

# Adaptive Response Planning to Sea Level Rise in Florida and Implications for Comprehensive and Public-Facilities Planning

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Sea level has been on the rise since the last glacial period ended some 18,000 years ago (Hansom, 1988), in response to millennial cycles of climate variability driven by irregularities in the earth's orbit around the sun and shifts in the tilt of the earth's axis (Houghton, 2004). Since the onset of industrialization in the mid 1800s, increases in emissions of carbon dioxide and other greenhouse gases have contributed to additional warming of the earth's atmosphere on the order of approximately 0.6° C (Houghton, 2004).

Warming of the atmosphere results in several phenomena which contribute to an increase in the volume of the oceans resulting in what is referred to as eustatic sea level rise: (1) thermal expansion of water as heat is transferred to it from the atmosphere, (2) melting of continental and alpine glaciers and ice caps, and (3) melting of the Greenland and Antarctic ice sheets. Because of the long lag time in transferring heat from the atmosphere throughout the depths of the oceans, eustatic sea level rise would continue for thousands of years if atmospheric temperatures were to be stabilized (Alley et al., 2007).

Sea level rise experienced by an observer on land is referred to as relative sea level rise. This is a function of changes in eustatic sea level as well as shifts in the elevation of the land. In some areas, the land is rising as part of the very slow phenomenon of "glacial rebound" or in response to other tectonic changes in the earth's crust. In others, the land is subsiding, due to tectonic activity or other factors such as excessive ground water pumping and extraction of oil and gas. At the same time, the ocean bottom is rising and falling in different areas in response to related phenomena. Because most areas of Florida are geologically stable, observed sea level primarily reflects the forces that drive eustatic sea level.

As is detailed further below, there is substantial agreement in the international scientific community that rates of sea level rise have increased in response to post-industrial global climate change. There remains, however, considerable uncertainty about precisely how high sea level will rise by any particular point in time. Projections of sea level rise between 1990 and 2100 presented by the Intergovernmental Panel on Climate Change (IPCC) in its *Climate Change 2007* report range from 0.6 to 2.6 feet (Meehl et al., 2007). An early analysis by the U.S. Environmental Protection Agency (1989) estimated that a 2-foot rise in sea level would inundate an area equivalent to the states of Massachusetts and Delaware combined, close to 10,000 square miles of land. Several scientists have warned that evidence of more rapid melting of the Greenland and West Antarctic ice

sheets indicates that sea levels could be as much as 4.5 to 16.5 feet higher by 2100 (Hansen, 2007; Rahmstorf, 2007a).

As is detailed further below, regardless of the rate of sea level rise over the next few decades and the measures that may be taken to reduce greenhouse gas emissions, it is clear that the earth is already committed to millennia of sea level rise because of the lag in achieving temperature equilibria in the atmosphere and the oceans. Authors of the IPCC's 2007 report, *Climate Change 2007: Impacts, Adaptation, and Vulnerability*, (Parry et al., 2007, p. 346) argue that

This raises long-term questions about the implications of ‘hold the line’ versus ‘retreat the line’ adaptation policies and, more generally, how best to approach coastal spatial planning. While shoreline management is starting to address such issues for the 21st century . . . the long timescales of sea-level rise suggest that coastal management, including spatial planning, needs to take a long-term view on adaptation to sea-level rise and climate change, especially with long-life infrastructure . . .

Fred Ludwig, in an article in the August/September 2007 issue of *Planning* entitled “Too Much Water or Too Little? Coping with the Inevitable” quotes James Titus of the U.S. Environmental Protection Agency as saying that it is very likely that existing urban areas will choose to defend themselves against rising sea levels by constructing flood protection works or raising the base elevation of entire urban areas (Ludwig, 2007, p. 30). Titus suggests that it is in areas that are not built out where other options may be feasible, but only if the planning is done now before capital investments are made in private development and public facilities and infrastructure.

Thus, while significant uncertainty remains about the magnitude and timing of sea level rise, development decisions that are being made today are committing public and private capital to land use patterns and associated infrastructure and facilities with design lives that reach well into the period of time when the impacts of sea level rise will be felt. The street and highway rights-of-way that are laid out for new development have expected operating lives of more than 100 years. Underlying water distribution and wastewater and storm water collection systems have design lives of 30 to 50 years or more. Sewage treatment and wastewater reclamation facilities have design lives close to 50 years. New bridges are built to last 75 years. In addition, elements of the natural infrastructure that helps to mitigate the vulnerability of human settlements to coastal storms, namely beach and dune systems and coastal wetlands, will be altered as sea level rises. Efforts to protect the built environment from sea level rise may compromise the ability of these natural systems to adapt.

Large areas of Florida are vulnerable to increasing sea levels as shown in Figure 1, which depicts areas that would be inundated by a 1-meter (3.3 feet) rise. Many of these areas are already developed. Thus there are likely to be substantial components of public infrastructure that already are vulnerable to sea level rise.

This report offers a snapshot of the status of adaptive response planning for sea level rise by comprehensive planning and infrastructure planning and management agencies in the state of Florida. Through telephone interviews primarily with local and regional planners, we have sought to determine the perceived importance of sea level rise as a planning issue, the efforts that are underway to address sea level rise, and the ways in which the state, in particular the Department of Community Affairs, can facilitate more effective adaptive response planning.

We have focused our attention on five major elements of local infrastructure: natural flood protection provide by (1) beach and dune systems and (2) coastal wetlands; (3) water supply systems that draw from aquifers or surface waters close to the coast; (4) centralized wastewater management systems located in low-lying areas near the coast, including those with surface water discharges of treated wastewater; and (5) highways, bridges, and causeways in coastal areas. We also briefly address storm water management systems in this analysis. However, we did not address them to the same degree as other infrastructure because the issues concerning these systems overlap considerably with those of wastewater management systems.

We supplemented our planner interviews with a comprehensive literature review and interviews with state and national experts designed to answer the following questions concerning sea level rise vulnerability and adaptation: (1) How fast is sea level rising and is the rate increasing? (2) How high will sea level rise by 2050 and 2100? (3) What are the primary anticipated effects of sea level rise on public infrastructure systems? (4) What adaptive responses may be feasible? (5) What initiatives are underway already to adapt to sea level rise?

We begin by describing the sample of jurisdictions and agencies for which we conducted interviews. We then address Florida's vulnerability to sea level rise in terms of both what the experts say and what our interviews tell us about the perceptions of long-range planners in the state. This is followed by an examination of adaptation options, drawn from our review of the literature and discussions with state, regional, and local experts and planners in the state. We then present an overview of the manner in which sea level rise is being addressed through the planning processes of state, regional, and local agencies that influence public infrastructure planning. We conclude with a series of recommendations for initiatives that we think merit consideration by the state Department of Community Affairs and other state agencies that can enhance the ability of local planners to effectively adapt to the impacts that sea level rise is likely to have on new and existing public infrastructure over the next 50 to 100 years.

### Our Sample

We conducted interviews with long-range comprehensive planners from a sample of 20 cities and counties that are most vulnerable to sea level rise based on a map compiled by Weiss and Overpeck (2005) of areas of the state likely to be inundated by a 1 meter rise in sea level (see Figure 1). We also interviewed 12 water supply planners and 9 wastewater facility planning officials whose agencies serve those same areas of the state

and whose existing facilities are likely to be vulnerable to sea level rise impacts. In addition, we interviewed long-range planners in 5 regional planning councils that participated in a recent sea level rise vulnerability project funded by the U.S. Environmental Protection Agency, as well as water supply planners in 4 water management districts. Our inquiries concerning transportation infrastructure were focused on State Department of Transportation officials because of the major role played by the state in financing and overseeing both construction of new transportation infrastructure and major repair and reconstruction efforts for existing systems. Table 1 lists the local, regional, and state agencies with which we conducted interviews.

### What Do We Know About Projected Sea Level Rise for Florida?

Almost all of the local comprehensive planners and water supply and wastewater facility planners with whom we spoke expressed significant uncertainty over how high sea level will rise and when. We explicitly asked the local comprehensive planners how high they think sea level will be in their jurisdictions by 2100. Almost half (45%) said they had no idea. Three of the eight respondents who offered an estimate said 1 to 3 feet, which is consistent with the predictions in the most recent reports from the IPCC – see below. Two estimated less than 1 foot; two said 4 to 5 feet; and one estimated more than 5 feet.

### *What Have Public Officials Been Hearing?*

The public media, as well as other information sources accessible to public officials in Florida, are carrying mixed messages about rates of sea level rise, sea level rise projections, and the implications of these possible changes over the next 50 to 100 years. Underlying uncertainty about the factors that explain observed changes in sea level coupled with limited historic data and high inter-annual and decadal variations in observed sea levels have resulted in divergent interpretations among scientists that have contributed to these mixed messages. In a few instances, media reports and public statements appear to have simply been incorrect.

### Estimates of Sea Level Rise Rates

We have uncovered only one article in a major Florida newspaper over the past 5 years that explicitly discusses the current rate of sea level rise in Florida (see Table 2). That article (Ritchie, 2007) quotes Florida State University geologist Dr. Joseph Donoghue as saying that the rate is 2.0 millimeters per year (mm/yr). Donoghue is quoted as saying that there is no evidence of accelerated sea level rise. However, the other scientist interviewed, Dr. Stephen Leatherman, Director of the International Hurricane Research Center at Florida International University, reportedly maintained that there is evidence of acceleration in the rate of sea level rise over the past decade or so. The Florida Cabinet has heard several reports about changes in sea level from presenters at its two recent Climate Change Conversations. At the second Conversation, in June 2007, Dr. James O'Brien (2007), emeritus professor of meteorology at Florida State University, reported that tide gage data indicate a long-term average rate of global sea level rise of about 2.1

mm/yr, while recent satellite altimetry data (1993-2003) indicate a global rate of 3.0 mm/yr. O'Brien maintained, however, that there is no proof of accelerated sea level rise.

### Estimates of Future Sea Levels

Recent newspaper articles that discuss likely future sea level conditions in Florida (Dean, 2006; Lollar, 2007; Mulkey, 2007a) have reported projections of global average increases in eustatic sea level due to climate change ranging from 0.6 to 20 feet by 2095 or 2100 (see Table 3). The Florida Cabinet has heard three apparently very different reports about projected sea levels from presenters at its two Climate Change Conversations. At the Conversation on April 3, 2007, Dr. Stephen Mulkey (2007b), Director of Research and Outreach/Extension for the University of Florida's School of Natural Resource and Environment, spoke in terms 2 feet of eustatic sea level rise by 2100 based on the IPCC's *Climate Change 2007* report (Meehl et al., 2007). In the subsequent Cabinet Conversation, on June 12, 2007, Kellee James (2007), an economist with the Chicago Climate Exchange, presented information attributed to the IPCC, the State of Florida, and the Natural Resources Defense Council, claiming that sea level in Florida will rise by 2 to 10 feet over the next 50 years. In his presentation at the second Conversation, O'Brien (2007) maintained that it will take 484 years for sea level to rise 5 feet. This translates to about 1 foot of sea level rise by 2100.

Dr. Earnest Estevez at the Mote Marine Laboratory developed sea level rise projection estimates for Sarasota Bay for the Sarasota Bay National Estuary Program's 1992 *Framework for Action* (Roat et al., 1992). He estimated a maximum potential increase of 64 centimeters (2.1 feet) by 2115 relative to the 1992 mean higher high water line for the area based on the extant global projections available at that time adapted for Sarasota Bay.

According to Brandt Henningsen, Chief Environmental Scientist with the Southwest Florida Water Management District (personal communication, July 26, 2007), the U.S. Geological Survey office in St. Petersburg, Florida, developed an estimate of sea level rise in about 1997 for use by the district in their Tampa Bay wetland restoration program. The USGS estimate was an increase of 12 to 18 inches over the next 100 years.

The South Florida Water Management District released a study in 1998 that assessed the impacts of possible sea level rise and associated saltwater intrusion on water resources in southeastern Florida (Trimble et al., 1998). This study, which was disseminated to county and regional planners, used a scenario of a 0.5-foot increase in sea level between 1995 and 2050 based on a U.S. Environmental Protection Agency (EPA) study authored by Titus and Narayanan (1995).

The Titus and Narayanan report also served as the basis for a series of studies completed more recently by several of the regional planning councils (RPCs) in the state (East Central Florida RPC, 2004; South Florida RPC, 2005; Southwest Florida RPC, no date; Tampa Bay RPC, 2006; Treasure Coast RPC, 2005), plus Walton County (Hudgens, 2003). The studies were undertaken with funding from EPA to "illustrate how

communities expect to address the most fundamental question about sea level rise: Where will we retreat and where will we hold back the sea?” (Southwest Florida RPC, no date). The EPA’s objectives included both mitigation of the vulnerability of people and property to increased erosion and flooding and promoting strategies to ensure the long-term survival of coastal wetlands (Tampa Bay RPC, 2006, p. 3).

Each of the RPC studies contains a table of regional sea level rise projections relative to 1990 for the years 2025, 2050, 2075, 2100, 2150, and 2200 based on the methods set forth by Titus and Narayanan (1995). Estimates are presented for a range of probabilities between 90 and 1 percent. The range of estimates for 2100 is 26 to 117 centimeters (0.9 to 3.9 feet) for each of the regions. The mean estimate for 2100 is 51 to 52 centimeters (1.7 feet).

Following the reasoning of Titus and Narayanan, the studies used the 10-foot contour interval to depict areas likely to be flooded by astronomical high tides on top of a 5-foot rise in eustatic sea level. Most of the reports explain in the text that a 5-foot rise in sea level was projected by Titus and Narayanan to be likely over a period of 200 years; however, this time context is not explicit on the maps included in the reports. A standard set of assumptions was used to map likely response strategies (protection almost certain; protection reasonable likely; protection unlikely; or no protection) based on existing land uses (Tampa Bay RPC, 2006, pp. 33-35).

The Tampa Bay RPC reviewed the study and maps with its Regional Planning Advisory Committee (p. 72). It also distributed draft maps to all of the local planning agencies in the region (pp 31-32). Some of the RPCs have posted the maps or reports on their website. Others have used the report as the basis for presentations to local planners and other local officials.

### *What Are the Experts Saying Now?*

Mixed signals from the popular press and other informal sources reflect in part continuing scientific uncertainty about contemporary rates of sea level rise and the levels to which sea level will rise by specific points in time.

### Estimates of Sea Level Rise Rates

The IPCC's fourth assessment report, *Climate Change 2007: The Physical Science Basis* reports that the rate of global eustatic sea level rise began to increase sometime after 1850 and appears to have increased further over the past decade or so. The rates reported in the report appear to support such a conclusion. However, scientists disagree as to whether or not the recent data are indicative of a significant trend of accelerated sea level rise.

In the IPCC chapter on sea level observations (Bindoff et al., 2007, p. 410), the IPCC reports a long-term average rate of global sea level rise of 1.7 millimeter (0.07 inch) per year for the 20<sup>th</sup> century (see Table 3). The observed rate for the period 1961 to 2003 is 1.8 mm (0.07 in) per year, while the observed rate for the period 1993 to 2003 is 3.1 mm



(0.12 in) per year (p. 419). These estimates are derived from reconstructions using long-term, spatially-sparse, land-based tidal gage data and near-global satellite altimeter data available since 1992 (Bindoff et al., 2007, p. 411).

Scientists disagree as to whether or not the tide gage and satellite altimeter data show evidence of an actual acceleration in the rate of sea level rise. Walton (2006) cites conflicting findings from previous studies by a number of authors including Church and White (2006), Donnelly et al. (2004), and Douglas (1991). Psuty and Ofiara (2002, p. 153) found that an exponential curve provided a better fit to tide gage data for Atlantic City, New Jersey, than a straight line, concluding, therefore, that an acceleration in sea level rise was evident at that location. Walton (2006) makes a related argument from his time-series analyses of five tide gage stations in Florida over the period 1941 to 2005.

Bindoff et al. (2007) note, however, that no long-term acceleration of sea level has been identified using 20<sup>th</sup> century data alone because of high inter-annual and decadal variability. They also observe that the higher observed rate of sea level rise during 1993 to 2003 may "partly reflect" decadal variability rather than an acceleration in the rate of sea level rise (p. 420). FSU geology professor, Joseph Donoghue (personal communication, June 28, 2007), maintains that the time period represented by the altimeter data is too short to be interpreted as a long-range trend. He says that because of the very large inter-annual and decadal variation of tide gage sea level data it is possible to find an array of "trends" for different 10-12 year samples of data points. As shown in Figure 2, there is very substantial noise in the tide gage data.

It is important to note that there is substantial regional variability in sea level observations. These are influenced by regional variations in sea water temperature and density, salinity, wind patterns, and ocean currents. According to Bindoff et al. (p. 409), sea level rise rates are several times greater than the global mean in some regions while in others, eustatic sea level is actually falling. As shown in Table 2, long-term data from tide gages maintained by the National Oceanic and Atmospheric Administration, show long-term relative sea level rise rates between 1.53 mm (0.06 in) per year at Apalachicola and 2.43 mm (0.10 in) year at Mayport (Zervas, 2001).

### Future Sea Level Rise Projections

As shown in Table 3, recently published projections of sea level rise by 2100 relative to approximately 2000 from credible scientific sources range from less than 1 foot to more than 15 feet. Some are based on analysis of current trends while others are derived from an array of scenarios based on different assumptions about future greenhouse gas emissions.

The IPCC *Physical Science Basis* chapter on global climate projections (Meehl et al., 2007, p. 820) presents estimated projections of mean global sea level rise rates as well as total mean global sea rise for a time period bounded by two time intervals: 1980-1999 to

2090-2099.<sup>1</sup> These estimates are based on a set of scenarios that encompass a range of possible greenhouse gas emissions ranging from best case (B1) to worst case (A1FI).<sup>2</sup> Scenario A1B represents an intermediate scenario.

The IPCC's projected rates of sea level rise for the 1980-1999 to 2090-2099 [~1990 to 2095] time period range from 1.5 to 9.7 mm (0.06 to 0.38 in) per year (see Table 2). The corresponding aggregate increases in sea level for the time period (see Table 3) range from 0.18 meter (0.6 foot) for the B1 scenario to 0.59 meter (1.9 feet) for the A1FI scenario. If recent melting rates of the Greenland and West Antarctica ice sheets increase linearly with global mean temperature, the upper bound of sea level rise could be as high as 0.28 meter (0.9 foot) to 0.79 meter (2.6 feet) by 2095.

In a recent article published in the journal *Science*, Stefan Rahmstorf, professor of physics of the oceans at Potsdam University, Germany, presents a semi-empirical analysis of the relationship between the magnitude of average atmospheric temperatures and the rate of sea-level rise (Rahmstorf, 2007a). Rahmstorf argues that sea level will rise as a response to an increase in temperature until a new equilibrium is reached. Paleoclimatic data indicate that the equilibrium level will be significantly higher and will take millennia to achieve. While there are uncertainties in how much sea level will rise, he maintains that a rise of as much as 1.4 meters (4.6 feet) by 2100 cannot be ruled out based simply on a continuation of the linear relationship between sea level rise and temperature observed in the 20<sup>th</sup> century. In a subsequent critique of the IPCC report, Rahmstorf (2007b) argues that adjustments for full ice sheet uncertainty and the effects of carbon cycle feedback<sup>3</sup> on global temperature rise would add 0.35 meter to the Meehl et al. (2007) range of 0.18 to 0.59 meter yielding a sea level rise increase by 2095 of 0.53 meter (1.7 feet) to 0.94 meter (3.1 feet).

Hansen (2007) criticizes the reticence of the IPCC report authors to fully address the implications of the apparent onset of disintegration of the Greenland and West Antarctic ice sheets. He argues that the sea level rise trend has become nonlinear and, as a result, linear extrapolations of observed rates of melting underestimate the likely magnitude of melting during the current century. Hansen maintains that the approximate 1 mm/yr increase in the observed rate of sea level rise over the past decade, i.e. the apparent increase from the satellite altimetry observations, is probably attributable to more than a doubling of the rate of ice sheet melting. He suggests that if the rate of ice sheet melting continues to double on an approximate 10-year basis that the amount of sea level rise by 2100 relative to 2000 could be as much as 5 meters (16.5 feet). However, he also concludes that it is now "impossible to accurately predict the sea level change on a specific date" because we have no valid predictive models for the melting process that is now taking place.

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<sup>1</sup> The IPCC chose to use these time intervals to reflect uncertainties in the climate change models. Taking the midpoints of these intervals, the projections are roughly for the period 1990 to 2095 (Rahmstorf, 2007b).

<sup>2</sup> See Appendix A for a synopsis of the emissions scenarios.

<sup>3</sup> Explain the carbon cycle feedback effect.

Recent formal analyses of contemporary rates of sea level rise in Florida are scarce. The only published analysis we have located is a recent article by Walton (2007) who employed exponential time-series analysis to model data from five tide gage stations in Florida to account for a possible acceleration trend in sea level rise. His results predict increases in relative sea level between 2006 and 2080 ranging from 0.25 meter (0.8 foot) to 0.35 meter (1.1 feet). As shown in Table 3, these estimates fall within the range of the IPCC's estimates without accelerated melting of the Greenland and West Antarctic ice sheets.

### Potential Impacts of Rising Sea Level

Sea level rise will have four major impacts that are relevant to comprehensive planning in general and the planning and management of public infrastructure in particular: (1) inundation and shoreline recession, (2) increased flooding from severe weather events, (3) saltwater contamination of ground water and surface water supplies, and (4) elevated water tables.

#### *Inundation and Shoreline Recession*

The most obvious impact of sea level rise is simple inundation of previously dry land. Titus (1991) calculated that the U.S. could lose as much as 20,000 square kilometers (7,720 square miles) of dry land due to inundation from a 1-meter rise in sea level if shorelines were allowed to retreat naturally. He estimated that 70 percent of these losses would occur in the low-lying coastal plains of the southeast.

As sea level rises, the elevation of the mean high-tide line will move landward at a rate determined by the gradient of the local topography. Along sedimentary shorelines, the extent of shoreline recession will also be a function of erosion unless there is a sufficient influx of new sediment to offset the erosion losses (NRC, 1987, p. 49). Along the protected shores of ocean bays, where the shoreline typically consists of salt marshes or mangrove swamps, the shoreline typically recedes more slowly than along sandy beaches due to steeper gradients. In these areas, which account for the majority of coastal land below 1 meter in elevation (NRC, 1987, p. 64), inundation is the primary impact of sea level rise. Erosion is more limited, accounting for only about 1 percent of coastal wetland loss (NRC, 1987, p. 69), because of more cohesive sediments and the presence of dense wetland vegetation (NRC, 1987, p. 49).

The general rule-of-thumb for recession of sandy shorelines in the face of sea level rise was defined by Bruun (1962). The so-called Bruun Rule, is that sandy shorelines will erode landward a distance that is determined by the amount of sea level rise and the slope of the beach. While the Bruun Rule is an oversimplification of the complexities of shoreline recession (NRC, 1987, pp. 55-57), it does offer a basis upon which some generalizations can be made in the absence of detailed site-specific analyses.

The values of this recession factor vary substantially from one location to another. The public is hearing a wide variety of estimates about how far Florida beaches are likely to

recede as sea level rises (see Table 4) ranging from 500 to 1,000 feet for every 1-foot rise in sea level (Dean, 2006; Lollar, 2007; Ritchie, 2007; Tasker, 2007).

Walton (2007) reports that the recession rate generally lies between 50 and 100 for the U.S., i.e. for a 1-foot rise in sea level, the shore will recede by 50 to 100 feet. Dr. Stephen Leatherman, Director of the International Hurricane Research Center at Florida International University, in a recent presentation to the Florida Cabinet (Leatherman, 2007), reported that the average recession factor is 78 for 5 locations on the east coast of the U.S.: Long Island, New Jersey, the Delmarva Peninsula, North Carolina, and South Carolina (see Table 4). In other words, a 1-foot rise in sea level would result in 78 feet of shoreline recession.

Titus et al. (2001) reported that the recession factor for Florida ranges between 100 and 1,000. Dr. Peter Howd of the U.S. Geological Survey is quoted in a recent article in the *New York Times* as saying that in much of Florida, the recession factor is only about 100 (Dean, 2006). On the other hand, Jeremy Weiss, a senior research specialist with the University of Arizona's Department of Geosciences, is quoted in an April 2007 article in the *Ft. Myers News Press* (Lollar, 2007) as saying that the range for southwest Florida is between 500 and 1,000. Tasker (2007) quotes Dr. Harold Wanless, a geologist at the University of Miami, as saying that the gradient on the Florida Keys and barrier islands such as Miami Beach may be as low as 1:2000.

Dr. Joseph Donoghue, professor of geology at Florida State University, reports that the average gradient in Florida is 1:1000 so that on average the shoreline recedes by 1.5 meters per year based on an average annual rate of sea level rise of 1.5 mm/yr (personal communication, June 28, 2007). If the upper bound of the sea level rise rates projected by Meehl et al. (2007) for the A1FI scenario is applied to this gradient, i.e. 9.7 mm/yr (see Table 2), an annual shoreline recession rate of 9.7 meters (32.1 ft) per year would be anticipated by approximately 2095 from eustatic sea level rise alone. The mid-level A1B scenario estimate of 6.0 mm/yr would result in a recession rate of 6.0 meters (19.8 feet) per year.

Nationwide, beach erosion rates are as high as 1 to 4 feet per year in many places (U.S. Federal Emergency Management Agency, 2000). In Florida, the state Department of Environmental Protection Bureau of Beaches and Coastal Systems (2007) has classified 387 of the state's 825 miles of sandy beaches (47%) as critically eroding.

Coastal wetland recession also varies with location. Wetlands naturally adapt to rising sea levels through accretion with sediment and biomass inputs (Nicholls and Leatherman, 1995, p. 238). Estuarine wetlands generally have been able to accrete at a rate equal to or greater than sea level along much of the east coast of the U.S., with the exception of Louisiana where rapid subsidence and a reduction in natural sediment inflow have contributed to substantial coastal wetland loss (NRC, 1987, pp. 66; 71). However, at some point the rate of sea level rise may exceed the ability of the wetland to keep pace. Wetlands that occur on the bay side of barrier islands may be able to keep pace with sea level rise if sufficient sediments are washed to the bay side by periodic overwash of

beach sediments associated with major storm events (NRC, 1987, p. 65). However, if the barrier island has sufficiently high elevation or if human-made structures impede overwash, back-barrier wetlands may be inundated over the long term (NRC, 1987, p. 65). Titus (1991) estimated that 29 to 69 percent of wetlands along the east coast of the United States would be lost with a 1-meter rise in sea level if only currently developed areas are protected.

Sea level rise may interfere with navigation under bridges by diminishing the above-water clearance. Titus (2002, p. 3) argues, however, that this will not be a major issue for most large bridges over primary shipping lanes. In Florida, the design clearance for bridges over salt water is 12 feet which provides a margin to accommodate some sea level rise for most watercraft. Higher elevations of saltwater bodies will increase exposure of bridge decking, beams, trusses, and girders to saltwater spray from wind, waves, storms, and watercraft. This may promote spalling (flaking) of the concrete and more rapid corrosion of steel bridge components and the rebar in concrete components as the concrete cracks with age. Newer bridges, however, are being constructed with concrete formulations that better resist cracking and spalling as structures age and epoxy-coated rebar that resists corrosion. Bridges over non-navigable, freshwater are designed with a "drift clearance" of 2 feet. Where sea level rise affects these streams, vulnerability to blockage and structural damage from floating debris will increase.

Infrastructure that lies in the path of shoreline recession due to elevated sea level rise and erosion may be adversely affected in several ways. As the mean high tide line moves landward, above-ground structures such as wastewater treatment and reclamation facilities, water supply treatment facilities, and sewer lift stations may initially be subject to intermittent flooding from spring high tides. This may cause short-term access problems at the least, as well as flood damage if facilities are not adequately flood proofed. Shoreline recession due to erosion may result in scouring and undermining of above-ground facilities, road bases, and bridge abutments. Buried pipes, including storm water and sanitary sewers and water supply lines, may be damaged along sedimentary coasts where resultant shoreline erosion and recession expose them to currents and wave forces (NRC, 1987, p. 110).

Pumping rates for wastewater discharge pipes with subsurface outfalls may need to be increased to counter increased hydraulic head due to increased sea level (NRC, 1987, p. 110). Similarly, discharge rates from gravity-flow storm sewers, ditches, and canals will be reduced if outfalls are partially submerged because of the decreased hydraulic head due to higher tailwater levels (Titus et al., 1987). The capacity of such systems will be further reduced due to increased siltation at lower flow velocities. The effectiveness of tide gates in storm water drainage canals and mosquito control ditches may be compromised by small increases in sea level (NRC, 1987, p. 111).

#### *Flooding From Severe Weather Events*

As sea level rises, the return frequencies of coastal floods of a given elevation will increase, i.e. higher floods will happen more often, and the boundaries of flood zones for

floods of a given return frequency will move higher and further landward. Shoreline recession due to erosion will further shift flood zones further landward.

Federal Emergency Management Agency (FEMA) 100-year flood boundaries, i.e. A-zones and V-zones, are often used to define areas within which infrastructure should not be built or areas within which infrastructure must be elevated or flood proofed. Sea level rise and shoreline recession will move the boundaries of the 100-year storm floodplains higher and further landward. Similarly, hurricane storm surge vulnerability zones will move landward, so that areas previously landward of the Category 5 surge zone will be vulnerable to hurricane flooding and areas closer to the sea will be subject to higher intensity storm surges than at present. Possible increases in the intensity of hurricanes associated with climate change (Alley et al., 2007, p. 16) will increase the likelihood that these areas will be subject to higher storm surges as well as higher maximum sustained winds.

For example, Kirshen et al. (2004) estimated the impacts of sea level rise on the elevations of the 10-year, 100-year, and 500-year storms in Boston Harbor. A US Army Corp of Engineers study conducted in 1993 (Weiner, 1993) had determined that the 10-year storm surge elevation in Boston Harbor was 2.8 meters, the 100-year elevation was 3.16 meters, and the 500-year elevation was 3.41 meters. Kirshen et al. (p. 55) estimated that at contemporary rates of relative sea level rise of 0.3 meter per century in Boston Harbor, the 10-year storm surge elevation would be equal to that of the 1993 100-year storm before the end of this century, and the 100-year storm surge elevation would equal that of the 500-year storm.

The primary implication here is that the level of flood protection previously afforded by the elevation or flood proofing of infrastructure will be reduced as sea level rises. Seawalls, bulkheads, revetments, and levees built to provide flood protection to public facilities and infrastructure will be over-topped more frequently. Drainage canals and ditches may be inundated for often resulting in longer delays in draining floodwaters from interior areas.

Furthermore, facilities previously sited in what were considered to be safe areas, e.g. outside the FEMA 100-year floodplain, may be exposed to floods with higher return frequencies, and structures designed to withstand the force of storm waves and moving floodwaters of a given intensity will be more likely to be subjected to stronger forces. Bridges and causeways along hurricane evacuation routes will have to be closed sooner for a given storm intensity. Highways, bridges, and causeways will be flooded more frequently. As sea level rises, incidents such as the vertical displacement of segments of the I-10 bridges over Escambia Bay during Hurricane Ivan in 2004 (see Figure 3) and Lake Pontchartrain during Hurricane Katrina (see Figure 4) will occur more frequently as will erosion of bridge abutments from storm waves and storm currents.

### *Saltwater Contamination of Ground Water and Surface Water Supplies*

As sea level rises and shorelines recede landward, saltwater intrusion into coastal surficial aquifers also will increase (Jacoby, 1990, p. 316; NRC, 1987, p. 113). Communities that withdraw water from surficial aquifers in various parts of Florida, including the Biscayne Aquifer in southeastern Florida, the Floridan Aquifer along the northeastern coast, and the Tamiami Aquifer in southwestern Florida, have already experienced problems with saltwater intrusion from the sea due to excessive withdrawals (Shoemaker & Edwards, 2003; Sonenshein, 1995; Spechler, 2001).

The “salt front” of the saltwater wedge in coastal rivers also will move further upstream as sea level rises (NRC, 1987, p. 115). The distance will be a function of the river’s gradient as well as the amount of freshwater flow down the river and the tidal cycle. Changes in precipitation regimes that accompany global climate change may, therefore, either serve to exacerbate or ameliorate this impact. Upstream extension of the salt front in coastal rivers will affect both surface water intakes as well as well fields in aquifers that are recharged by river water (Jacoby, 1990, p. 318; NRC, 1987, p. 115).

Hull and Titus (1986) estimated that a 2.4-foot rise in sea level in the Delaware estuary would push the 250 parts per million (ppm) isochlor of the Delaware River upstream an average distance of 7 miles. They also estimated that the sodium content of river water at one of Philadelphia’s intakes on the river would exceed the state standard of 50 ppm on 15 percent of the annual tidal cycles. Major (1992, p. 382) noted that upstream migration of the salt front in the Delaware River might require an increase in releases from the New York City water supply reservoirs in the Catskills.

Major also suggested that New York City’s Chelsea Pumping Station on the Hudson River, as well as the water supply for the City of Poughkeepsie, might be threatened by upstream migration of the salt front. Schwarz and Dillard (1990, p. 347) quoted a planner with the New York City Bureau of Water Supply as saying that the city’s emergency pumping station on the Hudson River at Hyde Park, more than 80 miles from the mouth of the river, should be moved immediately if sea level rise of 25 centimeters (10 inches) were imminent. At that time, the saltwater boundary of the river was reaching past the pumping station when high tides and low river flows coincided. Schwarz and Dillard (1990, p. 346) reported similar extant problems with high salinity at existing water supply intakes for the City of New Orleans located on the Mississippi River. The managers with whom they talked also noted that corrosion of the city’s cast iron water mains would become a problem at levels of increased salinity that would not affect potability.

The potential for salt front migration to affect water supplies in Florida is a function of both river gradients and rainfall volumes. Richard Verdi with the United States Geological Survey in Tallahassee (personal communication, August 7, 2007) indicated that the only river gradient data available for the state are those reported by Bridges (1982). Because that study was concerned with flood potential, most of the data points are several miles upstream from the mouths of the major rivers in the state. Thus the reported gradients are likely to be higher than those closer to the coast in some river

basins. Table 5 presents data for some of the major rivers in the state including gradients in feet per mile and an estimate of how far upstream the salt front would move with a 3-foot rise in sea level if all other factors were held constant. The gradients range from 0.51 foot per mile on the Suwanee River near Wilcox to 5.51 feet per mile on the Perdido River near Barrineau Park. Estimated distances for salt front migration with a 3-foot rise in sea level range from 5.9 miles on the Suwanee to 0.5 mile on the Perdido based on those gradients.

### *Elevated Water Tables*

Sea level rise also will cause increases in the elevation of fresh ground water that overlies saltwater in surficial aquifers in coastal areas. This may expose buried utility lines and pipelines to corrosion, especially where cast iron or concrete pipe is exposed to saltwater (NRC, 1987, p. 110). Higher water tables also may cause increased groundwater infiltration into sanitary and storm water sewers. Significant infiltration into sanitary sewers may impact the capacity of wastewater treatment plants, while infiltration into storm sewers may reduce the capacity of storm water detention, retention, or treatment facilities. Higher water tables also can lead to a reduction in the bearing capacity of some soils because of loss of friction between soil particles. This may affect the structural stability of road bases resulting in a need for more frequent resurfacing.

Sewers are routinely installed below the water table, however, prolonged exposure to groundwater infiltration can cause consolidation and weakened bearing strength of surrounding soils (Corbitt, 1990, p. 6.69) and result in cracks that progressively increase in size (Curran, 2006) and even displacement and structural failure of the pipe (*Illinois Municipal Review*, April 1993). The amount of infiltration is significantly affected by the hydraulic head due to the amount of groundwater that overlies the sewer (Hammer & Hammer, 2001, p. 356). Thus sewers originally laid above the water table may experience significant increases in infiltration where the water table rises partially or completely above the sewer line, especially if such sewers were not designed to withstand the hydraulic loads of overlying groundwater. In addition, sewers that were originally installed below the water table may experience increases in infiltration if sea level rise results in significantly increased water table elevations. Sewers constructed of light weight materials such as PVC plastic may be floated by rising groundwater tables if they are not properly backfilled when installed so as to prevent this from happening (Lamson Vylon Pipe, 2007, p. 20).

### Adaptive Response Options

Adaptive responses fall into three categories: protection, retreat, and accommodation. Titus (1991) suggests that choices among these options will be based on an evaluation of the value of the land and the built environment to be protected compared to the costs of protection. Titus predicts that highly developed coastlines will be protected from sea level rise with a combination of hard and soft engineering measures. In areas that are considered to be too expensive to adequately protect, Titus suggests that the sea may be allowed to advance and accommodation strategies such as raising the land or structures



will be implemented. Areas that are not heavily developed but that have other intrinsic value (such as barrier islands for their aesthetic value) may be protected. Retreat strategies are likely to be limited to less developed areas, without significant investments in infrastructure, and natural areas such as coastal wetlands that are capable of naturally adapting to sea level rise if not constrained by topography or the built environment.

Barnett and Beckman, in an article in the August/September 2007 issue of *Planning* (2007, p. 36), echo the authors of the recent IPCC report on adaptation to climate change (Parry et al., 2007), calling for planning and engineering studies now to plan both for the inevitable sea level rise that will occur regardless of future efforts to mitigate greenhouse gas emissions as well as against plausible scenarios of more catastrophic sea level rise that could accompany complete melting of the Greenland and West Antarctic ice sheets. They say “There needs to be serious public discussion about protecting every coastal city: what it will cost and how these costs can be met” (p. 37).

In this section we briefly summarize some of the strategies that have been proposed for adapting land use patterns and public facilities and infrastructure to advancing sea levels, shoreline recession, and the associated impacts of increased flooding, contamination of ground and surface water, and elevated water tables.

### *Protection*

The physical structures that can be used to protect developed areas from erosion and inundation include: offshore breakwaters, perched beaches, revetments, dikes, floodwalls, seawalls, bulkheads, dams, beach nourishment, dune building, and marsh building (Sorensen, Wesiman & Lennon, 1984). Beach nourishment can keep pace with sea level rise so long as affordable supplies of suitable beach sediment are available. However, at some point space must be allotted for the beach and dune system to move further landward to maintain a beach slope that is in equilibrium with sea level and the local wave environment. Doing so may entail retreat by upland land uses (see below). The protection afforded by built structures will be reduced as sea level rises. These will have to be modified or relocated as the oceans get deeper. Breakwaters, for example will have to be elevated to keep pace with sea level rise. As the shoreline inevitably recedes due to inundation, if not erosion, breakwaters also will have to be moved further landward. Only dikes and levees that completely contain an area, as have been constructed in The Netherlands and New Orleans, have the long-term capacity to provide protection against large increases in sea level. Titus (2002, p. 8) notes, however, that building dikes also requires the reconfiguration of storm water drainage systems including the use of check-valves and pumps to discharge rainwater at levels above the streets.

Where such structures are built, almost complete loss of coastal wetlands and beach and dune systems will ensue (Titus, 2000, p. 733). Thus, in the process of protecting uplands, the natural protective systems may be lost. According to Titus (2000), most states allow for the protection (armoring) of bay shores but not open-ocean shores. This is due to the public’s desire for beach access and subsequent opposition to anything that would limit that access. Also, many state policies designed to protect ocean shores take migrating

shores into account whereas policies designed to protect wetlands and bays generally do not include the concept of migrating wetlands. In fact, the Army Corps of Engineers issued Nationwide Permit No. 13 in 1996 (reviewed in 2007), which permits bank stabilization activities necessary to prevent erosion. While there are some restrictions on the extent to which stabilization measures can go, Titus argues that this permit essentially provides no allowance for the migration of wetlands.

Titus and Narayanan (1995, p. 140) report that the California Bay Area Conservation and Development Commission adopted a requirement in 1987 that all newly reclaimed land in San Francisco Bay be filled an additional 12 inches higher to account for accelerating rates of sea level rise. Nichols and Leatherman (1995) report that new seawalls in Great Britain and The Netherlands were being designed 0.25 to 0.66 meter higher to account for anticipated sea level rise within the 50 to 100-year design lives of the structures. The USACE redesign of the New Orleans levees reportedly will be designed to accommodate expected sea level rise over the next 50 years, the expected design life of the new levees (Ludwig, 2007, p. 31).

Well fields threatened by encroaching saltwater intrusion have been protected by reducing the permeability of sediments that lie between the sea and the well field, e.g. through installation of bentonite slurry walls and by enhancing freshwater recharge in the area that lies between the sea and the well field through the use of canals or injection wells (NRC, 1987). A 1998 study conducted by the South Florida Water Management District (Trimble et al., 1998) determined that water levels in coastal canals would need to be raised to provide additional recharge of the Biscayne Aquifer to offset saltwater intrusion from sea level. Doing so, however, would reduce the storm water drainage capacity of the canals. Surface water supplies susceptible to salt front intrusion may be protected through the use of tide gates where these do not interfere with navigation. Such structures are currently used in Hillsborough County, Florida, to protect two surface water supplies from incoming tides.

### *Retreat*

The primary option for large-scale retreat involves what Titus (2000, p. 737) refers to as a “rolling easement” under which "human activities are required to yield the right of way to naturally migrating shorelines." The concept is grounded on the Public Trust Doctrine, which dictates that the intertidal zone should remain in public hands, and the Law of Erosion, which stipulates that boundaries shift as land erodes. Texas, as well as Maine, Rhode Island, and South Carolina reportedly have instituted such rolling easements under which development permits are conditioned on relocation of a structure once it is threatened by a receding shoreline (Titus, 2000; U.S. Environmental Protection Agency, 2006). However, it is important to recognize that these doctrines vary substantially among the common laws of the individual states. They may provide the basis for leaving coastal property owners to their own devices if the state can effectively prohibit property owners building seawalls or other obstructions to shoreline recession. However, under some state statutes and common laws, government compensation may be necessary if the state precludes a property owner from protecting their property.

As noted above, Titus (1991) anticipates that retreat strategies will primarily be confined to minimally developed and natural areas where the costs of protection will not be warranted and where there remains the potential for natural coastal ecosystems to adapt naturally. In these areas, it may be feasible for government to acquire land from property owners as shoreline recession makes continued occupation impossible without armoring.

On a smaller scale, retreat options may be feasible for some infrastructure facilities. Well fields contaminated by saltwater intrusion may be abandoned where protection strategies are deemed to not be cost-effective. Road segments threatened by receding shorelines may be relocated further landward. This strategy, however, may prove to have limited application because of the high costs of right-of-way acquisition. Benefit-cost analyses conducted for two sections of U.S. 98 in the Florida panhandle that are subject to chronic damage from hurricane-caused erosion showed that periodic repair and replacement would be more efficient than relocation. A proposal to relocate portions of a county road in Indian River County, Florida, after sustaining damage from both Hurricane Francis and Hurricane Jean in 2004, was rejected because of right-of-way costs and the delays that relocation would entail. The state decided instead to armor 13 miles of the road.

#### *Accommodation*

New development can be directed away from areas that are anticipated to be affected by inundation, shoreline recession, and advancing coastal flood boundaries. Setbacks can be employed to require that new structures be built back from the shore by some multiple of the annual average erosion rate. However, the multipliers currently used, for example 30 in Florida, do not provide long-term accommodation for the amount of shoreline recession likely to occur as sea level rises over the next 50 to 100 years. A second, related option, is to prohibit development in larger hazard zones that are and will be susceptible to both shoreline recession and coastal storm flooding. However, a recent assessment of the effectiveness of Florida's mandate for local governments to adopt and implement policies to direct development away from coastal high hazard areas in the state (Chapin, Deyle, and Baker, under review; Deyle, Chapin, and Baker, under review) suggests that this is not likely to be accomplished without radical changes in state and local land use policies and underlying federal and state laws. Property rights law presents a formidable barrier to completely prohibiting development of such areas, while public funds for fee-simple acquisition are entirely inadequate to buy-out property owners.

New above-ground infrastructure can be designed to accommodate higher coastal flood elevations. Nicholls and Leatherman (1995, pp. 240-241) report several examples of decisions to increase the base elevation of infrastructure facilities to account for anticipated sea level rise. They cite Smith and Mueller-Vollmer (1993) as reporting that the Massachusetts Water Resources Authority designed the Deer Island sewage treatment plant with an additional 0.46 m of height so as to maintain gravity flows at higher sea levels without the capital and operating costs of additional pumping. Major (1992, p. 382) cites a report by Hurwitz (1987) that an outflow pipe for the Third City Tunnel of the

New York City water supply system on the Roosevelt Island was redesigned to explicitly account for anticipated long-term rise in sea level.

New infrastructure also can be sited outside the bounds of advancing coastal flood boundaries, if official maps of hurricane storm surge zones and 100-year floodplains are developed to depict both contemporary and future boundaries. According to Mark Viera with the Federal Emergency Management Agency Region IV Office in Atlanta (personal communication, August 13, 2007), FEMA's Map Modernization project has not yet produced revised coastal maps of A-zones and V-zones that account for anticipated sea level rise. Map updating to date has focused on non-coastal areas where much of the emphasis has been on simply digitizing older paper maps rather than conducting formal restudies that reassess where flood hazard boundaries should be drawn. Map updating in coastal areas is slated to begin in 2009 or 2010. According to Viera, these will be formal restudies. The agency's recently published guidelines for coastal flood hazard zone mapping along the Atlantic and Gulf Coasts (U.S. Federal Emergency Management Agency, 2007) do encourage "mapping partners"<sup>4</sup> to account for sea level rise: "mapping partners should consider the impacts of sea-level rise on floodplain boundary delineations . . . [within] "the probable lifetime of a particular [flood] study" (pp. D.2.4-25 and D.2.4-26). Viera anticipates that additional guidance may be forthcoming once the post-Katrina remapping is finished in coastal Louisiana and Mississippi.

Accommodation strategies for existing infrastructure include elevation and flood proofing for above-ground facilities. Elevation of major existing facilities such as wastewater or water supply treatment plants is unlikely to be cost-effective. Base elevations may be increased when facilities are upgraded or replaced onsite, but this may not be possible for wastewater treatment or reclamation facilities served by gravity sewers unless pump stations are added to lift incoming sewage to the treatment facility grade. Bridges can be rebuilt with higher elevations. However, doing so may necessitate acquisition of additional right-of-way for extended approaches.

Titus (2002, p. 6) observes that roads are typically constructed at lower elevation than surrounding land for drainage purposes and, therefore, are more susceptible to flooding. He suggests that while major elevation of roads will require additional fill and reconstruction of the entire roadbed, small increments in elevation to reduce flooding can be accomplished on local streets by paving over existing pavement. This strategy does not, however, account for the structural destabilization of the roadbed where rising sea level also results in elevated water tables. Titus predicts that many low-lying communities will accommodate larger increments of sea level rise through incremental elevation of the land with fill.<sup>5</sup> He suggests that doing so will also provide adaptation for roads.

Elevation of the ground surface will not address the impacts of rising sea levels on underground infrastructure. Sewer wet wells may need to be raised or otherwise protected

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<sup>4</sup> "Mapping partners" are the consultants who actually perform the remapping studies.

<sup>5</sup> Titus (2002, p. 6) reports that eight New Jersey communities on barrier islands have signed agreements with EPA pledging to adapt to rising sea level by gradually elevating the land and structures upon it.

against buoyancy resulting from elevated water tables. Manhole covers may need to be sealed to reduce inflow from street flooding. Accommodation strategies for increased infiltration and other impacts on underground sanitary and storm sewers associated with higher water tables include complete replacement of the sewer pipe, replacement of sewer bedding material, grouting of pipe cracks and/or surrounding soil, and lining with a smaller-diameter polyethylene plastic pipe (Corbitt, 1990, p. 6.69). Replacement is typically more expensive and time-consuming resulting in service disruptions and often interfering with surface transportation along sewer rights-of-way.

Titus et al. (1987, p. 219-220) identify three major accommodation strategies for storm water drainage systems in coastal areas aside from the option of accommodating more frequent flooding:

- (1) enhancement of gravity drainage through installation of large diameter pipes and widened drainage ditches to counteract the reduced head that results from higher tailwater elevations;
- (2) installation of forced drainage systems in low-lying areas where gravity drainage is no longer possible and increased pumping capacity for existing forced drainage systems to counteract higher tailwater elevations; and
- (3) delay of peak discharges and reduction of peak discharge volumes by enhancing storm water detention at upstream locations within drainage basins and incorporating other measures that enhance onsite detention and retention and infiltration of runoff such as use of porous pavements, roof-top detention, grassed waterways, etc.

Advancing salt fronts in tidally-influenced surface water supplies have been routinely managed through supplemental releases from upstream reservoirs (U.S. Environmental Protection Agency, 2006). However, maintaining sufficient quantities of water in storage to accommodate such releases may run counter to flood protection needs.

Accommodation options for saltwater intrusion into water supply well fields are well established because a number of coastal communities have already encountered the problem from excessive withdrawal rates. They include (1) reducing withdrawal rates by drawing more from alternative sources and promoting conservation and (2) the use of desalination (NRC, 1987, p.113; Sorensen et al., 1984). A number of water utilities in southern and southwestern Florida and the Tampa Bay area already employ desalination to treat water from deeper brackish aquifers and brackish surface waters including the cities of Ft. Myers, Ft. Pierce, and others are investigating the option of doing so. The Tampa Bay desalination plants treats water drawn from the bay, and other communities in the state, including Miami-Dade County, Ft. Myers, Ft. Lauderdale, and Port Everglades are assessing the feasibility of desalination of seawater (Ludwig, 2007; Southwest Florida Water Management District, 2006; Water Quality and Health Council, 2007). In areas such as the Florida Panhandle, where alternative surface water supplies are available, and northeastern Florida, where the Floridan Aquifer has low dissolved solids, desalination is considered to be less cost-effective.

### *The Costs of Protection and Accommodation*

The costs of protecting developed areas will be high and must be weighed against the economic value of the land and its improvements. Titus (1991) estimated that the cost of protecting developed shores along sheltered waters of the U.S. for a 1-meter rise in sea level would be approximately \$22.07 billion (in the southeast alone, \$8.91 billion). Protecting the open coast from 1 meter of sea level rise by elevating roads, structures, and beaches could range from \$7.8 billion along the Atlantic Coast to \$51.6 billion along the Gulf Coast, not including the cost of sand for renourishing beaches. The authors qualify this projection as too low because it ignores all of the impacts that could not be readily quantified.

Other estimates of the cost of protecting the shores of the U.S. have been made using different assumptions. In a study by Yohe et al. (1996) cited by Titus (2000), the authors estimated that the cost would only be \$45 billion to protect the U.S. shoreline if protection were confined to those areas where the value of the land and its improvements justify the protection. This cost could be further reduced to \$36 billion if landowners understood the need to abandon the shoreline well before the need arose and were, therefore, prepared for retreat.

Walsh et al. (2004, p. 593) argue that protection and accommodation are likely to be cost-effective in the medium-term (decades) but that eventually managed retreat will probably be necessary.

### Planning Responses to Sea Level Rise

Titus (2000) suggests that because sea level rise is such a long term problem it is possible that we do not need to prepare for it immediately but that it should be considered in the cycle of capital improvements, especially if the money spent on improvements could earn more money if invested somewhere else. There are two exceptions to this concept. One is the “retrofit penalty,” that is that if one is building a system anyway it may be cheaper and easier to build it with sea level rise in mind instead of having to retrofit the structure. The other is if there could be incidental benefit for incorporating sea level rise into planning from the beginning. For example, if a locale might build a flood control structure for what will be a common flood height in the future, building it now will also mitigate the smaller floods that happen in the meantime. However, Titus also states that while engineering decisions can be put off into the future, land use decisions should not be delayed. This does not mean that coastal areas will be off limits to building but simply that locales need to decide how to deal with land as the shoreline recedes.

Our interviews with local, regional, and state long-range planners and infrastructure managers reveal that, with few exceptions, sea level rise is not on the menu of immediate concerns nor is it likely to be dealt with explicitly within the planning timeframes and processes that are currently in place for comprehensive and infrastructure planning. In the following sections we summarize the frameworks that govern long-range comprehensive planning and infrastructure planning at the local and regional levels for land use, water

supply, wastewater, and transportation facilities. In addition we describe the findings from our surveys of local, regional, and state officials concerning these processes. We conclude with a description of the small number of initiatives that have been begun to address sea level rise adaptive planning in Florida.

### *The State Planning Framework*

The local comprehensive planning horizons stipulated in the state's Growth Management statute (Chapter 163, F.S.) do not provide an explicit context for considering the implications of short-term development decisions with respect to long-term gradual changes such as sea level rise, either in terms of shifting vulnerability to natural hazards such as coastal flooding or in terms of affecting the ability of natural systems, such as beaches and coastal wetlands, to adapt to such long-term changes.

Local comprehensive plans in Florida are required to encompass two planning horizons: a 5-year period after plan adoption and a second period covering at least 10 years (Chptr 163.3177(5)(a), F.S.). Local governments are encouraged to develop a community vision that provides for sustainable growth, recognizes its fiscal constraints, and protects its natural resources. Such a community vision must depict the desired land use patterns and character of the community during a 10-year planning timeframe (Chptr 163.3177(13), F.S.). A separate Future Land Use Element designates the proposed future general distribution, location, and extent of land uses in the community over the 10-year planning horizon (Chptr 163.3177(6)(a), F.S.). Requirements for a separate Conservation Element (Chptr 163.3177(6)(d), F.S.), which addresses the conservation, use, and protection of natural resources in the area, including ". . . wetlands, waterwells, estuarine marshes, . . . beaches, shores, flood plains, rivers, bays, lakes, harbors, . . . fisheries and wildlife, [and] marine habitat . . ." arguably could offer the context within which the expected impacts for climate change might be addressed if a much longer planning horizon were stipulated. The statutory requirement for the Coastal Element to address "avoidance of irreversible and irretrievable loss of coastal zone resources" (Chptr 163.3177(6)(g)1.d., F.S.) provides further leverage for considering the potential impacts of sea level rise, at least on natural systems.

### General Capital Facilities and Infrastructure Planning Requirements

Infrastructure planning is governed by two required local comprehensive plan elements: (1) a Capital Improvements Element and (2) a general sanitary sewer, solid waste, drainage, potable water, and natural groundwater aquifer recharge element (referred to hereafter as the Infrastructure Element) (Chptr 163.3177(3)(a)1. and (6)(c), F.S.).

The purpose of the Capital Improvements Element is to outline the principles for construction, extension, or increase in the capacity of public facilities, as well as the principles for correcting existing public facility deficiencies, which are necessary to implement the comprehensive plan (Chptr 163.3177(3)(a)1., F.S.). It must include a "financially feasible 5-year schedule of capital improvements" (Chptr 163.3177(3)(b)1., F.S.). Local governments that elect to designate an urban service boundary must adopt a

10-year financially feasible facilities plan (Chptr 163.3177(14), F.S.). Local governments that choose to adopt a long-term concurrency management system under Chapter 163.3180(9) F.S. must also adopt a long-term capital improvements schedule covering up to a 10-year or 15-year period (Chptr 163.3177(3)(d), F.S.).

The Infrastructure Element is intended to indicate ways to provide for the future potable water, drainage, sanitary sewer, solid waste, and aquifer recharge protection needs for the area (Chptr 163.3177(6)(c), F.S.). It must describe the problems and needs and the general facilities that will be required for solution of the problems and needs over the two planning periods encompassed by the comprehensive plan, i.e. 5 years and at least 10 years. The more detailed requirements set forth in the *Florida Administrative Code* dictate that facility needs for the two planning periods are to be “based on the projected demand at current local level of service standards for the facility, resulting from development permitted by local government, the projected population, land use distributions as indicated in the future land use element, and available surplus capacity identified” (Chptr 9J-5.011(1)(f), F.A.C.). The Infrastructure Element also must include an analysis of the problems and opportunities for facilities replacement and expansion and new facility siting. This appears to be the logical place to address the potential impacts of sea level rise on infrastructure, but to do so requires a planning horizon greater than 10 years.

Parallel requirements are included in the directives contained in the section of the *Florida Administrative Code* concerning the Coastal Element, which must be included in the plans of coastal communities in the state. Analyses are required of the demand upon, capacity of, and area served by existing infrastructure within the coastal planning area as well as estimates of future needs (Chptr 9J-5.012(2)(h), F.A.C.). Coastal communities with deepwater ports are required to include a Deepwater Port Master Plan in their comprehensive plans. These also have 5 to 10-year planning horizons including a plan for future port expansion for an initial 5-year period and in-water facility maintenance for at least a 10-year period (Chptr 9J-5.012(5)(d), F.A.C.). The port master plans also must assess the impact of port expansion and maintenance on coastal natural resources and land use and infrastructure of adjacent areas. This would be the appropriate place to address SLR for ports.

### Water Supply Planning

Florida statutes define a 20-year planning horizon for regional water supply planning and require coordination between the regional plans and local comprehensive plans. While water management districts have responsibility for regional-scale planning, the decisions to undertake specific water supply development projects rest with local governments and their water purveyors. There is nothing in the statutory language that provides an explicit context for addressing the long-term implications of sea level rise on water supply sources or water supply infrastructure.

The need for major water supply infrastructure in Florida is primarily identified through the preparation of district water management plans by each of the state’s regional water



management districts pursuant to Chapter 373.036(2) *Florida Statutes*. The district plans cover at least a 20-year time period and must be updated at least every 5 years. The major elements of these plans include the following:

- established minimum ground water levels and surface water flows,
- identification of one or more water supply planning regions within the district,
- technical data required to assist local governments in preparing the water supply sections of their comprehensive plans,
- a district-wide water supply assessment report that determines the adequacy of existing and anticipated water supply sources and conservation efforts for meeting the needs of all existing and reasonably anticipated legal water uses, and
- any completed regional water supply plans.

Specific considerations that must be reflected in the district water management plans include, among others:

- attainment of maximum reasonable-beneficial use of water resources,
- maximizing economic development of water resources consistent with other uses,
- managing water resources for environmental protection, drainage, flood control, and water storage,
- prevention of uneconomical or unreasonable uses, and
- preservation and enhancement of water quality.

Regional water supply plans must be prepared by water management districts pursuant to Chapter 373.0361 *F.S.* where a district "determines that existing sources of water [within a designated water supply region] are not adequate to supply water for all existing and future reasonable-beneficial uses and to sustain the water resources and related natural systems for the planning period." The regional plan includes a quantification of the water supply needs of the region for at least a 20-year period based on a 1-in-10-year drought scenario plus a list of specific water supply development<sup>6</sup> and water resource development<sup>7</sup> project options and the local governments and other water supply entities that should implement each project option. The plan also must address how the project options will prevent the loss of natural resources and avoid greater future expenditures for water resource or water supply development.

Water management districts also are required to complete consolidated district annual reports pursuant to Chapter 373.036(7) *F.S.* or they may substitute an annual strategic

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<sup>6</sup> "Water supply development" means the planning, design, construction, operation, and maintenance of public or private facilities for water collection, production, treatment, transmission, or distribution for sale, resale, or end use (Chapter 373.019(24) *F.S.*).

<sup>7</sup> "Water resource development" means the formulation and implementation of regional water resource management strategies, including the collection and evaluation of surface water and groundwater data; structural and nonstructural programs to protect and manage water resources; the development of regional water resource implementation programs; the construction, operation, and maintenance of major public works facilities to provide for flood control, surface and underground water storage, and groundwater recharge augmentation; and related technical assistance to local governments and to government-owned and privately owned water utilities (Chapter 373.019(22) *F.S.*).

plan which replaces both the district water management plan and the consolidated annual report. The annual report is required to include, among other elements, a 5-year capital improvements plan (pursuant to Chapter 373.536(6)(a)3 *F.S.*); an annual 5-year work program (pursuant to Chapter 373.536(6)(a)4 *F.S.*); and an alternative water supplies annual report that describes all alternative water supply projects funded that year and the quantity of new water provided (pursuant to Chapter 373.1961(3)(n) *F.S.*).

When a regional water supply plan is undertaken by a water management district, local governments within the water supply planning region may prepare their own water supply assessments which then must be considered by the district in preparing the regional plan. Local governments and other water supply entities are not required to implement the specific water supply development projects for which they are designated in the regional plan (Chapter 373.0361(6)). They may instead propose an alternative water supply development project sufficient to meet the needs identified by the district in the regional plan (Chapter 373.0361(7)(b)).

Local government comprehensive plans must be “coordinated” with any applicable water management district's regional water supply plan through the inclusion of a specific policy statement that addresses such coordination (Chapter 163.3177(4)(a) *F.S.*). The Future Land Use element of the local comprehensive plan must be based on the availability of local water supply (Chapter 163.3177(6)(a) *F.S.*). Within 18 months after the applicable water management district governing board approves an updated regional water supply plan, a local government must amend the Infrastructure Elements of its comprehensive plan to incorporate the alternative water supply project or projects selected by the local government from those identified in the regional water supply plan pursuant to Chapter 373.0361(2)(a) *F.S.* or proposed by the local government under Chapter 373.0361(7)(b) *F.S.* The element also must include “a work plan, covering at least a 10 year planning period, for building public, private, and regional water supply facilities, including development of alternative water supplies, which are identified in the element as necessary to serve existing and new development. The work plan shall be updated, at a minimum, every 5 years within 18 months after the governing board of a water management district approves an updated regional water supply plan” (Chapter 163.3177(6)(c) *F.S.*).

### Wastewater Planning

State law dictates a 10-year planning horizon for wastewater treatment facilities. Sea level rise is not explicitly addressed in regulations governing either the siting of new facilities or the operation and maintenance of existing facilities. Provisions governing the siting and design of new facilities explicitly require that treatment facilities be capable of withstanding the impacts of a 100-year flood. Officials in the state Department of Environmental Protection (DEP) who oversee the permitting of such facilities believe that other regulations should assure that both treatment facilities and collection and disposal systems are operated and maintained so as to adapt to the potential impacts of sea level rise.

There are more than 3,000 permitted, domestic and industrial wastewater treatment facilities in Florida, not including subsurface wastewater disposal systems, i.e. septic tanks. A little less than three-quarters of the individually permitted wastewater facilities in Florida are classified as domestic (municipal) wastewater facilities. These are principally designed to collect and treat sanitary wastewater or sewage from dwellings or homes, businesses, and institutions. The remaining individually permitted facilities are classified as industrial wastewater facilities.

Fewer than 25 percent of the permitted domestic and industrial wastewater treatment facilities discharge to surface waters of the state (Florida Department of Environmental Protection, 2007). The remaining facilities discharge solely to groundwater through land-application, beneficial reuse of reclaimed water, or deep well injection. Those that do discharge to surface waters (slightly more than 200 domestic wastewater facilities) are subject to the state's National Pollutant Discharge Elimination System (NPDES) permitting requirements. Approximately 110 of these facilities discharge to coastal rivers or streams likely to be affected by rising sea level. Only 6 discharge directly to the Atlantic Ocean. None discharge directly into the Gulf of Mexico or Florida Bay. Many of the NPDES facilities also discharge to groundwater.

The planning horizon for domestic wastewater management systems is essentially 10 years. As reported above, the state's laws governing the Infrastructure Element of local comprehensive plans requires a description of the facilities that will be needed to meet a community's infrastructure problems and needs over both 5-year and 10-year planning periods. Once the 3-month average daily flow exceeds 50 percent of the permitted capacity of an existing treatment plant or reuse and disposal system, the permit holder is required to submit a capacity analysis report to DEP (Chapter 62-600.405 FAC). The capacity analysis report is required to include flow projections, based on local population growth rates and water usage rates, for at least the next 10 years; an estimate of the time required for the three-month average daily flow to reach the permitted capacity; recommendations for expansions; and a detailed schedule showing dates for planning, design, permit application submittal, start of construction, and placing new or expanded facilities into operation.

State regulations issued by the Florida Department of Environmental Protection (DEP) which govern the siting of new wastewater treatment facilities do not explicitly address the potential impacts of sea level rise. However, per Chapter 62-620 FAC, an applicant to the State Department of Environmental Protection for a permit for a domestic wastewater facility must provide a preliminary design report containing among other things a site plan showing operations and unit processes, 100-year and 25-year flood elevations; approximate finish elevations for all major treatment units, pumping stations, and sanitary manholes; and a storm water management plan (Florida Department of Environmental Protection, 2001). Section 62.600.400(2)(c) FAC specifically requires the applicant to assess the potential for damage or interruption of operation because of flooding, including potential wave action, when siting new treatment plants and expansions of existing plants at inland or coastal locations. The treatment plant structures essential for the purpose of treating, stabilizing, conveying, or holding incompletely

treated waste and electrical and mechanical equipment must be protected from physical damage by the 100-year flood. The treatment plant also must be designed to remain fully operational and accessible during the 25-year flood.<sup>8</sup> Similar requirements apply to the siting of sewage pump stations (Chapter 62.604.400(2)(e) FAC). As noted above, FEMA maps of 100-year floodplain boundaries do not currently reflect estimates of potential sea level rise. However, there is the potential for restudy maps to be developed over the next several years that do reflect the impacts of sea level rise on future floodplain boundaries.

DEP does not currently have any initiatives underway to directly address the implications of sea level rise for existing wastewater collection and treatment systems. They do, however, have several rule provisions that they believe should serve to detect problems that become manifest as sea level rises and that would require corrective action by system operators. In particular, the state's requirement that wastewater treatment facility permit holders submit operation and maintenance performance reports every 5 years (Chapter 62-600.735 FAC) should provide a trigger for identifying excessive collection system inflow that may result as ground water levels rise in response to rising sea level in low-lying coastal areas.

Another possible impact of sea level rise is reduced discharge flows from submerged treatment plant outfalls as the hydraulic head increases with higher sea levels. DEP requires the regular submission of operation and maintenance reports that include documenting discharge rates (Chapter 62-600.410 FAC). The regulations specifically require that all wastewater treatment facilities and equipment to function as intended. If discharge rates were compromised, facilities might need to install larger pumps to deal with the increased hydraulic head. This rule also would require that corrective action be taken if a treatment facility or portions of the collection system were compromised by flooding or erosion.

At present there are only six municipal domestic wastewater treatment systems with ocean effluent outfalls (Koopman, Heany, Cakir, Rembold, Indeglia, & Kini, 2006). All six are in Palm Beach, Broward, and Miami-Dade counties. While the state does not have formal rules that explicitly require that such facilities be phased out, they have several initiatives in place that are designed to encourage the phasing out of all surface discharges of treated wastewater. These are motivated by two concerns: (1) water supply shortages in many parts of the state and (2) concerns with the effects of nutrient enrichment from treated wastewater effluent. DEP's anti-degradation policy discourages the permitting of new or expanded surface water discharges (including ocean outfalls). The state also requires utilities requesting domestic wastewater plant construction or expansion to investigate the feasibility of implementing water reuse.

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<sup>8</sup> Lesser flood levels may be designed for, if justified in the preliminary design report based on local conditions, water surface elevations, forces arising from water movement, wave heights, flood protection measures provided, and provisions for wastewater storage such that applicable water quality standards will be met; but in no case shall less than a 10-year flood be used.

## Transportation Planning

The Florida state highway system consists of approximately 12,000 miles of highways. About 4,000 miles of this system constitute the Strategic Intermodal System, which is managed directed by the state Department of Transportation (DOT). The remaining 8,000 miles are managed by local governments. All local transportation projects for communities situated within the boundaries of one of the state's 26 Metropolitan Planning Organizations (MPOs) that are funded with state or federal monies must be included in the MPO's 20-year Long Range Transportation Plan.

Local projects funded with state or federal monies also must comply with the state's *Project Development and Environment Manual* (PDE) review procedures and criteria, which address natural hazards and the environmental impacts of transportation projects including highways, bridges, and causeways.

Section 24-2.3 of the *PDE Manual* (Florida Department of Transportation, 1998) requires completion of a risk evaluation for all encroachments within 100-year floodplains. These must consider both risks to highway users from flood hazards and risks to nearby property owners where the encroachment might exacerbate flood impacts. The risk analysis also must include probable flood related costs for highway operation, maintenance, and repair during the service life of the facility. Twenty years is the typical time frame for defining the service life of the capacity of a highway. However, the service life of the right-of-way and roadbed is more on the order of 75 years. Coastal erosion hazards are not explicitly addressed in the *PDE Manual*, but discussions with state district project environmental engineers indicated that such hazards are routinely considered.

Section 18-2.3 of the *PDE Manual* (Florida Department of Transportation, 1999) requires determining the significance of the effects of alternative corridor options on wetland stability and quality, including both short-term and long-term effects. However, discussions with state district project environmental engineers revealed that these assessments do not consider the effects of transportation projects on the long-term ability of wetlands to adapt to sea level rise.

### *What Florida Planners Have to Say*

Here we summarize our findings from our interviews with local long-range comprehensive planners, regional and local water supply planners, and local wastewater systems planners.

#### Local Comprehensive Planners

We interviewed long-range planners in 20 coastal jurisdictions in the state (see Table 1). Most do not prepare plans with planning horizons greater than the 10-year minimum required under state statute, although a few extend the planning horizon to 15 to 20 years. Collier County reported that they extend the planning horizon for infrastructure to 25

years, and Hillsborough County reported that they have begun an effort that will employ a 50-year planning horizon.

We asked these planners about their perceptions of the threat posed to their community by sea level rise without specifying any specific projections. Thirty percent felt that it may be a major threat, another 30 percent said moderate, and 15% say minimal or not at all. Twenty percent of our respondents said they were unsure or did not know.

As reported above in the discussion of sea level rise projections, we also asked each planner how high they thought sea level would rise by 2100. **Nearly half (45%) said they had no idea, while another 15 percent offered no response.** Another 15 percent gave answers that fall within the range of projections made in the most recent IPCC report, i.e. 1-3 feet.

We also asked the planners what their impressions are of the distance inland the shoreline would move in their communities with a 1-foot rise in sea level. As reported above, the expert answers are fairly diverse ranging from 100 to 2,000 feet (see Table 4), so it is not surprising that the planners had diverse perceptions as well. **More than half (53%) said they did not know and another 10% did not respond. Only one of the respondents guessed that the distance might be as high as 100 feet.** However, when asked about vulnerable areas of their communities most referred either to coastal flood-hazard zones or coastal high hazard areas as the most vulnerable locations. Thus while they may have no good handle on how far landward sea level rise may reach, they do have a sense for the most vulnerable areas within their communities.

We received a range of responses to our question about whether or not sea level rise vulnerability is an issue that should be addressed in the long-range planning that these local planners do. Some went by the book saying that they would address it if it was added to the requirements under the 9J-5 rules. Several said yes, but they felt it was not feasible for them to do it at the local level. A few others said they thought it should be addressed but they believed it was not on the agenda of important planning issues for their citizens or elected officials. Two others said they personally felt that other issues were more important in their communities. Two respondents suggested that sea level rise was perhaps not the domain of the comprehensive planners. One of these respondents suggested that the issue might better be addressed by through the land development code. Two communities said they are addressing sea level rise. Miami-Dade County has recently formed a Climate Change Task Force (see details below) and Collier County explicitly addresses sea level rise in its comprehensive plan.

We formally asked the planners if the potential impacts of sea level rise are addressed in their plans. Only Collier County said that it is. However, a number of the respondents suggested that the provisions governing development within coastal high hazard areas or FEMA flood hazard zones offer some policies that are pertinent to sea level rise vulnerability.

The planners listed the following as constraints that limit their agency's concern with sea level rise: (1) political climate or other pressing issues (n=10); (2) lack of adequate information about potential impacts (n=8); and (3) too long a time frame (n=2).

When asked what resources might be made available from the state that would enhance their ability to account for the potential impacts of sea level rise in their long-range planning, the planners we interviewed listed the following: (1) credible predictions of sea level rise scenarios for which planning would be appropriate coupled with information about likely impacts and best practices for adaptation (n=18); (2) public education that can serve to raise public awareness of the importance of dealing with potential sea level rise impacts now (n=3); (3) policy direction as to how local governments should address sea level rise in comprehensive plans (n=5); and (4) funding to help defray the costs of conducting local vulnerability studies and assessments of practical adaptation options.

### Preliminary Recommendations

The following preliminary recommendations are offered for consideration by the Florida Department of Community Affairs and the Division of Community Planning.

1. Coordinate with DCA-DEM, DEP, and the Governor's Office to provide best possible data for mapping sea level rise scenarios at 1-ft intervals above NGVD. Consider using the intervals used by the South Florida Regional Planning Council for their Sea Level Rise Atlas: 1ft, 2 ft, 3 ft, and 5ft.
2. Coordinate with DCA-DEM, DEP-BBCS, Gov Office, (and others) to establish a Task Force (including reps from USGS, NOAA, Leatherman, Robert Dean, FSU CCCL folks) to
  - a. Define a range of possible Fla SLR scenarios for 2050 and 2100 with attendant probabilities [note however that SRES scenarios are not probabilistic]
  - b. Provide maps showing revised locations of the following for 1-3 scenarios each for 2050 and 2100
    - mean high tide line
    - SLOSH storm-surge boundaries
3. In collaboration with DCA-DEM, coordinate with FEMA Region IV to initiate formal accounting for sea level rise in conducting the FEMA flood hazard map restudies for the coastal areas of Florida pursuant to the provisions of Appendix D of the 2007 *Atlantic Ocean and Gulf of Mexico Coastal Guidelines Update*.
4. Coordinate with FDEP, FDOT, the Governor's Office, and other agencies as appropriate, to consider legislation and/or rules that would
  - a. Require long-range water supply planning out to 50-year horizons that accounts for sea level rise impacts on water supply sources with

- concomitant requirements in the Future Land Use and Infrastructure elements of local comp plans.
- b. Require adaptive strategies in the design of new water supply facilities, domestic wastewater collection and treatment systems, storm water management systems, and bridges and roads that account for potential sea level rise impacts over the next 75 to 100 years.
  - c. Require assessment of sea level rise-induced shifts in flooding and erosion hazards in assessing corridors for new state highways and local highways funded with state monies and in major amendments to the Future Land Use Element and Future Land Use Map in local comp plans.
  - d. Require long-term infrastructure adaptation, maintenance, and repair planning for water supply sources and storage, distribution, and treatment systems; domestic wastewater collection and treatment systems; roads and bridges; storm water conveyance, retention, detention, and treatment facilities that accounts for impacts of sea level rise-induced shifts in flooding and erosion hazards over the next 50 to 75 years and assesses structural adaptive measures.
  - e. Require formal assessment of the impacts of major developments and infrastructure projects on the ability of coastal wetlands to adapt to sea level rise by migrating landward.
  - f. Examine the feasibility of incorporating “rolling easements” in both state and local development permits for areas immediately adjacent to coastal waters of the state.
  - g. Provide guidelines and technical information to local governments for accomplishing a-d.
  - h. Fund several pilot projects to develop methodologies for accomplishing a-d.

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Appendix A  
SRES Scenarios Employed by the  
Intergovernmental Panel on Climate Change

The Emission Scenarios of the IPCC Special Report on Emission Scenarios (SRES)\*

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income.

The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis:

- A1FI - fossil intensive
- A1T - non-fossil energy sources
- A1B - a balance across all sources, where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies.

B1. The B1 storyline and scenario family describes a convergent world with the same global population as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

\* Excerpted from Alley et al. (2007).



**Table 1: Sample of Local, Regional, and State Agencies Interviewed**

<b>Jurisdiction/Agency</b>	<b>Comprehensive Planning</b>	<b>Water Supply</b>	<b>Wastewater Systems</b>	<b>Transportation Planning</b>
Local Governments				
Charlotte County	X			
Collier County	X	X		
Hillsborough County	X	X		
Lee County	X	X	X	
Miami-Dade County	X	X		
Santa Rosa County	X	X		
Walton County			X	
Apalachicola	X		X	
Boca Raton		X		
Ft. Lauderdale	X			
Ft. Myers	X	X	X	
Ft. Pierce	X	X	X	
Ft. Walton Beach	X	X		
Jacksonville/Duval County	X	X	X	
Key West	X			
Melbourne	X		X	
Naples	X	X	X	
Panama City	X			
Pensacola	X		X	
Pompano Beach	X			
Punta Gorda		X		
St. Augustine	X			
Tampa	X			
Regional Planning Councils				
East Central	X			
South Florida	X			
Southwest Florida	X			
Tampa Bay	X			
Treasure Coast	X			
Water Management Districts				
Northwest Florida		X		
St. Johns		X		
South Florida		X		
Southwest Florida		X		
State Agencies				
Dept of Transportation				X

**Table 2: How Fast is Sea Level Rising?**

<b>Date</b>	<b>Source</b>	<b>Author</b>	<b>Authority</b>	<b>Location</b>	<b>Time Period</b>	<b>SLR Rate (mm/yr)</b>	<b>Accelerating?</b>
<b>Estimates from Popular Press and Other Informal Sources</b>							
2007, June	<i>Tallahassee Democrat</i>	Ritchie	Leatherman	Florida	n/a	n/a	Yes
2007, June	<i>Tallahassee Democrat</i>	Ritchie	Donoghue	Global and Florida	Current	2	No
2007, June	Florida Cabinet Climate Change Conversation	O'Brien	Author	Global	Tide gage data (long term)	2.1 (relative)	No
2007, June	Florida Cabinet Climate Change Conversation	O'Brien	Author	Global	Altimeter data (1993-2003)	3.1 (eustatic)	No
<b>Estimates from Peer-Reviewed and Other Scientific Sources</b>							
2007, May	IPCC <i>Physical Science Basis*</i>	Meehl et al.	Authors	Global projected	1980-1999 to 2090-2099	1.5 to 9.7 (eustatic)	Yes
2007, May	IPCC <i>Physical Science Basis*</i>	Bindoff et al.	Authors	Global	1993-2003	3.1 ±0.7 (eustatic)	Yes
2007, May	IPCC <i>Physical Science Basis*</i>	Bindoff et al.	Authors	Global	1961-2003	1.8 ±0.5 (eustatic)	n/a
2007, May	IPCC <i>Physical Science Basis*</i>	Bindoff et al.	Authors	Global	20 <sup>th</sup> Century	1.7 ±0.5 (eustatic)	n/a
2005, July	<i>Proceedings 14th Biennial Coastal Zone Conference</i>	Stolz & Gill	Authors	Florida east coast	Tide gages	1-3 (relative)	n/a
2001	tidesandcurrents.noaa.gov/sltrends	NOAA	Zervas (2001)	Mayport, FL	Tide gages	2.43 (relative)	n/a
2001	tidesandcurrents.noaa.gov/sltrends	NOAA	Zervas (2001)	St. Petersburg, FL	Tide gages	2.40 (relative)	n/a
2001	tidesandcurrents.noaa.gov/sltrends	NOAA	Zervas (2001)	Miami Bch, FL	Tide gages	2.39 (relative)	n/a

2001	tidesandcurrents.noaa.gov/ sltrends	NOAA	Zervas (2001)	Ft. Myers, FL	Tide gages	2.29 (relative)	n/a
2001	tidesandcurrents.noaa.gov/ sltrends	NOAA	Zervas (2001)	Key West, FL	Tide gages	2.27 (relative)	n/a
2001	tidesandcurrents.noaa.gov/ sltrends	NOAA	Zervas (2001)	Pensacola, FL	Tide gages	2.14 (relative)	n/a
2001	tidesandcurrents.noaa.gov/ sltrends	NOAA	Zervas (2001)	Naples, FL	Tide gages	2.08 (relative)	n/a
2001	tidesandcurrents.noaa.gov/ sltrends	NOAA	Zervas (2001)	Fernandina Bch, FL	Tide gages	2.04 (relative)	n/a
2001	tidesandcurrents.noaa.gov/ sltrends	NOAA	Zervas (2001)	Cedar Key, FL	Tide gages	1.87 (relative)	n/a
2001	tidesandcurrents.noaa.gov/ sltrends	NOAA	Zervas (2001)	Apalachicola, FL	Tide gages	1.53 (relative)	n/a

\* Peer-reviewed sources and/or authorities.

**Table 3: How High Will Sea Level Rise Over the Next 100 Years?**

<b>Date</b>	<b>Source</b>	<b>Author</b>	<b>Authority</b>	<b>Location</b>	<b>Time Period</b>	<b>SLR Rise (ft)</b>
<b>Estimates from Popular Press and Other Informal Sources</b>						
2007, April	<i>The Stuart News</i>	Kirley (2007a)	National Academy of Sciences	Global	2007 to 2107	1
2007, June	Florida Cabinet Climate Change Conversation	O'Brien	Author	Global	2007 to 2100	1
2006, June	<i>New York Times</i>	Dean	Church et al. (2001)*	Global	1990 to 2100	1.7
2007, February	<i>The Gainesville Sun</i>	Mulkey (2007a)	Alley et al. (2007)*	Global	[~1990 to 2095]	0.6 - 1.9
2007, April	Florida Cabinet Climate Change Conversation	Mulkey (2007b)	Alley et al. (2007)*	Global	~1990 to 2095	2
2007, April	<i>The Stuart News</i>	Kirley (2007b)	Treasure Coast Regional Planning Council	Global	2007 to 2107	0.8 - 3.8
2007, April	Florida Cabinet Climate Change Conversation	James	Alley et al. (2007)*	Global	2006 to 2056	2 - 10
2007, April	<i>Ft. Myers News Press</i>	Lollar	Weiss and others at U. of Arizona	Global	[2007] to 2100	2 - 20
<b>Estimates from Peer-Reviewed and Other Scientific Sources</b>						
2007	<i>Ocean Engineering*</i>	Walton	Author	Florida (5 tide gage stations)	2006 to 2080	0.8 - 1.1
2007, May	<i>IPCC Physical Science Basis*</i>	Meehl et al.	Authors	Global	1980-1999 to 2090-2099 [~1990 to 2095]	0.6 - 1.9
2007, May	<i>IPCC Physical Science Basis*</i>	Meehl et al.	Authors	Global with accelerated ice	1980-1999 to 2090-2099	0.9 - 2.6

				sheet melting	[~1990 to 2095]	
2007, March	www.realclimate.org	Rahmstorf (2007b)	Author	Global	~1990 to 2095	1.7 - 3.1
2005, December	<i>Sea Level Rise in the Treasure Coast Region</i>	Treasure Coast Florida RPC**	Titus & Narayanan (1995)	SE Florida	1990 to 2100	0.9 - 3.9
2007, January	<i>Science</i> *	Rahmstorf (2007a)	Author	Global	2006[?] to 2100	1.6 - 4.6
2007, June	<i>Environmental Research Letters</i> *	Hansen	Author	Global with accelerated ice sheet melting	2000 to 2100	Up to 16.5

\* Peer-reviewed sources and/or authorities.

\*\* Similar estimates reported in East Central Florida RPC (2004), South Florida RPC (2005), Southwest Florida RPC (no date), and Tampa Bay RPC (2006).

**Table 4: How Fast Will the Shoreline Retreat as Sea Level Rises?**

<b>Date</b>	<b>Source</b>	<b>Author</b>	<b>Authority</b>	<b>Location</b>	<b>Shoreline Retreat (ft) per Foot of SLR</b>
2007, April	Florida Cabinet Climate Change Conversation	Leatherman	Author	Long Island, NJ, Delmarva, NC, SC	78
2007	<i>Ocean Engineering*</i>	Walton	Author	US	50-100
1962	<i>Jrnl Waterway, Port, Coastal &amp; Ocean Engrng*</i>	Bruun	Author	SE Florida	100
2006, June	<i>New York Times</i>	Dean	Howd	Florida	100
2007, June	<i>Tallahassee Democrat</i>	Ritchie	Donoghue	Florida	960
1991	<i>Coastal Management*</i>	Titus et al.	Author	Florida	100-1000
2007, April	<i>Ft. Myers News Press</i>	Lollar	Weiss and others	SW Florida	500 - 1000
2007, June	personal communication	Donoghue	Author	Florida	1000
2007, April	<i>The Miami Herald</i>	Tasker	Wanless	Florida Keys, Barrier Islands	200-2000

\* Peer-reviewed sources and/or authorities.

**Table 5: River Gradients and Estimated Salt Front Migration for Major Florida Rivers**

<b>River and Sample Location*</b>	<b>Measured Gradient (ft/mi)</b>	<b>Estimated Salt Front Migration with 3-Foot Sea Level Rise (mi)</b>
Ortega River near Jacksonville	2.41	3.0
Drainage canal tributary to St. Lucie Canal	1.68	1.8
Shell Creek near Punta Gorda	2.44	1.2
Cypress Creek near Sulphur Springs	2.10	1.4
Suwanee River near Wilcox	0.51	5.9
Choctowatchee River near Bruce	1.72	1.7
Yellow River at Milligan	3.31	0.9
Blackwater River near Baker	3.59	0.8
Escambia River near Century	2.17	1.4
Perdido River near Barrineau Park	5.51	0.5

\* No data available for areas south of Lake Okeechobee or the lower reaches of the Caloosahatchee River.

Source: Bridges (1982).

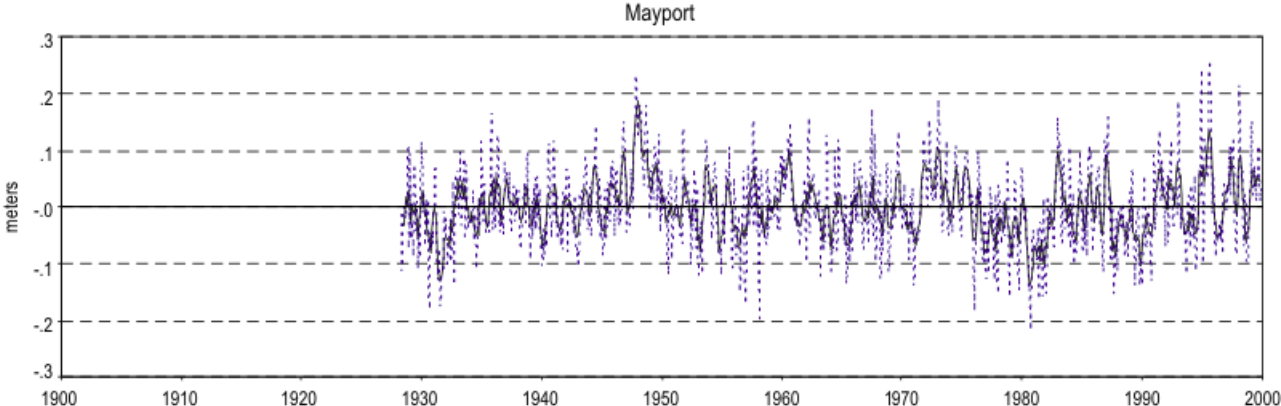
**Figure 1: Areas of Florida Likely to be Inundated by a 1 Meter Rise in Sea Level**



Source: Weiss and Overpeck (2005).



**Figure 2: Interannual variation of mean sea level for all data to 1999 for Mayport, Florida**



Source: Zervas (2001).

**Figure 3: I-10 Bridge over Escambia Bay, Florida after Hurricane Ivan, 2004**



Source: [www.govanleave.com/ivan/](http://www.govanleave.com/ivan/) (2004).

**Figure 4: I-10 Bridge over Lake Pontchartrain, Louisiana, after Hurricane Katrina, 2005**



Source: [www.zavadil.com/katrina/katrina.htm](http://www.zavadil.com/katrina/katrina.htm) (2007).