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Methodology for Predicting Local Impacts of Sea Level Rise

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Authors' contribution

Authors FB and NL designed the study. Author TA performed the field data collection. Author FB performed the statistical analysis in consultation with authors LB and NHH. Authors FB and NL wrote the protocol, and author FB wrote the first draft of the manuscript and managed literature searches. Authors FB, TA and NL managed the analyses of the study and authors FB and NHH performed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

In the future, south Florida will be flush with water due to sea level rise and increased storm intensity, meaning there are three options to deal with this problem – retreat, offshore discharges or finding a use for the water. The first is not an option so the others must be evaluated. To do so, the first task needed to identify solutions to this problem is to define the severity of the problem through a vulnerability analysis so the appropriate decisions can be made.

Aims: The objectives of this research were to develop an accurate methodology for predicting impacts of sea level rise and rainfall patterns 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 and flooding.

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Study Design: Based on a study of monitoring well water levels on Miami Beach, it was noted that during the year, groundwater levels fluctuate due to tidal levels and rainfall, with the Fall king tides creating the highest vulnerability to infrastructure and property. Once vulnerability is defined a toolbox of options can be developed to deal with local issues.
Results: The research found that the tides create a much larger vulnerability than current sea level rise analyses suggest and that the king tides drive the level of service for the community, while altering the dynamics of future stormwater planning efforts. To mitigate the impacts of flooding will require new ideas for dealing with excess waters. A toolbox of options was developed.
Conclusion: One item that arose was that there is potential to use stormwater adaptation strategies to create future water supplies.

Keywords: Sea level rise; flooding risk; alternative water supplies; infiltration galleries; horizontal wells.

1. INTRODUCTION

Climate change is expected to cause more intense rainfall events, such as thunderstorms and tropical cyclones [1-3], warmer temperatures [2,4] and increased sea levels due to increased rates of thermal expansion and ice melt from glaciers [1,5-18]). Gregory et al. [18] noted that in the last two decades, the global rate of sea level rise (SLR) has been greater than the 20th-century mean, and that there may be increasing contributions to global SLR from the effects of landmass snowmelt, groundwater depletion 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, climate change has manifested itself primarily as an increase in sea level [15,16], 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 developing flood management strategies [19-24]. Various researchers have already noted impacts on coastal and island environments [19-21,25-33].

The combination of rising seas and intense storms has the potential to overwhelm the 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, permitted development and controlled saltwater intrusion in south Florida [34]. The advent of sea level rise will present new challenges because the water table is currently maintained at the highest possible level to offset saltwater intrusion while maximizing water supplies [34-36]. As the sea level rises, it will disrupt the policy balance between flood risk and water supply availability [34].

South Florida has distinct wet and dry seasons [36]. 70 percent of the annual precipitation typically falls from June to September, just before the king tides. Despite receiving 60 inches of rainfall each year, ongoing flood protection efforts create a situation where south Florida is often water supply limited during the dry season as topography limits the ability to store excess wet season precipitation in surface reservoirs [36]. Soil storage is limited because the aquifer levels are often just below the surface in the wet season. It is this limited soil storage that leads to flooding, necessitating the extensive drainage works facilitate that discharge large volumes of water during the wet season, reducing availability in the dry, tourist season. These historical water management conflicts create periodic water restrictions, and led to a 2007 rule developed by the South Florida Water Management District that restricts further development of Biscayne aquifer wellfields [36].

Despite these historical water management conflicts and periodic disruptions, south Florida will remain a desirable place to live, so the interconnectedness of water will require the traditional barriers between water and storm water to be replaced with a more integrated solution that addresses the immediate concern about the sustainability of the Biscayne aquifer as a viable and efficient water supply source that will satisfy the public demands for future development in south Florida [34, 36], while protecting infrastructure and property from flood damage. New ideas will play a role. Storm water utility managers will need solutions to dispose of excess storm water that causes increased flooding frequency during routine rainfall as a result of soil storage capacity declines, while water supply utility managers are looking for reliable water supply solutions [36]. At present, there is a lack of good data to make decisions on what to do, when and with what priority. The vulnerability of infrastructure is of particular concern on coastal or island communities like those in southeast Florida.

A number of data sources are available to local officials to help initial screening of vulnerability. 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 [31,37-41]. However communicating the importance of sea level rise to low lying local entities requires higher resolution data because inches matter in many low-lying coastal areas [28,42-43]. An improvement to topographic maps is low resolution Light Detection and Ranging (LiDAR), which is available in many areas, but the coarse vertical definition (+/- 2 feet) is not useful for coastal areas that are within 3 to 5 feet of average sea level [34]. High-resolution elevation data are needed for investigating the influence of topographic complexity on landscape processes, including drainage canals and levees [41]. The increasing availability of high resolution LiDAR in coastal areas allows for improved assessments to be done over more areas and integrated into national datasets [44], and has led to an increased trust in using electronic measurements as a means for assessing vulnerable infrastructure and property [34,45-48]. The highest resolution LiDAR available is +/- 3 inches (0.1 m). Recent high resolution LIDAR data is often available in many vulnerable coastal areas of Florida [34,48-51].

The use of LiDAR has the benefit of translating easily to geographic information systems (GIS). The LiDAR data format used for this project was the American Standard Code for Information Interchange (ASCII) an uploaded to ArcGIS. The ASCII format is comprised of the raw LiDAR data type format, translated into a X, Y, Z global coordinate plane system [49,52]. While there are a number of topographical data repository sources, only the National Oceanographic and Atmospheric Administration (NOAA) offered the native data in ASCII format using the NAVD 1988 vertical datum [34,49-50].

Topography identifies vulnerable land, but soil storage capacity is what really identifies flooding potential. Where the soil can drain water, it will (although imperviousness can delay soil drainage). To identify areas with soil storage capacity issues, the groundwater levels need to be determined [49]. Bloetscher et al. [16,34] noted that prior efforts used a variety of elevations for high tide results, but found that the groundwater elevation would seek high tide as opposed to average tides. Where king tides and rainfall coincide the flooding potential was greatest.

1.1 Aims of the Study

This paper outlines an initial approach to assess sea level rise and flood vulnerability, as 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. A toolbox of options was developed to determine appropriate means to mitigate flood impacts.

2. METHODOLOGY

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. Each was outfitted with data loggers that collect salinity and water depth were placed in each of the monitoring stations in October 2012 to conduct continuous groundwater elevation monitoring (Fig. 1) [34]. An attempt was made to select locations at different distances from the ocean to characterize the tidal responses and the hydrogeologic/hydrologic characteristics of their locations [34]. Two rain gauges with an auto-tipping bucket system were also installed at two of the monitoring well locations. This data was collected for a period of thirteen months (October 2012 through October 2013), and continues to be collected. The data was downloaded monthly. Fig. 2 shows the results for one month. The monitoring wells indicated that the groundwater levels at five of the six sites varied with the tides. Fig. 3 is typical results from the 6 wells over the 13 month period. Fig. 3 shows that the groundwater table floats 0.2 to 0.5 ft above the high tide elevations.

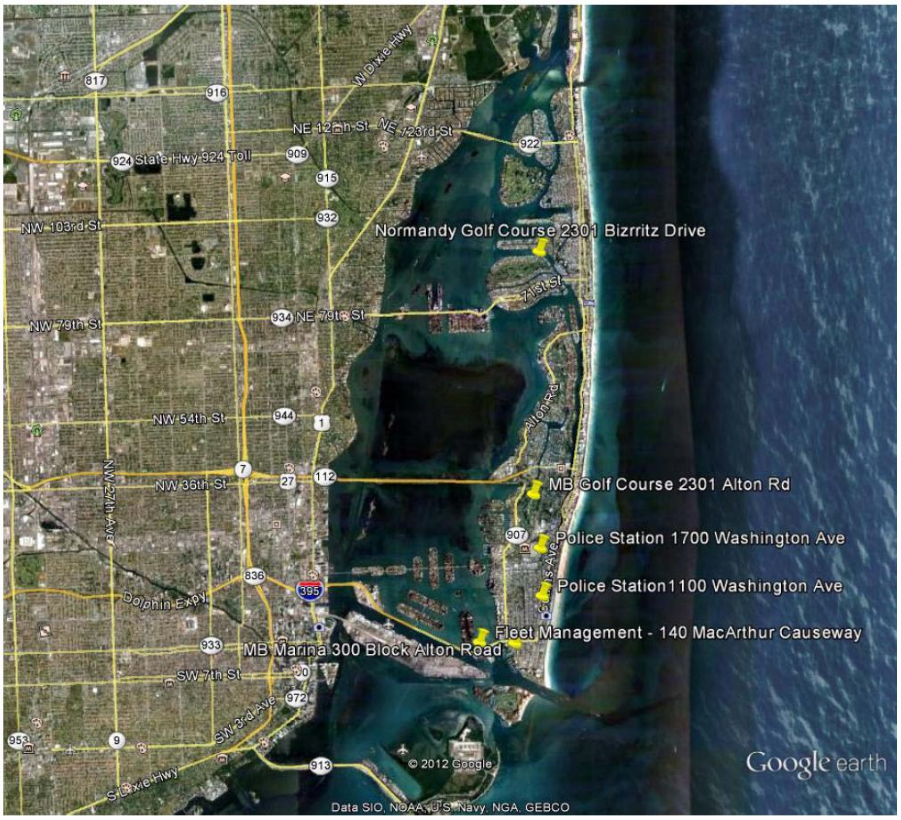

Fig. 1. Location of monitoring wells

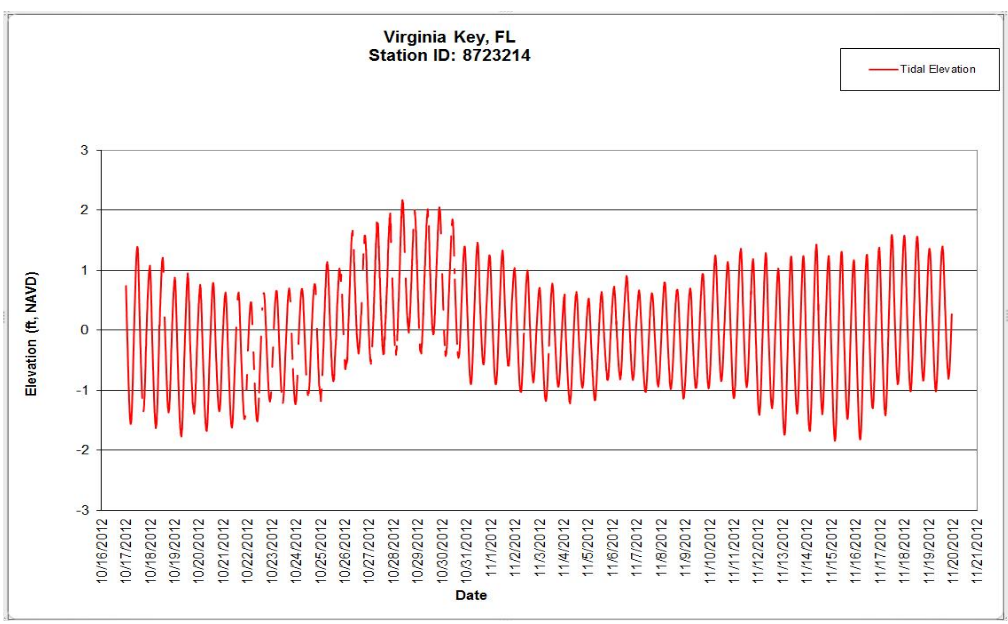

Fig. 2. Tides from October 1, 2012 to November 30, 2013. Note the highest 3 day total is 2.0 ft. Normal low water table tide 3 day events are above 1 ft.

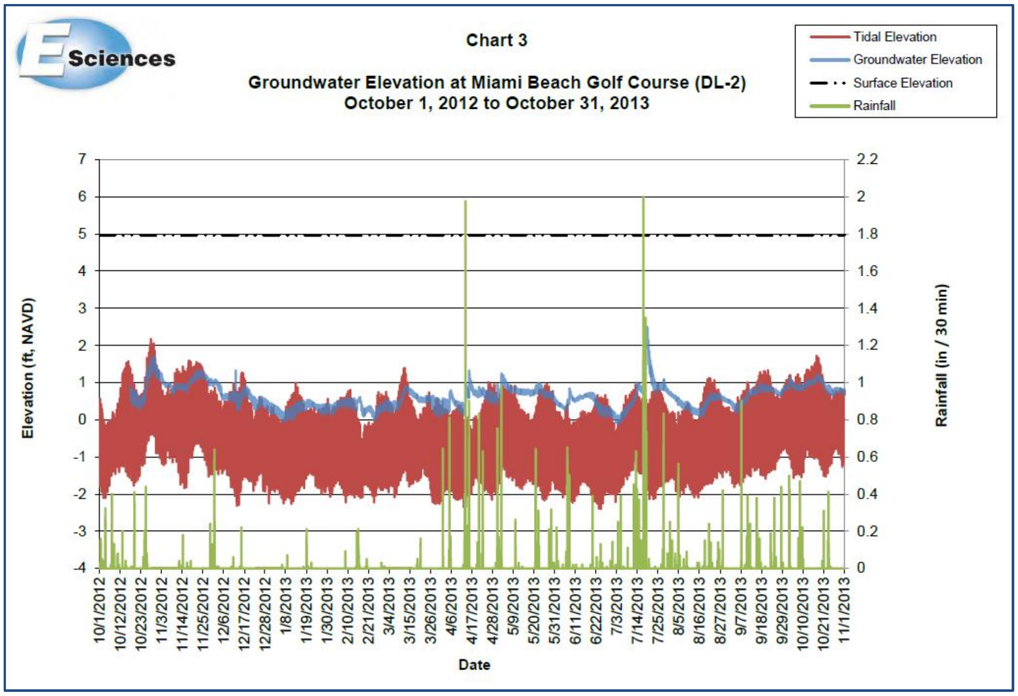

Fig. 3. Miami Beach golf course station. The Miami Beach golf course site shows that the groundwater level basically matched the high tide, but fluctuated 0.5 ft downward as tides went out

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 produced the best performance was ordinary krigging.

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 NAVD88. The frequency of flooding is a level-of-service issue and goes to the acceptability of flood frequency regardless of the source. While each community can define acceptable flooding frequency differently, the expectations of the public must be kept in mind. For example, Miami Beach, the one can assess the 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 [34], 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 this means that flooding would occur somewhere in the City every other day, which is not acceptable. However if flooding was permitted in certain low lying areas only 10% of the time, the planning level should be 1.2 ft [34]. For 5% of 1% the levels should be 1.39 and 1.72 ft respectively [34]. A level of service for vulnerability was defined as the 99th percentile - 4 flooding events per year (based on discussion with local officials) [34]. 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 [34]. This assessment was compared to the "bathtub" models used by other consultants and planners, which assumes that the groundwater is flat. Fig. 4 shows a substantial difference in the area that is vulnerable. Table 1 shows that the strategy used in this assessment obtains significantly more vulnerable property than the bathtub model today. The results are exacerbated with time.

3. FINDINGS

The high tides and the groundwater levels in the wells were krigged to create a groundwater surface elevation layer, and inserted into the GIS model. Two groundwater maps were developed: 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). It should be noted that hydraulic head values may need to be converted from NGVD 1929 to NAVD 1988, to match the terrestrial elevation dataset. Mapping the City with LiDAR and topographic maps verified that the mapping could identify flooding areas (red areas in Fig. 5a). 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, there is a 1% likelihood for there to be flooding somewhere in the City on any given day.

Fig. 5b shows the vulnerable areas in red. These are the areas that are vulnerable 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. Fig. 5c 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 (Fig. 5d).

3.1 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 water [34]s. Since offshore nutrient concentrations are of concern, direct discharge could pose a problem. 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 in southeast Florida. These systems work because the perforated piping is located above the water table. They cease to function if they are submerged [34]. However, exfiltration trenches could be replaced by stormwater gravity wells, Class V injection wells or infiltration galleries [34]. Stormwater gravity wells are a useful option where saltwater underlies the surface [34].

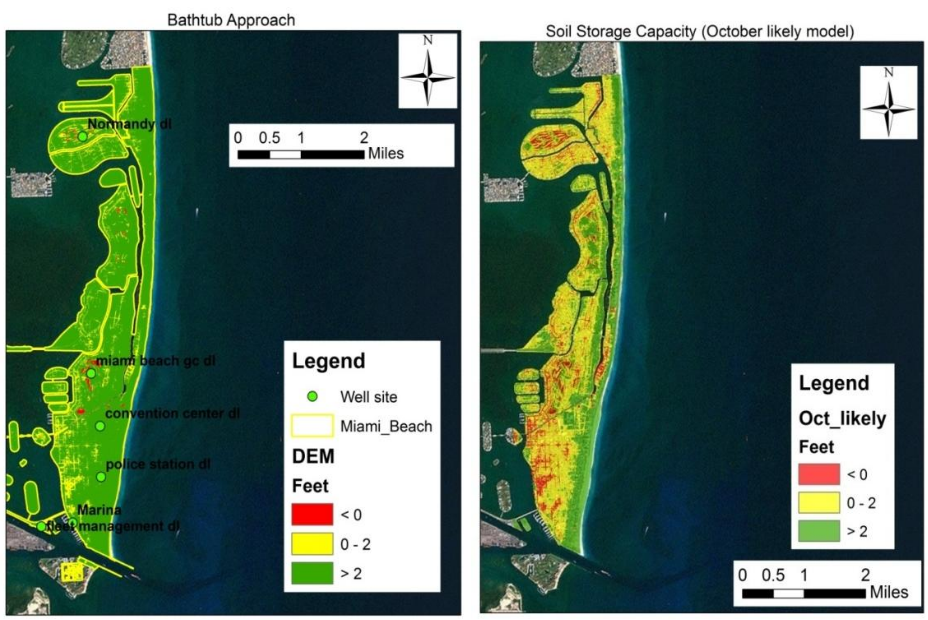

Fig. 4. Comparison of Bathtub model vs. Groundwater adjusted soil storage model

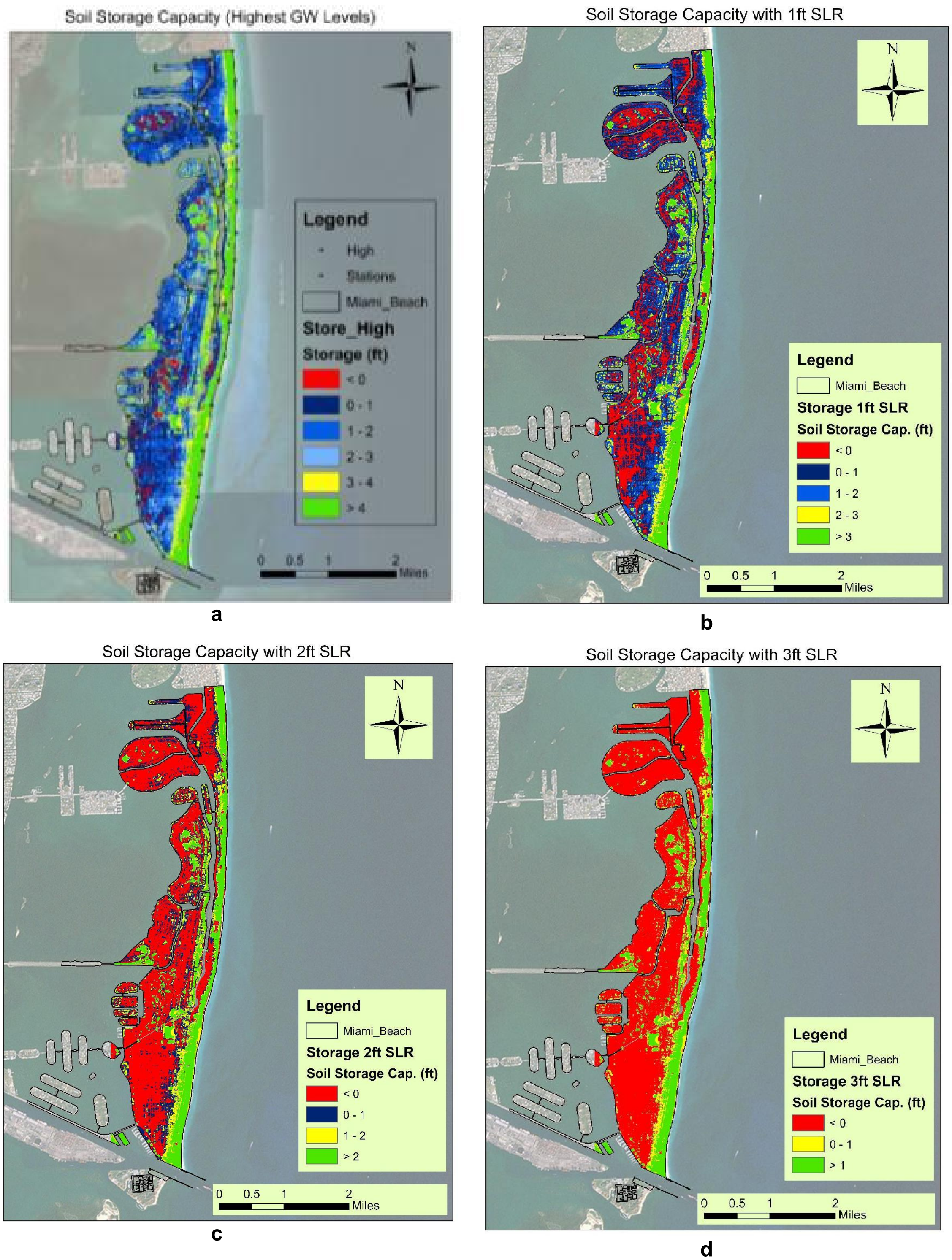

Fig. 5(a-d). Vulnerable and potentially vulnerable areas in the City of Miami Beach at present and assuming 1, 2 and 3 ft Sea level rise scenarios using soil storage model at 99 percentile tides

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

Class V drainage wells have been used to dispose of stormwater for years along the southeast Florida coast. Under the right conditions – head, salinity, depth, these wells can dispose of 1 MGD [34]. Because of the solids, turbidity and detrital matter from the surface, drainage wells require splitter boxes and filters and regular inspections to insure the wells are not plugged or backflowing saltwater to the surface [34]. However as sea level rises, the potential differential may be altered since the saltwater wedge may migrate inland as a result of surficial drainage efforts. Also, increased head due to a water table rise will alter pump characteristics.

For low lying areas, elevating roads may be an option. However, this option comes with two significant issues: the cost of raising roadway elevations and impacts on adjacent properties from same. Local roadway elevations will be limited by the adjacent buildings [34]. All adjacent properties would need pumps to remove their stormwater and prevent road runoff from entering their property. In addition, sanitary sewers, water mains and other utilities underlie these pavements and would need to be replaced. Right-of-way abandonment is also an option but has severe consequences to adjacent properties [34].

Wellpoint systems are a series of small diameter wells spaced regularly along excavations into the water table for dewatering construction sites. Wellpoint water is usually turbid, containing sand, silt and contaminants from runoff. This form of dewatering requires a discharge zone, which will require offsite property and a means to control turbidity. Wellpoint pump stations would need to be regularly spaced along the affected roadway to be successful in keeping low-lying roads dry [34]. 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 and better performance during rainfall events since they operate more like sanitary sewer lift stations [34].

There is commonality among most of these solutions – they can be implemented at the local level, they all have a cost of implementation, and they all require ongoing efforts to control and monitor water quality to discharge points – wells, private property or water bodies. All of these apply to Miami Beach, which is similar in characteristics to many coastal communities. As a result, finding unique solutions to mitigate the water quality impacts might lead to other beneficial solutions.

3.2 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 and the local public works entity. The traditional utility operations have separated “clean” 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 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.”

The challenge in low lying areas with increase rainfall intensity and sea level rise will be too much water, not too little as has been noted. Where water supplies are restricted, water supplies can be made more reliable, in the long-term sustainable through a comprehensive approach to water planning that combines alternative water sources and planning future infrastructure needs [34]. In keeping with these categories of protection and adaptation as defined by Deyle [53], the question is how to make infrastructure can serve multiple purposes and be able to be constructed incrementally over time and needs demand, without the need to abandon any of these investments. From a storm water/water supply perspective, the authors believe the answer is yes.

As noted in Bloetscher et al. [34], the uncertainty associated with sea level rise and the ongoing risk from saltwater intrusion as a result of managed aquifer levels, coastal wells will continue to be threatened as history has shown. Alternatives for new water supplies are limited (mostly saltwater sources) which can only be overcome with significant costs to build new water treatment facilities. Stormwater is rarely mentioned as a supply, but all rivers are stormwater runoff [34]. Coastal areas will not be able to store this runoff for topographical reasons, but, infiltration trenches will work continuously, and require a continuous point of discharge. A water treatment plant is a solution to the water quality and water supply conundrum.

The use of infiltration galleries along streets and would accomplish the same thing as wellpoints. The concept is not new as it is sued throughout the west as a means to obtain higher quality water from surface rivers and streams. In those places it is termed riverbank filtration. In island communities the technology is used to skim freshwater lenses that reside atop saltwater. Infiltration galleries or horizontal wells, have not been used in Florida because vertical wells have always been so productive. However the benefits is that infiltration galleries could spread the cone of depression and minimize drawdowns, which would facilitate the skimming of additional fresh water supplies from above the saltwater intrusion front, while concurrently increasing soil capacity. Since these systems will run continuously, they mimic water supplies.

4. CONCLUSIONS AND RECOMMENDATIONS

The hydrologic cycle is currently changing in many locales. Global climate change is having an impact upon the world's water resources which may exacerbate current trends. Experts expect more flooding from intense rains with time, especially in urban areas with altered surface conditions. At the same time, storm water utility managers are looking for a solution to identify vulnerable areas and to identify solutions to deal with increased flooding frequency that residents recognize, and water supply utility managers are looking for additional, and more reliable water supply solutions.

In this investigation, GIS mapping, high resolution LiDAR and groundwater mapping from well data was used to identify the vulnerable areas in Miami Beach from 0, 1,2 and 3 feet of sea level rise. The City has significant vulnerability which is not surprising. What was noted was that flooding occurs concurrently with king tides and the end of the wet season, which create the worst conditions on the island. The same can be applied to other south Florida island communities. The solutions indicated that the traditional barriers between utilities may frustrate efforts to derive unique solutions to address both stormwater excess and water supply needs. Infiltration galleries were identified as a tool that has the potential to reduce groundwater levels, which make soil capacity to absorb rainfall increase, while creating a constant water supply. Flooding frequency should decrease, while water supply sources increase. The infiltration gallery 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 while capturing water to treat for water supplies.

However the parameters that define infiltration galleries is site specific. 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, all of which are site specific. Hence any proposed infiltration gallery program will require a local testing program to define the productivity per foot of well screen. Once this value is 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 to demonstrate that the water used is direct rainfall capture. Once demonstrated, the final task will be to address the "groundwater under direct influence of surface" water issue in the Safe Drinking Water Act. This requirement places more frequent monitoring on the utility as compared with traditional groundwater sources. 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 being protective of both public health and property.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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