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Assessing municipal vulnerability to predicted sea level rise: City of Satellite Beach, Florida

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Abstract In the fall of 2009 the City of Satellite Beach (City), Florida, authorized a study designed to assess municipal vulnerability to rising sea level and facilitate discussion of potential adaptation strategies. The project is one of the first in Florida to seriously address the potential consequences of global sea level rise, now forecast to rise a meter or more by the year 2100. Results suggest the tipping point between relatively benign impacts and those that disrupt important elements of the municipal landscape is +2 ft (0.6 m) above present. Seasonal flooding to an elevation of +2 ft is forecast to begin around 2050 and thus the City has about 40 years to formulate and implement an adaptation plan. As an initial step, the Comprehensive Planning Advisory Board, a volunteer citizen committee serving as the City's local planning authority, has recommended a series of updates and revisions to the City's Comprehensive Plan. If approved by the City Council and Florida's Department of Community Affairs, the amendments will provide a legal basis for implementing specific policies designed to reduce the City's vulnerability to sea level rise.

1 Introduction

It is now widely accepted that global sea level will rise a meter or more by the year 2100 (Fig. 1; see also Rahmstorf 2007; Overpeck and Weiss 2009). 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. Johnson 2000; Deyle et al. 2007; California State Lands

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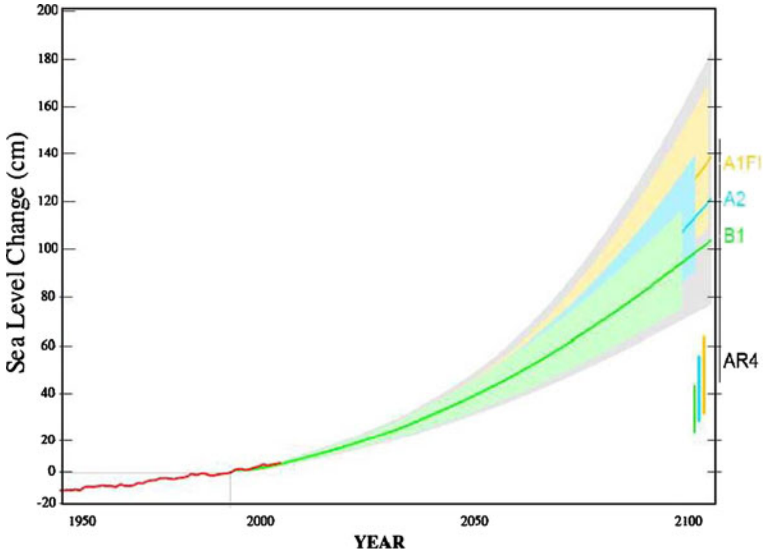

Fig. 1 Observed and projected sea level rise. *Alpha-numeric labels along right border* identify distinct modeling scenarios. The sea level range projected in the 4th Assessment of IPCC (Bindoff et al. 2007) is shown in the lower right corner (*AR4*). Modified from Vermeer and Rahmstorf (2009)

Commission 2009; EPA 2009). However, at the time of this investigation no local government along the 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

Fig. 2 Location map of the City of Satellite Beach, Florida. *Map inset* is Brevard County showing location of City. Geographic coordinates approximate City center-point. *GC* Grand Canal

change programs will require financing from local governments already struggling to meet existing demands.

Despite these obstacles, the City of Satellite Beach (City; Figs. 2 and 3) authorized a project designed to assess municipal vulnerability to rising sea level and facilitate discussion of potential adaptation strategies. The City's commitment to the project was secured by the availability of outside funds and a commitment to 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 promoted by designing a transparent scope of work based upon sound scientific principles and the best available scientific information.

The purpose of this paper is to provide a detailed description of the methods used to assess municipal vulnerability to sea level rise, principle findings of the assessment, and initial municipal actions proposed to reduce potential impacts. Given the limited funding (US$25,000) and project duration (1 year), it was conceived as a pilot project with possible application to other Atlantic coast municipalities of peninsular Florida. The project was authorized in the September:2009; in July 2010 (i.e., less than 1 year later) an initial adaptation strategy was presented to the City Council.

Fig. 3 Orthophotograph of the City of Satellite Beach showing municipal boundaries, major roads, and NOAA tide gauge used to establish vertical datum. *TI* Tortoise Island, *SI* Sampson's Island, *LI* Lansing Island, *FC* finger canals. *PC* Pelican Coast

2 Background

2.1 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 (Fig. 3). It consists of 8.8 km^2 of Holocene barrier island with east and west boundaries delineated by the Atlantic Ocean and Banana River shorelines, respectively. 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; only 2% is undeveloped.

The City's highest elevations are associated with the Atlantic Ocean coastal dune system and average about +15 ft (4.6 m) above sea level. Elevation and local relief decrease 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.

2.2 Existing hazards

2.2.1 Coastal erosion

All 36.5 miles (58.7 km) of Brevard County's beaches south of Cape Canaveral, including the entire shoreline of City, are designated by the Florida Department of Environmental Protection (Clark 2008) as critically eroded. A critically eroding shoreline is defined as imminently threatening upland development, recreational interests, wildlife habitat, or important cultural resources. Because sea level rise forecast to accompany global climate change will further disrupt the coastal "equilibrium profile" (Brunn 1962), both the rate and extent of erosion along the entire Brevard County coastline are expected to increase.

2.2.2 Storm surge

Although the City has not been subject to landfall of a hurricane in excess of a Category 2 storm since at least the mid nineteenth century, the potential devastating effects caused by flooding alone are enormous (Table 1). The magnitude of tropical

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 from Tara McCue, East-Central Florida Regional Planning Council (2010) Return period based upon Fig. 2.2–24 of Bailey (2000) storms and hurricanes originating in the equatorial waters of the eastern Atlantic Ocean is predicted to increase in association with climate change and concomitant rising temperature (Williams et al. 2009; Bender et al. 2010). This will elevate the risk and damage associated with storm surge, waves, wind, and rainfall. Furthermore, rising sea level will expand the extent and depth of inland flooding associated with the surge of these more powerful storms.

2.2.3 Sea level rise

Numerous factors can influence the relative direction and rate of sea level change. These include global phenomena such as an increase in the volume of sea water caused by the melting of continental glaciers, regional influences such as continental crust uplift (aka isostatic adjustments) triggered by the retreat of massive ice sheets, and local factors such as sediment compaction induced by extraction of groundwater and hydrocarbons (oil). The most significant factor influencing sea level change along the shorelines of central- and south-peninsular Florida is *global eustatic* change: a rise or fall in sea level elevation induced by an increase or decrease in seawater volume (respectively). The other factors are either absent (i.e., sediment compaction) or exert no significant influence (i.e., isostatic adjustments). This greatly simplifies any study attempting to quantify the causes or consequences of sea level change. The geologic record (i.e., sedimentology, stratigraphy, paleontology) of central- and south-Florida indicates the post-glacial marine transgression can be subdivided into three intervals, each characterized by a distinct rate of global eustatic sea level rise (hereafter sea level rise) and unique shoreline response (Table 2).

Long-term tide-gauge data indicate the rate of sea level rise averaged 1.7 mm/year during the twentieth century, 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

Table 2 Observed and predicted coastal response to sea level rise

Marine transgression interval	Period	Time interval	Rate (mm/year)	Coastal response
1	Late Pleistocene to early Holocene	20,000–8,000 ybp	10 to 20	Submergence, overstep, widespread shoreline retreat
2	Mid-Holocene	8,000 to 3,000 ybp	2	Formation of coastal environments, barrier islands, shoreline retreat
3	Late-Holocene	3,000 to present	0.1 to 0.2	Aggredation, shoreline stabilization, and progradation
	Historical	1870 to 2000	2	Shoreline retreat
NA	Recent	1993 to 2006	3.3	Shoreline retreat
	Predicted	2010 to 2100	7 to 16	Shoreline retreat, submergence, and overstep (with increasing rate)

Late Pleistocene to late Holocene data from Parkinson and Donoghue (2010). Historical, Recent, and Predicted rates of sea level rise described in text surface layer. All 30 coastal states have experienced moderate to severe erosion during this interval of accelerated sea level rise (Williams et al. 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 2007). This most recent interval of acceleration is a direct consequence of the increasing influx of glacial meltwater from Antarctica and Greenland (Vinther et al. 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 such as salt water intrusion into local aquifers.

3 Methods

3.1 Public education and outreach

To undertake an assessment of municipal vulnerability that ultimately triggers planning and policy actions 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 and is described in the following sections.

3.1.1 Project team

A team of local stakeholders was established by the project manager (author) to facilitate the successful completion of the project. It consisted of representatives from the City, Indian River Lagoon National Estuary Program, Brevard County Office on Natural Resources, and East Central Florida Regional Planning Council. This team met regularly throughout the duration of the project. Additional interested parties, including staff from other government and non-government agencies as recommended by team members, were kept advised of project progress by way of an email distribution list.

3.1.2 Public forums

Utilizing facilities located within and proximal to the City, a series of public forums were organized to provide information on climate change and sea level rise with increasing site- and project-specific detail over time. The Space Coast Climate Change Initiative (SCCCI), a local non-governmental organization with experience in public education and outreach, was tasked with managing the forums. The SCCCI was one of many local partners used to leverage EPA-provided resources and enhance project success. Each event was promoted for more than one month using a mixture of press releases, radio Public Service Announcements, event descriptions posted on SCCCI and City websites, and newsletters and websites of local environmental and civic organizations.

The first forum provided an overview of climate change and sea level rise. The second forum presented information on the potential effects of climate change and sea level rise to the Space Coast region using locally recognized experts. Subsequent forums focused on: (1) the CRE project goal and objects and (2) results and recommendations.

3.1.3 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* (hereafter Subcommittee). This ad hoc committee was composed of volunteers from the City's Comprehensive Planning Advisory Board (CPAB). Representatives of the project team met with the Subcommittee following each of the regularly scheduled CPAB monthly meetings to report on project results and convey recommendations regarding how the City might respond.

3.1.4 Ongoing media campaign

Throughout the duration of the project, press releases, op-ed pieces, and radio PSAs were submitted to the local media as a means of communicating project progress. The project team allotted time to communicate directly with local media contacts to facilitate timely publication. The media were also directed to the SCCCI website, where information on the general topics of climate change and sea level, as well as material used in conjunction with each public forum (i.e., speaker PowerPoint™ presentations) were posted.

3.2 Assessment of municipal vulnerability

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 its critical assets would be submerged by rising sea level through the end of this century (year 2100).

3.2.1 Modeling the city's landscape

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

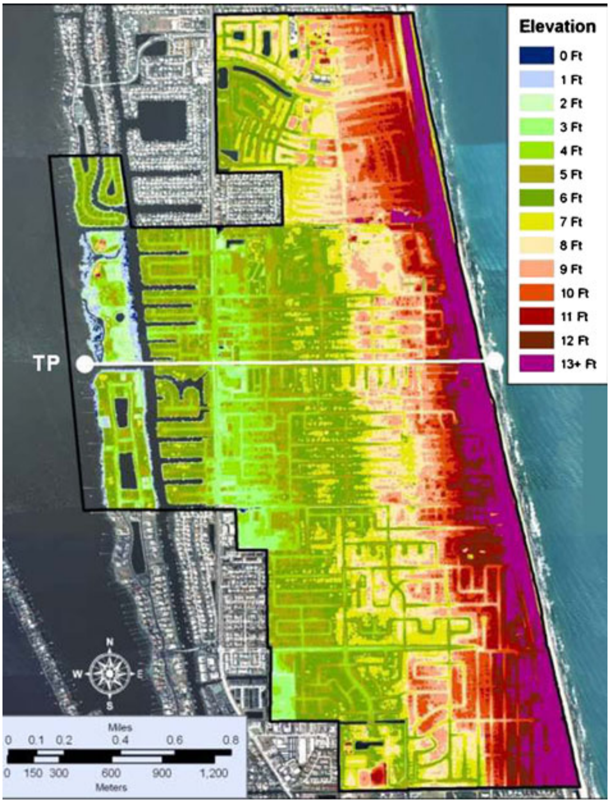

Fig. 4 City of Satellite Beach topography based upon LiDAR data acquired by Florida Division of Emergency Management. *TP* location of topographic profile (Fig. 7)

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; Fig. 3). The rationale for choosing a vertical datum linked to Banana River water level elevations was in large part the recognition that 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; Fig. 2) was ultimately used to establish the project's vertical datum. The mean water level (MWL) at Carters Cut between 1996 and 2001 is reported as −0.214 m (−0.702 ft) NAVD88 (T. Cera, St. Johns River Water Management District, unpublished 2010). This MWL elevation was increased by 0.025 m (0.08 ft) to account for sea level rise over the subsequent decade (i.e., 2001 to 2010) using a rate of 2.5 mm (0.1 in) per year (Lyles et al. 1988; Bindoff et al. 2007; Maul 2008). The adjusted vertical datum or MWL_{2010} is therefore −0.189 m (−0.62 ft NAVD88). This water level correction is less than the vertical resolution of current LiDAR technology (~6 in or 15.3 cm). However, it was applied to ensure future projects that may use this study as a template consider the complete suite of phenomena affecting local water level elevation before establishing a vertical datum of their own.

The resulting topographic model for the City (Fig. 4) depicts 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 (Fig. 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 +2 ft (0.61 m) will inundate approximately 5% of the City's landscape.

3.2.2 Critical assets

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 (Fig. 6, Table 3) was compiled by the project team using data provided by the City, East Central Florida Regional Planning Council, and other source agencies. The corresponding asset data and associated attributes (i.e., x and y coordinates, asset name or ID, source description) were then added to the GIS platform.

3.2.3 Municipal submergence

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 20 years, in large part a consequence of the maturation of general circulation models. The initial forecast considered for use

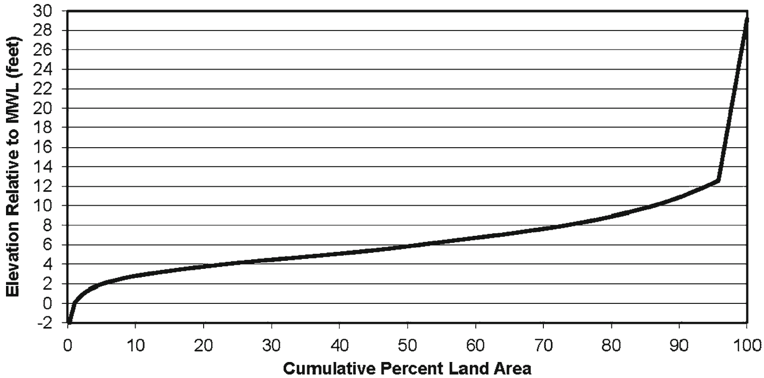

Fig. 5 City of Satellite Beach hypsographic curve generated using LiDAR elevation data

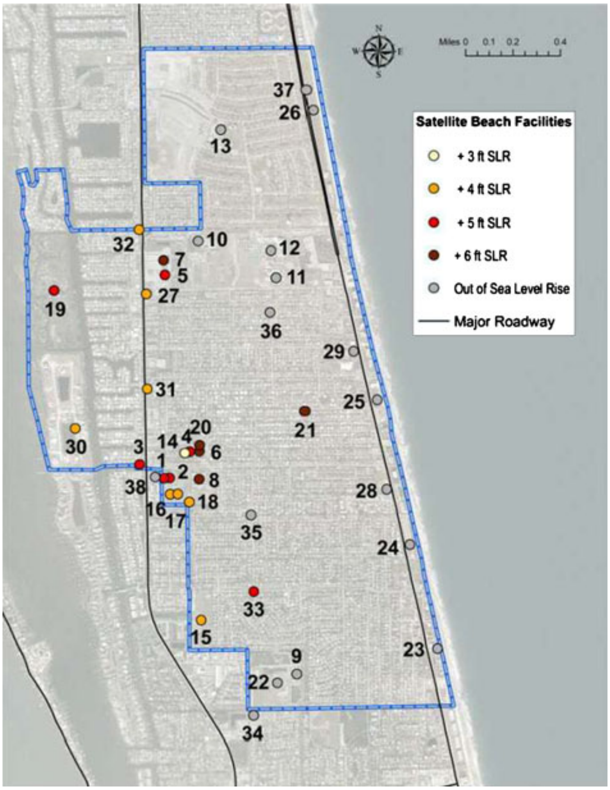

Fig. 6 Location and vulnerability of City's critical assets. *Colored dots* indicate impact elevation or when sea level is equal to or greater than asset elevation. *Labels* correspond to asset ID numbers in Table 3

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 of the IPCC assessment emerged shortly after its publication as the observed volume of meltwater from Greenland and Antarctic ice sheets was shown to be much larger than initially predicted. The project team eventually settled on the work of Rahmstorf and colleagues (Rahmstorf 2007; Vermeer and Rahmstorf 2009; Fig. 6) as representative of the currently accepted 'best guess,' i.e., a sea level rise of at least one meter 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, Department of Environment, Climate Change and Water 2009), (2) an emissions and corresponding sea level rise scenario (i.e., IPCC B1 or A1B; Burg 2010) and (3) a specific sea level elevation (i.e. +30 or +60 cm; Frazier et al. 2009). Given the ongoing debate 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 1 ft (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 (Fig. 1).

Table 3 List of critical infrastructure and other City assets evaluated during vulnerability assessment

Type of asset	ID #	Name	Source of file	Impact elevation (ft)
City service; 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 elementary	CSB	N/A
	13	45th Space wing technical library	ECFRPC	N/A
Parks and recreation	14	Cinnamon tot tot	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 and Jackson)	ECFRPC (Alt)	4
	28	Fuel facility (A1A and ocean spray)	ECFRPC (Alt)	N/A
	29	Fuel facility (A1A and 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 and Sherwood)	CSB	4
	32	Sanitary lift station (SR 513 north of Chevy Chase)	CSB	4
	33	Sanitary lift station (Jamaica and DeSoto)	CSB	5
	34	Sanitary sewer force main pump station	ECFRPC (Alt)	N/A
	35	Sanitary lift station (Kale and Maple)	CSB	N/A
	36	Sanitary lift station (Grant and 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

Location is shown in Fig. 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

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 assets 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.

3.3 Limitations of assessment

This impact assessment is based upon the flooding of static terrain; i.e., the topography does not change as rising seas inundate the landscape. This type of vulnerability assessment has 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 for 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 baseline from which an initial discussion regarding the magnitude and consequences of sea level rise could begin.

The magnitude of geomorphic change (i.e., erosion) induced by water-waves and currents during a relatively rapid rise in sea level will probably not be significant. This suggestion is based upon geologic studies conducted on Florida's continental shelf, where paleo-coastlines of early Holocene age were overstepped 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). Based upon these studies, erosion along segments of the City's shoreline and associated coastal dunes is expected to accelerate in the forthcoming years. However as sea level elevation and rate of rise continue to increase, much of the remaining low-lying landscape will likely be overstepped without significant topographic change; i.e. after exceeding local topographic elevations, the shoreline will advance landward to the next emergent landscape 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 are overtopped by rising water.

4 Results

4.1 Controls on landscape submergence

Two factors control spatial and temporal trends in landscape submergence associated with sea level rise: local relief and astronomic tides. The ability to predict how a coastal landscape may respond to rising sea level is therefore enhanced when these two factors are well understood.

4.1.1 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 landward as a consequence of diminishing wave energy. Hence the lowest elevations are located along the western margin of the City and adjacent to the Banana River. The Grand Canal (Figs. 2 and 3) was excavated through this low-lying western terrain during the late 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 placed between each of the newly constructed navigable waterways to increase the elevation of upland areas where new homes would be built.

Anthropogenic alteration of the island's geomorphology ultimately created a municipal landscape with minimum elevations coinciding with South Patrick Drive (Figs. 4 and 7). Terrain elevations increase both east and west of this roadway; however, western elevations are higher due to the presence of spoil material generated during construction of the City's canals. By contrast, terrain elevations to the east of

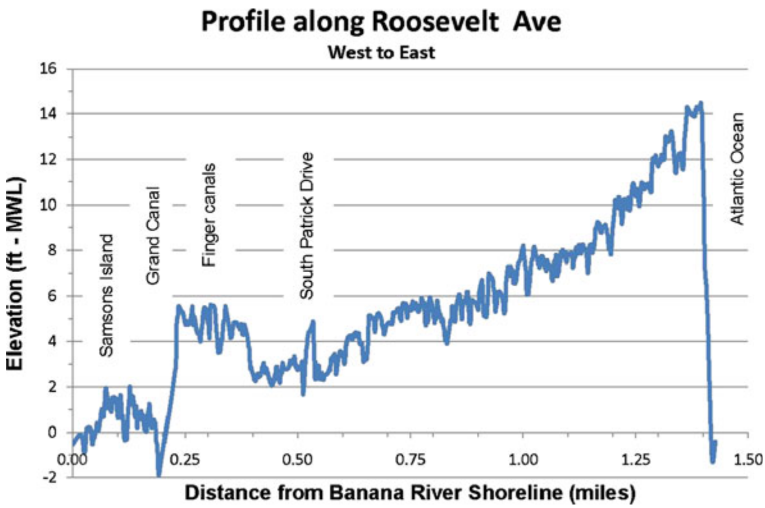

Fig. 7 West to east topographic profile illustrating elevation of terrain along Roosevelt Ave (Figs. 3 and 4). As is typical of Atlantic Coast barrier islands, landscape elevation increases towards high-energy coastline (eastward). The elevated interval between South Patrick Drive and the Grand Canal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

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 (Figs. 3 and 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. As a result, the residential landscape hosts a grid of narrow, linear depressions.

4.1.2 Seasonal flooding

Each fall, water levels in the Banana River rise approximately one foot as a consequence of astronomic tidal forcing (the 'fall rise'). As a consequence, neighborhoods proximal to the Banana River generally flood several times a year. The magnitude and extent of flooding can be compounded by concomitant heavy rain or 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 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.

Water level records collected at the Carters Cut tide gauge station (Fig. 3) include four fall rise events during the interval 1996 to 2000. In 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 inspecting the submergence data associated with the next one foot rise in sea level. To limit confusion, the term 'flooding' is used when referring to areas seasonally inundated. The term 'submerged' is used to describe areas inundated as a consequence of rising sea level.

4.2 Municipal submergence

The extent of municipal submergence forecast during a sea level rise of between +1 and +6 ft (0.3 and 1.8 m) is illustrated in Fig. 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) rise in sea level about 5% of the City's landscape will be 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 time there was no incentive to place additional fill on the island. Furthermore, segments of the

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

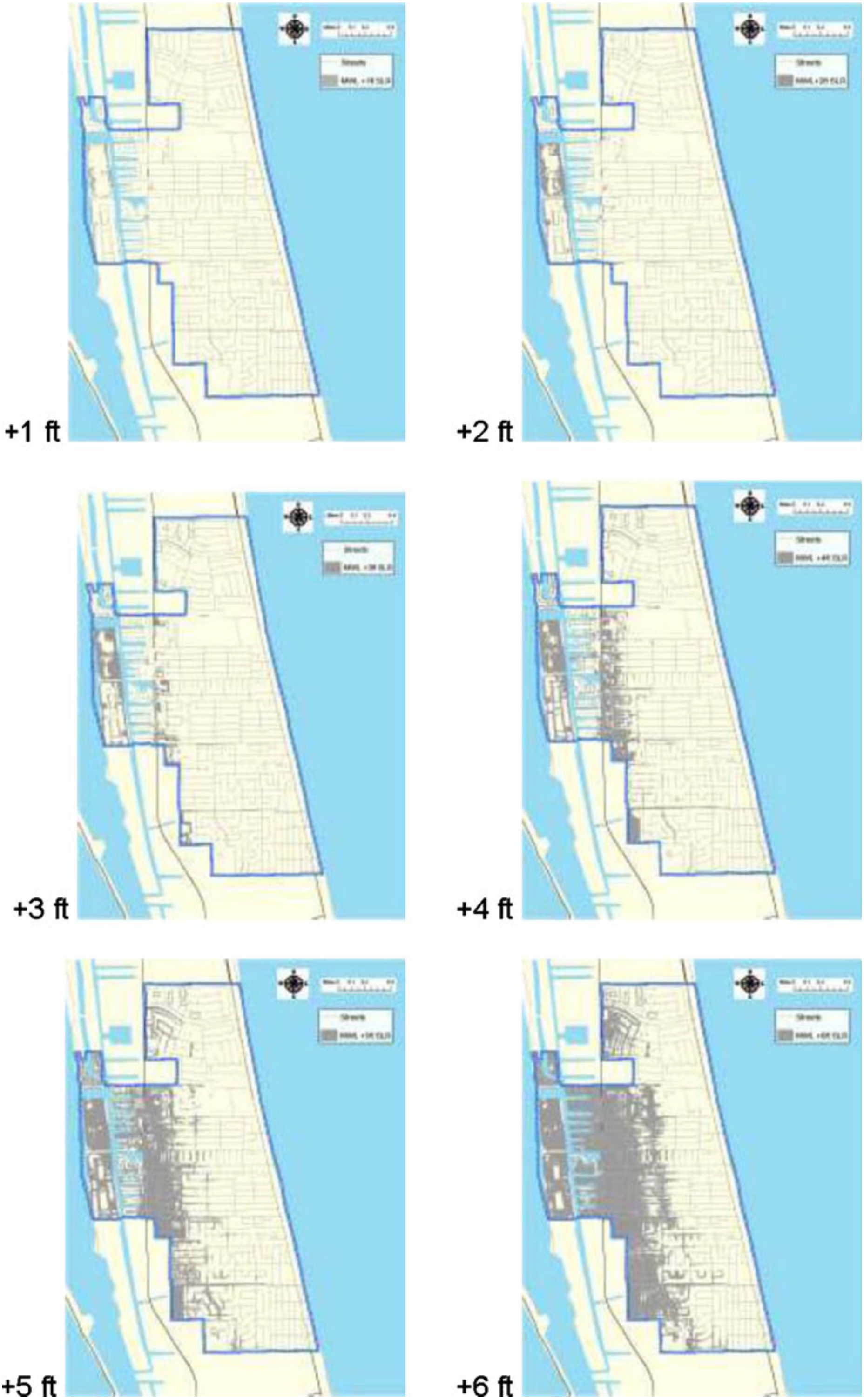
+1 ft
+2 ft
+3 ft
+4 ft
+5 ft
+6 ft

Table 4 Municipal vulnerability a function of long term inundation trends associated with predicted sea level rise compounded by seasonal flooding

Sea-level rise (ft)	Impact assessment: Submergence (% of City)	Impact assessment: Description	Loss of infrastructure and assets: ID #	Loss of infrastructure and assets: Name
1	3	Loss of fringing wetlands—Samsons and Lansing Island	None	
		Canal margins flooded—Tortoise Island		
2	5	Loss of fringing wetlands, encroachment into upland areas—Smasons and Lansing Island	None	
		Continued enchroachment of finger-canal margins		
		Enlargement of stormwater retention ponds proximal to SPD		
		Seasonal flooding of SPD at Cassia Bldv; extending northward and eastward 1/2 block		
		Seasonal flooding of Cassia Blvd and DeSotto Pkwy drainage ditches as much as 0.75 miles east of SPD		
		Seasonal flooding in DeSoto park, Hedgecock field, and around city hall		
3	12	Continued loss of uplands—Samsons and Lansing Islands	14	Cinnamon tot lot
		Submergence 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 DeSotto Pkwy drainage ditches submergence as much as 1/2 miles east of SPD		
		Submergence of portions of DeSoto park, including some parking		
		Seasonal flooding of streets and neighborhoods east of SPD between Cassia Bldv and Jackson Ave		
		Seasonal flooding of streets segment 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	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	17	Graboski field
			18	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
		Jackson Ave and Satellite Ave; isolated road segments as much as 3/4 miles east of SPD	4	Public works complex
			5	Schechter Island
			19	Sanitary lift station
		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 symmetrically 0.25 to 0.5 miles outward from SPD throughout the city	8	Surfside elementary
		Scattered submergence of street to within 1/3 miles of A1A	20	Olson field
		Samsons and Lansing Islands submerged	21	Stormwater park

See Fig. 3 for roads; Fig. 6 and Table 3 for infrastructure and asset information

SPD South Patrick Drive

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. Rising waters will further inundate 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 the limit of submerged land eastward to within one half mile of Highway A1A.

By the time sea level elevation reaches +6 ft (1.8 m) above MWL_{2010}, 52% of the City will be 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 border between Cassia Blvd and Satellite Avenue. Flooding along 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.

5 Discussion

5.1 Summary of findings

This project utilized a bathtub model to assess municipal vulnerability to a 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 of submergence through the year 2100. 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 by City decision makers.

The City is expected to lose 5% of its landscape during the initial +2 ft (0.6 m) of sea level rise, however much of this restricted to fringing wetlands and canals. 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. These results suggest the tipping point between relatively benign impacts of rising sea level and impacts that disrupt important elements of the municipal landscape is +2 ft MWL_{2010}. This point is clearly visible on the City's hypsographic curve as a distinct reduction in slope (Fig. 5). Seasonal flooding to an elevation of +2 ft is forecast to begin about 2050 and thus the City has about 40 years to formulate and implement a successful adaptation plan.

5.2 Managing sea level rise

There are three basic options in responding to sea level rise: (1) protect, (2) retreat, or (3) accommodate (Deyle et al. 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 et al. (2009) reported that most of the Atlantic coast is developed to the extent that 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.

Managing sea level rise along the barrier islands of east-central Florida will prove challenging, however, as even the basic response options listed above are not viable. First, the City is built upon a segment of barrier island consisting primarily of highly porous and permeable sand. Under conditions of rising sea level, an increase in hydrostatic pressure will induce the flow of water through the sands, either beneath or behind the structures constructed to prevent flooding. If unimpeded, this landward flow will continue until hydrostatic equilibrium is reached. Thus, the engineered solutions (i.e., dikes, levees, and seawalls) employed or proposed to protect other Atlantic Coast cities from rising water will simply not work. Secondly, the retreat option is not a realistic local response, as it is predicated on the availability of land at higher elevations into which new construction or re-development can be directed. This option may be viable on a larger geographic scale, but not within the City limits where only 2% of the landscape is undeveloped.

5.3 Municipal adaptation

Commensurate with the ongoing assessment of municipal vulnerability to sea level rise, members of the Sea Level Rise Subcommittee were tasked with reviewing technical papers or other publications on climate change, sea level rise, and municipal adaptation strategies. These documents were provided by the project team and other local partners to help prepare Subcommittee members for the task ahead: formulating an initial municipal response to the risks made apparent by the vulnerability assessment.

The Subcommittee ultimately decided upon a series of updates and revisions to the City's Comprehensive Plan as the most practical means by which to initiate an adaptation strategy. Their recommendations focused on four elements (future land use, housing, infrastructure, and coastal management/conservation) of the Plan and included: (1) 16 amendments to existing objectives and policies and (2) a new goal of the coastal management/conservation element, to provide "adaptive protection of private and public interests from adverse impacts due to long-term changes in sea level."

These recommendations were then debated by the full CPAB committee. A final version of proposed amendments to the Comprehensive Plan was then submitted to the City Council for their consideration. If approved by the City Council and Florida's Department of Community Affairs, these amendments will provide a legal basis for implementing specific actions designed to reduce the City's vulnerability to sea level rise as forecast to the year 2100. Under the current time line, the City Council will debate the CPAB recommendations in fall 2010. Thereafter, a series of workshops could be conducted to establish: (1) a City vision of adaptation (2011) and, thereafter, (2) an Adaptive Management Plan (2012).

Elements key to the success of this project include external funding, inclusion of municipal staff on the project team, establishing an ad hoc Sea Level Rise Subcommittee that reported directly to the Comprehensive Planning Advisory Board, effective public education and outreach, and stakeholder confidence in the objectivity of the investigation and its recommendations. This ultimately allowed for the project to be successfully completed in less than 1 year.

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