Municipal adaptation to sea-level rise: City of Satellite Beach, Florida

Submitted to:
City of Satellite Beach, Florida

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It is now widely accepted global sea level will rise a meter or more by the year 2100, yet prior to this investigation no local government along the east-central Florida coast had begun to seriously address the potential consequences of concomitant erosion and inundation. In the fall of 2009, the City of Satellite Beach (City), Florida, authorized a project designed to: (1) assess municipal vulnerability to rising sea level and (2) initiate the planning process to properly mitigate impacts.

Results indicate about 5% of the City landscape will submerge during the initial +2 ft (0.6 m) rise, with inundation generally restricted to fringing wetlands and finger canal margins proximal to the Banana River. At +4 ft (1.2 m), 25% of the City is submerged including South Patrick Drive, one of two major transportation corridors through the City. Residential areas in the north- (c.f. Pelican Coast) and south-west corners of the City are subject to limited inundation. At an elevation of +6 ft (1.8 m), 52% of the City is underwater including the entire western half centered on South Patrick Drive. Much of the Pelican Coast neighborhood is submerged, as are residential areas located in the southwest portion of the City. The function of "critical assets" (i.e., fire/rescue), designated emergency evacuation routes (i.e., South Patrick Drive), and the gravity driven storm-water system is compromised proportional to the magnitude of rise.

Based primarily upon the City's hypsographic curve, the "tipping point" towards catastrophic inundation is +2 ft (0.6 m), forecast to occur around 2050. Thus, the City has about 40 years to formulate and implement a mitigation plan. The City appears likely to respond through adaptive management. This is an on-going and iterative process that specifies one or more essential actions necessary to reduce the vulnerability to rising seas. As an initial step, the Comprehensive Planning Advisory Board, a volunteer citizen committee serving as the City's local planning authority, has approved a series of updates and revisions to the City's Comprehensive Plan. If approved by the City Council, the amendments will provide a legal basis for implementing an adaptive management plan and specific actions designed to mitigate the City's vulnerability to sea-level rise.

INTRODUCTION

It is now widely accepted global sea level will rise a meter or more by the year 2100 (Figure 1). In response, myriad documents have been written describing the rationale and methods for coastal municipalities to begin planning for the inevitable submergence of vulnerable areas within their borders (c.f. California State Lands Commission 2009, Deyle and others 2007, EPA 2009, Johnson 2000). However, at the time of this investigation no local government along east-central Florida coast (Volusia, Brevard, and Indian River Counties) had begun to seriously address either climate change or sea-level rise. This was in part due to perceptions regarding scientific uncertainty and that “climate change” programs will require financing from local governments already struggling to meet existing demands.

Despite these obstacles, the City of Satellite Beach (City; Figure 2 and 3) authorized a project designed to: (1) assess municipal vulnerability to rising sea level and (2) initiate steps to properly plan for anticipated changes to the built and natural environments. The City’s commitment to the project was secured by the availability of outside funds and an assurance of objectivity. Funds to conduct the assessment were provided by the United States Environmental Protection Agency (EPA) Climate Ready Estuaries (CRE) Program made available through the Indian River Lagoon National Estuary Program. The goal of this program is to enhance local efforts to develop a climate change adaptation plan that may not occur or otherwise be limited by inadequate financial resources. Objectivity was assured by designing a transparent scope of work based upon sound scientific principles.

The purpose of this paper is to describe the methods used to assess municipal vulnerability to sea-level rise and the initial planning process to mitigate submergence. Given the limited funding ($25,000) and project duration (1 year), it was conceived as a pilot project with application to other municipalities along the east-central Florida coast.

BACKGROUND

Description of the City of Satellite Beach

The City of Satellite Beach is located in Brevard County, Florida, east of Orlando and south of Cape Canaveral (Figure 3). It consists of 8.8 square kilometers of Holocene barrier island with east and west boundaries delineated by the Atlantic Ocean and Banana River shorelines. The island consists principally of an unconsolidated mixture of quartz and shell sand, locally capped by a thin layer of wetland peat or upland soil profile. The maximum width of the island within City limits is 2.5 km. The current population of 10,848 corresponds to a density of 1,233 residents per square kilometer. This population density exceeds 85% of Florida’s other municipalities due to a lack of extensive industrial or commercial development. Ninety-eight percent of the City’s landscape is built; leaving only 2% as undeveloped.

The City’s highest elevation barely exceeds 20 ft (6.1 m) and is associated with the Atlantic Ocean coastal dune system, which otherwise averages about ±15 ft (4.6 m) above sea level. Topography decreases westward and away from the coastal dune system, with approximately one-half of the City's landscape at elevations of +6 ft (8.1 m) or less.

Existing Hazards

Coastal erosion

All 36.5 miles (58.7 km) of Brevard County's beaches south of Cape Canaveral and including the entire shoreline of City are designated by the Florida Department of Environmental Protection (Clark 2008) as critically eroded. A critically eroded shoreline imminently threatens upland development, recreational interests, wildlife habitat, or important cultural resources. Sea-level rise forecast to accompany climate change is expected to increase the magnitude and extent of erosion along the entire Brevard County coastline.

Storm surge

Although the City has not been subject to landfall of a hurricane in excess of a moderate Category 2 storm since at least the mid 19th Century, the potential devastating effects caused by flooding alone are enormous (Table 1). An increase in the magnitude and/or frequency of storm landfall predicted to accompany climate change (c.f. Bender et al. 2010) will surely elevate risk associated with storm surge, water waves, wind and rainfall damage. Rising sea level will expand the extent and depth of flooding associated with storm surge.

Sea-level rise

Florida's geologic record (i.e., sedimentology, stratigraphy, radiocarbon dates, paleontology) indicates the post-glacial marine transgression can be subdivided into three intervals, each characterized by a distinct rate of rise and unique shoreline response (Table 2). These data clearly indicate Florida shorelines were subject to landward retreat by erosion and submergence when sea level rose at a rate of 2 mm/yr or more. The only interval of coastal stability occurred during the late Holocene (3,000 ybp to present), when sea level was rising a few tenths of a millimeter per year.

During the 20th century, long-term tide-gauge data indicate the rate of sea level rise averaged 1.7 mm/yr, with an increase in the rate of rise over this period. This rate is faster than the preceding 3,000 year interval and is attributed principally to rising atmospheric temperatures and concomitant thermal expansion of the ocean's surface layer. All 30 coastal states have experienced moderate to severe erosion during this interval of accelerated sea level rise (Williams and others 2009).

More recently (1993 to 2006), high precision satellite altimeters indicate sea level has been rising at 3.3 ± 0.4 mm (0.13 ± 0.02 in) per year (Rahmstorf and others 2007). This most recent interval of acceleration is a direct consequence of the increasing influx of glacial meltwater from Antarctica and Greenland (c.f. Vinther 2007). Given the strong relationship between the rate of sea level rise and Florida coastal response (Table 2), this recent acceleration has likely exacerbated historical trends in coastal erosion, flooding, and related deleterious effects (i.e., salt water intrusion into local aquifers).

Methods

To successfully undertake an assessment of municipal vulnerability that ultimately triggers action by the City Council it was deemed crucial to maintain a public education and outreach campaign during the entire duration of the project. This campaign was designed to target local stakeholders and decision makers. Activities consisted of:

- Project Team - a team of local stakeholders was established to facilitate the successful completion of the project. It consisted of representatives of the City and the Indian River Lagoon National Estuary Program, scientists, staff from Brevard County Office on Natural Resources, and the East Central Florida Regional Planning Council. This group met regularly throughout the duration of the project.

- Public Forums – utilizing facilities located within and proximal to the City, these events were designed to provide information on climate change and sea level rise with increasing site- and project-specific detail over time. Hence, an overview of climate change and sea-level rise were presented by "outside experts" during the first forum. The second forum presented information on the potential effects of climate change and sea-level rise to the Space Coast region using a locally recognized "expert". Subsequent forums focused on: (1) the CRE project goal and objects and (2) results and recommendations. Each presentation was posted on the website of the City and the Space Coast Climate Change Initiative for further educational and outreach purposes and for viewing at a later date.

- "Sea-level rise" sub-committee – to ensure effective transfer of technical information to the City's decision makers, the project team worked directly with a newly formed *Sea-Level Rise Subcommittee* of the City's Comprehensive Planning Advisory Board (CPAB). Representatives of the project team met with the sub-committee members during their regularly scheduled monthly meetings to report on project results and to convey recommendations regarding how the City might respond.

- Ongoing media campaign – Throughout the duration of the project, press releases, op-ed pieces, radio PSAs, and updates to the City newsletter were submitted to the local media as a means of communicating project progress. The project team also allotted time to communicate directly with local media contacts to facilitate timely publication.

The assessment of municipal vulnerability to sea-level rise was undertaken in three steps: (1) development of a three-dimensional model or "base map" of the City, (2) compilation and mapping of "critical infrastructure and assets" (hereafter assets), and (3) quantification of the extent to which the City and it's critical assets would be inundated by sea-level rise.

Modeling the City

Using a GIS platform (i.e., ArcGIS 9.3), a three-dimensional model of the City was constructed. Model elements included recent, geo-rectified orthophotography and shape-files representing roads, boundaries, water bodies, and other resources (c.f. Figure 3).

To emulate three-dimensions, landscape elevation was added to the base map using LiDAR and associated orthophotography acquired by the Florida Division of Emergency Management (FDEM). FDEM is responsible for developing and maintaining regional evacuation studies to assist disaster response personnel in preparing for all major hazards. The agency was directed by the Florida Legislature in 2006 to update coastal storm surge models using advanced high resolution technologies and computer-modeling. After a rigorous QA/QC review, these data were made available to Brevard County in 2009 (Figure 4).

The LiDAR elevation data is referenced to NAVD88. Extensive review of NOAA tide gauge stations located proximal to the City along the Atlantic Ocean and Banana River (c.f. No. 8721608 Canaveral Harbor Entrance, No. 8721843 Melbourne Causeway, No. 8721647 Merritt Causeway East, No. 8721789 Carters Cut, and No. 8722004 Sebastian Inlet), together with recommendations from other Florida Counties grappling with this topic (i.e., Hal Wanless, Miami-Dade Climate Change Advisory Task Force; Nancy Gassman, Broward County) yielded a determination that the vertical datum should be changed to reflect Banana River mean water level (MWL; Figure 3). The rational for choosing a vertical datum linked to Banana River water level elevations was in large part a consequence of the fact surging waters which overtop the City have historically originated from this water body. Submergence of the City by an Atlantic Ocean surge has generally been impeded by the presence of the contiguous coastal dune system with a minimal elevation of +14 ft (4.3 m).

The data collected at Carters Cut (NOAA tide gauge station No. 8721789; Figure 3) was ultimately used to establish the project's vertical datum. Mean water level (MWL) during the period 1996 to 2001 is reported as -0.214 m (-0.702 ft) NAVD88 (T. Cera, St. Johns River Water Management District, unpublished 2010). To adjust for the effects of rising sea level during the subsequent decade (i.e., 2001 to 2010) the MWL elevation was increased by 0.025 m (0.08 ft) or 2.5 mm (0.1 in) per year. This adjustment was based upon estimates of global sea-level rise (c.f., Bindoff and others 2007) and Florida tide gauge data (c.f. Lyles and others 1988; Maul 2008). The adjusted vertical datum or MWL_{2010} is therefore -0.189 m (-0.62 ft) NAVD88.

The resulting topographic model for the City is shown in Figure 4. These data depict a geomorphology that is typical of Holocene barrier islands along Florida's eastern coast including:

- Highest elevations of 20+ ft (6.1 m) associated with the modern Atlantic coastal dune system

- An undulatory or ridge and swale topography within the central portion of the island. These features can be traced northward into Cape Canaveral and Merritt Island; an extensive relict beach-ridge system.
- Lowlands of +6 ft (1.8 m) or less throughout the western half of the island
- Dredged canals, open water, and fresh- to brackish-water wetlands adjacent to the Banana River.

The LiDAR data were also used to construct a hypsographic curve for the City (Figure 5). This curve illustrates the cumulative percent of land area as a function of elevation and can be used to estimate the extent of municipal submergence associated with a particular rise in sea level. For example, a sea level rise of +2ft (0.61 m) will inundate approximately 5% of the City's landscape.

<u>Critical Assets</u>

The project team established a list of critical assets based upon a working definition –

Buildings and facilities essential to a municipality's economy and the quality of life of its residents

The asset list (Figure 5, Table 3) was compiled by the City, the East Central Florida Regional Planning Council, and other source agencies. The corresponding asset data and associated attributes (i.e., x & y coordinates, asset name or ID, source description) were then added to the GIS platform.

<u>Municipal Submergence</u>

As an initial step in modeling municipal submergence, the project team conducted a literature review of current sea-level rise projections. Projections of sea-level rise have evolved rapidly over the past twenty years in large part a consequence of the maturation of general circulation models. The initial forecast considered for use during this investigation was that published in the 4th Assessment of the IPCC (Bindoff et al. 2007). However, forecasts of sea-level rise well in excess the IPCC assessment emerged shortly thereafter as the volume of meltwater from Greenland and Antarctic ice sheets became ever larger and well documented. The project team eventually settled on the work of Rahmstorf and colleagues (c.f. Rahmstorf 2007, Vemeer and Rahmstorf 2009; Figure 6) as representative of the currently accepted "best guess". In all cases, a sea-level rise of at least one meter is now forecast by the year 2100.

At the time of this investigation vulnerability assessments were being described with reference to: (1) a specific year (i.e., 2060 or 2100; c.f. Department of Environment, Climate Change and Water 2009), (2) an emissions and corresponding sea-level rise scenario (i.e., IPCC B1or A1B; Burg 2010) and (3) a specific sea-level elevation (i.e. +30 cm or +60 cm; c.f. Fraiser 2009). Given the ongoing debates regarding the precise nature of future greenhouse gas emissions, atmospheric change, melting ice sheets, and resulting sea-level rise, the project team decided the most defensible approach was to evaluate the vulnerability of the City as a function of sea-level elevation. Therefore, the assessment would proceed by performing a time-series analysis of rising sea level at 1ft (0.3 m) intervals with an upper boundary of +6 ft (1.8 m) as representative of the current maximum elevation likely reached by the year 2100.

In all cases, City assets were "impacted" when the elevation of rising sea level (i.e., +1 ft above MWL) was equal to or greater than the elevation of the asset as indicated on the LiDAR-based topographic layer. The asset is initially *flooded* by *seasonal* high water in association with astronomic tides (aka the fall rise) and storm surge (details below). *Permanent submergence* follows as a function of long-term sea-level rise. The application of this impact rule is obvious for assets represented by a point. For those mapped as a line (i.e., roads), the geoprocessing function CLIP was performed to isolate individual sections of the line data submerged by each one foot rise in sea level. In the case of features mapped as polygons, the elevation of the asset's centroid was used to quantify vulnerability.

<u>Limitations of model</u>

This impact assessment is based upon the flooding of static terrain; i.e., the topography does not change as rising seas inundate the landscape. Vulnerability assessments conducted in this way have also been described as a "bathtub model" given similarity to the flooding in a bathtub as the level of water rises with increasing volume. The use of a bathtub model during this investigation was not considered a serious weakness in part because the project was designed as a pilot study to provide both stakeholders and decision makers with an objective base-line from which an initial discussion regarding the magnitude and consequences of sea-level rise could begin.

In addition, it is likely the magnitude of geomorphic change (i.e., erosion) induced by water-waves and currents will not be significant. This suggestion is based upon geologic studies conducted on Florida's continental shelf, where paleo-coastlines of early Holocene age were simply overtopped and bypassed by shoreline erosion when subject to rates of sea-level rise comparable to those now being forecast to accompany climate change (Table 2). Erosion along segments of the City's shoreline and associated coastal dune can be expected to initially accelerate, however, as the elevation and rate of rate of rise continue to increase much of the remaining low-lying landscape will likely be overtopped without significant topographic change; i.e., after exceeding local topographic elevations, the shoreline will simply advance landward to the next emergent feature until it too is overtopped. For the purposes of this study, dredge and fill operations (aka beach nourishment) were assumed to delay shoreline change and therefore contribute to a static shoreline as was modeled in this pilot study.

Finally, the use of a static landscape model is also justified by the presence of extensive coastal armoring along municipal shorelines; roughly one-third of the City's Atlantic shoreline and two-thirds of the canal shorelines are armored (J. Fergus, personal communication June 2010). These engineered structures will limit shoreline retreat until they too are overtopped by rising water.

Results

<u>Controls on Landscape Submergence</u>

Local Relief

The progression of municipal landscape submergence during sea-level rise over the balance of this century will be dictated primarily by the local relief encountered as rising waters of the Banana River advance eastward and into the City. The City's local relief is not haphazard or random, but instead has evolved over time in response to: (1) geological processes, (2) historical dredge and fill projects, and (3) urban construction activities.

In general, the surface of a barrier island is highest along the seaward shoreline and slopes westward as a consequence of diminishing energy (i.e., breaking waves). Hence the lowest elevations are located along the western margin of the City and adjacent to the Banana River. The Grand Canal (Figure 2 and 3) was excavated through this low-lying western terrain during the latter 1950s and the spoil material generated during the dredging process placed directly on top of Banana River wetlands which lay to the west. This spoil would ultimately become known as Tortoise, Samsons, and Lansing Islands. Additional spoil was generated during the construction of the finger canals to the east of the Grand Canal. This material was used to increase the elevation of upland areas (aka home sites) located between each of the newly constructed navigable waterways.

Anthropogenic alteration of the island's geomorphology ultimately created a municipal landscape with minimum elevations coinciding with South Patrick Drive (Figures 4 and 7). Terrain elevations increase both east and west of this roadway, however western elevations are higher due to the presence of Grand Canal and finger canal spoil material. By contrast, terrain elevations to the east of South Patrick Drive have not been subjected to extensive alteration and therefore are relatively low. Local relief of the barrier island south of Cassis Blvd, where the City lacks a western shoreline (Figure 4), has not been altered by extensive dredge and fill. Thus, the lowest elevations of the City in this area are located along the City's western boundary.

Trends in local relief and municipal landscape elevation were modified at a much smaller scale during construction of residential developments. To reduce the risk of flooding, planned home sites were elevated above natural grade using fill material gathered during the grading (lowering) of roadways and excavation of companion drainage ditches. The residential landscape thus hosts a network or grid of narrow, linear depressions.

Seasonal Flooding

Each fall, water levels in the Banana River rise approximately one foot as a consequence astronomic tidal forcing (aka the fall rise). As a consequence, neighborhoods proximal to the Banana River generally flood several times a year. The magnitude and extent of seasonal flooding can be compounded by concomitant heavy rain and "tidal"-surge associated with landfall of tropical storms and hurricanes. In the short term, this standing water renders streets impassable and disrupts the continuity of evacuation routes. The periodic saturation of sub-surface layers beneath the City's network of roads has also been shown to reduce structural integrity and design life. This in turn leads to rising costs for road maintenance. Seasonal flooding events can also disrupt the function of the City's gravity-driven storm-water system.

As a consequence, the City requested the project team track the location of seasonally flooded areas in response to sea-level rise. Water level records collected at the Carters Cut tide gauge station (Figure 3) include four "fall rise" events; 1996 to 2000. During the year 1999, Tropical Storm Irene made landfall, compounding flooding problems as the Banana River rose nearly a meter above mean water level. The project team chose to emulate the fall rise by simply inspecting the submergence data associated with next stage of rising sea level. To limit confusion, the term "flooding" is used when referring to areas seasonally inundated. The term "submerged" is used describing areas inundated as a consequence of rising sea level.

Municipal Submergence

The extent of municipal submergence anticipated to accompany a sea-level rise of between +1 ft and +6 ft (0.3 m and 1.8 m) is illustrated in Figure 8. The impact to the urban landscape and critical assets is summarized in Table 4 and as follows.

During the initial +2 ft (0.6 m) sea-level rise about 5% of the City's landscape is submerged including: (1) the wetland fringe and canal margins of Lansing and Tortoise Islands and (2) the banks of finger canals located east of the Grand Canal. Perhaps the most significant impact is to Samsons Island, wherein roughly one-half of the island is submerged. The relatively low elevation of Samsons Island is a direct result of two decades of management as conservation land, during which there was no incentive to place additional fill on the island. Furthermore, segments of the island's shoreline and interior have been lowered by removal of fill in conjunction with wetland mitigation.

The subsequent +2 ft (0.6 m) rise in sea level is of much greater consequence as an additional 20% of the City is submerged. There is continued inundation of the City's three islands and the municipal landscape along South Patrick Drive. By the time sea-level reaches +4 ft (1.2 m) above MWL_{2010}, the entire South Patrick Drive transportation corridor is submerged, as are neighborhoods in the southwest region of the City. Several major roads (i.e., Roosevelt Ave, DeSoto Pkwy) extend flooding eastward to within one half mile of Highway A1A.

Submergence is again widespread as sea level rise approaches +6 ft (1.8 m) above MWL_{2010}. By then, 52% of the City is underwater. This includes the entire western half of the City proximal to South Patrick Drive, most of the Pelican Coast neighborhood to the north, and about a third of the City's residential area located along its western boarder between Cassia Blvd and Satellite Ave. Major roads extend the limit of flooding and submergence eastward to within one quarter mile of Highway A1A.

In addition to expanded flooding and submergence, each stage in sea-level rise compromises the function of critical assets, emergency evacuation routes, and the gravity driven storm-water system.

Discussion

Summary of Findings

This project utilized a "bathtub" model to assess municipal vulnerability to sea-level rise of as much as +6 ft (1.8 m). The model's numerous simplifying assumptions (i.e., static Atlantic shoreline and groundwater table) yield a conservative estimate and supplemental work to refine the model will likely forecast inundation at an even larger scale. Regardless, the findings of this pilot project are sufficiently robust to warrant action.

The City is expected to lose 5% of its landscape during the initial +2 ft (0.6 m) of sea-level rise and this will be limited to fringing wetlands and canals. However, the subsequent +2 ft (0.6 m) rise is forecast to submerge an additional 20% including residential neighborhoods, important transportation corridors, and numerous critical assets. A "tipping point" of +2 ft MWL_{2010} is thus proposed for the City and clearly visible as a distinct reduction in the slope of its hypsographic curve. The tipping point elevation is forecast in 2050 and therefore the City has about 40 years to formulate and implement an adaptive management plan.

Managing Sea-Level Rise

There are three basic options in responding to sea-level rise: (1) protect, (2) retreat, and (3) accommodate (Deyle and others 2007). According to Titus (1991) choosing among these will be based upon an evaluation of the value of the threatened land (natural, built) and the cost of protection. More recently, Titus and others (2009) reported that most of the Atlantic coast is developed to the extent the likely response to sea-level rise will be construction of shore protection projects (i.e., beach and dune nourishment, seawalls, dikes) to limit the effects of erosion and inundation.

However, managing sea-level rise along the barrier islands of east-central Florida, including the City, will prove a unique challenge wherein even the basic response options described above are not viable. First, the City is built upon a segment of barrier island consisting primarily of unconsolidated sand. The porosity and permeability of island sands will allow infiltration beneath and behind these structures as rising waters migrate in response to hydrostatic pressure and until hydrostatic equilibrium is reached. Thus, the engineered solutions (i.e., dikes, levees, and seawalls) successfully employed to protect other City's along the Atlantic Coast from rising water will not work. Secondly, the retreat option is predicated on the availability of land at higher elevations and into which new construction or re-development can be directed. This option will have to be re-tooled given only 2% of the City is currently undeveloped.

The City appears to be responding to the threats imposed by rising sea level through adaptive management. Adaptive management is an on-going and iterative process that specifies one or more essential actions necessary to reduce the vulnerability of built and natural environments to rising seas. The overall plan and each specific action are monitored and adjusted as outcomes from management action(s) and other events (i.e. accelerated ice sheet melting) become better understood. Initial actions may be limited to: (1) the development of a timeline describing future actions and (2) implementing no-regret or low-regret policies. Reactive measures may be formulated and subsequently triggered by specific tipping points built into the plan. As uncertainty diminishes, consequences become palpable and quantifiable, and consensus emerges, more robust plans, programs, and proactive measures are implemented.

As an initial step, the CPAB has approved a series of updates and revisions to the City's Comprehensive Plan. If approved by the City Council, these amendments will provide a legal basis for implementing an adaptive management plan and specific actions designed to mitigate the City's risk. Under the current time line, the City Council will debate the CPAB recommendations in fall 2010. Thereafter, a series of workshops would be conducted to establish: (1) a City vision of adaptation (2011) and thereafter (2) an Adaptive Management Plan (2012).

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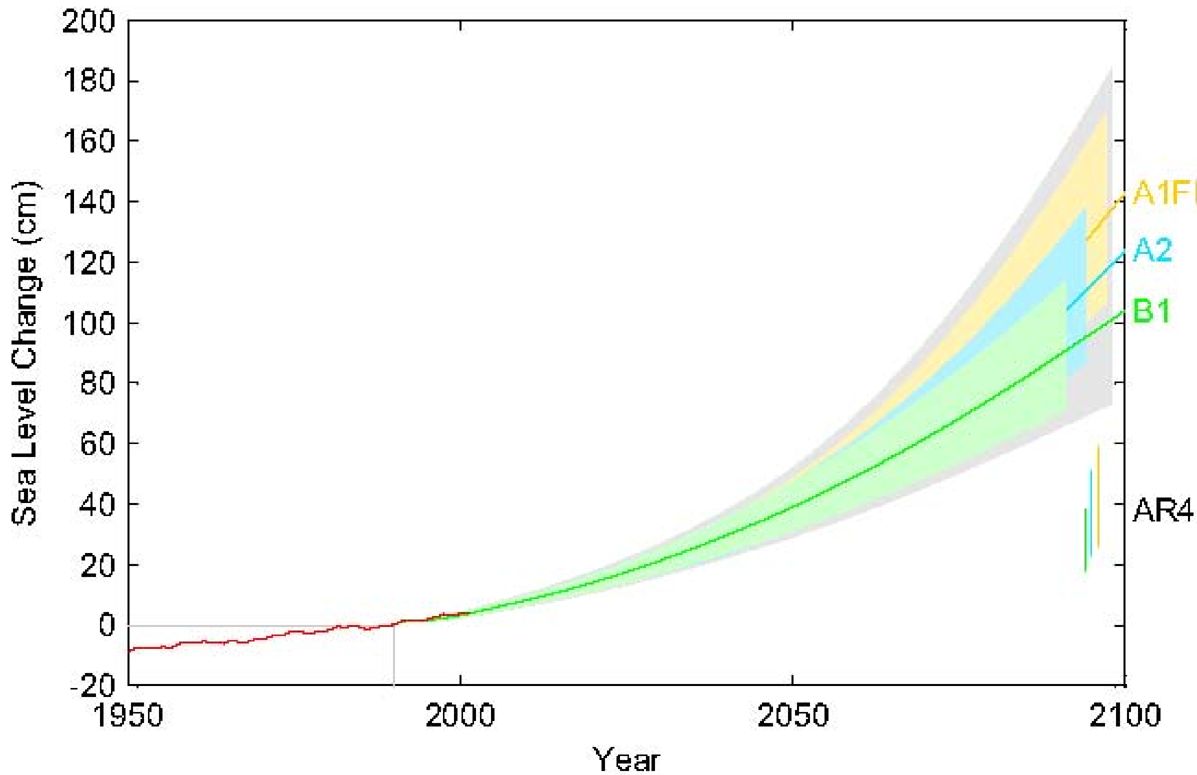

Figure 1 – Observed and projected sea-level rise. Alpha-numeric labels along right border identify distinct modeling scenarios. The sea-level range projected in the 4th Assessment of IPCC (2007) is shown in the lower right corner (AR4). From Vermeer and Rahmstorf (2009).

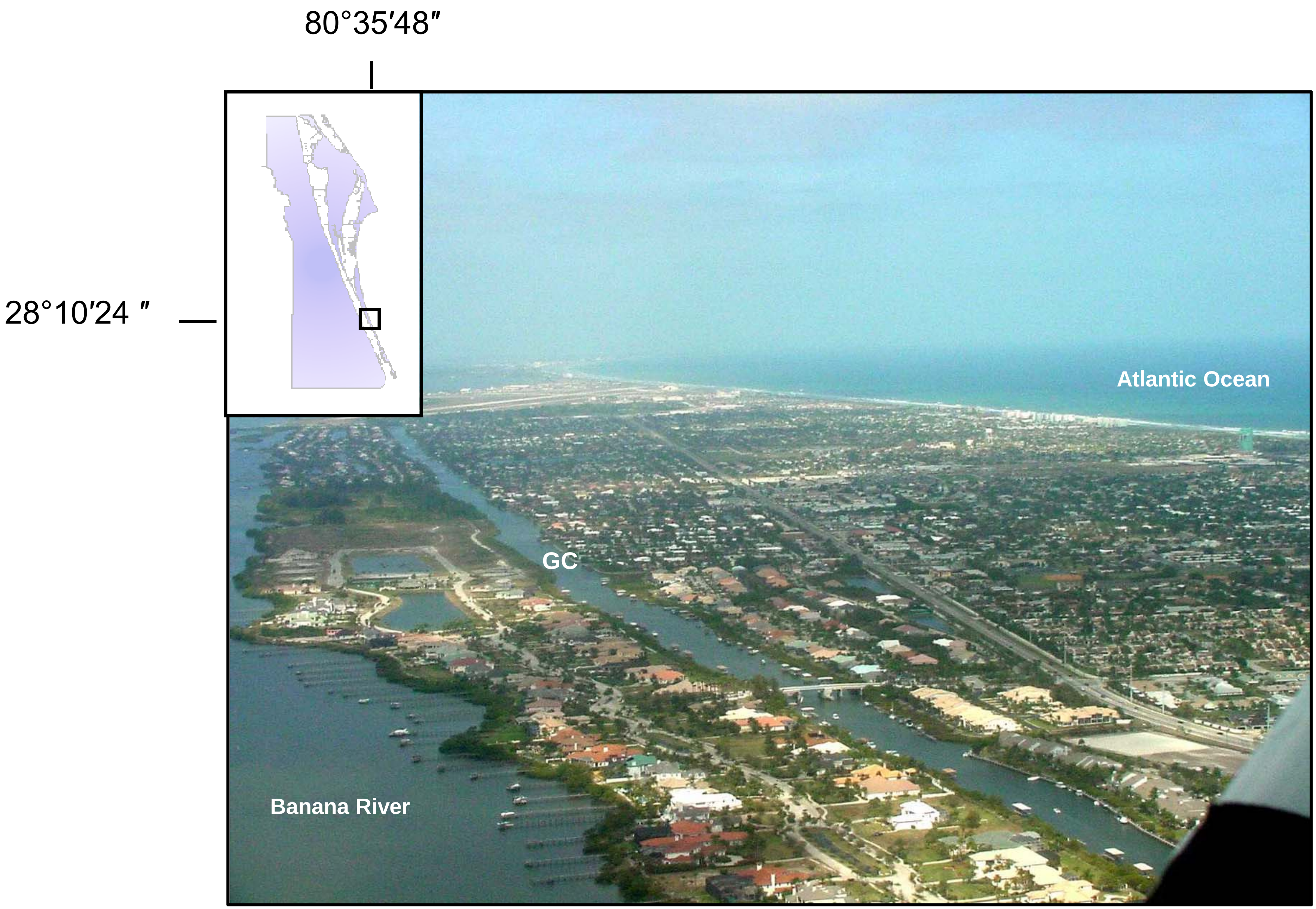

Figure 2 – Location map of the City of Satellite Beach, Florida. Map inset is Brevard County showing location of City. Coordinates are City's approximate center-point. GC = Grand Canal.

Figure 3 – Orthophotograph of City showing municipal boundaries, major roads, and NOAA tide gage used to establish vertical datum. TI = Tortoise Island, SI = Sampson's Island, LI = Lansing Island, FC = finger canals. PC =Pelican Coast.

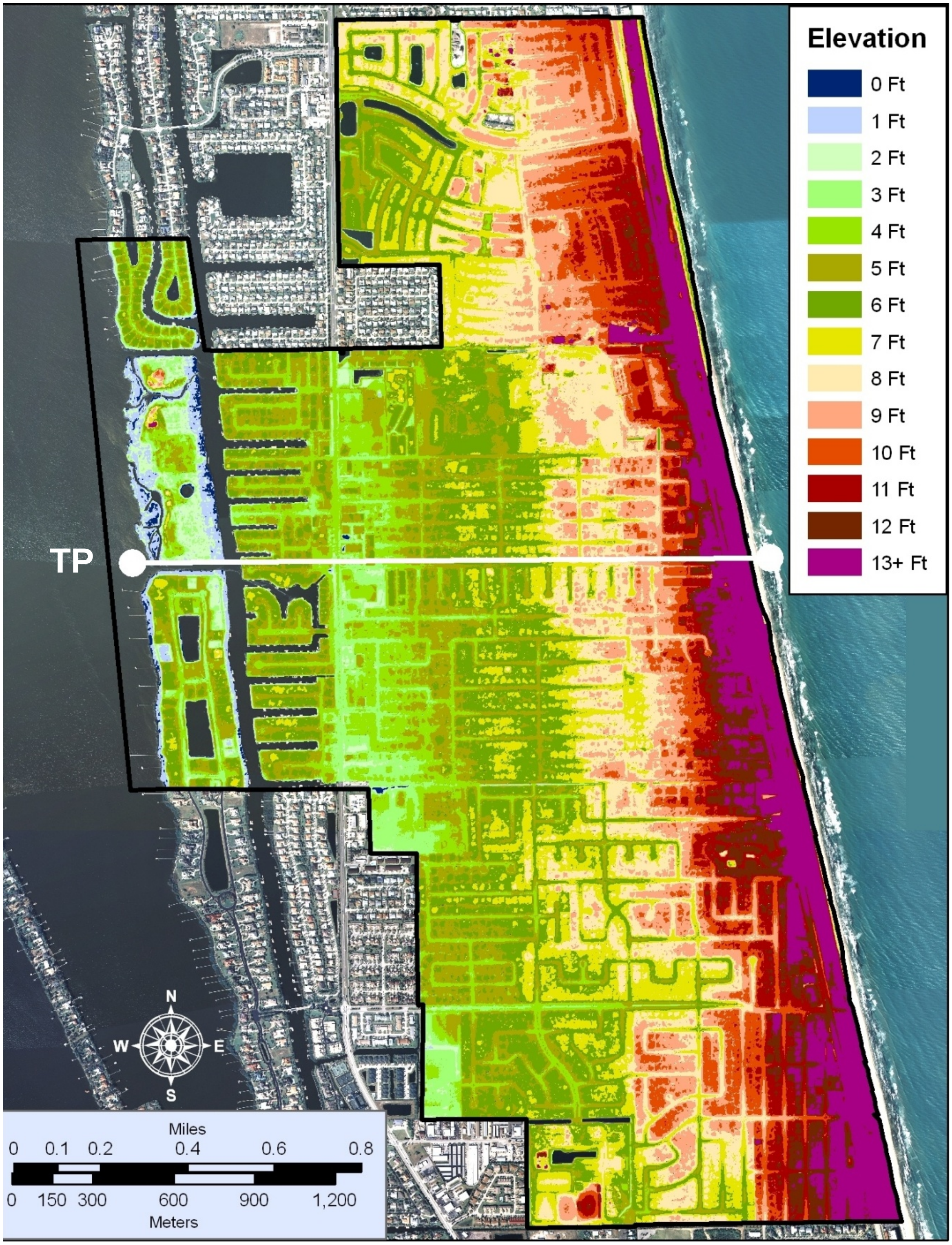

Figure 4 – City of Satellite Beach topography based upon LiDAR data acquired by Florida Division of Emergency Management. TP = location of topographic profile (Figure 7).

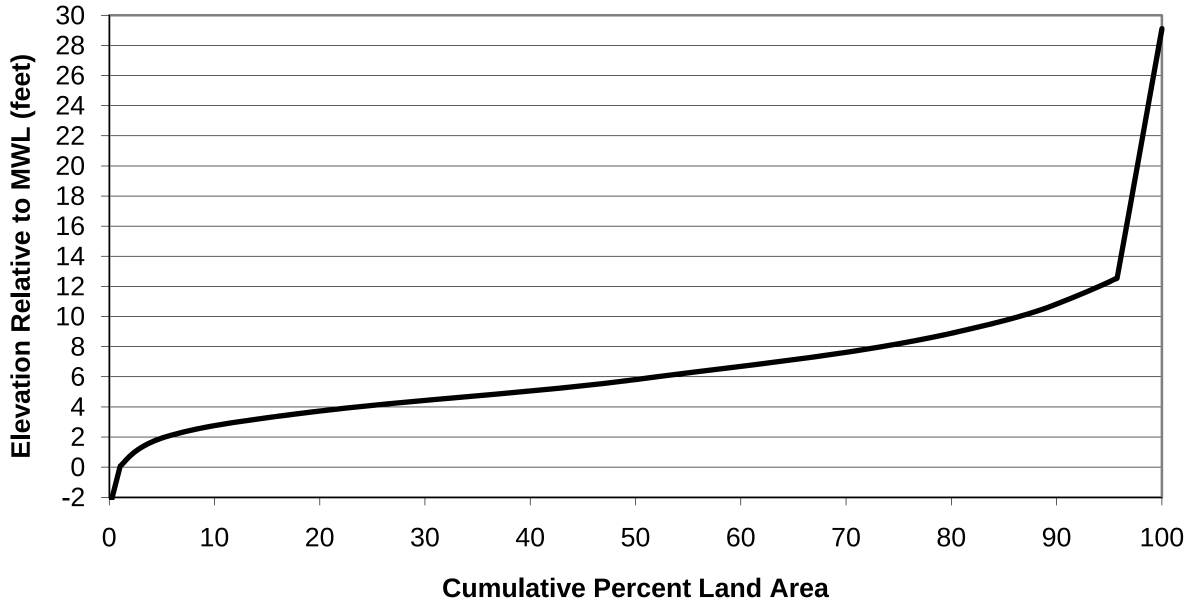

Figure 5 – City of Satellite Beach hypsographic curve generated using LiDAR elevation data.

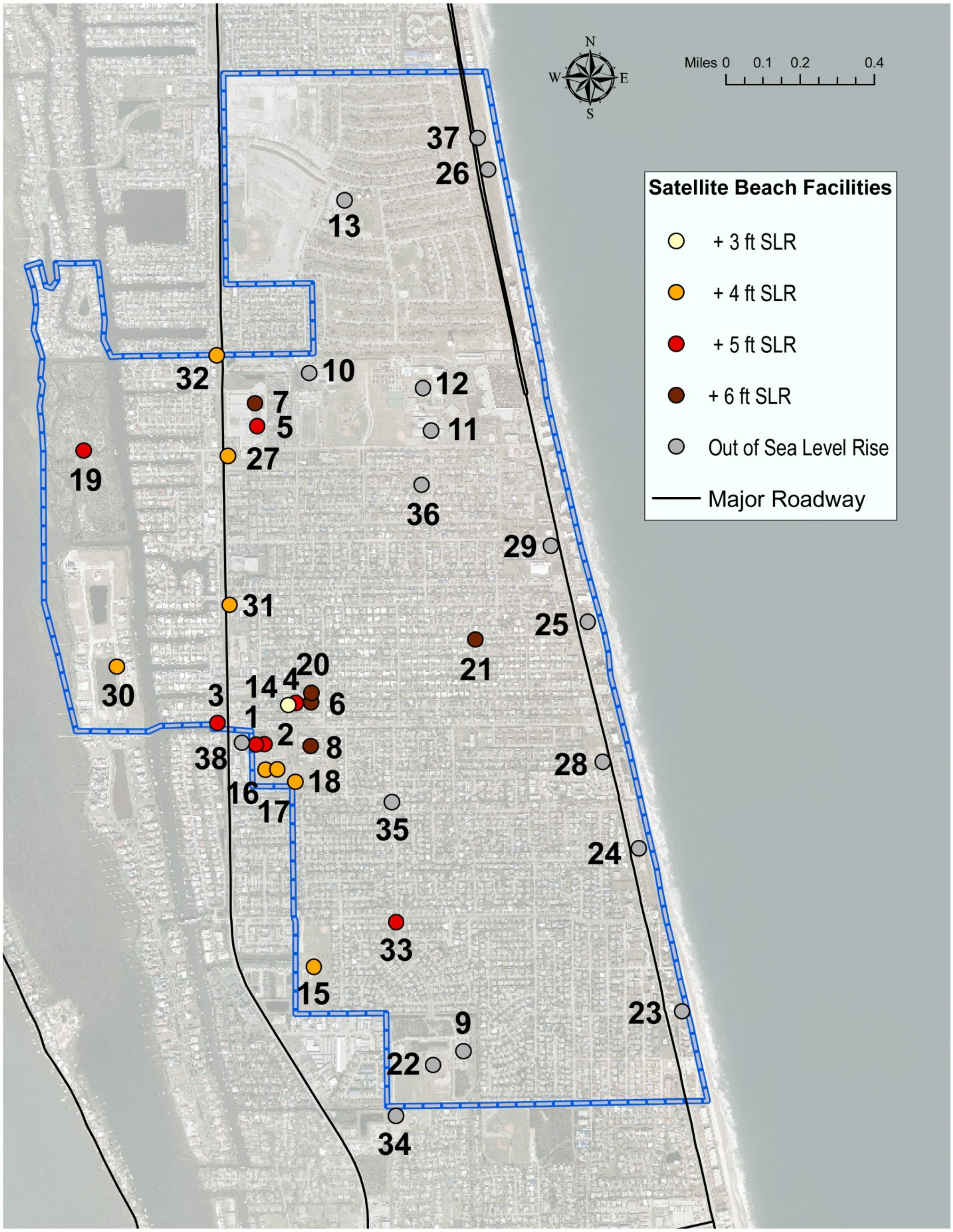

Figure 6 – Location and vulnerability of critical assets. Colored dots indicate "impact" elevation or when sea level is equal to or greater than asset elevation. Labels correspond to asset ID numbers in Table 3.

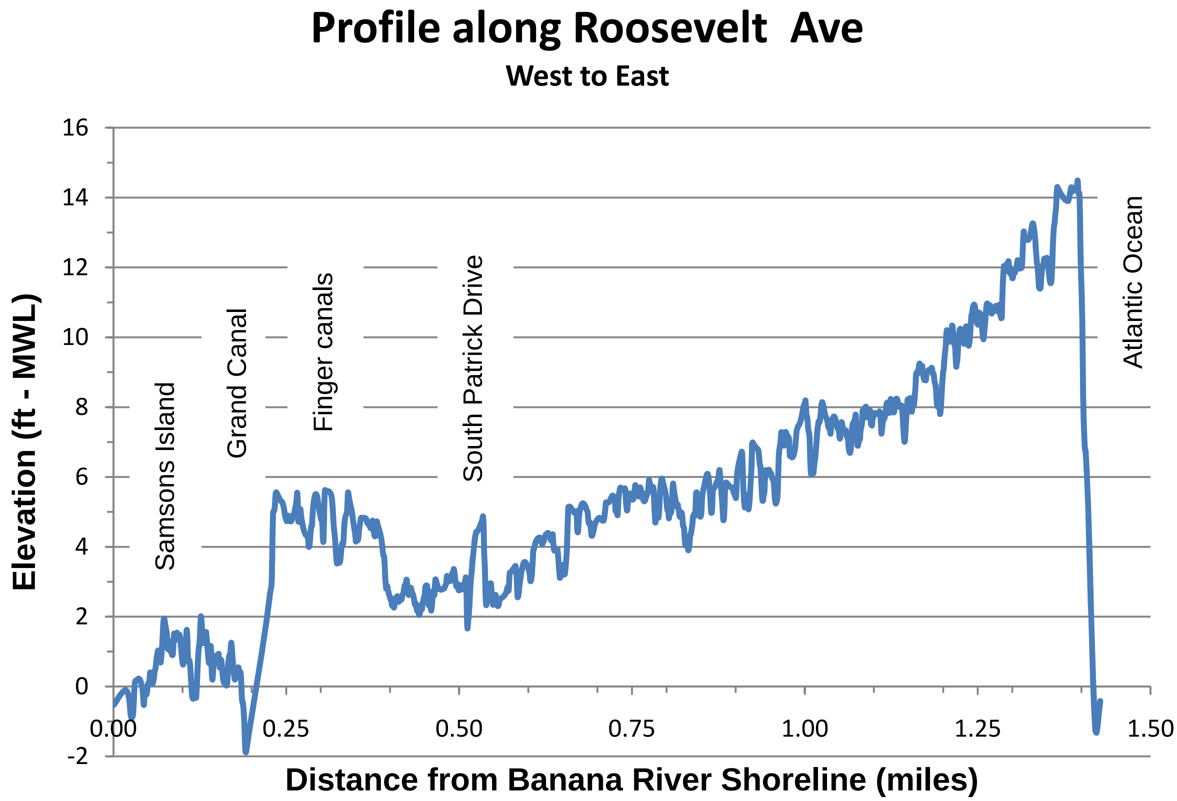

Figure 7 – West to east topographic profile illustrating elevation of terrain along Roosevelt Ave (Figure 3 and 4). As is typical of Atlantic Coast barrier islands, landscape elevation increases towards high-energy coastline (eastward). The elevated interval between South Patrick Drive and the Grand Canal reflects the presence of fill material acquired during dredging of the finger canals.

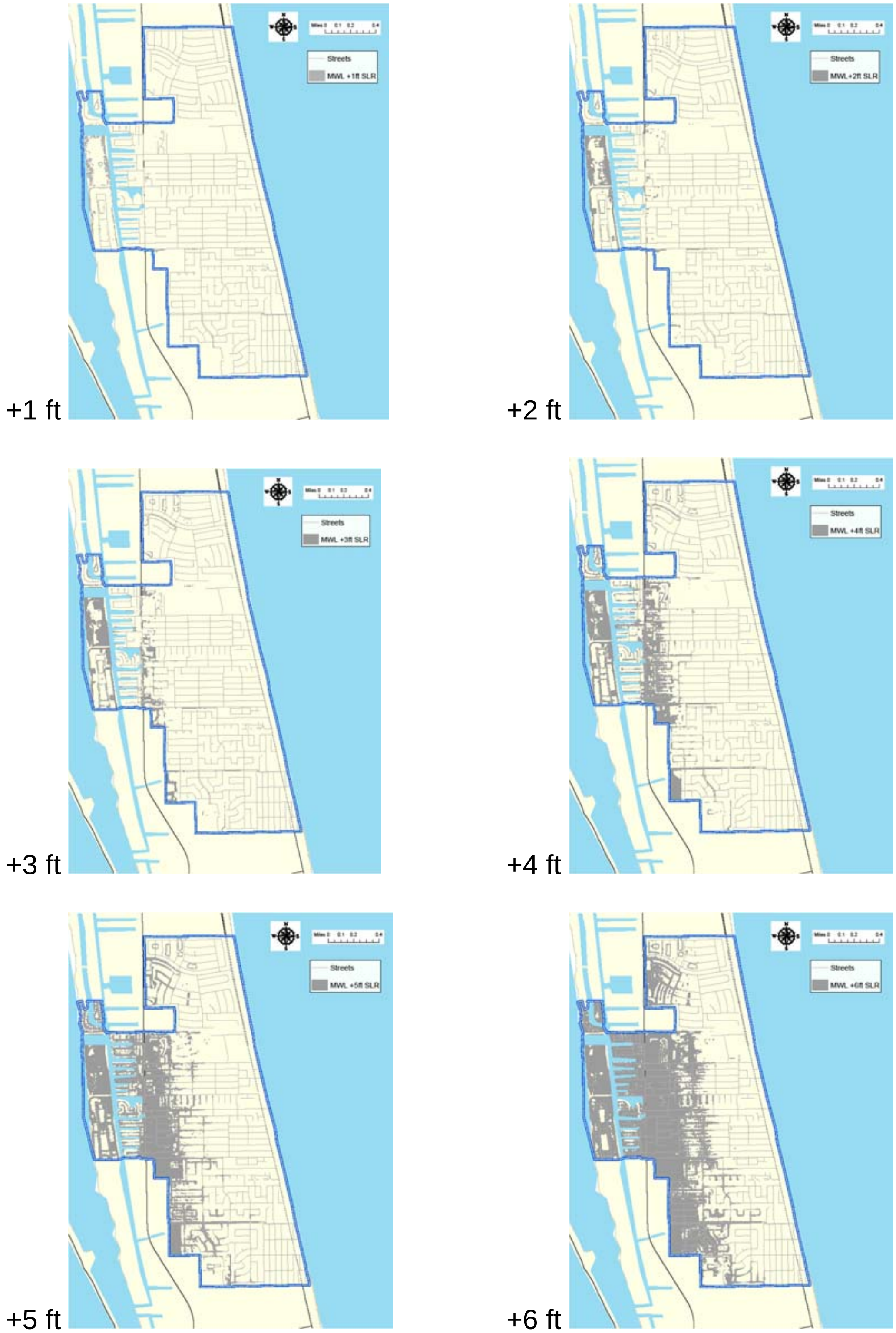

Figure 8 – Submergence sequence of City of Satellite Beach landscape during sea-level rise of +1 ft to +6 ft (0.3 m to 1.8 m) relative to Banana River MWL_{2010}. See Table 4 for detailed summation of impacts.

Table 1 - Summary of hurricane landfall conditions as a function of category

Storm Category	Sustained Wind (mph)	Return Period (yrs)	Surge Elevation (ft)	City Inundation (%)
1	74 - 95	10	5.2	40
2	96 - 110	25	11.2	92
3	111 - 130	100	17	96
4	131 - 155	300	22.8	98
5	>155	>300	25.9	100

Storm Category and Sustained Wind values of Saffir-Simpson Scale

Surge data provided by Tara McCue, East-Central Florida Regional Planning Council (2010)

Return period based upon Figure 2.2-24 of Bailey (2000)

Table 2 - Observed and predicted coastal response to sea-level rise (Parkinson and Donoghue 2010)

Period	Time Interval	Rate (mm/yr)	Coastal response
Late Pleistocene to early Holocene	20,000 - 7,000 ybp	10 to 20	Shoreline retreat, submergence and overstep
mid-Holocene	7,000 to 3,000 ybp	2	Formation of coastal environments, barrier islands, shoreline retreat
late-Holocene	3,000 to present	0.1 to 0.2	Aggredation, shoreline stabilization and progradation
20th Century	1900 to 2000	2	Shoreline retreat
Recent	1994 to 2008	3.4	Shoreline retreat
Predicted	1990 to 2100	3 to 14	Shoreline retreat, submergence and overstep

Table 3 - List of critical infrastructure and other City assets utilized during vulnerability assement. Location is shown in Figure 6 by reference to asset ID number (#). Impact elevation is height of rising sea level when asset centroid is submerged. CSB = City of Satellite Beach, ECFRPC = East Central Florida Regional Planning Council, Alt = data not readily available and ultimately acquired using alternate sources.

Type of Asset	ID #	Name	Source of File	Impact Elevation (ft)
City Services; security, social	1	Civic Center	CSB	5
	2	City Hall	CSB	5
	3	Satellite Beach Fire/Rescue	ECFRPC	5
	4	Public Works Complex	CSB	5
	5	Schechter Center	CSB	5
	6	Police Station	CSB	6
	7	Post Office	ECFRPC (Alt)	6
Public schools and libraries	8	Surfside Elementary	CSB	6
	9	Library	ECFRPC (Alt)	N/A
	10	Holland Elementary	CSB	N/A
	11	DeLaura Middle School	CSB	N/A
	12	Satellite High	CSB	N/A
	13	45th Space Wing Technical Library	ECFRPC	N/A
Parks and Recreation	14	Cinnamon Tot Lot	CSB	3
	15	Desoto Park	CSB	4
	16	Hedgecock Field	CSB	4
	17	Graboski Field	CSB	4
	18	Surfside Field	CSB	4
	19	Samsons Island	CSB	5
	20	Olson Field	CSB	6
	21	Stormwater Park	CSB	6
	22	Satellite Beach Sports and Recreation Park	ECFRPC	N/A
	23	Sunrise Park	CSB	N/A
	24	Pelican Beach Park	CSB	N/A
	25	Gemini Beach Park	CSB	N/A
	26	Hightower Beach Park	CSB	N/A
Gas production, transportation, distribution	27	Fuel Facility (SR 513 & Jackson)	ECFRPC (Alt)	4
	28	Fuel Facility (A1A & Ocean Spray)	ECFRPC (Alt)	N/A
	29	Fuel Facility (A1A & Roosevelt)	ECFRPC (Alt)	N/A
Water supply; drinking water, waste water/sewage, surface/storm water (e.g. dikes, canals)	30	Sanitary Lift Station (Lansing Island)	CSB	4
	31	Sanitary Lift Station (SR 513 & Sherwood)	CSB	4
	32	Sanitary Lift Station (SR 513 north of Chevy Chase)	CSB	4
	33	Sanitary Lift Station (Jamaica & DeSoto)	CSB	5
	34	Sanitary Sewer Force Main Pump Station	ECFRPC (Alt)	N/A
	35	Sanitary Lift Station (Kale & Maple)	CSB	N/A
	36	Sanitary Lift Station (Grant & Orange)	CSB	N/A
	37	Sanitary Lift Station (A1A at Hightower Beach Park)	ECFRPC (Alt)	N/A
Electrical production, transmission and distribution	38	FPL Electric Substation	ECFRPC (Alt)	N/A

Table 4 - City impact assessment as a function of sea-level rise between +1 ft and +6 ft (0.3 m and 1.8 m) MWL_{2010} . See Figure 3 for roads; Figure 6 and Table 3 for infrastructure and asset information. SPD = South Patrick Drive

Sea-Level Rise (ft)	Forecast Date (year)	Impact Assessment		Loss of Infrastructure & Assets	
		Submergence (% of City)	Description	ID #	Name
1	2040	3	Loss of fringing wetlands - Samsons and Lansing Islands		None
			Canal margins flooded - Tortoise Island		
2	2070	5	Loss of fringing wetlands, enchroachment into upland areas - Samsons and Lansing Islands		None
			Continued enchroachment of finger-canal margins		
			Enlargement of stormwater retention ponds proximal to SPD		
			Seasonal flooding of SPD at Cassia Blvd; extending northward and eastward 1/2 block		
			Seasonal flooding of Cassia Blvd and DeSoto Pkwy drainage ditches as much as 0.75 miles east of SPD		
			Seasonal flooding in DeSoto Park, Hedgecock Field, and around City Hall		
3	2090	12	Continued loss of uplands - Samsons and Lansing Islands	14	Cinnamon Tot Lot
			Submergance of SPD at Cassia Blvd; extending northward and eastward 1/8 mile		
			Submergence of portions of City Hall parking and Hedgecock Field outfield		
			Cassia Blvd and DeSoto Pkwy drainsage ditches submerged as much as 1/2 mile east of SPD		
			Submergence of portions of Desoto Park, including some parking		
			Seasonal flooding of streets and neighborhoods east of SPD between Cassia Blvd and Jackson Ave		
			Seasonal flooding of street segments on west side of SPD		
			Seasonal flooding of Public Works parking areas		
			Seasonal flooding of Schechter Center parking lot		
			Seasonal flooding of DeSoto Park fields, courts, and parking lot		
			Seasonal flooding of 1/4 mile segment of DeSoto Pkwy at western City boundary		
4	2100+	25	Expansion of residential lot and street submergence - Tortoise and Lansing Islands	15	Desoto Park
			Continued submergence divides Samsons Island into three separate land masses	16	Hedgecock Field
			Continued expansion of street and neighborhood submergence adjacent to SPD between Cassia Blvd and Roosevelt Ave; as much as 1/3 miles eastward along some street segments	17 18	Graboski Field Surfside Field
			Schechter Center parking lot submerged	27	Fuel Facility
			SPD north-south City right-of-way submerged	30	Sanitary Lift Station
			Isolated road segments between Cassia Blvd and DeSoto Pkwy submerged	31	Sanitary Lift Station
			City Hall parking and ball fields submerged	32	Sanitary Lift Station
			Public Works parking submerged		
			Seasonal flooding of streets from Shearwater Pkwy to Satellite Ave as far as 3/4 mile east of SPD		
5		40	Submergence of western portion of Shearwater Pkwy and streets in Pelican Coast	1	Civic Center
			Tortoise Island submerged	2	City Hall
			Nearly all roads in finger canal area submerged	3	Satellite Beach Fire/Rescue
			Submerged roads now extend easterward from SPD 1/4 mile in all neighborhoods between Jackson Ave and Satellite Ave; isolated road segments as much as 3/4 miles east of SPD flooded	4 5 19	Public Works Complex Schechter Center Samsons Island
			Submerged western neighborhoods between Cassia Blvd and DeSoto Pkwy	33	Sanitary Lift Station
			Seasonal flooding of streets to within 1/3 mile of SR A1A		
6		52	Almost all streets in Pelican Coast now submerged	7	Post Office
			Submergence now extends symetrically 0.25 to 0.5 miles outward from SPD throughout the City	8	Surfside Elementary
			Scattered submergence of streets to within 1/3 miles of A1A	20	Olson Field
			Samsons and Lansing Islands submerged	21	Stormwater Park