

Original Research Article**AN UNRESOLVABLE PARADIGM -
TOO MUCH WATER – LIMITED WATER SUPPLIES?
A SOUTH FLORIDA CONUNDRUM****ABSTRACT**

In the future, the coastal and low lying areas of Florida will be flush with water due to sea level rise and increased storm intensity, yet at the same time the area is often under water use restrictions due to lack of rainfall, seasonal demands and decreasing water levels during the dry (tourist) season. Within the same agencies, storm water utility managers are looking for a solution to dispose of excess storm water that causes increased flooding frequency that residents complain about, while water supply utility managers are looking for reliable water supply solutions that potentially limit development and inconvenience the same residents. What we know is that rainfall patterns will continue to change, southeast Florida will continue to be a desirable place to live and the interconnectedness of water will require the traditional barriers between water, wastewater and storm water to be torn down and replaced with a more integrated solution.

INTRODUCTION

Climate change is expected to cause more intense rainfall events, such as thunderstorms and tropical cyclones (IPCC, 2007; Karl, et al, USCCSP, & NOAA, 2007), warmer temperatures (IPCC, 2007; Singer, 2008) and increased sea levels due to increased rates of thermal expansion and ice melt from glaciers (Bindoff et al., 2007; Domingues et al., 2008; Edwards, 2007;

Gregory, 2008; Vermeer and Rahmstorf, 2009; Jevrejeva, Moore and Grinsted, 2010; Heimlich, et al. 2009; Bloetscher, 2009,2010, 2011; IPCC, 2007, 2012; Church et al. 2011; Gregory et al. 2012). Gregory et al. (2012) noted the last two decades, the global rate of sea level rise (SLR) has been larger than the 20th-century time-mean, and suggested further that the cause was suggested that there may also be increasing contributions to global SLR from the effects of groundwater depletion, reservoir impoundment and loss of storage capacity in surface waters due to siltation. Every part of the world may be affected although each community needs to evaluate which issues are of greatest concern to them. For example, in southeast Florida an increase in sea level has been observed (Bloetscher, 2012), which is expected to have significant consequences for coastal areas where the combination of sea level rise (SLR) and population growth makes it essential to continue improving flood management strategies (Parkinson, 2010; Zhang, et al. 2011, 2011a; NFIP, 2011; Schmidt, et al. 2011; Warner, et al. 2012). Various researchers have already noted impacts on coastal and island environments (NFIP, 2011; Purvis et al. 2008; Coombes et al. 2010; Zhang et al. 2011, 2011a; Parkinson 2010; Frazier et al. 2010; Poulter and Halpin, 2008; OECD, 2008; Murley et al. 2008; Church et al. 2001; Nicholls 2004; SFRCC, 2011; and Riggs, 2001). Concurrently, Florida is often water supply limited as topography limits the ability to store excess precipitation for use during the anticipated extreme dry periods. New ideas need to be employed.

The combination of rising seas and intense storms will overwhelm the current highly engineered storm water drainage system of canals and control structures that have effectively enabled management of water tables, reduced the potential for flooding of the low terrain and controlled saltwater intrusion. The advent of sea level rise will present new challenges; however, because the water table is currently maintained at the highest possible levels to counter saltwater

intrusion and maximize water supplies (Bloetscher, 2008). However as the sea rises, it disrupts the balance struck between flood risk and water supply availability. As a result there is a potential to place important infrastructure we rely on every day at risk, yet there is a lack good data to make decisions on what to do, when and with what priority. This is of particular concern on coastal or island communities like those in southeast Florida. This paper will discuss an initial approach applied to Miami Beach, a coastal island community of nearly 100,000 people. The objectives of the research were to develop an accurate methodology for predicting impacts of sea level rise at the local level by identifying how existing topographic, groundwater and tidal data sources can be utilized to identify infrastructure vulnerable to sea level rise.

METHODOLOGY

A number of data sources are available to local officials to help initial screening of vulnerability. The first means to assess what infrastructure is vulnerable to SLR requires detailed topographic information. Topography is a key parameter that influences many of the processes involved in coastal change, and thus, up-to-date, high-resolution, high-accuracy elevation data are required to model the coastal environment. Previous approaches to modeling inundation from simulated sea-level rise have been limited by coarse-resolution elevation datasets (surveys), field spot elevations, and United States Geological Survey (USGS) maps) as opposed to high resolution electronic imagery (Park et al. 1988; Moorhead and Brinson, 1995; Titus and Richman 2001; Nicholls, 2004; Titus and Wang, 2008; Duke et al. 2003). However communicating the importance of sea level rise to low lying local entities requires higher resolution data (Marbaix and Nicholls, 2007; Poulter and Halpin, 2007; Small and Nicholls,

2003). Low resolution Light Detection and Ranging (LiDAR) is available in many areas, but the coarse vertical definition (+/- 2 feet) is not useful for coastal areas where inches matter. High-resolution elevation data are needed for investigating the influence of topographic complexity on landscape processes, including drainage canals and levees (Duke et al. 2003). The availability of higher resolution LiDAR is among the factors that have led to an increased belief and trust in using LiDAR as a means for assessing vulnerable infrastructure and property due to their high horizontal resolution and vertical accuracy (Franklin, 2008; Stoker *et al.*, 2007; Gesch; 2009; NOAA, 2010, 2011). The increasing availability of high quality LiDAR in coastal areas allows for improved assessments to be done over more areas and integrated into national datasets (Gesch, 2007). The highest resolution LiDAR available is +/- 7 inches (0.2 m). Recent data is often available in many vulnerable coastal areas coastal Florida (Romah, 2012, 2013, NOAA, 2010, 2011).

The use of LiDAR has the benefit of translating easily to geographic information systems (GIS). The LiDAR data format use here was the American Standard Code for Information Interchange (ASCII) which is easily handled by ArcGIS software. The ASCII format is comprised of the raw LAS LiDAR data type format, translated into a geographically referenced X, Y, Z global coordinate plane system (FDOT, 2012). Of the different topographical data repository sources, NOAA offered the data natively in ASCII format. The dataset uses the NAVD 1988 datum.

Topography identifies vulnerable land, but soil storage capacity is what really identifies flooding potential. Where the soil can drain water, it will (although perviousness will delay soil drainage). To identify areas with soil storage capacity issues, the groundwater levels need to be determined (Romah, 2012). Bloetscher et al. (2013) noted that prior efforts used a variety of

elevations for high tide results and assumed that the groundwater elevation would seek high tide. However there may be a significant difference between mean high tide and the seasonal high tides which produce the most flooding. To generate the groundwater layer, six existing well locations were selected in Miami Beach to conduct continuous groundwater elevation monitoring as shown in Figure 1. An attempt was made to select appropriate locations based upon the proximity of wells to the coast, to each other, spatially and the hydrogeologic/hydrologic characteristics of their locations. Data loggers that collect salinity and water depth were placed in each of the monitoring stations in October 2012. Two rain gauges with an auto-tipping bucket system were also installed. This data was collected for a period of thirteen months (October through October 2013), and continues to be collected. The data was downloaded monthly. The monitoring wells indicated that the groundwater levels at five of the six sites varied with the tides. Figure 3 is typical of the wells, which shows that the groundwater table floats 0.1 to 0.3 ft above the tide elevations.

The monitoring well data was used to develop the ground water surface elevation layer. Various interpolation methods were considered to determine the surface. The resulting interpolation that produces the best performance measures was the ordinary krigging, which was then applied to the model as the groundwater surface elevation. A correction to groundwater data had to be completed to convert hydraulic head values from NGVD 1929 to NAVD 1988, to match the terrestrial elevation dataset. Two groundwater maps were developed as a result of significant changes in groundwater levels throughout the year: mean high tide as the current baseline, and peak seasonal water table (October after the wet season and corresponding to the seasonal high water table).

Next tide data was gathered. It was determined that the 95-100 percentile tides occurred primarily in the October timeframe (by listing all tides in order of smallest to largest). Tallying the tides for the 6 years in order, determined that the highest tides were nearly 2.3 feet. The frequency of flooding is a level-of-service issue and goes to the acceptability of flood frequency regardless of the source. Each community can define it differently, but the expectations of the public must be kept in mind when defining the stormwater level of service. For Miami Beach, the one can assume acceptability of flooding 50%, 10%, 5% or 1% of the days of the year. The mean condition results in a value of 0.795 ft (it should be noted that the initial planning level by the City's consultant used was 0.45 ft, and the prior City Engineer noted that asked the consultants to raise the level to 0.67 ft). However if flooding was permitted in certain low lying areas only 10% of the time, the planning level should be 1.2 ft. For 5% or 1% the levels should be 1.39 and 1.72 ft respectively. A level of service for vulnerability was defined as the 99th percentile - 4 flooding events per year (based on discussion with local officials). Since the tides occur coincidentally with the high water table (1.72 ft, with 0.3 ft of free float, a 2 foot October groundwater level/high, high tide data was krigged.

Overlaying the two maps identified the areas lacking capacity to drain the surface – low elevation and high water tables. Drilldown efforts using 10 x 10 ft ArcGIS tiles were used to identify “potentially vulnerable,” and thereafter “vulnerable” infrastructure which comports with directives from the United States Army Corps of Engineers that any coast or near-coast projects must include consideration of sea level rise. Based on identifying vulnerable areas, a toolbox of solution can be offered and barriers can be identified.

RESULTS

Mapping the City with LiDAR and topographic maps verified that the mapping could identify flooding areas (red areas in Figure 4a). The yellow areas are caution areas (within 2 feet of the high tide). The areas indicated in green represent land with elevations two feet above the referenced tidal datum, which would be considered low risk under current tidal conditions. Assuming the current high tide for planning purposes, where there is a 1% likelihood for there to be flooding somewhere in the City on any given day

Figure 4b shows the areas that are red are the vulnerable areas with a 1 ft increase in SLR. The yellow areas are caution areas (within 2 feet of the future high tide). There is a 36% likelihood for there to be flooding somewhere in the City on any given day with one foot of sea level rise. Figure 4c shows the areas that are red are the vulnerable areas with a 2 ft increase in SLR. there is a 97% likelihood for there to be flooding somewhere in the City on any given day with two foot of sea level rise. There is a 100% likelihood for there to be flooding somewhere in the City on any given day with three foot of sea level rise (see Figure 4d).

Meeting the Stormwater Challenge

Having identified the vulnerable areas of the City, the next step was to investigate potential options to remedy the situation. Pumping is an obvious answer but carries with it water quality impacts in nearshore waters. Table 1 is a list of potential stormwater solutions and the benefits and barriers. Transportation agencies and most municipalities rely heavily on exfiltration trenches or French drains. Southeast Florida is no exception. These systems work

164 because the perforated piping is located above the water table. They cease to function if they are
165 located below the water table. Exfiltration trenches could be replaced by stormwater gravity
166 wells or Class V injection wells. Stormwater gravity wells are a useful option where saltwater
167 underlies the surface.

168 Drainage wells along the southeast Florida coast can drain 1 MGD under certain
169 conditions. However as sea level rises, the potential differential may be altered since the
170 saltwater wedge may migrate inland as a result of surficial drainage efforts. Also, increased head
171 due to a water table rise will alter pump characteristics. Drainage wells require splitter boxes
172 and filters to remove solids, regular inspections to insure they are not plugged or backflowing
173 saltwater to the surface, maintenance to clean them, and permit compliance.

174 Class V injection wells may be useful as sea level rise progresses. A 24 inch Class V
175 injection well may have to be hundreds of feet deep and requires consideration of the
176 Underground Injection Control program under the Safe Drinking Water Act, something that is
177 not currently considered in most jurisdictions. Permitting and consistent monitoring of Class V
178 wells is required. As a result, the local entities will have to include ongoing stormwater efforts
179 for Class V well compliance.

180 For low lying areas, elevating roads may be an option. However, this option comes with
181 two significant issues: roadway elevations and impacts on adjacent properties. Local roadway
182 elevations will be limited by the adjacent buildings. All adjacent properties would need pumps to
183 remove their stormwater and prevent runoff from entering their property. In addition, sanitary
184 sewers, water mains and other utilities underlie these pavements and would need to be replaced.
185 Right-of-way abandonment is also an option but has severe consequences to adjacent properties.

Wellpoint systems are a series of small diameter wells spaced regularly along excavations of a project into the water table. Wellpoints are most commonly used in dewatering projects on construction sites. Wellpoint water is usually turbid containing sand, other particles, and contaminants from runoff. This form of dewatering requires a discharge zone, which will require offsite property. Wellpoint pump stations need to be regularly spaced along the affected roadway. As a result a series of pump stations might be needed for every mile of roadway since typical dewatering systems. Since wellpoints do not function in flood conditions, additional drainage measures must be taken to address wellpoint failure during heavy rainfall events. Infiltration trenches is a similar solution, but with larger capacity.

There is commonality among most of these solutions – cost and impacts to water bodies from water quality impacts of high nutrients and other materials. Solving the water quality impacts might lead to a beneficial solution.

Meeting the Stormwater and Water Supply Challenge Concurrently?

The production and delivery of drinking water, protection from flood waters and the treatment of wastewater are recognized as vital functions of society. The traditional utility operation has separated clean water (drinking water) from dirty waste and stormwater for public health simplicity. In most utilities, the crews and equipment are separate even if managed by the same public works of utility entity. In most cases, little linkage has been established despite efforts by various organizations to look at the total water. Some progress has been made in replacing irrigation with potable water with treated wastewater effluent, but stormwater is

generally outside the utility silo. Table 2 outlines the general strategies pursued by water supply utilities to deal with demand limitations.

It falls on governments to develop long-term strategies to sustain long-term economic viability and public health despite competing interests. The challenge in low lying areas with increase rainfall intensity and sea level rise will be too much water, not too little. Where water supplies are currently restricted, like much of the east coast, water supplies can become more reliable and sustainable through a comprehensive approach to water planning which includes using alternative water sources and planning future infrastructure needs with long-term trends in mind. In keeping with these categories of protection and adaptation as defined by Deyle, et al (2007), the question is whether infrastructure can serve multiple purposes. From a storm water/water supply perspective, the authors believe the answer is yes. The balance between water supply and flood protection will be adjusted by nature. Because of demands, the potential for saltwater intrusion and the uncertainty of sea level rise, coastal wells will likely be threatened further. Because the alternatives for new water supplies are limited (mostly saltwater sources), a small utility can be confronted by significant costs to build new water treatment facilities. However, many of those same communities will be dealing with increased flooding frequency because groundwater levels have consumed the soil storage capacity. Securing reliable water supplies for future generations and protecting land from flooding areas important in the face of changes in climatic patterns. Storage is one solution, but demands will vary widely creating difficulty in securing the “right” amount of storage. Most traditional pumping station solution will face a similar challenge – finding enough storage. However one set of solutions may benefit both water and stormwater managers – infiltration trenches.

Most of these communities are familiar with exfiltration trenches for drainage purposes, but as groundwater levels rise, these will cease to exfiltrate. But they will infiltrate. The use of horizontal well technology to reduce groundwater levels along streets and in neighborhoods would appear to be a solution to storm water that would appear to be a potential water supply options. Horizontal wells are used in conjunction with riverbank filtration and on island communities where water is limited. Horizontal wells have not been used in Florida because vertical wells have always been so productive. Horizontal wells could spread the cone of depression and minimize drawdowns to permit additional the skimming of fresh water just below the surface where it can increase soil capacity the most. Since these systems will run 24/7, they mimic water supplies.

Vertical well modeling and mathematics is related to the thickness, head and transmissivity of the aquifer. The thickness is not relevant to a horizontal well and the head is constant over the entire well screen. Horizontal wells must be screen, but can be much shallower than vertical wells as a result. Larger contact with the aquifer is also provided with a horizontal well. The horizontal well pulls equally surface, and as a result, the pumpage/capture can be matched to the seepage rate. No preferential flow paths result.

The production from a horizontal well is related to screen length, grain size of the sand, transmissivity of the sand, head, open space in the screen and other factors. A test program would need to be pursued to answer the productivity per foot of well screen. Once these values are known, the length of horizontal well is easily calculated and long-term development of additional horizontal wells is easily accomplished.

A bigger challenge will be permitting of the horizontal well. This may take time, and effort to demonstrate that the water used is direct rainfall capture. A final task will be to address the

groundwater under direct influence of surface water issue that is likely to arise due to the shallow nature of the horizontal well. A program must be designed for ongoing testing to comply with the groundwater under the direct influence of surface water rules, and identify appropriate treatment methods. But the use of infiltration trenches would seem to provide an opportunity to address soil storage capacity and water supply needs while protective both public health and property.

CONCLUSIONS

The hydrologic cycle is well understood in most areas, but it is currently changing. At the same time rainfall intensity is changing, despite the fact that precipitation patterns vary naturally from year to year, and over decades. There is strong evidence that global climate change is having an impact upon the world's water resources which may exacerbate current trends. As a result, flooding from intense rains will increase with time, especially in urban areas with altered surface conditions. Storm water utility managers are looking for a solution to deal with increased flooding frequency that residents recognize. Water supply utility managers are looking for reliable water supply solutions. The traditional barrier between utilities may prevent the potential for a unique solution to address both issues – infiltration galleries as storm water control tools. Infiltration galleries will reduce groundwater levels, which make soil capacity to absorb rainfall increase. Flooding will decrease. The systems will run 24/7. This solution has the potential to help many low lying areas and island communities extend the life of their communities from flooding damage by reduce flood risks. At the same time they may capture water to treat for water supplies.

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Table 1 Tools to Protect Infrastructure from Sea Level Rise Impacts

Solution	Benefits	Barriers
Increase stormwater drainage system capacity through more pumping	reduce flooding faster	nearshore water quality impacts if discharged to waterways; installation and operations cost, need to constantly increase capacity
Increase the number of pumping stations specifically installed to drain roadway right-of-ways	reduce flooding faster	nearshore water quality impacts if discharged to waterways; installation and operations cost, need to constantly increase capacity
Install gravity wells	Provide place for water to go	Only works where saltwater underlies freshwater, cost, need to constantly increase capacity
Install Class V injection wells	Provide place for water to go; high capacity	Permits, operations and installation cost, need to constantly increase capacity
Identify offsite stormwater retention areas to divert excess stormwater	Water quality and quantity benefit	will become inundated as sea level rises
Exfiltration trenches as a drainage solution	reduce flooding faster	will cease to work as groundwater levels rise
Raise roadway elevations	reduce flooding	offsite impacts, right-of-way acquisition
Abandon roadways too low and with neighboring areas too low to elevate without private property impacts	eliminates public sector cost	offsite impacts, lost infrastructure investment, loss of access to property, potentially catastrophic
Reengineering canal systems, control structures and pumping stations	reduce flooding faster	cost, nearshore impacts
Install wellpoint dewatering technology for permanent use	creates soil capacity for drainage, reduces flooding	nearshore water quality impacts if discharged to waterways; installation and operations cost,

		need to constantly increase capacity
Install infiltration dewatering technology for permanent use	creates soil capacity for drainage, reduces flooding	nearshore water quality impacts if discharged to waterways; installation and operations cost, need to constantly increase capacity

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439 Table 2 Summary of Water Supply Benefits and Climate Change Benefits from various Tools in
440 Toolbox
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Water Conservation	Lowers per capita use, stretched current supplies	Reduces stress on vulnerable water supplies
Protection of Existing Water Sources	Protects water quality and supply	Reduces stress on vulnerable water supplies
Desalination	New water source	Replaces vulnerable water supplies
Wastewater Reclamation	Replaces use of fresh water for irrigation and industrial use	Replaces vulnerable water supplies
Aquifer Recharge	Reduces raw water requirements	Recycles existing water to increase available fresh water
Aquifer Storage and Recovery	Storage mechanism for existing	Increased fresh water available for countering impacts
Capture and Surface Storage of Excess Runoff	Storage mechanism for existing	Increased fresh water available for countering impacts
Regionalization of Alternative Water Supplies	Shared risks of water supply options; Economies of scale	Economies of scale for wastewater and stormwater recovery and reuse
Re-engineering Canal Systems	Controlling water tables and protecting against contamination	Flood control
Regional Solutions	Recycles existing sources	Adds water to vulnerable sources

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Figure 1 Location of Monitoring wells.

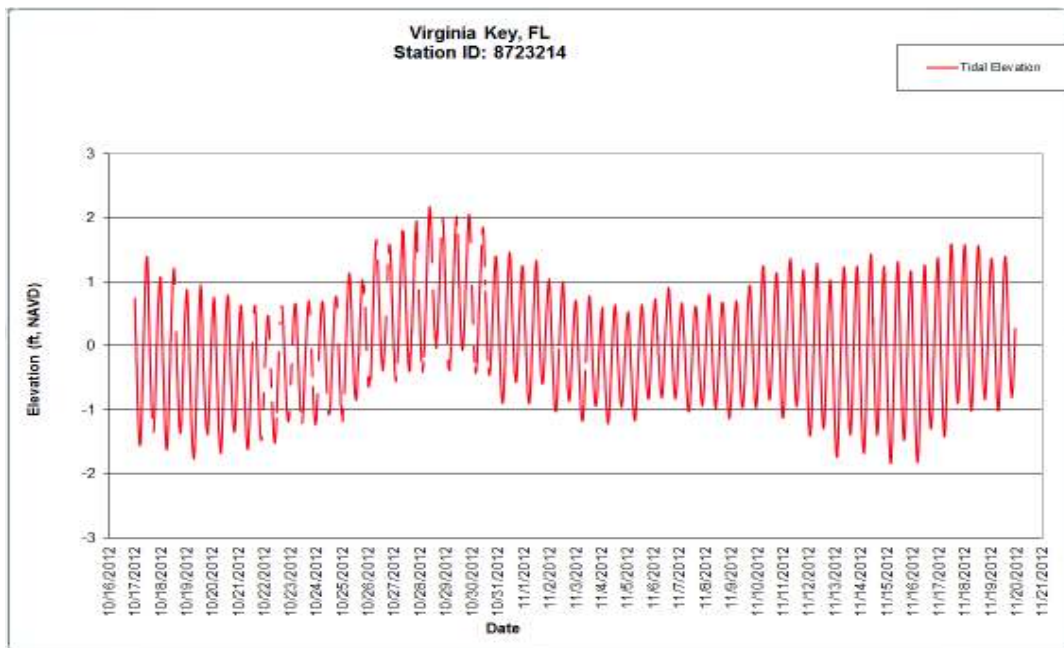
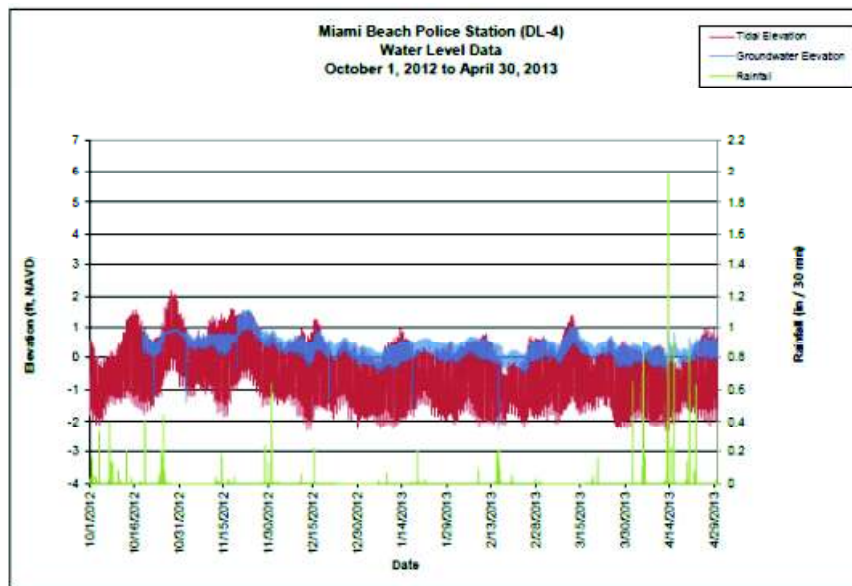


Figure 2 Tides from October 1, 2012 to April 30, 2013. Note the highest 3 day total is 2.0 fr. Normal low water table tide 3 day events are above 1 ft.

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Figure 3 Miami Beach Police station. The Miami Beach Police station site shows that the groundwater level basically matched the high tide, but fluctuated 0.5 ft downward as tides went out.

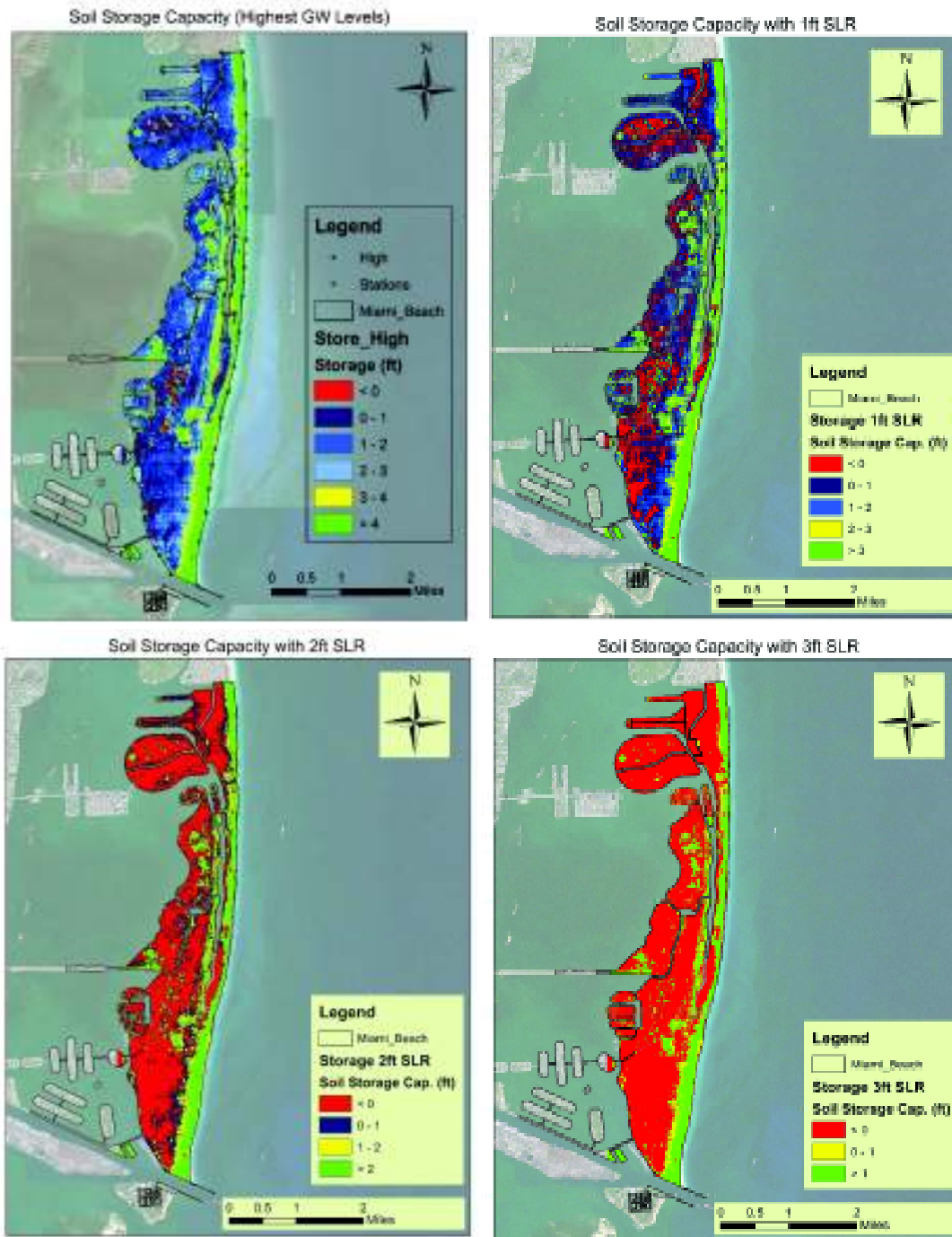


Figure 4a - d – Vulnerable Areas of Miami Beach under 0, 1, 2 and 3 ft Sea level rise scenarios