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# ASSESSING SEA LEVEL RISE VULNERABILITY AND COSTS IN A DATA LIMITED ENVIRONMENT

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**Abstract:**

*"Resiliency" for communities at risk from sea level rise and its effects means preserving as much property and associated economic activity as possible without disrupting current activity or expending funds on projects that provide limited long-term utility or social value. Of interest is how the coincidence of these events impacts the need for storm water improvements and the financial obligations they will entail. This research project focused on the impacts of a non-coastal, groundwater influenced southeast Florida community and the long-term funding they will need to reduce flooding in the community using GIS. This research involved defining surface elevations and groundwater levels, assessing the impacts of sea level rise on groundwater, assessing impacts to storm water from rainfall, identifying likely improvements, and assessing the scale for improvements. The analysis used three extreme rainstorm events under the 0-, 1-, 2-, and 3-foot sea level rise scenarios to determine the magnitude of the cost of the improvements. For a 35-square mile community, our research estimated that the cost could exceed $300 million. For a community not directly adjacent to the coast, the magnitude of these costs should be of interest to similarly placed communities.*

**Keywords:** *Sea Level Rise; Groundwater, Stormwater Costs.*

## 1. Introduction

Florida has been shaped by water – too much being the most frequent concern. Local and regional stormwater management systems have been used for over 80 years to drain the water table to create land for development. Stormwater systems within new communities are a more recent effort to lessen the impact of development of the larger drainage works. Yet as

development and impervious surface areas increase, and sea level rise continues to put communities at risk, there is a need to understand the impact of flooding events to create cost effective stormwater infrastructure and policy solutions. Coastal communities are not the only ones impacted by sea level rise. As noted in Bloetscher and Romah (2015), Bloetscher and Wood (2016) and Bloetscher et al (2014), inland communities are projected to have risks from elevated groundwater, and must address excess water to avoid disruptions to economic and social activities.

Sea level rise (SLR) is an ongoing climatic phenomenon that continues to put coastal populations at risk for increased flooding after storms and during king tide events (Bloetsscher, et al 2016). Nearly half the US population lives within 50 miles of the coast, including most major commercial, leisure and import/export enterprises (Bloetscher and Wood, 2016). Hence much of the economic activity of the nation is tied to coastal communities. This is particularly acute in southeast Florida where 6.6 million people, $6 trillion in property and nearly $400 billion per year economy support much of the rest of the state. Various researchers have already noted impacts on coastal and island environments and most coastal communities are cognizant of the ongoing discussion about SLR, the associated loss of soil storage capacity and more intense storms overwhelming the current stormwater infrastructure (Hansen et al, 2011; SRFCC, 2012, Parkinson, 2009; Tebaldi, et al, 2012; Titus and Richman, 2001; Weiss and Overpeck, 2011; Heimlich et al, 2009). At the same time, much focus is on the coastal impacts, not inland impacts (Bloetscher and Romah, 2015). As a result, vital infrastructure the region relies on may be at risk every day. While the rate of SLR may be increasing, it is relatively slow, allowing communities time to evaluate and plan for SLR to ensure that stranded infrastructure or the failure to construct projects are exceptions to the norm (Bloetscher and Romah, 2015).

Sea level rise as a climate impact has unequivocal proof and has been extensively documented. During the past 100 years, an increase in sea level has been observed along the Atlantic coast, which combined with population growth, makes it essential to continue improving flood management strategies (NFIP, 2011; Parkinson, 2010; Schmidt, et al., 2011; Warner, et al., 2012; Zhang, et al., 2011, 2011a). Gregory et al. (2012) note that within the last two decades, the global rate of sea-level rise has been greater than the 20th-century time-mean. Various researchers have already noted impacts on coastal and island environments (Church et al., 2001; Coombes et al., 2010; Frazier et al., 2010; Murley et al., 2008; Nicholls and Cazenave, 2010; NFIP, 2011; Noss, 2011; Parkinson 2010; Poulter and Halpin, 2008; Purvis et al., 2008; SFRCC, 2011; Zhang et al., 2011, 2011a). Prior studies have shown that SLR impacts will be felt globally, but the South Florida region, with its low-lying coasts, subtropical climate, porous subsurface formations, and hydrology, is one of the world's most vulnerable areas (Heimlich et al., 2009, Bloetscher et al., 2009; Pachauri and Reisinger, 2007).

While coastal populations are particularly at risk of SLR inundation and storm surge, interior populations are also susceptible to rising water tables and extended periods of inundation caused by the inability to drain inland areas (Bloetscher and Wood, 2016; Romah, 2012; Bloetscher et al 2015). Higher groundwater levels equate to reduced soil storage capacity, which means less capacity for soil to absorb precipitation, thereby increasing the risk of groundwater flooding (Romah, 2012). Chang et al (2011) describes an overall "lifting process" by which there is a 1:1

ratio in water table elevation that correlates to sea-level rise. Sea level rise impacts groundwater which increases the short-term impacts and frequency of flooding in low-lying areas.

The purpose of SLR vulnerability modeling is to predict future vulnerabilities of infrastructure and property due to the increase in sea level by predicting areas with low elevations that may be affected by inundation from the ocean directly, from rising groundwater levels, and inundation from the inability of inland areas to drain. Much focus has been on the coast, but Bloetscher and Romah (2015), Bloetscher and Wood (2016) and Bloetscher et al (2012) have noted impacts inland may also exist. In addition, assessing vulnerability requires local officials to define the critical or "acceptable" level of service (E Sciences, 2014).

Making long-term decisions about the need for infrastructure will be important because infrastructure and development are expected to last 50 years or more. Such impetus requires short- and long-term planning and assessment of vulnerable areas. Hence it is in the community's interests to develop a stormwater planning framework which adapts to SLR and protect vulnerable infrastructure through a long-term plan. While uncertainties in the scale, timing and location of climate change impacts can make decision-making difficult, response strategies can be effective if planning is initiated early.

This research aimed to develop a means to identify the magnitude of infrastructure expenditures over time in a non-coastal community. In this project, a non-coastal, Broward County community was evaluated for stormwater needs. The community has a population of about 91,000 people. The stormwater conveyance system serving the community includes primary, secondary, and tertiary canals operated by others; a canal operated by the South Florida Water Management District (SFWMD) and other canals operated by local drainage districts. The canal systems pump the stormwater west to the Everglades and east to the Atlantic Ocean. The community's stormwater system consists of structures (catch basins, curb inlets, culverts, canals, swales, pump stations, ditches and manholes) that help channel the stormwater to the canals. The community's stormwater system must maintain compliance with Broward County's MS4 stormwater permit, which requires additional record-keeping, policy development, inspections and maintenance than is currently being performed.

The goals were to provide guidance in developing a means to prioritize infrastructure to maximize benefit to the community. To accomplish this task, the investigators applied the following to the effort:
1) Establish Baseline Sea Level and Groundwater Elevations at present, and develop maps based on the best available information with respect to increases over time.
2) Develop topographic maps specific to climate change analysis.
3) Identify vulnerable areas
4) Modeled rainstorms in conjunction with groundwater changes
5) Identified needed stormwater improvements on a macro-scale
6) Develop costs for stormwater infrastructure to address the impact of SLR

The following sections demonstrate our methodologies to prepare necessary geographical information system (GIS) data and economic data to come up with a reasonable cost estimate for different sea-level rise scenarios.

## 2. Materials and Methods

This section of the paper is classified into two major steps: data preparation and sea level rise prediction model generation.

### *Data Preparation:*

The process of determining sea level rise vulnerability requires that the data going into the prediction model are accurate. To this end, the data includes both topographic data from NOAA LiDAR flights and water level (via monitoring well data from the South Florida Water Management District (SFWMD) DBHYDRO website) for the study area where the methodology was implemented. The required GIS data includes, high resolution and most recent DEM (Digital Elevation Model), a ground water level elevation map, existing stormwater infrastructure locations, location of built-infrastructure (roads and buildings), pervious and impervious area maps, location and extent of waterbodies and property values. The ancillary data are the information associated with geographic data such as condition of storm water infrastructure, hydrographs of rivers and canals and cost of infrastructure to mitigate against sea level rise per square mile, per foot of sea level rise.

Digital Elevation Model (DEM) is the most important data in sea level rise vulnerability mapping as it provides information on low lying and higher elevations. The DEM for the study site was derived from LiDAR data that was collected in 2007 by Florida Division of Emergency Management (FDEM) in collaboration with National Oceanic and Atmospheric Administration (NOAA) for coastal Florida. The data was collected with approximately 2 points per square meter and vertical accuracy of ground points in unobscured areas is not to exceed 18 cm (0.6-feet) RMSE. This research used the DEM generated by the South Florida Water Management District (SFWMD) with a spacing of 3 meters (10 feet) using above mentioned LiDAR data. This methodology is the same as that used for case studies for Dania Beach, Miami-Dade County, Miami Beach, West Palm Beach, Punta Gorda and Key Largo, which demonstrate the effectiveness of LiDAR for mapping efforts for precise identification of at risk infrastructure and predictions of impacts on physical infrastructure and on communities (Romah, 2012, Bloetscher and Romah, 2015, Bloetscher and Wood, 2016).

The next task was creating a groundwater surface layer. After downloading and developing the LiDAR maps of the land surface into GIS layers, the second step for creating the model was incorporating a groundwater surface elevation. A series of data sources had to be mined and related to past events. These include data derived from the South Florida Water Management District's data storage and retrieval system called DBHYDRO. The database includes historical information for monitoring wells, canal stages and permit data for modeling water supply wells. Priority was placed on monitoring locations with 15 or more years of data, and in particular, recent data since tidal information indicates that king tides have been increasing. The goal was to find common dates for high groundwater levels. This data was collected, and then compared using Excel® spreadsheet programs. Data points for determining the groundwater surface elevations used the monitoring well data gathered from the SFWMD DBHYDRO database for the period from 1995 through a range of end to dates between May 2014 to December 2014. Older wells had less development impacts and therefore are less representative of current

groundwater levels.   The results were then tabulated in ascending order and reviewed to determine common dates within the 98-100th percentile of highest elevations. The fall of 2012 was common to the most data sets (Bloetscher and Wood, 2016).  The critical levels consisted of the 99-percentile occurrence (4th highest in a given year).  This is the October high tide in southeast Florida.

Various interpolation methods were used to determine the surface that produced the best results. Some of the interpolation methods considered were Inverse Distance Weighting (IDW), ordinary kriging, co-kriging, and kernel density functions. The resulting interpolation that produces the best performance measures was the ordinary kriging, which was then applied to the model as the groundwater surface elevation. The output groundwater surface model was created as a raster image using 10 ft.

Future groundwater surface elevation models were created by adding a specified height to the existing groundwater table. The assumption made was that an increase in SLR would shift the starting point of the hydrological gradient, the ocean coast interface, by the same distance along the entire gradient line based on the work of Bloetscher and Romah (2015) and Chang et al. (2011).  The final inundation model was created in GIS by subtracting the groundwater surface model from the digital elevation model.

In the event of a storm event, one of the factors that influence on how fast water drains is the availability of stormwater infrastructure such as catch basins, curb inlets, culverts, canals, swales, pump stations, ditches and manholes. It is important that the location of these structures is collected, so a better estimate on the impact of sea level rise can be estimated by accommodating the volume of water that will be drained through them. As for this project, the inventories of stormwater structures were collected using field data collection techniques. GNSS (Global Navigation Satellite System) based receiver with a capability to get RTK (Real-time Kinematic) corrections were used in the field. The approximate positional accuracy of the structures was maintained to less than $1/10^{th}$ of a foot or 3 cm. In addition to positions, the data collection included condition of the structure namely excellent, good, fair and poor.

Roadways data for the study site was acquired from the Town, Broward County and from the Florida Department of Transportation (FLDOT). GIS database of the roadways are frequently updated by the FLDOT using airborne photogrammetric techniques. The roadways data used in the research were updated in 2016. Even though this GIS databased has only the centerline of the roads, the road region is computed using nominal width of each kind of the roads. Since roadways and other infrastructure is normally designed for 50 to 100-year service life, and a rarely abandoned, long-term planning for climate impacts is of critical concern, especially when storm events may create temporal impacts that damage infrastructure and make is impossible to access certain services.  Roadways are useful for predictive purposes since most other public infrastructure uses (Romah 2012).

Classification of pervious and impervious area was the next area of interest. Parcel maps of the project site were acquired from Broward county GIS repository. In addition to extent of the parcels, the database contains information about the area of the built area which was used to classify pervious and impervious areas. The database also contains information about the

property values that are published by the Broward County every year Likewise, data on waterbodies were acquired from Broward County GIS repository database containing rivers, channels, lakes, ponds and retention tanks.

Discussions with the community staff were held regarding the storm scenario for modeling. The decision was 1:10 storm event used for roadways by FDOT. However more extreme events have become more common so hydrographs were created for not only the 1:10 event, 5 inch rain event (defined in the Florida Building Code) and 25 year 3 day (12 inch) event (defined by the SFWMD for stormwater permitting). The FDOT standard 1:10 was developed from FDOT 1988 information and may be short of the true event in 2015. This event was used in modeling the stormwater system.

The model chosen for the stormwater system was the SFWMD's model Cascade 2000 was used to simplify the modeling by focusing on surface activities and topography. This was undertaken. Construction of stormwater modeling requires interpretations of data which must be synthesized on a global as well as a local scale. GPS field location efforts were used to gather information on individual structures, but while these details can stormwater models can predict results with relative accuracy, they can overwhelm are impacted when large areas are modeled. In addition, small impacts, like missed inputs from outside the boundary of the model, and derail the best intentions. Cascade is less specific than some other packages, but is used for permitting by the District, and accomplishes a number of goals including identifying heads given certain topography and outlet conditions. Cascade prefers delineated boundary conditions such as ridges and canals. Canals were used as the boundary condition on the outlet end for all basins in this project. Ten areas were delineated, all discharging to the regional system. The following data was generated for each area from the topographic layers:

- Area of the basin
- Highest and lowest points
- Acreage by elevation in 1 ft intervals
- Average estimated groundwater elevation in the basin
- Stage
- Area of lakes
- Area of roads
- Area of buildings
- Pervious area
- Routing scenarios
- Downstream water levels
- Groundwater depth below the surface
- Outlet conditions

For the project the following initial assumptions were made:
- Current land topography based on 2007 LiDAR
- Outlet from basins to the canal system with staging at 4.0 ft
- 99 percentile groundwater elevations (meaning groundwater a few inches below the surface)
- Current sea level

Table 1: Assumptions

| Assumptions | Current | 1 ft SLR | 2 ft SLR | 3 ft SLR |
|---|---|---|---|---|
| GW | up to 3 in | up to 1 in | 0.01 | 0.01 |
| C11 | 2.5 | 3.5 | 4.5 | 5.5 |
| Weir | 4 | 4 | 4.75 | 5.75 |
| Pump off | 2 | 3.5 | 4.5 | 5 |
| Pump on | 4.5 | 4.5 | 4.5 | 4.5 |
| Goal | 4 | 4.5 | 4.5 | 4.5 |
| Initial stage in basin | 4 | 4 | 4.5 | 4.5 |

Table 1 summarizes the initial assumptions and the stage for each based on 3 storm events: the 1:10 used by FDOT (Assumes 2.75 inches in 24 hours), the Florida Building Code event that includes a 5 in in one hour event (7 in in 24 hrs), and the 3 day 25 year event (9.5-11 inches). The results for the current condition are shown in Table 1.

The stage elevations were then placed into the topographic LiDAR maps. All values where the stage was above a given topographic level, the areas were colored blue for flooding. A couple of notes are required on the assumptions. It was assumed that the regional canal stage was able to be kept below 4.5 ft and that the staging was not more than 4.5 ft under any scenario. The canal stops being a useful drainage structure for the lower lying areas at 1 ft SLR. This is in the near-term and matches the District's estimates that with 9 inches of SLR, 70% of the regional system capacity will be lost at peak tides. The community will need to look at other measures, like berm and backflow valves, to minimize potential flooding from the inability of the regional system to flow.

The staging assumption of 4.5 ft works until 2 ft SLR, when the tailwater elevation at the 99 percentile event matches the 4.5 ft. The weir will need to be raised which subjects the community to far more flooding and transforms much of the pumping capacity from intermittent pumping based on rain events to more permanent 24/7 flooding to keep groundwater down. This explains why the 7 inch Florida Building code (FBC) event ends up being more costly in the long-term than the 3 day 25 year event – the latter happens over 3 days vs a 2 hour peak. Pumping ends up being more critical with the peak event under 24/7 pumping.

At 3 ft SLR, a change to the regional system is required. The weir must be raised to 5.75 ft, but the 4.5 ft stage goal is maintained for the town. This necessitates more 24/7 pumping to control soil saturation. Major structural efforts on the regional system need to be modeled for this event. Modeling for the community only does not capture impacts from cities to the south and west, nor limitations imposed by the need to minimize flooding to the east. As a result those modeling results should be assumed to be underestimating needs, perhaps significantly. Discussions with the SFWMD and surrounding communities should be undertaken.

To determine capital needs, an understanding of the existing assets is required and a means to evaluate potential flooding areas is required. The impacts of SLR of groundwater should be considered given that the community stretches over 10 miles east-west and generally is sloped to the west, which means that western areas may flood faster than the eastern areas due to

groundwater levels and elevation, as demonstrated by prior efforts by FAU focused on the impacts of flooding on roadways and water systems in Florida, with added emphasis on southeast Florida.  Several reports and peer reviewed articles have been developed as a result of these efforts (Bloetscher et al 2010, 2011, 2012; Heimlich et al 2009; Bloetscher and Romah, 2015). The objectives of the prior FAU research included developing recommendations for forecasting impacts in Florida for use by government agencies for planning purposes and developing recommendations for how existing data sources could be integrated with information systems for identifying infrastructure at risk. A major output of all investigations included a toolbox to apply to various situations to protect existing infrastructure, secure appropriate timing for improvements, provide a means to "step into" infrastructure improvements, and provide a tool to help staff deal with the public and elected officials.  This project extended those past efforts by creating inundation models for the community based on three storm events in order to gain some understanding of the costs that the community may face in light of SLR based on the toolbox of options.  Specific design requirements are a much more focused engineering exercise, but the larger view is required to gain a magnitude of cost estimate.

### 3. Results and Discussion

Figure 1 is the LiDAR map developed from the NOAA data. The data shows there to be a ridge in the center of the city, but that aside from man-made changes, the land sloes slightly to the west (typical of south Florida). Figure 2 is a record from 2008 to 2013 that shows the tides. South Florida experiences one king tide each year – in the early fall. These tides occur at the end of the rainy season, meaning groundwater levels are highest already, and cannot drain due to the tides (as intended by the regional drainage system). Figure 3 is the krigged groundwater map. The groundwater map was used for both the stormwater modeling and the vulnerability map. Figure 4 outlines the impervious area in the Town, which was used for modeling purposes. Likewise Figure 5 shows the stormwater infrastructure the Town has.
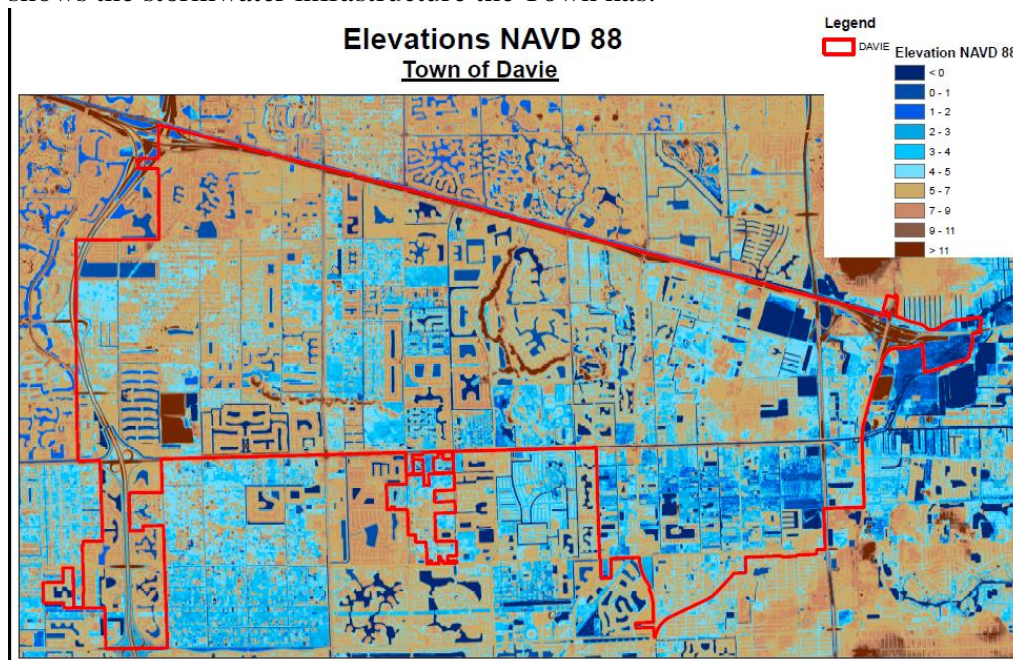


Figure 1: LiDAR topographic map of the community

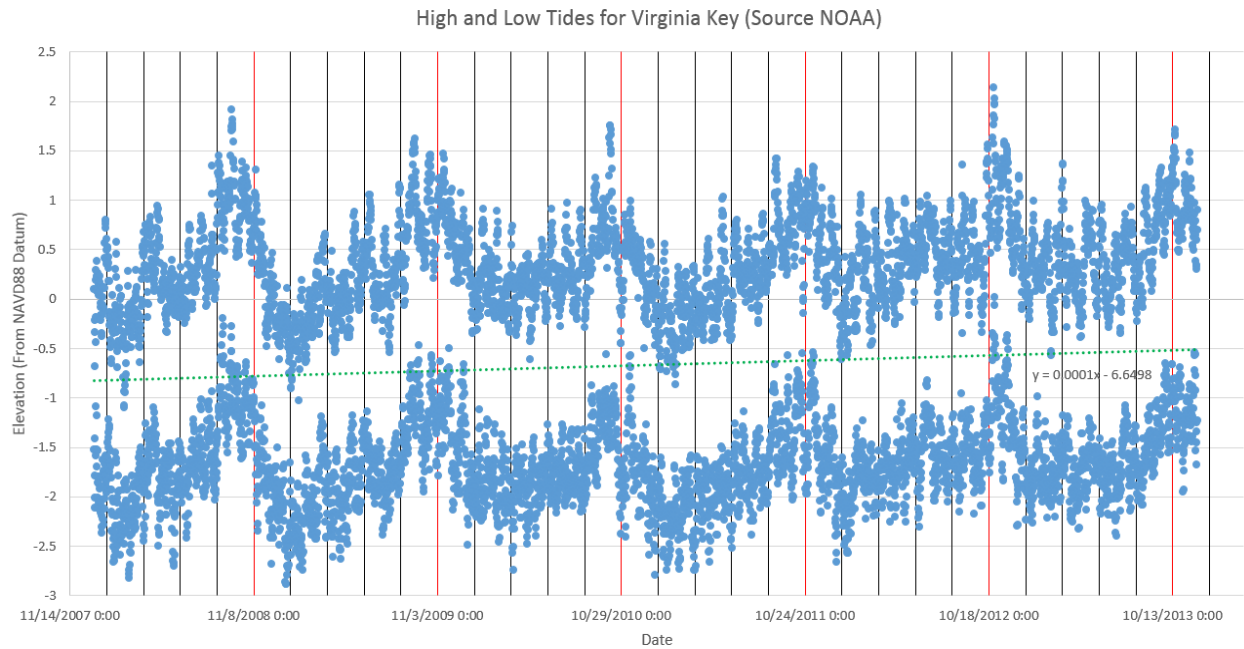High and Low Tides for Virginia Key (Source NOAA)

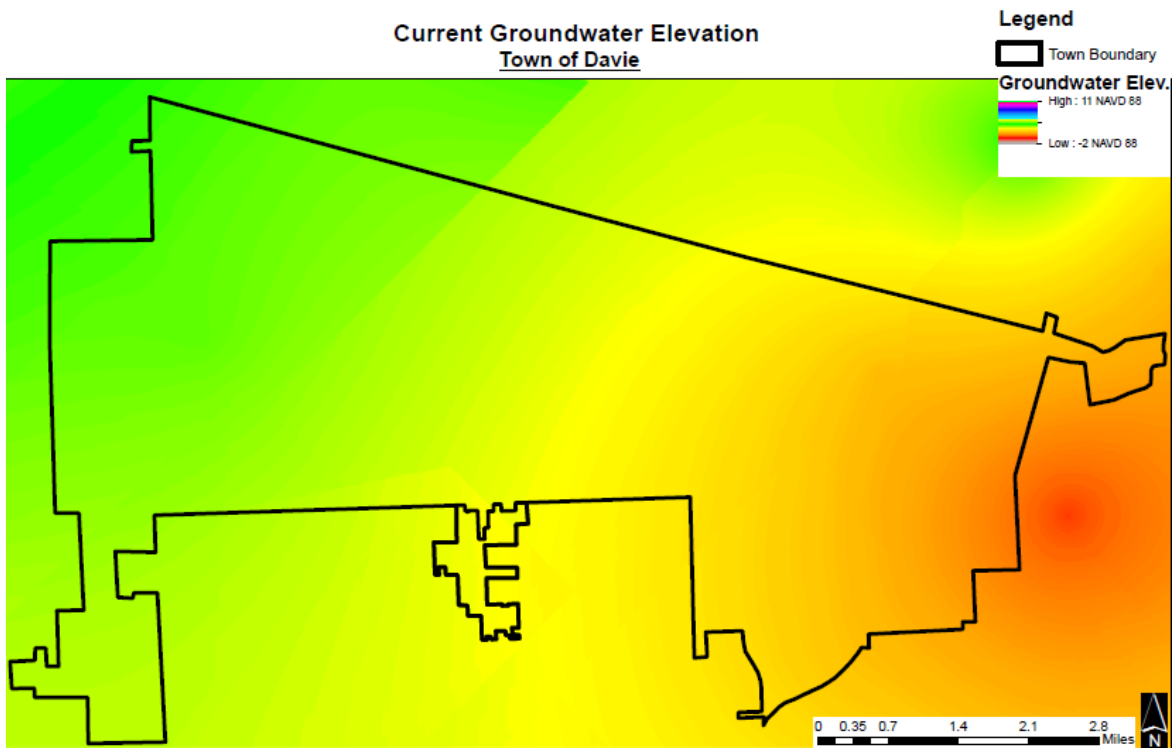

Figure 2: Tidal levels with time (2008 – 2014)



Figure 3: Groundwater levels in the community – 99 percentile condition
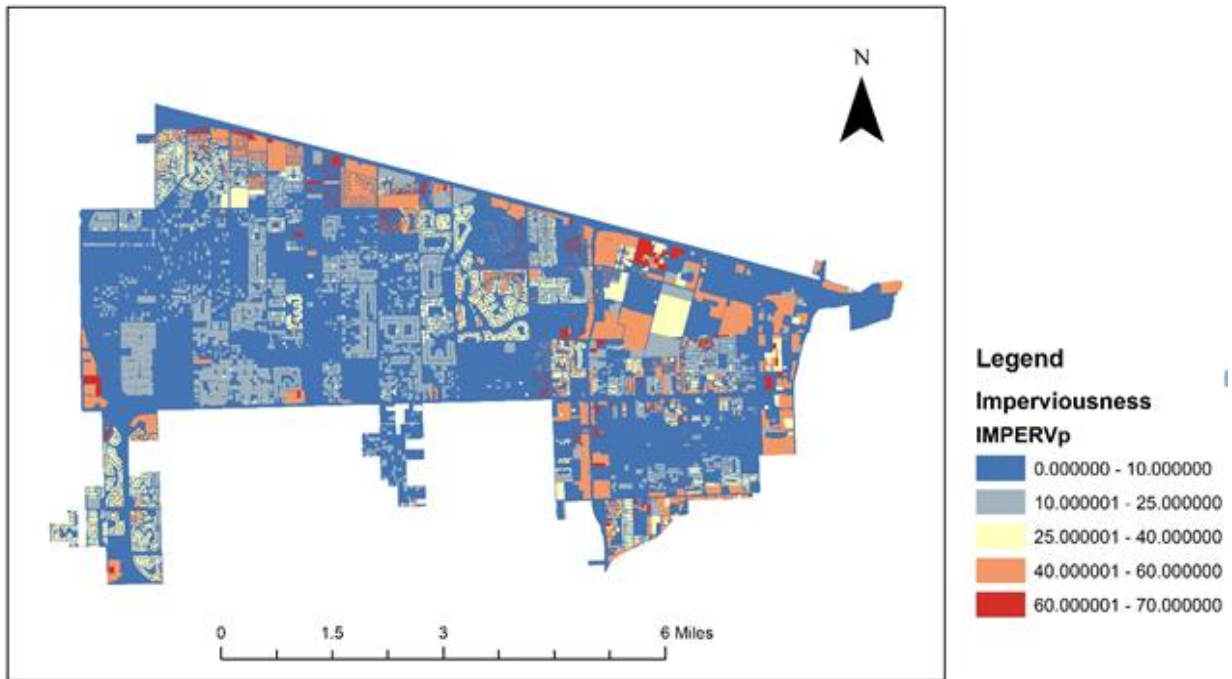
Figure 4: Impervious area in the community

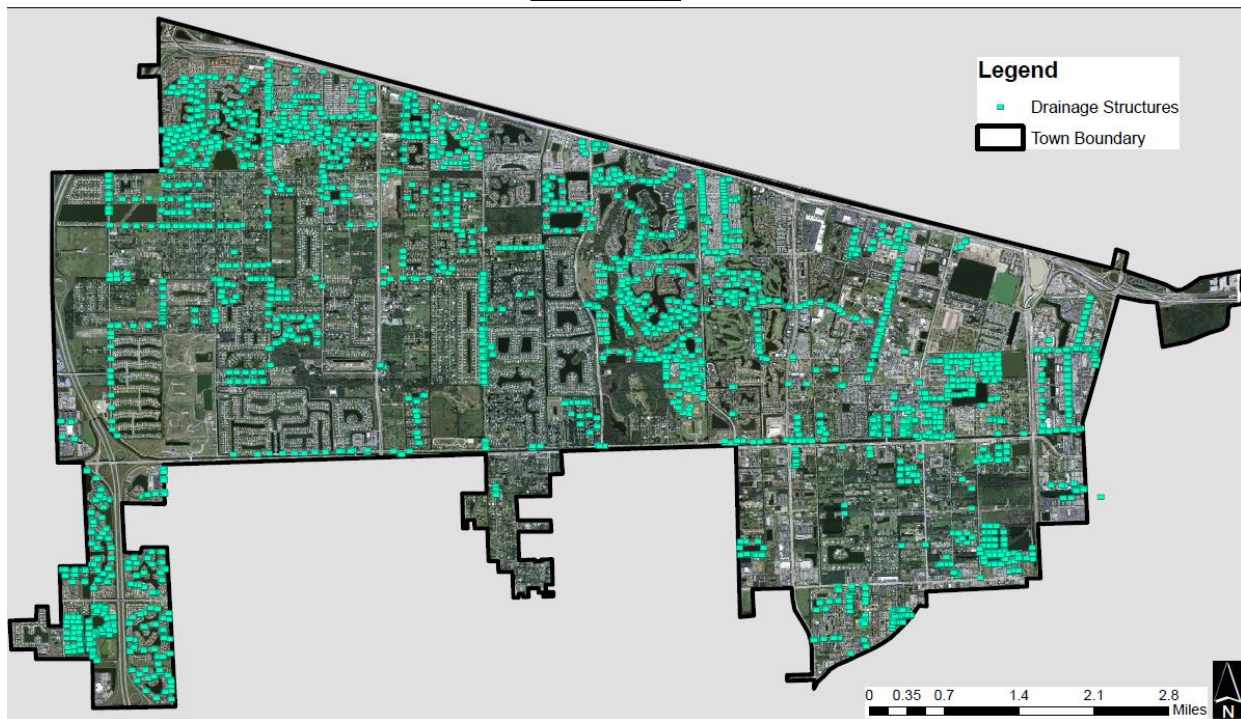**Mapped Drainage Structures**
**Town of Davie**



Figure 5: Location of stormwater infrastructure in the Community

Based on the LIDAR and groundwater maps, Figure 6a-d shows the vulnerability maps for the Town. These maps show the vulnerable areas in red. Using the protocol of Romah (2012), this means that the LiDAR surface elevation is lower than the elevation of the krigged groundwater Layer. E Sciences (2014) demonstrated that this method was useful as a predictor of flooding under the 99 percentile event. These areas are also likely to have drainage systems in the areas (but not always). The areas in yellow indicate potentially vulnerable property – whereby the groundwater was within 2 feet of the surface. Green areas are more than 2 ft above the groundwater. As can be seen in the maps, as sea level rises, the amount of property in the community that becomes vulnerable increases substantially, especially in the central and western areas. This is not the result most residents expected for an inland community. Instead they expected that areas further inland would be less prone to the effects of groundwater but the fact that the groundwater table is rising, while the topography is decreasing is not well understood by the public or policy-makers, but the experience in the community suggests extensive flooding.
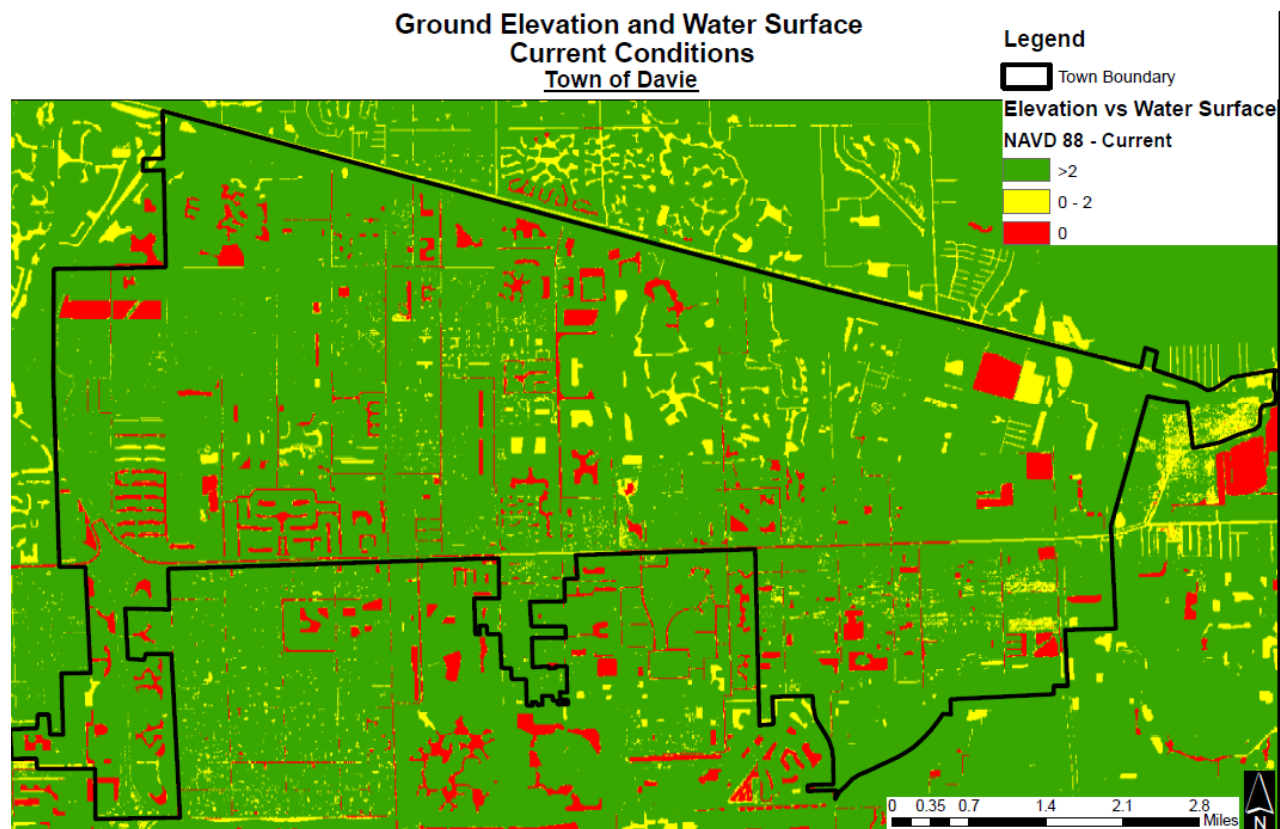


Figure 6a: Current condition - the red areas a vulnerable to flooding – any rainfall will have difficulty draining into the ground.
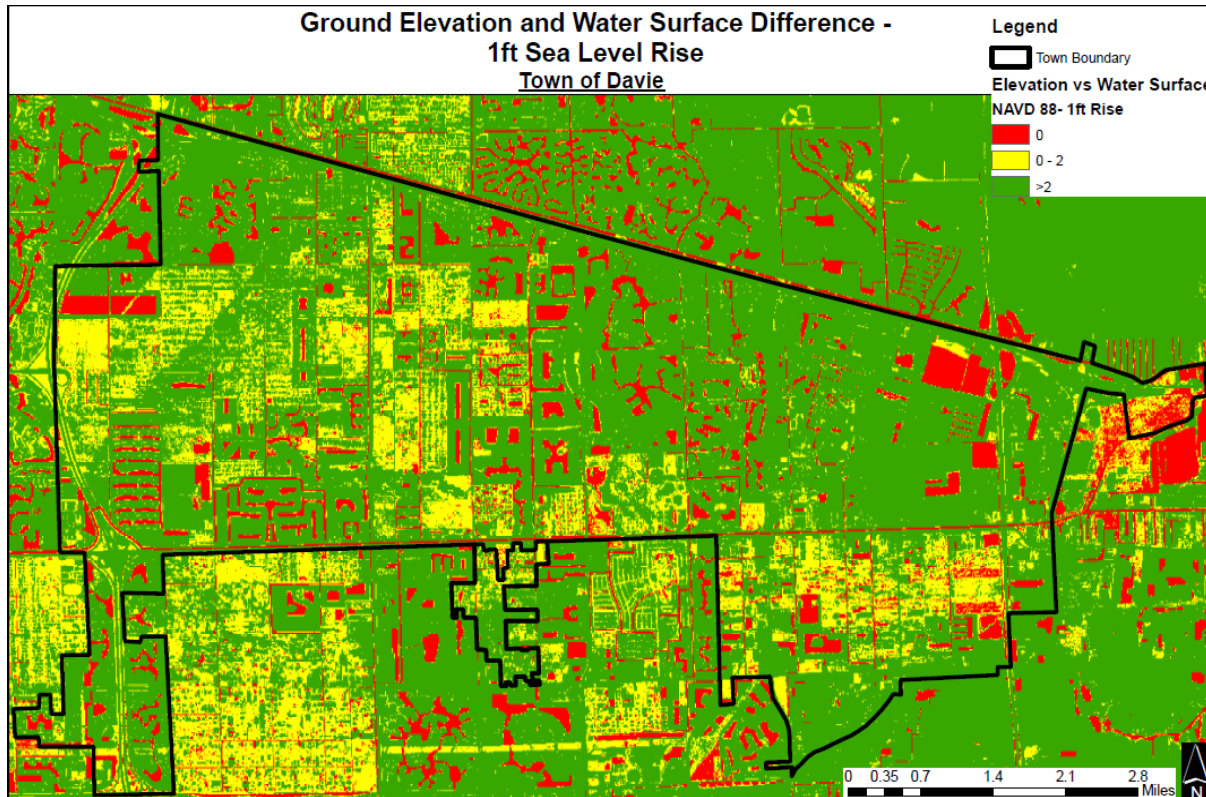
Figure 6b: With 1 ft of sea level rise, under the high groundwater condition, the red areas a vulnerable to flooding – any rainfall will have difficulty draining into the ground.
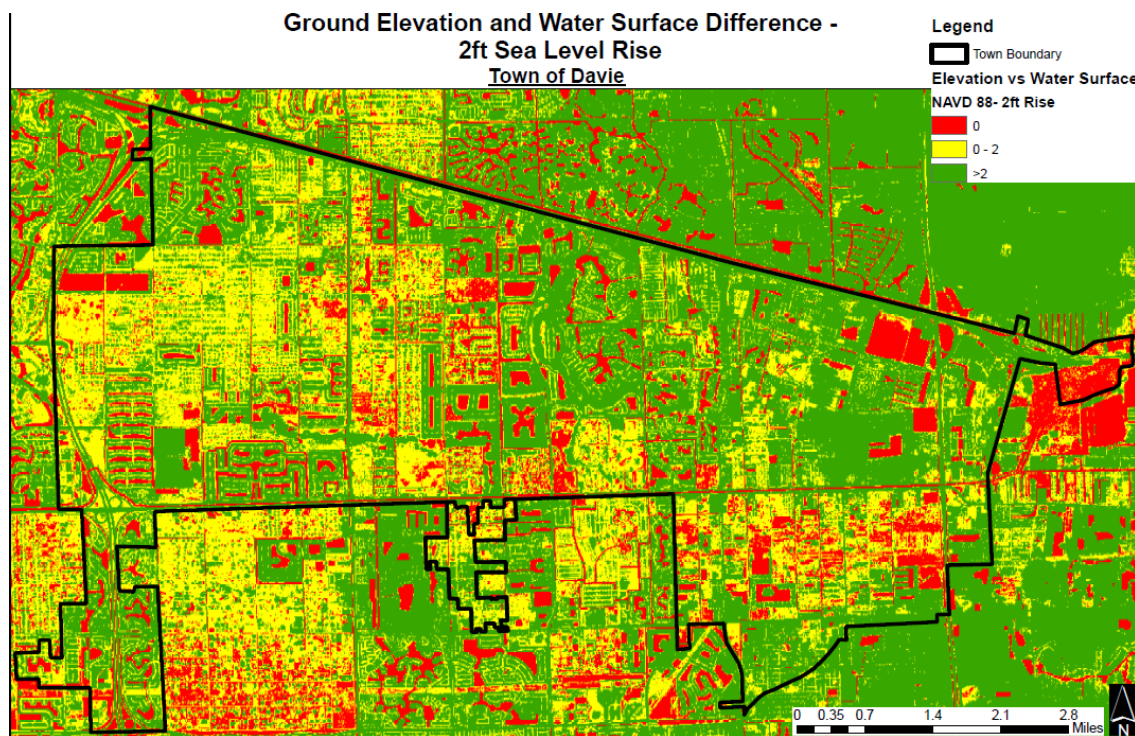


Figure 6c: With 2 ft of sea level rise, under the high groundwater condition, the red areas a vulnerable to flooding – any rainfall will have difficulty draining into the ground.
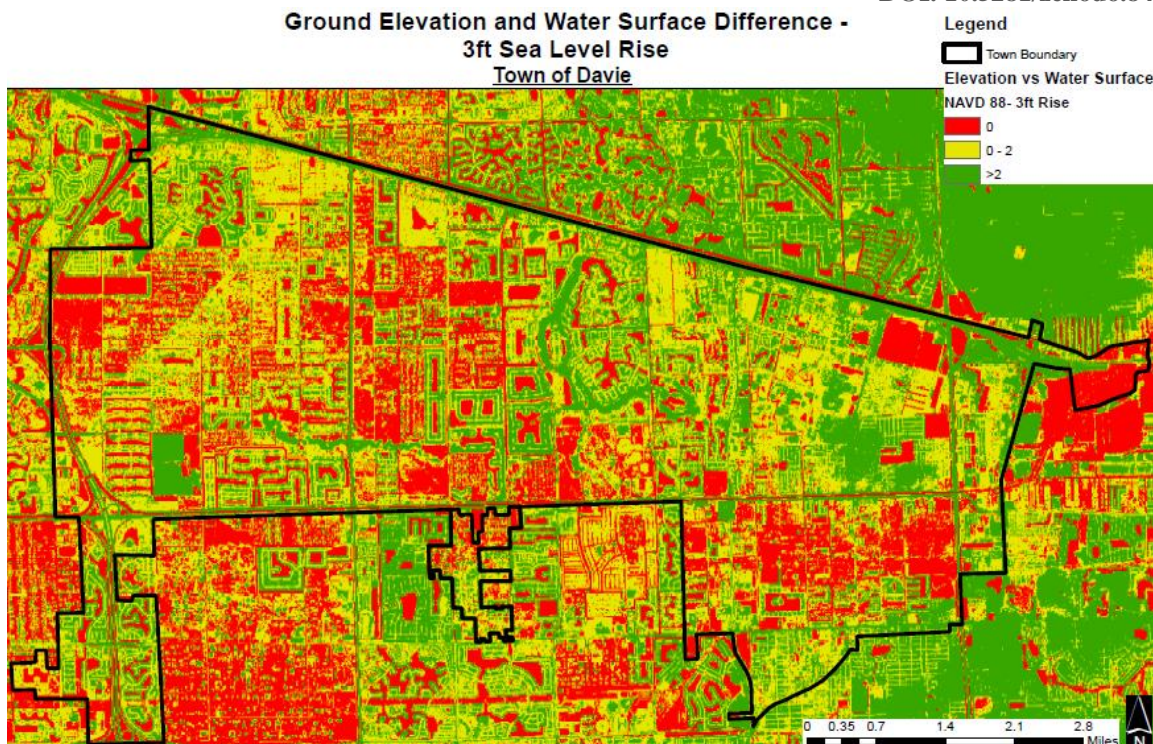
Figure 6d: With 3 ft of sea level rise, under the high groundwater condition, the red areas a vulnerable to flooding – any rainfall will have difficulty draining into the ground.

Modeling rainfall events was the next step. The entire community was modeling in the 4 SLR scenarios for the three different storm events. Of no surprise is that the flooding increases as rainfall increases. The current condition, 1, 2 and 3 ft SLR scenarios were run at the 99 percentile groundwater and tidal dates and levels. Flood stages were developed for each scenarios. Figure 7 is an example of one area of the Town under the modeled rainstorms with no SLR. The final task was designed to involve the development of scenarios whereby a toolbox options are utilized to address flooding in the community. The modeling results were then evaluated based of the accompanying infrastructure that is typically associated with same. A summary of the timelines and expected risk reductions were noted in the tables associated with storm and SLR scenarios. Existing infrastructure was used to reduce current infrastructure needs in the models.

The final result was to create the costs for the recommended improvements and a schedule for upgrading infrastructure will be developed in conjunction with staff. Each area was then modeled with a series of improvements that led to less flooding to get to the flood stage goal. It should be noted that the regional system has a major pumping station on the east side of the community. This pumping station would have to pump against the tide elevation of 5.5 ft under the 3 ft SLR scenario. Table 2 outlines the infrastructure costs, from a long-range planning perspective, needed for each basin under each scenario, for each event. Depending on which event the Town wishes to plan for, the associated costs can be identified (in 2015 dollars). As the effort was Town-wide, the costs are at the macro-level. Specific sizing of improvement must be designed to achieve water quantity and quality requirements (quality is not part of the software). The costs vary from an initial need of $30 million to over $300 million long-term.

The long-term needs of the Town averages about $5 million per 100 acres, which matches a prior effort (Bloetscher and Wood, 2016) in Palm Beach County.
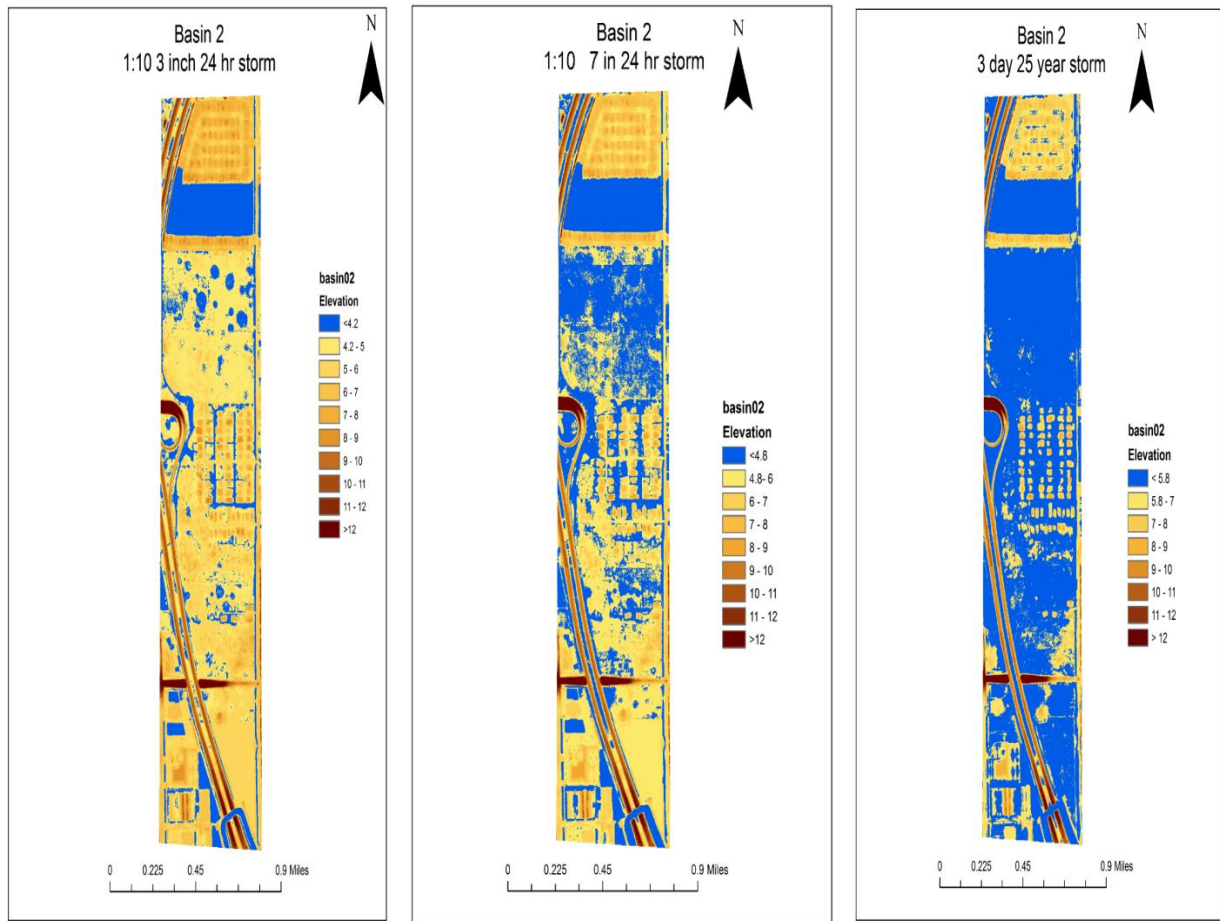


Figure 7: Example of an area of the community under the 1:10, 3day, 25 year and 1:100 years storm events as it relates to severity of flooding
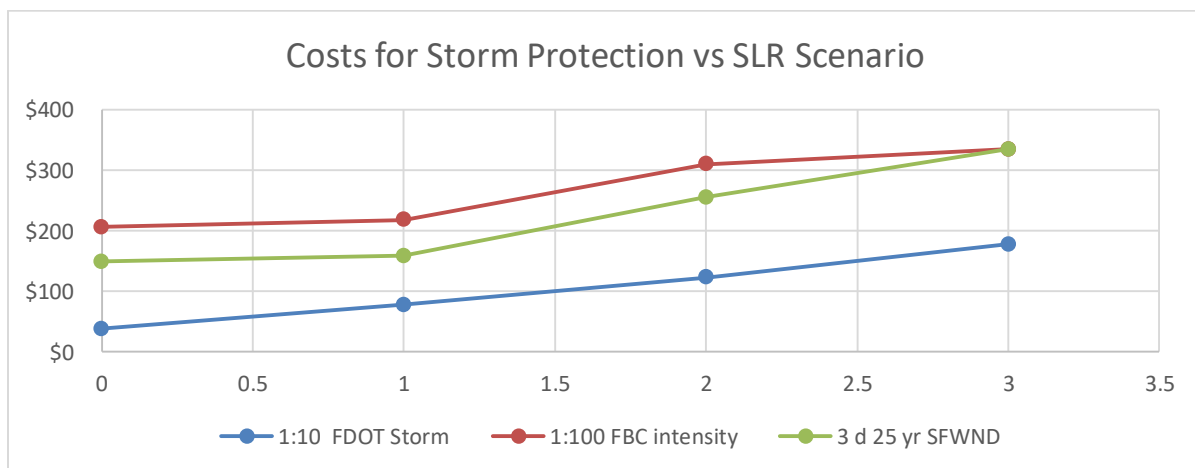


Figure 8: Summary of Costs over the 3 ft of potential sea level Rise by 2011, under the 3 storm planning concepts.

### 4. Conclusions

The purpose of SLR vulnerability modeling is to explore future vulnerabilities of infrastructure, buildings and facilities on public and private property due to the increase in sea level by predicting how areas with low ground surface elevations may be affected by inundation from the rising ocean directly, from rising groundwater levels, and inundation from the inability of inland areas to drain.

The objectives of this paper were to: 1) establish baseline sea level and groundwater elevations and develop maps based on the best available information; 2) develop topographic maps specific to climate change analysis; 3) identify vulnerable areas; and 4) develop costs for stormwater infrastructure to address the impact of SLR for a non-coastal community. The project assessed the impact of soil storage capacity and groundwater levels on the potential to flood or damage infrastructure as they primarily focus on coastal regions and average mean tides (or mean high tides). The results for the models that incorporate the loss of soil storage capacity created by rising groundwater levels. For this community, a number of potential options are available to deal with sea level rise. The perception that they were less vulnerable was found to be incorrect given that the coastal ridge appears to control groundwater levels in the community and surrounding areas. The data revealed that over $300 million in current dollars might be needed to address stormwater issues arising from SLR before 2100.

Given that the costs were similar to a concurrent project, the methods appear to be useful to apply on a macro-basis to other communities for planning purposes. The probability of flooding (tolerance), a storm event for planning purposes and existing infrastructure must be identified. Having more specific data on the existing infrastructure is helpful as it reduces assumptions. Likewise having data on past flooding events as related to rainfall is useful for calibration purposes. This data can be easily collected in the immediate aftermath of the storm.

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