Implications of Climate Change on Florida's Water Resources

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Water resources systems in Florida are unique and exhibit significant diversity in hydrogeologic characteristics and in rainfall and temperature patterns. In many parts of the state, both surface and groundwater systems are complex, highly interconnected, and any change in hydrologic drivers such as rainfall or temperature has the potential to impact the water resources of the urban, agricultural, and ecological systems. Because of this diversity, it is not possible to present a single overall outlook regarding the implications of climate change on the water resources of the state. This chapter presents brief summaries of individual studies that are available for major water resources systems in the state, which include the Everglades, the Tampa Bay region, the St. Johns River watershed, and the Suwannee River and Apalachicola River basins. Available climate models and their downscaled versions have varying degrees of bias and lack of skill that need to be considered in impact analyses. In all regions, projected changes in rainfall, temperature, and sea level may have significant impacts on water supply, water levels in environmentally sensitive areas, flood protection, and water quality.

Key Messages

- Water resources are an integral contributor to Florida's economy, but there is increasing competition for water supply among the urban, agricultural, and environmental sectors due to population growth in the state.
- Climate change along with rising sea levels will exacerbate the competition for water and it is extremely important to understand the potential impacts on this vital resource through actionable science that is relevant to this region.
- Although different climate models predict a consistent increase in future temperatures, future precipitation is not yet consistently predicted and could be higher or lower. Differences in precipitation propagate into significant differences in future streamflow, groundwater levels, and ET predictions.
- The range of future hydrologic conditions predicted by climate models allows an evaluation of the spectrum of possible future risks, but does not provide actionable information because the uncertainty is so high. Improvement in the ability of the climate models to simulate both retrospective and future rainfall patterns will be required before their projections can reliably be used for water resource planning and management
- Impact assessment to date on large-scale, regional basins in the state demonstrates that future climate change has a significant potential to impact both water quantity and quality, and as a consequence, additional research is necessary to develop standardized climate projections and conduct impact assessment on the water resources systems on a statewide basis.

- Potential increases in temperature, and the variations in precipitation patterns may degrade water quality, exacerbate algae problems, and cause eutrophication of important water bodies.

Keywords

Rainfall; Temperature; Groundwater; Sea level rise; Water quality; GCM, Downscaling; Uncertainties

Introduction

The state of Florida includes more than 1,700 streams and rivers, 7,800 freshwater lakes, 700 springs, 11 million acres of wetlands, and numerous freshwater aquifers, all of which play an important role in meeting water needs of both humans and the environment (Marella 2015). Water use data in the state, which have been collected by the US Geological Survey, show that the combined fresh and saline water withdrawals have increased 465% (over 12,000 million gallons a day) between 1950 and 2010. During the same period, the population has increased by 580% (16 million) (Fig. 3.1 reproduced from Marella 2014). Increased withdrawal of freshwater for human use is triggering significant challenges for maintaining the water supply to environmentally sensitive areas, which are experiencing significant pressure from urbanization. The potential decrease in water supply due to future climate change, along with the contamination of freshwater aquifers from sea level rise, will exacerbate the challenges in meeting the water supply needs of Florida's urban, agricultural, and environmental sectors.

In Florida, 64% of the state's freshwater supply is from groundwater and it is a vital resource essential to public and private water supply, irrigation, aquaculture, and industrial use. Groundwater is recharged by infiltration of precipitation and seepage from canals, lakes, and streams. Groundwater flows down a hydraulic gradient and ultimately into wells, canals, streams, lakes, or to the ocean through seeps and springs, thus closing the continuous water cycle between land, ocean, and atmosphere (Mwashote et al. 2010, 2013). As groundwater use has increased in coastal areas, so has the recognition that groundwater supplies are vulnerable to overuse, contamination, and climate change impact. Any change in recharge and withdrawal from groundwater aquifers due to climate change has the potential to change the water budgets of the various parts of the state.

Man-made and natural water resources systems in Florida are unique, complex, and diverse. The landscape of Florida varies significantly from north to south, with different patterns and extents of urban, agricultural, and natural systems. The state's hydrologic systems are influenced by changes in rainfall patterns, evapotranspiration (ET), and sea level—the primary hydrologic drivers of both surface water and groundwater conditions (both quality and quantity). In addition, the supply and demand of urban, agricultural, and environmental sectors vary from one part of the state to another. Consequently, it is not possible to discuss the implications of climate change on water resources in the state as a single entity. There is currently no comprehensive statewide assessment of the potential impacts of climate change on water resources. Implications of potential changes to climate are being investigated by numerous institutions, and the number and quality of such studies are evolving rapidly. There have been some pilot efforts to assess the impacts of climate change on some regions of the state and those are considered to be the best available investigations to date. This chapter presents a summary of such investigations, focusing on some large water resources systems in the state and concluding with a general assessment of climate change implications on water quality in Florida.

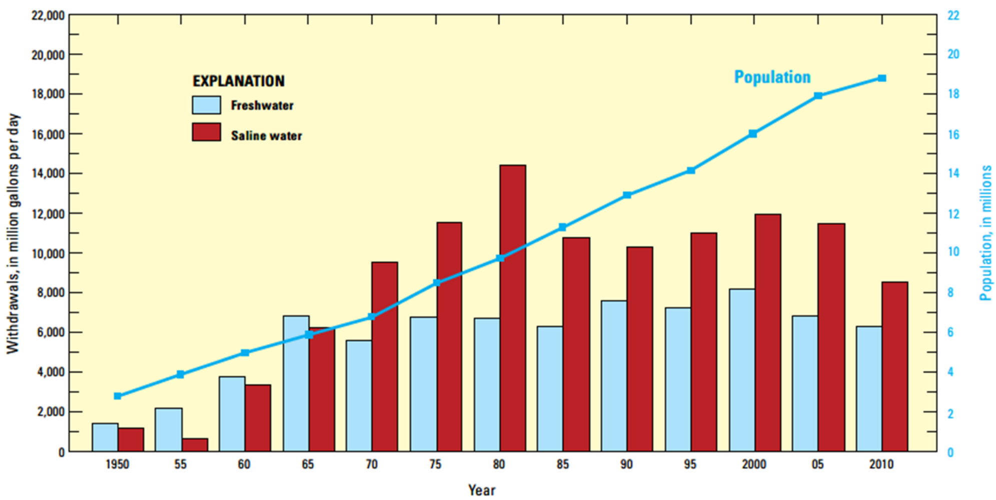

Figure 3.1. Historic total population, freshwater, and saline water withdrawals in Florida 1950–2010 (Marella 2014).

Major Water Resources Systems in Florida

Management of water resources in Florida is delegated to five water management districts (WMDs) that include the (Fig. 3.2): (a) South Florida Water Management District (SFWMD); (b) Southwest Florida Water Management District (SWFWMD); (c) St. Johns River Water Management District (SJRWMD); (d) Suwanee River Water Management District (SRWMD); and (e) Northwest Florida Water Management District (NWFWMD). In general, the WMDs administer flood protection, water supply, water quality, and environmental protection through a variety of functions including planning, operations, and regulation. There are numerous watersheds of varying size in the state; however, this chapter will only cover the current state of knowledge regarding climate change investigations associated with four large and important systems in the state. They include the following regions (maps showing them are provided later in this chapter):

- Greater Everglades Ecosystem

- Tampa Bay Region
- St. Johns River Region
- Suwannee River and Apalachicola River Basins

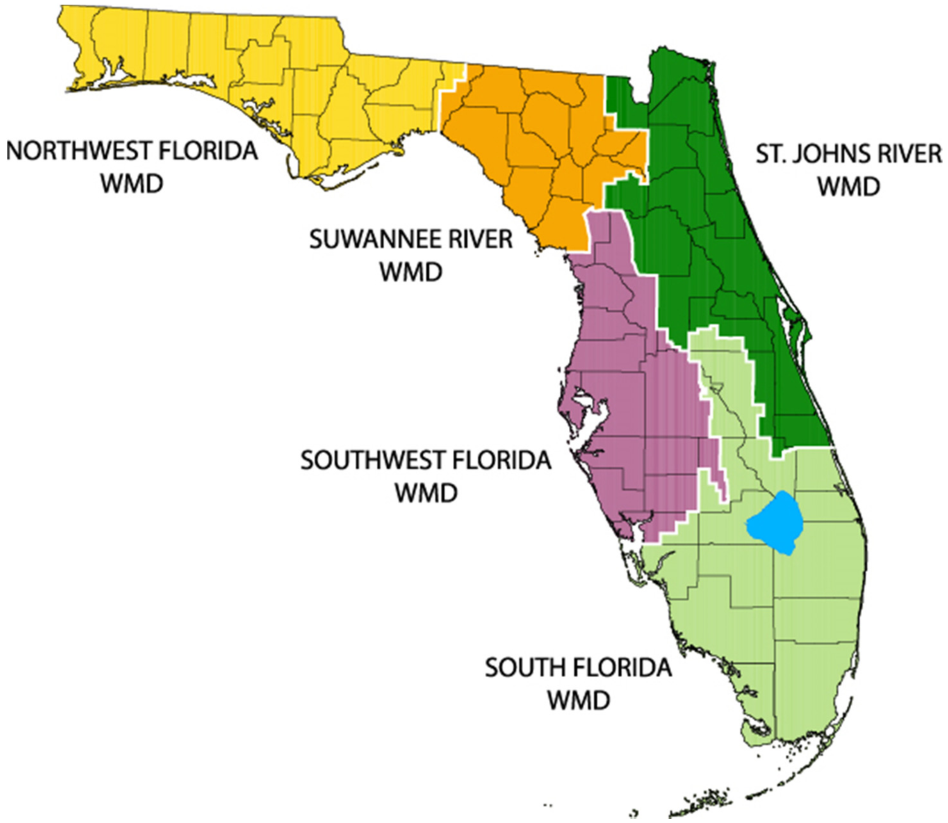

Figure 3.2. Five water management districts in Florida.

Greater Everglades Ecosystem

Background

The Greater Everglades Ecosystem spans from the Kissimmee River Basin, north of Lake Okeechobee all the way south to Florida Bay; and it includes a national treasure, America's Everglades. The climate of this ecosystem is strongly seasonal and exhibits significant inter-annual variability with prolonged drought and wet periods. The water resources system originates in the upper chain of lakes in the Kissimmee River Basin, and includes Lake Okeechobee, the Everglades Agricultural Area, the Water Conservation Areas, and Everglades National Park. It is bordered by heavily urbanized areas of Florida's lower East Coast (Fig. 3.3 showing areas below Lake Okeechobee). The natural, urban, and agricultural systems in the region are strongly interconnected in terms of supply and demand for water, and any change in rainfall patterns, evapotranspiration (ET), or sea level can have a significant impact on water quantity and quality in any or all of the systems. The urbanized lower east coast area has a unique geology due to the presence of the highly porous and permeable limestone aquifer known as the Biscayne Aquifer. Projected sea level rise will significantly influence saltwater intrusion along the coast affecting numerous wellfields that supply water to the rapidly expanding population.

Implications of Changing Climate

There have been several attempts to assess the implications of climate change and sea level rise on the Greater Everglades Ecosystem (e.g., Obeysekera et al. 2011). The general approach that has been used for such investigations is shown in Fig. 3.4 and it includes the detection of historical trends from observations, understanding the role of teleconnections, skill testing of global and regional climate models, and finally, the assessment of impacts on water resources systems.

Irizarry et al. (2013) evaluated the observed data with the objective of detecting trends in both temperature and precipitation in the entire state. The observations consisted of long-term (1892–2008) precipitation and raw temperature records at 32 stations distributed throughout the state. They used several climate metrics based on both averages and extremes. The trend detection techniques included the non-parametric Mann-Kendall Trend Test (Kendall 1976), Sen-Theil Regression (Sen 1968), and the nonstationary Generalized Extreme Value distribution fitting for the extremes. The results showed a general decrease in wet season precipitation, most evident for the month of May and possibly tied to a delay in the onset of the wet season. The number of wet days during the dry season, especially during November through January, were found to have increased over the period of record. The number of "dog days" (temperature above 26.7 °C during the wet season) per year has increased in many locations. A decrease in the daily temperature range was also observed and it was attributed to an increase in daily minimum temperature. Although there was no attempt to attribute the trends to climate change or anthropogenic causes, "urban heat island" effects were conjectured to have caused observed trends at some locations. In addition, climate teleconnections due to phenomena such as the Atlantic Multi-decadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO), and the El Niño-Southern Oscillation (ENSO) have significant effects that are tied to seasonal and decadal trends (see Chapter 16), and it is difficult to separate observed trends into natural versus anthropogenic causes.

Following the approach in Fig. 3.4, there have been several attempts to evaluate the skills of the general circulation models (GCMs) of both the CMIP3 and CMIP5 suites of models (IPCC 2007, 2013). Comparison of simulation results of the late 20th century GCM output to historical data has shown that the GCMs do not capture the statistical characteristics of the regional rainfall patterns and temperature adequately. Due to the coarse resolution of most present-day GCMs, the region of south central Florida is not well represented. Some models do not adequately represent large areas of the land mass of Florida (Obeysekera et al. 2011). As a consequence, the models are unable to mimic temporal and spatial patterns resulting from mesoscale phenomena such as sea and lake breezes. Furthermore, it is not clear how well such models are able to simulate teleconnections to global phenomena such as the AMO, the ENSO, and the PDO (Trimble et al. 2006). Such teleconnections include, but are not limited to, wetter (drier) than normal precipitation during winter months of El Niño years (La Niña years), and wetter (drier) conditions during warm (cold) phase of both AMO and PDO.

There have been several attempts to downscale GCMs to produce higher-resolution historical rainfall and temperature records for water resources investigations. They have included both statistical downscaling (Maurer et al. 2007) and dynamical downscaling (Mearns et al. 2012; Stefanova et al. 2012) of temperature, precipitation and other climatic variables. Obeysekera et al. (2011) document the evaluation of 112 finer-resolution (1/8 degree), statistically-downscaled ensemble datasets based on 15 climate models of the CMIP3 scenarios B1, A1B, and A2 for the period 1950–2009 (Maurer et al. 2007). The analysis of bias-corrected, statistically-downscaled data showed that the simulation of climatology and the variability of temperature are adequate. However, the precipitation values still showed some biases. The dynamically-downscaled data (NARCCAP) were not much better, as they exhibited significant spatial biases although they mimicked the seasonal patterns of both precipitation and temperature well. The conclusion was that, even for dynamically-downscaled data, further bias correction may be necessary. A careful review of the downscaled products for Florida indicate that a reasonable range for percent change in annual rainfall is ± 5% for 2040 and ± 10% for 2070. For temperature, the corresponding range for 2040 is +0.5° to +1.5° C (+0.8° to +2.4° F) with a median value of +1° C (+1.6° F). For 2070, a reasonable planning range is +1° to +3° C (+1.6° to +4.8° F) with a median value of +2° C (+3.2° F) (Obeysekera et al. 2011; Dessalegne et al. 2016)

Efforts are underway to assess the CMIP5 suite of GCM models and the corresponding downscaled datasets. The bias-corrected constructed analogs (BCCA, Maurer et al. 2010) of precipitation and daily minimum and maximum temperature projections at 12 km resolution have been analyzed (Dessalegne et al. 2016). The analysis included identification of future trends in precipitation and temperature based on a total of 119 models covering three RCP scenarios for the period 1950–2099. In an attempt to identify trends in precipitation and temperature, percent change in precipitation for near future (2025–2055) and far future (2055-2085) as compared to change in mean annual temperature were computed. Spatial trends in temperature and precipitation as a function of latitude are shown in Fig. 3.5. The results show that the there is a robust increase in temperature as expected. However, trends in precipitation are scenario-dependent, with RCP85 showing the largest average increase up to about 10%. Some models do show a reduction in precipitation (Fig. 3.5b) and, as with CMIP3 models, precipitation change is more uncertain than change in temperature. However, in all cases, temperature increases are expected in the future.

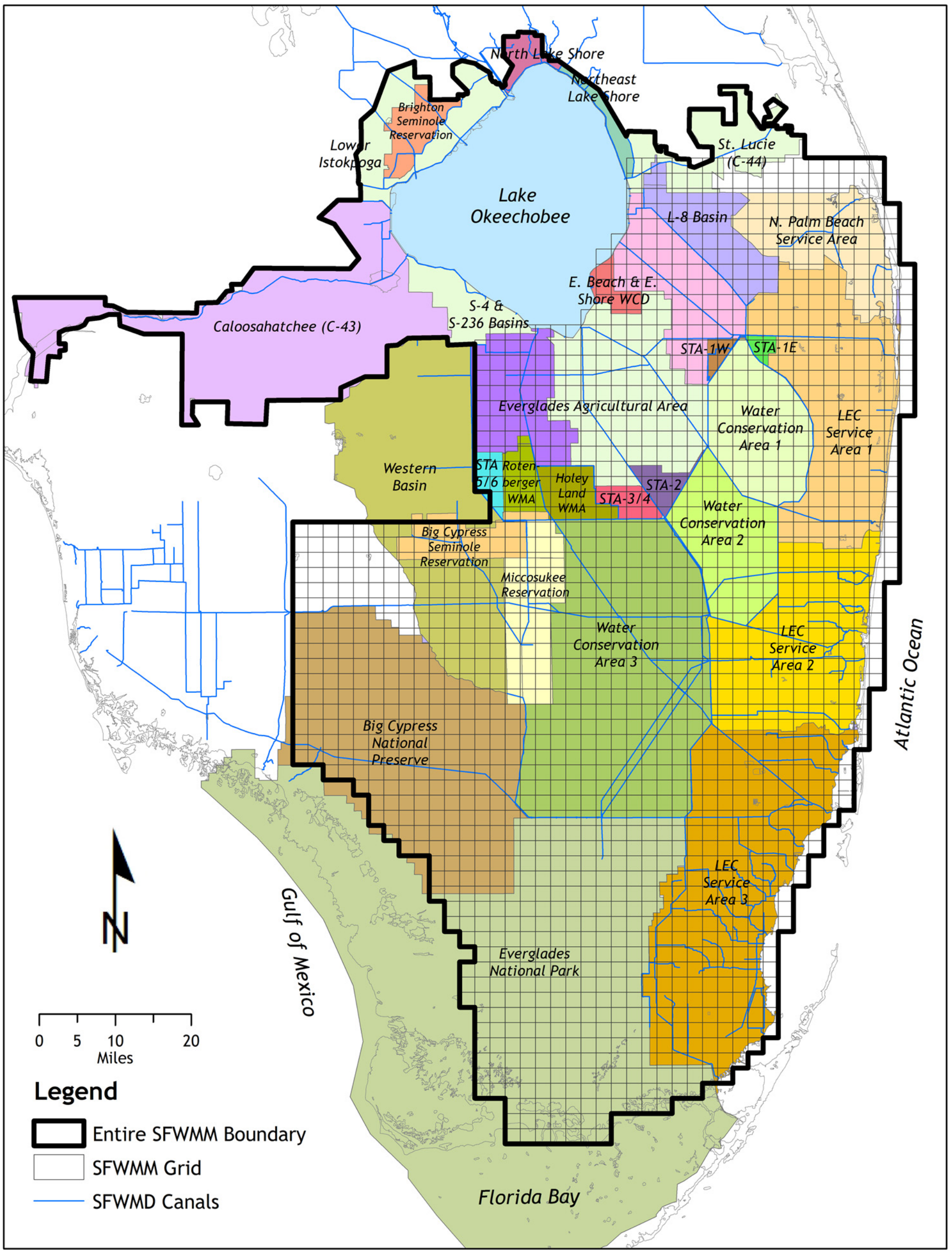

Figure 3.3. Map of South Florida with primary hydrologic regions and domain simulated by the South Florida Water Management Model (thick black outline); the southeast sub-region of the model domain below Lake Okeechobee is modeled using a distributed hydrologic model with a mesh of 3.2 km x 3.2 km (2 mile x 2 mile) cells. This figure shows the region of the Greater Everglades Ecosystem, south of Lake Okeechobee.

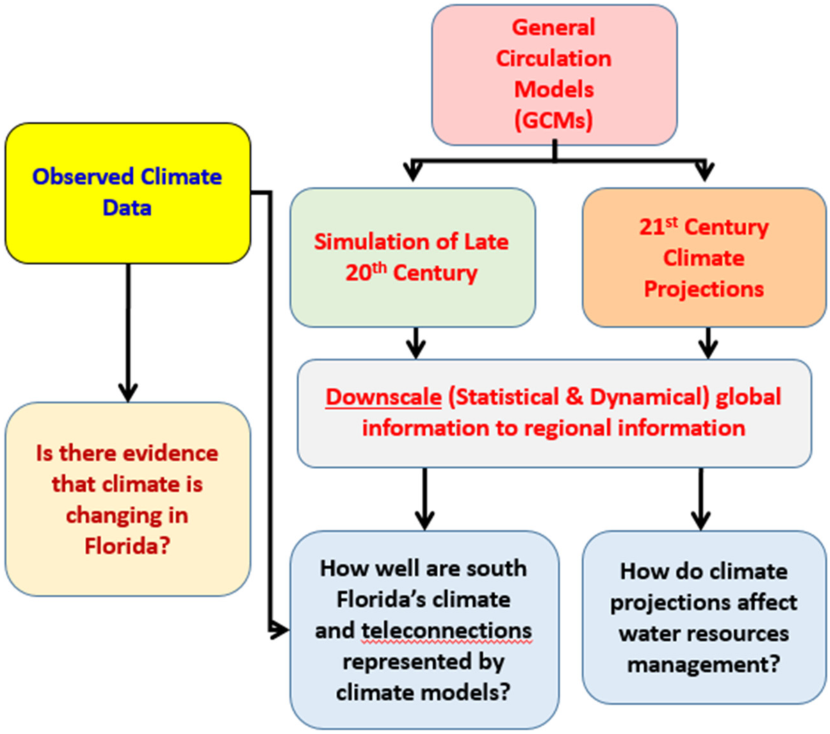

Figure 3.4. General approach for using climate data and projections for water resources investigations in the Greater Everglades Ecosystem Region of South Florida (Obeysekera et al. 2011).

Sea Level Rise

Tide gage records show that relative sea level is rising along the entire Florida coastline. This can have significant implications for coastal areas with low relief and highly permeable geology. The implications may include direct flooding of coastal landscape during storms and high-tide (including what is known as "nuisance flooding"), inefficiencies in coastal water control systems affecting flood protection, saltwater intrusion into water supply wells, and inundation of natural systems such as the Southern Everglades (SFWMD 2009). Sea level estimates based on the Unified Sea Level Rise Projections of the Southeast Florida Regional Climate Change Compact agencies are used for planning purposes (Fig. 3.6). They include at least three scenarios covering a planning range and a high curve that is intended for evaluating high-risk projects (SFRCCC 2015).

Evaluation of Climate Scenarios

Obeysekera et al (2014) focused on general implications of potential changes in future temperature, and associated changes in ET, precipitation, and sea levels within the regional boundary of Southeast Florida. Using a Bayesian approach known as the reliability ensemble average (REA) (Tebaldi et al. 2005), Obeysekera et al. (2011) provided probabilistic projections of both precipitation and temperature that are used to define scenarios for the water resources impact assessment. Based on this analysis, and the analysis of CMIP5 data sets (Dessalegne et al. 2016), +/-10% for precipitation scenarios and the single scenario of +1.5 °C for temperature were selected for an assumed planning horizon of 2060. The sea level projection, assumed to be coincident with temperature increase, was assumed to be 1.5 ft. Based on the above information, seven modeling scenarios were developed (Table 3.1).

Table 3.1. Water resources modeling scenarios based on temperature, precipitation, and sea level rise projections used for evaluation of climate change impacts on water resources in the Greater Everglades Ecosystem Region of South Florida.

Scenario Name	Temperature Change	Precipitation Change	Sea Level Rise	Coastal Canal Levels Increased?
BASE	No change	No change	No change	No
-RF	No change	-10%	No change	No
+RF	No change	+10%	No change	No
+ET	+1.5 °C (2.7 °F)	No change	0.46 m (0.81 ft)	Yes
-RF+ET	+1.5 °C (2.7 °F)	-10%	0.46 m (0.81 ft)	Yes
-RF+ETnoC	+1.5 °C (2.7 °F)	-10%	0.46 m (0.81 ft)	No
+RF+ET	+1.5 °C (2.7 °F)	+10%	0.46 m (0.81 ft)	Yes

ET = Evapotranspiration; RF = Rainfall; noC = No change in canal maintenance levels.

The hydrologic implications of the above scenarios were investigated using the South Florida Water Management Model (SFWMD 2005). This model simulates groundwater and surface water movements, including the complex operations and water management, over the entire Greater Everglades Ecosystem including the heavily urbanized areas of the Lower East Coast (Fig. 3.3), on a gridded mesh with a cell size of 2 miles × 2 miles.

The extreme rainfall scenarios together with warming show that the water budget of South Florida could be altered significantly, affecting the performance of all sectors (agricultural, ecosystems, and urban). In particular, the -RF+ET scenario would dry out the Everglades significantly, which would greatly alter its ecosystems and water supply function. One of the major implications of the reduction in rainfall and the increased ET is that tributary inflows (e.g. from the Kissimmee River basin) would be reduced by a large percentage, causing a significant lowering of Lake Okeechobee levels. The only positive aspect of this scenario would be the significant reduction in damaging high flows to estuaries. The infrastructure could handle increased rainfall, but this may cause considerable harm to the estuarine and wetland ecosystems in terms of too much water. Depending on the rainfall and ET scenario, the agricultural and urban demands would be increased or decreased by a significant percentage. In the worst case scenario, the demands not met by the agricultural service areas would increase significantly (by as much as 50–60 percent). A thorough analysis of the scenarios are available in a series of published papers (Aumen et al. 2015).

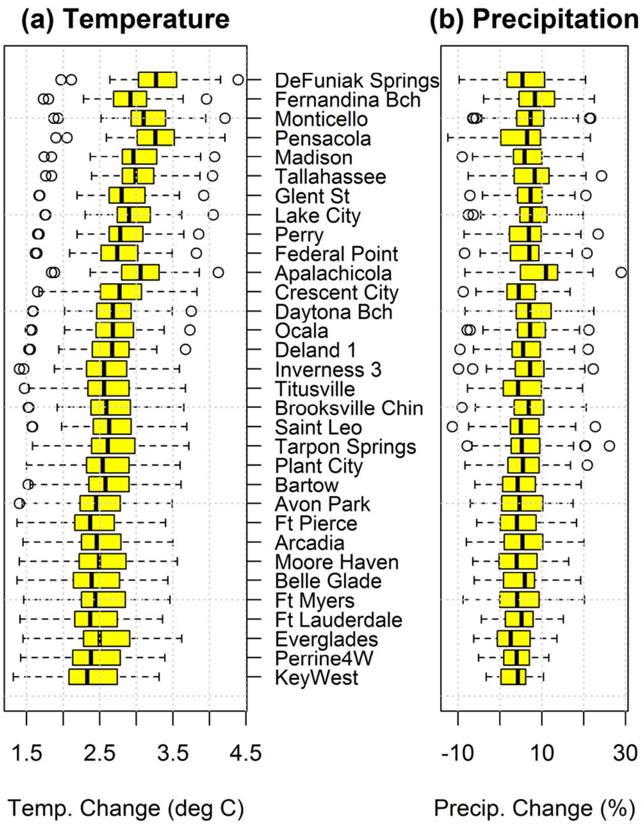

Figure 3.5. Box and whisker plots of temperature and precipitation change from 1970–2000 to 2055–2085 sorted by increasing latitude for the RCP 8.5 Scenario (Obeysekera et al. 2011; Dessalegne et al. 2016).

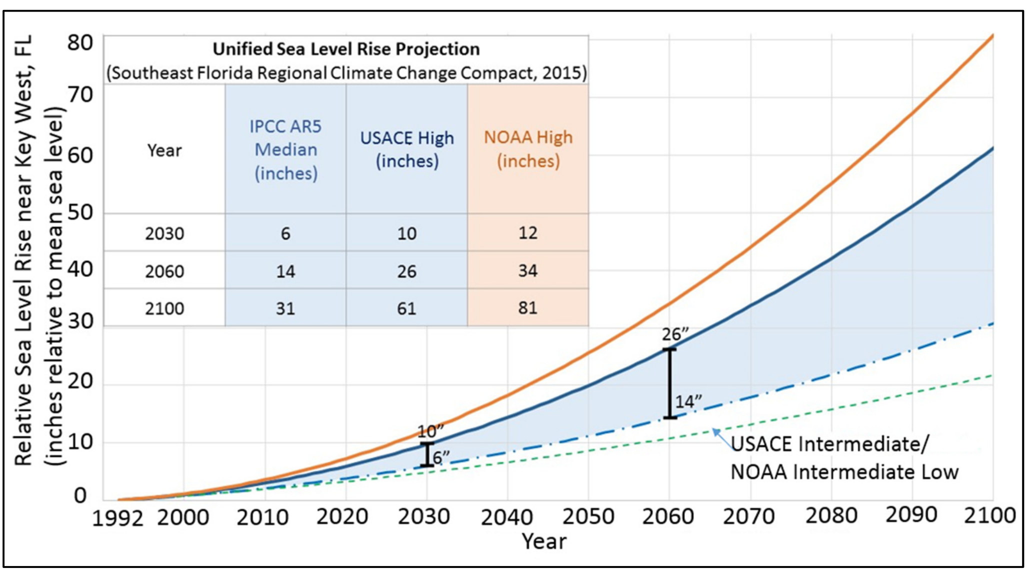

Figure 3.6. Unified sea level rise projections for regional planning purposes (SFRCCC 2015).

In summary, there are still considerable uncertainties in climate projections of hydrologic drivers such as precipitation and ET affecting the Greater Everglades region. Consequently, most studies have employed a scenario approach for impact assessment of climate change. Over the next 50 years, such scenarios to date cover 1.6 to 4° F (0.5 to 2.2° C) of temperature increase, ±10% change in rainfall, and 13 to 26 inches (0.33 m to 0.66 m) in sea level rise. Hydrologic modeling using the scenarios demonstrate that if such changes materialize, significant impact to the water resources of South Florida could occur.

Tampa Bay Region

Background

Tampa Bay is the largest estuary in Florida and extends about 50 km (30 miles) inland from the Gulf of Mexico. Tampa Bay Water, a wholesale regional drinking water supplier, operates a diverse water supply system in this region that includes regional well fields, river withdrawals from the Hillsborough and Alafia rivers, and a seawater desalination plant.

Within the Tampa Bay region, there are eight major watersheds: the Pithlachascotee, Anclote, Hillsborough, Alafia, Little Manatee, Withlacoochee, Peace, and Manatee river watersheds. In addition, an anthropogenically-altered surface conveyance system, the Tampa Bypass Canal system, operates as both flood protection and water supply for the City of Tampa and Tampa Bay Water. Besides the major river watersheds and the Tampa Bypass Canal, there are various smaller creeks in the region including Bullfrog, Delaney, Pinellas County Coastal creeks, Northwest Hillsborough Creek, and various minor coastal creeks. All of these creeks discharge either to the Gulf of Mexico or to Tampa Bay (Geurink and Basso 2013). A variety of land cover types are present in the study area, including urban, grassland, forest, agricultural, mined land, water, and wetlands.

Average annual rainfall for region from 1989 to 2001 was approximately 1230 mm (48.5 inches). The region typically has eight drier months followed by four months of wet summer season when 50-70% total annual rainfall occurs. Currently, depending on the rainfall and prevailing conditions, ET accounts for 30-90% of the water balance (Geurink and Basso 2013). Accurate prediction of seasonal, interannual, and decadal climate variability, as well as potential long-term climate change, are crucial to water resources planning and management in the region. Changes in rainfall frequency, seasonal shifts such as the onset and end of rainfall, as well as increases in temperatures have important implications for surface and groundwater availability. Higher than average temperatures can significantly change the hydrologic water balance, increasing water losses to the atmosphere through higher ET.

The Tampa Bay region is one of the most urbanized regions in Central Florida, and public water supply is one of the largest water users in the region. During the 1980s and 1990s, the

Tampa Bay region experienced severe drought. This problem was further exacerbated by a 108% increase in population between 1970 and 2000 to over 2 million people. Lack of adequate rainfall and continuous reliance on only the Upper Floridan aquifer for public water supply led to dewatering of the region's wetlands that resulted in significant environmental impact. The ensuing regional conflict and need to balance municipal and agricultural water use with natural system needs resulted in the creation of Tampa Bay Water as a regional water supply utility (see Asefa et al. 2015 for history). Since then, Tampa Bay Water has diversified its public water supply sources to include surface water (50-60%), groundwater (30-40%), and desalinated sea water (0-10%) in its portfolio.

The shift from an all-groundwater source supply to significant surface water reliance changed the risk profile for the agency and led to the need to understand the potential impacts of climate change on water supply and demand. Changes in climate could have important implications for utilities like Tampa Bay Water; e.g., changes in public water supply operations due to changes in the magnitude and seasonality of surface and groundwater availability, changes in wetland and lake ecosystems and associated regulatory programs due to change in ET and precipitation, and impacts on asset management programs for infrastructure than might be affected by rising temperatures. In response to these needs, dynamically downscaled CMIP3 GCMs were bias-corrected for the Tampa Bay region and used as climatic input for the integrated hydrologic model developed for the region by Tampa Bay Water and the Southwest Florida Water Management District.

Hydrologic Model

There are strong interactions among surface, subsurface, and ET processes in the Tampa Bay area due to the complex geology and relatively flat topography in the region (Geurink and Basso 2012). In order to understand and predict the dynamic surface–groundwater interactions in this complex system, two regional water management agencies, Tampa Bay Water and the Southwest Florida Water Management District, jointly developed an integrated surface/subsurface hydrologic model for the area. The Integrated Hydrologic Model (IHM) couples the EPA Hydrologic Simulation Program-Fortran (HSPF; Bicknell et al. 2001) and the USGS MODFLOW96 (Harbaugh and McDonald 1996) for surface and groundwater modeling, respectively (Geurink et al. 2006). The model is characterized as deterministic, semi-distributed, and semi-implicit with variable time steps and spatial discretization (Ross et al. 2004). Subsequently, Tampa Bay Water developed the Integrated Northern Tampa Bay (INTB) model application using the IHM to improve hydrologic assessment capabilities of West Central Florida. The hydrologic model domain for INTB is bordered by the Gulf of Mexico on the west (Fig. 3.7), by the Floridan aquifer flow lines on the north and east, and by a general head boundary condition at the southern boundary, which located far enough from the area of interest for this study to minimize the influence of the boundary condition (Geurink et al. 2006). The INTB model was calibrated and verified for the Northern Tampa Bay Region using hydrologic observations from 1989 to 2006 (Geurink and Basso 2012).

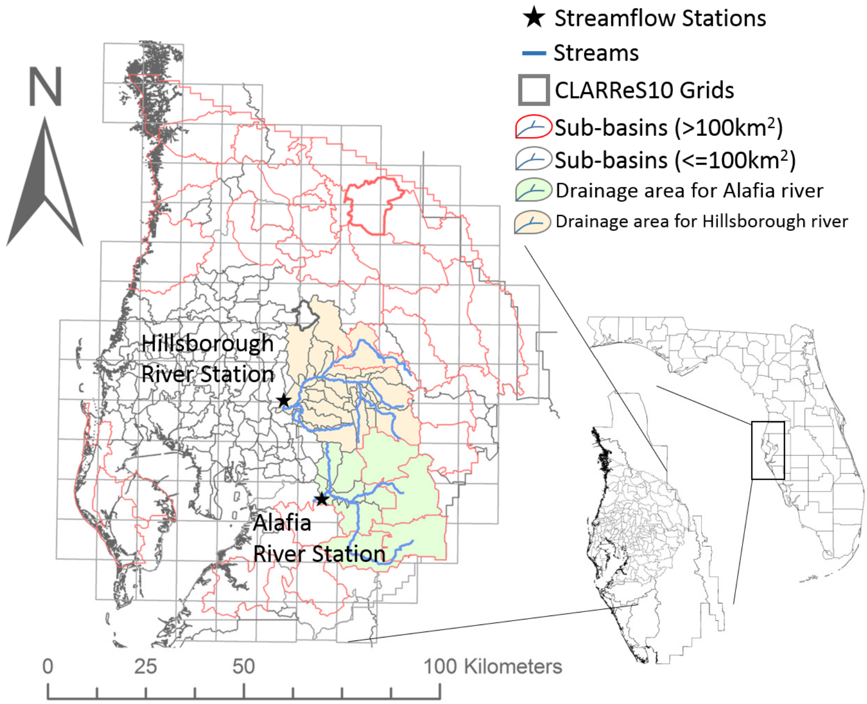

Figure 3.7. Map of the Tampa Bay region including the extent of the integrated hydrologic model, the locations of the streamflow predictions shown, and the CLARReS10 grid. Colored areas indicate the contributing areas for the streamflow prediction locations. (1 km=0.62 miles)

CLARREnCE10 Data Products

The CLARREnCE10 dataset was developed by the Florida State University (FSU) Center for Ocean Atmospheric Prediction Studies (http://floridaclimateinstitute.org/resources/data-sets/regional-downscaling). The data includes retrospective predictions (historical climate conditions, 1969–2000) and future climate scenario projections (A2 scenario for years 2039–2070) from three CMIP3 GCMs that were dynamically downscaled to 10 km resolution using the FSU Regional Spectral Model (RSM) (see Fig. 3.7). The three GCMs selected by FSU for downscaling were the Community Climate System Model (CCSM), version 3 of the Hadley Centre Coupled Model (HadCM3), and the Geophysical Fluid Dynamics Laboratory (GFDL). Emission scenarios were generated by the Intergovernmental Panel on Climate Change (IPCC) and are described in the IPCC Special Reports on Emission Scenarios (IPCC 2000). Scenarios were developed that describe different storylines about possible future social, economic, technological, and demographic developments. The emission scenarios have internally consistent relationships that were used to describe future pathways of greenhouse gas emissions. The A2 scenario describes a very heterogeneous world and represents a "high future CO_2 emissions" scenario. Projected CO_2 concentrations affect the Earth's radiative energy budget, and thus are the key forcing input used in global climate model simulations of future conditions.

Methodology

GCMs are run at coarse resolution (100- to 200-km (60 to 120-mile) grid cells) to make them computationally tractable. As a result, GCMs typically show bias in the model outputs. Regional climate models (RCMs) are run at much finer scale (10 to 50-km (6 to 30-mile) grid cells) in order to capture local scale processes that may not be well-represented by large-scale GCM models. However, previous studies have shown there is still a need to bias-correct even high-resolution RCM output for the Tampa Bay region in order to accurately reproduce historic rainfall totals and predict historic streamflows using hydrologic models (Hwang et al. 2013). Therefore in this analysis, the daily precipitation and temperature data for the retrospective predictions from each GCM were bias-corrected using a monthly cumulative distribution function (CDF) mapping approach (Panofsky and Brier 1968; Wood et al. 2002; Hwang and Graham 2013).

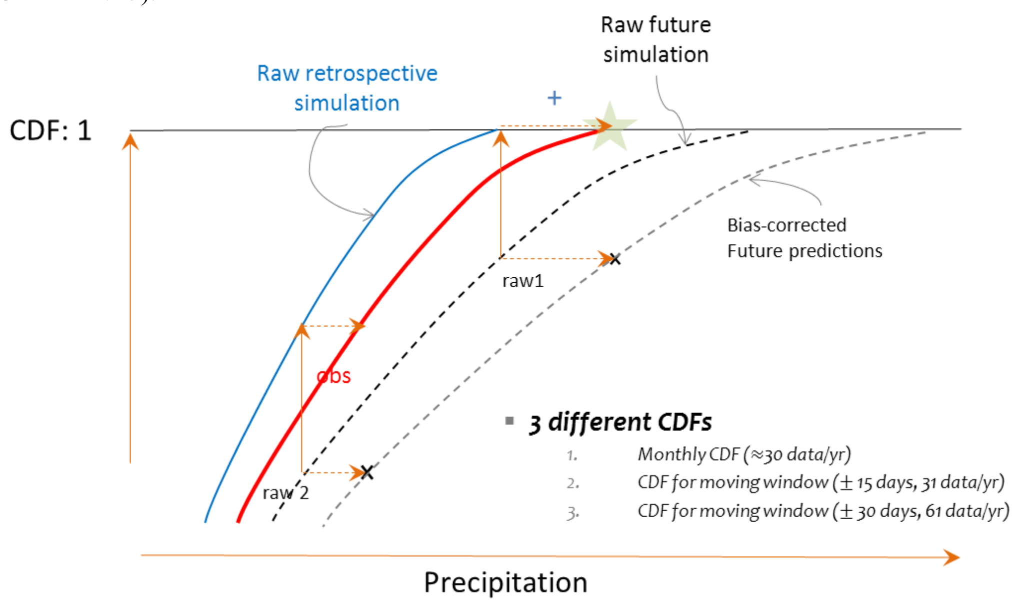

Figure 3.8. Schematic representation of bias-correction procedure (CDF mapping) used in this study. The process is conducted for each monthly cumulative distribution function (CDF).

For future scenarios, the bias for a particular daily value of precipitation or temperature was assumed to be the same in the retrospective and future periods. Thus, for each daily future projection, the bias-correction for the retrospective prediction with that same value was applied (Fig. 3.8). This method assumes GCM biases at a given temperature or rainfall amount stay the same in future simulations. The bias-corrected, dynamically-downscaled retrospective and future daily precipitation and temperature data were used as inputs for the Tampa Bay Water INTB model. All other parameters, forcing terms, and initial boundary conditions for hydrologic simulation were identical to those used in the calibrated model.

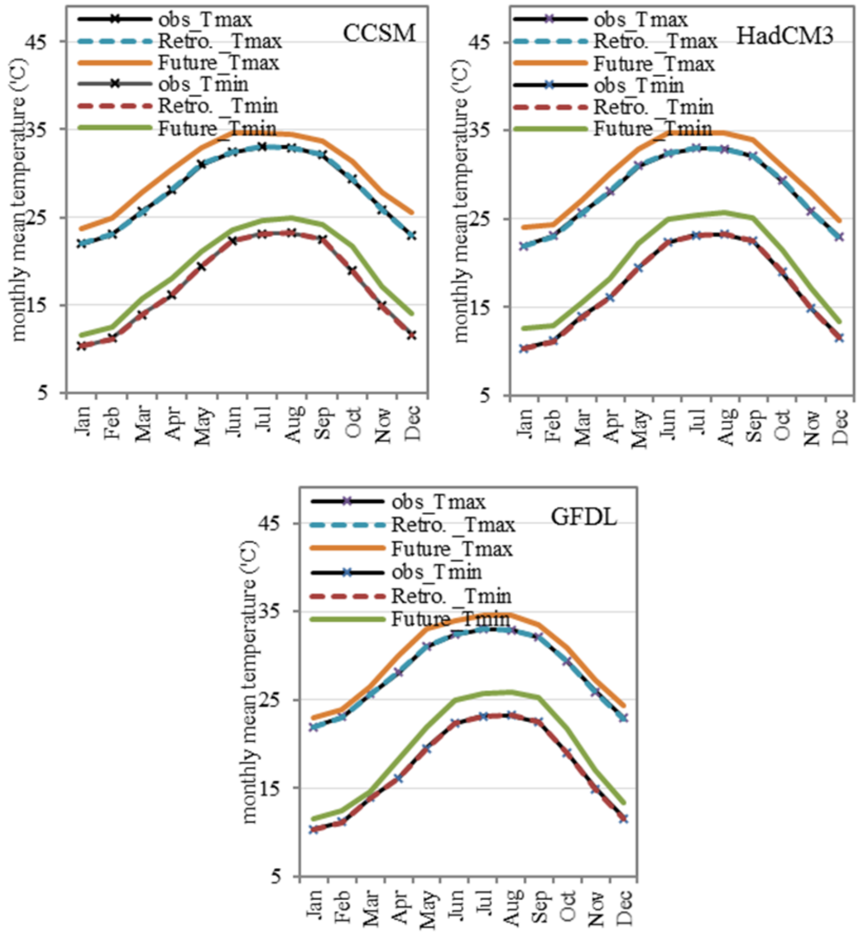

Figure 3.9. Monthly mean of T_{max} and T_{min} of bias-corrected CLAREnCE10 data for CCSM (top left), HadCM3 (top right), and GFDL results (bottom) using monthly CDFs for retrospective (1969–2000) and future (2039–2070) periods. (°C= (°F-32)*5/9)

Results

Temperature

Fig. 3.9 compares monthly mean T_{max} and T_{min} for observed and bias-corrected CLAREnCE10 data for the retrospective and future periods. This figure indicates that the annual cycle of observed mean T_{max} and T_{min} were accurately reproduced by all three GCMs after bias-correction, and that all bias-corrected GCMs predict a systematic increase in T_{max} and T_{min} over the entire annual cycle. Fig. 3.10 compares the predicted change in future monthly mean T_{max} and T_{min} (future–retrospective) for each GCM in the CLAREnCE10 experiment. Bias-corrected

CLAREnCE10 results predict that the average monthly increase of temperature will range from 1–3 °C (1.8–5.4° F), with some variation among different GCMs.

Precipitation

Fig. 3.11 compares monthly mean precipitation for observed and bias-corrected CLAREnCE10 data for the retrospective and future periods. Fig. 3.12 compares the predicted change in future precipitation (future–retrospective) for the three bias-corrected GCMs. The bias-corrected CCSM predicts a decrease in precipitation for all months in the future. The bias-corrected HadCM3 shows a slight increase in precipitation in the winter months and a decrease in the summer months. GFDL shows a significant decrease in July precipitation but increases in precipitation for most months of the year.

Streamflow

Fig. 3.13 compares the annual cycle of mean monthly streamflow predicted by the IHM-INTB using bias-corrected retrospective predictions and future projections to both historic streamflow observations and the calibrated IHM-INTB results for the Alafia and Hillsborough rivers. Differences between retrospective and future predicted mean monthly streamflow for each GCM are plotted in Fig. 3.14. These results show that predicted changes in the annual cycles of future streamflow for each GCM generally follow the predicted mean monthly precipitation change pattern (Fig. 3.12). The differences among the streamflows for different GCMs are significant, with the CCSM predicting much lower mean monthly streamflow throughout the entire year, HadCM3 predicting a slight decrease in mean monthly streamflow in July and August, and GFDL predicting an increase in streamflow throughout most of the wet season (June through October).

Fig. 3.15 compares retrospective and future mean annual ET and the ET-to-precipitation ratio to the calibrated IHM-INTB estimate (all averaged over the study area). The retrospective ET predicted by the hydrologic model using the bias-corrected GCM precipitation and temperature is similar to the ET predicted by the calibrated model for all GCMs. The future HadCM3 and GFDL results predict an increase of ET compared to the retrospective results due to projected increases in temperature, but a decrease in the ET to precipitation ratio, indicating that more excess precipitation is available for groundwater recharge or streamflow generation. In contrast, the CCSM results predict a significant decrease of mean annual ET and a significant increase in the ET to precipitation ratio. For the CCSM future, projected ET decreases because available water in the soil zone decreases due to the decrease in precipitation in all months (Figs. 3.10, 3.11, and 3.12). Thus, the ET becomes more moisture-limited for the CCSM future scenarios, whereas the ET remains largely energy-limited for the HADCM3 and GFDL future scenarios.

Tampa Bay Region Summary

The results of this investigation show that although each of the GCMs predicts a consistent increase in future temperature, differences among future precipitation estimates propagate into significant differences in future streamflow and ET predictions. In other words, the precipitation signal overwhelms the temperature signal in predicting hydrologic implications of projected future changes. Due to the large variation in precipitation and thus streamflow and ET estimates across the three GCMs considered here, this analysis does not provide actionable information for water resource planning. Additional GCM model projections (using multiple greenhouse gas emission scenarios and the next generation of GCM models) must be examined to more rigorously evaluate the expected magnitude of, and variation among, future hydrologic projections from the existing generation of GCMs. Improvement in the ability of the GCMs to simulate both retrospective and future rainfall patterns will be required before their projections can reliably be used for water resource planning and management in the Tampa Bay region. This is the same conclusion arrived at for the Greater Everglades region.

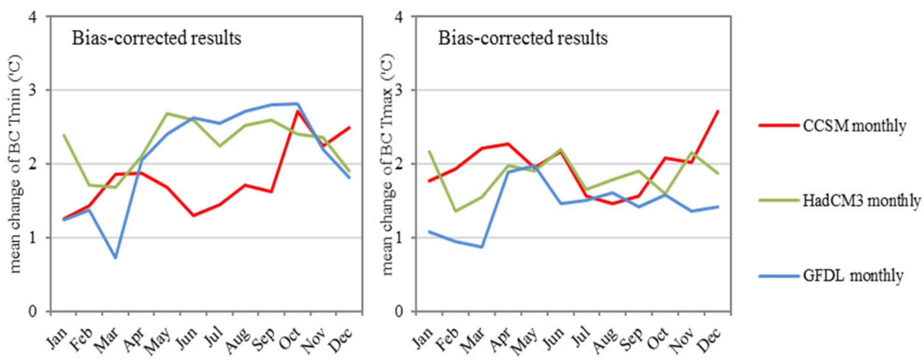

Figure 3.10. Predicted change in future bias-corrected monthly mean T_{min} (left) and T_{max} (right) for each bias-corrected GCM. (°C= (°F-32)*5/9)

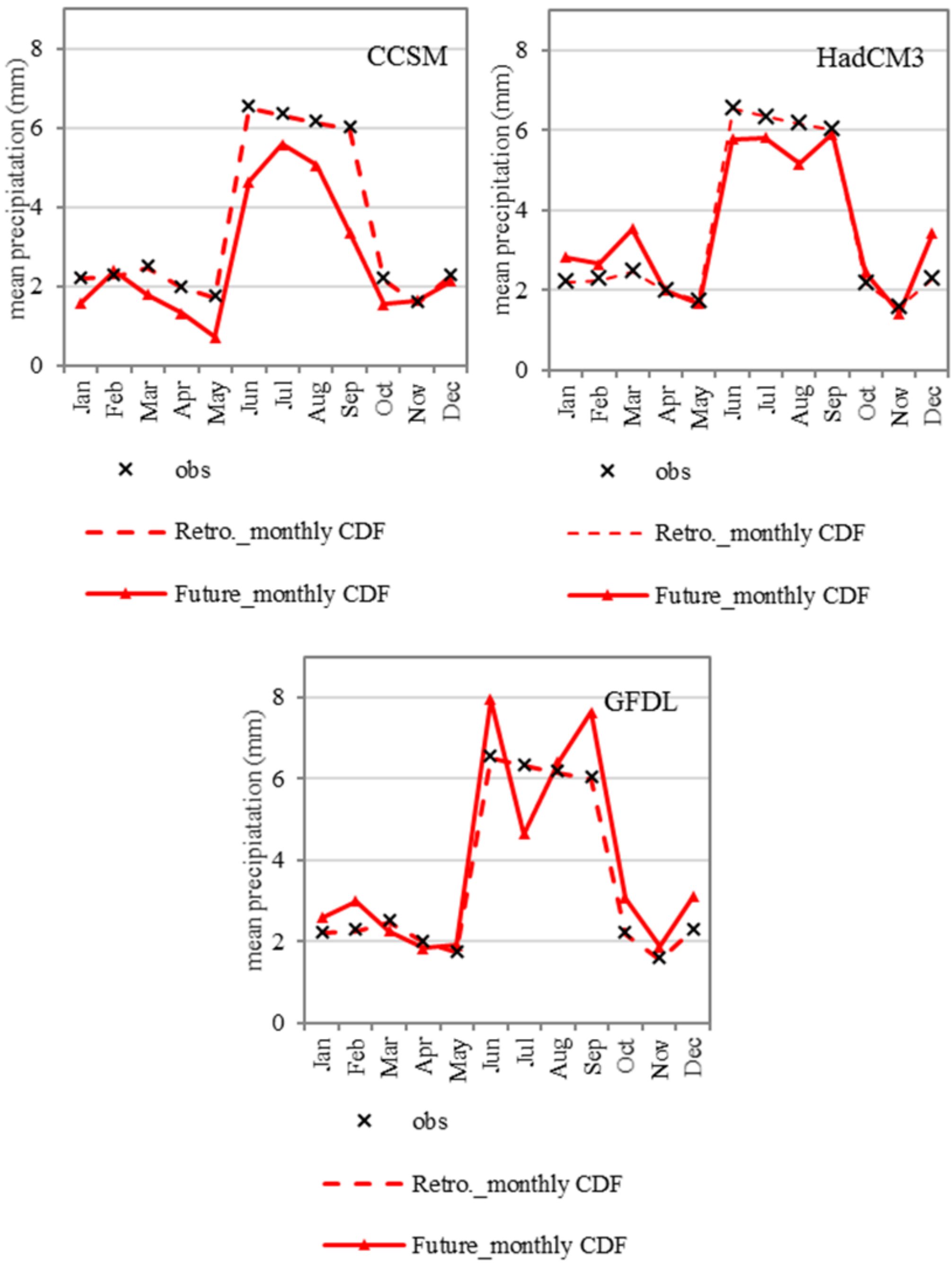

Figure 3.11. Daily mean precipitation of bias-corrected CLAREnCE10 precipitation data for CCSM (first column), HadCM3 (second column), and GFDL results (third column) for retrospective (1969-2000) and future (2039-2070) periods.

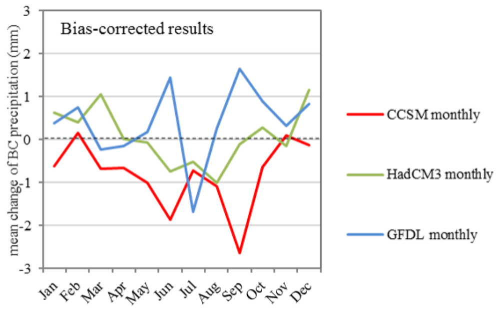

Figure 3.12. Predicted change in future bias corrected mean precipitation for each GCM. (1 mm = 0.04 in).

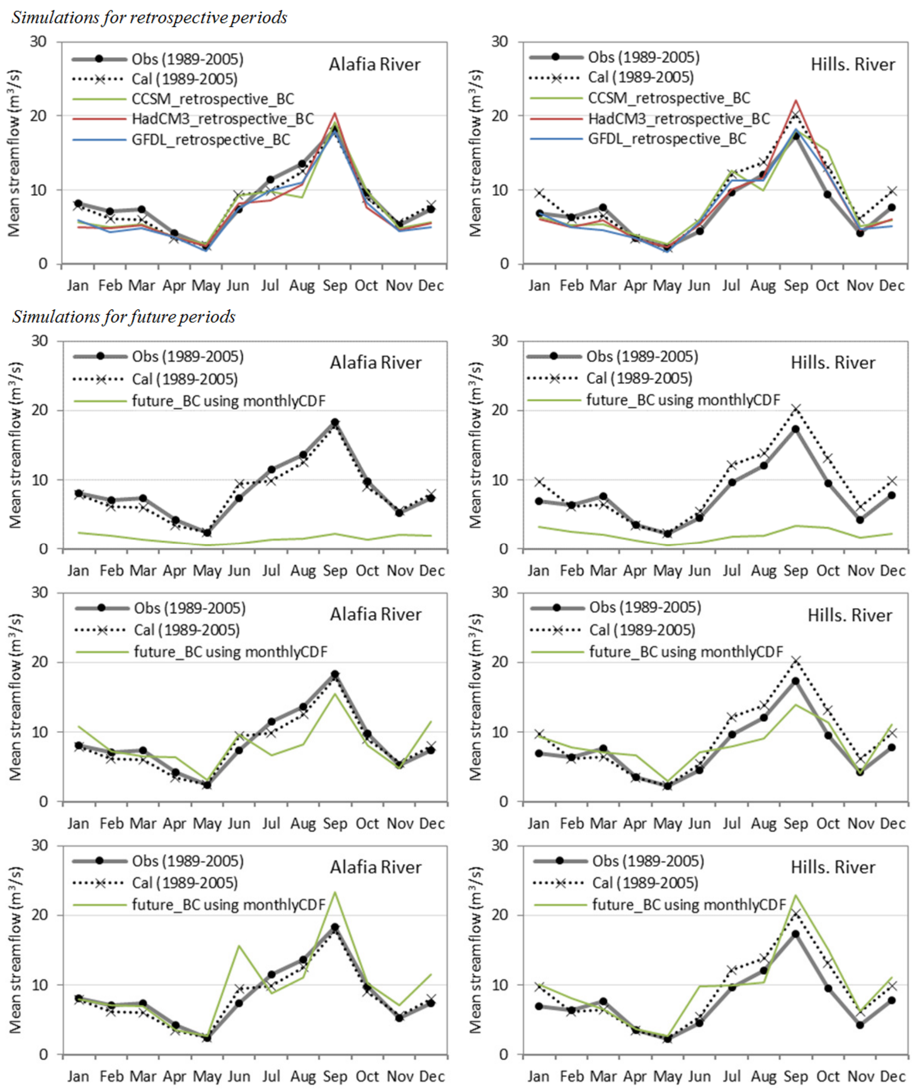

Figure 3.13. Simulated daily mean streamflow using bias-corrected retrospective CLAREnCE10 data (1969–2000, first row) and future data (2039–2070: CCSM (second row), HadCM3 (third row), and GFDL (fourth row) for Alafia River (left column) and Hillsborough River (right column). (1 m^3/s = 35.3 cfs)

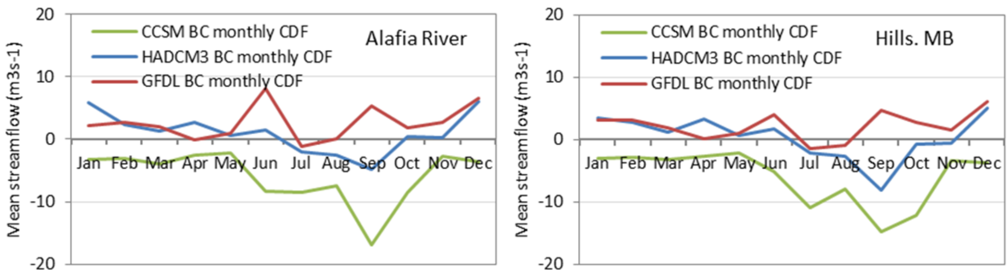

Figure 3.14. Predicted change in future streamflow simulations for each GCM for Alafia River (left column) and Hillsborough River (right column). (1 m^3/s = 35.3 cfs)

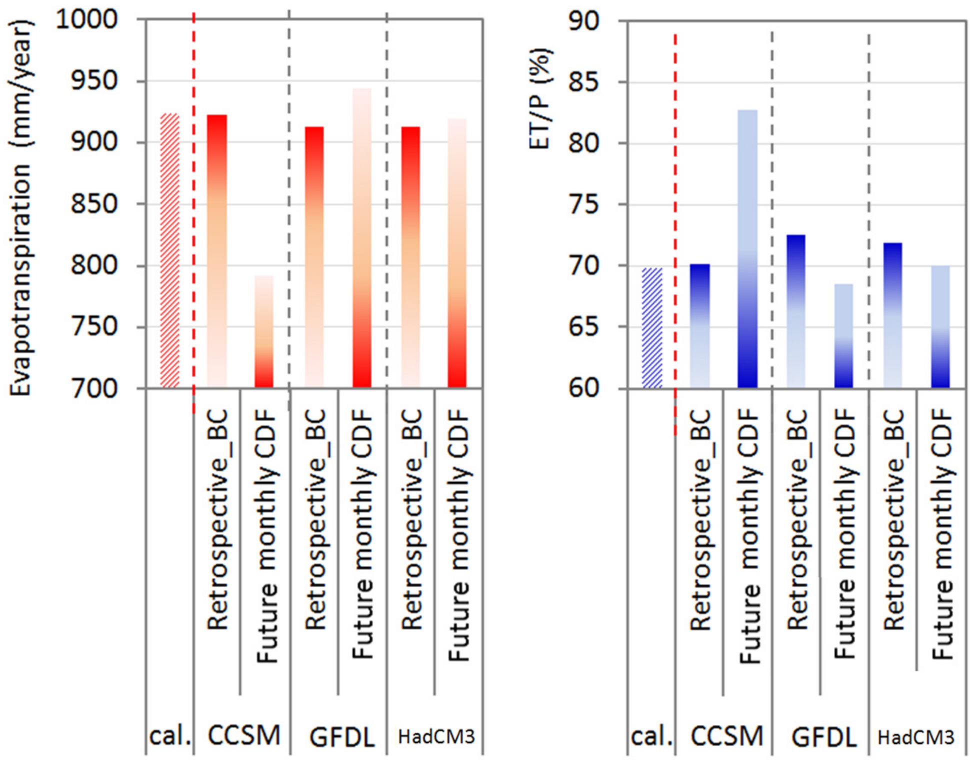

Figure 3.15. Comparison of calibrated, retrospective and future mean annual evapotranspiration (left column) and evapotranspiration ratio to precipitation (right column), averaged over the study area. (1 mm = 0.04 inches).

St. Johns River Region

Background

The watershed of the lower St. Johns River Basin encompasses 7000 km^2 and extends from Lake George to the mouth of the river at the Atlantic Ocean near Jacksonville. The landscape of the lower St. Johns River Basin is relatively low and flat, with surface elevations ranging from a maximum of 77 m near the western boundary to a minimum of sea level (0 m) at the river mouth. The lower St. Johns River is a low-gradient, lake-like river (Bacopoulos et al. 2009). The average bed slope of the river is only 0.000022 (Toth 1993), which allows tidal effects to extend up to Lake George, although the tidal range there is only a few centimeters (Giardino et al. 2011).

Hydrologic Modeling and Climate Change Impacts

The water level and flooding extent of the lower 200 km of the St. Johns River in northeast Florida under a 100-year flood event are evaluated by coupling hydrologic and hydrodynamic models. The 1% annual exceedance probability flood (i.e., 100-year flood event) is the basis for the National Flood Insurance Program. Therefore, Tropical Storm Fay in 2008 is selected in this analysis since it is an approximate 100-year return period rainfall event (Bacopoulos et al. 2017). Tropical Storm Fay passed over Cuba and the Florida Keys into the Gulf of Mexico (August 18, 2008), steered into Naples, Florida (August 19, 2008), crossed over the state, and emerged into the Atlantic Ocean off the east-central Florida coast (August 20, 2008). Then, changes in atmospheric conditions set up a broad flow pattern causing Fay to turn north and track at slow speeds of 1.5 to 2 m/s (3.4 to 4.5 mph), which allowed heavy rain bands to continually pass over northeast Florida for several hours. As the broad flow pattern weakened, a high pressure ridge set in north of Fay causing it to turn westward making a third Florida landfall near Flagler Beach (August 21, 2008). The westward motion was maintained across the northern Florida peninsula and Fay emerged into the extreme northeastern Gulf of Mexico (August 22, 2008), later making a fourth and final Florida landfall near Carrabelle in the Florida Panhandle (August 23, 2008).

The coupled model integrates a hydrologic model (SWAT) and a hydrodynamic model (ADCIRC). SWAT (Arnold et al. 1998) is a Soil and Water Assessment Tool used for prediction of water, sediment, nutrient, and pesticide yields with reasonable accuracy on large, ungauged river basins. SWAT has been successfully applied to many areas around the world at annual, monthly, and daily scales (Wang et al., 2011). ADCIRC is an ADvanced CIRCulation numerical code for simulating shallow water flow (tides and surge) in shelves, coasts, and estuaries. ADCIRC solutions consist of time-dependent variables of water surface deviation from a datum and depth-integrated velocities in the longitudinal and latitudinal directions for all nodes of the computational mesh (Luettich et al. 1992).

The flows of tributaries and the upper main river stem affect the hydrodynamics of the lower main river stem. To accurately model this effect, runoff from the upper St. Johns River and tributaries of the lower St. Johns River is integrated with ADCIRC as inflow boundary conditions. Due to the limited number of streamflow gauges at the outlets of tributaries, a spatially distributed hydrologic model is applied to the lower St. Johns River Basin to provide simulated inflows. This integration of hydrologic and hydrodynamic models is set up such that the hydrologically computed inflows from any tributary are incorporated into the hydrodynamic simulation directly within the domain of flooding. Therefore, the constraints of limited observed flows for boundary conditions of ADCIRC, especially under extreme rainfall events, are overcome by the model integration.

In summary, it was shown that most of the flooding due to Tropical Storm Fay occurred in the upstream parts of the lower St. Johns River Basin (river km 130–160) where the incoming storm surge combined with high influx of watershed runoff, causing water levels to rise above the river banks and inundate the local floodplain. River flooding due to Tropical Storm Fay and the associated large amount of watershed runoff was shown to increase well beyond that of tidal conditions, and the filling and draining of water within watershed basins adjacent to the river during and after the peak of the local surge was shown to vary both spatially and temporally. The results indicate that the ADCIRC model can accurately capture storm surge if boundary conditions are complete and reliable.

The impacts of climate change and sea level rise on flood inundation were assessed based on the developed coupled model. Fig. 3.16 shows the inundation map for the simulated 100-year rainfall event represented by Tropical Storm Fay. Fig. 3.17 shows the inundation map under sea level rise and climate change impacts. The sea level rise is set to 0.51 m and the rainfall intensity is increased by 10% from Tropical Storm Fay.

Climate Change and Sea Level Rise Impact on Groundwater

In coastal aquifers, saline and fresh groundwater are in a dynamic equilibrium, and a landward shift of the equilibrium can cause landward encroachment of saline groundwater, resulting in the occurrence of saltwater intrusion (SWI). The low-lying alluvial plains and barrier islands located in coastal portions of the St. Johns River Basin are also vulnerable to flooding from rising water tables driven by sea level rise (SLR), because the water table depth is usually shallow and can even breach the land surface during and after a heavy rainfall. Water quality of the shallow coastal aquifer is also vulnerable to SLR-induced SWI, especially during prolonged drought. Hence, the low-lying coastal alluvial plains and barrier islands are dynamically influenced by climate change, and the negative effects include, but are not limited to, shoreline erosion, wetland inundation and migration, SWI, and alterations of the distribution and productivity of vegetation communities.

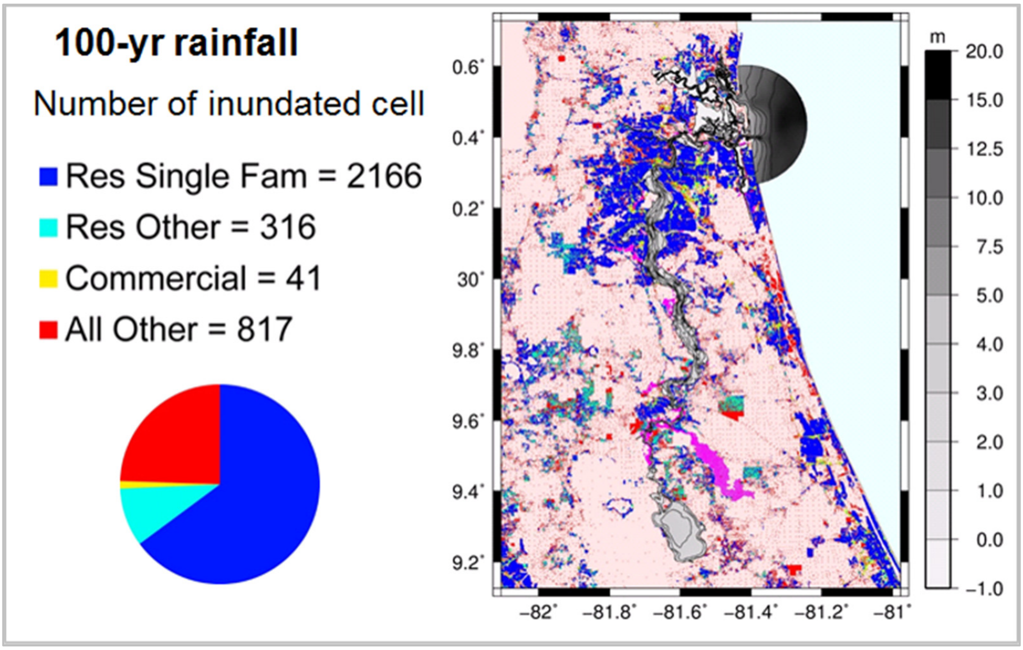

Figure 3.16. Inundation map of the lower St. Johns River under an 100-year extreme rainfall event (Tropical Storm Fay). The pink color represents simulated flooding.

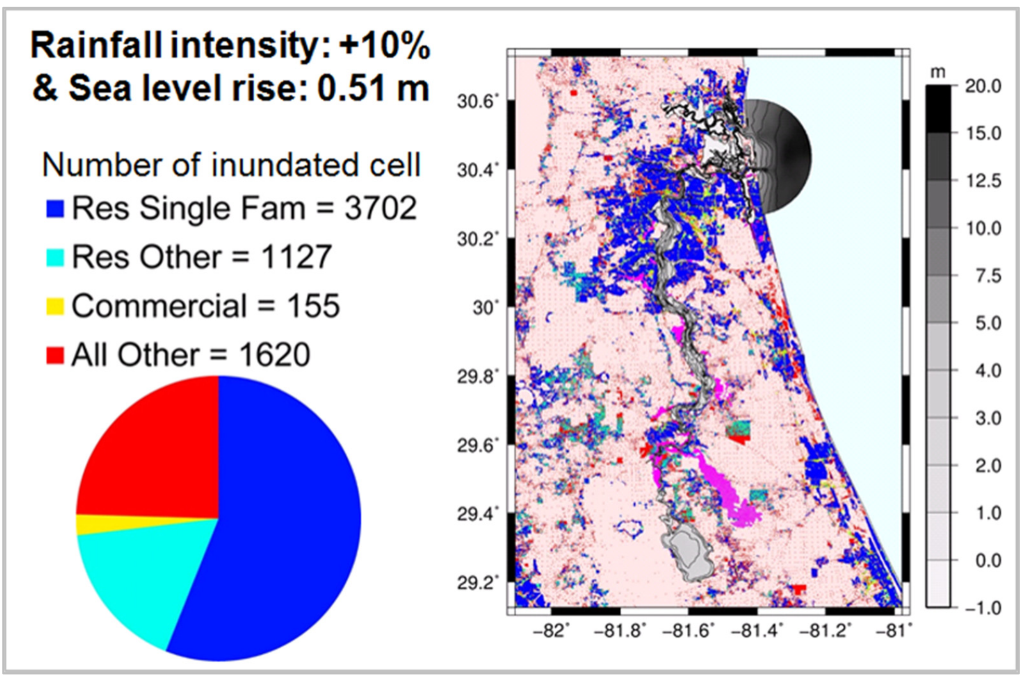

Figure 3.17. Inundation map of the lower St. Johns River under 100-year extreme rainfall event (Tropical Storm Fay) +10% and a 0.51 m increase in sea level. The pink color represents simulated flooding.

The SEAWAT model (Langevin et al. 2008) was applied to simulate the spatial variation of water table depth and salinity in the surficial aquifer system at Cape Canaveral Island and Merritt Island under steady-state 2010 hydrologic and hydrogeologic conditions. The model was calibrated against the field-measured groundwater levels monitored from 2006 to 2014. The calibrated model was used to evaluate climate change and SLR impact on the surficial aquifer system (Xiao et al., 2016).

Compared to 2010, precipitation is estimated to vary from a 7% decline to a 17% increase, while SLR is estimated to be 13.2 cm, 31.0 cm, and 58.5 cm for the low, intermediate, and high ice melt projections, respectively. These downscaled projections for 2050 are developed using data provided by Radley Horton and Daniel Bader, Center for Climate Systems Research, Earth Institute, Columbia University as part of the NASA Climate Adaptation Science Investigators Program (Rosenzweig et al. 2014).

Fig. 3.18 shows the simulation results, and the 'sensitive' areas are highlighted in yellow-brown. The predictions indicate that the effects of SLR and precipitation change are significant in west Merritt Island. This area is particularly vulnerable because of its low-lying coastal areas with flat topography and shallow water table depth having a high risk of being inundated during and after an extreme rainfall event. Also, low land surface elevation corresponding with low potential for freshwater recharge due to shallow water table result in low fresh groundwater pressure head and low hydraulic head gradient between inland fresh groundwater and coastal saline groundwater, which further results in a low rate of submarine groundwater discharge. This reduces the protection from SLR-induced SWI offered by freshwater groundwater recharge. In west Merritt Island, the land cover is mainly composed of fresh marsh, intermediate marsh (less saline than brackish), brackish marsh, and saline marsh.

Landward migration of saline water into the traditionally freshwater areas can cause degradation of ecologic systems and alter the distribution and productivity of vegetation communities. Increased rainfall can contribute to flushing, while prolonged drought can intensify salinity problems. Salt tolerance of plant communities is dependent on vegetation type, duration of exposure to saline water, rate of salinity increase, mineral content of soil, and degree of submergence. Some species can tolerate a wide range of salinity and can recover quickly once the salinity declines. However, some species die off quickly and cannot recover. Potential consequences of exposure to salinity include, but are not limited to, shift of wetland from fresh or less saline marsh to brackish or saline marsh, vegetation species dieback and limited recovery, shift in vegetation species composition from less salinity-tolerant species to more salinity-tolerant species, and reduction in biomass production. SWI not only affects marshes/wetlands, but also affects agriculture. Citrus is the main agricultural product in this area, and a reduction in citrus production due to increased groundwater salinity might be a big problem. Currently, no consumptive use wells operate in this area, and SWI does not have a negative effect on public drinking water supply.

The rates of growth of the aquifer areas affected by SWI were computed. The intruded area growth rate is faster at first and then slightly declines. At the beginning, the growth rate is high because west Merritt Island is vulnerable to even a small amount of SLR due to its low elevation and flat topography. Afterwards, the growth rate slightly declines because the amount of SLR assumed for the 2050 time horizon is not large enough to affect Cape Canaveral Island and east Merritt Island significantly.

In order to prevent saltwater intrusion, it is very important to minimize the effects of SLR, since its effects are clearly more influential than the effects of precipitation change. In order to 'balance' SLR, it is necessary to increase the inland fresh groundwater pressure head by artificial recharge. Recharge wells could be constructed close to the coastline, along with detention ponds designed for flood control to avoid inland flooding, since the region is humid subtropical with plenty of precipitation especially in the rainy season. The designed detention ponds could be used to temporarily hold the excess rainwater while slowly draining to the coastal recharge wells. Artificial recharge is even more important in the dry season because of less precipitation. It is not necessary to 'shut off' the two pumping wells that are used occasionally for lawn irrigation, since the pumping rates are very low and the effect would be tiny.

In summary, the increased inundation area due to intensified rainfall and rising sea levels is significant in the lower St. Johns River Basin, especially residential and commercial areas. In terms of groundwater, the predictions indicate that the effects of SLR and precipitation change will not be significant in Cape Canaveral Island and east Merritt Island by 2050. Both areas serve as the primary recharge area due to its high elevation, deep water table depth, land cover (forest and pasture), and soil type (sand). However, it is estimated that the negative effects could be noticeable if SLR and precipitation change turn out to be greater than projected.

Suwannee and Apalachicola River Basins

Suwannee River Basin (SRB)

The SRB (Fig. 3.19) covers approximately 11,042 square miles and is located entirely within the coastal plain physiographic region of the southeastern U.S.— extending from Cordele, Georgia to Cedar Key, Florida at the Gulf of Mexico (Katz and Raabe 2005). The SRB extends from its eastern headwaters in the Okefenokee Swamp to the Gulf of Mexico, and it is considered one of the most pristine and undeveloped river systems in the United States (Fig. 3.18). The SRB typically entails a unique mix of subtropical and temperate forests, swamps, fresh and tidal wetlands, and a rich habitat for aquatic and terrestrial wildlife. This significantly expansive, grassy estuary provides one of the most scenic nearshore habitats within the northeastern Gulf of Mexico.

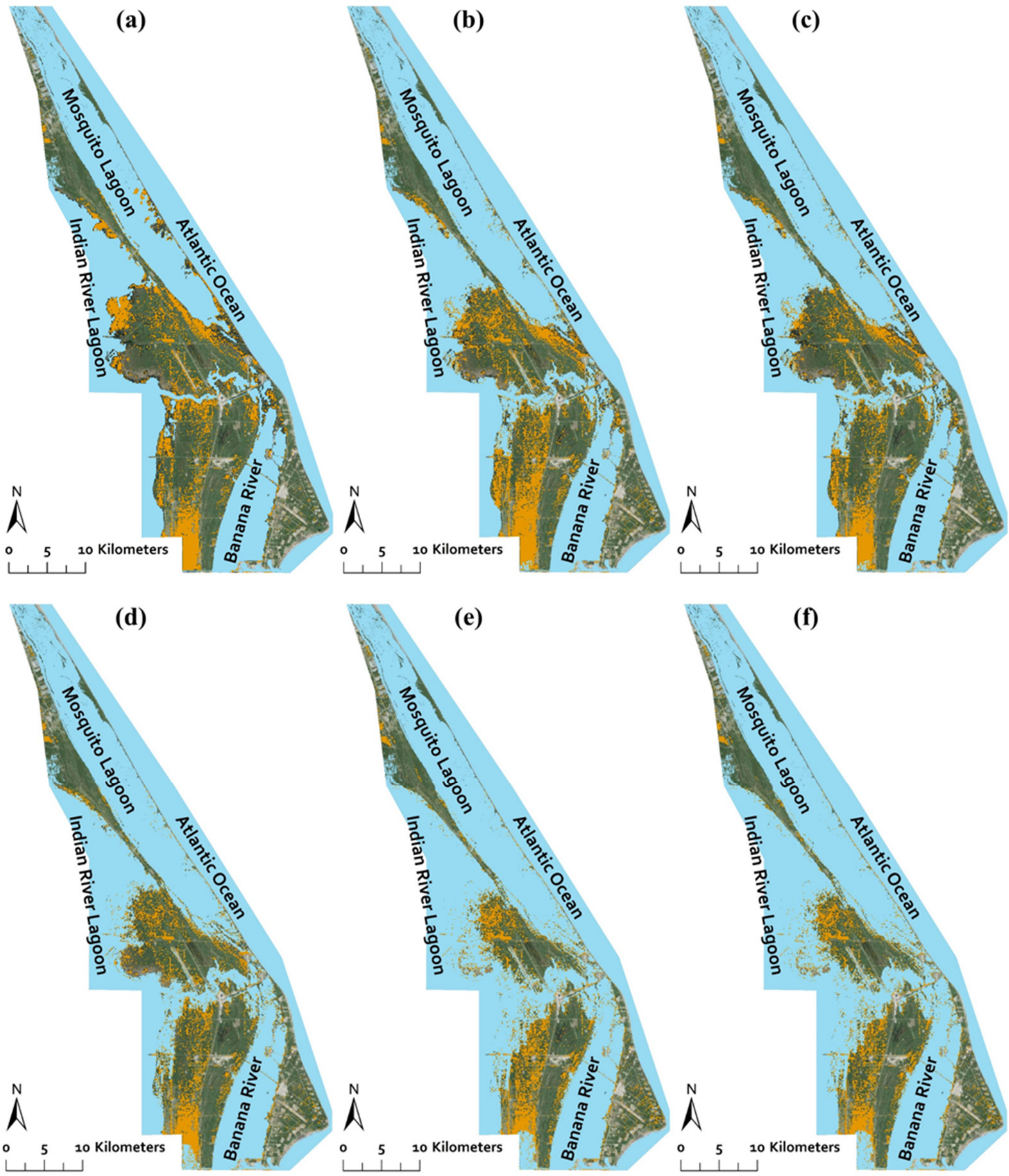

Figure 3.18. The area, which is sensitive to sea level rise and/or rain-induced flooding, is represented by yellow-brown color: (a) Case 0; (b) Case 1 (13.2 cm SLR, +17% precipitation); (c) Case 2 (13.2 cm SLR); (d) Case 3 (31.0 cm SLR); € Case 4 (58.5 cm SLR); and (f) Case 5 (58.5 cm SLR, -7% precipitation).

Groundwater resources in the SRB are supplied by the Floridan aquifer system, which is one of the most productive groundwater resource reservoirs in the United States. The system is a major water source throughout much of Florida and most of South Georgia (Lindsey et al. 2009). The Floridan aquifer underlies the rest of the southern portion of the basin. It is overlain by approximately 25–125 feet of sandy clay residuum derived from chemical weathering of the underlying rock. The total thickness of the Floridan aquifer in the basin ranges from a few tens of feet in the north to more than 400 feet to the southern portion of the basin.

Apalachicola River Basin (ARB)

The Apalachicola River Basin (ARB), which is part of the larger Apalachicola-Chattahoochee-Flint (ACF) river basins, is a basin in the Florida Panhandle that drains a watershed of some 20,000 square miles (Fig. 3.20). The northern reaches of the basin include a dramatic picturesque landscape of steep bluffs and deep ravines that are some of the most significant natural features of the southeastern coastal plain. The river and its surrounding forests, prairies, and coastal habitats are recognized as one of six biodiversity hotspots in the United States. The river basin has the highest species diversity of reptiles and amphibians in the U.S. and Canada, with more than 40 species of amphibians and 80 species of reptiles (Couch et al. 1996). The Apalachicola National Forest, which borders the river, is one of the largest contiguous public lands east of the Mississippi River.

The geology of the Chattahoochee River Basin largely determines the groundwater characteristics of the ARB area. The Chattahoochee River makes its way to the coastal plain. Aquifers in the coastal plain consist of porous sands and carbonates, and include alternating units of sand, clay, sandstone, dolomite, and limestone that dip gently and thicken to the southeast. Most of these aquifers remain reliable and consistent prolific producers of groundwater. The aquifers in the coastal plain typically comprise of two types: unconfined and confined. The unconfined aquifers are hydraulically interconnected to surface water bodies. The confined or artesian aquifers are buried and hydraulically isolated from surface water bodies. Confining units between these aquifers are mostly silt and clay. The five major aquifers that underlie the Chattahoochee River Basin include: 1) the Floridan aquifer system (one of the most productive aquifers worldwide). The complex hydrogeology of the Floridan aquifer system is reflected by highly variable transmissivities ranging from 2,000 to 1,300,000 ft^2 per day (Miller, 1986); 2) the Claiborne aquifer – an important source of water in part of southwestern Georgia (McFadden and Perriello, 1983); 3) the Clayton aquifer, another important source of water in southwestern Georgia; 4) the Providence aquifer system, the deepest of the principal aquifers in South Georgia that serves as a major source of water in the northern one-third of the coastal plain (McFadden and Perriello 1983); and 5) the Crystalline rock aquifer, a bedrock aquifer that underlies the Chattahoochee River Basin.

The Apalachicola River receives streamflow and sediment from the Chattahoochee and Flint rivers, and flows through the Florida Panhandle eventually draining into the Gulf of Mexico. As the source of 90% of Florida's oyster production, Apalachicola Bay is an important marine nursery area. Streamflow and sediment load from the Apalachicola River have a direct impact on the ecosystem, particularly commercial oyster production in Apalachicola Bay. It is important to assess the impact of climate change on the Apalachicola River's streamflow and sediment load to identify potential ecological effects.

Hydrologic Modeling

A SWAT model developed for the Apalachicola River region was used to simulate runoff and sediment loading under present and future conditions (Chen et al. 2014). The model was calibrated and validated for historical conditions (1984–1994) and then used to simulate 30 years of daily discharge and sediment load under present (circa 2000) and future (2100) conditions. Future scenarios incorporated changes in climate, land use and land cover (LULC), and coupled climate and LULC. Wang et al. (2013) assessed projected climate change impact on extreme rainfall events in the ARB based on RCMs. Downscaled climate data for three GCMs and LULC projections detailing changes for 16 distinct land classes are characterized by the IPCC Special Report on Emissions Scenarios (SRES) scenarios A2, A1B, and B1 for 2100 (IPCC 2000). The Long Ashton Research Station Weather Generator (LARS WG) was selected for downscaling GCM data due to its ability to generate site specific, daily, stochastic temperature and precipitation (Semenov and Stratonovitch 2010). In keeping with IPCC carbon emission scenarios, projected 2100 A2, A1B, and B1 LULC provided by the United States Geological Survey Earth Resources Observation and Science (USGS EROS) Center were selected to assess LULC change impacts (USGS EROS Center 2014). Detailed procedures for model calibration and validation, as well as climate change and LULC projections, are described in Hovenga et al. (2016).

The coupling of both future climate and LULC change was simulated for each GCM. Climate based on different GCMs plus LULC change produced large variation in flow outputs. That is, the HADCM3 model predicted higher high flows and lower low flows, IPCM4 indicated overall lowered runoff, and MPEH5 produced generally increased flow. The general seasonal behaviors for sediment loading were very similar to the climate-only simulation results.

Climate change predicted by individual GCMs showed noticeable differences in future rainfall seasonal patterns, with no single carbon emission scenario resulting in higher values, emphasizing structural differences among GCMs. The consensus on temperature is that it will increase, with the A2 scenario predicting the highest values and B1 predicting the lowest. When incorporating climate change into the SWAT model, output in terms of runoff and sediment loading showed large distinctions between GCMs, implying that these parameters might have been driven more by rainfall than temperature. Both the runoff and sediment loading responded to future climate change, yet the ways in which they responded may be conflicting between

GCMs. Under present conditions, high flows occur around October to December. Results from all GCMs are in agreement that flow increased for the months of September and October, indicating the current wet season may occur earlier in the year and with greater magnitude. Sediment loadings were also predicted to increase for these months. Further, sediment loading for the baseline period was at its minimum from July to September, yet a seasonal shift may occur with minimal loading occurring earlier in the year, around April to June. This response may be driven by lowered future precipitation predicted during these months.

LULC change had little effect on the runoff response. Surface runoff was computed using the Soil Conservation Service (SCS) curve number method. While individual curve number values assigned to the distinct land classes varied within the model, the weighted cumulative curve numbers for the circa 2000, 2100 A2, A1B, and B1 land cover datasets within the study domain were 46.9, 48.7, 45.7, and 44.4, respectively. The slight variability between curve number values might explain why runoff was so minimally affected by LULC change. An alternative future LULC class assignment than the one used in this study may result in a more significant response. Further, response to alterations in LULC may be more appropriately assessed using a finer temporal resolution capable of addressing peak runoff. The slight increase that does occur from August to October for the A2 scenario land cover might be explained by the plant growth model and consequent ET that is incorporated into SWAT.

Sediment loading was more evidently impacted by changes made to land cover than runoff. The loading increase observed from the A2 LULC may be a result of the increase in agricultural lands and loss of forested area. Sediment loading decreased for all months as a result of the B1 coverage. Compared to the circa 2000 coverage, B1 had more forested regions and less agriculture. It is inferred that the amount of agricultural and forested lands was directly related to sediment loading and that an increase in agriculture and/or loss of forest may have caused loading quantities to increase.

Runoff response for simulations that coupled climate and LULC change produced runoff values that were very similar to those produced by incorporating climate change only, suggesting future climate change may affect flow more than LULC change. Regardless of the behavior of increased or decreased runoff predicted by the individual models, the patterns of amplification and de-amplification were alike, demonstrating a homogenous interaction occurring within the simulations that was not affected by the GCM data. Sediment loading response was more reactive. When climate and LULC both independently modeled sediment as increasing or as decreasing, the coupled response resulted in sediment values that were overall larger than would be estimated from the individual, added deviations from the baseline. This suggests climate and LULC change effects amplify one another, resulting in larger loadings than if estimated by the separately modeled responses.

Many of the biological species in the Apalachicola region are sensitive to salinity and total suspended solids levels, which can affect both their productivity and distributions (Scavia et al. 2002). The increase in high flow magnitude and seasonal shifts for runoff and sediment caused by climate change have implications for threatening the phenology of the system by affecting migration, breeding, and distributions. Additionally, as land types change, adverse effects may become amplified. Given the time horizon of this study, results may provide guidance in establishing both short- and long-term monitoring activities and mitigation strategies. Short-term efforts may focus on responses with less uncertainty, i.e., those in agreement among all GCMs. Long-term strategies, with more flexibility to adapt, can help coastal managers adjust sustainability efforts and regulatory procedures as more knowledge is acquired, e.g., how the region is changing and region-specific performance of GCMs. The suite of SRES scenarios provides yet another dimension to adaptation planning.

Climate Change Factors Affecting Groundwater within ARB and SRB

The threats to the water and associated natural resources of the SRB and ARB require a better understanding of the sources and effects of contamination, water withdrawals, and climate change, as well as interactions among these stressors. Climate variation alone can result in significant impacts on these resources. For instance, changes in rainfall patterns alone can cause far-reaching impacts on surface water and groundwater supply. Natural fluctuation in water supply, coupled with water consumption, can place added stress on biological communities. Intermittent droughts in Florida over the last two decades have heightened concerns about management of water resources within the watershed. It therefore seems desirable that future consideration be focused on improving interagency communication and coordination for effective water resource monitoring covering both groundwater and surface water, including development of better predictive measures.

SWI (which is the movement of saline water into freshwater aquifers) is an especially significant potential threat to the potable water supply in areas along the SRB. Based on historical data and hydrogeological principles, the water-level fluctuations can affect the position of the freshwater and saltwater interface.

Increased demands for groundwater from intensifying urban development and extensive agricultural activities in this part of the basin have resulted in increased withdrawals of water from the Upper Floridan aquifer. As an example of water–quantity-related problems in the recent decade, some springs within the ARB and SRB are increasingly being depleted and essentially stop flowing at times of the year due to lowering of the water table. Increased water withdrawals have also caused a secondary deleterious impact on the groundwater resource by salt water intrusion. This phenomenon will be exacerbated by potential decreases in precipitation in the future due to global climate change.

Although studies in the basins indicate generally good overall water quality, there are other ever-increasing threats to the water resources within the ARB and SRB areas. These include nitrogen and phosphorus contamination of groundwater from fertilizers, animal waste, sewage effluent (septic tanks and land application of treated sewage effluent), and atmospheric deposition. These threats are raising concerns regarding both human and ecosystem health. Elevated nitrate concentrations in rivers can cause eutrophication, which can result in algal blooms and depletion of oxygen that can lead to fish kills (Bledsoe and Phlips 2000). Increases in nitrate concentrations from human activities may cause adverse ecological effects, indicated by an increase in periphyton biomass along the middle and lower reaches of the Suwannee (Hornsby and Mattson 1998).

Several human health concerns are also associated with elevated nitrate concentrations in groundwater used for drinking. A typical example is for infants under six months of age who are susceptible to methemoglobinemia when they ingest nitrate in drinking water, which can lead to reduced blood oxygen levels that can result in death. For these health concerns, the U.S. Environmental Protection Agency (EPA) established a maximum contaminant level for nitrate of 10 mg/L as nitrogen for drinking water. Recent studies have also shown that pharmaceuticals, endocrine-disrupting chemicals (hormones), and other organic wastewater contaminants are present in streams throughout the U.S. (Kolpin et al. 2002). Although present in generally very low concentrations, little is known about the potential effects on human health and the health of aquatic organisms that may occur from complex mixtures of organic wastewater contaminants and their metabolites in surface waters.

During prolonged wet periods, when river floodwaters flow into the karstic aquifer system along the Lower Suwannee River corridor, there is an opportunity for waterborne pathogens (such as Cryptosporidium and Giardia oocysts) to enter the aquifer system. These waters also contain very high concentrations of naturally occurring organic matter that could react with disinfectants such as chlorine and produce harmful trihalomethanes and haloacetic acids.

In addition to influencing temperature and precipitation around the world (Chiew et al. 1998; Roy 2006; Keener et al. 2007), the ENSO phenomenon also has impacts on groundwater resources (McCabe and Dettinger 1999; Gurdak et al. 2007). Studies have found strong correlation between ENSO, precipitation, and streamflow (Berri and Flamenco 1999; Simpson and Colodner 1999). These studies have shown that ENSO can have strong correlations with temperature and precipitation in the North America and reported that the northern United States experiences less precipitation and warmer winters during El Niño events.

Possible Adaptation Measures and Research Opportunities

The most practical mitigation measures for water resource issues within the ARB–SRB area should broadly focus on basin-wide optimization of water resource information and management. Suggested measures include, but are not limited to, the development and proper application of: consistent and comparable data collection and analysis methods; improved techniques and their coordination among agencies and across jurisdictions; integrated land use and land cover databases that comprise past, present, and future; and improved groundwater/surface water interaction workable models that will enhance predictive capabilities. Past advances in understanding the ARB–SRB call for continued and sustained research priorities within the ARB–SRB area that should address the following:

- Extent and significance of SWI on freshwater systems
- Fate of nitrate in drinking water and aquatic systems
- Radionuclide occurrence in drinking water and associated health issues
- Pathogens and bacteria influx to karstic groundwater during flood periods
- Elevated natural organic material and the formation of disinfection byproducts
- Endocrine disruptor chemicals and organic wastewater compounds
- Mercury methylation and other toxic elements accumulation in edible fishery

Water Quality Impacts

Climate change impacts on water resources have been studied extensively from the perspective of changes in quantity, but far fewer studies consider potential changes in water quality and their implications for water and wastewater utilities. Understanding impacts on water quality is important to assess the full implications for water resources because climate change is expected to exacerbate existing water quality problems and create new problems. The principal impacts on water quality are often related to temperature increases, variations in precipitation, SLR, and deposition of gases and particulates from the atmosphere.

At the global scale, increases in temperature and SLR are expected, while precipitation patterns would vary depending on geographical location; some may experience increased precipitation while others may experience reduced precipitation or drought (IPCC 2014). In general, Florida is expected to experience increasing air temperatures (Florida Oceans and Coastal Council 2009). Carter et al. (2014) reported that temperatures in the southeastern U.S. have risen by an average of 2^{o} F since 1970.

Temperature Increase

Increased temperature impacts water quality in a number of ways. It increases ET levels that may lead to higher concentration of pollutants, and it can change water chemistry and biochemical reaction kinetics that affect dissolution, complexation, and biological degradation processes. Increased temperature will also result in lower dissolved oxygen (DO) concentration due to lowering of saturation levels. Reduced DO and increased temperature can cause changes in water chemistry, such as increased mobility and bioavailability of heavy metals (John and Leventhal 1995). In addition to effects on chemical characteristics, increased temperature also leads to higher pathogen levels as microorganisms will remain viable longer in the environment. To help maintain stable water quality and minimize water loss due to increased evapotranspiration and temperature, utilities may consider aquifer storage and recovery, which has regulatory and cost implications and possibly its own water quality issues.

Figure 3.19. Location map showing the Suwanee River Basin and estuary system (Katz et al. 2005).

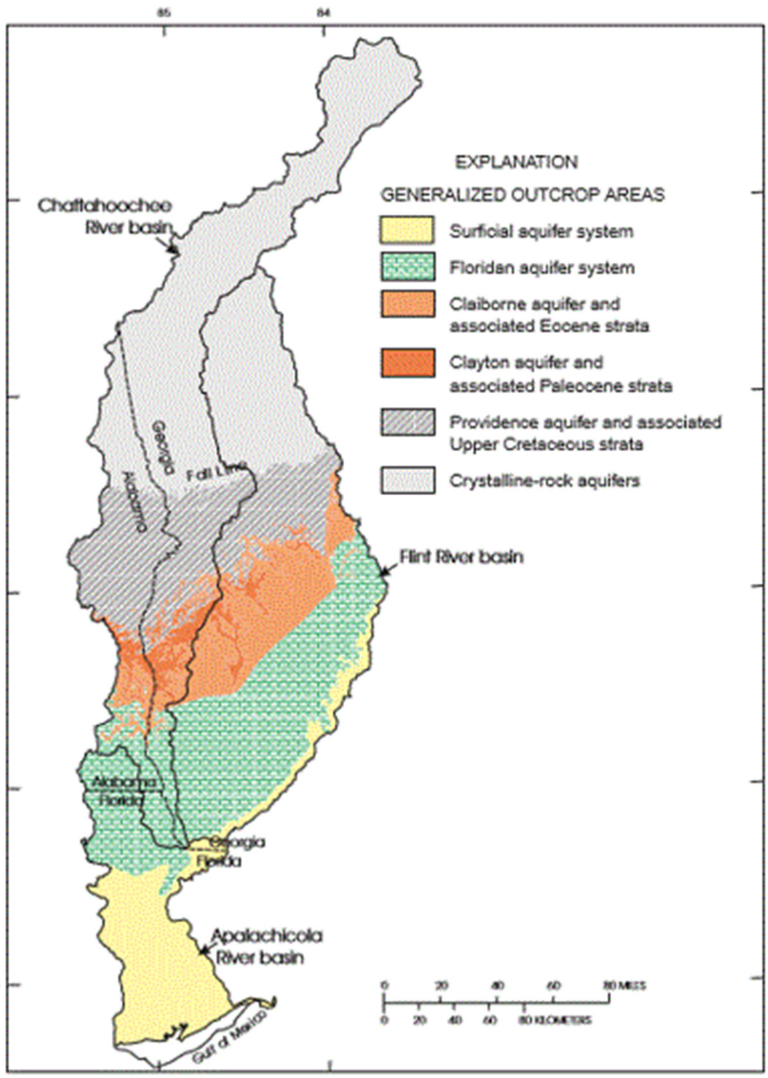

Figure 3.20. Hydrological units underlying the Apalachicola-Chattahoochee-Flint River Basin (Couch et al. 1996).

In the case of higher temperatures coupled with high nutrient loads, lakes, reservoirs, and low flow streams would experience more intense eutrophication and algal blooms. This results in increased levels of cyanobacteria biomass and development of anoxic conditions that affect water quality negatively, and hence can increase water treatment requirements or cost. Based on model simulation of some lakes under higher temperatures, some studies predict extended lake stratification periods with low DO in the hypolimnium layer in summer and consequent phosphorus and heavy metals dissolution, and increased lake turbidity. (Sahoo et al. 2011; Taner et al. 2011; Dupuis and Hann 2009).

Elevated algal blooms also result in higher levels of organic loads that lead to increased disinfection byproducts that are thought to be carcinogenic. Based on experimental study, Kovacs et al (2013) reported that a 1 to 5ºC temperature increase above normal values resulted in higher organic load that increased disinfectant needs by up to 15% and resulted in a corresponding increase in disinfection byproducts formation. In wastewater systems, low DO levels can create septic situations in sewers that may corrode pipes and result in offensive odors and other toxic volatile gases.

Precipitation Variations

Changes in the timing, intensity, and duration of precipitation can negatively affect water quality. In places where lower precipitation is expected, lower velocities and hence higher water residence times in rivers and lakes will enhance the potential for toxic algal blooms and reduced DO levels. Lower water levels in lakes or rivers also lead to the release of sediments, organic carbon, and other contaminants into intake structures for water treatment. On the other hand, increased rainfall duration and intensity can result in higher runoff and subsequently higher level of salts, pathogens, heavy metals, and nutrients that will complicate water quality and treatment. Increased precipitation and consequent flooding can also overload combined sewer and wastewater treatment plants, resulting in the direct discharge of untreated or partially treated wastewater to water bodies. The timing of these changes may also have some undesirable consequences. Whitehead et al (2009) reported that storms that terminate drought periods can generate acid pulses in acidified catchments. Such events also flush nutrients from urban and rural areas, which would increase risk of eutrophication in lakes. However, increased runoff also has the potential to reduce such risks because nutrients could be flushed from lakes by more frequent storms and hurricanes. Overall, increased runoff results in negative impacts on water quality due to increased pollutant loads.

Sea Level Rise (SLR)

As sea level continues to rise, the extent of SWI will increase, especially during periods of drought in areas where aquifers are mainly recharged by rainfall and surface water flows. Coastal aquifers in Florida such as the Biscayne aquifer have long experienced SWI due to pumping, seawater movement up canals during high tides and storms, the lowering of water tables by drainage, and reduced flows from the Everglades (Miller et al. 1989; Prinos, et al. 2014). Preventing such impacts has become an expensive endeavor for the South Florida Water Management District involving the construction of salinity control structures, some of which must now be actively pumped to move freshwater to the sea and avoid inland flooding. It is expected that the Comprehensive Everglades Restoration Plan will increase freshwater flow to the southern Everglades, which will help offset the effect of SLR. SLR would also increase saltwater inflows to sewer collection systems and cause changes to the salinity of wastewater, which may impact biological treatment processes.

The IPCC report (2014) stated that expected climate change phenomena will, in general, impact raw water quality and pose risks to drinking water quality. In addition, climate change will also affect discharge permits of wastewater utilities due to more complex environmental conditions and reduced dilution effect of receiving water bodies in reduced precipitation areas. The EPA has identified the drinking water, surface water, discharge permits, and Total Maximum Daily Loads (TMDL) programs that could face potential impacts from air and water temperature increases.

It is important that the linkages between observed effects on water quality and climate be interpreted cautiously for different localities and water bodies due to the nonuniformity of climate change and water quality.

In summary, climate change can have a range of impacts on water quality for utility operation and management that could challenge meeting the regulations of the Safe Drinking Water and Clean Water acts. Additional processes or adaptation measures in water and wastewater treatment systems and stormwater management would likely be required in some cases. Conventional water treatment processes would need to be upgraded to advanced processes that might involve costly operations to handle increased levels of contamination and to comply with stringent standards that may be associated with impacts of climate change.

Some of the important adaptation measures for water and wastewater utilities include:

- Consideration of options for modular systems to provide additional capacity and improved performance or to add flexibility to treatment processes
- Careful consideration of climate change uncertainties in developing asset management strategies
- Enhanced long-term monitoring of temporal and spatial water quality information and development of more precise methods of projection of water quality changes
- Development of robust watershed management systems and holistic approaches to water quality and quantity management that take potential climate change impacts into consideration
- Identification of threshold water quality parameters for upgrading and planning new facilities

Conclusion

Florida has a diverse portfolio of water resources. Groundwater and surface water are intimately linked in many parts of of the state. Urban, agricultural, and ecological systems in Florida depend on water resources and the state relies heavily on groundwater for many of its water supply needs. Large uncertainties in climate projections for Florida make assessment of climate change impacts on water resources challenging. Only a few early assessments of likely future climate conditions in portions of the state have been completed so far. There is good agreement among the available climate models that temperatures will be higher in the future, but there is less consensus about future precipitation. A limited number of global climate models have been downscaled for Florida using both statistical and dynamical modeling approaches and the assessments to date have been used to determine the sensitivity of the water resources system to potential changes in precipitation, temperature, and SLR.

Since there is no statewide, comprehensive assessment of water resources impacts due to climate change, this chapter has provided summaries of several studies associated with four major regions including the Greater Everglades ecosystem, the Tampa Bay region, the St. Johns River basin, and the Suwanee and Apalachicola river basins. Although such studies have been diverse, they can be used to make several general and specific conclusions until more comprehensive, statewide assessment using standardized data and methods become available.

Climate change is likely to impact the drivers of hydrologic cycle in Florida, which primarily include precipitation, temperature, ET, and SLR. Because climate in Florida is also influenced by natural phenomena such as the ENSO, AMO, and others, it is important to understand how the interactions between climate and the teleconnections due to such natural phenomena may change in the future. Unfortunately, the available climate projections do not appear to have sufficient capacity to provide accurate predictions of hydrologic variables that will ultimately influence water resources systems. For this reason, much of the work in Florida has taken a scenario approach based on potential magnitude of the changes or pathways that have been identified for global change.

Impact assessments in various regions have demonstrated that the corresponding impact on water resources could be significant, particularly if the precipitation amounts decrease in the future. Water supplies are vulnerable to decreased recharge from higher ET associated with almost certain higher temperatures in the future. More precipitation could partially or wholly compensate for more ET, but less precipitation coupled with expected higher ET could place severe stresses on water supply systems. There is a great need to enhance the ability to predict future precipitation.

SLR threatens coastal areas with flooding and SWI into water supply aquifers. Near term, this is especially problematic in Southeast Florida, but other areas are beginning to be affected or will be in the more distant future.

There are numerous water quality issues associated with climate change and SLR. Exacerbation of algae and eutrophication problems due to higher temperatures may be one of the most immediate challenges. Water and wastewater treatment are likely to be affected by water quality changes due to climate change and SLR.

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