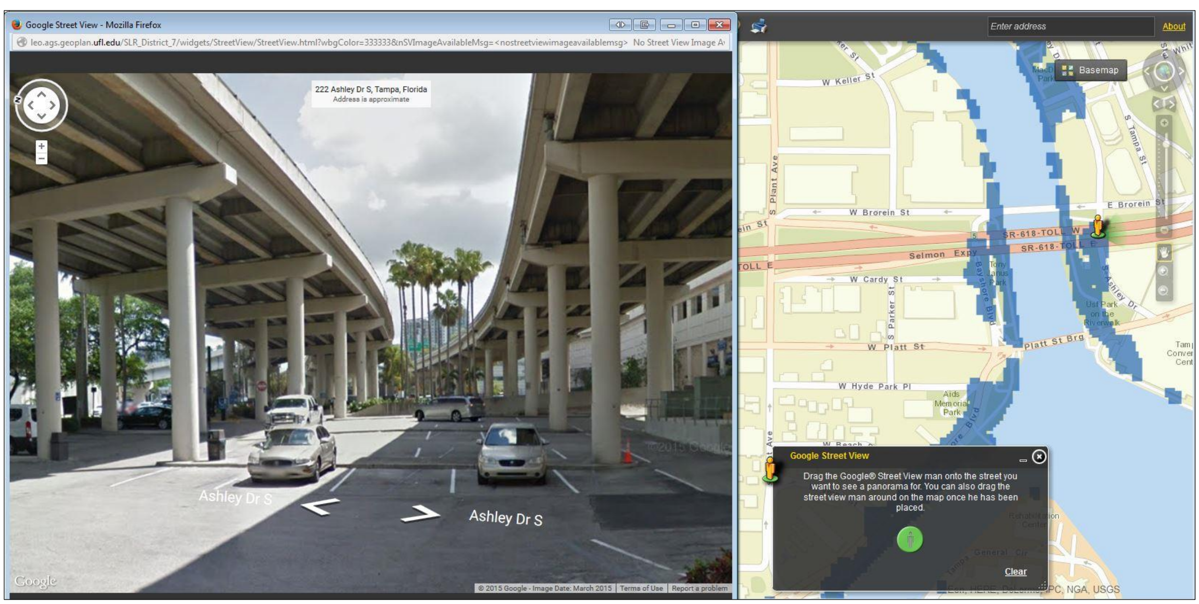


Figure 2. Map Viewer for FDOT District 7 showing Google Street View tool.



First, Lidar data was obtained as LAS files (laser file format) containing "point clouds", or a highly dense collection of three-dimensional points representing locations where elevation measurements were recorded. See Figure 3 for a 3-D view of an example Lidar point cloud. Additional data layers were obtained with the LAS files, in particular an overpass layer representing bridges and overpasses. Figure 4 shows the overpass layer (outlined in black), overlaid with the Lidar point cloud in a two-dimensional view. The overpass layer was used to clip the Lidar point cloud, which was necessary due to the large file size and high density of points. After the point cloud was clipped, a raster digital surface model (DSM) was created from the Lidar first returns. Figure 5 shows the resulting DSM of the Selmon Expressway Bridge approaches and overpasses. The overpass layer is shown in black outline around the DSM layer, which is colored in brown, yellow, and blue representing respectively low to high elevations. It should be noted that using the Lidar first returns creates some artificially high elevations that do not represent the true elevation of the bridge deck. For example, the strips of blue in Figure 5 show the elevations of physical features like mast poles above the roadway. While DSMs can be utilized for correcting the false positives of the inundation layers, it should not be combined or merged into the existing bare earth DEM.

The detailed methodology is included in Appendix A. It should be noted that bridge deck elevations are included in the overpass layer; however, the resulting elevations only represent the edges of the bridge deck. For the purposes of correcting the inundation layers, a data layer covering the entire width of the bridge deck was desired. The methodology developed was tested for Hillsborough County as a proof of concept and used in Southeast Florida. When the SLS Sketch Planning Tools are updated, these methods should be used to correct the false positive inundation areas.

Figure 3. 3-D view of the Lidar point cloud of Selmon Expressway area in downtown Tampa.

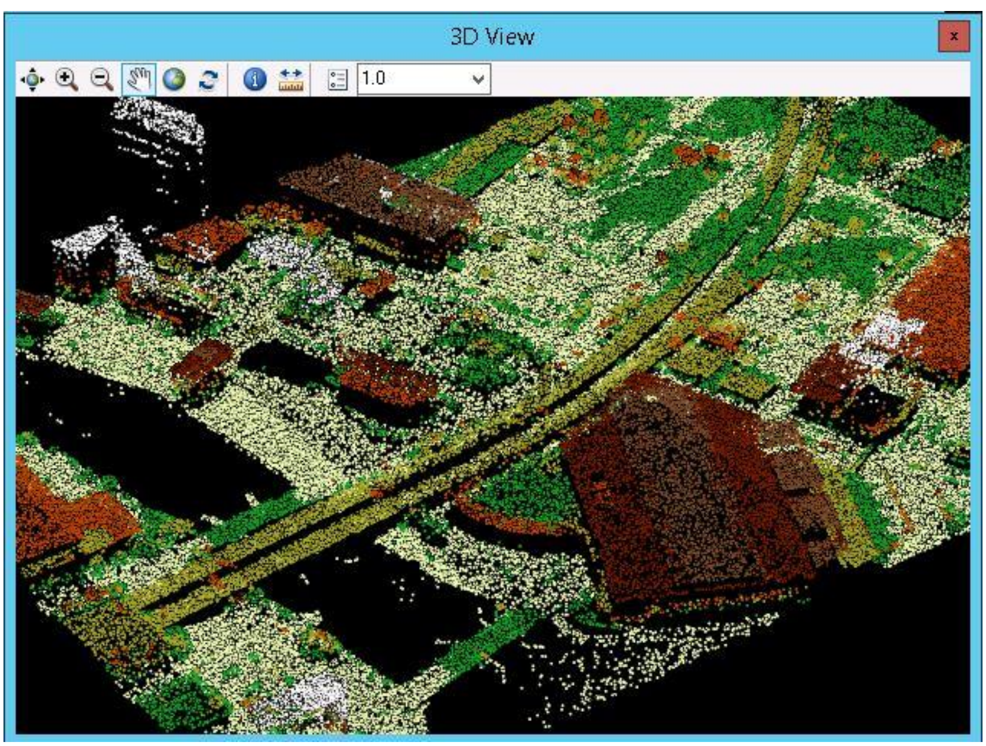


Figure 4. Overpass layer (outlined in black), overlaid with Lidar point cloud (2D view).

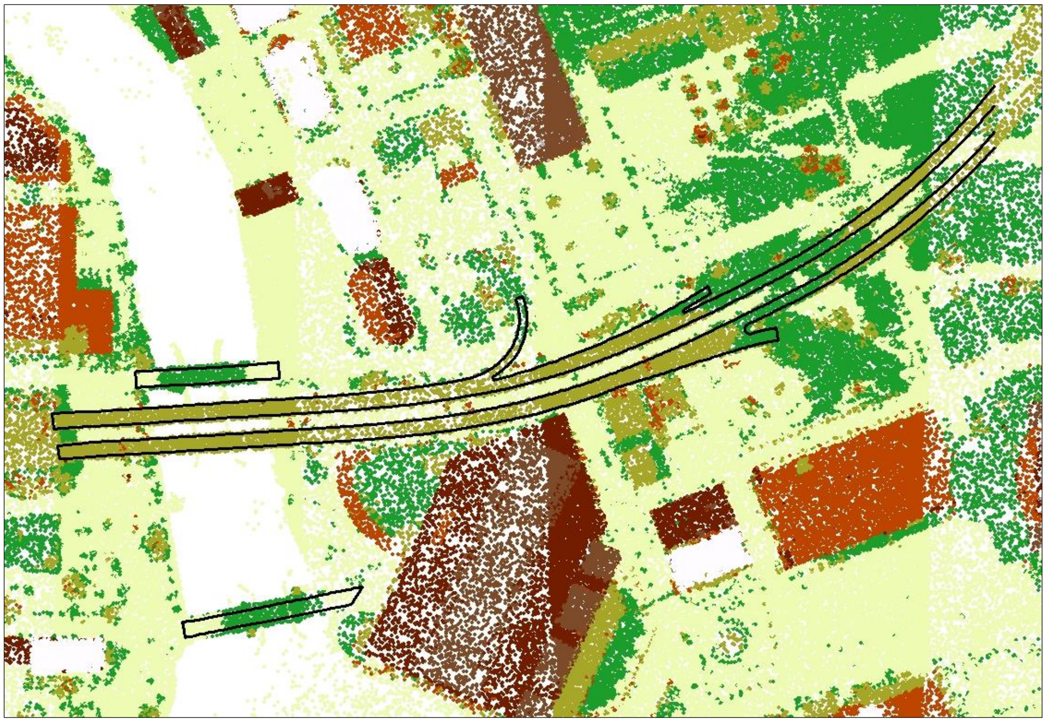
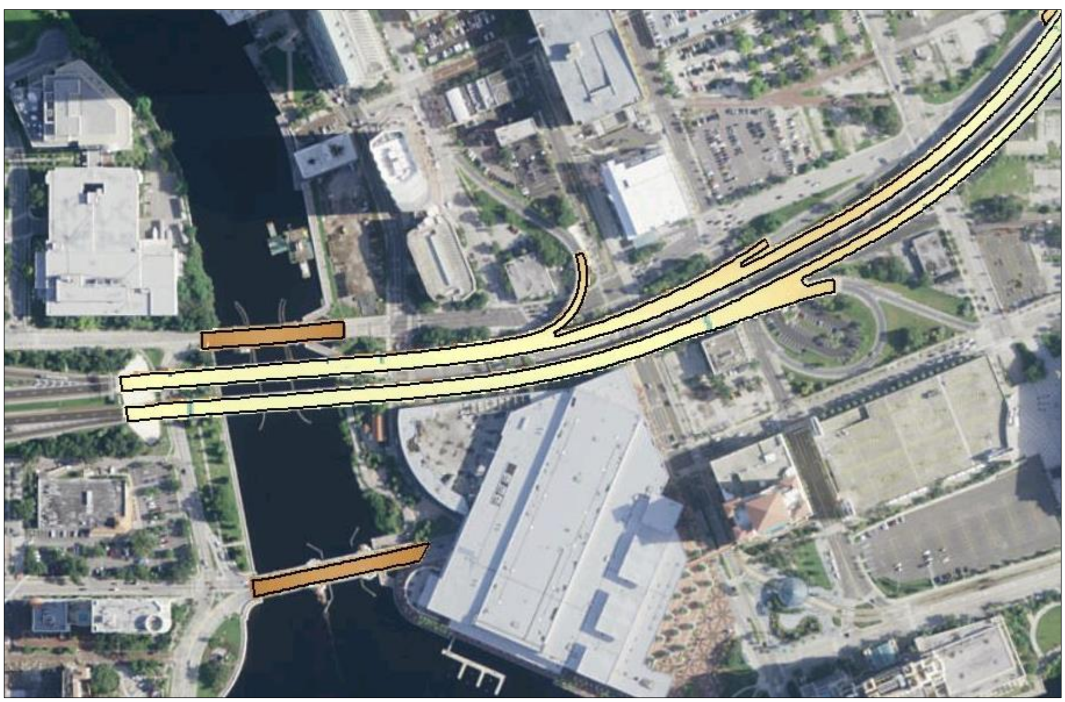


Figure 5. Digital Surface Model (DSM) of the Selmon Expressway Bridge approaches and nearby overpasses.



Imagery Sources for Figure 5: Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

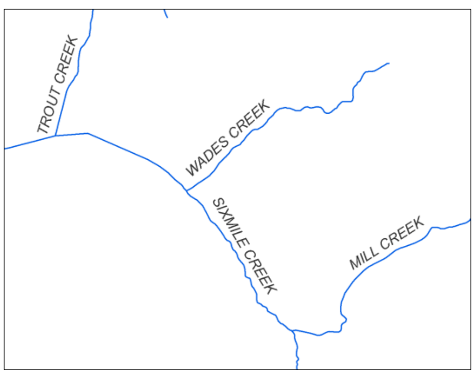
Create High Resolution Elevation Dataset

Work on Task 1 included the exploration of methods to create a Digital Elevation Model (DEM) with higher horizontal resolution (smaller pixel size) than 5-meters. The resulting DEMs were used to examine the difference that varying resolution data inputs have on areas identified as inundated due to SLR. Before the methods are explained, a brief primer on GIS data types, raster cell size, and resolution and accuracy are provided below.

GIS Data Types, Cell Size & Resolution

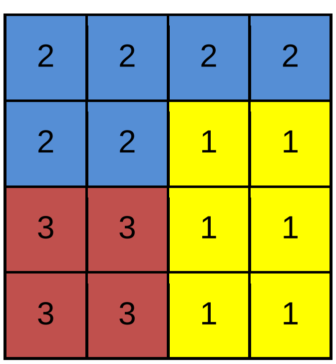
There are two main ways in which GIS data is stored: vector and raster. In vector GIS data, features are represented with points, lines, or polygons; and associated attributes (information about the features) are stored with each feature. Figure 6 shows an example vector line layer of streams and its associated attribute table. Raster-based GIS is a way of storing geographic information into a matrix that is divided into a grid of equally sized cells (also called pixels). Each cell represents an area on the Earth's surface; for example, a cell could represent one-square meter. Each cell is assigned a value, which corresponds to what it contains on the ground. Figure 7 shows an example raster dataset of land use and its associated attribute table; the cell values represent land use types. Digital images are a common example of files stored in a grid format.

Figure 6. Example Vector Dataset (Streams) and associated attribute table



Feature ID	Stream Name
1	Trout Creek
2	Wades Creek
3	Sixmile Creek
4	Mill Creek

Figure 7. Example Raster Dataset (Land Use) and associated attribute table.

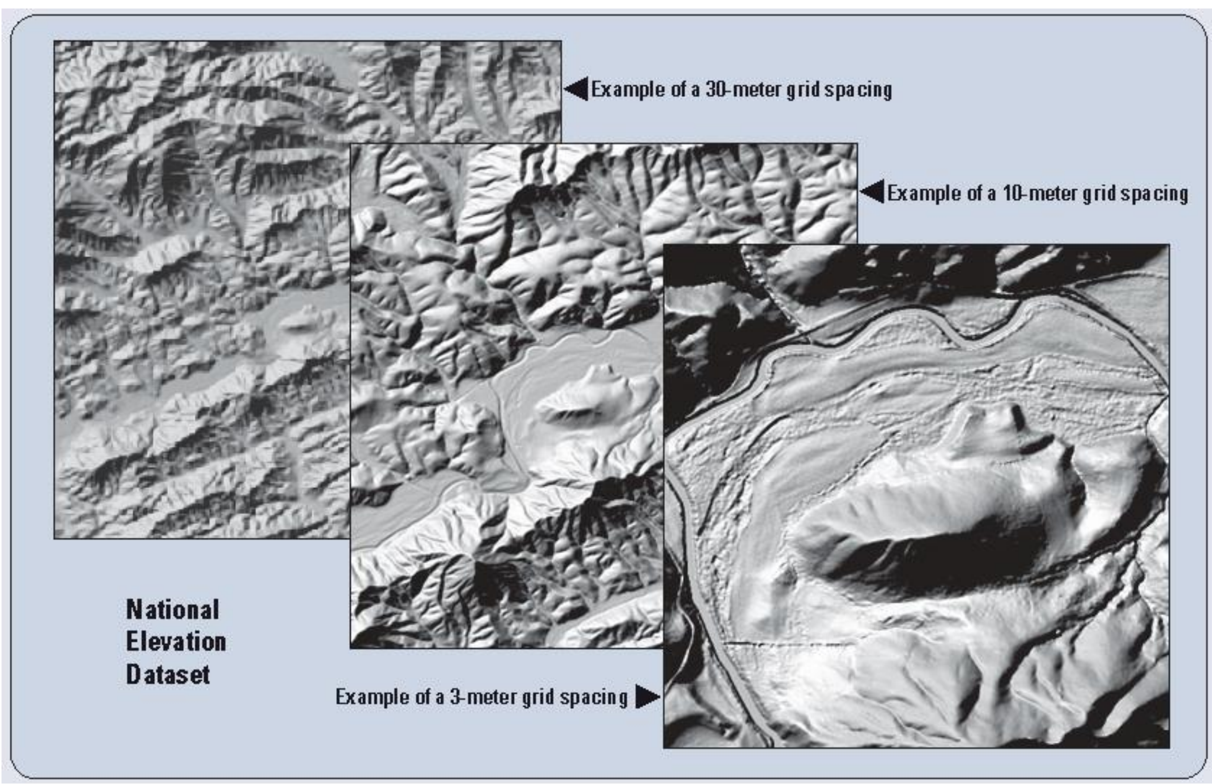


Cell Value	Cell Count	Land Use Type
1	6	Residential
2	6	Office
3	4	Mixed Use

For raster data, the cell size (or pixel size) corresponds to the length of one side of one grid cell. Cell size determines cell area, which is equal to cell size squared. The cell size determines the grid's horizontal resolution, or the finest level of detail that can be depicted on the map. For example, if a cell size is 10 meters, then the finest level of detail for that map will be 10 meters in width by 10 meters in height, or an area of 100 square meters. Features smaller than the cell size can be shown, but they may be represented larger than actual size. Figure 8 shows examples of elevation datasets at three horizontal resolutions (30-meter, 10-meter, and 3-meter cell sizes). The graphic shows the increased detail that is represented as the cell size decreases; the example 30-meter layer shows the coarsest resolution and the example 3-meter layer shows the highest resolution or finest detail. The image in Figure 8 is from the United States Geological Survey (USGS) Fact Sheet 2009-3053, April 2010: *The National Map* – Elevation (Gesch et al. 2009).

When working with raster-based GIS, choosing an appropriate cell size involves consideration of the features being represented or modeled, the geographic extent of the area of interest, any existing input data that is already in raster format, and hardware computing capabilities. Cell size is important because it determines the level of accuracy that the features represent (horizontal resolution) and it is a factor in file size and computer-processing times to run analyses. For a grid of the same extent, a smaller cell size will result in a greater total amount of cells in the grid, a larger file size, and longer computer processing times for analyses.

Figure 8. Shaded relief images derived from three National Elevation Dataset (NED) resolutions (Gesch et.al. 2009)



Sources of Elevation Data
The United States Geological Survey (USGS) compiles and distributes the National Elevation Dataset (NED), a raster dataset intended to provide seamless elevation data for the United States, U.S. territories and other areas of North America. The NED is continually updated with new elevation data and serves as a valuable resource for scientists, researchers, and planners.

NED layers are available at various horizontal resolutions. Seamless coverage of the US is offered at three horizontal resolutions:

- 1/3 arc-second (approximately 10 meter cell size)
- 1 arc-second (approximately 30 meter cell size)
- 2 arc-second (approximately 60 meter cell size)

Additional high resolution layers are available, but not available seamlessly nationwide:

- 1/9 arc-second (approximately 3 meter cell size)
- 1-meter layer – Available by specific geographic areas starting in 2015. Collection of high resolution, elevation data is underway with the USGS 3D Elevation Program (3DEP).

Lidar has recently become a popular elevation data source. Lidar technology, or Light Detection and Ranging, is a remote sensing technique used for collecting high accuracy elevation data. While it is expensive to collect, process, and distribute, grant programs (including the USGS 3DEP Program) have supported Lidar acquisition. In addition, local, state, and federal government agencies have seen the demand for and benefits of utilizing Lidar and Lidar-derived data for flood modeling, urban planning, shoreline monitoring, forest management, and much more. Until recently, high resolution elevation data derived from Lidar has not been available on wide scale.

For more information on the NED, see the USGS website at: http://ned.usgs.gov/index.html
For more information on 3DEP, see the USGS website at: http://nationalmap.gov/3DEP/

Accuracy and Resolution
The American Society for Photogrammetry and Remote Sensing (ASPRS) define accuracy as "the closeness of an estimated value (for example, measured or computed) to a standard or accepted (true) value of a particular quantity" (ASPRS, 2015, p. A4). On a map with elevation (also known as "Z" values), vertical accuracy provides a measure of confidence in the elevation measurement. Horizontal accuracy, as it applies to vector data, provides a measure of confidence in the positional accuracy of the mapped features. For example, the United States National Map Accuracy Standards state that "for maps on publication scales larger than 1:20,000, not more than 10 percent of the points tested shall be in error by more than 1/30 inch, measure in publication scale". Horizontal resolution is different in raster data, as individual features cannot be tested in the same ways vector features are tested for accuracy. Horizontal resolution for raster data usually refers to the cell size or pixel size, which determines the finest level of detail that can be depicted on the map.

In Phase 1, the inundation layers were created using a 5.4 -meter horizontal resolution DEM from NOAA, which was created with the FDEM Coastal Lidar Collection. The 5.4 meter measure corresponds to the elevation dataset's cell size (or pixel size). According to the Baseline Specifications[1], the Lidar collection supports a horizontal accuracy of 3.8 foot (1.16-meter) and a post-spacing/ pixel size of 4 foot (1.22-meter). Hence, the Lidar could support a 4-foot cell (1.22-meter) size DEM. The vertical accuracy remains unchanged for this discussion. As noted in the Phase 1 SLR Report, the vertical accuracy of the Lidar-derived DEM is about 10 inches[2]. What is being discussed here is the effect of varying resolution (cell size) on resulting modeled areas.

While the Lidar collection can be used to create DEMs and inundation surfaces with smaller cell (or pixel) sizes, it remains to be seen how much benefit or accuracy is gained from these smaller cell sizes. Using the smallest cell size possible may not be the wisest use of resources, as smaller pixel sizes take longer to process and require more disk space to store input and output data. Cell size determination is a balance of processing time, physical storage constraints, and the level of detail needed in the analysis. This task was a cursory exploration of that balance, using the following research question to guide findings: *what is the difference in area identified as inundated using DEMs with varying levels of horizontal accuracy?*

Digital Elevation Model Methods

To answer the question above, DEMs at 2-meter and 3-meter horizontal cell size were derived from the Lidar data. Then, inundation layers for various sea level change scenarios were created from each of the DEMs, and compared against 5.4-meter horizontal resolution inundation layers for the same geographic extent. The goal here was to compare the amount of area identified as inundated in the layers derived from varying resolution DEMs.

To create the DEMs, Lidar data was first obtained as LAS files. For this testing, a study area covering portions of Hillsborough and Manatee Counties was used; this corresponded to Woolpert "Area C" (Woolpert was one of the consulting companies that collected the Lidar data). Then, using ArcGIS software, 2-meter and 3-meter horizontal cell size DEMs were created using the Ground filter to represent bare earth or ground conditions. Next, using the SLR Inundation Surface Calculator, inundation layers were created for 12 sea level change scenarios and run for each of the three DEMs (2-meter DEM, 3-meter DEM, 5.4-meter DEM). For each scenario, two model outputs were run: the bathtub model and hydro-connectivity model, producing 24 inundation layers for each DEM. All scenarios are based on the FDOT District 7 sea level trend values, which utilize the data from the Clearwater Beach and St. Petersburg tide stations:

[1] Baseline Specifications for Orthophotography and Lidar V 1.2, 12/12/2007. Developed by Florida Department of Emergency Management, Florida Water Management Districts, Florida Fish and Wildlife Conservation Commission, Florida Department of Environmental Protection, Army Corp of Engineers Jacksonville District, and other state and federal agencies: http://www.floridadisaster.org/gis/specifications/Documents/BaselineSpecifications_1.2.pdf

[2] For discussion on the vertical accuracy of the Lidar-derived DEM, see the Phase 1 Final Report entitled: "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", Page 15, Section 2.4 Uncertainty and Data Limitations: ftp://ftp.sls.geoplan.ufl.edu/pub/sls/docs/FDOT_BDK75_977-63_Final_Technical_Report.pdf

Results and Discussion

In Phase 1, the inundation layers were created using a 5.4 -meter horizontal resolution DEM from NOAA, which was created with the FDEM Coastal Lidar Collection. In this task, inundation layers were created from 2-meter and 3-meter horizontal resolution DEMs and compared to the 5.4-meter layers to examine the differences in area inundated. Below are quantitative and qualitative analyses of the results of the methods described above. The methods produced inundation layers for various SLR scenarios using 2-meter, 3-meter, and 5.4-meter DEMs.

Table 1 below shows the difference in file sizes for the different inundation layers. The layers are stored as raster layers in a compressed ESRI File Geodatabase. The first column lists the compressed size, while the second column lists the uncompressed size. The 2-meter layers are almost double the size of the 3-meter layers, and 3.78 times the size of the 5.4-meter layers. The 3-meter layers are more than double the size of the 5.4-meter layers.

Table 1. File Size Comparison of Inundation Layers

DEM Size	Size of Inundation Layers (Compressed)	Size of Inundation Layer (Uncompressed)
2-meter	174 MB	3.8 GB
3-meter	95 MB	1.69 GB
5.4-meter	46 MB	528 MB

Table 2 below shows the approximate computer processing times for creating the inundation layers with the SLR Inundation Surface Calculator in ArcMap. Each set of layers was run multiple times for testing purposes, so the processing time is an average of all model runs for each cell-size. Each set of layers was created on the same computer. The 2-meter layers took 3.5 times longer to process than the 3-meter layers, and 6.8 times longer to process than the 5.4-meter layers. The 3-meter layers took almost twice the amount of time to process than the 5.4-meter layers.

Table 2. Processing times to create inundation layers per DEM cell size.

DEM Size	Processing Time per layer
2-meter	54 minutes, 30 seconds
3-meter	15 minutes, 34 seconds
5.4-meter	7 minutes, 59 seconds

Table 3 (on the following page) shows the compiled statistics for acreage inundated and percentage of total acreage inundated using the different cell-size DEMs (2-meter, 3-meter, and 5.4-meter). Columns 3, 4, and 5 show the acreage of inundated areas using each of the three DEMs. Following that, Columns 6, 7, and 8 show the difference in acreage between the layers. As expected, the higher the inundation level (Column 2), the higher the difference in acreage. Visually inspecting the differences between the layers show minor discrepancies between areas inundated. Smaller cell size DEMs offer more precise delineation of features, especially along edges of physical features so differences in areas inundated are commonly seen along linear features like canals and river/ stream banks. Figures 9 & 10 depict two sea level scenarios with three resolution (cell size) layers. Figure 9 shows inundation layers for the Tampa area at 2-meter (dark blue), 3-meter (red), and 5-meter cell size (light blue), under the following sea level scenario: 2050, USACE high, MHHW, District 7. As can be seen in the graphic, the differences between the layers are minor, mostly along the edges of the inundated areas. Figure 10 shows inundation layers for the Tampa area at 2-meter (dark blue), 3-meter (red), and 5-meter cell size (light blue), under the following sea level scenario: 2100, USACE high, MHHW, District 7. Similar to Figure 9, the layers show minor differences along the edges of the inundated areas.

Additional differences between the layers show the hydro-connectivity model outputs resulting in greater differences between the cell sizes than with the bathtub model outputs. This is not unusual, due to algorithms that define connectivity. A difference of one or two individual cells could "break" the connectivity of the inundation layer and cause a group of cells not to be identified as both hydrologically connected and inundated.

One interesting thing to note is that the 5.4-meter cell size inundation layers consistently show less inundated acreage than the 2-meter and 3-meter layers, while the 3-meter cell size layers show the most acreage inundated for each scenario. This is contrary to what might be expected, which is that higher cell size (coarser data) will produce an over-estimation of inundated areas and result in more area inundated. It may be that the smaller cell sizes (2-meter and 3-meter) identify more total acreage than the 5-meter due to its ability to delineate smaller features, which could "add up" to more area inundated.

When evaluating the differences from the perspective of percentage inundated, the differences are relatively small. The six columns (Columns 9-14) on the right side of the table show statistics based on Percentage of Total Acreage Inundated. These percentages were calculated by first calculating the total acreage of the DEM grid (i.e. grid cells with elevations). This acreage represents the land area within the DEM, as water is classified as "no data" or null values. Then, the acreage inundated under each scenario was divided by the total acreage of the DEM to give a measure of percent of the area inundated. The results are similar; the higher the inundation level, the greater the difference. However, the results show very little difference in the percentages of total area inundated. The largest percent difference is about one-half of one percent (SLR scenario – 2100, High, MHHW, Hydro-connectivity model, 78 inches).

The results of this limited testing do not show a substantial difference in the areas inundated under each of the horizontal resolution DEMs. A study comparing DEMs of more varied resolutions (i.e. – 30 meter, 10 meter and 5 meter) would very likely show a greater difference in inundated areas. These tests were run on a regional area (parts of Hillsborough and Manatee Counties). Considering the large differences in file size and processing time and the relatively small differences in the resulting inundation layers, using a smaller cell size would not be recommended for analysis of this regional scale (or a larger area). For projects involving small, limited geographic extents, smaller cell sizes may be desirable if time and resources exist, but may not be necessary to achieve analytical results. For those projects where a smaller cell size is warranted, the SLR Inundation Surface Calculator allows users to input a DEM of any resolution and to create inundation layers from that input DEM.

Figure 9. Inundation layers at 2-meter (dark blue), 3-meter (red), and 5-meter cell size (light blue).

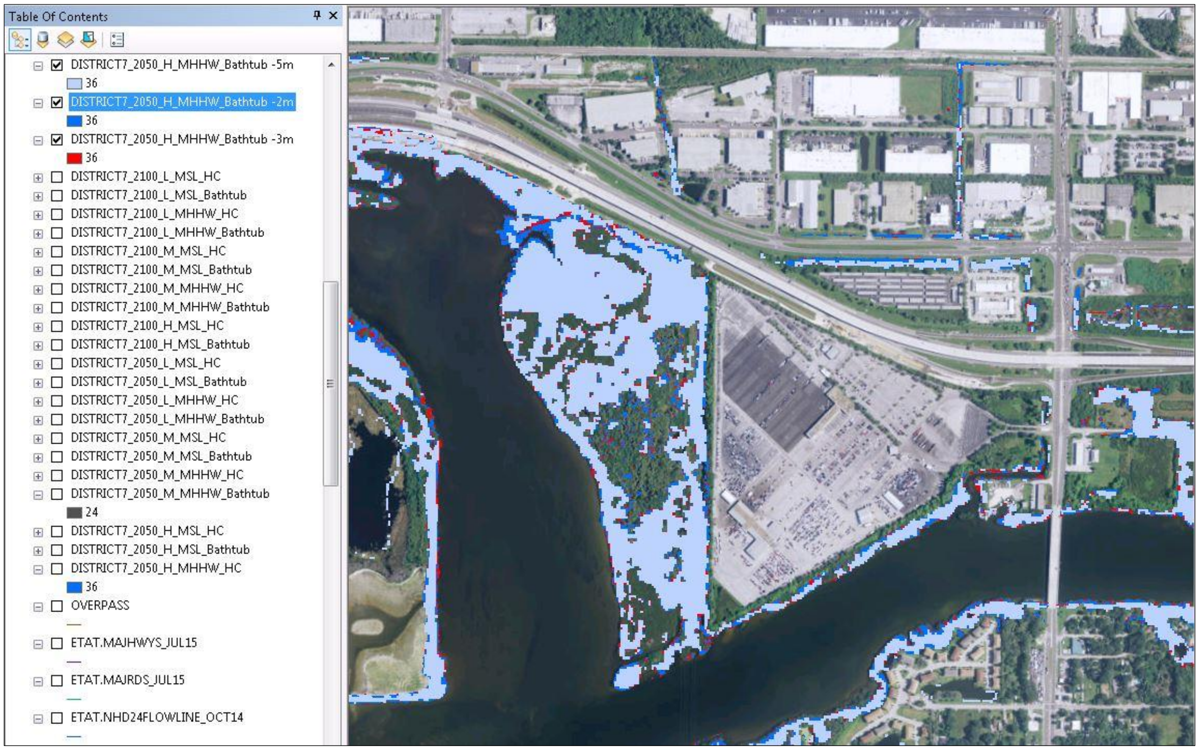


Figure 10. Inundation layers at 2-meter (dark blue), 3-meter (red), and 5-meter cell size (light blue).

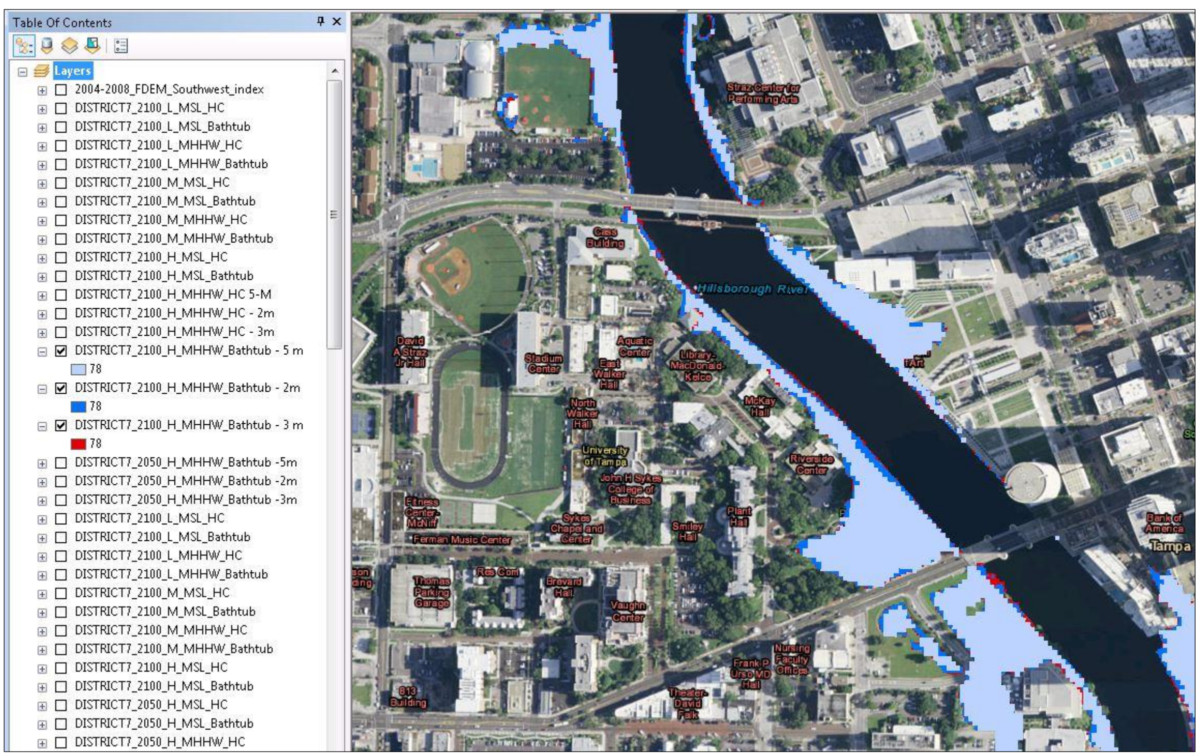


Table 3. Statistics on Inundated Acreage and Percent Inundated for different cell sizes

		Acreage Inundated						Percent of Total Acreage Inundated					
SLR Scenario (Year, Rate, Tidal Datum, Bathtub or Hydro-Conn)	Inundation Level inches	2 meter	3 meter	5.4 meter	3m-to-2m diff	5m-to-2m diff	5m-to-3m diff	2 meter	3 meter	5.4 meter	3-to-2 meter diff	5m-to-2m diff	5m-to-3m diff
2050_L_MSL_B	5	1,145.59	1,273.75	527.89	128.16	-617.69	-745.86	0.498%	0.520%	0.218%	0.021%	-0.280%	-0.301%
2050_M_MSL_B	9	2,179.64	2,395.19	1,598.59	215.55	-581.04	-796.60	0.948%	0.977%	0.662%	0.029%	-0.287%	-0.316%
2050_H_MSL_B	20	8,099.87	9,042.89	8,098.90	943.02	-0.97	-943.98	3.524%	3.690%	3.352%	0.166%	-0.172%	-0.338%
2050_L_MHHW_B	21	8,654.04	9,688.01	8,611.76	1,033.97	-42.28	-1,076.24	3.765%	3.953%	3.564%	0.188%	-0.201%	-0.389%
2050_M_MHHW_B	24	10,187.05	11,464.40	10,402.72	1,277.35	215.67	-1,061.68	4.431%	4.678%	4.305%	0.246%	-0.126%	-0.372%
2050_H_MHHW_B	36	15,264.81	17,102.02	15,713.23	1,837.20	448.41	-1,388.79	6.640%	6.978%	6.503%	0.338%	-0.137%	-0.475%
2050_L_MSL_HC	5	860.57	1,024.89	296.96	164.31	-563.61	-727.92	0.374%	0.418%	0.123%	0.044%	-0.251%	-0.295%
2050_M_MSL_HC	9	1,673.54	1,942.41	1,150.69	268.87	-522.85	-791.72	0.728%	0.793%	0.476%	0.065%	-0.252%	-0.316%
2050_H_MSL_HC	20	7,086.36	8,177.06	7,296.62	1,090.71	210.26	-880.44	3.083%	3.336%	3.020%	0.254%	-0.063%	-0.317%
2050_L_MHHW_HC	21	7,657.93	8,854.16	7,849.37	1,196.24	191.45	-1,004.79	3.331%	3.613%	3.249%	0.281%	-0.083%	-0.364%
2050_M_MHHW_HC	24	9,116.41	10,523.53	9,582.52	1,407.12	466.12	-941.00	3.966%	4.294%	3.966%	0.328%	0.000%	-0.328%
2050_H_MHHW_HC	36	13,894.60	15,866.11	14,682.24	1,971.51	787.64	-1,183.87	6.044%	6.474%	6.076%	0.429%	0.032%	-0.397%
2100_L_MSL_B	10	2,549.27	2,799.75	1,896.50	250.48	-652.78	-903.25	1.109%	1.142%	0.785%	0.033%	-0.324%	-0.357%
2100_M_MSL_B	22	9,186.29	10,307.22	9,333.36	1,120.93	147.06	-973.87	3.996%	4.206%	3.863%	0.209%	-0.133%	-0.343%
2100_L_MHHW_B	26	11,090.49	12,497.72	11,350.98	1,407.23	260.49	-1,146.74	4.824%	5.099%	4.698%	0.275%	-0.127%	-0.402%
2100_M_MHHW_B	38	16,075.20	17,983.43	16,553.53	1,908.24	478.34	-1,429.90	6.993%	7.338%	6.851%	0.345%	-0.142%	-0.487%
2100_H_MSL_B	62	26,268.67	28,863.28	27,322.87	2,594.61	1,054.20	-1,540.42	11.427%	11.777%	11.308%	0.350%	-0.119%	-0.469%
2100_H_MHHW_B	78	33,618.26	36,695.22	35,208.20	3,076.97	1,589.95	-1,487.02	14.624%	14.973%	14.571%	0.348%	-0.053%	-0.401%
2100_L_MSL_HC	10	1,966.59	2,285.44	1,408.96	318.85	-557.63	-876.48	0.855%	0.933%	0.583%	0.077%	-0.272%	-0.349%
2100_M_MSL_HC	22	8,149.95	9,468.99	8,538.99	1,319.04	389.04	-930.00	3.545%	3.864%	3.534%	0.318%	-0.011%	-0.330%
2100_L_MHHW_HC	26	9,943.71	11,544.30	10,516.42	1,600.60	572.71	-1,027.89	4.326%	4.710%	4.352%	0.385%	0.027%	-0.358%
2100_M_MHHW_HC	38	14,655.75	16,651.33	15,510.53	1,995.57	854.78	-1,140.80	6.375%	6.794%	6.419%	0.419%	0.044%	-0.375%
2100_H_MSL_HC	62	24,334.48	27,131.40	26,137.36	2,796.91	1,802.88	-994.03	10.586%	11.070%	10.817%	0.484%	0.231%	-0.253%
2100_H_MHHW_HC	78	31,983.92	35,326.30	33,989.92	3,342.38	2,006.00	-1,336.37	13.913%	14.414%	14.067%	0.501%	0.154%	-0.347%

Infrastructure Data

In addition to examining the accuracy and resolution of bridge and elevation data, GIS data layers of infrastructure, which were analyzed in Phase 1, were evaluated for appropriateness at the MPO or local scale. The purpose here was to determine if any additional data layers are needed in the SLS Sketch Planning Tool for analysis of vulnerable infrastructure. Working with the Federal Highway Administration (FHWA) Climate Change Resilience Pilots in Florida (which is described in detailed in the following section on Task 2), allowed for assessment on the suitability of using the existing infrastructure data for MPO level analyses.

The transportation data analyzed in Phase 1 was a multi-modal collection of transportation facilities covering local, county, and state roads; interstates; railways; airports; sea ports; space ports; and connectors (highway and freight). Three primary data sources were analyzed:

- **FDOT Road Characteristics Inventory (RCI):** The FDOT RCI is a computerized database of physical and administrative data related to the roadway networks that are either maintained by or are of special interest to the FDOT. Two primary data layers from the RCI database were used in Phase 1 (1) RCI On-System Roads, which are roadways maintained by FDOT, and (2) RCI Off-System Roads, which are city or county owned roads not maintained by FDOT. The source data of the RCI data was April 2013.
- **Florida's Strategic Intermodal System (SIS):** The current designated SIS is a network of high-priority critical transportation facilities of statewide and interregional significance. SIS data layers used in Phase 1 included Highway Corridors, Highway Connectors, Rails, Freight Connectors, Freight Terminals, Passenger Terminals, Airports, Seaports and Spaceports. The source date of six SIS layers were from March 2013, three of the SIS layers were from February 2011.
- **FDOT's Unified Basemap Repository (UBR):** The UBR was developed to address data coordination and sharing across jurisdictional boundaries. For Phase 1, NAVTEQ© Interstates, US Highways, County Roads, and State Roads downloaded from the UBR were used for the infrastructure analysis. The source date of the NAVTEQ layers was July 2012.

Feedback from the pilots did not indicate the need for additional transportation data layers for analyzing impacts to the transportation system. Rather, the data needs were updating the bridge elevation data and updating the analysis of infrastructure data with newer versions of the transportation data layers. As noted in the data source descriptions above, the transportation data layers analyzed in Phase 1 are currently 2-4 years old and more current versions of the data should be obtained, where available, and re-analyzed for their potential risk to sea level inundation.

Task 1 Summary

In this task, issues of data resolution and accuracy were examined to determine how the SLS Sketch Planning Tool could be scaled down for use at the MPO or local scale. Methods to correct the accuracy of the bridge elevations were successfully developed and tested in Hillsborough County and in four counties in Southeast Florida. These methods should be utilized to correct the false positive inundation areas in the rest of the state. Methods to create higher resolution DEMs were also successfully developed and tested. The testing conducted in this task indicates that considering file size, processing time, and the differences in areas inundated, the current horizontal resolution of 5.4-meter is appropriate for use at the regional and state planning scale. If financial, temporal and computer resources exist, then smaller cell sizes (higher horizontal resolutions) can be used for analysis and the SLR Inundation Surface Calculator supports the input a DEM of any resolution from which inundation layers can be created. Finally, the transportation infrastructure data was reviewed and found appropriate for analysis at the MPO or local scale. However, the data sources should be checked for updates, and where available, update the analysis of potentially at-risk infrastructure.

Task 2 – Work with Adaptation Pilots to Test Tools for Regional Scale Use

In Task 2, the GeoPlan Center worked with regional partners to test the use of the SLS Sketch Planning Tool and gather feedback on the usability of the tool. Partners included two regional organizations, Hillsborough MPO and Broward MPO (serving as the lead agency for the southeast Florida four-county region of Broward, Miami-Dade, Palm Beach, and Monroe Counties). Both MPOs were awarded second-round grants through the U.S. Department of Transportation (USDOT) Federal Highway Administration (FHWA) Climate Change Resilience Pilot Program, which will be discussed below.

Federal Highway Administration Climate Adaptation Initiatives

Near the beginning of the George W. Bush administration (circa 2002), FHWA began evaluating the effects of climate change on the transportation system. Since then, FHWA has studied the impacts of climate change on transportation systems; developed tools and information for DOTs and MPOs to assess vulnerabilities; researched adaptation strategies for improving resilience; and worked to integrate climate resilience into FHWA programs. As part of these efforts, FHWA has supported multiple studies and projects to add to the body of knowledge about how to prepare the nation's transportation infrastructure to the effects of climate change. Findings from these studies and projects indicated that FHWA's fundamental goals of safety, system reliability, asset management, and financial stewardship were indeed threatened by the effects of climate change.

One key study was the "Impacts of Climate Variability and Change on Transportation Systems and Infrastructure: The Gulf Coast Study", a two-phase study of the impacts of climate change on the transportation system in the Central Gulf Coast region (U.S. Department of Transportation, 2013). This study was sponsored by U.S. DOT, in partnership with U.S. Geological Survey (USGS). The first phase, which was completed in 2008, evaluated climate change impacts to roads, ports, air, rail and public transit on a regional scale (from Houston/ Galveston, Texas to Mobile, Alabama). Climate effects studied included temperature and precipitation changes, sea level rise, and severity and frequency of tropical storms. The second phase of The Gulf Coast Study, which was completed in 2015, focused on a smaller geographic area (Mobile, Alabama) for which more detailed risk assessments (engineering level) could be conducted for the most critical and vulnerable transportation assets. This phase evaluated several climate impacts (temperature, precipitation, storm surge, and sea level rise) for the area. Also developed in this phase were screening tools intended to facilitate identification of transportation facilities at risk to the effects of climate change. The Gulf Coast Study and the other projects supported by FHWA provide important guidance and resources for other decision makers to utilize when planning for transportation resilient to climate change.

In December 2014, after nearly 12 years of research and development of methods to assess the vulnerability of transportation facilities to climate change and extreme weather events, FHWA issued Executive Order 5520 "Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events". This order solidified FHWA's commitment to climate change preparedness and resilience by establishing policy that explicitly includes considerations of climate change and extreme weather events into current and planned transportation systems. The order states: “The FHWA will work to integrate consideration of these risks into its planning, operations, policies and programs in order to promote preparedness and resilience; safeguard Federal investments; and ensure the safety, reliability, and sustainability of the Nation’s transportation systems” (U.S. Department of Transportation Federal Highway Administration, 2014a).

Climate Change Resilience Pilot Program

The FHWA Climate Change Resilience Pilot Program is just one of the climate adaptation initiatives of the agency. Through two rounds of grants, this program has funded partners to assess infrastructure vulnerability to the impacts of sea level changes and extreme weather events and to determine adaptation options and improve resiliency of infrastructure. The first round of FHWA Climate Change Resilience Pilots (2010-2011) funded MPOs and DOTs to test a conceptual model for assessing vulnerability of transportation infrastructure to the impacts of climate change and extreme weather events. The model was intended to assist transportation decision makers in identification of the assets most at risk to the impacts of climate change and extreme weather events. Across the United States, the effects of climate change and extreme weather events vary greatly, and hence each pilot focused on those effects most threatening their respective region. The first round pilots assessed one or more of the following: sea level rise, storm surge, flooding, precipitation, fire risk, strong winds, intense rainfall, and extreme temperatures.

The experiences and feedback from these first-round pilots was used to refine the model and ultimately develop the FHWA’s Climate Change and Extreme Weather Vulnerability Assessment Framework (“FHWA’s Framework”). FHWA’s Framework is “a guide for transportation agencies interested in assessing their vulnerability to climate change and extreme weather events” (U.S. Department of Transportation Federal Highway Administration, 2012). Through three primary steps, FHWA’s Framework guides agencies through defining objectives, conducting vulnerability assessments, and integrating vulnerability into the decision-making process (See Figure 11).   The first step (Define Scope), involves identification of the key climate variables of concern, articulation of assessment objectives, and selection of relevant assets to be assessed. The second step (Assess Vulnerability) involves determining a subset of critical assets to be evaluated; determining the sensitivity of those assets to climate impacts; collection of asset location data; development of climate input data; identification and ranking of vulnerable assets; and assessment of risk. The third and final step (Integrate into Decision Making), involves incorporation of vulnerability information into decision making processes such as long range transportation plans, asset management systems and emergency management and hazard mitigation plans. Ideally, the vulnerability information can be used in project prioritization. Additionally, the third step involves a public outreach and education component to engage stakeholders and build public support for the need to incorporate vulnerability assessments into the planning process.

The FHWA’s Framework also includes case studies and lesson learned from the five FHWA pilot projects funded in the first round of grants. These case studies provide important guidance and tools for state DOTs and MPOs who are interested in increasing the resiliency of their transportation infrastructure to the effects of climate change and extreme weather events.

The second round of FHWA pilots (2013-2015) funded 19 MPOs, DOTs, and Federal Land Management Agencies to utilize FHWA’s Framework for conducting vulnerability assessments of transportation infrastructure and evaluating adaptation opportunities for improving infrastructure resiliency. As stated previously, two Florida MPOs (Hillsborough MPO and Broward MPO, representing four counties in southeast Florida) were awarded second-round FHWA grants. This was a unique opportunity to test the use of the SLS Sketch Planning Tool with regional partners in Florida, who could benefit from the Tools, while providing critical feedback on usability enhancements. UF GeoPlan Center offered technical assistance to the partners in their community resiliency and adaptation planning efforts. Meanwhile, useful feedback from these regional partners was gathered regarding data gaps or desired improvements to the map viewer, data, and SLR Inundation Surface Calculator.

Working with these MPO partners and their pilot projects allowed the GeoPlan team a valuable opportunity to learn in depth about FHWA's Framework and about how these pilots conducted their assessments of climate risks. The nineteen second-round pilots considered a variety of climate risks including temperatures and extreme heat, extreme precipitation and flooding, flash floods, sea level rise, storm surge, drought, wildfire, dust storms, landslides, coastal bluff erosion, and species migration. Of particular interest for the enhancements to the SLS Sketch Planning Tool are the methods the pilots used for assessing sea level rise, storm surge, and inland flooding, since these are most threatening to the State of Florida. Following the work of the Florida pilots allowed the GeoPlan team to better understand how to model these effects and learn about the limitations of particular modeling approaches. Depending upon the scope and geographic scale of the pilot, varying levels of analysis were used for assessing the impacts of sea level rise. Some pilots utilized planning level analyses for the state and regional scale, while others utilized engineering level analyses for smaller geographic regions.

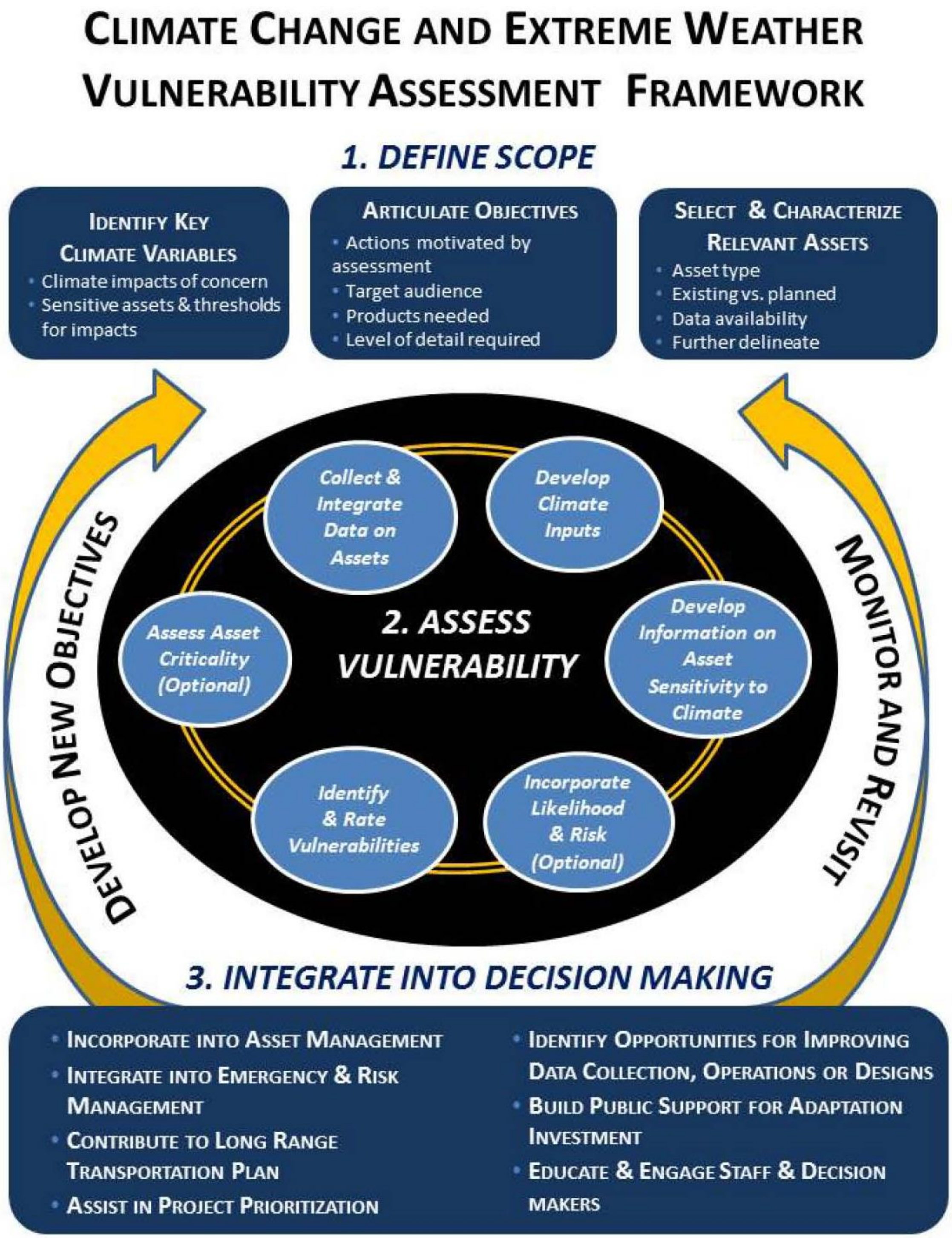
In addition to the FHWA pilots, over the course of Phase 2, more testing opportunities arose with the City of Satellite Beach and Monroe County, who were each engaged in community resiliency and adaptation planning efforts.

A considerable amount of time was spent working and coordinating with the FHWA pilots and the additional communities, including but not limited to:

- Attending Technical Advisory Committee meetings and other partner coordination meetings (via web or teleconference).
- Answering technical questions on the SLS Sketch Planning Tool and associated data, via both email and phone conversations.
- Creating custom data products for use by the FHWA pilots and communities (example: bridge deck elevation dataset and custom SLR inundation layers for Satellite Beach)
- Meeting time to discuss methods related to extreme weather events from flooding and storm surge.

The following section will detail how the SLS Sketch Planning Tool was used in the various communities.

Figure 11. FHWA's Climate Change & Extreme Weather Vulnerability Assessment Framework



Hillsborough MPO Climate Change Vulnerability Assessment and Adaptation Pilot Project

The Hillsborough County MPO Vulnerability Assessment and Adaptation Pilot Project ("Hillsborough Pilot") was the first project that the GeoPlan Center coordinated with for Task 2. The pilot project was managed by the Hillsborough County MPO and City-County Planning Commission. Cambridge Systematics served as the lead consultant for the pilot, assisted by Jacobs Engineering Group, Inc. and Florida Atlantic University. The project team included numerous entities: Florida Department of Transportation Office of Policy Planning, Hillsborough County Public Works Department, Tampa Bay Regional Planning Council, University of Florida GeoPlan Center, and University of South Florida School of Public Affairs. Additional involvement included: City of Tampa, Florida Department of Transportation (District 7 office), Hillsborough Area Rapid Transit (HART), Hillsborough County Aviation Authority, Hillsborough County Local-Mitigation Strategy Working Group, Port Tampa Bay, Tampa-Hillsborough Expressway Authority, and University of South Florida Office of Community Engagement.

Beyond conducting a vulnerability assessment of regional transportation infrastructure at risk to SLR inundation, the Hillsborough Pilot sought to find cost-effective approaches to mitigate the risks of three climate stressors: inundation from sea level rise, storm surge, and inland flooding. These approaches were then targeted for inclusion in key transportation plans and emergency management plans for the County, respectively – the Hillsborough County MPO's 2040 Long Range Transportation Plan (LRTP) and the County's Post Disaster Redevelopment Plan (PDRP). The Tampa Bay region is fortunate to have a wealth of expertise in the areas of planning for resiliency and emergency preparedness, and the Hillsborough Pilot built off of the prior work in those topic areas.

In brief, the asset risk analysis for the FHWA pilot was completed in three technical phases[3]. In Phase 1, five to ten critical assets were identified for in-depth analysis of inundation risk due to various scenarios of sea level rise, storm surge, and inland flooding. Criticality of an asset was estimated through a screening process which analyzed activity centers and assets linking those centers to determine the regional significance of each asset. In Phase 2, traffic demand models were run to simulate disruption of those assets and then estimate regional mobility losses. In Phase 3, economic losses from disrupted critical assets were estimated using the Regional & Economic Models, Inc (REMI) tool. Based on the economic analysis, adaptation strategies were developed.

In addition to the critical assets analyzed for the FHWA pilot, a complementary region scale analysis was conducted for developing recommendations for the Hillsborough County 2040 LRTP. Recommendations were targeted for inclusion in the Vulnerability Reduction section of the Safety and Security program, which aims to reduce infrastructure vulnerability to flooding. To develop

[3] For more information on the Hillsborough County MPO Vulnerability Assessment and Adaptation Pilot Project and access to the final report, appendices, and supplemental documents, see the MPO's website at: http://www.planhillsborough.org/hillsborough-transportation-vulnerability-assessment-pilot-project/

the recommendations, a regional assessment and analysis of flooding vulnerability was conducted, along with an estimation of the economic losses of those flooded facilities.

In the first technical phase of the pilot, analyses of inundation risk from sea level rise, storm surge and inland flooding was conducted. For sea level rise, the pilot utilized the following scenarios from the SLS Sketch Planning Tool:

- 2040 (Hillsborough LRTP horizon year)
  - USACE Low rate at Mean Higher High Water (MHHW)
  - USACE High rate at Mean Higher High Water (MHHW)
- 2060 (Florida Transportation Plan horizon year)
  - USACE Low rate at Mean Higher High Water (MHHW)
  - USACE High rate at Mean Higher High Water (MHHW)

The pilot team modeled storm surge on top of sea level rise using NOAA's Sea, Lakes, and Overland Surges from Hurricane (SLOSH) model outputs and the SLOSH Depth with Sea Level Rise Tool developed by the Tampa Bay Regional Planning Council (TBRPC). The TBRCP tool assists emergency managers by estimating the depths of inundation on land during major storm surge events (i.e. hurricanes). The amounts of SLR were added to the SLOSH Maximum of Maximums (MOMs) outputs, which is a composite product based on thousands of storms. The MOMs intentionally overestimate storm surge heights in an effort to model the worst case scenario. The pilot used eight scenarios of storm surge and sea level rise (four scenarios for 2040 and four scenarios for 2060) as follows:

- Time periods 2040 and 2060:
  - USACE Low rate at MHHW, Category 1 Storm Surge
  - USACE Low rate at MHHW, Category 3 Storm Surge
  - USACE High rate at MHHW, Category 1 Storm Surge
  - USACE High rate at MHHW, Category 3 Storm Surge

While this is a coarse method for estimating future effects of sea level rise on storm surge, the pilot team considered it to be the best option considering the scale of analysis, resources available, and the time lime of the pilot. This additive type method is common for planning level analysis and is discussed in more detail in the section on Task 4. For the complementary regional analysis conducted for the LRTP recommendations, the team modified the modeling approach to estimate storm surge disruption for the entire County's transportation system. Instead of using the MOM outputs, which would greatly overestimate surge impacts, a single Category 3 surge event was modeled: the historic 1921 Tarpon Springs hurricane with one scenario of SLR added (2040, USACE High rate at MHHW). The team suggested that an engineering level modeling platform (such as ADCIRC) could be used for single, high value assets.

The pilot team also assessed transportation vulnerability to inland flooding through the use of the Federal Emergency Management Agency's (FEMA) 100-year floodplain maps. Because of limited resources, the pilot team did not attempt to expand the extents or adjust the depths of the floodplains to account for future impacts of sea level rise. Flooding hotspots were also collected from the County's Engineering and Construction Service Section.

After conducting the detailed analysis of risk for the five assets, impacts to regional mobility due to asset inundation and cost-effectiveness analyses of adaptation options were conducted. First, traffic demand models were run to simulate the effect of removing each inundated asset from the transportation system. The model estimates the following changes in mobility due to the disrupted travel patterns: changes in hours of delay, changes in vehicle miles traveled (VMT), and lost trips (commuter and truck). Next, the Regional & Economic Models, Inc (REMI) tool was used to calculate economic losses from the affected assets. Then, for each of the five affected assets, adaptation strategies were developed, with an estimated cost for implementation. Finally, these results were used to develop a cost-effectiveness (avoided losses) analysis for each asset to compare the difference between implementing an adaptation strategy and not implementing an adaptation strategy. Three of the five assets studied showed a net loss (negative return on investment), while two assets showed a net benefit of implementing an adaptation strategy. The pilot team concluded that due to the conservative approach of the traffic modeling, the mobility losses and economic impact were underestimated and hence the net loss results should be interpreted with caution.

The final report for the Hillsborough Pilot included next steps for future research; some of which are listed below: These offer important points to consider for future enhancements to the SLS Sketch Planning Tool and valuable guidance for incorporation of climate impacts into the transportation planning process:

- Further assessment could include an engineering level analysis for a specific facility or corridor to generate more detailed findings and potentially a full Cost-Benefit Analysis.
- For future research, the team suggested a study with longer timeframes, to match the projected lifespan of particular assets (such as bridges). This is especially relevant considering that SLR impacts are projected to increase significantly after mid-Century. Hence the pilot assessment years of 2040 and 2060 do not capture the magnitude of potential impacts to the transportation system.
- The pilot team recommended the vulnerability assessment process be updated for each LRTP cycle to incorporate the latest science and best practices.
- Suggested that partner agencies such as FDOT, Port Tampa Bay, Amtrak and others could leverage the work of the Hillsborough Pilot to inform planning efforts and enhance decision making.

The SLS Sketch Planning Tool data and maps, and additional data and resources from the GeoPlan Center were utilized numerous times in the Hillsborough Pilot efforts. In Phase 1 of the asset-level analysis, the SLS Sketch Planning Tool was used to establish the sea level rise scenarios that would be used to assess inundation risk to the critical transportation assets. The SLS Sketch Planning Tool online map viewer for FDOT District 7 was used by the Hillsborough team to quickly view already mapped scenarios of SLR inundation and potentially at-risk transportation assets in the Hillsborough MPO study area. The Hillsborough team also used batch geoprocessing scripts developed by the GeoPlan Center to facilitate the identification of potentially exposed transportation assets to storm surge and flooding. Additional resources utilized by the Hillsborough Pilot included Digital Elevation Model (DEM) data compiled by the GeoPlan Center for the SLS Sketch Planning Tool, and Federal Emergency Management Agency (FEMA) Digital Flood Insurance Rate Map (DFIRM) data distributed through the Florida Geographic Data Library, which is hosted and maintained by the GeoPlan Center. Throughout the Hillsborough Pilot, the GeoPlan Center conducted multiple phone conversations with staff from Cambridge Systematics and Hillsborough MPO, as well as attended project status update meetings (via teleconference).

South Florida Climate Change Vulnerability Assessment and Adaptation Pilot Project

The South Florida Climate Change Vulnerability Assessment and Adaptation Pilot ("The South Florida Pilot") and was conducted under the leadership of the Broward MPO and covered the four counties participating in the Southeast Florida Climate Compact: Broward, Miami-Dade, Palm Beach, and Monroe. The pilot utilized FHWA's Vulnerability Assessment Framework for assessing transportation facilities at risk to climate stressors. Objectives of the pilot included analyzing adaptive capacity of facilities, identifying adaptation opportunities, providing feedback to the planning process, integrating risk information into the transportation planning process, and strengthening institutional capacity[4].

The pilot engaged a long list of participants and partners. Prime participants were: Broward MPO, Palm Beach MPO, Miami-Dade MPO, and Monroe County Planning and Environmental Resources Department. Members of the Technical Advisory Committee included representatives from numerous city and counties, regional agencies (MPOs participants, Miami-Dade Expressway Authority, South Florida Regional Planning Council, South Florida Regional Transportation Authority), FDOT District 4, FDOT District 6 and FDOT Central Office, Florida Atlantic University, University of Florida GeoPlan Center, Miami Herald, and various consulting agencies.

The South Florida Pilot focused on three climate stressors: sea level rise, storm surge, and inland flooding from heavy precipitation. For sea level rise, the pilot team analyzed three scenarios (1-ft, 2-ft, and 3-ft) and utilized the SLS Sketch Planning Tool GIS data layers of inundation to assess transportation infrastructure at risk of permanent inundation under those scenarios. To assess inundation from storm surge and inland flooding, the pilot team developed indexes to assess current and future exposure to these periodic flooding events. The modeling approach for these indexes was to utilize return period flood events (specifically the 100-year flood event or 1% annual chance of occurrence) to indicate current flood risk and guide identification of future flood risk. The current flood risk index was calculated per transportation segment by multiplying the percent of the segment inundated by the 100-year flood zone and the average depth of inundation. The future flood potential index was calculated per transportation segment (road or railroad) by

[4] For more information on the South Florida Climate Change Vulnerability Assessment and Adaptation Pilot Project and access to the final report (April 2015), appendices, and supplemental documents, see the Broward MPO's website at: http://www.browardmpo.org/planning/adapting-to-climate-change

weighting two measures: distance from the segment to the closest 100-year flood zone and the difference in elevation between the segment and the flood level of the closest flood zone. The concept of this index was that low-lying roads or rails closer to flood zones are more exposed, especially considering future expansion of flood zones.

The vulnerability of each transportation asset to the climate stressors was assessed using three variables: exposure (how susceptible is the asset to the climate stressor), sensitivity (how sensitive is the asset to the climate stressor), and adaptive capacity (to what extent can the asset be modified to respond to the changing conditions). Exposure for transportation assets was estimated by three measures: the percent of each segment inundated by 1, 2, and 3 ft. of sea level rise; index of current flood exposure; and index of future flood potential. These three variables were used to rank the regional assets (road and passenger rail) in the regional transportation network. The most vulnerable regional facilities shared similar characteristics of low-lying elevations, lack of alternative routes and/or long detour routes, and high flood exposure. The pilot study found Monroe County regional facilities, causeways and facilities on barrier islands, and roads traversing the Everglades to be most vulnerable to the three climate stressors.

To promote resiliency, the pilot team recommended a series of actions in five areas of decision making: transportation policy, planning and prioritization; rehabilitation or reconstruction of existing facilities in high risk areas, new facilities in high risk areas; systems operations; and systems maintenance. The four recommendations in the area of transportation policy, planning and prioritization are the most relevant to the enhancement of the SLS Sketch Planning Tool. They include: (1) develop a goal statement regarding climate change that can be used to guide the transportation planning process; (2) identify criteria that can be used to prioritize projects based on their vulnerability to climate stressors; (3) apply performance measures to promote resiliency of the transportation system; and (4) utilize tools that facilitate identification and assessment of climate change impacts.

Additionally, the pilot team compiled some lessons learned from the study. These important points offer valuable insight for future enhancements to the SLS Sketch Planning Tool:

- "The availability and quality of data is one of the most important factors in the overall success of the study" (Broward Metropolitan Planning Organization, 2015, p.44). Data needed to support the adaptation planning process should be thoroughly considered. Where data is unavailable or unfit, proxy data should be identified. Future studies such as this would benefit greatly if specific data (i.e. size of hydraulic openings for bridges or culverts) were captured by transportation or planning agencies during normal data collection (i.e. asset management systems).
- Conducting a vulnerability analysis on a large four-county region was a challenge due to the long computer processing times needed to complete spatial analyses.
- Because of the long time frame and uncertainty of climate change impacts, the adaptation planning process should not be conducted on a one time basis. Planning for climate adaptation should be an iterative part of the transportation planning and decision making process.

Throughout the pilot project, the GeoPlan Center participated in the Technical Advisory Committee meetings (via teleconference), presented information on topics as requested, and answered questions from the consultant team (via email and phone) regarding utilization of the SLS Sketch Planning Tool data and maps. The SLS Sketch Planning Tool was used by the project team for mapping inundation and analysis of facilities at risk due to sea level change. The GeoPlan Center also assisted the project team with data correction issues, namely the development of a methodology to create a spatial layer of bridge deck elevations. This methodology is discussed in more detail in Task 1 of this report. Finally, the GeoPlan Center had multiple phone meetings with the consultants to discuss methods for mapping and estimating storm surge, which was a particular challenge for the South Florida region.

Use of SLS Sketch Planning Tool in Other Communities

City of Satellite Beach and East Central Florida Regional Planning Council

The GeoPlan Center assisted East Central Florida Regional Planning Council (ECFRPC) with their Natural Hazard Risk and Vulnerability Analysis project for the City of Satellite Beach. In this project, ECFRPC analyzed the impacts of four hazards (storm surge, flooding, coastal erosion, and sea level rise) in five categories: financial exposure, exposure to built parcels by build year, land use exposure, critical facility exposure, and ecological and environmental exposure. ECFRPC was interested in utilizing the SLS Sketch Planning Tool to assist in the development of sea level rise scenarios and identification of areas affected under sea level change (SLC) scenarios.

The City of Satellite Beach is located in Brevard County, on the east coast of Florida, situated between the Atlantic Ocean (the eastern border of the City) and the Indian River Lagoon Intracoastal waterway (the western border of the City). Modeling SLR inundation for intracoastal areas presents a challenge in that those areas do not experience the same tidal fluctuations as the Atlantic Ocean coast. The Sketch Planning Tool's SLC projections (from USACE) utilize tide gauge data for coastal areas that include tidal datum levels which capture long-term tidal trends. For a more accurate representation of inundation on the intracoastal side (western border) of the City, tide gauges located in the intracoastal should be used to get a more accurate estimate of the mean water levels and high tide conditions. While the USACE methods for projecting SLC could still be applied, different tide gauge data were needed.

The GeoPlan Center developed and mapped two sets of SLC inundation scenarios for the City of Satellite Beach: inundation from the Atlantic Ocean and inundation from the Indian River Lagoon. Calculations of projected sea level rise on both the Atlantic side and Indian River Lagoon side used the Daytona Beach tide station's sea level trend values, which incorporate local subsidence or uplift rates. Hence, the amount of projected SLC under each scenario is the same for both sides of the municipality. What differs is the starting water level. On the Atlantic side, the projected amount of SLC was added on top of MHHW datum. Since the Indian River Lagoon does not experience the same tidal variations as the Atlantic, the projected amount of SLC was added on top of the Carter's Cut Mean Water Level (MWL) + 1 foot (to represent the average of highest seasonal tide). Based on these two sets of SLR scenarios, the GeoPlan Center created GIS layers of inundation and provided the resulting GIS layers to ECFRPC staff to use in their vulnerability analysis.

This was a valuable learning experience. This provided a unique opportunity to address better modeling of intracoastal areas, which had not previously been addressed in the SLS Sketch Planning Tool. As part of this project, GeoPlan staff attended phone meetings with ECFRPC staff and attended two Technical Advisory Committee meetings (via teleconference) to discuss the project and methods.

Detailed methods on the GeoPlan Center's contribution to this project are included in ECFRPC's Final Report, entitled "Natural Hazard Risk and Vulnerability Analysis, Satellite Beach, Florida", and can be accessed from ECFRPC website at: http://www.ecfrpc.org/getdoc/85e52bd1-aafe-4ffa-97f8-a0ca085739f3/Satellite-Beach.aspx (link name: "Vulnerability Analysis – 2015").

Monroe County

Erin Deady, P.A. and Dr. Jason Evans of Stetson University were under contract with Monroe County, Florida to assess the impacts of sea level change and climate change on community assets. This project was part of GreenKeys, a sustainability initiative of Monroe County focused on making the Keys more resilient to climate change. The Monroe study team used the SLS Sketch Planning Tool to model transportation assets potentially vulnerable to sea level rise. The GeoPlan Center attended a phone meeting with Dr. Evans and Monroe County Engineer Judith Clarke to learn about their project and gather feedback. Dr. Evans followed up with the GeoPlan Center, offering positive feedback and recommendations.

Outreach & Presentations about SLS Sketch Planning Tool

The SLS Sketch Planning Tool generated a considerable amount of interest and inquiry from communities, planners, researchers, and others interested in assessing the impacts of sea level change on their transportation and community facilities. The GeoPlan Center and FDOT OPP were contacted numerous times to give presentations and provide information about the tool for others to benefit and utilize.

Presentations and outreach provided:

- Presentation to the Florida Department of Economic Opportunity (DEO) Community Resiliency Focus Group Webinar, July 25, 2013.
- Presentation at the National American Planning Association (APA) Annual Conference, for Session entitled "Planning for Climate-Resilient Transportation". Presented with FHWA Climate Resiliency partners Hillsborough County MPO, Broward County MPO, Cambridge Systematics and Parsons Brinkerhoff, April 27, 2014.
- Webinar for 1000 Friends of Florida "Planning for Sea Level Rise: State Resources for Florida's Communities". The webinar focused on state resources available to assist communities with developing workable planning strategies to adapt to sea level rise. September 10, 2014.
- Presentation to the Florida League of Cities, Center for Municipal Research and Innovation, Fall Research Symposium, November 12, 2014.
- Presentation to University of Florida Urban and Regional Planning Graduate Class: Transportation and Land Use Coordination, November 24, 2014.

- Webinar for the Florida Department of Economic Opportunity, Community Resiliency Initiative Focus Group, November 24, 2014.
- Presentation to Florida State University Law Class: Current Issues in Environmental Law & Policy Seminar, February 10, 2015
- Presentation and Live Tool Demonstration to the University of Florida IFAS Extension In-Service Training, February 24, 2015
- Presentation to FDOT Florida Transportation Plan Planning Team. March 6, 2015
- Southeast Florida Regional Climate Compact Regional Climate Action Plan (RCAP) Transportation Workshop, April 30, 2015.
- Presentation and Live Tool Demonstration to the IFAS/ SeaGrant conference: Gulf Climate Outreach Community of Practice, May 19, 2015.
- Webinar for FLURISA, the Florida Chapter of the Urban and Regional Information Systems Association, June 17, 2015.

The SLS Sketch Planning Tool has also been referenced in resource guides and reports that list tools and/or data available to communities interested in adaptation planning and community resiliency:

Planning for Sea Level Rise: A Guide for Managers, Owners and Regulators of Water-Dependent Infrastructure. This guide was prepared for the Florida Department of Economic Opportunity's Community Resiliency Initiative by the University of Florida, Levin College of Law Conservation Clinic. The SLS Sketch Planning Tool was referenced as a resource and the GeoPlan Center provided maps of sea level scenarios and affected facilities for a "fact sheet" publication summarizing the full publication. Figure 12 shows a map of potential impacts to Port Tampa Bay and Figure 13 shows a map of potential Impacts to Florida Ports, both created by the GeoPlan Center. The guide is available at: http://www.law.ufl.edu/_pdf/academics/centers-clinics/clinics/conservation/resources/final-deliverable-2b2-guidance-document-on-slr-and-water-dependent-infrastructure.pdf

Sea Level Rise Projection: Needs Capacities and Alternative Approaches. This document was prepared for the Florida Department of Economic Opportunity's Community Resiliency Initiative by the Florida Planning and Development Lab, Department of Urban and Regional Planning, The Florida State University. The SLS Sketch Planning Tool is discussed in detail in the document and specifically on Page 43 that "FDOT's grant to support model development of sea level rise inundation and transportation system vulnerabilities by GeoPlan is one of the most promising efforts to bring together data at a statewide level that could be utilized by local governments and regional planning agencies to integrate sea level rise projections and scenarios into adaptation planning". Information regarding the report, and access to the report is available at: http://fpdl.coss.fsu.edu/Research-Projects/Sea-Level-Rise-Projection-Needs-Capacities-and-Alternative-Approaches

Figure 12. Map of potential sea level inundation impacts to Port Tampa Bay.

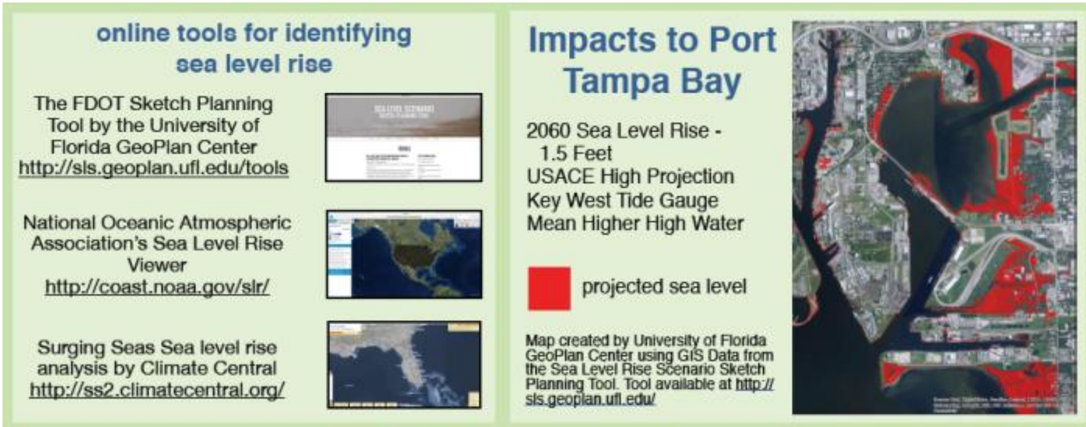
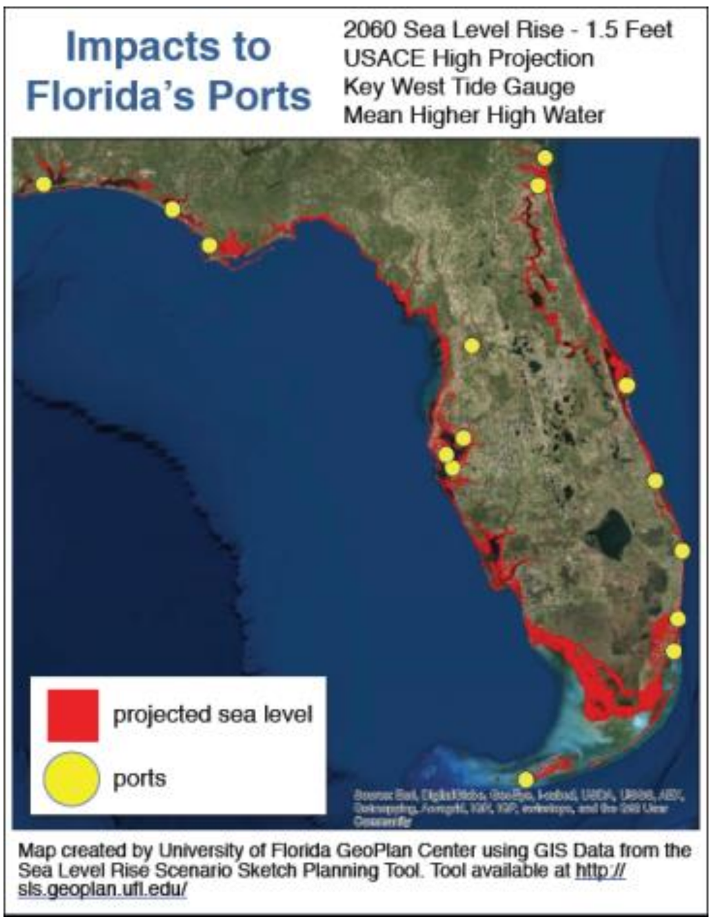


Figure 13. Map of potential sea level inundation impacts to ports in Florida.



Working with Pilots: Feedback and Lesson Learned

Task 2 took considerably longer than projected in the original scope of work. This was partially due to the fact that data issues were hard to predict at the onset of the project. However, the primary reason is that the SLS Sketch Planning Tool generated a high volume of inquiry from communities, planners, researchers, and others interested in assessing the impacts of sea level rise on their transportation and community facilities. While much time was expended, the experience was invaluable, providing insight into the types of data and resources needed and the common issues that arise when assessing at-risk transportation facilities in order to plan for adaptation and resilience. Gathering feedback from real-world projects, such as the FHWA pilots and climate resilience initiatives in other communities, is critical for prioritizing enhancements to the SLS Sketch Planning Tool to increase its efficacy as a decision support tool. Feedback was gathered from the FHWA pilots and other communities via informal communication and through an online survey. Feedback and suggestions were also communicated to the GeoPlan team during presentations and webinars.

Below is a summary of the major feedback provided and the GeoPlan response to address each:

- Prior to the start of the Phase 2 work, there was a documented and known issue with the bare-earth derived DEM falsely identifying bridge approaches as inundated areas. While this was a known issue, continued feedback from multiple sources reinforced it as a high priority for correction of this issue.
    - ➢ In response to this feedback, GeoPlan developed a methodology to extract the correct bridge elevations from the Lidar data and create a GIS layer of bridge deck elevations. The bridge elevation data was completed for the coastal areas of Hillsborough, Broward, Palm Beach, Miami-Dade, and Monroe Counties. The South Florida pilot successfully utilized this GIS layer in their vulnerability assessment process to more accurately represent potentially inundated transportation facilities.
- Feedback from numerous sources to include other GIS data layers useful for assessing vulnerability of infrastructure to various climate stressors: bridge data with elevations, floodplains and flood hazard areas, storm and surge data.
    - ➢ Bridge elevation data has been addressed (above). For the next Phase of this work, GeoPlan is planning to incorporate floodplains, flood hazard zones, and storm surge data into the SLS Sketch Planning Tool. One approach that NOAA has implemented is an index of inundation, where areas are analyzed for their vulnerability to multiple sources of inundation. Sea level rise is only one of the inundation threats that face communities and infrastructure; nuisance coastal flooding is increasing and storm surges are on the rise, both exacerbated by increases in mean sea level (National Oceanic and Atmospheric Administration, 2014).
- Suggestion to have summary generation tools available, such as the ability to generate vulnerable facilities by functional class, facility type, or county (geography).
    - ➢ Summary generation tools would be a powerful analytical addition to the SLS Sketch Planning Tool. For the next approved scope of work, which will involve

training of the MPOs, GeoPlan will develop state, regional, ad local (MPO) profiles. The profiles will include statistics and reports summarizing the potentially inundated areas from sea level rise and affected transportation infrastructure using the data developed in the SLS Sketch Planning Tool. It is intended that these profiles will assist each MPO in understanding how future sea level rise may impact their transportation system.

- Suggestion to invest resources into building a simple Table of Contents for the map viewer and customize it to make it easy to use. For example, a mechanism to load scenarios and layers based on user input
    - The SLS Sketch Planning Tool's public web map viewer was built using ESRI's ArcGIS Viewer for Flex, which was a great tool for quickly deploying online maps, but has limited ability for customization. Moreover, the map viewer needs to be migrated to a different software platform because the ArcGIS Viewer for Flex will be deprecated (no longer maintained or supported) by ESRI and will be replaced by the ArcGIS API for JavaScript. In Phase 2, GeoPlan began the migration of the map viewer to the ArcGIS API for JavaScript. In the next Phase of this work, GeoPlan is completion of the map viewer to the ArcGIS API for JavaScript, which will modernize the software platform and address this feedback from the FHWA pilots on how to improve the usability of the map viewer interface.
- Feedback to include the NOAA curves in the SLS Sketch Planning Tool.
    - While the USACE does not officially include NOAA sea level projection curves in their most recent guidance on incorporating sea level rise into civil works programs, the NOAA curves are included in their Sea Level Change Curve Calculator. Furthermore, NOAA is the lead federal agency engaging in scientific research regarding sea levels and flooding. The NOAA SLR curves are an important projection to consider. In the next phase of this work, GeoPlan proposes to include the NOAA curves (specifically the intermediate high and high) in the SLS Sketch Planning Tool.

Beyond data, participation with the pilots offered an opportunity to learn about the broader adaptation planning process outlined by FHWA for promoting resiliency in the Nation's transportation systems. While quality data is essential for successful vulnerability assessments, data and analysis are just one part of the larger planning approach. Community outreach and public education are critical components to the adaptation planning process. Understanding and communicating the climate risks specific to each region is essential for building support for these types of vulnerability assessments. Also critical is the integration of vulnerability and risk information into the transportation planning process as another variable to consider when making infrastructure investment decisions. An iterative process for evaluating risks and prioritizing investments based on vulnerability and risk will be crucial for increasing the resiliency of transportation systems.

Each pilot offered different, but equally important learning lessons. The Hillsborough Pilot covered only one county, and this smaller project scale offered advantages in project and data management and local engagement. The pilot team was able to produce very detailed inundation profiles and cost-effectiveness adaptation analyses for five assets deemed both critical to the transportation system and vulnerable to climate impacts. This resource intensive approach offers valuable information for a limited number of assets. For assessing regional transportation and developing recommendations for the 2040 LRTP, a complementary sketch level analysis was performed for the regional system. This coarser analysis offered a broader look at asset vulnerability, travel disruption, and adaptation options for the region. The pilot was fortunate to have both levels of analysis completed, each serving different objectives. The pilot team was also fortunate to have the assistance of the County's Local Mitigation Strategy Working Group, a mix of local government officials, local business representatives, and private citizens. The Group provided advice, feedback, and expert input to determine critical infrastructure. One disadvantage of working at the county scale is that the multi-county, regional impacts are not fully represented. This is especially relevant for the Tampa area, which is highly interconnected with Pinellas County and the coastal areas to the west.

The South Florida Pilot covered four counties, which proved difficult on various levels. However, the project team was able to overcome some obstacles and provide a valuable analysis of regional transportation vulnerabilities. Due to the large geographic study area, the pilot team encountered many issues with data availability, data quality, and long processing times for computing spatial analyses. Storm surge modeling also proved to be difficult, but the pilot team was able to develop proxy measures at estimating future flooding using return period information (i.e. – 100 year storm event). Additionally, because of the large study area, the Technical Advisory Committee (TAC) was also a large group, comprised of numerous county, city, MPO, and RPC representatives. While the TAC members offered invaluable local expert input, it seemed difficult to accommodate the varying interests and expertise of the individual members. Where this project exceled was the prioritization and ranking system developed for the regional network. The scoring and weighting system used to prioritize roads and railroads offer a replicable method that others could utilize. The analysis results and maps of the vulnerability rankings make it clear which assets are at risk and offer a regional view of vulnerability.

Working with the FHWA pilots and other communities was essential to testing the SLS Sketch Planning Tool developed in Phase 1 to ensure applicability for planning purposes. If addressed in future phases of work, the feedback regarding data gaps, functionality enhancements, and usability improvements will strengthen the Tool's efficacy as an assessment and decision support tool. The involvement with the FHWA pilots and other communities demonstrated the demand and need for better planning level tools to assess inundation risks and incorporate risk information into the planning process to ensure resilient infrastructure and protect public investments.

Task 3 – Tool Enhancements

In Task 2, GeoPlan gathered feedback from pilots and other users regarding their experiences using the SLS Sketch Planning Tool. The feedback is discussed in detail in the previous section regarding Task 2. In brief, feedback included the following suggestions: additional data layers to be included to the SLS Sketch Planning Tool for further analysis of inundation risks (floodplains, flood hazard areas, storm surge, enhanced bridge data with elevations); modification of the map viewers to include a simpler and easier to use Table of Contents; summary generation tools to better analyze vulnerable facilitates; and the addition of the NOAA SLR curves. In addition, testing of the SLR Inundation Surface Calculator yielded feedback for improvements and identification of minor bugs.

While not all of the feedback could be addressed under the current scope of work, significant progress was made on tool enhancements. The bridge data issue was addressed in Task 1 (data enhancements) and discussed in detail in that section of this report. The suggestion to add floodplains, flood hazard data, and storm surge data layers to the SLS Sketch Planning Tool was taken under advisement and studied in further detail in context of Task 4. A major focus of Task 4 was to research the most appropriate methods to represent future flood and storm surge risks, with the underlying premise that sea level rise will very likely exacerbate both risks. That is discussed in more detail in the following section regarding work on Task 4. Based on the other feedback regarding the SLR calculator and map viewer, details of the work completed during Phase 2 are listed below.

SLR Inundation Surface Calculator: Enhancements and Bug Fixes

In this task, the GeoPlan Center made updates and bug fixes to the SLR Inundation Surface Calculator, an add-in tool for ArcGIS Desktop, which assists users in creating GIS layers representing potentially inundated areas due to various sea level rise scenarios. The calculator is available from the project website, on the "Tools" page, accessible at:
http://sls.geoplan.ufl.edu/tools/

The following enhancements and bug fixes were incorporated into the SLR Calculator Version 1.5.2 release (November 2014):

- Added input for DEM Vertical Units, which converts the vertical units (feet or meters) of the input DEM to inches to correspond with the USACE sea level change projections, which are stored in inches for the SLR calculator. If the input DEM is inches, then no conversion will take place.
- "Add to Map" functionality added in dialog after layers have been created. This function allows user to easily add the inundation outputs to the map for viewing and analysis. Previously, users would have to open and separate "add layers" dialog and navigate to their chosen output directory to add the outputs.
- Various bug fixes, including: "No bathtub" errors when running only the hydro-connectivity outputs; overwrite errors – if the output file name already exists, the calculator will now increment the file name with a unique ID.
- Some of the calculator inputs have been reordered.

- The option for a vector (polygon) output added for bathtub model.

Update of the SLR Inundation Surface Calculator Guide for Version 1.5.2. Posted on the project website at: ftp://ftp.sls.geoplan.ufl.edu/pub/sls/docs/SLR_Calculator_Guide_v1_5_2.pdf

Additional features are currently in development for the next release of the SLR Calculator. These enhancements, which are listed below, are still in the testing phase and being migrated to the latest release of ArcGIS Desktop.

- Upgrade support for the SLR Calculator to ArcGIS Desktop 10.1.
- Clip to County feature – allows user to clip to their area of interest for processing of SLR inundation layers.
- Clip to Custom Area – allows the user to create a custom area of interest for processing of SLR inundation layers.
- Add Map Service – allows a user to add a digital elevation model (DEM) map service to the calculator as an input DEM and create inundation layers using the map service DEM.

Map Viewer Enhancements:

In this task, the GeoPlan Center began development of a new map viewer using the ArcGIS API for JavaScript. This is a major redesign effort, using different underlying software to build the map viewer components and functionality. While time consuming, the new map viewer will be built on a more modern software platform that will increase the longevity of the maps and allow for more flexibility in customizations. Specifically addressed in the new design is a simplified and more user-friendly table of contents for loading scenarios and layers. The following pages show images of the new map viewer in development, highlighting some of the map features and functionality in progress. Figure 14 shows the new map viewer in development, with filters at the top for dynamically loading scenarios based on user input. Figure 15 shows the new map viewer in development, with a selected sea level scenario (at top) and expanded Table of Contents (at left)displaying legends for data layers. Figure 16 shows the new map viewer in development, with the view attribute table functionality (at bottom) and Google Street View tool (at left).

In the next Phase of this work, GeoPlan is planning to complete and test the new map viewer, which will modernize the software platform and address this feedback from the FHWA pilots on how to improve the usability of the map viewer interface.

Figure 14. Map Viewer in development, showing filters for loading scenarios.

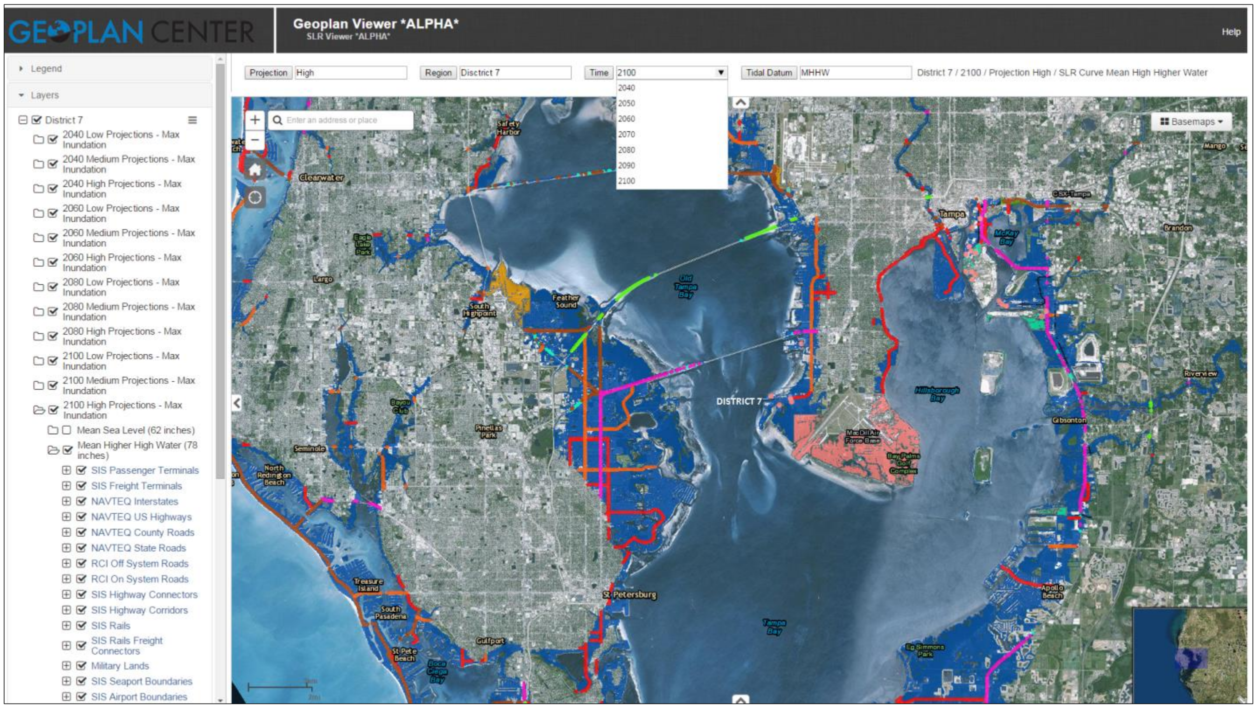


Figure 15. Map Viewer in development, showing table of contents and layer legends.

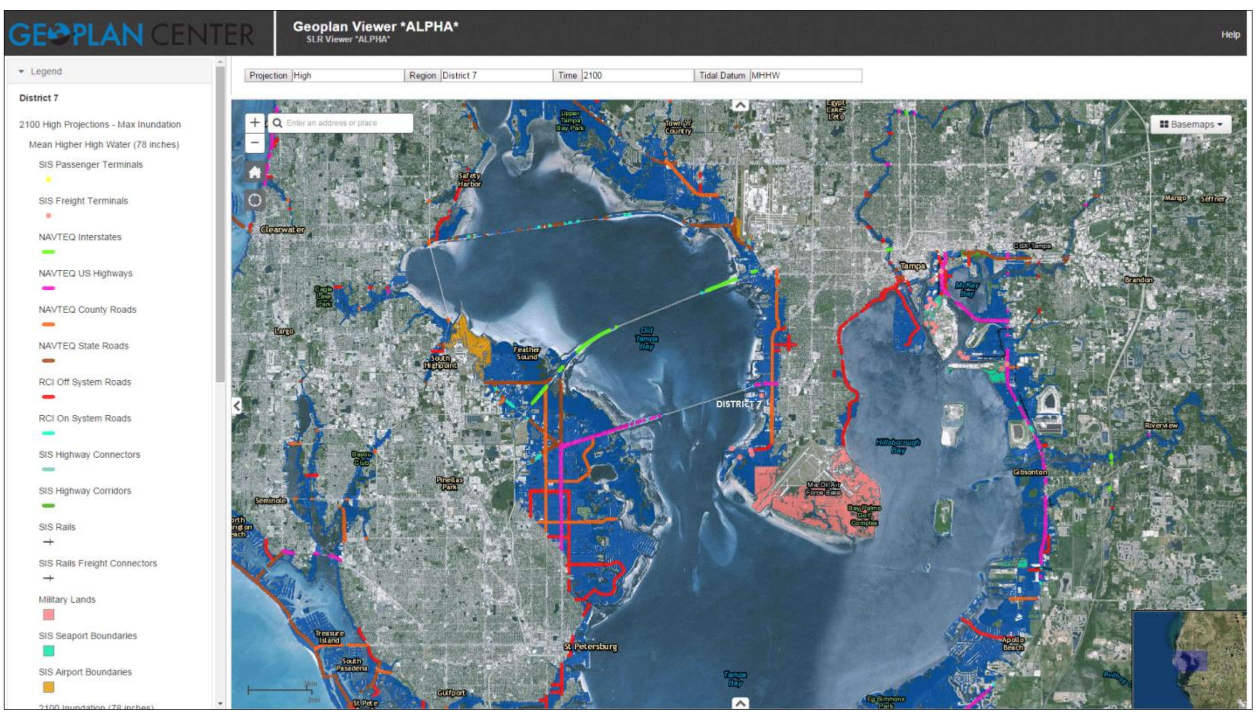
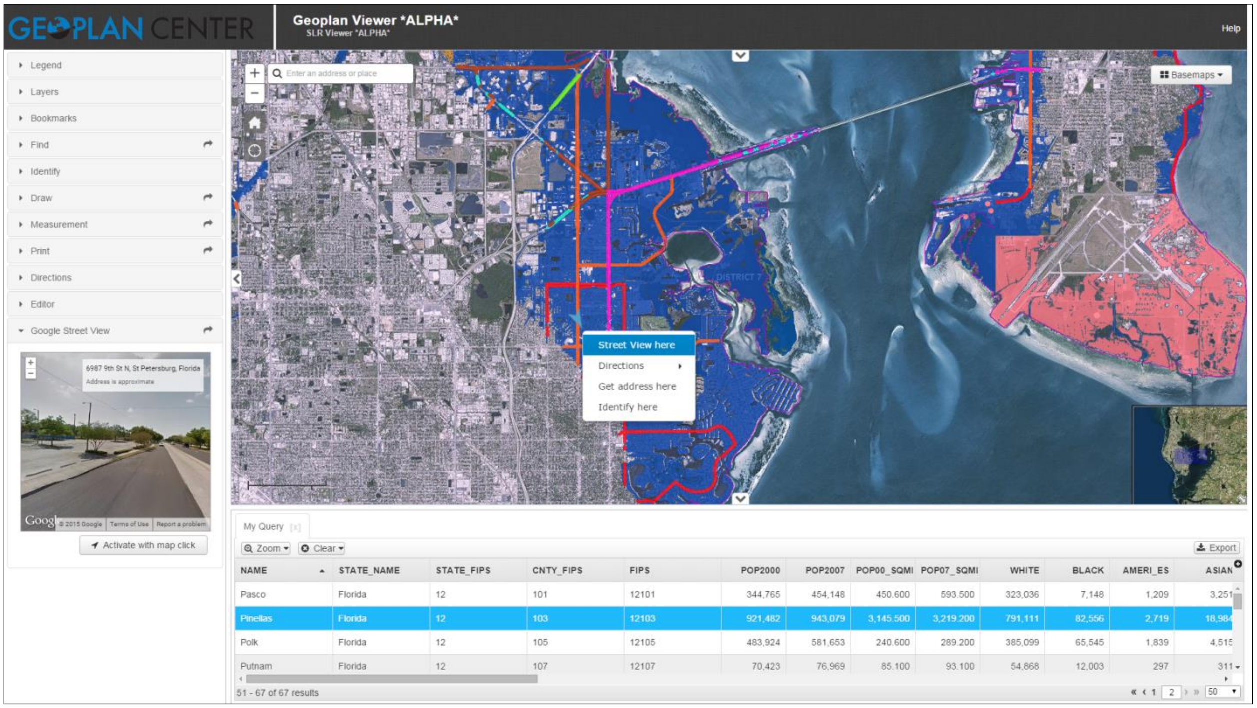


Figure 16. Map Viewer in development, showing attribute table and Google Street View tool.



Task 4 – Enhanced Sea Level Change Modeling for Combined Effects

The goal of this task was to research methods for modeling storm surge and flood hazard zones in the context of sea level change scenarios, in an effort to better model and estimate future infrastructure vulnerabilities from multiple inundation risks. First, storm surge models and current literature were reviewed to determine whether any best practices are emerging for storm surge modeling. Next included is a discussion of the updated FEMA Federal Flood Risk Management Standard, which heightens the previous standards in order to strengthen resiliency of federal infrastructure to increased flooding risk due to climate change. Following that, is an in-depth discussion of the New York City Panel on Climate Change's methods to map and estimate future flood risks. Finally, Hazus-MH and SLOSH models were utilized in an effort to create a proof of concept for modeling storm surge, which could then be replicated at the regional or state level.

This section describing Task 4 has five main sections, including:

- Approaches to Modeling Storm Surge
- Storm Surge Models
- Updated FEMA Federal Flood Risk Management Standard, 2015
- Estimating Future Flood Risks: New York City Panel on Climate Change
- Storm Surge Model Testing

Approaches to Modeling Storm Surge

The effect of rising sea levels on storm intensity and frequency has been inconclusive. However, what is clear is that rising sea levels will increase storm surge flood depths and the frequency of coastal flooding due to the higher "launch point" or water level for the surge to push onto the land (Kirshen, 2008a, Neumann, et al. 2015, Sweet and Park, 2014, Tebaldi et al. 2012). The increase in surge depths may not be a linear or one-to-one relationship; a one-foot increase in mean sea level will not necessarily equate to a one-foot increase in surge depth (U.S. Department of Transportation Federal Highway Administration, 2014b, Zhang et al., 2013).

Approaches to modeling the effects of sea level rise on storm surge vary widely from simple additive models to complex hydrodynamic models. Common modeling approaches include additive processes that add an increment of sea level rise on top of storm surge model outputs; analysis of coastal storm flood frequencies; and analyses of historical extreme water levels. Other approaches include hydrodynamic models used for engineering scale applications, which are also capable of analyzing sea level rise effects on storm surge. Modeling approaches depend on a variety of factors including scale of analysis, geographic extent of analysis, and resources available (financial, temporal, and expertise).

Additive Models

The additive modeling approach involves the addition of SLR to existing data products of storm surge zones that depict the extent and depth of surge. Two commonly available data sets of coastal surge zones are storm surge inundation maps (SSIMs) and coastal flood rate insurance maps (FIRMs). SSIMs are typically generated with the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model and output maps depict a worst case scenario flood level for each storm category using the Saffir-Simpson scale (SLOSH model outputs discussed in more detail in the next section). SSIMs are used for developing hurricane evacuation zones and not for regulatory purposes. SSIMs also do not account for wave action and do not include probability of occurrence. FIRMs are regulatory documents developed by FEMA to support the National Flood Insurance Program (NFIP). The FIRMs identify Special Flood Hazard Areas (SHFA), which depict areas of possible riverine and coastal flooding subject to NFIP regulations for communities participating in the NFIP. Storm surge and wave action (where applicable) are used to determine the flood hazard areas in coastal areas. Numerical, hydrodynamic models are run multiple times with historic and hypothetical storms to estimate the frequency, or return period, of coastal storm flood elevations (i.e. – 100 year flood elevation). The FIRMs are based on a flood event with a certain probability of occurring; the SSIMs are not. The USACE recommends the use of both SSIMs and FIRMs for coastal planning applications, and that combined, will give a more complete picture of coastal flood risk (U.S. Army Corps of Engineers, 2011).

A common modeling approach involves the addition of SLR to the storm surge depth using available, existing storm surge data products, and then comparison of those new depths against elevation data. SLOSH model surge depths for a particular category of storm are commonly utilized (Hillsborough Metropolitan Planning Organization, 2014, Maloney and Preston, 2014, Shepard et al. 2012). In one method reviewed, the Digital Elevation Model is first "dropped" to simulate elevations under future sea level rise (Frazier et. al. 2008). For example, if one meter of SLR is projected, then one meter would be subtracted from the DEM to represent new water levels with SLR and then the surge zones are mapped on top of the dropped DEM. In the New York Panel on Climate Change methods for mapping future floodplains, increments of SLR were added to FIRM base flood elevations (BFEs) for the 100-year and 500-year storms and then compared against elevation data (Leslie et al., 2015). This method is discussed in detail in the following section.

Analysis of Storm Flood Frequency

Another storm surge modeling approach involves analysis of storm return periods and frequency of occurrence. For some of these approaches, the FEMA 100-year storm event (1% annual chance of occurrence) is used as a baseline measure of current flood hazard areas and surge elevations. Some methods use statistical analyses of tide gauge records to compare the frequency of the 100-year storm elevations with and without measures of SLR. For many locations, the elevations for many return periods (i.e. 20-year, 50-year, 100-year storms) are already being exceeded earlier than their respective return period (Sweet and Park, 2014) and with the addition of SLR this trend is projected to continue (Kirshen, 2008a, Tebaldi et al. 2012). In Neumann et al 2015, SLR scenarios for 2050 are combined with simulated storm surge levels for the 100-year event. SLOSH was used to determine a storm surge exceedance curve, or a base case of surge heights without SLR. Then the SLR scenarios were added to the curves to estimate how SLR increases the frequency of storms. Tebaldi et al. 2012 analyzed long-term data records from 55 NOAA tide gauges around the U.S. and developed SLR projections at each gauge location. Detailed tide gauge records were then used to analyze patterns of extreme high water events and combined with SLR projections to forecast how the frequency of local extreme water levels would change under SLR scenarios. The techniques involved in some of these analyses require substantial statistical expertise.

Analysis of Historical Extreme Water Levels

Other methods for estimating the effects of SLR on storm surge involve the use of historical tide gauge data to analyze trends in extreme water levels. One study used the highest observed water levels (HOWLs), which represent the highest recorded water level at a particular NOAA tide station and include the date of the water level observation. In this study, increments of SLR were added to HOWLs to represent areas at-risk to periodic storm surge inundation under future scenarios of SLR (U.S. Department of Transportation Center for Climate Change and Environmental Forecasting, 2008). In another study, the addition of SLR to the highest storm heights (by event) was used to model future storm surge impacts (New Hampshire Coastal Risks and Hazards Commission, 2014). In this study, predicted and observed water heights from the largest storm surge events along the New Hampshire coastline since 2003 were analyzed (the top 10 of these events were extratropical storms also known as nor'easters). Three SLR scenarios for 2050 and 2100 were then added to the highest observed water heights for these storm events to estimate the potential high water levels from similar storms with the addition of SLR. The New Hampshire study utilized SLR scenarios from the U.S. National Climate Assessment (NCA), which are also used by NOAA. The NCA includes four scenarios of future global SLR: Low (0.7 feet by 2100), Intermediate Low (1.6 feet by 2100), Intermediate High (3.9 feet by 2100), and Highest (6.6 feet by 2100). The NCA Low and the USACE Low scenarios are equivalent, representing the observed historic sea level trend extrapolated into the future. The NCA Intermediate Low is equivalent to the USACE Intermediate. The USACE High scenario (5-feet by 2100) is in between the NCA Intermediate High and NCA Highest. The report maintains that there is "considerable scientific support for a maximum value for sea level rise of close to 2 meters (6.6 ft.) by 2100" (New Hampshire Coastal Risks and Hazards Commission, 2014, p. 22).

It should be noted that FHWA does not recommend using frequency statistics developed directly from historical water level data (tide gauges) for vulnerability assessments or designs for extreme events unless those extreme water levels can be verified (U.S. Department of Transportation Federal Highway Administration, 2014). The concern here is that during extreme events, gauges can become inoperable due to physical damage, power loss, or gauge design not equipped for those extreme elevations.

Numerical Modeling

Numerical, hydrodynamic models typically used for engineering scale applications are also capable of analyzing sea level rise effects on storm surge. These complex numerical models (e.g. ADCIRC, SWAN, CoSMoS) simulate tidal flows, water levels, and constituent transport (sediment, contaminants, etc) using two and three-dimensional models. These models require substantial technical expertise, usually from a coastal engineer with expertise in hydrodynamic modeling, and are time and computationally intensive. Additionally, these models are computationally intensive, often incurring long run times and/or high performance computing infrastructure. Numerical modeling was used in U.S. DOT's Gulf Coast 2 Study to map storm surge and waves for extreme events under various scenarios of sea level rise (U.S. Department of Transportation, 2013). A recent U.S. Geological Survey report stated that "These model types are not necessarily appropriate or useful for generating future sea-level rise projections or impact assessments based on design or function but are relevant in other ways, such as for parallel efforts to better understand the effects of river and coastal management on coastal geomorphology and tidal change" (Doyle et al., 2015, p.18).

Tiered Modeling Approach

Considering the complexity of the relationship between sea level rise and storm surge, which varies based on region and storm characteristics, and recognizing the expert knowledge needed to conduct assessments, a range of approaches is needed to effectively model the effects of sea level rise on storm surge. There is "no one-size fits all" modeling approach and a tiered or scaled approach is needed to address the range of modeling situations. For planning level analyses covering large geographic areas, GIS data estimating the effects of SLR on storm surge is not generally available, due to the region-specific variables and resources needed to run models. Maloney and Preston, 2014, attempt to fill that data gap by employing methods to "scale-up previously published methods for the integrated assessment of coastal vulnerability to hurricane storm surge and sea-level rise) to develop contiguous, process-based, geospatial inundation layers for the U.S. coastlines of the Gulf of Mexico and the Atlantic Ocean." Additionally, the Federal Highway Administration, who has been working on climate adaptation initiatives to increase infrastructure resiliency to climate change and extreme weather events (see Task 2), offer sound guidance on a tiered modeling approach, which is described in detail below.

Federal Highway Administration Framework for Assessing Extreme Events and Climate Change

FHWA's 2014 Hydraulic Engineering Circular No. 25 - Volume 2, *Highways in the Coastal Environment: Assessing Extreme Events* offers guidance for modeling approaches. The purpose of the circular is to "provide technical guidance and methods for assessing the vulnerability of coastal transportation facilities to extreme events and climate change…" with a focus on "quantifying exposure to sea level rise, storm surge, and wave action" (U.S. Department of Transportation Federal Highway Administration, 2014, p. 1). Vulnerability assessments range from high level planning overviews to very detailed engineering level studies, due to the varying expertise and financial resources available. Recognizing this range, chapter 4 of the circular recommends a framework for conducting vulnerability assessments based on level of effort, expertise, and resources. The framework includes three levels of effort; for which the detail and level of complexity increases with each level:

- Level of Effort 1: Use of Existing Data and Resources – Use established inundation or hazard maps to determine the exposure of infrastructure under various sea level change scenarios. Lowest level of effort, simplest approach.
- Level of Effort 2: Original Modeling of Storm Surge and Waves –Model storm surge and wave fields for region-specific extreme events and climate change scenarios. Middle level of effort (more effort than Level 1, less effort than Level 2).
- Level of Effort 3: Modeling in a Probabilistic Risk Framework – Model storm surge, sea level, currents, and waves, accounting for the effects of climate change, in a probabilistic risk framework. Highest level of effort, most complex approach.

The Level 1 approach is intended as a screening tool to identify areas or infrastructure exposed to inundation from sea level rise. Areas can then be assessed in more detail with refined analysis or included in a Level 2 or 3 approaches. Existing data for Level 1 analyses include FEMA flood rate insurance maps (FIRMs) and the corresponding Flood Insurance Studies (FIS), which quantify rare/ extreme flood events (i.e. 100-year and 500-year floods).

The Level 2 approach is meant to provide more detailed information about infrastructure exposure from extreme events under scenarios of climate change. This approach attempts to determine the climate impacts on coastal systems by incorporating climate change scenarios into model simulations. Simulations involve one or two carefully selected events, such as a specific historic hurricane or storm that caused significant damage to an asset (i.e. – bridge failure), or a synthetic storm, which is based on a historic storm but with some modifications (i.e. shifting the storm track). The models are first run for validation of the historic storm (hindcast simulations) and then run under various climate change scenarios for comparison of results. These model results are not generally probabilistic in nature. The use of hydrodynamic models that simulate storm surge and waves are required for conducting a Level 2 approach. The ADvanced CIRCulation Model (ADCIRC) is commonly used in the Gulf and South Atlantic regions for modeling surge from tropical storms and hurricanes.

The Level 3 approach defines exposure in terms of probability and risk. The modeling approach is similar to the Level 2 approach, but is more robust and requires many more model simulations (dozens to hundreds) to be run to determine the probability of certain events. This level follows a probabilistic approach similar to how FEMA develops their FIRMs. Level 3 is the highest level of effort, requiring expertise in coastal engineering, numerical modeling, hazard analysis, probability and risk. FHWA notes that “the level of effort, time, and cost to perform such a large number of model simulations may be prohibitive” (U.S. Department of Transportation Federal Highway Administration, 2014, p. 68).

FHWA’s Framework outlines sound guidance for assessing transportation vulnerabilities to extreme events and climate change. The tiered, level of effort approach offers a gradient of modeling approaches based on the geographic region, scale of analysis, technical expertise, and resources available (time, funding). Furthermore, subsequent levels of effort can be leveraged; for example, assets identified as exposed in Level 1 could be targeted for more detailed assessment in Level 2.

Storm Surge Models

Following here is a brief description of common models used for estimation of storm surge, coastal flood risk, and waves.

ADCIRC – The ADvanced CIRCulation Model

Developed by the University of North Carolina at Chapel Hill, the University of Texas at Austin, and the Computational Hydraulics Laboratory at Notre Dame, ADCIRC is “a system of computer programs for solving time dependent, free surface circulation and transport problems in two and three dimensions” (University of North Carolina). ADCIRC is widely used by various federal agencies for prediction of storm surge and flooding, modeling tides and wind driven circulation, and risk and vulnerability assessments of coastal infrastructure.

Example applications of ADCIRC and the federal agency utilizing include:

- Assessing coastal currents and water surface elevations (USACE)
- Design of flood risk mitigation systems (USACE)
- Coastal flood assessments (USACE)
- Evaluation of hurricane flood risk along U.S. East and Gulf Coasts (FEMA)
- Forecasting of tides, extra-tropical storms, and tropic storms (NOAA)

ADCIRC is a high level and computationally intensive software. It requires several data inputs such as bathymetry, topography, boundary information, tidal characteristics, nodal attributes, river inflow, meteorological forcing input, and wave radiation stress forcing, and others based on geography. ADCIRC code is freely available to academic, government, and not-for-profit uses. A license is required for commercial use. The official ADCIRC website: http://adcirc.org/

SWAN – Simulating WAves Nearshore

Developed at Delft University of Technology, SWAN is a third-generation wave model that generates wind-driven waves and accounts for nearshore wave behavior such as wave breaking and wave setup. The SWAN software is freely distributed under the GNU General Public License. The publicly available SWAN and SLOSH models are used in the Hazus-MH Coastal Storm Surge Model to estimate storm tide and coastal wave heights produced by a single hurricane event. The SWAN model has also been coupled directly with ADCIRC to simulate waves and surge from hurricanes. "Within the directly coupled model, the SWAN component develops the offshore and nearshore waves, and the ADCIRC component develops the hydrodynamics and storm surge" (Bender, et al 2012). Delft University SWAN information page: http://www.swan.tudelft.nl/

CoSMoS – Coastal Storm Modeling System

CoSMoS is a physics-based numerical modeling system for assessing coastal hazards on the West Coast. It was originally set up as part of the USGS Southern California Coastal Hazards Project. It predicts coastal hazards for the full range of sea-level rise and storm possibilities using global climate and ocean modeling tools (California Ocean Protection Council, 2012). Applications include climate impacts assessments; coastal impacts for range of possible current and future conditions (SLR and storms), assessing infrastructure and ecosystem vulnerability, and integration into Web-based coastal planning applications. There is publicly available data and access to support the model as well as active scientific development. For more information on CoSMoS, see: https://walrus.wr.usgs.gov/coastal_processes/cosmos/

SLOSH - Sea, Lake, and Overland Surges from Hurricanes

The National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) developed the SLOSH model to conduct risk assessments of coastal flooding from storm surges. SLOSH is a numerical model that estimates storm surge heights from historical, hypothetical, or predicted hurricanes using parameters of atmospheric pressure, size, forward speed, and track data. The SLOSH model is run by region, called basins, which are geographically centered on areas vulnerable to storm surge (inlets, ports, areas with large coastal populations, and low elevation areas). The basins are comprised of grid cells. There are 32 basins covering the entire coastlines of the U.S. Atlantic and Gulf of Mexico, as well as Hawaii, Puerto Rico, Virgin Islands, and the Bahamas.

SLOSH models outputs, Storm Surge Maximum Envelope of Water (MEOW) and Storm Surge Maximum of the Maximum Envelope of High Water (MOM), are used for hurricane evacuation planning by determining the potential storm surge for a location. The MEOW is not storm specific, but represents a worst case surge scenario for a hypothetical storm with the same storm parameters (category, forward speed, storm trajectory, and initial tide level). The MEOW output is a compilation of multiple, parallel SLOSH model runs with the same parameters (as above) but with a storm track that is to the left or right of the main track. The MEOWs are calculated when a basin is developed or updated. The MOM output is a compilation of maximum storm surge heights for all hurricanes of a particular category, regardless of the storm parameters (category, forward speed, storm trajectory, and initial tide level). MOMs are developed by first gathering all MEOWS for a particular basin and separating them by category and tide level. Then for each basin grid cell, the MEOW with the highest storm surge value is selected. The MOMs are also not storm specific and are calculated when a basin is developed or updated. Both the MOMs and MEOWs estimate the worst case scenario of storm surge for a particular location and NOAA/ NWS is very clear that no single storm will produce the regional flooding shown in the MEOWs or MOMs. However, these outputs are very important in hurricane evacuation planning.

As part of Florida's Statewide Evacuation Study Program, the Regional Planning Councils in Florida have been developing directional atlases. These maps use SLOSH output data to create a clustered MEOW, also called a Direction of Maximums (DOMs). "Each DOM is a cluster of MEOWs in a generalized direction retaining the aggregated maximum SLOSH values from those individual compass directions and all forward speeds" (West Florida Regional Planning Council, 2015, p.7). For each region, emergency management staff determined the MEOW clusters to be analyzed, based on which clusters were representative of likely storm behavior in each geographic region.

For more information on SLOSH, see NOAA/ NWS website:
http://www.nhc.noaa.gov/surge/slosh.php

Hazus-MH - Multi-Hazard Loss Estimation Methodology

The Multi-Hazard Loss Estimation Methodology (Hazus-MH) is a standardized methodology created by the Federal Emergency Management Administration (FEMA) "to estimate potential losses from earthquakes, hurricane winds, and floods"[5]. Hazus-MH contains multiple models for estimating losses from various hazards; for example the Earthquake Model, the Flood Model, and the Hurricane Model. The Flood Model is used to estimate riverine and coastal flood hazards and potential damage to buildings, infrastructure, and land use. Also contained within the Flood Model

[5] The Multi-Hazard Loss Estimation Methodology Flood Mod Developed by: Department of Homeland Security Federal Emergency Management Agency Mitigation Division Washington, D.C. el User Manual, 2013. (DHS FEMA 2013) http://www.fema.gov/media-library-data/20130726-1820-25045-8814/hzmh2_1_fl_um.pdf

is an option to combine the flood hazard and hurricane to produce hurricane-induced coastal surge. The Hazus-MH Hurricane Wind Model is used to estimate hurricane winds and potential damage to buildings for the Atlantic and Gulf Coast regions and Hawaii. FEMA's Hazus-MH website: https://www.fema.gov/hazus

For this task, Hazus-MH and SLOSH were chosen to test and develop a proof of concept. First, these models do not require expert knowledge of coastal or environmental engineering, but do require some basic knowledge of coastal systems and dynamics. These models also offer planning-level analyses which are appropriate at the regional scale. Computationally, these models are not as intensive or time consuming as the more complex models. These models were more accessible given the level of expertise in house and the level of effort to conduct model runs.

Updated FEMA Federal Flood Risk Management Standard, 2015

One primary goal of the President's 2013 Climate Action Plan was to prepare the Nation for the impacts of climate change by increasing the resiliency of community infrastructure. To protect federal infrastructure investments from future flood risks, the Plan called for the federal government to "update their flood-risk reduction standards for federally funded projects to reflect a consistent approach that accounts for sea-level rise and other factors affecting flood risks" (Executive Office of the President (2013). Executive Order 13690 issued on January 30, 2015, established a new FEMA Federal Flood Risk Management Standard that calls for a higher flood standard for federally funded structures and facilities built or retrofit near floodplains in an effort to increase resiliency of these structures, protect public investments, and decrease taxpayer burdens from flood damage. The new standard outlines three methods for achieving the higher flood standard when building facilities: (1) the use of data and methods informed by the best-available, actionable climate science; (2) building two feet above the 100-year (1% annual chance) flood elevation for standard projects and three feet above for critical infrastructure; or (3) building to the 500-year (0.2% annual chance) flood elevation. These updated guidelines offer definitive and replicable methods for estimating future flood risk, and should be incorporated into the SLS Sketch Planning Tool.

Estimating Future Flood Risks: New York City Panel on Climate Change

In 2008, Mayor Bloomberg convened the first New York City Panel on Climate Change (NPCC1), a group of climate scientists, social scientists, and risk management professionals, to advise the Mayor on climate change and adaptation issues. The second panel (NPCC2) was convened in January 2013 after Hurricane Sandy and charged with providing the most current scientific information and analyses regarding climate risks (New York City Panel on Climate Change, 2013). These risk data were utilized in *A Stronger, More Resilient New York* (The City of New York, 2013), New York City's comprehensive plan for rebuilding with increased resiliency. The latest NPCC report was released in 2015 and includes the NPCC's work from January 2013 to January 2015. The NPCC continues to analyze the latest climate trends and projections for the New York region and provide recommendations for increasing infrastructure resiliency to climate risks. The 2015 NPCC report developed new maps of flood risks due to climate change, and provides a comparison of static versus dynamic modeling of future coastal flooding. This important case study offers a good comparison between resource intensive dynamic modeling and less intensive static modeling.

Since the late 1970s, coastal flood studies have been used to assist in the determination of federal flood hazard insurance. "These studies consist of a comprehensive examination of the region's storm climate, combined with numerical modeling to convert storm climatology to statistical measures of storm surge elevations" (Federal Emergency Management Agency, 2014). The studies incorporate information on tropical storms (hurricanes) and extratropical storms (nor'easters and blizzards) to develop the flood zones and elevations for the 100-year and 500-year floods (Orton et al., 2015, p. 58).

Static Modeling

For mapping future floodplains, the NPCC used a "static" method in 2010, 2013, and 2015 which involved adding SLR projections to the base flood elevations (BFEs) for 100-year and 500-year storms to represent future BFEs. FEMA defines the base flood elevation as the "computed elevation to which floodwater is anticipated to rise during the base flood"[6] (100-year flood). After adding SLR projections, future BFEs were then mapped landward to include the new elevations, with the requirement that the elevations must be connected to open water. SLR projections were based on ranges or percentiles of the distribution of model-based outcomes. Three ranges of SLR estimates were used: the low-estimate of SLR representing the 10th percentile, the middle range representing the 25th to 75th percentile, and the high-estimate representing the 90th percentile. For the area mapped, the middle range SLR projection is 4-8 inches and the high estimate is 11 inches by 2020s. NPCC1 maps used the FEMA flood elevations from the 2007 Flood Rate Insurance Maps (FIRMs), while the NPCC2 maps used updated flood elevations from the 2014 coastal storm surge study and resulting Preliminary FEMA FIRMS.

Dynamic Modeling

In 2015, the NPCC also utilized dynamic (or "hydrodynamic") models to map future floodplains and to compare results against the static maps. "Dynamic flood modeling is a physics-based computer simulation technique that includes the effects of factors such as wind, atmospheric pressure, and friction in the calculation of flood elevations (this technique is also known as hydrodynamic modeling)" (Orton et al., 2015, p. 58). FEMA's 2014 coastal storm surge study featured a dynamic modeling approach, using the ADCIRC (Advanced CIRculation)/ SWAN (Simulating Waves Nearshore) model to run storm-surge simulations (Federal Emergency Management Agency, 2014). The NPCC dynamic modeling effort followed the FEMA approach, which included the 30 strongest historical extratropical cyclones over a 50 year period, and 159 synthetic tropical cyclones; synthetic storms were used because tropical cyclones are not common in the region floods (Orton et al., 2015, p. 59). The NPCC first conducted baseline assessments of storm surge without factors of SLR included, and then repeated the modeling with the addition of NPCC2 SLR projections. The dynamic modeling approach targeted higher risk SLR scenarios, using the 90th percentile SLR projections for the time periods 2020s, 2050s, and 2080s (11, 31, and 58 inches of SLR, respectively).

[6] Definition taken from FEMA's website: http://www.fema.gov/base-flood-elevation

Three geographic areas in the study region were highlighted and utilized for conveying and comparing results. Flood exceedance curves, 100-year and 500-year still water elevations, and mapped 100-year flood zones were compared across the three sites for the three time periods analyzed. The results of the static and dynamic methods of the mapped 100-year flood zones at 2050 showed very similar results. In many instances, the differences were merely plus or minus a few inches. When comparing the calculated Stillwater elevations (SWE) of the dynamic versus the static modeling methods at the three highlighted sites, the differences were not the same at each highlighted site. One site showed the dynamic SWE just below the static; another site showed the dynamic SWE equal to or a few inches higher to the static; and the third showed a greater variation - with dynamic SWE greater than 6 inches above the static.

Overall, the static and dynamic methods for mapping future flood risks under SLR scenarios yielded results within +- 6 inches in most locations. The NPCC study concluded that "therefore, the flood zone boundaries produced from these two methods are very similar" (Orton et al., 2015, p. 65). The results of also showed that the static methods are not necessarily the more conservative approach; i.e. they do not always over-estimate the impacts of SLR on flood heights as might be expected with a less refined modeling approach. The NPCC recommends the use of both static and dynamic methods, where funding is available. Funding, however, can be an obstacle with dynamic modeling, which is more time and computer intensive and requires more technical expertise. The NPCC report also noted that "despite its limitations…the static approach is a useful tool for planners and stakeholders and can be used to inform decisions on infrastructure investments and land use policy" (Leslie et al., 2015, p.48). The static method, which is simpler, less time and computer-intensive, can be a more accessible and quicker way to start assessing future flood risk without sacrificing accuracy.

Storm Surge Model Tests

This section discusses the storm surge test runs conducted by the GeoPlan Center in an effort to create a proof of concept for modeling sea level rise impacts to storm surge. Hillsborough County was used as the test study area. The modeling discussed in this section was completed by Dr. Paul Zwick, Professor of Urban & Regional Planning at the University of Florida, former director of the GeoPlan Center, and a Hazus-MH Trained Professional.

Flooding is the most common result of storm surge. Weather events that cause storm surge are typically organized cyclonic systems that include high winds and low-level circulation. In the United States, depending on maximum sustained winds, many of these systems are called t*ropical depressions*, *tropical storms*, or *hurricanes*. Even storms that do not meet the wind thresholds of these named systems can pose a threat of flooding and storm surge.

Models Test Runs

This task looked at a number of ways to first model sea-level rise (SLR) impacts to storm surge using Hazus-MH and SLOSH, and then to compare results between the two models. The use of Hazus-MH Coastal Flood Hazard Model was run for probabilistic storm surge modeling and the Coastal Surge Model was used for modeling historic storm surge using SLOSH inside of Hazus-MH.

It should be noted that this research was limited in scope, and more research remains for SLR modeling of storm surge with the Hazus-MH Coastal Surge Model.

Hazus-MH Coastal Flood Hazard Model

The Coastal Flood Hazards component of the Hazus-MH Flood Model was used to analyze the impact of a baseline 100-year storm surge for three scenarios in Hillsborough County, Florida: (1) the base 100-year storm surge; (2) the change in the base 100-year storm surge resulting from a one-half meter sea level rise (SLR); and (3) the change in the base 100-year storm surge resulting from a one-meter sea level rise. In these scenarios, SLR amounts are added to the Stillwater Elevation (SWEL), or the water level of a 100-year storm event not including wave effects. The goal is to analyze the impacts of the base storm 100-year surge on existing development and to understand the implications for storm surge along Florida's coastal areas as a result of an increase in mean sea level because of SLR.

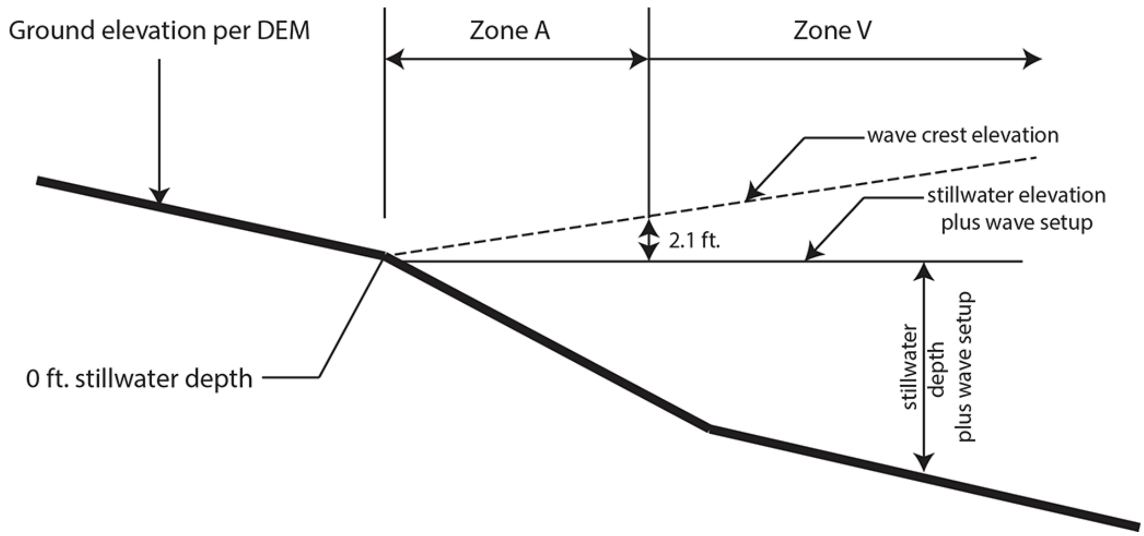
The Hazus-MH Coastal Flood Hazards model follows FEMA's methodology for developing the Flood Insurance Rate Maps (FIRMs), where flood frequency and flood magnitude (or depth) are used to define flood hazard. The model analyzes storm surge as shown in Figure 17. Hazus-MH relies on the 100-year SWEL and Stillwater depth (SWD) to identify the inland impacts of storm surge using transects perpendicular to the coastline and a digital elevation model. SWD is the depth difference between the 100-year SWEL and the ground elevation. Hazus-MH calculates storm surge wave setup as the Flood Insurance Study 100-year SWD with wave setup. The wave crest elevation is determined by Hazus to be one-half the SWD plus wave setup and is added to the SWD to account for wave height as the storm surge moves inland from the coastline (see Figure 17). For example, a base 100-year SWD plus wave setup of 9 feet has a wave crest height of 4.5 feet for a storm surge depth of 13.5 feet. The SWD plus wave setup decreases as the storm surge moves inland and the base land elevation increase the wave crest also decrease. An estimated wave crest greater than 2.1 feet defines Zone "V" the location of maximum wave impact. Less than 2.1 feet of wave crest is Zone "A".

The following methodology was employed to investigate the impacts of increasing SLR on storm surge, using the Hazus-MH Coastal Flood Hazards Model:

1. From the county FEMA Flood Insurance Study, obtain the 100-year Stillwater Elevation (SWEL).
2. Utilizing the Digital Elevation Model compiled by the GeoPlan Center and Hazus-MH Level 1 analysis, run the base storm surge model to create scenarios for:
    a. The 100-year probabilistic storm for the SWEL;
    b. The 100-year probabilistic storm for the SWEL plus a ½ meter SLR;
    c. The 100-year probabilistic storm for the SWEL plus a 1 meter SLR.
3. Remove any spurious polygons that are disconnected from the storm surge boundaries.
4. Run the loss analysis for the three previous scenarios.
5. Generate the summary output reports for the three previous scenarios.
6. Clip the 2014 property parcel data to the scenario storm surge flood boundaries.

7. Using the three property parcel datasets for the scenarios summarize the flood statistics per parcel.

Figure 17. Hazus-MH storm surge model. Source: Hazus Hurricane Flood User Manual, Page 4-98.



This methodology is similar to the NPCC's static methods for mapping future floodplains. The main difference is that in the Hazus method, the amount of SLR is added to the SWEL; in the NPCC's method, the amount of SLR is added to the BFE. The difference is in how wave effects are calculated. The BFE includes wave effects (wave setup and wave height). The SWEL does not include wave effects. In the Hazus methods, the wave crest elevation is one-half the SWD plus wave setup. A follow-up to these test runs could include a comparison of the outputs when adding SLR to the SWEL versus the BFE.

Hazus-MH Coastal Surge Model (using SLOSH)

The Hazus-MH Coastal Surge Model combines storm surge and wave hazard modeling using SLOSH for storm surge and SWAN for wave heights. Previously, wind and flooding damage estimates were only available separately, in the Hurricane Wind and Flood Models. This more recent Hazus model combines the wind and flood losses into an overall estimate for a single hurricane event. Since SLOSH does not include waves or tide, SWAN can be used to optionally model waves inside Hazus.

For this task, two model runs were conducted using the Hazus-MH Coastal Surge Model:

1. Base storm surge for the 100-year event.
2. 1921 Unnamed Historic Storm that struck Northern Pinellas and Hillsborough Counties, Florida.
    a. First, used Hazus-MH Hurricane Wind Model to generate wind field for historic Unnamed 1921 storm.
    b. Then used output of Hurricane Wind as an input for SLOSH model to estimate wind-drive storm surge over land.

The results of the base storm surge for the 100-year event are shown in Figure 20. The results of the combined wind and storm surge estimates for the historic Unnamed 1921 Storm are show in Figures 21 & 22.

Model Outputs & Results

GIS data outputs for the Hazus-MH Flood Model with and without SLR included:

- A storm surge polygon area defining the extent of storm surge for the 100-year probabilistic storm for the SWEL;
- A storm surge polygon area defining the extent of storm surge for the 100-year probabilistic storm for the SWEL plus a ½ meter SLR;
- A storm surge polygon area defining the extent of storm surge for the 100-year probabilistic storm for the SWEL plus a 1 meter SLR.

GIS data outputs for the Hazus-MH Coastal Surge Model:

- A storm surge polygon area defining the extent of storm surge using for the Unnamed 1921 storm that struck Northern Pinellas and Hillsborough Counties, Florida.
- A storm surge polygon area defining the extent of storm surge for the 100-year base storm event.

Additional outputs summarizing damage estimates were generated from the Hazus model runs of the 100-year probabilistic storm surge. However, due to the long lengths of these documents, they are not included in this report. They are available upon request:

- The base Summary Information Reports created by Hazus-MH using Census Block Data Aggregation.
- Individual parcel summary statistics for minimum, maximum, mean, and standard deviation storm surge depth. These statistics were gathered for individual property parcels within the storm surge polygonal area using the 2014 Hillsborough County Property Appraiser GIS data as gathered from the FGDL data. (Not included in this report because of the length; available on request).

The following pages present selected results from the modelling completed for this study. Figure 18 is a graphic of the DEM, the Coastline, and transects used for the three models. Figure 19 is a graphic of the three storm surge events place to indicate the difference in storm surge inundation as the SLR increase from no SLR to ½ meter and then to 1-meter.

Figure 18. Base Map Depicting Coastline, Hazus Transects (red lines), Interstates (yellow lines), and DEM (multi-colored basemap).

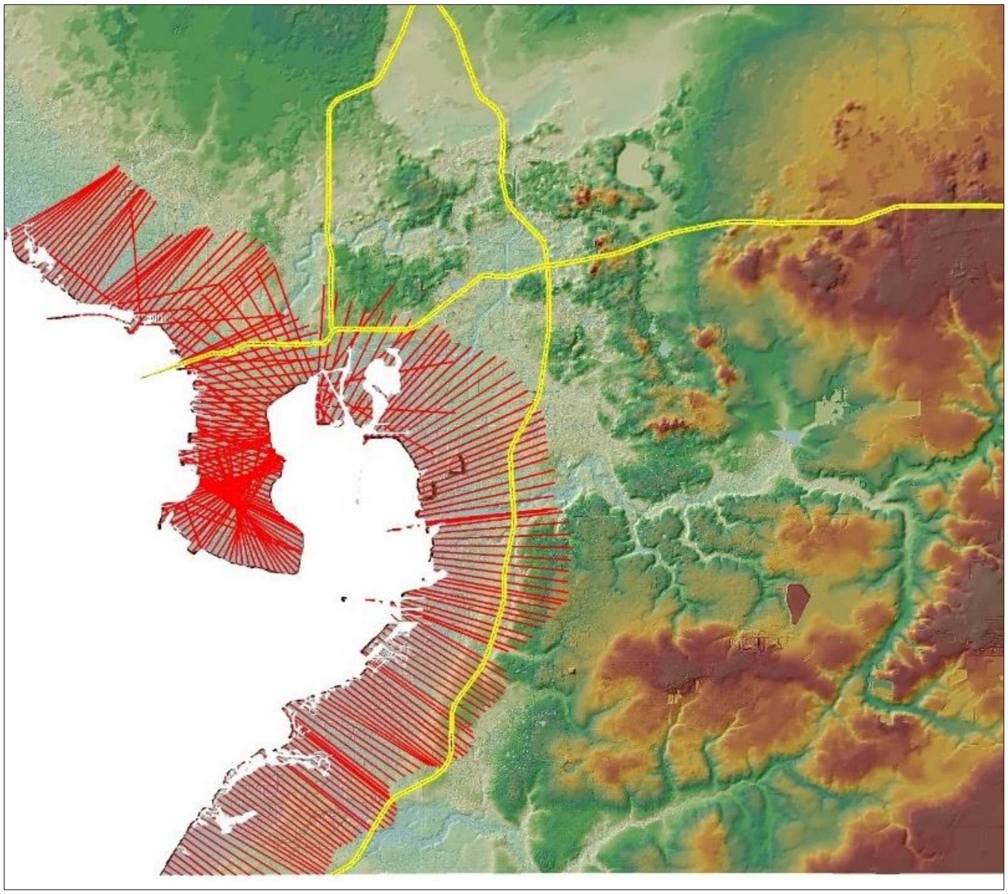


Figure 19. Three storm surge events (100-year base storm surge dark purple, 100-year half-meter storm surge light purple, and 100-year full meter storm surge light blue).

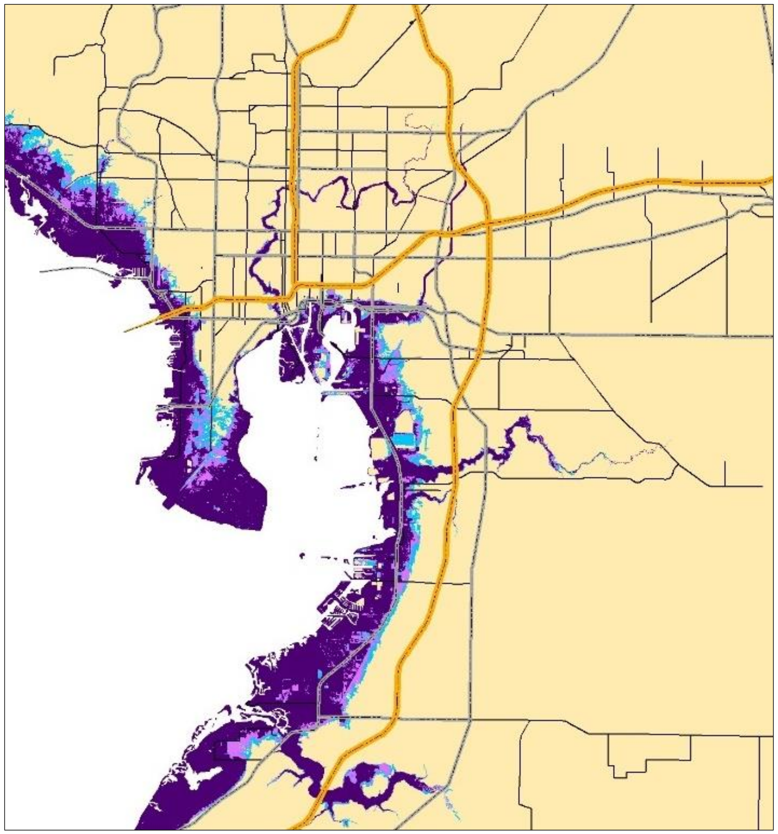
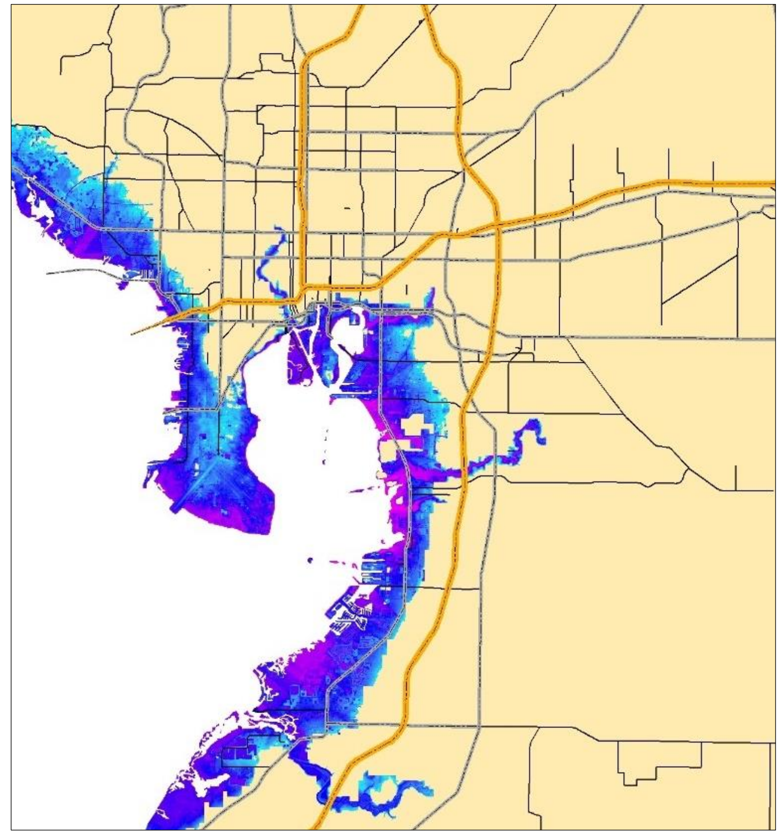


Figure 20. The Hazus-MH SLOSH Model 100-year base storm surge model. Deepest flooding from purple to light blue.



One interesting impact of the Hazus-MH SLOSH model implementation is that the 1921 storm would produce an equivalent storm surge when compared with the probabilistic Hazus-MH storm surge including a full-meter SLR. Therefore taking into account the winds generated by the storm dramatically increases the Hazus-MH storm surge impacts. This is not unexpected and possibly indicates that the most preferred Hazus-MH storm surge model should be the Hazus-MH SLOSH implementation.

Figure 21. The 1921 Historic base storm surge inundation area (in red), run using the SLOSH model as part of the Hazus-MH Coastal Surge Model.

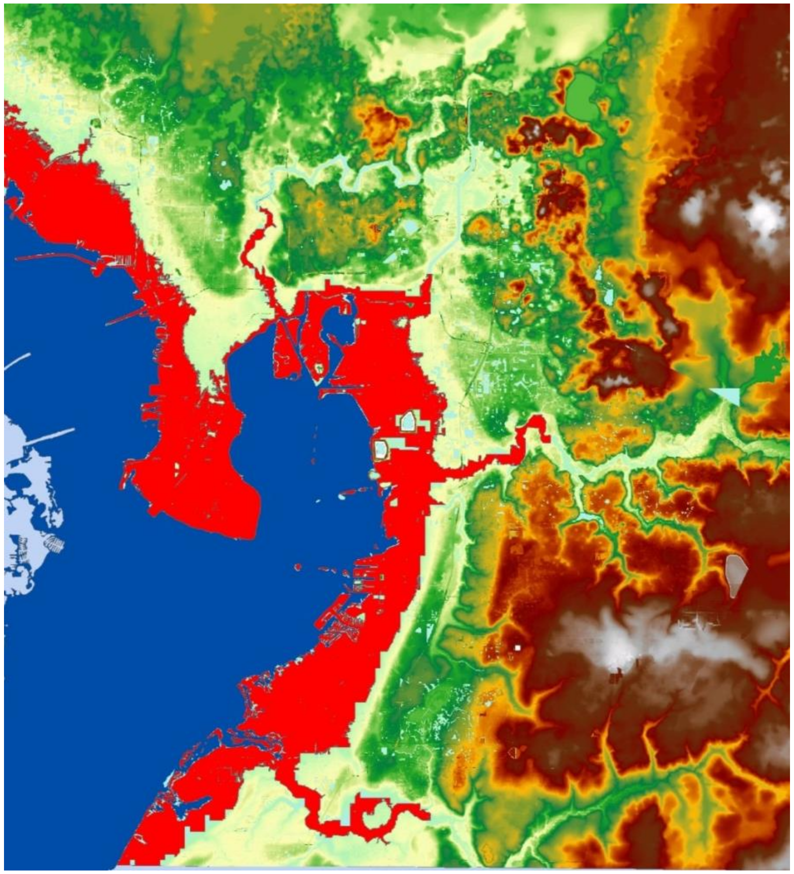
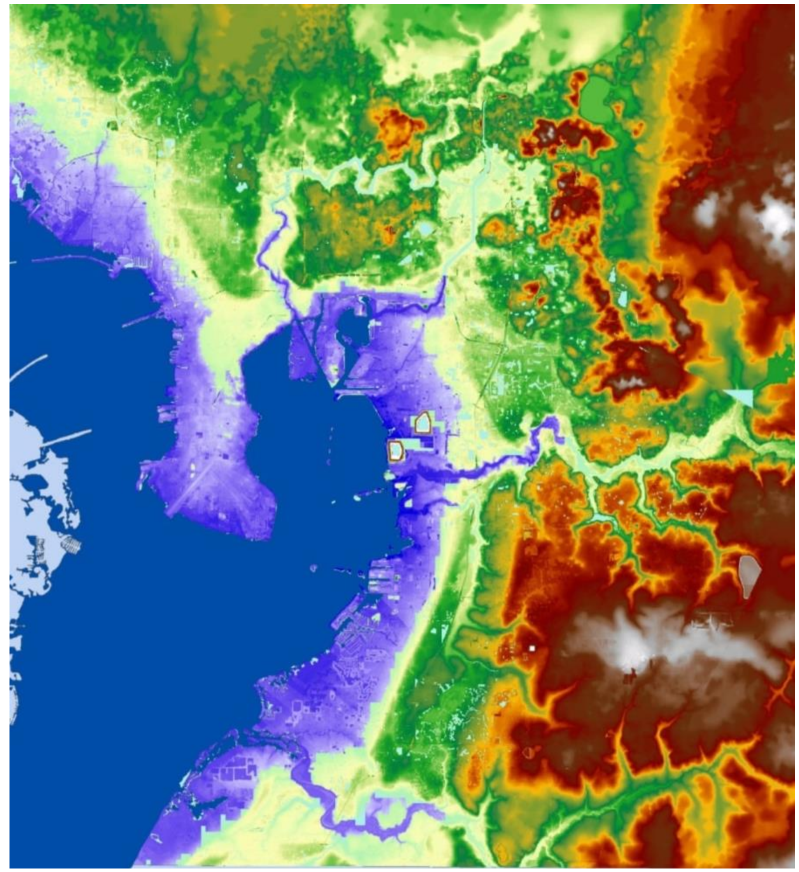


Figure 22.Inundation depths for the 1921 base storm surge. The depths range from a maximum of 23.15 feet (purple near the coastline) to zero feet (yellow)



Future Recommendations for Storm Surge Modeling:

The most interesting and perhaps the most productive model is the Hazus-MH combined wind and surge with the SLOSH model. Based on the model runs, the following steps are recommended for future study. First, continue to run the base probabilistic storm in Hazus-MH using Coastal Flood Hazard model. This type of model identifies a base storm surge area and delineates impacts within the base area. Knowing the base storm surge impact helps to set a reference for comparison of SLR impacts when added to storm surge impacts. Next, continue to run the probabilistic storm surge with SLR added to Stillwater elevation using Hazus-MH using Coastal Flood Hazard model. This type of model begins to estimate future flood hazard areas.

Additionally, run the base storm surge model for a known historic storm surge using the Hazus-MH implementation of SLOSH. Modeling a known storm allows for testing the accuracy of the model against known data from the storm and provides information about the models capabilities while spatially identifying the model inundation errors. One example would be to model Hurricane Charley's impact on the South Florida Gulf Coast. If the Hazus-MH SLOSH implementation predicts the impacts of Hurricane Charley reasonably well, then we could move the storm to other counties along the gulf coast and model the impacts of this known storm on those Gulf Coast counties. Additionally, if the Hazus-MH implementation of SLOSH provides reliable outputs, then SLR models can be run in combination with the known storm impacts.

Finally, the spatial combination of all models (probabilistic and historic/ known storm impacts) for a county will provide for the identification of depth and inundation area while also identifying how many models have produced storm surge impacts for each location. If all models indicate a location is flooded then the area is clearly indicated as having a high potential for storm surge and storm surge with SLR included. Furthermore, the development of minimum storm surge and storm surge with SLR inundation depths for individual parcels is important for transportation analysis. If the parcels served by the road are flooded as a result of SLR or SLR and storm surge then there may be no need to maintain a road that serves no population.

Summary & Conclusions for Task 4

The ability to assess infrastructure vulnerabilities from multiple inundation risks can improve infrastructure resiliency and protect public investments. However, estimating the effects of sea level rise on storm surge and flood hazard areas is a complex issue; with no one size fits all solution for modeling these effects. FHWA's Framework outlines sound guidance in this area. The FHWA tiered, level of effort approach offers a gradient of modeling approaches based on the geographic region, scale of analysis, technical expertise, and resources available (time, funding).

Below are suggested steps that can be taken to model storm surge and coastal flooding, along with topic areas of continued research:

- For estimating coastal flood hazard areas, investigate a tiered approach (the first step is the simplest approach, followed by progressively more complex approaches):
    1. Use the current, best available FEMA 100-year floodplain maps to assess Florida transportation *currently* exposed to coastal flooding. The Digital Flood Rate Insurance Maps (DFIRMs) have been updated for most counties in Florida; hence this data is readily available.
    2. Use the current, best available FEMA 500-year floodplain maps to assess Florida transportation facilities exposed to *future* flood risk. Under the new FEMA flood risk standards, the 500-year floodplains are used as a proxy for future flood risk, based on research that concludes rising sea levels will increase storm surge flood depths and the frequency of coastal flooding. The Digital Flood Rate Insurance Maps (DFIRMs) have been updated for most counties in Florida; hence this data is readily available.
    3. Further investigate the NPCC static method for mapping future floodplains and use a pilot area to test the methods. While this data is not readily available and must be developed, the methods offer a relatively quick way to assess future flood risk. Though not as refined as the dynamic method, the NPCC found that the static method produced very similar results to the dynamic method. Ultimately, the static method is a worthwhile approach for informing infrastructure investments and land use policy decisions.
    4. Further evaluate the Hazus-MH Coastal Flood Hazard model to run 100-year probabilistic storms with addition of SLR to the Stillwater Elevation (SWEL). Compare outputs to NPCC methods to evaluate difference between adding increments of SLR on top of SWELs versus Base Flood Elevations (BFEs).
    5. For individual infrastructure projects with a long expected lifespan, investigate the use of hydrodynamic modeling with qualified coastal engineers.
- For modeling coastal storm surge with the effects of sea level rise, the following approach should be investigated further:

1. Use the current, best available SLOSH model outputs (MOMs - Maximum of Maximums), to assess Florida transportation infrastructure *currently* exposed to flooding from storm surge. This data is readily available.
2. Investigate the use of the Hazus-MH Coastal Surge Model to run historic storms with the addition of SLR. Instead of using the SLOSH MOMs, which overestimates the storm risk, historic storms could be utilized to represent a more realistic surge risk. Shifting of the storm track could be investigated if resources are available. These methods should be investigated for a pilot area.

A large body of research is emerging on this topic. The GeoPlan team should continue to monitor and stay abreast of current research is this area to understand and adopt the most appropriate approaches and best practices, considering financial and temporal constraints, as well as planning context and scale. Additionally, model results and data products from other studies should be investigated for incorporation into the SLS Sketch Planning Tool.

Task 5 – Web Support and Training Materials

In this task the UF GeoPlan Center maintained and updated the project website with relevant information. In addition, the GeoPlan Center developed some basic training materials for the SLS Sketch Planning Tool. The training materials are intended to guide users in how to use the SLS Sketch Planning Tool to identify potential areas of inundation and affected infrastructure, and create reports. The following section describes the training materials created and/or updated for this task. All materials are available on the Documents & Links page of the website: http://sls.geoplan.ufl.edu/documents-links/

Quick Start Guide for the Sea Level Scenario Sketch Planning Tool

This short document is an introduction to the data and tools available in the SLS Sketch Planning Tool. It is intended to guide and inform interested users on how the SLS Sketch Planning Tool can be used for assessing transportation infrastructure at risk to sea level rise. The guide also communicates how the SLS Sketch Planning Tool should not be used. This six page guide includes Frequently Asked Questions and essential background information and methods detailed in the Phase 1 Technical Report.

The Quick Start Guide is available from the Tools & Documents page of the website, or directly from the following link:
ftp://ftp.sls.geoplan.ufl.edu/pub/sls/docs/SLS_Sketch_Planning_Tool_Quick_Start.pdf

Map Viewer User Guide

The Map Viewer User Guide for the SLS Sketch Planning Tool is a detailed guide to step users through how to use the Map Viewers. This 15-page guide first provides an overview of the SLS Sketch Planning Tool and methods used to create the data and tools. The guide then walks through how to access the Map Viewers and each of its components. The guide explicitly describes the functionality of each map “widget” (tool) with screenshots of the Map Viewer.

The Map Viewer User Guide is available from the Tools & Documents page and the View Maps page of the website; or directly from the following link:
ftp://ftp.sls.geoplan.ufl.edu/pub/sls/docs/SLS_Map_Viewer_User_Guide_2015.pdf

SLR Inundation Surface Calculator User Guide

The SLR Inundation Surface Calculator User Guide is a detailed guide on how to install and run the calculator add-in for ArcMap. It includes software requirements, installation instructions, data inputs included in the calculator, a description of the data output options, and explicit details on the calculator parameters. It also includes a “What’s New” section describing the changes since the prior release of the calculator.

The SLR Calculator Guide is available from the Tools & Documents page of the website, or directly from the following link:
ftp://ftp.sls.geoplan.ufl.edu/pub/sls/docs/SLR_Calculator_Guide_v1_5_2.pdf

Recording of Webinar Presentation

A presentation about the SLS Sketch Planning Tool, with a demonstration of the map viewer was given for the Southeast Florida Regional Climate Compact Regional Climate Action Plan (RCAP) Transportation Workshop, April 30, 2015.

The recording is available from the Tools & Documentation page on the website, and online at: https://vimeo.com/128157344

Conclusion

This phase of work on the Sea Level Scenario Sketch Planning Tool involved testing and enhancement of the tool to increase its use at the MPO or local scale and to increase its efficacy as a planning level screening tool. Work included efforts to enhance data inputs to the tool, partnership with FHWA Climate Resiliency Adaptation Pilots to test the tools, map viewer and tool improvements, research and testing of storm surge and flooding models, and update of documentation and supporting materials for the tool.

Phase 2 proved to be a valuable learning experience on multiple levels. Partnership with two FHWA Climate Resiliency Adaptation Pilots and other communities allowed for testing of the SLS Sketch Planning Tool in a real-world application at the MPO scale. These testing opportunities provided technical feedback on data gaps and needs and features that would be helpful in facilitating their risk assessment process. Working with the pilots and other communities also showed the demand for data to assess inundation risks from storm surge and coastal flooding, in addition to sea level rise. Where possible, data issues were addressed and specific characteristics of the SLS Sketch Planning Tool were enhanced or targeted for improvement. Several proofs of concepts were developed for addressing bridge data elevations, higher resolution digital elevation models for finer scale analyses, and modeling of coastal flood hazard areas. To the extent possible, feedback from the FHWA pilots and other communities have been utilized for prioritizing enhancements to the SLS Sketch Planning Tool. If further addressed in future phases of work, the feedback regarding data gaps, functionality enhancements, and usability improvements will continue to strengthen the Tool's efficacy as an assessment and decision support tool.

Additional work in Phase 2 included numerous presentations, webinars, and opportunities for others to learn about the tool. These outreach activities and the testing of the SLS Sketch Planning Tool demonstrated the need for planning level tools and data to assess inundation risks and incorporate this information into the planning process to increase resiliency of community infrastructure and protect public investments. Communities, planners, researchers, and others are highly interested in assessing the impacts of climate risks on their transportation and community infrastructure, and many are ready to move forward with assessments. Positive feedback was received during the outreach activities. The ability to view scenarios of sea level rise for various time periods and to download data for further analysis is helpful for facilitating assessments of at-risk facilities.

While the available functionality in the SLS Sketch Planning Tool is useful, addition work remains to maintain its relevancy and increase its utility. First, the GIS data layers in the tool need to be updated. The inundation layers should be corrected with the updated bridge elevation data and the analysis of at-risk infrastructure should be re-analyzed with the most current versions of the GIS infrastructure layers. Additionally, current and future coastal flood hazard areas need to be incorporated. For estimating future flood hazard areas, the approaches from the NPCC ("static method") and the use of the Hazus-MH Coastal Flood Hazard Model should be further developed and results compared. Incorporation of future storm surge risk (accounting for the effects of sea level rise) is a more complex topic that needs further investigation. While dynamic models like

ADCIRC and SWAN appear to offer the most robust analyses for modeling storm surge and SLR, they are too time and computationally intensive for planning level analyses. The most promising approach for planning level analyses is the utilization of the Hazus-MH Coastal Surge Model with SLOSH to run historic storms, which represent a more realistic surge risk. If the historic storms can be validated, then SLR can be added and modeled.

Furthermore, additional consideration should be given to how to incorporate this climate risk information into the transportation planning process. The vulnerability assessment process is iterative in nature and will need to be revisited as new climate and transportation data becomes available. Working with MPOs and providing them with readily available data on infrastructure vulnerabilities would facilitate this iterative process and ultimately increase the resiliency of the State's infrastructure and protect public investments.

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Appendix A. Bridge Elevation Methods

Methodology for Creating Bridge/ Overpass Elevation Dataset:

1. Obtained Lidar data covering coastal areas of Hillsborough and Pinellas counties (GeoPlan obtained from Jones, Edmunds, and Associates). Lidar data products obtained include LAS tiles and an Esri file geodatabase with Lidar-derived topographic feature classes (includes an overpass line feature class covering bridges and overpasses and other breakline layers)
2. Using ArcGIS Desktop 10.2.1:
    - Converted the overpass line feature class to polygon and created a small buffer (100 feet) around the individual overpass polygons.
3. Using Fusion software:
    - Clipped the LAS files to the overpass buffered polygons.
4. Using EzLAS converter software:
    - Converted LAS files to zLAS (compressed LAS file).
5. Using ArcGIS Dekstop 10.2.1:
    - Created a LAS dataset using compressed zLAS files. Remove files with 0 points.
    - Converted LAS dataset to raster and created a Digital Surface model (DSM). Used first returns to extract highest elevation returns from Lidar data. Parameters chosen: cell assignment type = max; output data type = float.
    - Copied Raster – change pixel depth to 16-bit signed.
    - Projected raster to desired output processing map projection (FGDL Albers).

Appendix B. Digital Elevation Model Methods

Methodology for Creating a High Resolution DEMs and Inundation Layers

1. Obtained Lidar data (LAS files)
2. Using EzLAS converter software:
   - Converted LAS files to zLAS (compressed LAS files).
3. Using ArcGIS Dekstop 10.2.1, created DEMs with vertical units of inches and cell-sizes of 2-meter and 3-meter
   - Created a LAS dataset using compressed zLAS files.
   - Filtered LAS dataset. Used predefined settings of "Ground" (class 2 = Ground and class 8 = Model Key)
   - Converted LAS dataset to raster. Ran in ArcMap with ground filter set. Parameters chosen: cell assignment type = average; output data type = float; sampling type = cellsize; sampling value = 6.562 for 2m; 9.843 for 3m
   - Copied Raster – changed pixel depth to 16-bit signed
   - Projected raster to desired output processing map projection (FGDL Albers)
4. Created Inundation Layers
   - Using the SLR Inundation Surface Calculator 1.5.2 in ArcMap 10.1, ran 12 SLR scenarios for each of the three DEMs (2-meter DEM, 3-meter DEM, 5.4-meter DEM). For each scenario, two model outputs were run: the bathtub model and hydro-connectivity model, producing 24 inundation layers for each DEM. All scenarios are based on the FDOT District 7 sea level trend values, which utilize the data from the Clearwater Beach and St. Petersburg tide stations:
     - 2050, High Rate, Mean Sea Level (MSL), Bathtub and hydro-connectivity model
     - 2050, High Rate, Mean Higher High Water (MHHW), Bathtub and hydro-connectivity model
     - 2050, Intermediate Rate, MSL, Bathtub and hydro-connectivity model
     - 2050, Intermediate Rate, MHHW, Bathtub and hydro-connectivity model
     - 2050, Low Rate, MSL, Bathtub and hydro-connectivity model
     - 2050, Low Rate, MHHW, Bathtub and hydro-connectivity model
     - 2100, High Rate, MSL, Bathtub and hydro-connectivity model
     - 2100, High Rate, MHHW, Bathtub and hydro-connectivity model
     - 2100, Intermediate Rate, MSL, Bathtub and hydro-connectivity model
     - 2100, Intermediate Rate, MHHW, Bathtub and hydro-connectivity model
     - 2100, Low Rate, MSL, Bathtub and hydro-connectivity model
     - 2100, Low Rate, MHHW, Bathtub and hydro-connectivity model
5. Compiled statistics on inundation layers. For each of the 24 inundation layers created, compiled statistics:
   - File size
   - Processing times

- Cell count (representing area inundated under each scenario)
- Acreage of area inundated under each scenario
- Percentage of total area inundated