Southeast Florida's Resilient Water Resources

Adaptation to Sea Level Rise and Other Impacts of Climate Change

Center for Urban and Environmental Solutions at Florida Atlantic University

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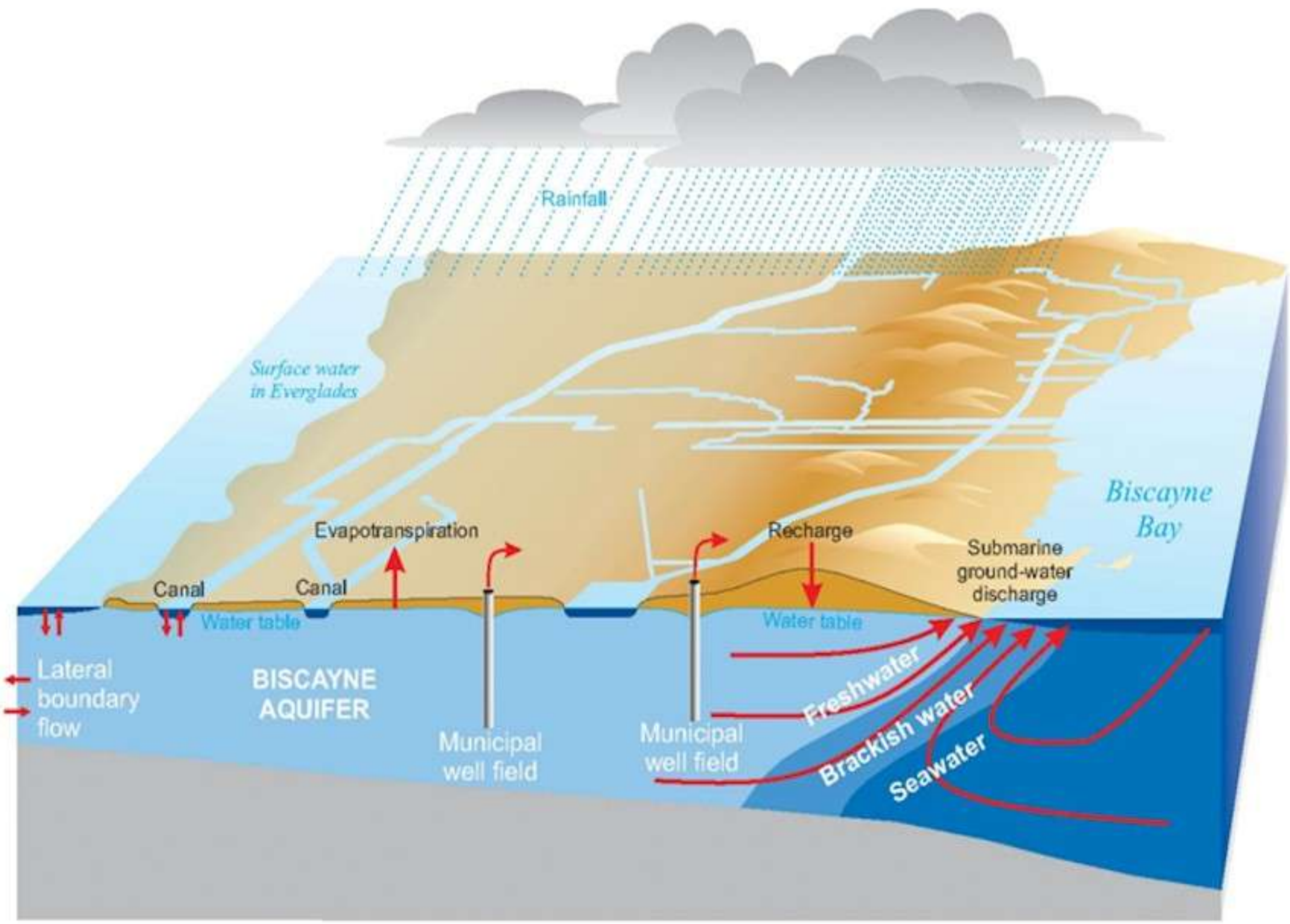

Figure 1 – Schematic diagram of the hydrological cycle in Southeast Florida. Southeast Florida receives approximately 60 inches of year annually. Most of Southeast Florida sits on the Biscayne Aquifer, an open coastal aquifer of high porosity and transmissivity. (Graphic: USGS)

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and
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<u>Sponsored by:</u>

National Commission on Energy Policy

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This research relied heavily upon input from 35 experts who generously donated their time and expertise in open consultations both in person and over the telephone. They are listed with their titles and affiliations in Appendix B. Those who participated in consultations in person and over the telephone include: John Abbott, P.G.; Bevin Beaudet, P.E.; Leonard Berry, Ph.D.; William Brant, P.E.; Randolph Brown, M.B.A.; Albert Carbon, P.E.; Lynette Cardoch, Ph.D.; Michael Davis, Ph.D.; Patrick Davis, P.E.; Shannon Estenoz; Susan Glickman; Rohit Goswami, Ph.D.; Howard Hanson, Ph.D.; Christian Langevin, Ph.D.; David Major, Ph.D.; Sean McCracken; Donald McNeill, Ph.D., P.G.; Victoria Morrow, GISP; John Mulliken; Albert Perez, P.E.; Robert Renken; Winnie Said; Leo Schwartzberg, P.E., C.E.P.; Georgio Tachiev, Ph.D.; Lenny Vialpando, P.E.; Hal Wanless, Ph.D.; and Michael Zygnerski, Ph.D. The report was reviewed by: John Abbott, P.G.; George Cavros, Esq.; John Crouse, P.E.; Rohit Goswami, Ph.D.; Dan Kimball; Elizabeth Plater-Zyberk, F.A.I.A., C.N.U.; Leo Schwartzberg, P.E., C.E.P.; and Henry Sniezek, AICP. Special recognition goes to Jennifer Jurado, Ph.D.; Jayantha (Obey) Obeysekera, Ph.D., P.E., D.WRE; and Doug Yoder who significantly contributed through active dialogue and debate and by reviewing multiple drafts of the report. Ellen Heimlich, Esq. proofread this report and gave moral support to the lead author, both of which are greatly appreciated.

About the Authors

The study was carried out by the Center for Urban and Environmental Studies (CUES) at Florida Atlantic University, in partnership with FAU's Department of Civil, Environmental, and Geomatics Engineering, under the sponsorship of the National Commission on Energy Policy. The project team included:

Barry N. Heimlich, Lead Researcher of the project, is a Senior Fellow at CUES and co-author of *Florida's Resilient Coasts: a State Policy Framework on Adaptation to Climate Change*. He is a member of the Broward County Climate Change Task Force, and was chair of the Ad Hoc Subcommittee on Global Warming that recommended its formation to the county commission. He serves on the built environment adaptation, greenhouse gas reduction, and science and technology committees of the Miami-Dade Climate Change Advisory Task Force and the Broward County Climate Change Task Force. Since 2003, he has served on the Technical Advisory Committee of the Broward County Water Advisory Board. Mr. Heimlich is a chemical engineer with a Master of Science in Engineering degree from the University of Michigan. He formerly held executive, management and engineering positions in the pharmaceutical and petroleum industries.

Frederick Bloetscher, Ph.D. spearheaded the Case Study of the Pompano Beach Water Utility in this study and contributed his expertise to this research report. He is an assistant professor in FAU's Department of Civil, Environmental, and Geomatics Engineering. Dr. Bloetscher's related research focuses on groundwater injection, water quality, and public water and wastewater utility management and finance. He is author of three civil engineering textbooks: *Well Drilling, Groundwater Injection* and *Water Basics for Decision Makers – Local Officials' Guide to Water & Wastewater Systems*, published by the American Water Works Association.

Daniel E. Meeroff, Ph.D. is an associate professor in FAU's Department of Civil, Environmental, and Geomatics Engineering, and he is the Director of the Laboratories for Engineered Environmental Solutions (Lab.EES). Dr. Meeroff's related research focuses on water quality issues, pollution prevention, and water and wastewater treatment process design and infrastructure management.

Jim Murley was, Principal Investigator of the project, is Director of the Center for Urban and Environmental Studies. Previously he served as Florida Secretary of Community Affairs in the Cabinet of Governor Lawton Chiles at Florida Atlantic University. Mr. Murley was appointed in 2008 by Florida Governor Charlie Crist to be chair of the Florida Energy and Climate Commission. He is vice chair of the Miami-Dade Climate Change Advisory Task Force and a member of the Broward County Climate Change Task Force, where he also chairs the Subcommittee on Built Environment and Infrastructure Adaptation. He serves on the Water Resources Advisory Committee (WRAC), the technical advisory body of the South Florida Water Management District. He was Principal Investigator of *Florida's Resilient Coasts: a State Policy Framework on Adaptation to Climate Change.*

1 Executive Summary

Anthropogenic activity is now widely accepted by the overwhelming majority of the world's scientists as the major cause of global climate change (IPCC, 2007); (Karl, etal, USCCSP, & NOAA, 2009); (International Alliance of Research Universities, 2009). Climate change is driven primarily by the accumulation in the atmosphere of greenhouse gases from the burning of fossil fuels, deforestation, land use, and agricultural practices. Climate change has begun to exert significant effects in many regions of the world and there is already enough energy stored in the oceans, atmosphere, and land for adverse impacts to continue for centuries. In addition to an aggressive, concerted, global mitigation program to reduce greenhouse gas emissions in order to limit the extent of climate change, forward-thinking local adaptation is needed to cope with the unavoidable, potential, area-specific impacts of climate change.

Southeast Florida, comprised of Miami-Dade, Broward, Palm Beach, and Monroe Counties with a combined population of 5.5 million (US Census, 2008), was reported to be one of the ten most vulnerable coastal metropolitan areas in the world, ranking 4th in terms of exposed population and 1st in terms of the value of exposed assets by the Organisation for Economic Co-Operation and Development (Nicholls & OECD, 2008). The region is especially susceptible to sea level rise and expected changes in local weather patterns. Recent reports from the U.S. Global Climate Change Science Program (Karl, etal, USCCSP, & NOAA, 2009) and the International Alliance of Research Universities (IARU, 2009) indicate that global average sea level may rise by approximately 2 to 4 feet or more by 2100, an amount that will have significant effects on coastal Southeast Florida.

Southeast Florida's vulnerability derives from its geographic location, low elevation, porous geology, unusual ground and surface water hydrology, subtropical weather patterns, and proximity to the Atlantic Ocean and Gulf of Mexico. Its highly engineered water infrastructure and flood control systems play an essential role in assuring that region's habitability. Water managers must balance demand for potable water and agricultural and landscape irrigation with ground and surface water management, flood control, and the needs of the natural environment including the Everglades, coastal and freshwater wetlands, and coastal marine habitat. Because the region's hydrological system is very interdependent and interactive, water supply cannot be considered separately from the other elements of the region's water resources, such as wastewater management, flood control, and stormwater management, which are addressed comprehensively in this study.

How and to what extent sea level rise and other climate change impacts are likely to influence Southeast Florida's water supply, wastewater reuse alternatives, and ground and surface waters are subjects of this research. Engineering options and management strategies for enhancing the resilience of the region's water systems are described. A Case Study of the City of Pompano Beach Water Utility exemplifies how these tools can be applied to improve the resilience of a local water utility. An adaptive planning framework is outlined for management of the region's water resources as sea level continues to rise and as drought and more severe storm events worsen with time.

Until now, planning has implicitly assumed "stationarity" (Obeysekera, 2009), that environmental conditions, such as climate patterns and sea level, will remain within historic ranges and that only changes in human circumstances, such as population, technology, and the economy, need be considered. This assumption is no longer valid. Unprecedented conditions in the future and uncertain potential consequences demand that climate change be considered in all future planning and policymaking concerning water resources, other infrastructure, and land use. Furthermore, current practices, policies, and regulations should be critically reviewed and revised in consideration of climate change. New ideas and new approaches that may possibly conflict with current thinking will be needed if the forecasted ranges of sea level rise and weather extremes are realized.

1.1 Unforeseen Near-term Consequences

Increased hydrostatic backpressure on the Biscayne Aquifer is likely to increase saltwater intrusion and reduce groundwater flow to the ocean. Furthermore, sea level rise of as little as 3 to 9 inches within the next 10 to 30 years will decrease the capacity of existing coastal flood control structures (Obeysekera, 2009) and may significantly compromise the region's stormwater drainage system, increasing the risk of flooding during heavy rainfall events. Compounding this problem, the amount and intensity of torrential rain events and tropical cyclones are expected to increase (IPCC, 2007); (Karl, etal, USCCSP, & NOAA, 2009). These impacts are expected to worsen as sea level continues to rise.

Increased hydrostatic back-pressure on the Biscayne Aquifer is likely to increase saltwater intrusion and reduce groundwater flow to the ocean. Furthermore, sea level rise of as little as 3 to 9 inches within the next 10 to 30 years will decrease the capacity of existing coastal flood control structures (Obeysekera, 2009) *and may significantly compromise the region's stormwater drainage system, increasing the risk of flooding during heavy rainfall events. Compounding this problem, the amount and intensity of torrential rain events and tropical cyclones are expected to increase* (IPCC, 2007)*;* (Karl, etal, USCCSP, & NOAA, 2009)*. These impacts are expected to worsen as sea level continues to rise.*

Adaptation measures may have to be implemented in the near future to contend with the following consequences:

1. Intensified saltwater intrusion in the region's easterly water wellfields.
2. Reduced availability of fresh water for potable use, especially during periods of intensified drought.
3. Increased risk of flooding during major rain events.

1.2 Major Conclusions

Within the short span of the next 10 to 30 years, sea level rise and changes in weather patterns may begin to exert significant impacts on Southeast Florida's water supply and increase the risk of severe flooding.

1. Sea level rise of as little as 3 to 6 inches is likely to intensify saltwater intrusion, and it could reduce the amount of fresh water available for potable use.

2. The likelihood of recurring drought during the dry winter-spring season may cause water shortages and exacerbate saltwater intrusion.

3. More intense rainfall events and wetter hurricanes may significantly increase the risk of flooding.

4. Sea level rise of as little as 3 to 6 inches may begin to compromise the effectiveness of the area's coastal flood control structures reducing their capacity by as much as 20 to 40% by 2030. By about 2040, 6 to 9 inches of sea level rise may reduce their capacity by 65 to 70%. Most of these early impacts will be felt in southern Miami-Dade County where water tables are low due to the area's extremely low elevations.

5. Sea level rise would increase the damage potential of hurricanes due to storm surge. Storm surge could penetrate further inland and cause temporary saltwater contamination of potable water supplies.

6. As sea level rises throughout the 21st Century, the southernmost Everglades are likely to be progressively converted into a saltwater marsh. This would change its ecology and could eventually threaten to contaminate the southern part of the Biscayne Aquifer with brackish water.

7. These risks are likely to worsen as sea level continues to rise throughout the 21st Century and beyond.

1.3 Major Recommendations:

1. Climate change should immediately be formally incorporated into all planning and policymaking concerning the region's water resources.
2. Current water resource management plans and policies should be reevaluated within the context of climate change and revised as necessary.
3. Workshops and conferences should be convened at the earliest opportunity to bring scientists, engineers, water managers and decision makers together to exchange knowledge about the impacts of climate change on the region's water resources and to begin developing a comprehensive list of policy and planning recommendations for enhancing the resilience of Southeast Florida's water resources.
4. Further study including integrated hydrological modeling should be undertaken at the earliest opportunity to confirm and build upon the conclusions of this report.
5. Evaluation of impacts of sea level rise and other climate change impacts on saltwater intrusion and development of plans for protecting the Biscayne Aquifer should be accelerated.
6. Comprehensive engineering evaluations should be undertaken to assess the vulnerability and enhance the resilience of Southeast Florida's flood control structures and stormwater drainage systems to sea level rise and more intense rainfall events.

7. As much fresh water should be retained in the system as practical without increasing the risk of flooding. This calls for continued development and implementation of water conservation, alternative water supply, wastewater recovery and reuse, and stormwater storage programs.
8. State and local governments, water resource agencies, and water utilities should develop policies and comprehensive plans that set short, intermediate, and long range goals and establish adaptive management implementation strategies for water resources under their jurisdiction that address the likely impacts of climate change and its operational, economic, and environmental implications.
9. State and local water resource agencies and water utilities in cooperation with the state university system should establish a comprehensive research program to develop scientific and technical knowledge regarding the impacts of climate change and adaptation technologies for the region's water resources.
10. Alternatives analysis and feasibility studies of large scale regional advanced water treatment facilities should be undertaken to establish the applicability of:
    a. Advanced treatment of stormwater or wastewater for aquifer recharge and/or Everglades hydration.
    b. Production of potable water from brackish water, treated wastewater, or stormwater.
    c. Potential for realizing economies of scale.

Adaptation measures are likely to incur high costs that will have to be justified on the basis of loss avoidance in comparison with estimates of the cost of inaction rather than on the basis of economic return. Eventually, withdrawal from vulnerable locations may become necessary if local circumstances preclude feasible and cost-effective adaptation. It will take innovation and leadership by policymakers and water managers to choose between difficult alternatives and apply them in a timely and cost effective manner.

Adaptation measures are likely to incur high costs that will have to be justified, not on the basis of economic return, but rather on the basis of loss avoidance in comparison with projected costs of failing to act. Eventually, withdrawal from vulnerable locations may have to be considered if local conditions preclude feasible and cost-effective adaptation. It will take innovation and leadership by policymakers and water managers to choose between difficult alternatives and implement them in a timely and cost-effective manner.

This report is intended for the South Florida Water Management District (SFWMD); the U.S. Army Corps of Engineers (USACE); the Florida Energy and Climate Commission (FECC); Florida Department of Environmental Protection (FDEP); The South Florida Everglades Restoration Task Force (SFERTF); the water resources task forces, water advisory boards, and climate change task forces of Miami-Dade, Broward, Palm Beach, and Monroe Counties; state, regional and local policymakers, and planners; water resource managers, water utility and drainage district managers; and other interested parties.

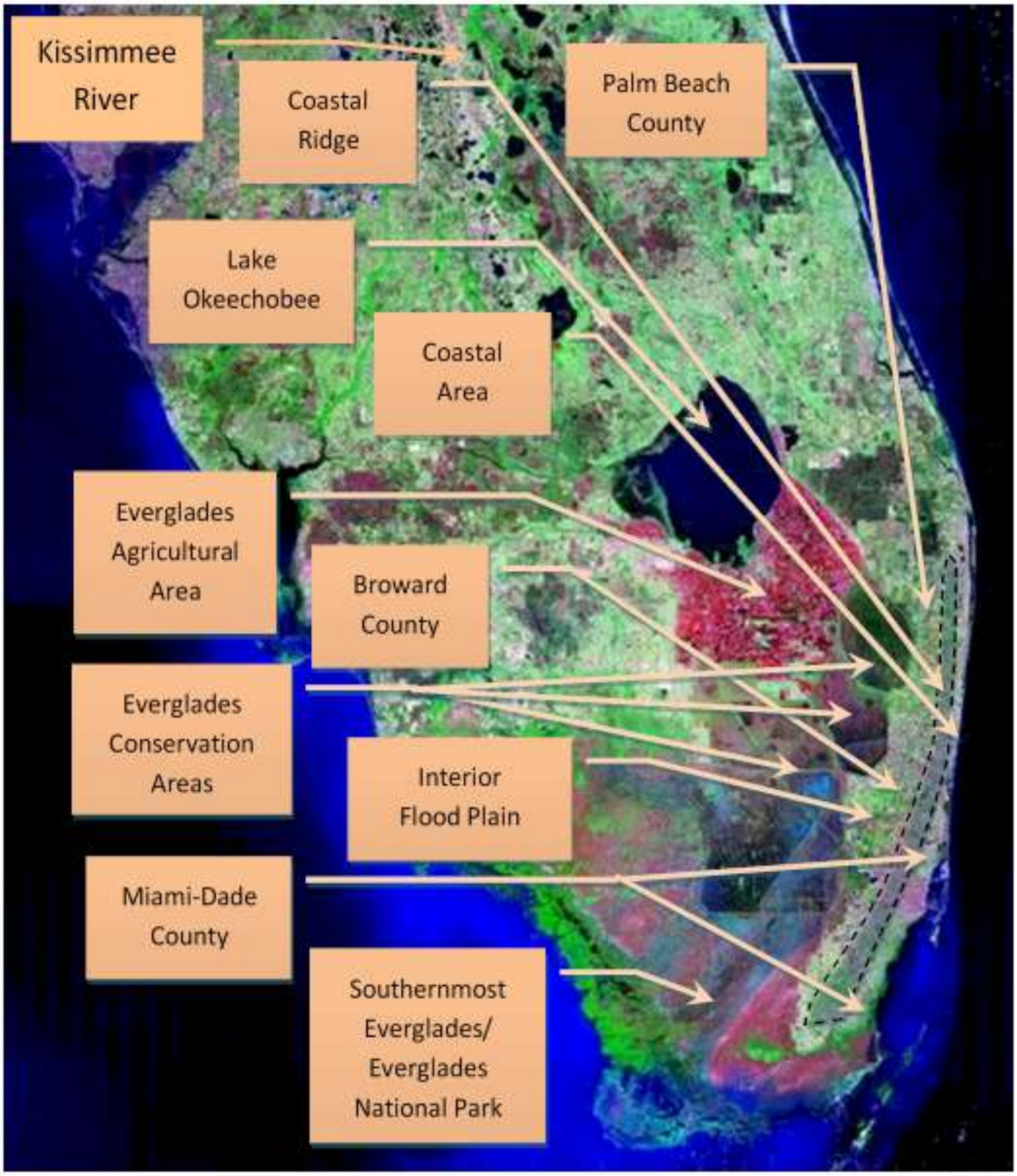

Figure 2 - South Florida's subtropical climate is strongly influenced by the surrounding waters and the interior Everglades. The Florida peninsula is surrounded by the Gulf of Mexico to the west, the Atlantic Ocean to the east and Florida Bay to the south. Lake Okeechobee to the north is fed by the Kissimmee River from central Florida. The Everglades is a wide, shallow river flowing south from the lake to Florida Bay and the Gulf. Annual rainfall averages approximately 60 inches.

Figure 3–A typical sunny winter day in Miami

2 Introduction

Southeast Florida is recognized as one of the most vulnerable regions of the world to the impacts of global climate change. Of critical concern is the potential threat that sea level rise and other impacts of climate change could have on Southeast Florida's water supply. This study is among the first to examine Southeast Florida's water infrastructure through the lens of climate change. It is hoped that it will heighten awareness to this critical issue, bring climate change to the forefront of water resource planning and policymaking, and stimulate new policy and planning for improving the resilience of Southeast Florida's water infrastructure to climate change.

This is the second of a series of studies concerning Florida's resilience to climate change conducted by the Center for Urban and Environmental Solutions (CUES) at Florida Atlantic University (FAU) sponsored by the National Commission on Energy Policy (NCEP). The first report published in 2008, entitled *Florida's Resilient Coasts – a State Policy Framework for Adaptation to Climate Change* (Murley, Heimlich, Bollman, 2008), presented a policy framework for improving the resilience of Florida's coasts statewide that was accepted as the foundation for recommendations on adaptation policy made by the Florida Governor's Action Team on Energy and Climate Change. (Florida Energy and Climate Change Action Plan, Chapter 8, 2008). The vulnerability of Southeast Florida's water supply was identified in that report.

There is strong evidence that global climate change is already impacting the world's water resources (Dragoni, 1998); (Buffoni, 2002); (Labat, 2004); (IPCC, 2007); (Huntington, 2006); (Dragoni & Sukhija, 2008). A critical concern for water managers is that climate change is altering the hydrologic cycle in ways that might not be readily predicted. In 2008, a coalition of eight leading national water management associations called upon the U.S. Congress to recognize the severe impacts of global climate change on water resources in the United States (AWWA, et al, 2008). The water organizations stressed that:

Figure 4 - A typical summer afternoon in Miami - thunderstorms forecasted

> *"Many of the most critical impacts of global climate change will manifest themselves through the hydrologic system, and there is already strong evidence that climate change is having an impact on the world's water resources. … Because the exact effects of climate change on water resources are uncertain and will vary by region, the drinking water, wastewater, flood management, and stormwater utilities responsible for managing water resources for local communities face daunting challenges."*

There is nowhere that these statements are more applicable than in Southeast Florida, the location of the Miami-Fort Lauderdale-West Palm Beach Metropolitan Statistical Area with a growing population of approximately 5.5 million (US Census, 2008). Its water supply is jeopardized by the anticipated effects of climate-change-induced sea level rise on the area's surface and ground waters, increased flooding due to hurricane storm surge and torrential rains, and prolonged periods of drought.

The impacts of climate change that are most likely to affect water supplies in Southeast Florida are: 1) uncertainty in the amount and timing of precipitation and 2) sea level rise induced effects on the area's surface and ground waters including saltwater

"Many of the most critical impacts of global climate change will manifest themselves through the hydrologic system, and there is already strong evidence that climate change is having an impact on the world's water resources. … Because the exact effects of climate change on water resources are uncertain and will vary by region, the drinking water, wastewater, flood management, and stormwater utilities responsible for managing water resources for local communities face daunting challenges. …"

Joint statement of eight leading national water management associations, May 20, 2008

intrusion and changes in flows and levels. Many regions, including Florida, will see wetter wet seasons and drier dry seasons (Karl, etal, USCCSP, & NOAA, 2009).

The Intergovernmental Panel on Climate Change 4th Assessment Report (IPCC, 2007) reported that

"Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, rising global average sea level, and acidification of the oceans."

The report indicates that it is "very likely," meaning with greater than 90% certainty; these changes in world-wide climate are due to rapidly increasing atmospheric greenhouse gas concentrations from the combustion of fossil fuels, deforestation, agriculture, and other anthropogenic activities. Average global temperatures could rise by several degrees Centigrade and the warming trend could last for centuries.

The United Nations Framework Convention on Climate Change (UNFCCC) will be held in Copenhagen in December 2009 to develop a global response to the threat of climate change and as a successor to the Kyoto Agreement, which is scheduled to expire in 2012. In anticipation of this convention, the International Alliance of Research Universities held an international scientific congress on climate change in Copenhagen from March 10-12, 2009. In its report issued in June 2009 (IARU, 2009), it stated,

"The scientific evidence today overwhelmingly indicates that allowing the emission of greenhouse gases from human activities to continue unchecked constitutes a significant threat to the well-being and continued development of contemporary society."

The report also stated in its *Key Message 1 - Climatic Trends*:

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"Recent observations show that greenhouse gas emissions and many aspects of the climate are changing near the upper boundary of the IPCC range of projections. Many key climate indicators are already moving beyond the patterns of natural variability within which contemporary society and economy have developed and thrived. These indicators include global mean surface temperature, sea-level rise, global ocean temperature, Arctic sea ice extent, ocean acidification, and extreme climatic events. With unabated emissions, many trends in climate will likely accelerate, leading to an increasing risk of abrupt or irreversible climatic shifts."

International Alliance of Research Universities

Synthesis Report, CLIMATE CHANGE: Global Risks, Challenges & Decisions

Copenhagen, 10-12 March, 2009

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Many of the effects of climate change in Florida are occurring gradually and are expected to worsen throughout the 21st Century. They are masked by the normal extremes of weather events and are difficult to differentiate from natural cycles. Long periods of time can lapse before underlying trends become evident, especially when incremental changes do not have an early detectable effect on everyday circumstances. Also, people tend to be reactive rather than proactive, especially when considering the possibility of uncertain future disasters. People are likely to at first deny or make excuses not to prepare adequately or are just slow to act. On the other hand, when disaster does strike, such as in the case of a major hurricane or flood, people are quick to react in order to recover and rebuild and prepare better for a possible recurrence, assuming that everything will return to normal and life can resume as before – i.e. the assumption of stationarity. Furthermore, it may be difficult to determine whether what has been considered a 100-year natural disaster has become a 25-year or 10-year event as a result of gradual changes in underlying climatic conditions. For example, if in the next 15 to 25 years, a 0.5^{o}F increase in sea surface temperatures coupled with a 6 inch rise in sea level takes place, it could result in a multifold increase in the probability of a Category 4 or 5 hurricane that could cause severe wind damage, storm surge that penetrates for miles inland, flooding that may overwhelm the region's stormwater drainage systems, temporary saltwater contamination of the water supply, and weeks-long power disruptions. Predictions are needed to ascertain the effects of climate change on the likelihood of such events. If increased risk can be established, it may be possible to justify precautionary adaptation modifications to the flood control system and other infrastructure in order to reduce the severity of property damage and personal injury in such a catastrophic event.

The region's geographic location, extremely low topography, porous geology, ground and surface water hydrology, subtropical weather patterns, and proximity to the ocean comprise an extremely complex and interactive system. Water managers must balance demands for potable water and agricultural and landscape irrigation with ground and surface water management, flood control, wastewater management, and the needs of the natural environment including the Everglades, the coastal and freshwater wetlands, and the coastal marine habitat, all of which are intricately linked through the hydrological cycle. The region's water supply is highly interdependent and interactive with the other elements of the region's water resources. A narrow focus on water supply in isolation would not suffice because the increased threat of flooding resulting from sea level rise, more intense rain events and hurricanes will have direct and indirect impacts on the water supply. Therefore, this report considers water supply resilience within the context of the entire hydrological system including the impacts of climate change on ground and surface waters and the reuse and discharge of treated wastewater.

2.1 Project Goals

This purpose of this study was to determine the likely effects of climate change on Southeast Florida's water resources and to identify engineering and management options for improving their resilience. The study set out to accomplish this by undertaking the following:

1. Gather the best available scientific and technical knowledge relating to the impacts of climate change on Southeast Florida's water supply and communicate it in language that can be understood by non-technical as well as technical people engaged in policymaking and management of the region's water resource.

2. Identify, discuss and prioritize relevant areas of concern, challenges, opportunities, solutions, policies, conclusions and recommendations through consultation with water experts, policymakers, and stakeholders.

3. Undertake a case study of a representative coastal city water utility in Southeast Florida in cooperation with its management and staff to gain insight into the issues facing local utilities and to exemplify application of the tools presented in this study. Determine the vulnerabilities of the utility to predicted climate change impacts and make specific recommendations for improving its resilience.

4. Propose an adaptation planning framework for protecting Southeast Florida's water supply from the unavoidable consequences of global climate change.

2.2 Methodology

The project goals were met through the use of three modes of research: 1) consultation with scientists and experts in fields related to water management, 2) literature research, and 3) the water utility case study. Scientists, water engineers, water managers, planners, and environmentalists from universities, engineering consulting firms, the United States Geological Survey (USGS), the South Florida Water Management District, local governmental agencies, water utilities, and drainage districts were consulted to gather information and their opinions, concerns, questions, recommendations, and collective wisdom on climate change and the water supply. These discussions were confidential, open-ended, and without preconceptions in order to discover both expected and unexpected issues and concerns. The specific content of disclosures made by each expert is not revealed in this report except for citations of selected published literature, internet postings, and public presentations. The collective disclosures and opinions of the experts and reviewers of the draft report were used in deriving the authors' conclusions, recommendations, and opinions, which are those of the authors and do not necessarily reflect the opinions of participating experts or reviewers. Experts and reviewers are listed in Appendix B.

Consultations with experts were supplemented with literature research. The literature search focused on 1) applicable science and technology, 2) potential impacts of climate change on Southeast Florida water supply, 3) applicable water laws and policies, and 4) approaches to water supply resilience taken in other regions. Although the literature search was extensive, it should not be regarded as exhaustive.

A Case Study of the City of Pompano Beach Water Treatment Utility was conducted by Frederick Bloetscher, Ph.D., P.E., and Daniel Meeroff, Ph.D., E.I. both members of the faculty of FAU's Department of Civil, Environmental, and Geomatics Engineering. This utility was chosen for several reasons. It employs state-of-the-art water treatment, alternative water supply, and water reuse technologies. It is located near the coast and has a skilled and experienced technical management team whose input contributed materially to the study. The utility's eastern wellfields are vulnerable to saltwater intrusion. It is undertaking studies of advanced methods including wastewater reuse and recharge and hydrological barriers to protect its raw water supply. USGS and the Broward County Environmental Protection and Growth Management Department have developed a hydrological model of the North Broward area, which the utility is using to guide its alternative water supply projects. The utility's management and others provided input and ideas and reviewed the results of the Case Study.

Figure 5 - Miami Beach – Hibiscus (foreground) and Palm Islands are manmade islands in Biscayne Bay. Living on the edge.

The Case Study set out to: 1) determine utility-specific vulnerabilities of its water supply and its facilities to climate change, challenges, opportunities, solutions, conclusions and recommendations; 2) conduct an engineering assessment of current operating strategies, 3) recommend improvements to resilience to the utility's water supply and its facilities with associated capital investments and operating cost estimates; and 4) present generalized methodology and recommendations that other water treatment facilities in Southeast Florida and elsewhere might be able to use as a guide.

3 Southeast Florida's Topography, Geology, Climate, and Hydrology

3.1 Topography

Figure 6 - Topography of the Florida Peninsula showing that most of South Florida south of Lake Okeechobee is at very low elevation. (USGS)

In order to understand the subject matter of this report, it is necessary to first be familiar with the unique characteristics of Southeast Florida's topography, geology, and hydrology, i.e., the flow characteristics of groundwater and surface water. Figure 6 is a topographic (relief) map of the Florida Peninsula bounded by 25° and 30° north latitude and 80° and 83° west longitude. What is striking about this map is that there is no discernable relief south of Lake Okeechobee, i.e. the land is virtually flat. In fact, almost all of the land is at elevations of less than 15 feet elevation and much of it is less than 3 meters (10'). Also, the peninsula is surrounded by the warm waters of the mid-Atlantic Ocean on the east and the Gulf of Mexico on the west. Down the middle of South Florida from Lake Okeechobee to Florida Bay is the Everglades, mostly a freshwater marsh –actually a very shallow, broad river that dominates the watershed and is a major source of recharge water for the Biscayne Aquifer, Southeast Florida's primary water source.

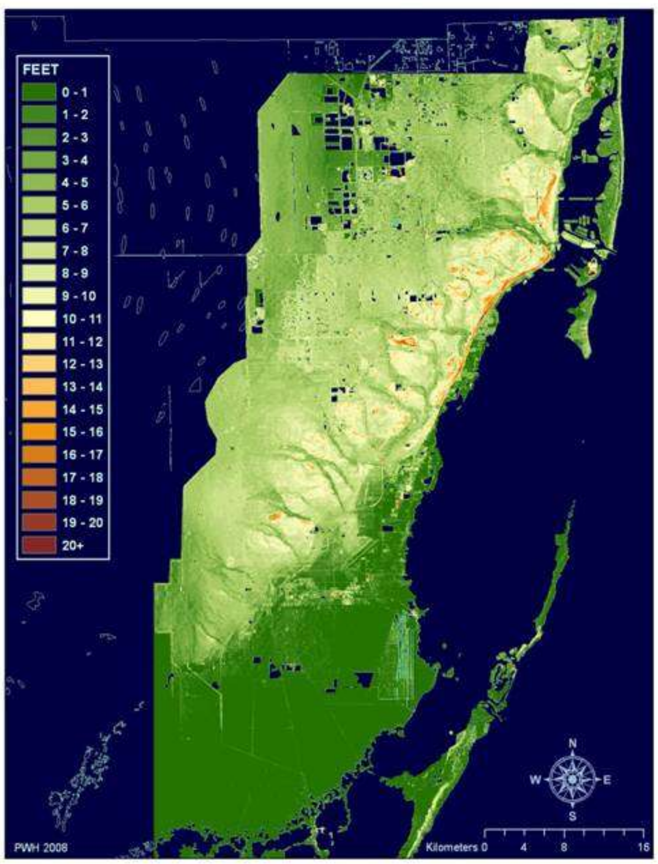

Figure 7 - Preliminary LIDAR map of Miami-Dade County illustrates elevations above sea level (NAVD 88). Areas up to 4 to 5 feet shown in shades of dark green could be at risk of serious flooding as sea level rises. (Harlem, 2009)

In 2008, LIDAR (Light Detection and Ranging) elevation data were obtained for most of the urban areas of Southeast Florida. The Geographic Information Systems (GIS) departments of the county governments are developing high resolution elevation maps using these data and will also overlay them with various datasets of infrastructure, roads, developments, water tables, and other features. Preliminary LIDAR map of Miami-Dade County in Figure 7 illustrates elevations above sea level (NAVD 88). Areas up to 4 to 5 feet shown in shades of dark green could be at risk of serious flooding as sea level rises. As shown in Figure 8 approximately 29% of urban Broward County is below 5 feet elevation (in purple). These maps illustrate how flat and low Southeast Florida is and how vulnerable it is to sea level rise.

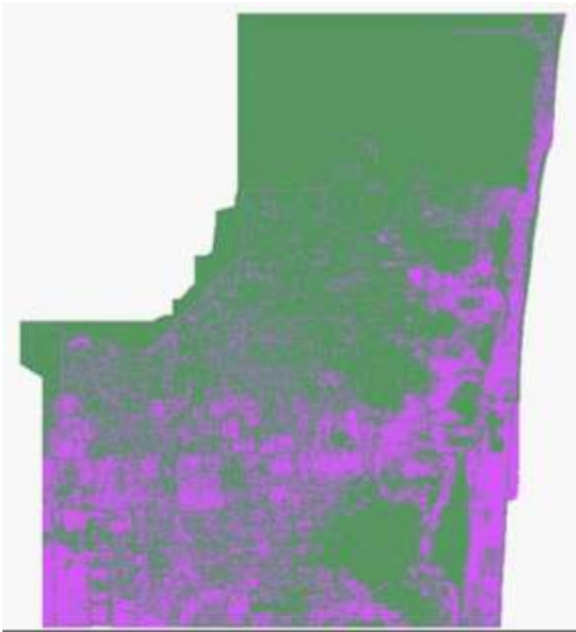

Figure 8 - Approximately 29% of Broward County is less than 5 feet above current sea level, shown in purple, based on LIDAR topographical data. (Source: Broward County GIS)

3.2 Geology

South Florida's geology is dominated by shallow surficial aquifers as shown in Figure 9. Substantially all of Southeast Florida from its southern tip northward to just south of West Palm Beach sits on the Biscayne Aquifer. This is one of the most productive freshwater aquifers in the world due its high porosity, transmissivity, and heavy rainfall that falls on Southeast Florida (55 to 60 inches annually). The land is primarily made up of porous sand and limestone enabling rain to rapidly percolate through the ground to the permeable porous limestone aquifer. The surficial aquifers are also are fed by the Everglades and Lake Okeechobee.

The geology of the region is represented in simplified form in Figure 10. Southeast Florida obtains most of its water supply from the extremely porous and transmissive Biscayne Aquifer, which is located directly under the land surface and is wedge-shaped from the Everglades in the west to the Atlantic Ocean to the east, where it is between about 80 and 240 thick (Also see Figure 43 on page 45). Water from the Biscayne Aquifer is generally of good quality due to the natural filtration and purifying properties of the aquifer. Groundwater drawn from the western parts of the urban areas is high in tannins and other organics present in water derived from the Everglades. These can be readily removed by carbon filtration and chemical treatment. Water drawn from wells to the east of the coastal ridge is generally of better color and quality overall. For that reason, utility directors prefer to use water

Figure 9 - Aquifers of the lower Florida peninsula. (USGS)

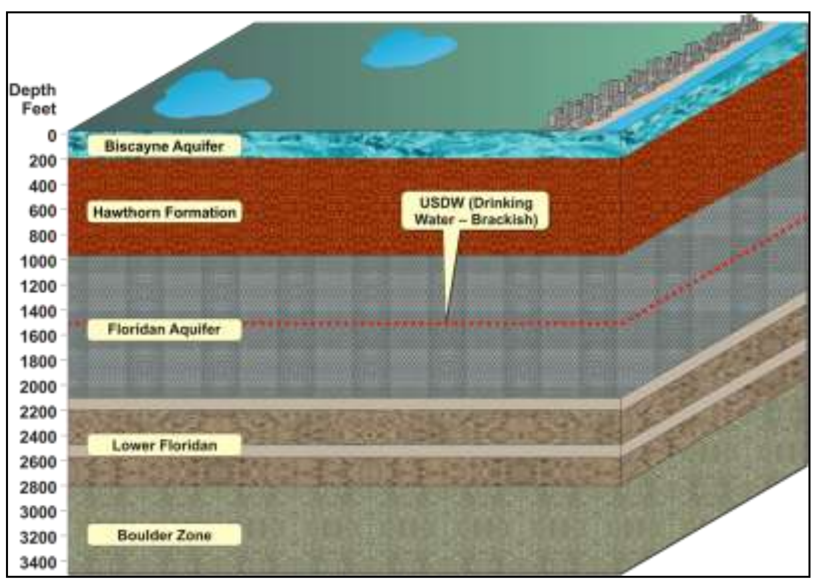

Figure 10 - The Biscayne Aquifer is a surficial aquifer bounded beneath by semi-confining clay called the Hawthorne Group. Below that is the Floridan Aquifer, the Lower Floridan, and the Boulder Zone. (SFWMD)

from easterly wells where possible.

The Biscayne is an unconfined coastal aquifer, meaning that it is open to the surface and the ocean as shown in Figure 11. It is composed mostly of highly porous karst limestone (See Figure 12). Water flows through the aquifer to the ocean and pushes against and mixes with saltwater in what is called the "zone of dispersion" or the "intrusion zone." Since seawater is about 2.5% denser than fresh water, fresh water tends to flow above the seawater forming a wedge as illustrated. The position of the zone of dispersion is a function of the rate of fresh water flow which in turn is affected by the amount of rainfall, the height of the water table relative to sea level, and the amount of water withdrawn from the aquifer for urban consumption, landscape irrigation and agricultural use.

Because of the low elevation of the land, the water table, i.e. the upper surface of the groundwater in the Biscayne Aquifer, is often within a few feet below the surface. The area is honeycombed with natural and manmade lakes, ponds, wetlands, rivers and canals, the surface of which provides a ready indicator of the water table because of the high porosity and transmissiveness of the land and the aquifer. Generally, wherever a hole or trench is dug in Southeast Florida, if deep enough to penetrate the water table, water fills it at approximately the level of the water table. In the urban areas, ground water levels are generally 3 to 5 feet below their historic levels due to the effectiveness of the stormwater drainage system consisting of levees, canals, and control structures. In the Everglades Conservation Areas, west of the levees and control structures that separate them from the urban areas, water is above ground for a significant part of the year.

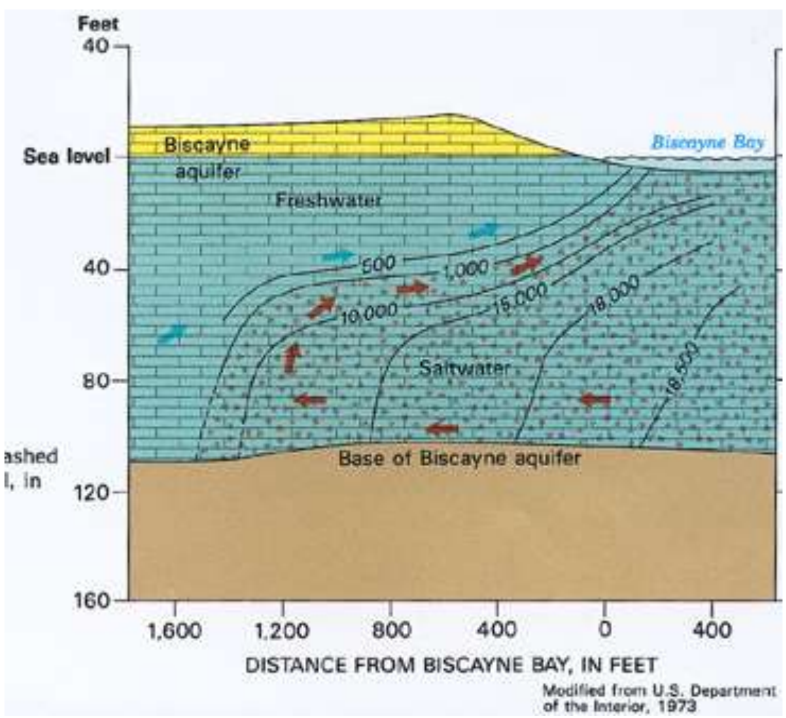

Figure 11 - The Biscayne Aquifer is unconfined and open to the Atlantic Ocean. Lines is equal chloride concentration (isochlors) are shown. Numbers are in mcg/ml. (USGS)

Figure 12 -Biscayne Aquifer is a karst formation with high porosity and variability. (D. McNeill, U. Miami)

Because of the low elevation, proximity to the ocean, high rates of rainfall throughout the peninsula especially during the summer rainy season, the landscape has been highly engineered for stormwater drainage to control flooding. In Broward County alone, there are over 1800 miles of canals.

Beneath the Biscayne Aquifer, is a thick, semi-confining clay layer known as the Hawthorn Formation. The Hawthorn Formation acts as a barrier layer between the fresh water of the Biscayne Aquifer and the brackish water of the underlying Floridan Aquifer.

The top of the Floridan Aquifer in South Florida (Meyer, 1988) occurs at depths of 500 to 1000 feet and averages 3,000 feet in thickness. It is an artesian continuation of the surficial aquifer in central and northern Florida. It is composed mostly of carbonate rocks and is divided into three hydrogeologic layers called the Upper Floridan, the middle confining unit, and the Lower Floridan. The brackish Upper Floridan Aquifer is a secondary raw water source for Southeast Florida that is being used increasingly with the aid of reverse osmosis purification to meet increasing demand related to population increases. The middle confining layer contains salty water in a low permeability layer, and the Lower Floridan contains essentially seawater.

Below the Floridan Aquifer is a hydrogeologic feature called the Boulder Zone, a thick, highly cavernous and permeable limestone and dolomite formation containing highly mineralized water with little artesian pressure. It is now used as a major underground depository for disposal of treated wastewater.

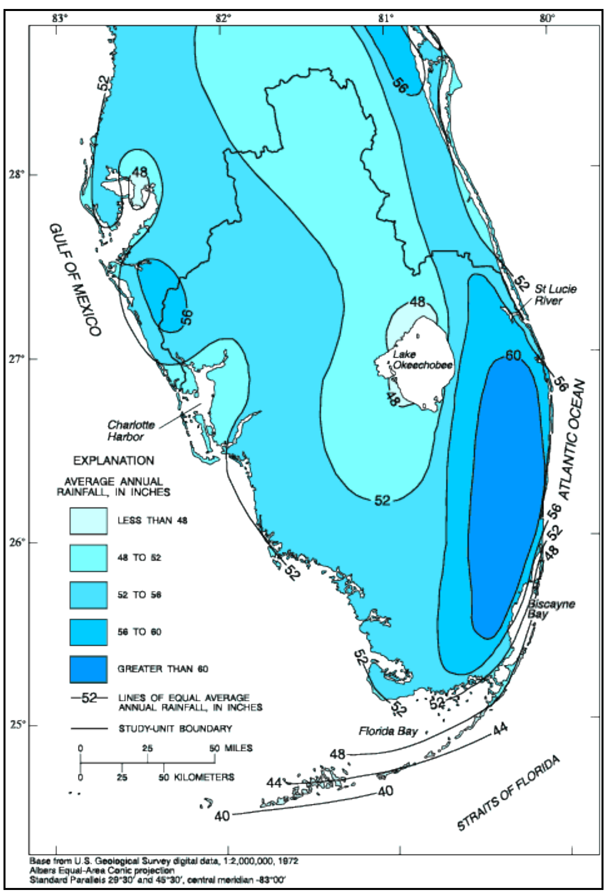

Figure 13 - Southeast Florida receives approximately 60" of rain per year. (USGS)

3.3 Climate

Southeast Florida enjoys a subtropical climate with warm, dry, sunny winters and spring followed by hot, humid, and wet summers and autumns. Southeast Florida's climate is strongly influenced by the Gulf of Mexico, the Caribbean Sea and the Atlantic Ocean, which contribute significant moisture that results in substantial rainfall, high humidity, and moderate winter temperatures (Twilley, 2001).

3.3.1 Rainfall Patterns

Southeast Florida receives on average approximately 60 inches of rain annually of which about 70% occurs during the rainy season. The rainy season lasts from mid-May through late November. During the rainy summer season, average lows range from about 70° F to 75° F and highs range from about 85° F to a relatively tepid 92° F considering how far south it is. Figure 15

Figure 14 - Large thunderstorms frequently develop over the Everglades in the summer. This photo shows a typical super cell over the sugarcane fields of west Palm Beach County in August. (Photo: B. Heimlich)

illustrates the seasonality of temperatures and rainfall. Summer temperatures are moderated by the southeasterly sea breezes, frequent rain, and cloudiness. At this time of year, the heat index is high due to temperatures in the low 90s and high humidity. There are afternoon thunderstorms on most days and occasional torrential rains associated with hurricanes and tropical waves, depressions, and storms. The dry season lasts from December through early May. During the dry season, average low temperatures range from about 55°F to 70°F and highs average from about 75°F to 85°F with infrequent cold snaps when northern winter cold fronts are strong enough to push through. South Florida's famous winter weather explains why it is an important winter tourist destination and why so many people have winter homes or retire in the area. Rainfall is a fraction of the amount received during the rainy season. Meeting year-round demand for water is a significant challenge to South Florida's water managers. The region's highly seasonal rainfall pattern and limited opportunity for surface water storage because of the flat topography create the problem of balancing water supply and demand. This is offset by the high storage capacity of the Biscayne Aquifer and the Everglades. Further, Southeast Florida's extensive system of manmade, canals, retention ponds and lakes, besides providing flood control, also provides capacity for shallow surface water storage. But the storage capacity of the aquifer is limited by potential flooding of low-lying terrain. With the most active portion of the hurricane season occurring towards the

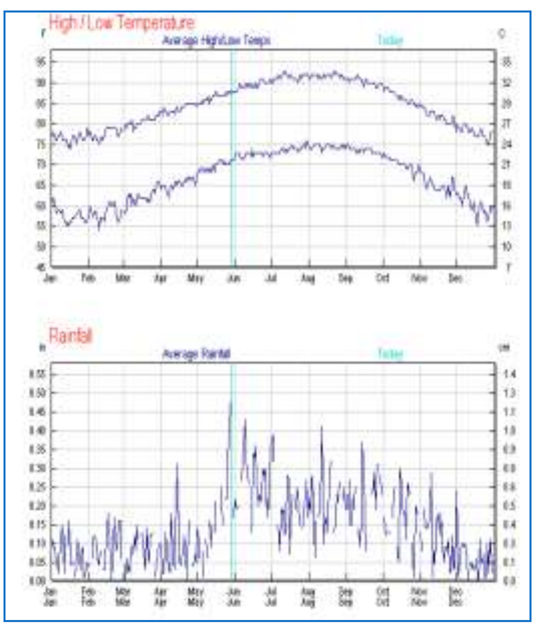

Figure 16 - Southeast Florida rainfall pattern is highly seasonal with relatively dry winter and spring and rainy summer and autumn. Approximately 70% of its rainfall occurs during the rainy season. (SFWMD)

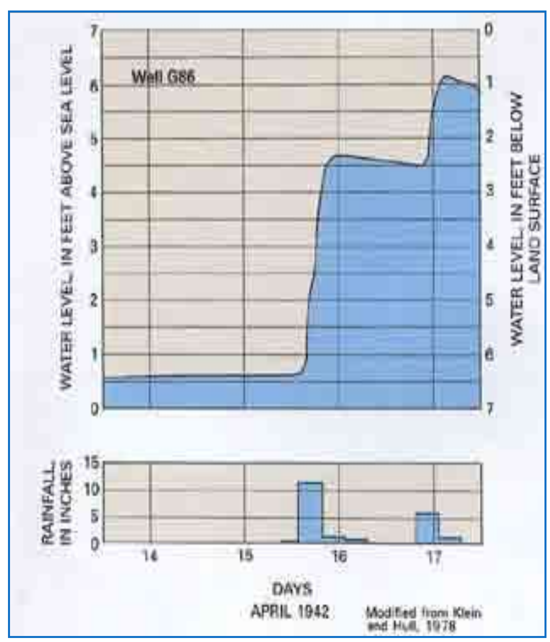

Figure 15 - Water table in Biscayne Aquifer responds rapidly to rainfall. (USGS)

end of the wet season, water managers' efforts to end the wet season with high ground water levels to maximize storage for the dry season represent a significant risk when late season storms develop.

The length of the rainy season is influenced by the location and relative strength of the Bermuda High pressure systems during the summer (Twilley, 2001). If the Bermuda High remains strong in the summer, the wet season is delayed and there is drought. The Bermuda High is small and located to the south and east of Florida during the winter. In the spring, it expands and moves northward.

The El Niño/Southern Oscillation (ENSO) has significant influence on Florida's climate. El Niño episodes feature the development of abnormally warm sea-surface temperatures across the eastern tropical Pacific. This is the opposite of the normal condition when the warmest waters are in the western Pacific. During La Niña episodes, there are abnormally cold sea-surface temperatures across the eastern tropical Pacific. El Niño is associated with significant shifts in the position of the jet stream over North America and elsewhere. El Niño significantly decreases temperatures in winter and spring in Florida. During La Niña, warmer temperatures during fall and winter seasons in the Gulf region followed by higher than average temperatures in summer often contribute to regional drought. ENSO events also strongly influence the number of hurricanes in the North Atlantic Basin. During La Niña events, the average number of hurricanes making landfall in Florida and the Gulf Coast is typically higher than during El Niño years (Twilley, 2001).

As will be discussed later, climate change is expected to exacerbate the seasonal variability of Southeast Florida's rainfall, with more extended and dryer dry seasons and shorter wet seasons with more intense rain events.

3.3.2 Hurricanes

Southeast Florida is extremely vulnerable to hurricanes and tropical storms. Florida, with 1350 miles of coastline on the subtropical, hurricane-prone mid-Atlantic Ocean and Gulf of Mexico, experiences more landings of tropical storms and hurricanes than any other state in the United States, and Southeast Florida's location exposes it to an above average share of hurricane landfalls. Florida was battered by 7 hurricanes during the hurricane seasons of 2004 and 2005 resulting in $56 billion in property damage statewide. Of these, 4 passed through Southeast Florida: Hurricanes Frances and Jeanne in 2004, and Hurricanes Katrina, and Wilma in 2005. In 1992, Hurricane Andrew made landfall in Miami-Dade County as a Category 5 storm with sustained winds exceeding 155 mph.

Figure 17 - Hurricane Jeanne, 2004 (NHC)

In the North Atlantic Basin the annual hurricane season starts on June 1 and extends through November. The most active period of tropical cyclone activity is from mid-August through mid-October and it peaks sharply in September as shown in Figure 18. Monthly averages since 1995 have increased above the averages since 1950 in every month and 2008 was a particularly very active year. This is consistent with a worldwide increase in tropical cyclone activity in recent years. (Holland, 2007). Florida, unlike Texas and Louisiana, was spared in 2008 except for a very rainy Tropical Storm Fay, which provided relief from what otherwise had been an extreme drought which persisted from 2006 until the spring of 2009.

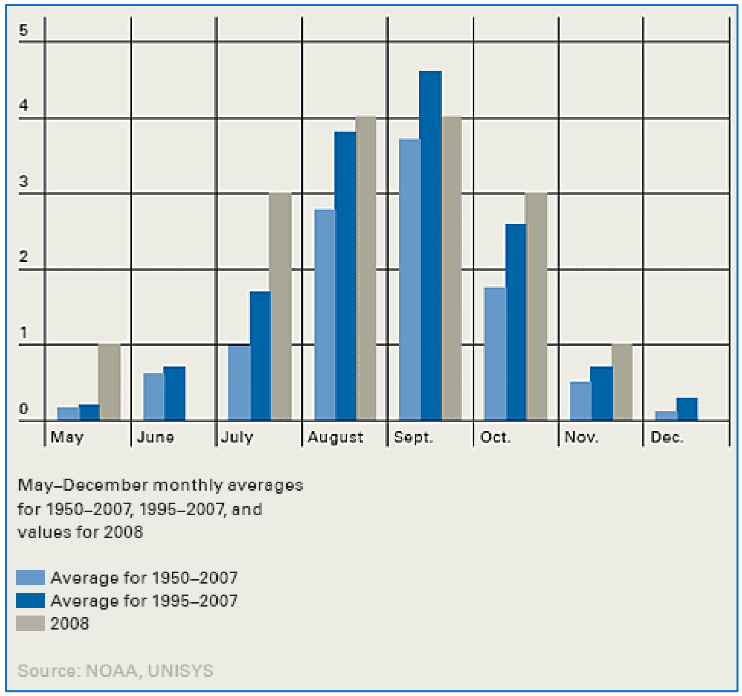

Figure 18 - Monthly average number of hurricanes. (NOAA)

What effects climate change may have on the extent, frequency, and intensity of hurricanes and tropical storms in the North Atlantic Basin is a subject of intensive research and vigorous debate. According to IPCC 2007, tropical cyclone activity in the North Atlantic basin may extend further north, storm frequency may decline slightly due to more intense wind shear in the mid-Atlantic, but a higher percentage of storms may be more intense as a result of higher sea surface temperatures resulting from global warming.

3.4 Hydrology

Groundwater generally flows from the Everglades southeasterly to the Atlantic Ocean through the Biscayne Aquifer as shown in Figure 19. Billions of gallons of water flow daily through the surficial aquifers from the Everglades to the ocean.

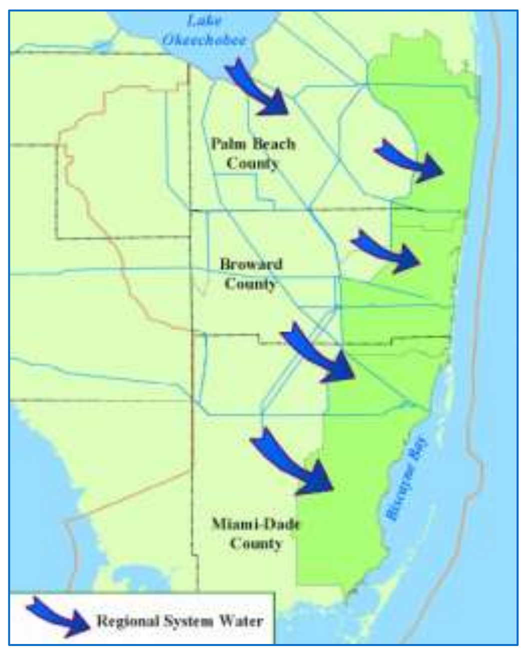

Figure 19 - Billions of gallons of water flow daily through the surficial aquifers from the Everglades to the Atlantic Ocean. (Graphic: SFWMD)

3.4.1 Hydrological Model

Figure 20 provides a simplified illustration of Southeast Florida's urban hydrology and the various processes affecting Southeast Florida's water supply. Fresh groundwater flows laterally through the Biscayne Aquifer. The aquifer is recharged by percolation of rainwater through the porous soil. Nearly half of average annual rainfall is lost by evapotranspiration (labeled "ET"). Freshwater withdrawals from wellfields in the Biscayne Aquifer are the primary source of potable water. Rainfall, irrigation, surface water in canals and ponds, and groundwater inflow from the Everglades recharge the aquifer. Treated wastewater is currently discharged to ocean outfalls or by deep well injection into the Boulder Zone, shown in Figure 10. A small but increasing amount of treated wastewater is being reused for irrigation and industrial cooling.

Prior to land development during the 20th Century, most of the land west of the coastal ridge was originally part of the Everglades. The low-lying floodplains to the west of the coastal ridge have been drained by an elaborate network of canals, shown in Figure 21, enabling land use for agriculture and urban development. The flood control system enables control of the water table and stormwater drainage during heavy rainfall and major storms including hurricanes. The water table, i.e. the upper surface of the groundwater in the Biscayne Aquifers, is only a few feet below the surface in the low elevation floodplains.

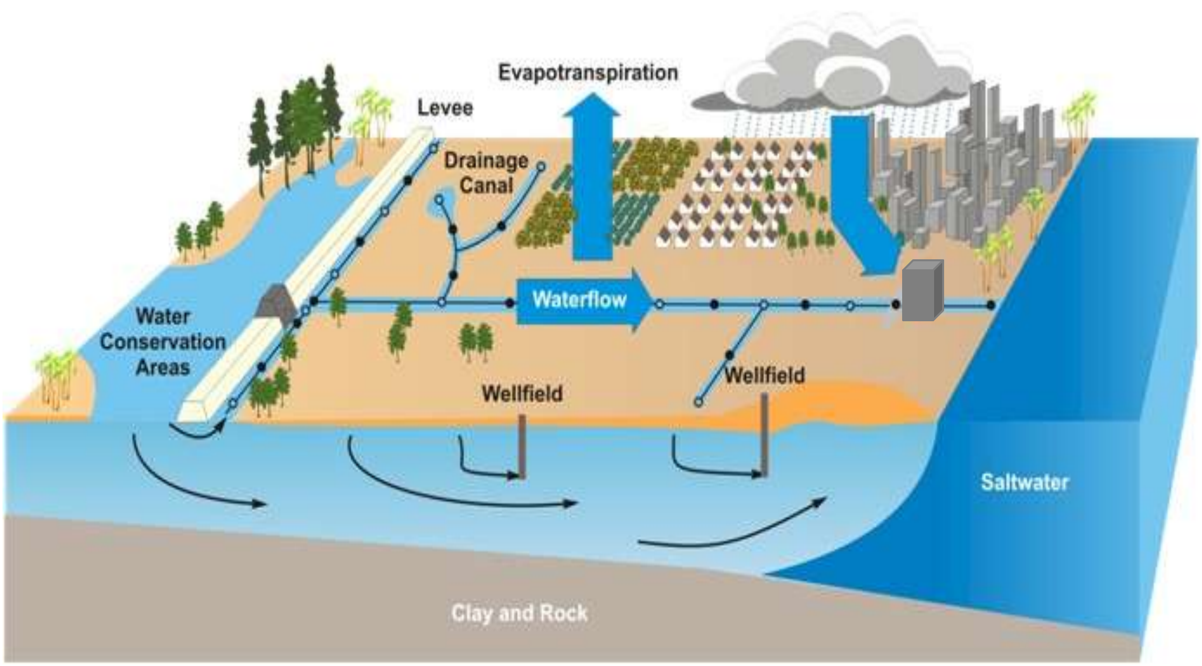

Figure 20 - Schematic model of Southeast Florida's hydrology. Billions of gallons per day of fresh water from rainfall and the Everglades flow through the Biscayne Aquifer, the primary source of potable water. Stormwater drainage canals enabled recovery of land that was originally Everglades marshland for urban development and agriculture. (SFWMD)

Figure 21 - The urban area is separated from the Everglades Water Conservation Areas by a levee. A seepage canal captures water the seeps under the levee. Drainage canals throughout the urban area maintain water tables and control flooding.

Control structures along the levees separating the Everglades from the urban area are used to control flow of surface water from the Everglades Water Conservation Areas (WCAs). Salinity or flood control structures near the coast are used to control levels in the primary drainage canals, which in turn control the water table. Groundwater flow is driven by rainfall and higher water surface elevation in the Everglades WCAs. The water table is held at about 3 to 5 feet above sea level where possible to provide the head necessary to assure groundwater flow and to prevent saltwater intrusion. As sea level rises, this stepwise hydraulic gradient will be reduced, lowering surface water drainage capacity and groundwater flow, which is likely to increase the risk of flooding, as will be explained in Section 4.1.2.

Seepage canals run along the urban side of the levees separating the Everglades WCAs from the urban area, as illustrated in Figure 22. Their purpose is to capture water that seeps under the levees. This water is either pumped back to the Everglades or flows to drainage canals to recharge the aquifer or discharged to tide.

As the groundwater flows easterly and approaches the coast, it mixes with seawater. As was illustrated in Figure 11, the zone where fresh water and seawater mixing occurs is called the "zone of dispersion" or the "saltwater intrusion front." When the rate of water flow through the Biscayne Aquifer decreases, the saltwater front moves inland. This phenomenon is called "saltwater intrusion." Conversely, when water flow increases, the saltwater front moves seaward, although this is a slower process than intrusion. The amount of water

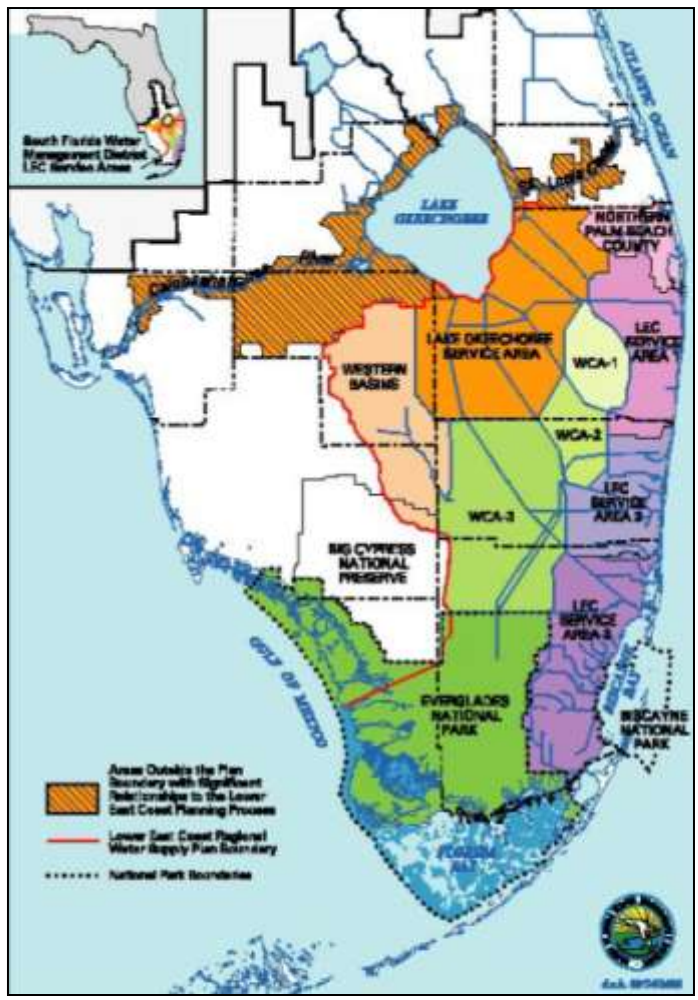

Figure 22 - SFWMD Lower East Coast Planning Area showing the network of primary canals used for flood control. (SFWMD)

flowing depends upon the amount of recharge from rainfall, groundwater flowing from the Everglades, wastewater reuse, urban water withdrawals, and other variables, as will be discussed later.

3.4.2 Water Budget

Figure 23 shows estimated water budget from Broward County's Integrated Water Resources Plan (Broward County IWRP, 2008) in billions of gallons of water per 100 square miles per year (BGY/100sq.mi.). These numbers are estimated averages of where the water comes from and where it goes for years 1965-2000.

1. Rainfall averaged 99 BGY/100sq.mi.(57 inches/year) or approximate 1 billion gallons per square mile per year.
2. Of this, 40 BGY/100sq.mi.(25 inches/year) were lost by evapotranspiration from landscaping and agriculture irrigation.
3. The remainder of 59 BGY/100sq.mi. (32 inches/year) recharged the aquifer and was added to 21 BGY/100sq.mi. (12 inches/year) of lateral seepage from the Everglades plus 5 BGY/100sq.mi. (3 inches/year) recovered from landscape irrigation, which totals 85 BGY/100sq.mi. (47 inches/year) of raw water available.
4. Of this, about 26 BGY/100sq.mi. (12 inches/year) were withdrawn from the aquifer by the water treatment plants for municipal use, of which 21 BGY/100sq.mi. (9 inches) goes for human consumption and 5 BGY/100sq.mi. (3 inches/year) for landscape irrigation, which recharges the aquifer. The 21 BGY/100sq.mi. consumed for potable use is discharged as treated waste and is either injected into the deep boulder zone or sent to ocean outfalls. The small amount returned

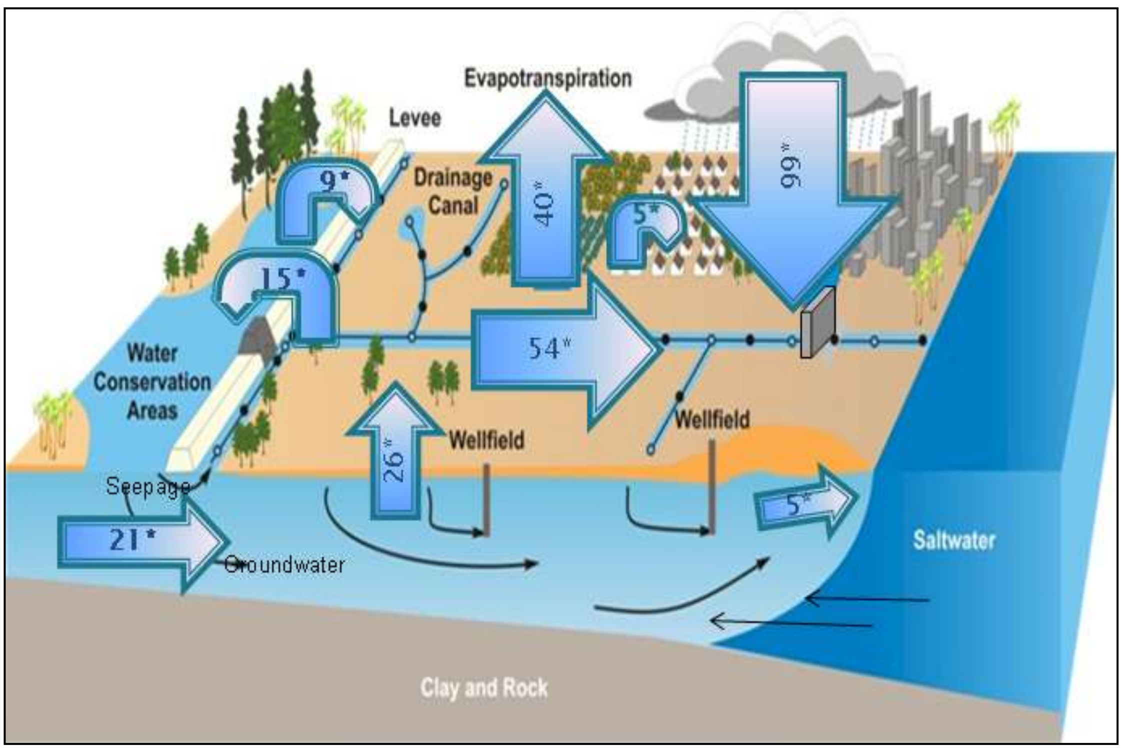

Figure 23 - Schematic water balance model (1965-2000 annual avg.). Based on data from Broward IWRP (2008).

to the groundwater from septic tanks was not considered in this analysis.

5. Seepage to the ocean from the aquifer is estimated to be 5 BGY/100sq.mi. (3 inches/year). The basis for this value could not be ascertained as of this writing, but it is a very critical value because hydrostatic backpressure due to sea level rise can dramatically affect groundwater flow to the ocean. This value is 10% of 54 BGY/100sq.mi. (31 inches/year) discharged to the ocean via the primary canal flood control system. The effect fo sea level rise on groundwater flow to the ocean relative to surface water flow via the canals is very important and will be discussed in Section 4.2.2.
6. The remaining 57 BGY/100sq.mi. (32 inches/year) plus 8.7 BGY/100sq.mi. (5 inches/year) drainage from the Everglades plus 3.5 BGY/100sq.mi. (2 inches/year) surface water runoff from rainfall is discharged from the urban area. At the time of that study, 13.9 BGY/100sq.mi.(8 inches/year) were pumped back to the Everglades water conservation areas and 54 BGY/100sq.mi. (31 inches/year) was sent to tide. In recent years, discharge to the Everglades water conservation areas has been greatly reduced to reduce phosphorus contamination. This water is now also released to tide with the help of modifications to the stormwater drainage system.

These values are summarized in Table 1. As stated before, annual rainfall in Southeast Florida is approximately 1 billion gallons per square mile. Almost 2 trillion gallons of rain falls annually on the approximately 1800 square miles of total urban area in Miami-Dade, Broward, and Palm Beach Counties.

Table 1 - Water balance based average inches rainfall per year 1965-2000, (Broward County IWRP, 2008)

Aquifer Water Budget	Flow in	Flow Out	Flow in	Flow Out
	inches/year		BGY/100 sq.mi.*	
Annual Rainfall	57		99.1	
Everglades seepage to aquifer	12		20.9	
Pumpage to Canals from WCA	5		8.7	
Irrigation recharge	3		5.2	
Surface water runoff to canals	2		3.5	
Evapotranspiration		25		43.5
Pumpage to WCA		8		13.9
Groundwater seepage to tide		3		5.2
Municipal withdrawals		12		20.9
Canal discharge to ocean		31		53.9
Totals	79	79	137.3	137.3

*** BGY/100sq.mi. = billions of gallons per year per 100 square miles.**

Lake Okeechobee, which is northwest of Palm Beach County, is the only body of fresh water having substantial holding capacity and it serves as the primary backup water supply for Southeast Florida. The lake itself covers approximately 730 square miles (SFWMD, 2009), which makes it the second largest freshwater lake wholly contained within the United States. With an estimated average depth of 9 feet (SFWMD, 2009), it has an average volume of over 1 trillion gallons, approximately half of the annual rainfall on the tri-county urban area. Recharge is provided from rainfall across a watershed including the Kissimmee River and Fisheating Creek that is approximately 6 times the area of the lake itself. Assuming that average annual rainfall is 1 billion gallons per square mile, there is over 4 trillion gallons of rainfall on the watershed feeding Lake Okeechobee. The Everglades add another ___ square miles and approximately ___ trillions gallons of rainfall annually.

Large areas of the northern Everglades have been developed as "stormwater treatment areas" (STAs). STAs provide storage, retention and water quality treatment for runoff from the Everglades Agricultural Area (EAA) south of Lake Okeechobee. The EAA is an area of intense sugarcane production. Figure 2 is a map showing these areas.

3.4.3 Stormwater Drainage System

South Florida's landscape has been changed dramatically by construction of its elaborate system of canals, dikes, levees, flow control structures, pumps, and other water control facilities. These changes in the landscape allow Southeast Florida to be one of the largest metropolitan areas in the United States.

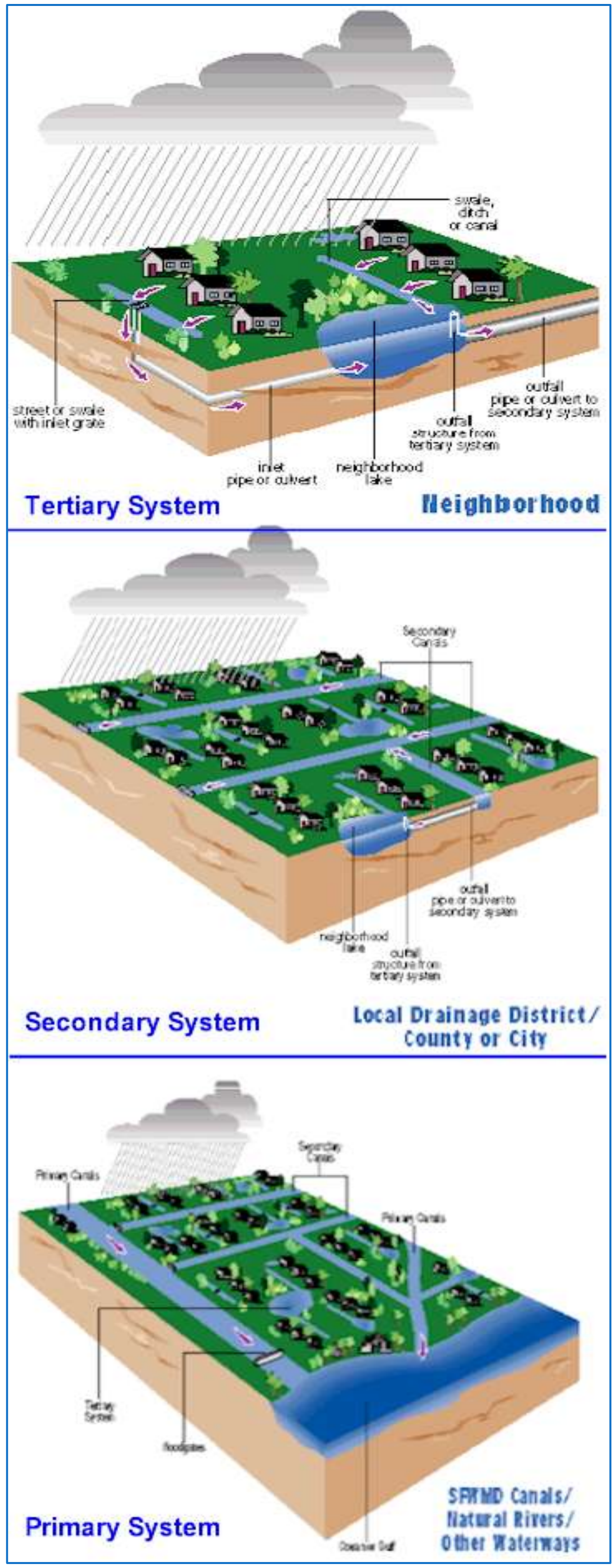

Figure 24 - Southeast Florida's extensive stormwater drainage system is indispensible to its habitability. (Image credit: SFWMD)

As illustrated in Figure 24, Southeast Florida stormwater drainage system is comprised of primary, secondary, and tertiary canals and numerous control structures and other elements. Stormwater is collected locally in neighborhoods in swales, ponds, small lakes, ditches and small canals as shown in the upper diagram to the right. These are connected through canals and conduits to the secondary system under the jurisdiction of local drainage districts or city or county governments. This system of mid-sized canals and control structures, as shown in the center diagram of Figure 24, control the retention and release of stormwater to the primary system. The primary system, shown on the bottom diagram of Figure

24, is operated by the South Florida Water Management District (SFWMD). Levels and flows in the primary canals are controlled using flood control structures, which also serve as salinity barriers that keep tidal water from flowing inland. By maintaining the highest water table levels possible that are consistent with adequate flood control, saltwater intrusion is minimized. Fresh water is conserved by releasing as little fresh water to tide as possible. During periods of excessive rainfall or in anticipation of major rainstorms or hurricane landfall, levels in the canals and the water table are lowered to increase stormwater storage capacity. The performance of the stormwater drainage system may be adversely affected by sea level rise, as will be discussed in Sections 4.2.2 and 4.2.3.

Figure 25 - Broward County has over 1800 miles of canals used for stormwater drainage, water storage, aquifer recharge, and to convey water where needed.

These canal systems serve several important purposes: 1) flood control, 2) stormwater storage, 3) aquifer recharge, 4) water table level control, and 5) conveyance of water from areas of high local rainfall to areas where rainfall was less during any given time interval. Because rainfall in Southeast Florida comes primarily as localized showers and thunderstorms, the ability to convey water is important to optimizing water table levels throughout the region. Broward County, for example, has an extensive system of over 1800 miles of secondary and tertiary canals, as illustrated in Figure 25. Not only are these systems highly efficient for stormwater drainage, collectively they serve as a reservoir of significant capacity and a major facilitator of aquifer recharge.

Significant ecological damage was done by diverting so much water for municipal and agricultural supply and flood control purposes away from the southern Everglades including Everglades National Park. In order to rectify this situation, the State of Florida and the federal government have joined forces to bring about the largest environmental restoration project in world history - the Comprehensive Everglades Restoration Plan (CERP) (SFWMD, 2009). The purpose of CERP is to "get the water right" – improving the quality, quantity, timing, and distribution of water in the Everglades while providing water supply needs and flood control to urban Southeast Florida.

4 Climate Change Impacts on Southeast Florida's Water Resources

Increasing concentrations of greenhouse gases, especially carbon dioxide, methane and nitrous oxide, absorb increasing amounts of solar energy in the atmosphere. As a result, temperatures worldwide are increasing at an unprecedented rate and this in turn is causing rapid changes in climate globally. The consequences are that the atmosphere is warming globally and in turn is warming the oceans, melting ice fields and glaciers, and causing other climatic effects. After several millennia of stable sea levels prior to the 20th Century, sea levels have been rising at accelerating rates due to thermal expansion of the oceans and runoff from ice melt. The early impacts of climate change have begun to adversely affect the world's freshwater resources. Table 2 summarizes the potential impacts of climate change in Southeast Florida, the likely effects on its water resources, and other major effects.

Table 2 - Summary of Climate Change Impacts on Southeast Florida's Water Resources

Climate change impact	Potential threats to fresh water supply	Potential threats of severe flooding	Other effects
Sea level rise	• Saltwater intrusion of easterly wellfields • Inundation of Southernmost Everglades with seawater potentially affecting the Biscayne Aquifer in south Miami-Dade. • Reduced groundwater flow • Reduced fresh water available for municipal use	• Compromised stormwater drainage systems • Reduced capacity of canals and coastal control structures. • Greater potential for flooding due to heavy rain storms and hurricanes • Reduced groundwater flow • Rising water tables • Reduced soil storage capacity • Increased risk of flooding of coastal and low-lying inland areas	• Barrier islands subject to inundation and washout • Beach erosion • Coastal wetlands and southernmost Everglades encroachment
Changes in rainfall patterns	• Longer, more severe drought during dry season • Greater likelihood of multiyear droughts • Reduced annual rainfall (10-15%) • Increased risk of ground and surface water contamination due to flooding	• Shorter, wetter rainy seasons • More severe rainfall events • Severe flooding during more intense rain events	• Stresses on agriculture, landscaping, and natural systems due to drought
More intense hurricanes	• Increased risk of contamination with seawater due to storm surge, • Power interruptions and damage to water infrastructure	• Enhanced storm surge • More intense rainfall	• Greater wind and storm surge damage • Beach erosion • Coastal inundation • Power failures
Higher temperatures	• Increased evapotranspiration reducing water available for urban and natural areas • Increased water requirements for firefighting • Increased potential for biological contamination of water supply and surface waters		• Heat stress on people, ecosystems and marine life • Dehydration of plants and soils • Greater risk of urban fires and wildfires • Hypoxia of coastal waters and algae blooms • Increased risk of insects and insect-borne disease

In addition, oceans are being acidified by carbonic acid formed from dissolved carbon dioxide. Other significant effects caused by global warming are heat waves and extremes in precipitation patterns (drought and intense rainfall) and more violent weather (hurricanes, severe thunderstorms, tornadoes, etc.). These climatic effects have already begun to have deleterious effects on the environment and ecologies worldwide. Virtually every component of the biosphere is being affected. The details of how this occurs have been described in many publications (IPCC, 2007), (Karl, etal, USCCSP, & NOAA, 2009), (International Alliance of Research Universities, 2009), and is summarized in the Science Section of our previous report entitled *Florida's Resilient Coasts* (Murley, Heimlich, & Bollman, 2008) on coastal adaptation policy.

Climate change is likely to 1) threaten the integrity and availability of fresh water supplies and 2) increase the risk of flooding, not only in the low-lying coastal areas, but also in the interior flood plains. The water supply is in jeopardy because (a) saltwater intrusion will be intensified by sea level rise, (b) prolonged droughts will contribute to water shortages, and (c) heavier rains during the rainy season and hurricane storm surge may increase the risk of contamination of the aquifer due to flooding. More frequent and damaging floods are likely to become an ever-increasing problem as sea level continues to rise because of (a) increasing levels of interior ground and surface waters, (b) reduced groundwater flow through the aquifer, (c) increasingly compromised stormwater drainage systems, and (d) more frequent inundation of barrier islands and coastal areas. What follows is a more detailed discussion of how these impacts will evolve as climate change progresses and how they will adversely affect Southeast Florida's water supply and increase the risk of widespread flooding.

4.1 Sea Level Rise

Sea level rise is the most serious climate change threat to low lying Southeast Florida. By itself sea level rise will cause saltwater intrusion and inundation of coastal areas. What is less apparent is that it will significantly magnify the adverse impacts of hurricanes, severe rain events, and drought. Factors contributing to the rate and extent of sea level rise include 1) thermal expansion of the oceans due to global warming, which has been the major component until now, 2) normal seasonal melting of land-based ice from mountaintops worldwide, and 3) more rapid melting, flow and disintegration of glaciers in the polar regions, which is accelerating as temperatures rise rapidly in the Arctic and Antarctic due to climate change.

Glacial melting and flow are not as yet well understood and are difficult to quantify. Recent observations of glacial behavior in Greenland and Antarctica suggest that melt rates and disintegration of ice sheets and glaciers have increased multifold in recent *years* and may become the primary driver of accelerated sea level rise in the future (Karl, etal, USCCSP, & NOAA, 2009); (International Alliance of Research Universities, 2009). Sea level rise is expected to continue for centuries even if greenhouse gas emissions are sharply reduced in the near future because substantial energy has already been absorbed in the oceans. Substantial sea level rise that will impact Southeast Florida during the 21st Century is inevitable and adaptation will be required.

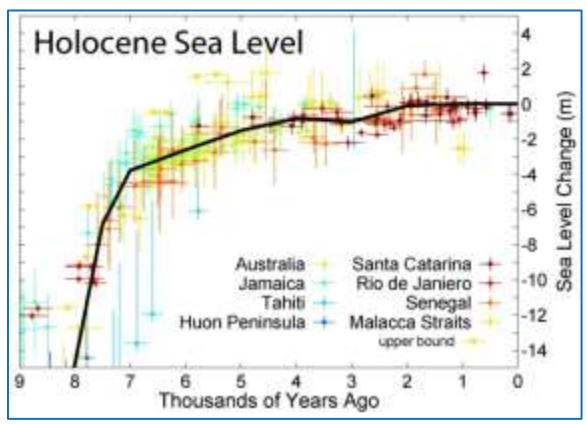

Figure 26 - Sea level rise sharply at the end of the last ice age and rose sharply until about 5000 years ago. Sea level was virtually *constant* for the past 2000 years until the late 19th century. (IPCC, 2007)

Historically, as shown in Figure 26, sea levels were much lower during the last ice age and rose rapidly during the Holocene period until about 2400 years ago, when sea level rise slowed significantly to a rate of about 30 mm (1 ¼”) per century, approximately 10% of the current rate.

Table 3 - Average rates of sea level rise globally and in Southeast Florida

Global average sea level rise, 1860-2005	1.7 mm/yr	IPCC, 2007
Global average sea level rise, 1870-1990	2.0 mm/yr	Church & White, 2006
Global Average sea level rise, 1993-2007	3.1 mm/yr	Cazenave, et al, 2008
Miami, Florida, 1931-1999	2.39 ±0.22 mm/yr	US EPA, 2009
Key West, Florida, 1913-1999	2.27 ±0.09 mm/yr	Maul, 2008

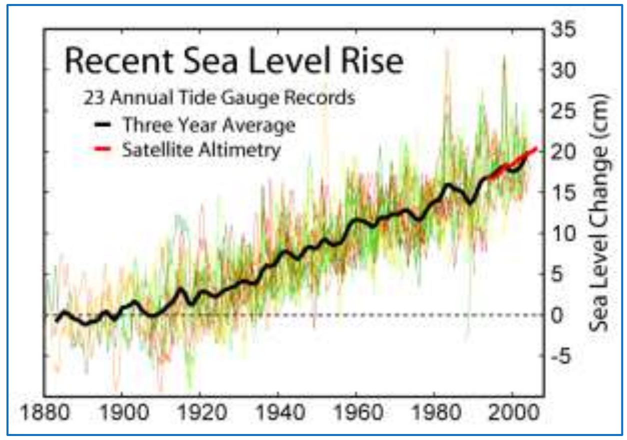

Figure 27 - Sea Level began rising in about 1900 and rose by about 20 cm (8") during the 20th Century. (IPCC, 2007)

Approximately 100 years ago, early in the Industrial Revolution, sea level rise began to accelerate as shown in Figure 27, averaging about 2.0 mm/yr during the 20th century (IPCC AR4, 2007) and 3.1 mm/yr since 1993 based on satellite altimetry (Cazenave, Lombard, & Llovel, 2008). A Florida Institute of Technology Report (Maul, 2008) shows an average rate of sea level rise of 2.27 ± 0.04 mm per year from 1915 to 2005 based upon tide gauge readings in Key West, which has the Western Hemisphere’s longest sea level record. Sea level has risen by approximately 200 mm (~8”) during the past century (IPCC AR4, 2007). A January 2009 report of the U.S. Climate Change Science Program (US EPA, 2009) cites the average rates for South Florida indicated in Table 3. Global rates are listed for comparison. There does not appear to have been a significant difference between sea level rise during the 20th Century between Florida and globally.

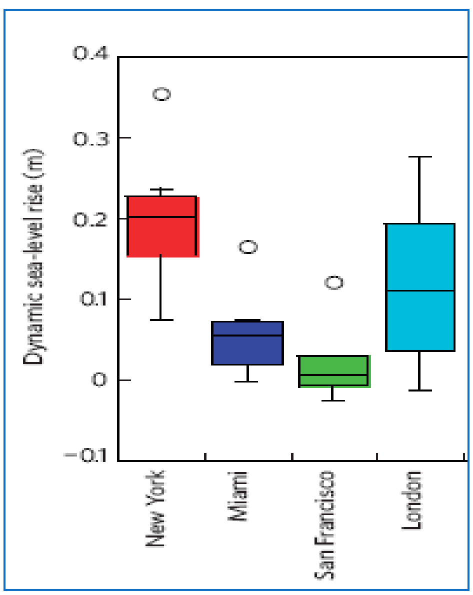

Figure 28 - Effect of climate change on Atlantic meridional overturning current by 2100 on incremental sea level rise. A minor incremental effect is predicted for Miami (Yin, 2009).

A recent paper from Florida State University by Yin, et al, evaluated the effect of climate change on the Atlantic meridional overturning circulation (AMOC), the major oceanic current that includes the Gulf Stream and Atlantic Current that flows north along the east coast of the United States and across to the British Isles and Europe. Yin predicts a significant reduction of AMOC flow that will cause regional variation in sea level rise, especially in the northeast coast of the United States and the coasts of the British Isles, where dynamic increments of 15-21 cm (6-8 inches) for New York City and 5-20 cm (2-8 inches) for London are predicted by 2100 as show in Figure 28. The paper acknowledges Florida’s vulnerability to sea level rise but projects a minor local difference of less than 0.08 meter (<2 inches) for Miami in comparison to global sea level rise. Therefore, global and local sea level rise are used interchangeably in this report.

4.1.1 Sea Level Rise Forecasts

The Intergovernmental Panel on Climate Change 4th Assessment Report released in 2007 (IPCC AR4, 2007) projected sea level rise of at least 23-59 cm (9-23 inches) during the 21st Century. IPCC's work was based on published reports through 2005 and did not account for glacial melting in Greenland and Antarctica because of the lack of reliable data as of that cutoff date. Glacial activity in Greenland, Antarctica, and elsewhere is now receiving major attention. Recent papers cite evidence that dramatic increases in melt rates are likely to make significant additions to sea level rise. There is a growing consensus, including the Copenhagen Congress held in March 2009 (International Alliance of Research Universities, 2009), that sea level rise will be significantly greater than estimated by the IPCC in 2007. This is reaffirmed in the recently published United Nations Climate Change Science Compendium 2009 (UNEP, 2009) which reports that climate change is occurring more rapidly than the worst scenarios reported in IPCC 2007. Some papers indicate that seas could rise by many meters in the event of catastrophic collapse of the Greenland and Antarctica glaciers and ice sheets. James Hansen, head of NASA's Goddard Institute of Space Studies and a leading voice on global warming, stated in 2007, "There is enough information now, in my opinion, to make it a near certainty that IPCC "Business As Usual" climate forcing scenarios would lead to a disastrous multi-meter sea level rise on the century timescale."

Greenland alone holds enough ice to raise sea levels by about 6 meters (20 feet), and the Western Antarctica Ice Sheet has enough ice to raise sea levels by another 3-6 meters (International Alliance of Research Universities, 2009). Pfeffer (2008) indicates that with Greenland alone (i.e. not including Antarctica), sea levels by 2100 could reasonably rise up to 0.8 meter (2.6 feet) based upon ice kinematics from historical peak movements of Greenland's glaciers. He also indicated in the less likely event that all glaciers in Greenland moved simultaneously at their historical maximums, sea level rise could be as much as 2.0 meters (6.6 feet). Geological evidence shows that sea level was as much as 20-25 feet above current levels during the last interglacial period about 125,000 years ago (IPCC, 2007).

An increasing number of papers concerning sea level rise due to climate change are appearing in the scientific literature. Those listed in Table 4 are selected as the most pertinent as of this date. Rahmstorf (2007) and Grinsted (2009) developed correlations of global average sea levels versus historical global average temperatures; these correlations were then applied to temperatures predicted by IPCC's climate models for the various IPCC scenarios. Sea level rise projections for 2100 according to Rahmstorf range from 0.5-1.4 meters (1.7-4.6 feet) and 0.9-1.3 meters (2.9-4.3 feet) according to Grinsted. These projections agree reasonably well with the earlier estimate of 3-5 feet by the Miami-Dade Climate Change Advisory Task Force's Science Committee (Wanless, 2008). Broward County's Climate Change Task Force, Science and Technology Subcommittee, decided upon a 2100 sea level rise value of 2-4 feet based upon a comprehensive literature search and analysis conducted by County staff (Gassman, 2009), relying on the USCCSP/NOAA report (Karl, etal, USCCSP, & NOAA, 2009) as representative of ranges reported in other recent reports.

Table 4 - Sea level rise – most relevant recent publications and reports.

Author	2100 Projection, feet	2100 Projection, meters	Basis	Notes
IPCC AR4 (2007)	0.6'-1.9'	0.18-0.59	Model projections for 17 scenarios	Thermal expansion contributes 70-75%. Does not include Greenland and Antarctica contributions for lack of data.
Rahmstorf (2007)	1.7'-4.6'	0.5-1.4	Linear regression of sea level vs. temp. 1870-2007.	Extrapolated on IPCC 2007 temperature forecasts using climate model scenarios.
Grinsted (2008)	2.9'-4.3'	0.9-1.3	Regression of 4 parameter 1st order rate model using 1800 year history of sea level vs. global temp.	Extrapolated on IPCC 2007 temperature forecasts using climate model scenarios.
Wanless, Miami-Dade Climate Change Advisory Task Force (2008)	3'-5'	0.9-1.5	Based on assumed increases of rates of thermal expansion and ice sheet melt.	Forecasted as minimum for 21st century with at least 1.5' by 2058.
Karl, Melillo, Peterson, USCCP, NOAA (2009)	2'-4'	0.6-1.2	Consolidation of related work of USGS and NOAA on climate change.	Issued by NOAA and the Science and Technology Office of the President of the United States.
IARU, Copenhagen, (2009)	1.6'-4.9'	0.5-1.5	Findings of the Climate Change Congress on Climate Change, Copenhagen, March 2009	Review by leading researchers worldwide in anticipation of the climate summit to be held in Copenhagen in December 2009.

Publications and reports to date apply relatively simple empirical correlations and extrapolations based upon limited historical data and may not be reliable for the following reasons: 1) most of the sea level rise in the 20th century was due to thermal expansion as a result of rising global temperatures, 2) a relatively small contribution was from the melting of ice sheets and glaciers and may not be a reliable guide for the increasing contributions due to melting in the 21st Century, and 3) the mechanisms of glacial melt and flow are not well understood. Extensive research is underway on this important issue and better projections will no doubt be forthcoming.

4.1.2 Predicting Interim Sea Level Rise Using a Quadratic Acceleration Equation

Much of the literature on sea level rise focuses on predictions for 2100. Adaptation planning requires estimated timeframes for sea level rise thresholds throughout the 21st Century. To provide a method of generating this information, the lead author of this report, developed a method (Heimlich, 2009) presented in Appendix C that using a quadratic acceleration equation. Recently the U.S. Army Corps of Engineers published guidelines for predicting sea level rise that employs a similar method (USACE, 2009).

To attain sea level rise values ranging from 2 to 6 feet or more by 2100, as published in post-IPCC predictions, sea level rise would have to accelerate considerably as shown in Appendix C, Table C-2. In developing an empirical method for predicting sea level rise throughout the 21st Century, sea level rise is assumed to accelerate as melt rates increase in proportion to rising temperatures in Greenland and Antarctica. This approach is supported by Church & White (2006), which demonstrates that sea level rise during the 20th Century can be correlated with an acceleration model as illustrated in Figure 29.

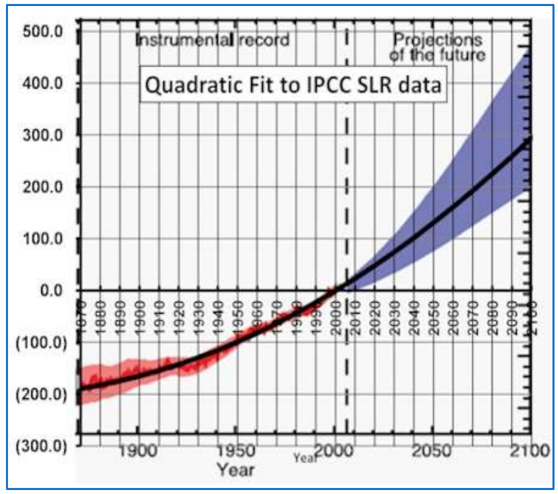

Figure 29 - Sea level rise has been accelerating at about 0.013 mm/yr^2 during the 20th Century. (Church & White, 2006)

Figure 30 is a graph showing predicted sea level rise values during the 21st Century with 2000 as the base year. The rate of sea level rise for base year 2000 is assumed to be 3.1 mm/yr, i.e. the average rate from 1993 to 2003 as determined from satellite measurements (Cazenave, Lombard, & Llovel, 2008). Sea level rise in year 2100 is assumed to range from 2 through 4 feet based on Karl, et al (Karl, etal, USCCSP, & NOAA, 2009). On the right side of Figure 30 is a bar chart showing the values of sea level rise predicted

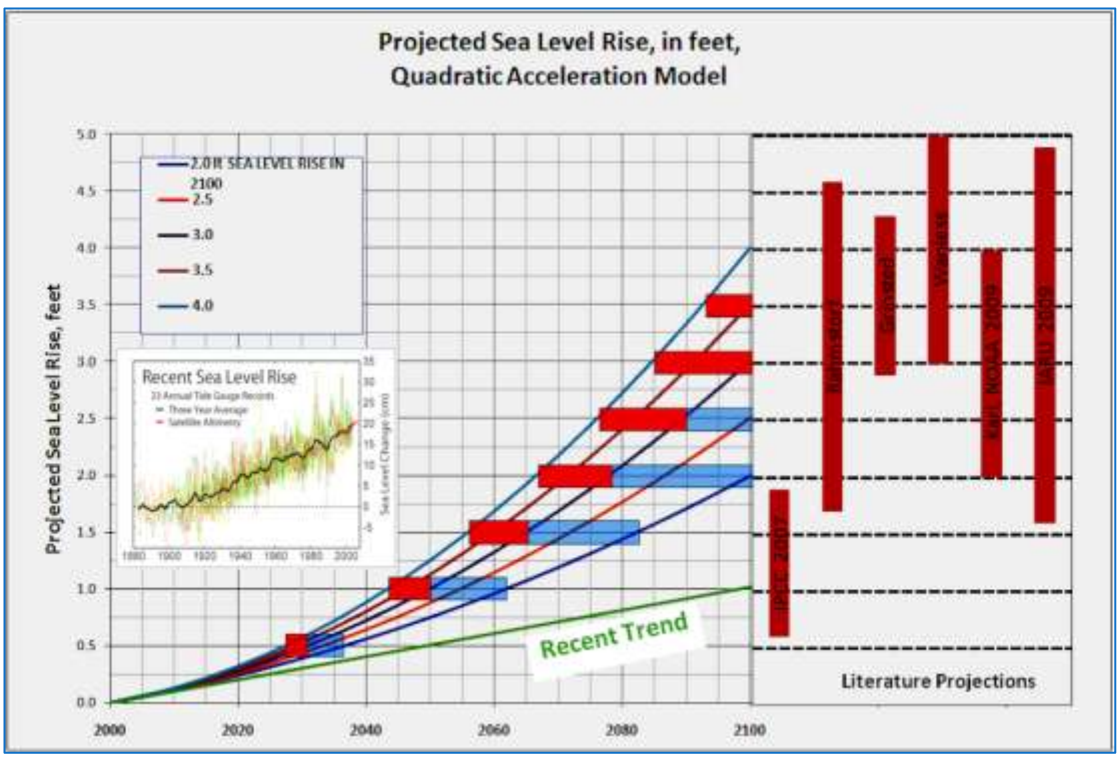

Figure 30 - Prediction of sea level rise using a Quadratic Acceleration Equation (Heimlich, 2009).

for 2100 from the publications listed in Table 4. Also shown for reference in green is a linear extrapolation of the current rate trend according to Cazenave, et al. (2008).

Superimposed on the graph are horizontal timelines for sea level rise values at 0.5 foot intervals. Since topographical maps are developed at elevation increments, usually 1 foot, it is useful for planning purposes to define timeframes for specific event horizons. For example, having a projected timeframe of 2043 to 2048 for 1 foot sea level rise is more useful for planning purposes than having a projected sea level rise of 1.0 to 1.7 feet for 2060. The planner can determine the projected consequences of a 1 foot sea level rise with precision, but not for 1.3 feet, the approximate median value for 2060.

Table 5a on the next page provides projected range of sea level rise values at 10-year intervals throughout the 21st Century. Table 5b shows dates for the indicated sea level rise thresholds corresponding to a 2100 sea level rise of 4, 3, and 2 feet. For planning purposes, it is recommended that a more conservative approach of using projected date ranges corresponding to 3 and 4 feet of sea level rise in 2100 be utilized. These values appear as the horizontal red bars in Figure 30. To illustrate, for a projected sea level rise of 1.0 feet, it is recommended that the planner use a date range of 2043-2050 from Table 5b as a conservative range for the time that a 1.0 foot sea level rise might occur. The recommended date range from Table 5b for a 0.5 foot sea level rise is 2027-2031, i.e. only 18 to 22 years from 2009.

Table 5 - Sea level rise projections and timeframes

Table 5a

Year	Sea level rise since 2000, feet		
2000	0.00	-	0.00
2010	0.11	-	0.12
2020	0.24	-	0.32
2030	0.39	-	0.57
2040	0.56	-	0.88
2050	0.75	-	1.25
2060	0.96	-	1.68
2070	1.19	-	2.17
2080	1.44	-	2.72
2090	1.71	-	3.33
2100	2.00	-	4.00

Table 5b

Sea level rise since 2000, feet	Projected date ranges Sea level rise in 2100: 4ft Early	3ft Mid	2ft Late
0.00	2000	2000	2000
0.25	2017	2018	2021
0.50	2027	2031	2036
0.75	2036	2041	2050
1.00	2043	2050	2062
1.50	2056	2065	2082
2.00	2067	2078	2100
2.50	2076	2090	2116
3.00	2085	2100	2130
3.50	2093	2110	2144
4.00	2100	2119	2157

It is noted that acceleration for sea level rise would have to increase by a factor of 4.6, 9.3 to 14.0 over the historical acceleration of 0.013 mm/yr^2 reported by Church and White (2006) to obtain sea level rise values of 2, 3, and 4 feet respectively in 2100 (See Table C. That sea level rise could accelerate by as much is surprising. Nonetheless, Greenland and Antarctica have more than enough ice to raise sea levels by these amounts and much more, and glacial melt is increasing significantly. It is a question of how rapidly the ice sheets can melt or disintegrate; the answer is not known with any certainty at this time. There is significant concern in the science community that a threshold could be reached at an uncertain

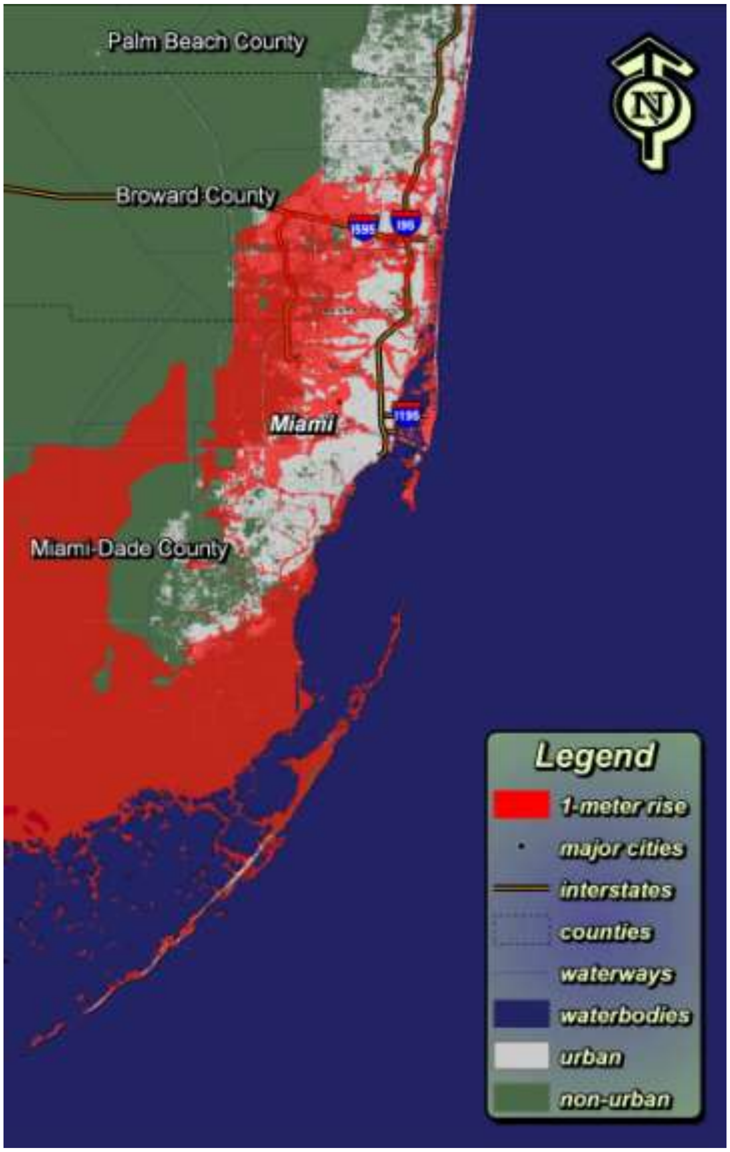

Figure 31 - Southeast Florida approximate susceptibility to 1 m (3.25'). The area shown in red is at an elevation equal to 1 meter above current mean high tide. It is not a reliable prediction of inundation since it does not account for tidal action or surface or groundwater hydrology. Nevertheless, it is an indicator of the potential vulnerability of Southeast Florida to sea level rise. (Image Credit: Weiss and Overpeck)

time when glaciers and ice sheets could suddenly collapse causing a dramatic stepwise increase in sea level.

Weiss and Overpeck at the University of Arizona have developed an interactive map of the world with 1 meter increments of elevation above mean high tide. Shown to the left is a map of South Florida indicating in red the area equivalent in elevation to 1 meter (3.25') above mean high tide. It is a first order approximation of the region's vulnerability to sea level rise. At 1 meter sea level rise, most of the barrier islands, the Florida Keys, the southern tip of the Florida peninsula including virtually all of Everglades National Park, the interior flood plains of western Miami-Dade and southwest Broward Counties, and areas of the cities of Miami, Miami Beach, and Fort Lauderdale would be at or below the elevation equivalent of mean high tide. Coastal areas worldwide would be in jeopardy. As will be discussed later, saltwater intrusion of the Biscayne Aquifer along the Atlantic coast, and inundation of the southernmost Everglades could contaminate the Biscayne Aquifer with saline water.

The map in Figure 31 is an approximation of the effect of 1 meter sea level rise; it is a static representation of water filling all areas that are at elevations below mean high tide. In order to obtain a more reliable representation of what might actually happen, high resolution topographical maps and dynamic hydrological model predications of groundwater and surface water flows and levels including tidal action should be utilized. Also important is how the region will respond to torrential rainstorms and hurricane storm surge in conjunction with sea level rise. The next section of the report discusses how sea level rise is likely to affect Southeast Florida's groundwater and surface water hydrology.

4.2 Impacts of Sea Level Rise on Southeast Florida's Water Resources

Sea level rise will result in the following impacts on coastal areas (Murley, Heimlich, Bollman, 2008):

1. Inundation of barrier islands and coastal property.
2. Beach erosion.
3. Encroachment of coastal wetlands including the southern Everglades with significant modification of wetland habitat as they become more saline.
4. Impacts on the region's water resources, namely the water supply and groundwater and surface water hydrology.

In this report, we focus upon the hydrological effects that will impact the region's water resources. These could include:

1. Saltwater intrusion.
2. Reduced fresh groundwater flow through the aquifer.
3. Compromised stormwater drainage due to rise in the water table causing reduced groundwater storage capacity and reduced hydraulic gradient between inland surface waters and sea level.
4. Inland penetration of saline surface waters as a result of hurricane storm surge.
5. Inundation of the southern Everglades watershed with saline water.

4.2.1 Saltwater Intrusion

As sea level rises, the ocean's hydrostatic head will increase. This would cause the saltwater interface to migrate inland, especially if the water table is held constant, as has been historically assumed in extensive hydrological modeling by the USGS and Broward County (Zygnerski & Langevin, 2007) (Zygnerski M. , 2008). In addition to the extent of saltwater intrusion, sea level rise can affect groundwater flow and water table height which will seek a new equilibrium with the risen ocean that depends on the extent of sea level and the rates of rainfall, evapotranspiration, wellfield withdrawals, stormwater drainage, and lateral groundwater flow in or out at the boundaries of the area under study.

In accordance with the Ghyben-Herzberg Relation, which governs flow in an open coastal aquifer like the Biscayne Aquifer (Todd & Mays, 2008), and assuming uniform aquifer transmissivity, the depth of the saltwater interface, z, will be approximately 40 times the height of the water table, h, at equilibrium according to the equation below, where ρ_f is the density of freshwater, 1.000 gm/ml, and ρ_s is the density of seawater, approximately 1.025 gm/ml. Therefore, the ratio, $z/h = \sim 1.0/(1.025\text{-}1.000) = \sim 40$.

$$z/h = \rho_f / (\rho_s - \rho_f) = \sim 40$$

Figure 32 is a set of schematic diagrams illustrating the effects of rising sea level with and without water table rise as predicted by the Ghyben-Herzberg Relation. The upper diagram represents the current situation and illustrates the various terms of the Ghyben-Herzberg Relation. The middle diagram in Figure 32 illustrates what would happen if the water table is allowed to rise by about the same amount as sea level, i.e. $h_2 = h_1$. The extent of saltwater intrusion would be relatively small, but ponding could occur in areas of low elevation as indicated. The lower diagram illustrates the case where the water table is held constant as sea level rises. In this case, the height of the water table above sea level is reduced by the amount of sea level rise from h_1 to h_2. The Ghyben-Herzberg Relation predicts that the depth of the saltwater interface below sea level will decrease from z_1 to z_2, i.e. by 40 times the amount of sea level rise, since $(z_1 - z_2)/\Delta S = 40$. Because sea level is displaced by the amount of sea level rise, the saltwater interface rises by 41 times sea level rise. Therefore, holding the water table at current levels as sea level rises would lead to significant saltwater intrusion. This analysis assumes equilibrium is attained. In practice it will take some time for the levels to go from one equilibrium state to another, which requires dynamic hydrological modeling to predict the rate at which this would occur.

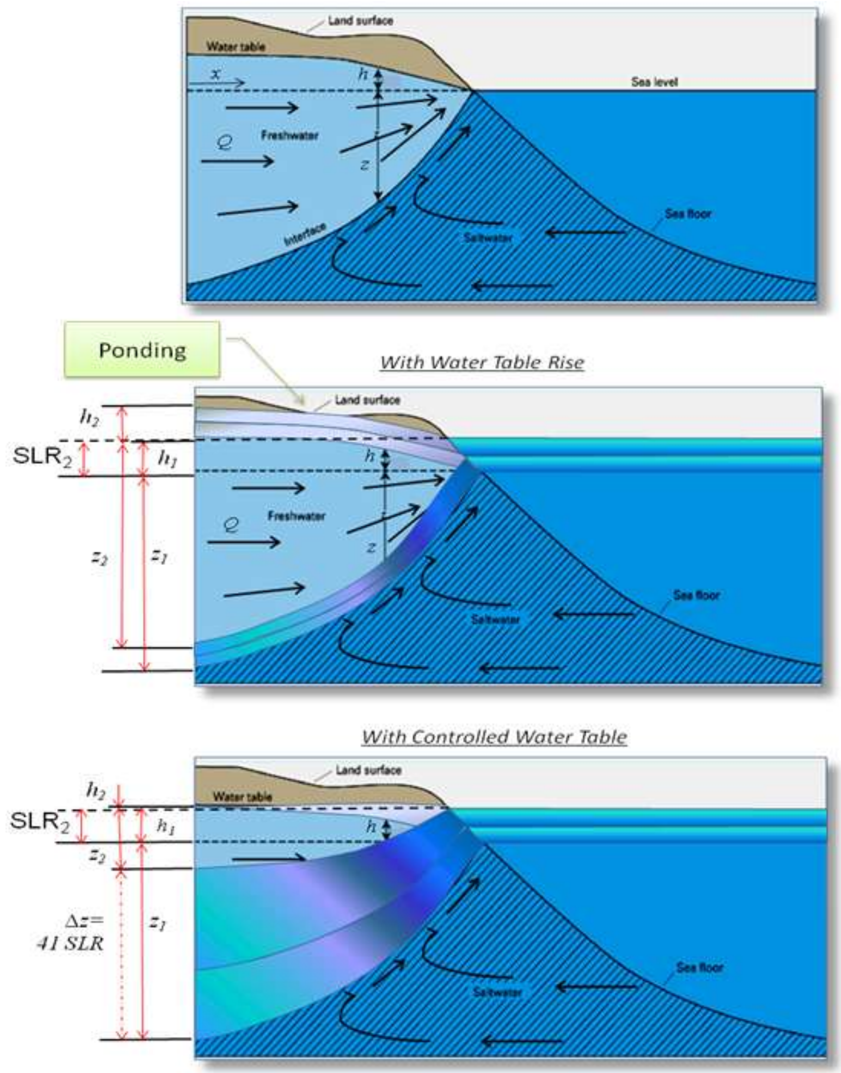

Figure 32 - Sea level rise will affect groundwater flow, water table height, and the extent of saltwater intrusion. If the water table is allowed to rise as shown in the second drawing above, saltwater intrusion can be minimal. However, there is increased risk of ponding in areas of low elevation, and reduced soil storage capacity increases the risk of flooding during heavy rainfalls. Conversely, if the water table is controlled at current levels as shown in the bottom drawing above, the consequences would be diminished groundwater flow that can contribute to flooding and severe saltwater intrusion, which would threaten the integrity of freshwater supplies. At equilibrium, the saltwater interface would rise 41 feet for each foot of sea level rise according to the Ghyben-Herzberg Relation.

Water managers in Southeast Florida have little latitude to raise water tables, however, because of Southeast Florida's low elevation; water tables are already held at the highest practical levels consistent with flood control in order to minimize saltwater intrusion. Therefore, efforts will have to be made to hold the water table close to the current level by means of the flood control system. The unfortunate conclusion for Southeast Florida is that sea level rise would result in extensive saltwater intrusion. Literature reports indicate that saltwater intrusion can extend by miles inland as a consequence of sea level rise (Placeholder3). Other means that can be used to protect wellfields from saltwater intrusion are discussed in Section 5.2 and include hydrodynamic barriers, horizontal wells, relocation of salinity structures, and relocation of wellfields away from the saltwater interface.

While considering of the hydrological science concerning this issue, it became apparent that the effect of sea level rise on groundwater flow, stormwater runoff, water table level, and flood control has not been extensively evaluated to date in hydrological modeling or by local water managers and decision makers. As we delved into these issues, it was concluded that sea level rise will not only threaten saltwater intrusion in Southeast Florida, but it could substantially increase the risk of flooding as discussed in the next section.

4.2.2 The Effect of Sea Level Rise on Groundwater and Surface Water Flow

The theoretical analysis that follows is based upon established hydrological theory and it should be subjected to further study and verification including testing with integrated surface and groundwater hydrological models that can predict the effects of sea level rise, seasonal rainfall patterns, and heavy rainfall events.

Maintaining the water table as sea level rise progresses at current levels may become increasingly difficult and costly. Sea level may rise to the point where it may become impossible or impractical to prevent the water table from rising with increased risk of flooding as a consequence. Surprisingly, hydrological theory predicts that maintaining water tables at current levels as sea level rises may also lead to increased susceptibility to flooding.

Sea level rise is likely to result in:

1. Increased risk of severe flooding during heavy rainfall events.
2. Reduced effectiveness of flood control and stormwater drainage systems.
3. Increased water table levels that could increase the risk of flooding.
4. Reduced groundwater flow through the aquifer to the ocean.
5. Reduced availability of fresh water potable use, especially during the dry season.

Complicating these concerns, climate change is expected to cause more intense rainfall events, such as more severe thunderstorms and tropical cyclones (IPCC, 2007); (Karl, etal, USCCSP, & NOAA, 2009).

The effects of sea level rise on open coastal aquifer using an idealized hydrological model were studied by Werner and Simmons (2009) in two distinct cases: 1) where water table level is held constant and 2) persistent flow of groundwater discharge to the sea despite increased sea level. In the constant water table case, reduced groundwater flow and significant saltwater intrusion is predicted. In the persistent flow case, rise of the water table is predicted and saltwater intrusion would be substantially reduced as is illustrated in Figure 32.

Southeast Florida presents a more challenging problem than the idealized cases however. High recharge due to rainfall is inevitable, yet close control of the water table is essential to prevent flooding of the low terrain. Groundwater flow rates are high as a result of the high permeability of the aquifer. Another consequence of the aquifers permeability is that saltwater intrusion, water table levels, and groundwater flows are very responsive to changes in rainfall, aquifer withdrawals, stormwater management, and sea level rise. The highly engineered stormwater drainage system of canals and control structures described in Section 3.4.3 has effectively enabled management of water tables and saltwater intrusion. The advent of sea level rise will present new challenges, however. Water tables are already maintained at the highest possible levels in order to counter saltwater intrusion but are consistent with prevention of floods in Southeast Florida's low-lying terrain.

Increased hydrostatic backpressure as a result of sea level rise will reduce the flow of fresh groundwater toward the ocean. According to Darcy's Law, the primary force driving flow is the differential hydrostatic pressure or "head" between the water table and sea level. As illustrated in Figure 32, the saltwater interface would migrate inland, which would threaten saltwater intrusion of coastal freshwater wellfields. Extreme saltwater intrusion caused by sea level rise may eventually result in reduced availability of raw fresh water for potable use. As sea level approaches the water table level, net flow of groundwater could become zero. If sea level rises further, the direction of flow could reverse and seawater could backflow into the aquifer.

As shown in Figure 33, the water table near the Broward County coast is controlled at about 2 feet

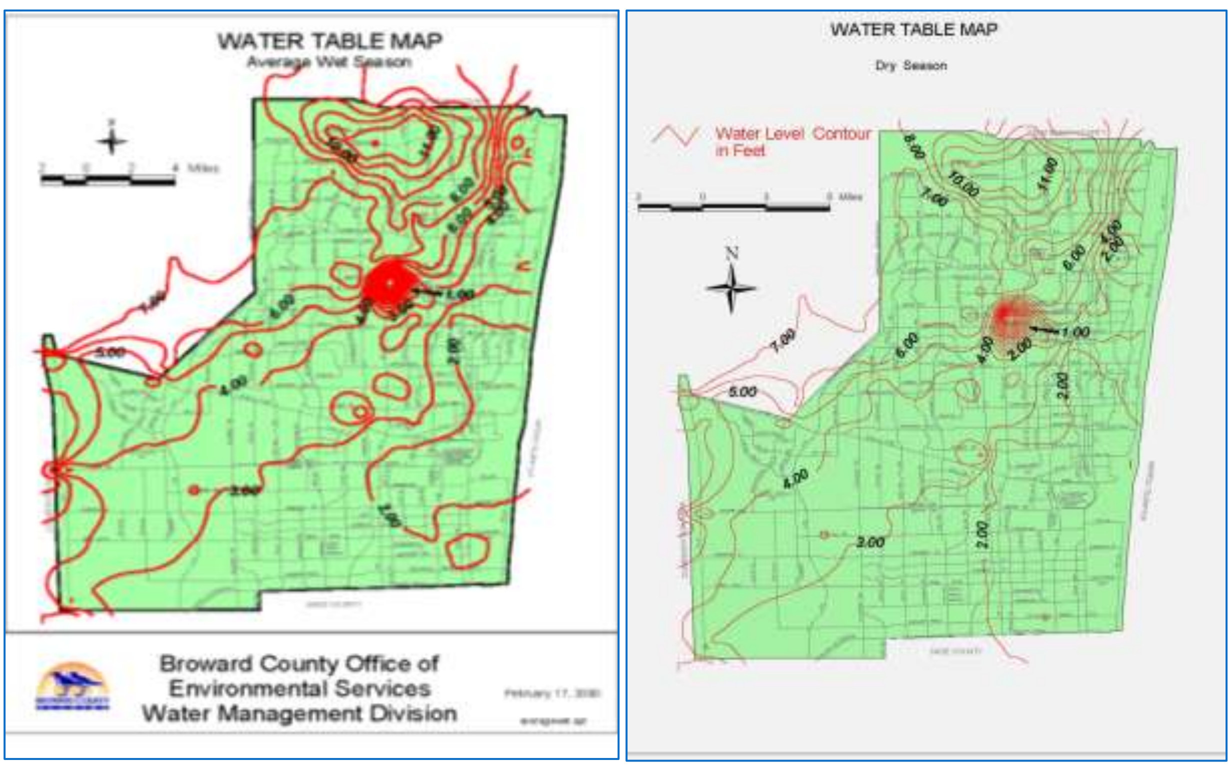

Figure 33 - Water table maps for Broward County (2000). Water table levels are 2 to 4 feet in south Broward County where elevations are for the most part below 5 feet. Map on left is for wet season; map on right is for dry season (Broward County).

above mean tide to control saltwater intrusion, i.e. barely above high tide. In the approximately 20 miles across southern Broward County from the ocean to the Everglades Conservation Area at the western edge of the urban area, the water table gradually increases from about 2 feet to about 4 feet during the wet season as shown on the left in Figure 33, an indication of the high transmissivity of the aquifer and the effectiveness of the stormwater drainage system. The water table is only slightly lower during the dry season as shown on the right side of Figure 33. It is also important to note that much of southwest Broward County is below 5 feet elevation, as shown in Figure 7, meaning that the water table is just below the surface. The same situation exists in adjacent northwest Miami-Dade County. As sea level rises and reduces or reverses groundwater seepage, this water table gradient is likely to be affected. Most likely the water tables would tend to raise putting an increased burden on the stormwater drainage system.

The water budget for Broward County discussed in Section 3.4.2 and illustrated in Figure 23 and Table 1 (Broward County IWRP, 2008) is assumed in the following discussion. The primary source of fresh water is approximately 99.1 billion gallons per year per 100 square miles (BGY/100 sq.mi.). For each 100 square miles, 1 inch of rainfall equals 1.74 billion gallons of water. The major share of water flows to the sea through the canals, i.e. the flood control system, and a lesser amount flows through the aquifer. Approximately 53.9 BGY/100 sq.mi. flows to the ocean through the canals compared to groundwater seepage through the aquifer 3 inches per year = 5.2 BGY/100sq.mi. Therefore, groundwater flow is about 10% of total water flowing to the ocean. The remaining 90% portion flowing through the primary canals is controlled by the coastal flood control structures. As groundwater seepage to the ocean decreases due to sea level rise, the reduction in groundwater flow must be made up by flow through the canals to prevent the water table from rising.

The effect of sea level rise on groundwater and surface water flow through the canals to the ocean is estimated as follows. Assuming that the current average differential head is 2 feet at the coastal flood control structures, sea level rise of 0.5 feet would reduce the hydraulic head differential by about 25%; 1 foot of sea level rise would reduce the head differential by about 50% as illustrated in Figure 34. According to Darcy's Law, flow through an aquifer is proportional to the pressure or head differential. Groundwater flow would be reduced and surface water discharge through the canals and structures would have to make up the difference. Sea level rise of 1 foot would result in about a 5% increase in the canal discharge rates from 53.9 to 56.5 BGY/100 sq. mi. As sea level approaches the level of the water table, groundwater seepage would

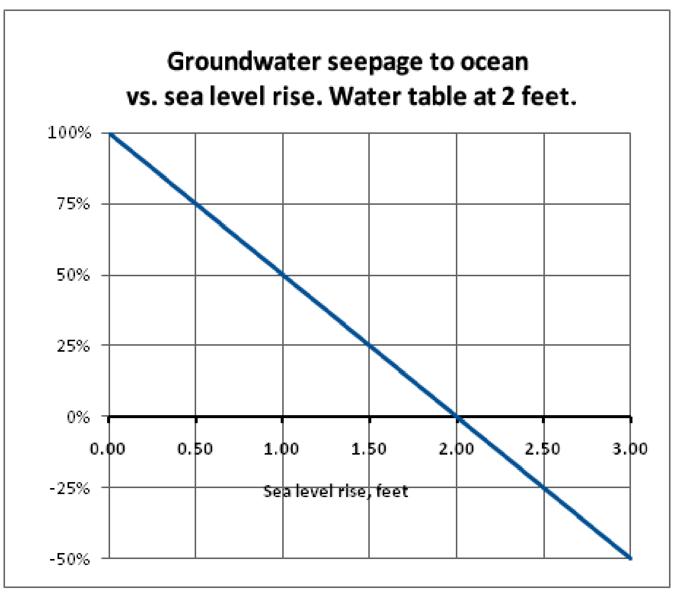

Figure 34 - Groundwater seepage to the ocean will decrease as sea level rises.

approach zero and could even reverse when sea level rises above the water table (Todd & Mays, 2008). This will increase the burden on the canals and coastal control structures. At the same time, the capacity of the coastal control structures will be reduced by sea level rise, as will be discussed in Section 4.2.3.

A matter of concern is that the estimate of groundwater seepage in the water budget is crude at best. If groundwater seepage is higher than the current estimate, the effect of reduced groundwater seepage due to sea level rise on the volume of stormwater discharge to the ocean could be greater, as shown in Figure 35. For example, if groundwater seepage is 2 to 4 times the current estimate, a 1 foot sea level rise would increase the volume of surface water discharge from the initial rate of 53.9 by to up to 20%

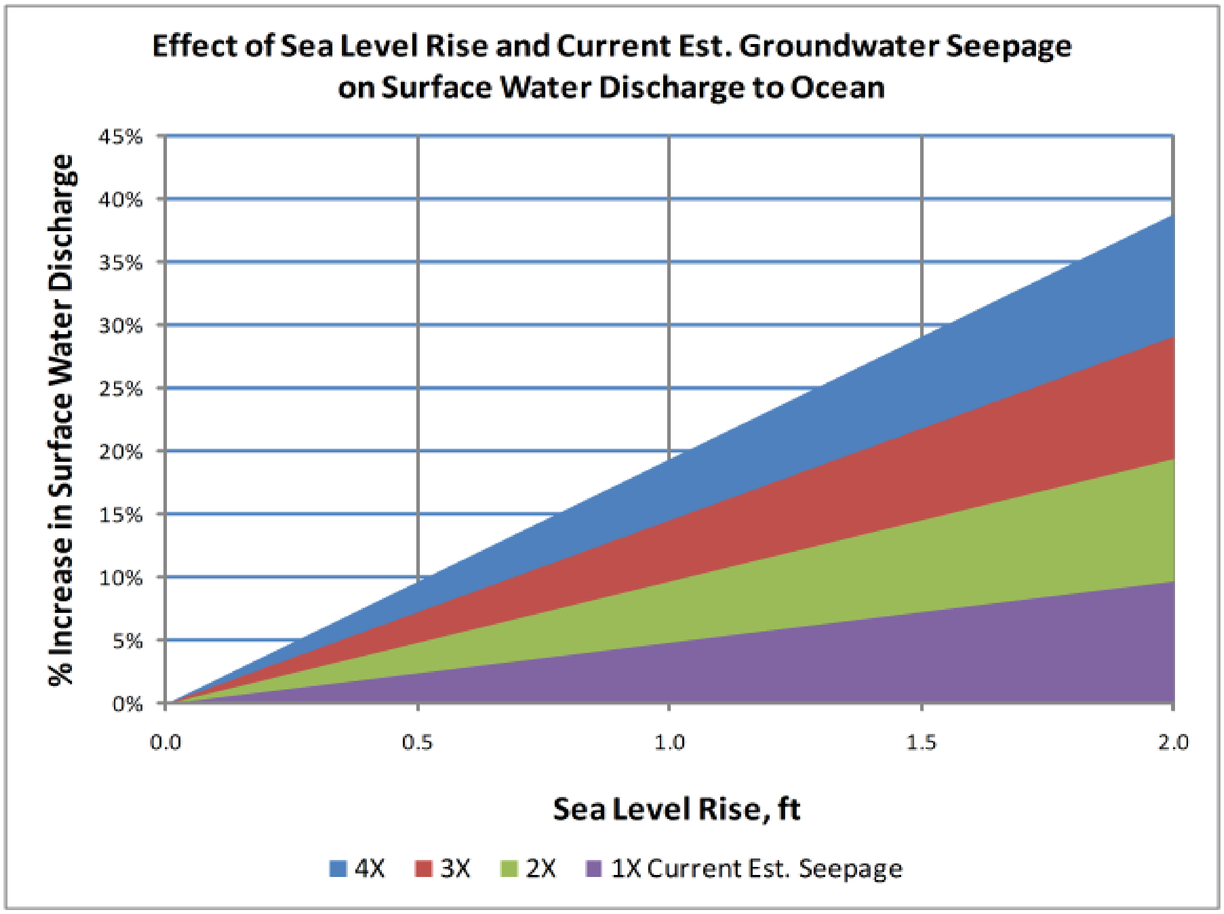

Figure 35 - If current groundwater flow is greater than currently estimated, there will be a greater increase in surface water drainage resulting from sea level rise.

to 66.9 GY/100 sq.mi. A 2 feet sea level rise would increase surface water discharge from the initial rate by 39%. Considering that surface discharge is so sensitive to sea level rise and the ratio of current groundwater seepage rate to surface water discharge, and that there is uncertainty in the current rate of groundwater seepage, additional research is needed to determine groundwater flow rates throughout the region more accurately. Furthermore, the water budget based on averages for 1965 to 2000 is out of date and should be updated.

From the foregoing, it is plausible that as little as 0.5 feet of sea level rise could result in saltwater intrusion, reduced groundwater flow, and significant increases in surface water discharge rates from the canals and coastal control structures. As explained in the next section, sea level rise will also reduce the capacity of the coastal flood control structures and increase the risk of flooding.

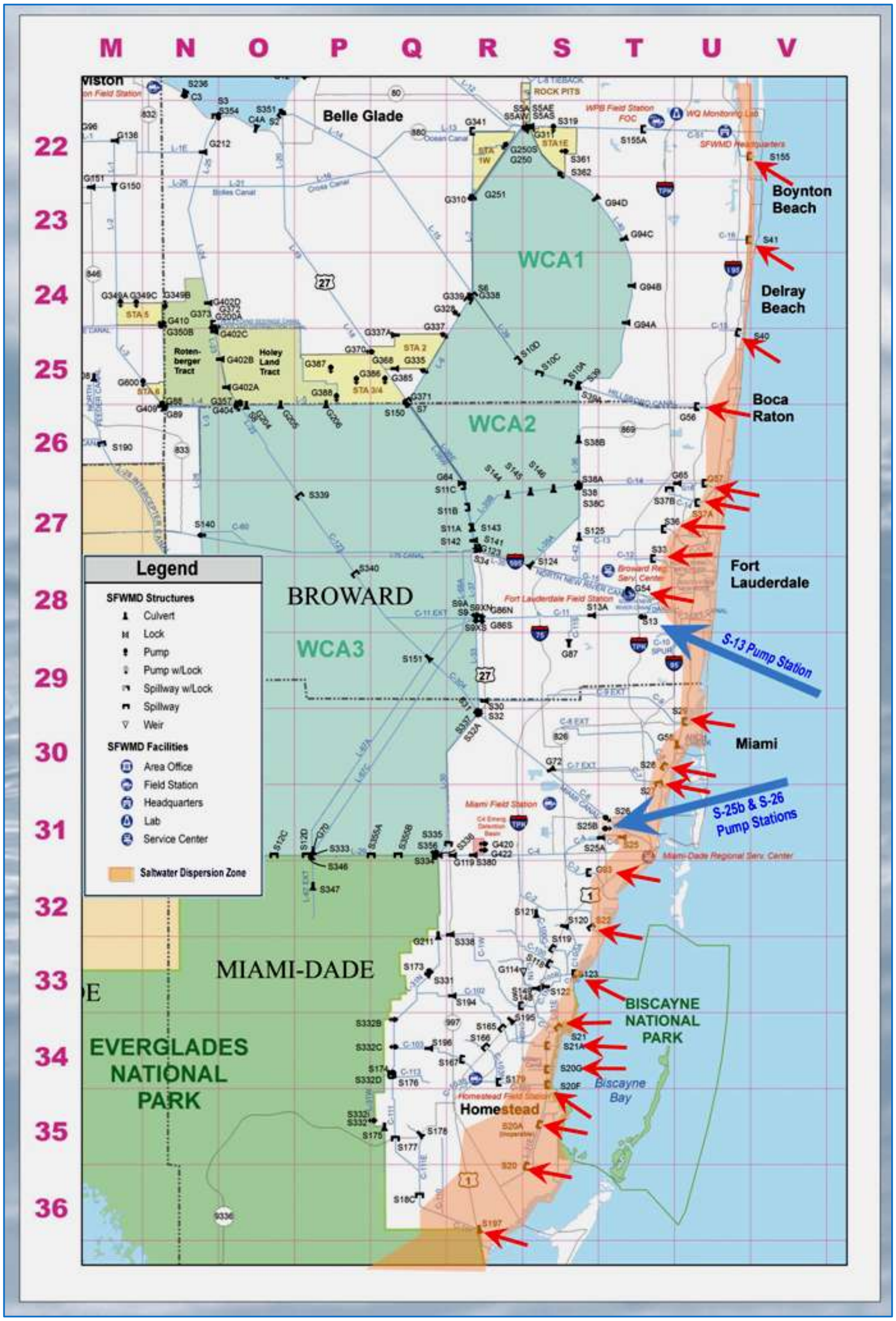

Figure 36 - Map showing the Lower East Coast planning area including Everglades Water Conservation Areas (WCA) 1, 2, and 3, the primary canal drainage system, and the locations and types of flood control structures. Those indicated with red arrows are coastal structures used for primary flood control and to control saltwater intrusion. The S-13 Pump Station is indicated by the blue arrow. There are also 3 coastal structures north of the upper boundary of the map that are not shown. The pink shaded area delineates the approximate position of the saltwater dispersion zone. It illustrates the effectiveness of the salinity structures for limiting saltwater intrusion. (Map: SFWMD)

4.2.3 Impact on Coastal Flood Control (Salinity) Structures

The South Florida Water Management District is responsible for allocating the water resources for the entire Everglades watershed including the Kissimmee River, Lake Okeechobee, Big Cypress Swamp and the Everglades. Figure 36 is a map of the Lower East Coast planning area that shows the locations of Everglades Water Conservation Areas 1, 2, and 3, the primary drainage canals, and the flood/salinity control structures. Also indicated by pink shading is the approximate zone of saltwater intrusion. The coastal structures pointed out by the red and blue arrows are used for primary flood control and to control saltwater intrusion. The effectiveness of the flood/salinity control structures is illustrated by how well the western limit of the saltwater intrusion zone lines up with the locations of the structures. As shown on the map in Figure 36, all but three of the coastal structures, indicated by the symbol are spillways that rely on gravity for flow. Most of the spillways are sluice gates, such as the one shown in Figure 37, or gated culverts. They are used for flood control by releasing canal water to tide when there is a flooding threat. There are three (3) pumping stations indicated by the blue arrows and the symbols, the S-13, located on the C-11 canal in Broward County and pictured in Figure 38, and the S-25B and S-26 on the C-4 canal and the Miami River in central Miami-Dade County.

Figure 37 – Typical coastal flood/salinity control structure of the sluice gate type. (SFWMD)

As sea level rises, the flow capacity of sluice gates and gated culverts decrease. If sea level rises to the point that there is no longer any difference in water levels across a gate, there can no longer be any flow through that gate. The percentage of the number of 28 coastal control structures in Miami-Dade, Broward, and Palm Beach Counties that would cease to operate as sea level rises was presented by SFWMD's Obeysekera (2009) and shown in blue in Figure 39 and listed in Table 6. These data indicates that almost two-thirds of the structures could lose their operability by the time sea level rises by 8 inches, which could occur by about 2040. Most at risk are the structures located in southern Miami-Dade County, which have the lowest operating levels due to the extremely low elevations of that area.

Figure 38 - S-13 Pump station located on C-11 canal at US441 and Orange Drive in Davie, FL. It has a rated capacity of 540 cfs, and can pump approximately 14.5 million gallons per hour (SFWMD, 2007).

A rigorous analysis of the effect of sea level rise of the capacity of each structure is beyond the scope of this study. However, in order to determine whether partial loss of capacity due to sea level rise could be significant, capacity loss as a function of sea level rise was approximated using a simplified calculation method presented in Appendix D. Flow rates for structures of these types vary approximately as the square root of the head difference across the structure.

The results are listed in Table 6 and represented by the red line in Figure 39. Table 6 also presents projected timeframes using the method presented Section 4.1.2, Table 5b, and described in Appendix C.

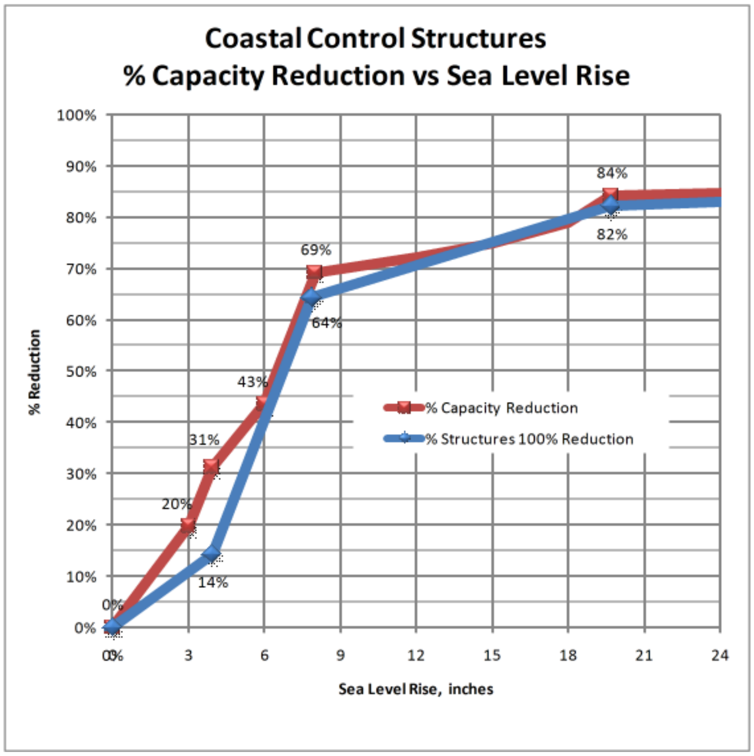

Figure 39 - Effect of sea level rise on capacity of coastal flood control (salinity) structures in Southeast Florida. Blue curve is data from Obeysekera (2009).

The two curves agree closely except for the initial 6 inches of sea level rise. In this range, capacity loss of higher structures is significant. For example, at 4 inches of sea level rise, which could occur as early as about 2020, about 30% of the total system capacity could be lost. Because these approximations

Table 6 - Projected timetable for loss of coastal structure operability and capacity.

Sea level rise since 2000, inches	Timeframe estimate from Table 5b, Early	Timeframe estimate from Table 5b, Mid	% Structures losing 100% operability*	% Est. Capacity reduction
0	2000	2000	0%	0%
3	2017	2018		20%
4	2020	2023	14%	31%
6	2027	2031		43%
9	2033	2039	64%	69%
12	2043	2050		72%
20	2059	2069	82%	84%
24	2067	2078		85%

* (Obeysekera, 2009)

indicate that capacity loss could be significant in the near future, definitive engineering analysis of the effect of sea level rise on coastal structure capacity should be carried out in the immediate future.

According to the map in Figure 36, the only coastal pump stations in Southeast Florida are the S-13 on the C-11 canal in Broward (pictured in Figure 39), the S-25B on the Miami River, and the S-26 on the C-4 canal in Miami-Dade. The C-11 canal serves the C-11E basin with an area of 35 square miles. It is designed to maintain the freshwater side of the C-11 canal at a level of 2 feet above current mean tide and has a rated capacity of 540 cubic feet per second (14.5 million gallons per hour) when pumping against a static head of up to 4 feet (SFWMD, Li, & Wilsnack, 2007). Eventually as sea level rises, many spillways will have to be modified with pumping stations similar to the S-13. Such pumping stations are costly to design and build, costly to operate, and require large amounts of electric power. If a pumping station cannot keep pace with the rate of rainfall, levels in the primary canals, the connecting secondary canals, and the surrounding water table could rise for an extended period until it seeps to the canal system and be pumped to tide.

Consider for example that a heavy rainstorm delivered an average of 5 inches of rain (approximately 8.7 billion gallons/100 sq. mi.) to the C-11E basin over a period of a few hours. During this short time period, there would be little evapotranspiration and minimal seepage through the aquifer to the ocean. Over 90% of this rainfall would have to be discharged through the canal system. Operating 24/7, it could take a pump the size of the S-13 approximately 181 hours or 7.5 days to pump that quantity of water as calculated below:

$$\frac{8.7}{100} \times .90 \times 35 \times 1000/14.5 \ = 189 \text{ hours } \ = \ 7.9 \text{ days}$$

The conclusion from this estimate is that pumping stormwater to tide could require installation of very large pumping stations, probably larger than the S-13, as sea level rises and gravity-driven coastal structures are no longer functional.

Another concern is whether the rate of rainwater seepage from the soil to the drainage canals during a rain event is sufficient to prevent local flooding during major rain events. Since soil void volume is approximately 20-30%, each inch of rainfall fills approximately 3 to 5 inches of soil. Groundwater seepage to nearby canals as illustrated in Figure 40 occurs in accordance with Darcy's Law. Canal levels may increase as sea level rises when discharge from coastal spillways or pumping stations cannot keep up during major rainstorms.

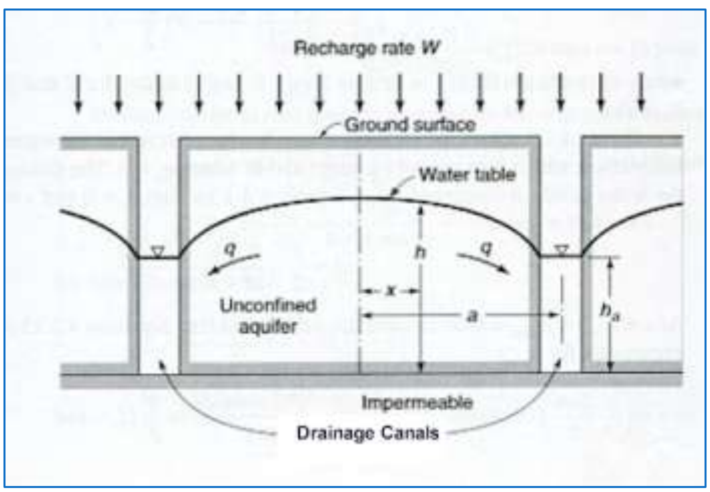

Figure 40 - Schematic diagram showing seepage of rain water to drainage canals in an unconfined aquifer like the Biscayne. Groundwater can flow to the canals only if the water table is above the level of the canals (Todd & Mays, 2008).

Stormwater can backup through the drainage system increasing the risk of flooding during periods of heavy rainfall. Figure 41 illustrates how the secondary stormwater drainage system could be

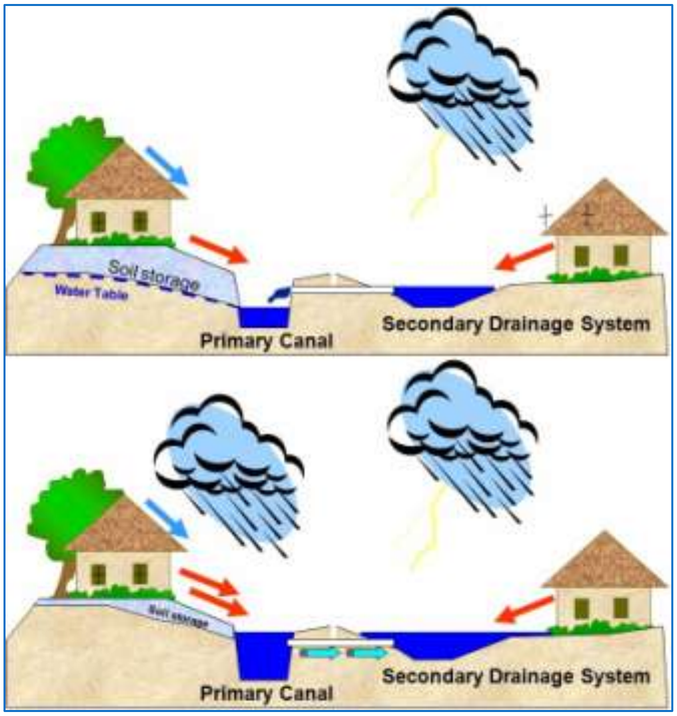

Figure 41 - Rise in sea level and water table compromises stormwater drainage systems increasing risk of flooding during rainstorms. (Obeysekera, SFWMD, 2009)

adversely affected by rising levels in the primary canal and water table (Obeysekera, 2009). Soil storage capacity would decrease and normal flow patterns could be disrupted. As shown in the bottom drawing, flow from the secondary drainage canals to the primary canals would reverse if primary canal level increases above secondary canal level. This in turn could cascade to the tertiary system and increase flooding. It may become necessary to install lift pumps to move stormwater from tertiary to secondary to primary canals if this situation occurs more frequently.

As explained previously, as sea level rises groundwater flow to the sea will slow unless the water table is allowed to rise. Unless the water table lies above sea level, groundwater flow could reverse and seawater can advance inland (Todd & Mays, 2008), possibly reducing the reliability of the Biscayne Aquifer as a source of fresh water. This could necessitate greater reliance on desalination and other costly alternative water supplies (Section 5.3). The ecology of the region could change, especially in coastal and low-lying freshwater wetlands and other low-lying areas. Plants and wildlife that are not salt tolerant may be displaced. It may become necessary to allow the water table to rise at greater risk of flooding in order to protect the aquifer and the freshwater ecology of the region. More extensive use of levees, dikes, and pumps may become necessary in areas prone to flooding. Creative approaches not yet conceived may be necessary to preserve fresh water supplies and for flood control.

In the face of ever increasing sea level rise, it is reasonable to question how effectively the water table can be controlled by flood control structures with or without forward pumping. It may not be possible to prevent transient water table rise during periods of heavy rain when ground and surface water flows are compromised by sea level rise. Soil storage capacity is reduced when the water table rises, increasing the likelihood of flooding during heavy rainfall events. It is also conceivable that low elevation inland areas could be inundated by rising groundwater. Especially vulnerable to this possibility are the flood plains west of the coastal ridge in northwest Miami-Dade and southwest Broward Counties where the water table is 1 to 3 feet below the land surface. Definitive conclusions concerning the issues raised in this report require validation additional research including simulations using integrated hydrologic modeling.

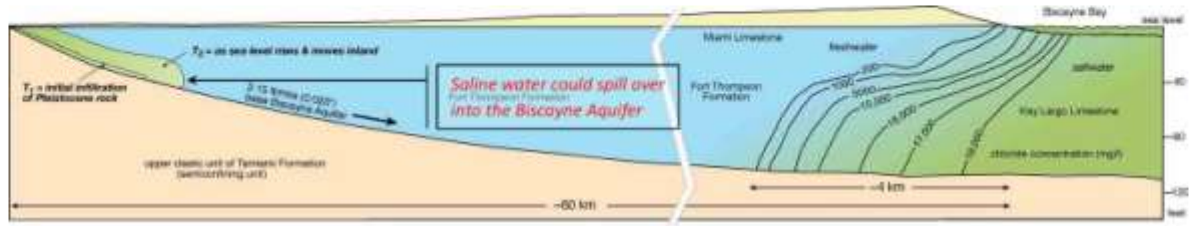

Figure 42 - Cross section of Biscayne Aquifer in South Miami-Dade showing saltwater intrusion and potential spillover of saline water from Everglades in advent of sea level rise (McNeill, 2008)

4.2.4 Saltwater Intrusion in the Southern Everglades

As sea level rises, the saltwater intrusion zone in the southern Everglades (pink area in Figure 43) will move northward. Saline water could also inundate the surface waters of the southern Everglades watershed as indicated previously in Figure 31. As salinity levels in the ground and surface waters in the southern Everglades migrate northward, it will threaten the wellfields in southwest Miami-Dade County by contaminating the southern Biscayne Aquifer at its head waters. As shown in Figure 42, the Biscayne Aquifer is wedge-shaped – its bottom surface slopes downward from the Everglades toward Biscayne Bay and the Atlantic Ocean. Because saline water is denser than fresh water, it will flow downward along this slope as illustrated. To protect the water supply in south Miami-Dade County, it is critical to slow the northward migration of saltwater in the southern Everglades. This can be accomplished by increasing fresh water flow to the southern Everglades, which is precisely the primary goal of the Comprehensive Everglades Restoration Program (CERP). Sea level rise makes the case for CERP even more compelling. Quantification of these effects using hydrological models is needed.

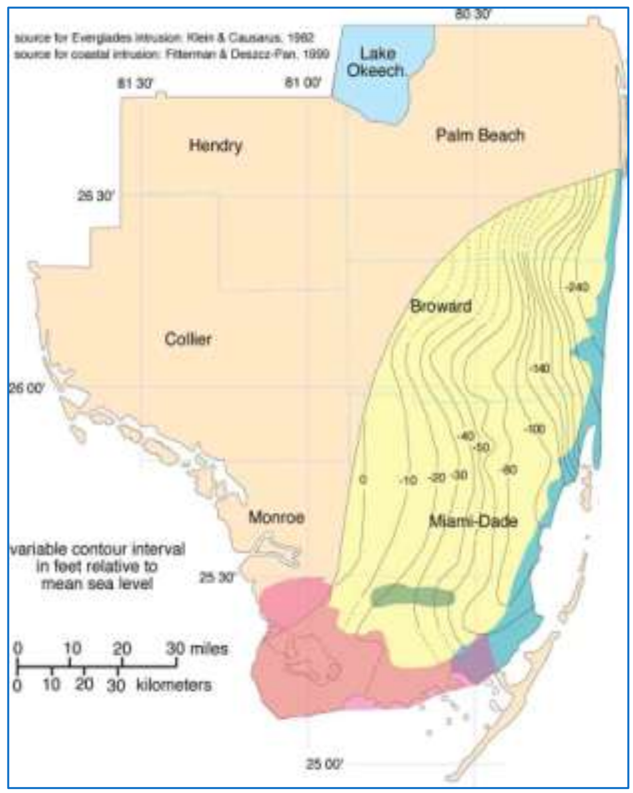

Figure 43 - Biscayne Aquifer lower contour in feet relative to mean sea level. Areas shown in blue and pink are the saltwater intrusion zones. (USGS)

4.2.5 Addressing the Threats Posed by Sea Level Rise

Successful adaptation to these threats will require creative solutions. A possible solution currently under consideration in suitable locations is hydrodynamic barriers (infiltration trenches) that strategically mound freshwater to hold back the saltwater interface. Another solution might be staging the canals in a way that raises the water table in areas of relatively high elevation such as the coastal ridge while using pumps to drain areas of low elevation. Pumping stormwater against a rising ocean may prove difficult, costly and wasteful. Another solution used before that may be worth considering again would be to drain stormwater to the Everglades where more fresh water is needed, but this approach would require sufficient stormwater treatment to comply with current environmental standards for contaminants such as phosphorous. Some of these solutions are discussed later in this report that deal with wastewater and stormwater treatment and disposal. Some solutions are beyond the scope of this study, but deserve further consideration and detailed feasibility studies.

4.3 Rainfall Patterns

More extreme seasonal variations in precipitation patterns will pose challenges for South Florida since topography limits storage of excess precipitation for use during the anticipated extreme dry periods. Extremes in weather phenomena are not new to Florida, where hurricane occurrence cycles have occurred about every 20 years and periodic droughts are noted to occur in roughly seven year cycles. The concern is that these extremes may worsen as a result of climate change.

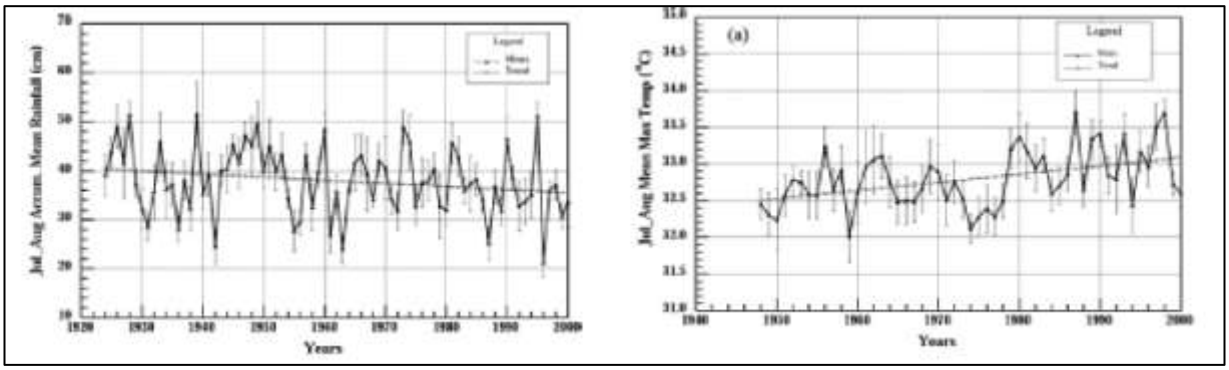

Figure 44-Change in average rainfall and average temperature for July and August from 1924 to 2000.Wet season rainfall are decreasing while temperatures are increasing. (Source: Marshall, et al 2003)

Climate models predict a continued increase in average regional air temperatures in Florida in the coming decades, including more frequent and severe heat waves, which can exacerbate drought conditions (IPCC 2007a). Since the atmosphere's capacity to hold moisture is increased at elevated temperatures, global warming can be expected to contribute to longer periods of drought and more intense rainfall events. An atmosphere containing higher energy and more water vapor would tend to cause more violent weather associated with strong cold fronts in the winter and severe summertime thunderstorms, including torrential rains, and tropical cyclones.

Current climate models are less certain in identifying how global warming will affect changes in average precipitation patterns on a local and regional level. For example, two of the more prominent climate models – the Hadley Centre Model and the Canadian Climate Centre Model – make conflicting projections for precipitation changes in Florida. The Hadley model projects a decrease in average annual rainfall, while the Canadian model projects an increase in rainfall, especially in South Florida (Twilley, et al., 2001). Both models agree, however, that Florida will experience greater precipitation extremes, including more intense rainfall events and more droughts (Twilley, et al., 2001). The effects of climate change may have already be influencing weather over in Southeast Florida. Rainfall has decreased over the past 30 years, and the daily summer pattern of convective storm activity appears to be the most affected (Marshall, Pielke, Steyaert, & Willard, 2003). Marshall states that "because the sea breezes are driven primarily by contrasting thermal properties between the land and adjacent ocean, it is possible that alterations in the nature of the land cover of the peninsula have had impacts on the physical characteristics of these circulations." This mechanism accounts for the primary wet season precipitation contributing over 70 percent of the annual rainfall. Their modeling suggests that land use changes have reduced total rainfall by 12 percent since 1900, especially in the summer, probably as a result of the loss of wetlands. Future changes in climate will likely worsen these effects. Figure 44 shows the trends of higher temperatures and lower rainfall causing reduced aquifer recharge. Already, there is strong evidence that global warming is affecting Florida's water supplies. Additional research and high resolution climate modeling for the Florida peninsula is needed before definitive conclusions can be drawn.

Figure 45 - Lake Okeechobee experienced record low levels in 2008 after several consecutive years of drought.

4.4 Hurricanes and Tropical Storms

Regardless of whether climate change will increase the frequency or intensity of hurricanes, they are likely to be more destructive to coastal areas as a result of higher sea levels. Aside from the significant wind damage that is inflicted by hurricanes, higher sea levels will result in more severe flooding and an increased threat to Southeast Florida's water supply.

Elevated sea level will cause higher storm surges that will penetrate further inland causing a higher risk of property damage, flooding by seawater, and seawater contamination of the land, surface water and ground water. The Sea, Lake and Overland Surge from Hurricanes (SLOSH) model is being updated. It predicts storm surge of up to 9 feet for the coasts of Broward County and northern Miami-Dade for a Category 5 storm making landfall in the vicinity of downtown Miami from the east. As shown in Figure 47 in dark red, there would be coastal flooding of most of

Figure 46 –The day after a hurricane.

the areas east of the coastal ridge and deep inland penetration along rivers and canals. Storm surge in Miami-Dade County can be much higher. The storm surge associated with Hurricane Andrew reached almost 17 feet in some places. With elevated sea level, storm surge will be greater by more than the amount of sea level rise because surge and wave action are accentuated on deeper waters (Alvarez, 2008). SLOSH model projections are needed to predict storm surge when sea level is elevated.

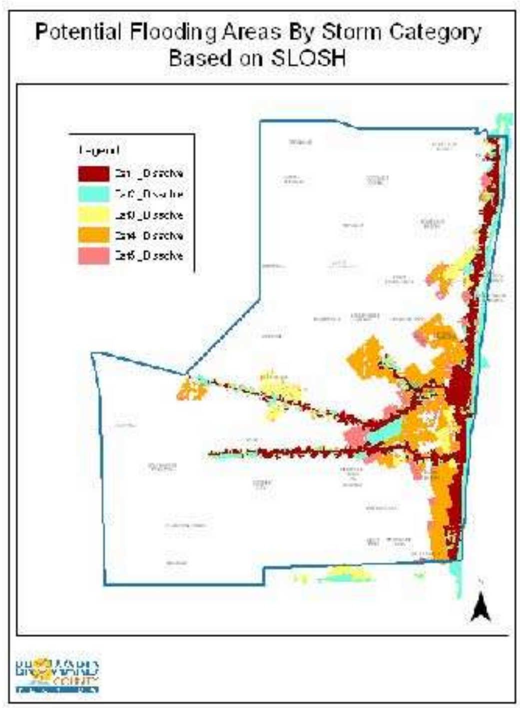

Figure 47 - Model forecast of storm surge in Broward County. Map shows that all area east of coastal ridge would be flooded in a major hurricane and surge would penetrate well inland along major rivers and primary canals.

Storm surge could temporarily contaminate the water supply with saltwater and other contaminants. Because stormwater drainage would be compromised by elevated water table and sea levels, flooding due to heavy rains will be more severe. Saltwater contamination will eventually be purged by rainfall and flow of surface and groundwater. Heavy rains usually associated with tropical cyclones would facilitate this cleansing. Occasionally, however, storms are followed by dry periods, which would extend the time needed to cleanse the aquifer. After Hurricane Andrew in 1992, storm surge in south Miami-Dade County did not cause a significant or lasting effect on the aquifer, but the surge did not appear to reach the vicinity of the water wellfields since they are not located near the coast.

Disruption of power at water treatment facilities and pumping stations during storms must be avoided by use of backup generators and adequate fuel supplies. Water and wastewater treatment plants are among the largest users of electric power in Southeast Florida. Severe storms in the past have caused extended power interruptions of days and even weeks.

4.5 Elevated Temperatures

The IPCC 2007 report (IPCC, 2007)estimates there will be a 1°C increase by 2020 in global atmospheric temperatures. Beyond 2020, IPCC cites several emissions scenarios that could result in a global temperature increase ranging from 2°C to 4°C through 2100. Increased air temperature is likely to impact water resources. As air temperatures rise, there are likely to be changes in water temperature, availability, quality, and chemistry on global, regional and local scales.

Because of water's high heat capacity and the huge mass of the oceans, approximately 80% of the thermal energy is absorbed by the oceans. The magnitude and timing of surface water temperature change is uncertain, subject to regional variability and is related to climate driven changes in the water cycle as well as socioeconomic changes that drive increased water demand (IPCC 2007).

Three key factors of the hydrologic cycle, namely evaporation, transpiration and atmospheric humidity, increase in response to increased atmospheric temperature, and all three contribute to increased urban and agricultural water demand. Increased evaporation from warmer water surfaces reduces lake levels and river flows. Increased transpiration increases water required to support terrestrial plant life, both agriculture and landscape, while soil moisture decreases as evaporation increases water needed for irrigation. High temperatures also increase the amount of water required to prevent and fight wildfires during the dry season.

Higher temperatures increase water required to sustain human life. During heat waves, increased fluid intake is needed to satisfy thirst caused by increased perspiration. Additionally, expected increases in bacteria, algae and contaminants will require higher levels of potable water treatment and will increase risks to human health.

Industrial cooling is one of the largest users of the world's water supply. Increased water temperature decreases cooling efficiency and increases the quantity of industrial water needed for water-cooled air conditioning systems, electric power production, and other processes, thereby reducing the amount of water available for human and natural life while further increasing water temperatures.

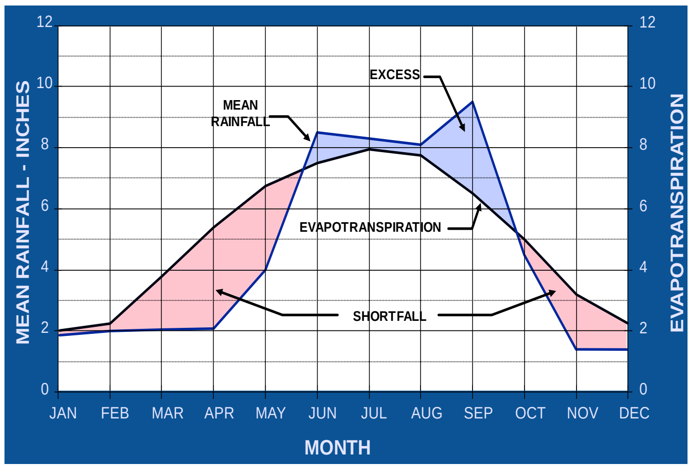

Figure 48 - Monthly averages for evapotranspiration and rainfall in Southeast Florida. Rainfall exceeds consumption during the wet season from May through September, when lack of adequate storage capacity requires stormwater release to tide to prevent flooding, especially during heavy summertime rains. There is usually a significant shortfall during the rest of the year. Water shortages are experienced toward the end of the dry season in the spring. These extremes are expected to worsen. These patterns vary over an 11 year El Niño/La Niña cycle.

Higher air temperatures change can decrease surface waters quality. Increased water temperature decreases dissolved oxygen levels. The combination of higher temperature and lower oxygen level causes surface waters to be more sensitive to nutrient and bacteria levels that contribute to eutrophication and algal blooms. Aquatic flora and fauna are sensitive to temperature, oxygen level, and aquatic chemistry. Episodes of elevated temperatures can cause fish kills and die off of aquatic plant life that would foul the water.

Elevated air temperature change in brackish estuarine waters can increase evaporation rates and concentrate salt concentrations, especially near the surface in coastal tributaries during periods of drought when runoff is decreased. These factors can lead to aquatic life kills as is experienced in Florida Bay from time to time. More freshwater flow to estuary and bays would help mitigate this problem.

4.6 Climate Change Impacts in Combination

Certain climate change impacts can be magnified synergistically when they occur in combination. The most obvious of these is that sea level rise will amplify storm surge, wave damage, and flooding due to hurricanes. A matrix analysis of the combined effects of the relevant climate change impacts when taken two at a time is shown in Table 7.

The second column of Table 7 lists the most important effects of each impact when considered alone. In the following columns, each cell presents synergistic effects if the impacts listed in the title row and title column were to occur in combination. The total effect of each combination would be the solo effects of each impact plus the synergistic effects. Major conclusions from this analysis are detailed in the sections that follow.

4.6.1 Sea Level Rise in Combination with Other Impacts:

With increasing sea level, there will be increased beach erosion, coastal inundation, encroachment of coastal wetlands and Everglades, rising water tables, and increased levels in surface waters, such as canals, retention ponds, lakes, etc. In addition, sea level rise will exacerbate the impacts of hurricanes, drought, and torrential rains, as described below.

4.6.2 Sea Level Rise with Hurricanes:

The combination of sea level rise and hurricanes can take an especially heavy toll on coastal areas and the barrier islands as severe beach erosion, coastal inundation, and substantially increased damage from storm surge and wave action. Interior flooding can be more extensive because stormwater drainage is compromised by sea level rise. The water supply is threatened by hurricanes because surface waters and the aquifer are more likely to become contaminated with seawater and runoff due to storm surge and flooding. On August 24, 1992 for example, hurricane Andrew struck southern Miami-Dade County as a Category 5 storm with gusts of over 170 mpg and 17' storm surge measured on Biscayne Bay. Property damage was estimated at $25 billion. Because there were no water wellfields in the area where storm surge occurred, there was no significant effect on the water supply. However, if a similar event occurred in North Dade or Broward County, where some wellfields are relatively close to the coast, saltwater contamination from storm surge is a possibility.

4.6.3 Sea Level Rise with Drought:

The threat of saltwater intrusion in coastal wellfields is more serious during periods of drought and the dry winter/spring season, and this is likely to be reinforced by sea level rise, as explained in Section 4.2.1. Increased backpressure caused by sea level rise reduces aquifer flow gradients and could reduce freshwater availability. Surface migration of saline water in the southernmost Everglades because of sea level rise will be exacerbated by reduced sheet flow due to diminished rainfall.

4.6.4 Sea Level Rise with Torrential Rains

Severe summertime thunderstorms, tropical storms and hurricanes are likely to be more intense as a consequence of climate change. As discussed in Section 4.2.2, sea level rise is likely to cause reduced groundwater flow and/or elevated water tables, along with a compromised stormwater drainage system and reduced flood control structure capacity. Sea level rise and torrential rains may substantially increase the region's vulnerability to flooding.

Table 7 - Interaction of Climate Change Impacts on Water Resources

	Solo Effects	Elevated Temperatures	Torrential Rains	Severe Drought	Intense Hurricanes
Sea Level Rise	• Saltwater intrusion • Water table rise • Surface water level rise • Beach erosion • Coastal inundation • Encroach coastal wetlands and Everglades	• Increased saltwater intrusion due to increased evapotranspiration and water demand • Increased salinity of southern Everglades surface waters	• Rise in water tables and canal levels • Reduced flow capacity of canal structures • Severe Interior and coastal flooding	• Increased saltwater intrusion • Reduced groundwater flow • Reduced water availability • Increased seawater encroachment in southern Everglades	• Severe beach erosion • Inundation/breaching of barrier islands • Increased storm surge • Increased wave damage to coastal property • Increased interior flooding
Intense Hurricanes	• Storm surge • Flooding • Wind damage • Beach erosion • Power failures	• Proliferation of insects • Insect/water borne disease • Heat stress due to power and water interruptions	• Extreme flooding • Aquifer contamination • Proliferation of insects • Insect/water borne disease	• Saltwater contamination of aquifer due to storm surge and short term flooding	
Severe Drought	• Water shortages • Less annual rainfall • Increased likelihood of multi-year drought • Increased evapotranspiration • Fire hazard in urban areas • Wildfire risk	• Extreme water shortages • Increased risk of fire • Damage to agriculture and landscaping • Increased water demand • Increased heat stress	• Water management challenges • Extremely dry winters and • Extremely wet summers • Water shortages and floods		
Torrential Rains	• Shorter, wetter rainy seasons • Flooding and runoff • Contamination of ground and surface water	• Biological contamination of water • Proliferation of insects • Insect/water borne disease			
Elevated Temperatures	• High evapotranspiration • Increased water demand • Heat stress • Dryness, fire risk • Severe thunderstorms • Possible tornados • Heating and hypoxia of shallow coastal waters			**CELLS HIGHLIGHTED IN MEDIUM BLUE INDICATE MAGNIFIED EFFECTS ON WATER RESOURCES**	

4.6.5 Elevated Temperatures in Combination with Drought

As previously discussed, elevated temperatures increase evapotranspiration. Higher temperatures combined with drought intensify the consequences of water shortages for municipal supplies, agriculture and the natural environment. Water demand would increase as the region becomes parched. Heat stress would be exhibited by human and natural systems. The risk of fire increases in urban areas, forests and grasslands. When extreme drought is combined with heat waves, severe drying in the Everglades can set up conditions for peat fires that can cause long-term ecological damage. Water needed to fight fires at the very time was water is in short supply. Crops and landscaping are damaged by the lack of adequate water as emergency conservation measures are put in place and enforced. These conditions will become more likely as climate change increases the frequency and intensity of heat waves and longer, more severe periods of drought.

5 Toolbox for Protecting Water Resources

A recurring theme in offsetting sea level rise and drought caused by climate change is to provide and maintain as much fresh water in the hydrologic system as possible within the constraints of stormwater management. The alternatives break down into five major categories: 1) conservation, 2) protection of existing sources, 3) development of alternative water sources, 4) reclamation and reuse of treated wastewater, and 5) stormwater management.

Table 8 – Tools for Protection Water Resources from Climate Change Impacts

Water Resource Adaptation Alternatives
Water conservation • Reducing requirements for additional treatment capacity and development of alternative water supplies (AWS)
Protection of existing water sources • Hydrodynamic barriers: aquifer injection/ infiltration trenches to counteract saltwater intrusion using treated wastewater • Horizontal wells • Salinity structures and locks control advance of saltwater intrusion • Relocation of wellfields when saltwater intrusion or other threats render wellfield operations impractical
Development of alternative water sources • Desalination of brackish waters • Regional alternative water supplies • Capture and storage of stormwater in reservoirs and impoundments • Aquifer storage and recovery (ASR)
Wastewater reclaim and reuse • Irrigation to conserve water and recharge aquifer • Industrial use and for cooling water • Indirect aquifer recharge for potable water
Stormwater management • Reengineering canal systems, control structures and pumping

5.1 Water Conservation

Water conservation, which has many short and intermediate term benefits not related to climate change, is also one of the most cost effective tools for climate adaptation.

Water conservation programs encourage reduced per capita water usage. It is said that: *"the cheapest water is the water you don't use."* From the utility perspective, it enables utilities to support population growth and economic development while avoiding or delaying the need for expanding treatment capacity and developing costly alternative water supplies. Conservation programs work best as an ongoing long-term effort aimed at incentivizing installation of water saving devices, eliminating waste, and changing end user habits, but it can take years to achieve significant results. During periods of rapid growth as occurred in Southeast Florida before the recent (presumably temporary) economic turndown, immature water conservation programs may not be able to keep up with increasing demand. This is a strong reason why conservation programs should be initiated sooner than later.

Another major benefit of conservation is that it facilitates maintaining service during periods of water shortage such as severe droughts. Emergency restrictions are employed effectively in Southeast Florida during periods of extreme drought such as has been experience in recent years, but temporary restrictions, primarily on landscape irrigation, do not provide the full range of benefits attainable with concerted conservation programs.

Reduced per capita usage through conservation can enable utilities to defer capital costs for plant expansion or development of alternative water supplies for years. Another important benefit is that conservation widens safety margins during periods of severe drought. Reduced withdrawals reduce the risk of saltwater intrusion caused by water table drawdown in vulnerable wellfields. It may also make capacity available for supplying the needs of nearby utilities for additional supplies.

Well run water plants have significant fixed costs such as debt service, amortization of capital, lean operating staffs, and administrative expense. Thus, capacity under-utilization can cause budgetary problems due to reduced revenues that can only be fractionally offset by reduction of variable costs for electric power, chemicals consumed, etc. Therefore, effective conservation programs may require rate increases or surcharges to balance budgets, meet bond covenants, etc. This can cause negative public response by the perception that it penalizes good behavior. Furthermore, capacity underutilization can cause operating problems such as increased maintenance including flushing of lines. These problems are offset in the long run as population growth increases demand, capacity utilization, revenues, and especially when capital costs for plant expansions are avoided or delayed.

The Florida Building Code requires high efficiency water fixtures and rain sensors with automatic shut- off devices in new construction and major renovations. Further savings can be achieved through soil moisture sensors and control devices to prevent unnecessary irrigation. A Broward County study (Bloetscher et al, 2009) showed that one of the most cost effective programs is rebates for retrofits with high efficiency fixtures and appliances. Since irrigation represents about half of the water usage in South Florida, one of the best approaches from an environmental standpoint is landscaping with native species that are drought and pest resistant and require less water, fertilization, and pesticides. Broward County's NatureScape Broward initiative is a model, prize-winning program that promotes such landscape principles and recognizes compliant landscapes. Irrigation with reclaimed wastewater is discussed elsewhere in this report. The U.S. Green Building Council, in its LEED green building certification program, provides incentives for water conservation through use of water saving devices and irrigation with gray water, cisterns, air conditioning condensate. Application of these approaches can substantially reduce water consumption.

Rate structure modifications can be a powerful tool to encourage water conservation. Sewage charges in most utilities in Southeast Florida are based upon water usage but are often capped. In some municipalities, garbage collection is also indexed to water usage with a cap. Furthermore, high volume users often receive lower unit rates above threshold levels. Therefore, unit cost decreases for high volume water consumption. Inverted rate structures where rates increase at high use levels can be a strong incentive for conservation.

Water conservation programs require expenditures for staff, incentives, outreach, etc. Approximate costs for the Pompano Beach utility are provided in the attached Case Study Report. Nevertheless, conservation programs can provide significant long term payback.

Information received from the City of Pompano Beach during our case study reveals how effective conservation programs can be. The city is promoting water conservation through the implementation of several ordinances, including mandated hook-up to its reuse system for commercial users and charging eligible residents an availability fee to encourage hook-up where available. Other city ordinances restrict irrigation, require installation of rain sensor devices, promote xeriscape, or require the use of ultra low volume plumbing. In addition, the City is considering new ordinances for permanent year round water restrictions and incentives for reuse.

Since 2007, the City of Pompano Beach has experienced restricted landscape irrigation due to the water shortage orders issued by the SFWMD. The City's 2007 records show a significant water use reduction mainly attributed to the landscape irrigation restrictions and the city's conservation program. The per-capita water usage was reduced from 222 gal/day in 2006 to 181 gal/day in 2007. This per-capita reduction is equivalent to water savings of approximately 430-580 million gallons from 2008 through 2025.

5.2 Protection of Existing Water Sources

Protection of existing water sources is a high priority in water resource management. As sea level rises, wellfields in the vicinity of the saltwater intrusion front will become more vulnerable. Limiting wellfield withdrawals is an obvious strategy. Already, many easterly wellfields have had to reduce withdrawals or shut down altogether. As described in the Case Study report for example, Pompano Beach experienced saltwater intrusion in their easterly wellfield as withdrawals increased to meet growing demand. Withdrawals had to be reduced and output from the westerly wellfield was increased. In an effort to preserve capacity and possibly increase output of the easterly wellfield, the utility is partnering in undertaking an experimental demonstration of aquifer injection to create a saltwater barrier.

5.2.1 Hydrodynamic Barriers and Infiltration Trenches

Injection of reclaimed wastewater directly into the aquifer is a viable approach for countering saltwater intrusion. In this concept, treated wastewater is injected into the aquifer downstream of the wellfields to create a freshwater barrier to offset sea level rise.

The hydrodynamic barrier works by raising the water table with treated wastewater purified using full membrane treatment. The method increases hydraulic head between the saltwater interface and the wellfield and pushes back the saltwater intrusion front (See Figure 49). A preferred method for protecting a large wellfields is to use shallow horizontal injection wells, called infiltration trenches.

The Pompano Beach Water Utility and Broward County are partnering in a feasibility study to test the effectiveness of infiltration trenches for preventing saltwater intrusion in its easterly wellfield (CDM, 2009). Hydrologic modeling is being performed at Broward County using a USGS model (Zygnerski & Langevin, 2007). The pilot demonstration is planned using groundwater or potable water to test infiltration rates. If successful, other tests will be run. Ultimately, the goal is to use highly treated wastewater from the City's reuse water plant and incorporation of a membrane bioreactor process and disinfection to assure water quality. The approach is expensive with capital costs in the range of $10-12/gal treated water and high energy consumption and operating costs. Economic justification depends upon receiving an allocation credit from SFWMD for the aquifer recharge so that the City's can increase raw water withdrawals from the Biscayne Aquifer, but the maintenance of existing wellfield capacity might also warrant pursuit of such recharge strategies as sea level rise and the potential for further saltwater intrusion of potable wellfields requires more active management.

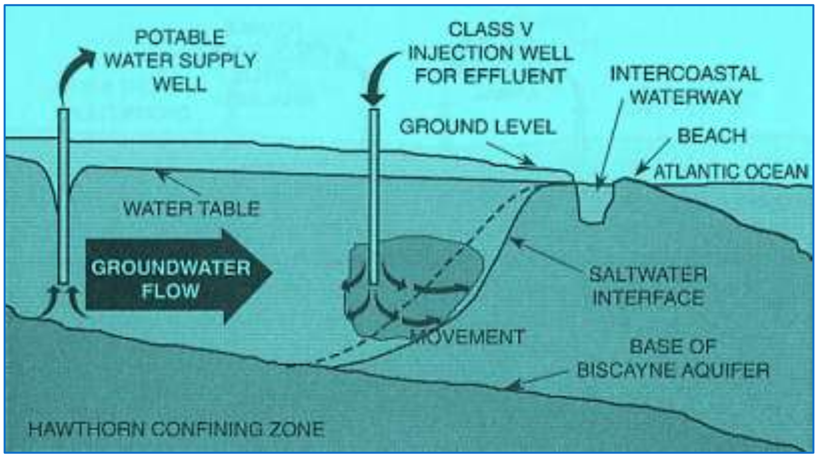

Figure 49 - Direct injection of reclaimed water to create a saltwater barrier.

The possibility of wellfield contamination by backflow from the injection well would be avoided by applying a high degree of treatment to the recharge water and by locating the injection wells at a safe distance downstream. Another concern is that raising the water table reduces soil storage and increases the possibility of flooding, especially when sea level rise reaches at least 1 to 1.5 feet or more, which is projected for the 2040-2060 timeframe. (See Section 4.2.1 on Predicting Sea Level Rise). Earlier model calculations indicate that the water table could rise by 5 feet or more at recharge rates assumed at that time, which could be acceptable given land elevations in the vicinity of the wellfield (Dunn, 2007). Excessive water table rise may be counterbalanced by reducing injection rates or by increasing aquifer withdrawals at the protected wellfield. The relatively high elevation of Pompano Beach's eastern wellfield is one of the factors favoring this project. However, water table rise of several feet or more may not be tolerable in some low elevation locations. Nevertheless, this approach applied strategically and where supported by hydrological modeling may be an effective tool for protecting wellfields from saltwater intrusion caused by sea level rise.

A potential problem is clogging of infiltration wells with algae, which is the reason for proposing treating with membrane bioreactors and disinfection.

5.2.2 Horizontal Wells

As saltwater intrusion becomes more of a threat to a wellfield, an alternative worth considering is replacement of vertical wells with shallow horizontal wells as indicated above. Because saltwater has higher density than fresh water, the fresh groundwater tends to flow above the saltwater as it approaches the coast. A vertical well causes a steep drawdown cone in the water table and sucks up a

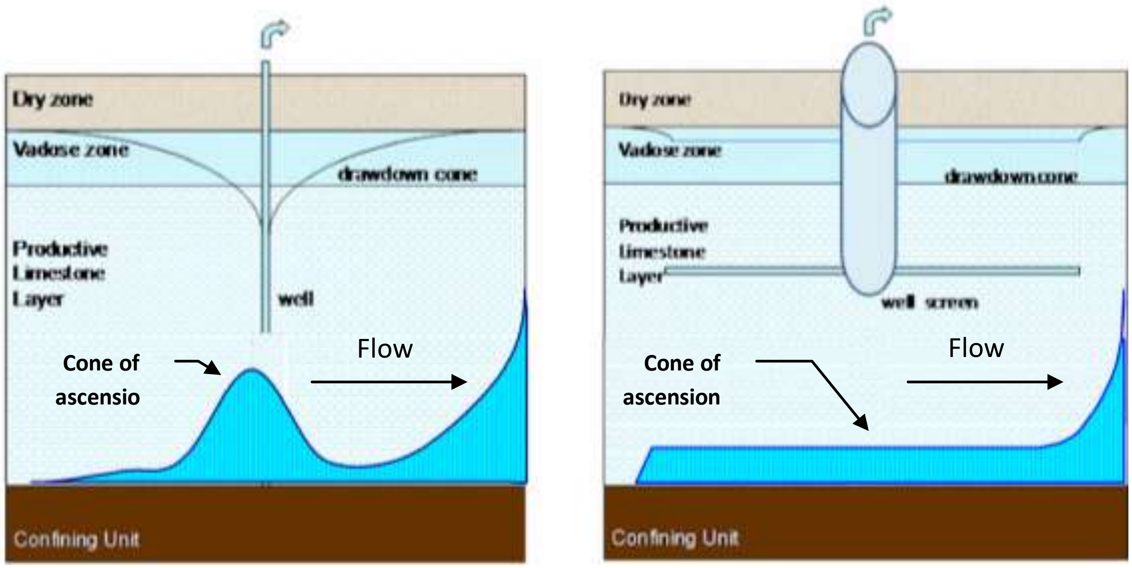

Figure 50 - Horizontal wells (on right) can reduce the risk of saltwater intrusion by withdrawing water over a wider area and at less depth than standard wells (Bloetscher & Muniz, 2008).

sharp cone of ascension from the zone of dispersion as shown in Figure 50 on the left. A horizontal well spreads the region of influence over a much wider area and also, because it can be located in a shallower position in the aquifer, it has a much shallower drawdown cone and cone of ascension as indicated in the figure on the right. Horizontal wells enable drawing fresh water from the shallow lens of fresh water in the upper aquifer, making it possible to draw good quality fresh water when a vertical well might be intruded by saltwater. Another advantage is that horizontal wells, if properly designed, can often have higher capacity than vertical wells where saltwater intrusion is a concern.

One drawback with horizontal wells is that since they are placed in a shallow location, the water they draw may be considered "groundwater under the influence of surface water." Consequently, the permitting process is likely to be more challenging and the water is likely to require a higher level of treatment for removal of nutrients and other contaminants. Nonetheless, this tool can extend wellfield life when saltwater intrusion becomes a serious threat that cannot be countered by other means.

5.2.3 Salinity Structures

Primary canals and control structures operated by the SFWMD were originally built to control flooding through discharge of stormwater to tide. In recent years, surface water managers have also used them to great effect to control water table levels, since water table is controlled by the extensive system of canals. By maintaining high canal levels, the canals and aquifer are used as reservoirs with substantial capacity. As much rainfall as possible is captured and retained, substantially reducing the release of water to tide except during extraordinary downpours or in anticipation of major storms such as hurricanes.

These control structures prevent the inland migration of seawater and substantially define the location of the saltwater intrusion line. There is fresh water on the inland or "headboard" side of the structures, whereas waters on the ocean or "tailboard" side are tidal and brackish. This has become such an important function of the control structures, that they are often called "salinity structures" rather than "flood control structures" as they were originally termed. Both terminologies are used in this report depending upon which of their functions is being discussed.

Figure 51 - Salinity structures control flooding by releasing primary canal water to tide when necessary. They are also used to maintain elevated canal levels for stormwater storage and to recharge aquifers and control saltwater intrusion. (SFWMD)

There are long stretches where salinity structures are spaced far apart, such as where there are natural riverine systems and coastal wetlands. There are also navigable rivers used by pleasure boats to access the ocean throughout much of Miami-Dade, Broward, and Palm Beach Counties, and salinity control structures may be as much as 3 to 5 miles inland. Boating and fishing are important contributors to the local lifestyle and economy.

Easterly wellfields that are close to the salinity front, such as in Pompano Beach, are vulnerable to saltwater intrusion. This is especially true during periods of drought and during the later months of the dry season in the spring. The western wellfields being further from the ocean and closer to the Everglades are not as prone to saltwater intrusion, which is why westward relocation of wellfields is an attractive alternative despite some compromise in water quality. However, under the Regional Water Availability Rule that prevents any additional demands on the regional system associated with urban water management activities and consumptive use demands, i.e. that might result in withdrawals from the Everglades conservation areas, locating wellfields to the west has become much more challenging.

An alternative method suggested for protecting the eastern wellfields from saltwater intrusion would be to relocate salinity structures closer to the ocean, which in some areas would require construction of locks to allow ocean access for boats. This idea would likely meet substantial resistance from boat owners, marina operators, and owners of property on the rivers and canals with ocean access. It would be politically unpopular and could have adverse effects on Southeast Florida's tourist and marine industries. There would have to be very compelling justification in order to be justified in lieu of alternatives such as well relocation or alternative water supplies.

5.2.4 Relocation of Wellfields

Strategic relocation of wellfields to areas where water supplies are plentiful and reliable is one of the most attractive options to be considered when current wells are threatened by saltwater intrusion or other impacts. Site selection is critical and must take into account variations in local geology, recharge capability, groundwater flow, impacts on the Everglades, and potential vulnerability to future climate change impacts and other threats. With regards to water supply planning, care must be taken not to exceed safe yield, the volume of water that can be withdrawn without adversely affecting the aquifer, water quality, or depleting the resource.

It is also critical that urban and economic development plans consider long range water supply needs and protect potential wellfield sites with an eye on projected climate change impacts on the land and water supplies. This not only includes protecting areas that might be valuable future wellfield locations, it should also assess the vulnerability of current wellfields that might have to be abandoned and replaced in the future.

High recharge capacity from rainfall and nearby green space such as freshwater wetlands, canals, lakes, and swale areas is a critical element of site selection. There is relatively little undeveloped land in Southeast Florida so whatever land may be needed for wellfield development in the future should be included in land use allocations. Because Palm Beach County had the foresight to reserve the wetlands adjacent to its wastewater treatment plant in Boynton Beach, despite the fact that the area was under intense development, it enabled creation of the prize-winning Wakodahatchee and Green Cay Wetlands for aquifer recharge.

Figure 52 - Water well drilling rig

Under the Regional Water Availability Rule, which limits raw water withdrawals from the Biscayne Aquifer, there are restrictions on withdrawals where model predictions indicate that further groundwater withdrawals are likely to result in additional seepage from the Everglades conservation areas. This places significant constraints where to locate sites for new wells needed to replace eastern wellfields threatened by saltwater intrusion. It is important that land use planners fully assess the potential vulnerability of current wellfields and attractiveness of locations that may be suitable for further water resource development including consideration of potential impacts due to sea level rise, saltwater intrusion, and other impacts cause by climate change. As saltwater interface migrates further inland due to sea level rise threatening the usefulness of easterly wellfields, it may eventually become necessary to reevaluate the Regional Water Availability Rule in order to assure adequate water supplies in the future, since westward relocation of wellfields is one of the most viable options.

5.3 Development of Alternative Water Sources

Development of alternative water sources is an important strategy for conserving raw water resources, assuring that there are sufficient water supplies to meet municipal demand and also to provide the water needed to rehydrate the Everglades under CERP. It is also an important tool for adaptation to the effects of sea level rise and other climate change impacts. Alternative water sources can be developed in several practical ways, such as 1) desalination of brackish water, 2) reclamation of treated wastewater for reuse, such as irrigation and industrial uses, 3) aquifer recharge with treated wastewater or stormwater

5.3.1 Desalination by Reverse Osmosis

Recovering fresh water from seawater or brackish water using reverse osmosis membrane diffusers is a preferred option where quality fresh water is in limited supply (Bloetscher & Muniz, Water Supply in South Florida - The New Limitations, 2008). The largest seawater desalination plant in the United States is located nearby in Tampa, Florida. It is an attractive option for adaptation to climate change since rising seas and saltwater intrusion threaten to reduce supplies of fresh water from the Biscayne Aquifer. The energy requirements and costs of seawater desalination are much higher than for brackish water since energy required increases with osmotic pressure which in turn increases with salt concentration. Therefore, it is unlikely that Southeast Florida would have to resort to seawater desalination considering the availability of more dilute brackish water. Reverse osmosis could also be used to reclaim treated wastewater and stormwater.

This technology, first developed in the 1960s, has been the subject of ongoing research and development, and major improvements have significantly been made in improved membrane performance, reduced costs and lowered energy requirements. Ongoing development continues to yield improvements. At the current state of development, 50% recovery is achievable from seawater and up to 85% for mildly brackish water like that from the Upper Floridan.

Figure 53 - A modern large scale reverse osmosis installation

The Floridan Aquifer is brackish with salinity increasing with depth and proximity to the coastline. Dissolved chloride in the upper Floridan Aquifer ranges between 2,000 and 5,000 mg/L (much less than seawater at 35,000 mg/L) depending on precise location, making this source suitable for low pressure reverse osmosis. Desalination of brackish water requires substantially less energy than seawater desalination since the osmotic pressure that must be overcome increases proportionally with salt concentration. The Floridan is sufficiently productive in most locations to produce approximately 1 to 2 million gallons per day of raw water with relatively closely spaced wells (Bloetscher & Muniz, Water Supply in South Florida - The New Limitations, 2008). This source is being increasingly tapped as a practical alternative water source since restrictions were placed on withdrawals from the Biscayne Aquifer under the Regional Water Availability Rule. The Floridan may have limited capacity however because it is not locally recharged and only moderately transmissive. This is a subject of study and planned modeling.

As sea level rise increases the likelihood of saltwater intrusion of the Biscayne Aquifer, as discussed in Section 4.2.1, desalination of brackish water from the Biscayne Aquifer may be a preferred alternative depending on salinity, productivity, and economic considerations.

Desalination is a molecular filtration process capable of retaining salt and other dissolved solids and allowing very pure water to permeate through semi-permeable membranes. Figure 53 is a photograph of a typical large scale desalination installation. The treatment system is illustrated schematically in Figure 54 below. Raw water is filtered to remove suspended solids and then pumped under moderate to high pressure to the first stage reverse osmosis membrane cartridges. Each cartridge contains a bundle of porous tubes with inner surfaces coated with a semi-permeable membrane. Purified water, called "permeate," diffuses through the membranes and is collected in holding tanks. The retained dissolved solids are concentrated in "concentrate," sometimes called "retentate." The concentrate is repressurized with pumps and flows to that second stage of membrane cartridges to recover additional permeate in the same manner. Permeate from all of the cartridges is combined and collected in storage tanks for further treatment by chemical stabilization and final disinfection before it can be used as potable water. The concentrate from the second stage is disposed, usually by injection under pressure to deep wells in the Boulder Zone (shown in Figure 62). The process requires substantial electrical energy (about three times that required for conventional treatments such as lime softening) to drive the pumps and other equipment required.

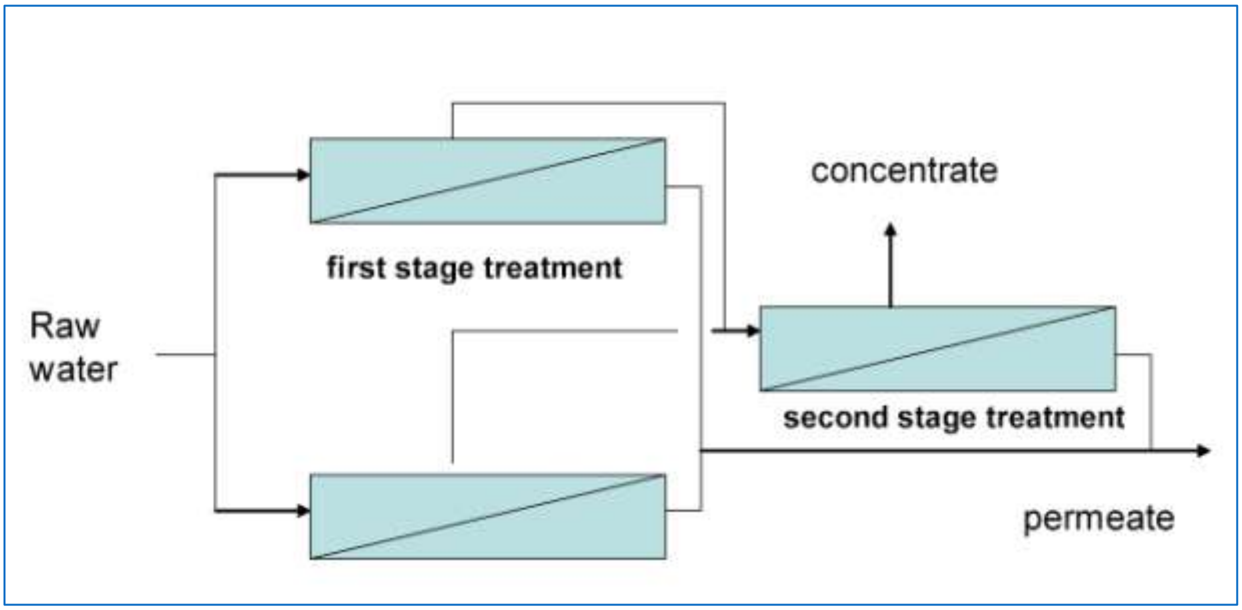

Figure 54 - Schematic flow diagram for a 2-stage reverse osmosis desalination facility

The capital cost for a reverse osmosis treatment facilities are site specific and fluctuate depending on a number of variables. A preliminary planning value for capital costs are in the order of $5-7/gal capacity. Operating costs are likely to be in excess of $3.00 per 1,000 gallons, about three times that of conventional treatment.

Several issues with desalination by reverse osmosis are noteworthy:

1. Raw water is best recovered from wells rather than surface waters to avoid problems with suspended solids and microscopic biological contaminants.
2. Membrane fouling, either biological or other, is an ongoing concern.

3. Electric power requirements are significant, and increase geometrically as the concentration of dissolved solids in the raw water increases.
4. Disposal of the concentrate by deep well injection or otherwise is problematic.

Raw water from the upper Floridan aquifer is brackish and contains ammonia, arsenic and low levels of radioactive substances (radionuclides), which are removed in the process but complicate processing and disposal.

Federal regulation for underground injection is published in the Code of Federal Regulations (40 CFR 146). In Florida, this program is delegated to the Florida Department of Environmental Protection (FDEP) with ongoing oversight by the federal Environmental Protection Agency (USEPA). Chapter 62-528 of the Florida Administrative Code (F.A.C.) is the legislation protecting underground sources of drinking water, preventing degradation of the quality of adjacent aquifers, and governing the construction and operation of injection wells.

The regulatory status of underground concentrate injection is uncertain however. The USEPA has promulgated regulations to require costly Advanced Water Treatment (AWT) and high intensity disinfection with demonstrations, monitoring and ongoing review. EPA proposed limiting the applicability of the rule to "specific counties and under certain geologic conditions in Florida," including Broward, Miami-Dade, Monroe, and Palm Beach. Local utilities contend that, because the concentrate is injected beneath the impervious Boulder Zone, there is no possibility of contamination of Underground Sources of Drinking Water (USDW), i.e. the Biscayne and Floridan aquifers. Therefore, such costly treatments should not be necessary. This position is supported by risk assessments conducted by the University of Miami (Englehardt, et al., 2001), Bloetscher, 2001, (Bloetscher, et al., 2005)) and USEPA (EPA, 2002) which indicate that injection wells are safe alternatives for disposal of wastewater and concentrate, a position that is opposed by some environmental groups. Consequently, there is ongoing litigation which increases the risk of regulatory uncertainty.

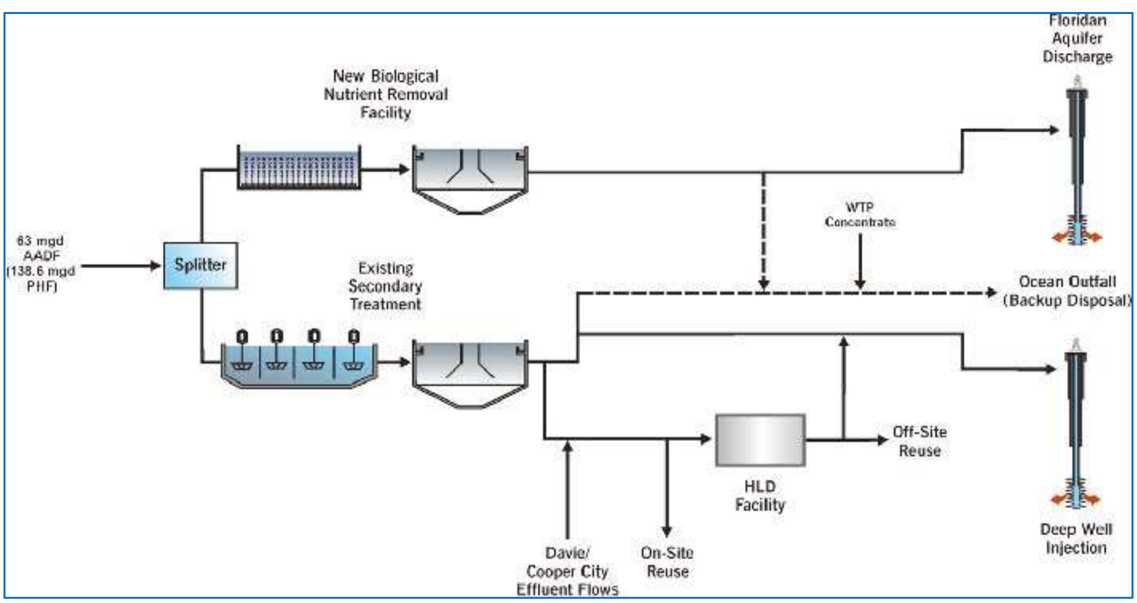

Figure 55 - Advanced treatment technologies are required for aquifer recharge by well injection.

5.3.2 Aquifer Recharge

There are various methods of recharging surficial aquifers using stormwater or treated wastewater. These include:

1. Diverting storm water to impoundments located on permeable land
2. Discharging treated water into surface waters for aquifer recharge
3. Direct injection to the aquifer of treated stormwater or surface water from reservoirs
4. Percolation ponds or wetlands using tertiary treated wastewater
5. Direct injection of highly treated wastewater using reverse osmosis
6. Other similar variations of these approaches

Figure 56 - Green Cay Wetlands in Palm Beach County, along with Wakodahatchee Wetlands, were constructed for recharge of the surficial aquifer with tertiary treated wastewater from the nearby wastewater treatment plant. (Photo credit: Barry Heimlich)

Artificial recharge with stormwater is an option used in many regions of the country. Diversion of stormwater to large impoundments or reservoirs is employed in the Everglades Storm Treatment Areas (STAs) and the Water Conservation Areas (WCAs) for that matter.

FDEP concluded that introducing wastewater into surface canal systems in South Florida would be indirect potable reuse. Therefore surface water recharge, as suggested by SFWMD, would require full treatment according to state and local standards including reverse osmosis, ultraviolet disinfection and advanced oxidation at high cost. A 2006 FDEP report indicated that local benefit would be reduced because a significant amount of reuse water introduced to canals would go to the ocean. Broward County rejected the recommendation to reduce its surface water standards for phosphorous and other contaminants, which are stricter than the state's.

Discharge of tertiary treated wastewater to percolation ponds built on permeable land is already used in Southeast Florida. Examples are the manmade Wakodahatchee and Green Cay Wetlands in Palm Beach County. Palm Beach County uses tertiary treated wastewater to recharge its surficial aquifer by percolation in two manmade wetlands, which have become spectacular wildlife preserves that attract birdwatchers, photographers and tourists from all over the country. This method unfortunately was shown not to be feasible in Broward County by CH 2M Hill, the engineers for the Palm Beach wetlands, primarily because suitable land was not available.

Treated wastewater has been employed for recharge for decades at the Orange County, California Water District's Water Factory 21. Water Factory 21 was the worldwide prototype treatment facility for reuse of highly treated wastewater. It began operations in 1976 and has continuously met or exceeded the U.S. EPA drinking water standards. Purified reclaimed water is produced using various advanced processes, including reverse osmosis and ultraviolet disinfection. The water is also supplied to industry and used for irrigation. The facility is a model that has been visited annually by more than 1,000 water specialists, scientists, and leaders from more than 30 countries around the world (U.S. Water News Online , 1998). Based on Water Factory 21 experience, construction costs for similar facilities in Southeast Florida would approach $12/gal of treatment plant capacity (CDM, 2009), and operational costs over $10/1,000 gallons treated.

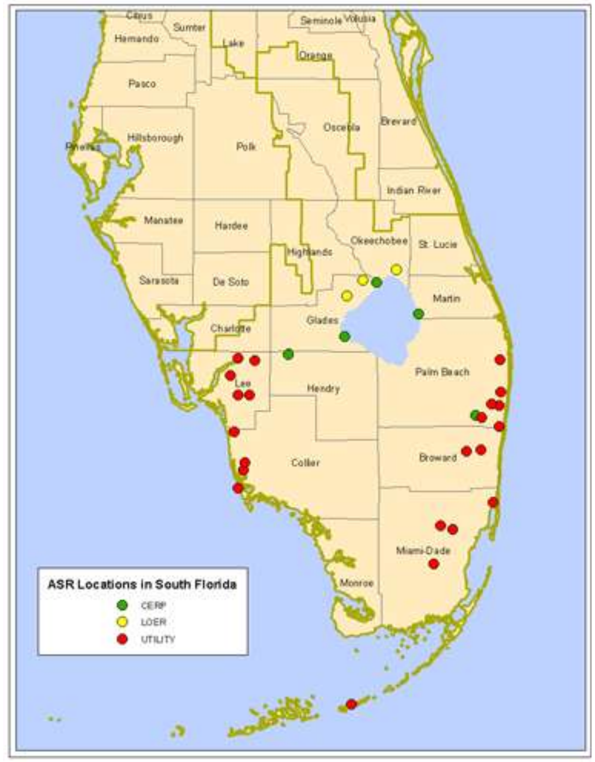

Figure 57 - Significant efforts have been made to develop Aquifer Storage and Recovery in South Florida with limited success to date.

5.3.3 Aquifer Storage and Recovery

Aquifer storage and recovery (ASR) is a method used in many areas of the country to store excess water underground. Its use was to be an important part of the Comprehensive Everglades Restoration Plan. Many attempts at ASR have been made in Southeast Florida as illustrated in Figure 57. After years of effort, only one ASR well has been successfully operated to recover potable water on successive cycles at a rate deemed useful - the City of Boynton Beach. Projects have been unsuccessful for a number of reasons including heavy metals contamination, leakage and others. As a result, efforts to apply the method are at lower priority. Instead, more emphasis is being given to surface water storage, and tighter restrictions have been place on Biscayne Aquifer withdrawals and use of Everglades and Lake Okeechobee water for municipal supply under the Regional Water Availability Rule in order to encourage conservation and reserve freshwater for the Everglades. A significant opportunity to increase surface water storage currently being explored is the "River of Grass" purchase of a major tract used by U.S. Sugar Corporation for sugar cane production.

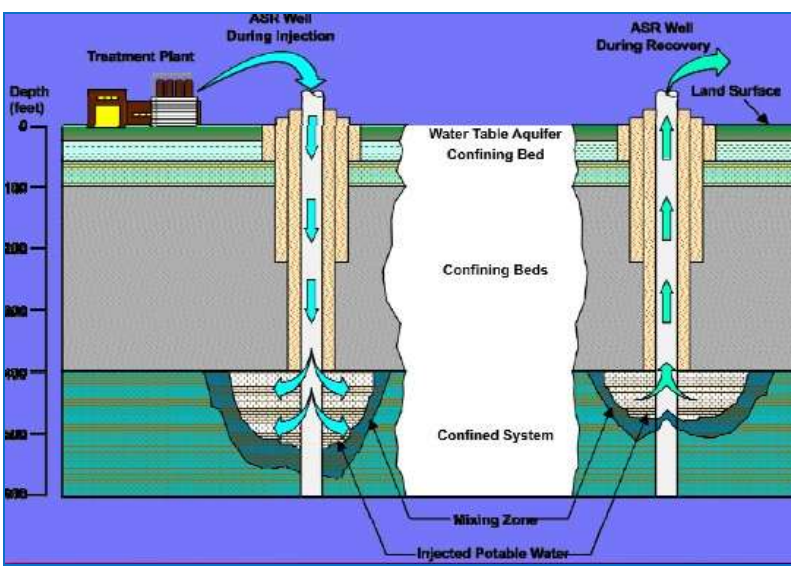

Figure 58 - Aquifer Storage and Recovery (ASR) uses a confined aquifer to store excess water for later withdrawal during periods of water shortage (Broward County).

In ASR, a confined aquifer, such as the Floridan in South Florida, is used to store water during times of excess to be recovered to meet peak demand during times of shortage (see Figure 58). It can be applied to potable water, treated wastewater, or treated stormwater as deemed applicable. During the wet, low-demand months between June and October, underutilized water treatment plant capacity can be used to treat water for injection underground into a confined brackish water aquifer for future recovery. In theory, a bubble of treated freshwater is formed. When demands exceed water treatment plant or wellfield capacity or during an equipment shutdown, the stored water is recovered, disinfected, and blended with newly treated water.

Ideally, with effective use of ASR, water treatment facilities can be sized and operated for average demand rather than peak demand, with the ASR water only requiring disinfection and blending with the newly treated water. Considerable investment in capacity can be saved and more efficient overall operation can reduce operating cost and conserve energy providing there are good recovery yields. The economics are especially attractive for large scale reverse osmosis facilities.

For an ASR system to satisfy the requirements of the FDEP, the U.S. EPA, and other regulatory agencies, the injected water must be treated to meet the applicable water quality standards for the aquifer selected for storage. Presently, this requires treatment to potable water standards to store water in a G-2 aquifer, the designation for storage of drinking water.

However, some mixing of the stored water with native water usually occurs, and the recovered water will contain some natural groundwater constituents. At the beginning of the recovery process, water quality is very near that of the injected water. However, as water is withdrawn, its quality tends to approach that of native water. Upon startup of a new ASR well, recovery generally shows significant deterioration in quality; however, recovery efficiency usually improves after each cycle if the ASR well is installed in a desirable formation. Boynton Beach for example reports recovery efficiency between 70 and 95 percent. The suitability of an ASR system depends upon the system design and the hydrogeologic characteristics of the aquifer. In the final analysis, what matters is whether the zone can both receive and return water of the approximate quality at which it was injected and at what cost.

Figure 59 - A typical ASR well head.

An advantage of aquifer storage and recover over surface water storage is that it avoids evaporation losses. However, full recovery of water stored underground is never achieved either. Losses can occur in two ways, by leakage of stored water through the upper or lower confining layers, or by leakage of native water through the confining laying into the stored water.

Despite difficulties to date in applying ASR as conceived under CERP, there may be a ways of employing it to advantage as an adjunct to wastewater and stormwater reclamation and reuse. For example, filtered and possibly disinfected stormwater or wastewater could be stored underground during the wet season. It could then be recovered and treated to the appropriate level either for irrigation during the dry season or for potable use. Although this approach does not have the advantage of using excess potable water treatment capacity during periods of low demand, it would provide an underground reservoir to store excess stormwater or wastewater during the wet season when the need for irrigation is reduced and enable recovery for reuse or potable supplies during periods of drought. If water tables become elevated in response to sea level rise, it may not be feasible to irrigate with reclaimed water during the wet season because of the potential for flooding. ASR could be a valuable tool for reserving excess water for use during shortages.

5.3.4 Capture and Surface Storage of Excess Runoff

Retaining as much fresh water in the system as possible to protect the water supply is a general theme throughout this report. Because Southeast Florida has such flat topography, there are limited opportunities for surface water storage such as reservoirs. Taking advantage of opportunities to capture fresh water that would otherwise go to tide seems obvious. Several important opportunities have been identified and are being considered:

5.3.4.1 Reservoirs

A collaboration of public utilities in Broward and Palm Beach Counties has joined to evaluate the feasibility of creating a new reservoir in west Palm Beach County. A somewhat unique feature of this project is that unlike most reservoirs that are created by damming a river, this reservoir would be specifically dug for this purpose as a quarry or rock pit. The project, referred to as the C-51 Reservoir and similar to the nearby L-8 reservoir, proposes capturing fresh water from the C-51 "Hillsborough" Canal and storing it in western Palm Beach County in a rock pit serving as an in-ground reservoir in the rock pit. It is similar in concept and would be adjacent to the L-8 reservoir that already exists in the area. There are a number of technical and political challenges to overcome, the most notable is to establish that the area is geologically suitable, i.e. impervious and that groundwater will not be contaminated. Another is how best to allocate and convey water from the reservoir to the participating utilities. Preliminary analysis indicates that about 160 MGD could be recovered at an estimated capital cost of $2.50-3.00/MGD) that is substantially less than other alternative water supply approaches. It represents a significant portion of Southeast Florida's projected water supply shortfall of approximately 250 MGD by 2025. Further feasibility studies are proceeding with oversight by the advisory task forces of both counties and the SFWMD.

Figure 60 – Stormwater treatment areas provide habitat for egrets, herons, wood storks, roseate spoonbills and other wading and water birds. (Photo credit: Barry Heimlich).

5.3.4.2 Water Treatment Areas/Impoundments

The U.S. Army Corps of Engineers (USACE), which is responsible for the construction work associated with CERP, has converted a vast area of the upper Everglades into large impoundments which collect rainfall and runoff from sugar cane and sod fields of the Everglades Agricultural Area. These waters are too high in phosphorus and other nutrients to release to the Everglades without doing ecological damage. These impaired waters are held in the impoundments, called stormwater treatment areas or STAs, which enables phosphates to be biologically removed and/or precipitate out of the water. Many square miles of impoundments have been constructed as a very effective method of capturing these waters for hydration. These areas have also become outstanding habitat for fish, birds, alligators, and other wildlife.

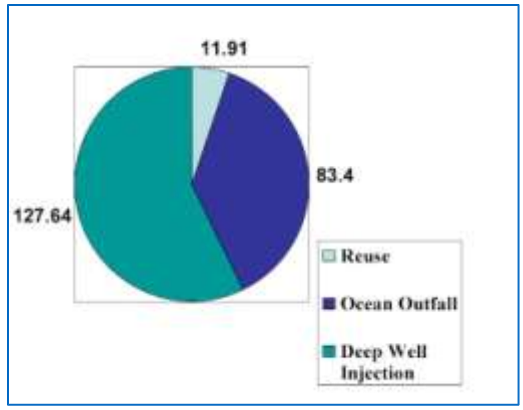

Figure 61 - Broward County wastewater disposition as of 2006. (SFWMD). Approx. 57% goes to deep well injection, 37% to ocean outfall, and 5% to reuse.

Another project in its latter stages is to capture urban stormwater runoff to substantially reduce water currently being discharged into the Everglades to enable recharge of the Biscayne Aquifer. Two impoundments called C-9 and C-11 are to be constructed by USACE in western Broward County to collect stormwater from the C-9 and C-11 drainage basins for this purpose.

In 2008, Florida Governor Charlie Crist seized the opportunity to acquire a large tract of land (up to 180,000 acres) south and east of Lake Okeechobee currently owned by the U.S. Sugar Corporation under a program dubbed *Reviving the River of Grass*. This land is primarily used to grow sugar cane. If the state can successfully negotiate and finance this purchase, cane production will eventually be phased out of over several years and the land converted to water treatment areas or restored to nature, greatly increasing water available for the region. Although this land acquisition has delayed CERP temporarily, if successful, it will greatly enhance the restoration plan.

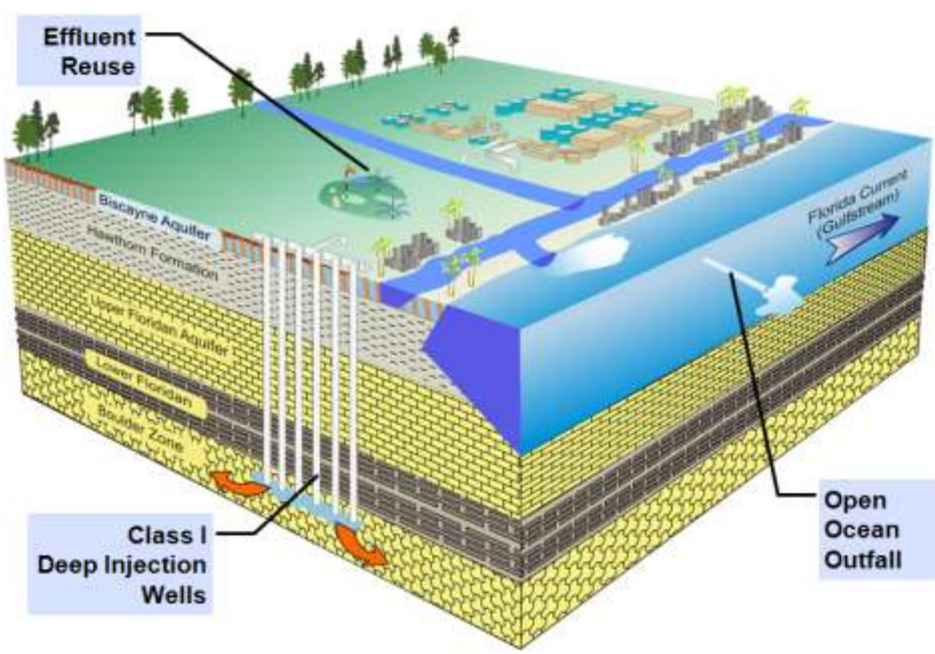

Figure 62 - Wastewater discharge and reuse options. Ocean discharge and deep well injection are currently primary means of disposal. Ocean outfalls are being eliminated under state legislation out of environmental concerns. (Crouse; Garcia; Broward County, 2008)

5.4 Wastewater Reclaim and Reuse

Presently, most of the treated wastewater generated in Southeast Florida is either discharged to the ocean or deep well injected into the Boulder Zone. In the 2006 update of the Lower East Coast Water Resources Plan, state legislation mandated elimination of ocean outfalls by 2025 to comply with environmental requirements. Furthermore, the Regional Water Availability Rule of 2007 caps utility withdrawals from the Biscayne Aquifer. As a result, major efforts are being made on wastewater reclamation and reuse. Primary applications that do not require costly advanced treatment are irrigation and industrial cooling, such as for cooling towers in large air conditioning systems, cooling water for power plants, and other industrial uses.

5.4.1 Reclaimed Wastewater for Irrigation

Florida is among the leaders in reclaimed water use in the United States, with some 400 facilities using reclaimed water in a variety of ways, including irrigation of agricultural land, golf courses, roadway medians, landscaping, cemeteries, residential lawns and gardens, and industrial uses such as cooling towers. Southeast Florida, however, has lagged behind the rest of the state in wastewater reuse. The

state and its agencies, including the SFWMD, are aggressively encouraging local utilities toward reuse of treated wastewater for conservation, to recharge the aquifer, and to eliminate ocean outfalls. Southeast Florida, with high populations, dense development, access to the ocean, and deep injection well disposal, has utilized relatively large regional systems since the 1960s and 1970s. Centralized wastewater treatment plants made ocean outfalls and injection wells economically justifiable (Englehardt et al, 2001, Bloetscher, et al, 2005). Phase-out of ocean outfalls has increased incentives for developing wastewater reuse in order to avoid the cost of deep-well injection while obtaining use credits for recharge by irrigation and other reuse methods.

State rules (62-610, F.A.C.) define requirements for reclaimed water systems. The intent is to prevent low level contaminants in reclaimed water reaching water supply sources. For all slow-rate reuse systems involving irrigation of sod farms, forests, fodder crops, pasture land, or similar areas, the reclaimed water must meet secondary treatment and basic disinfection levels before land application, and there are rigid standards regarding where slow rate irrigation can be applied so as to minimize pathogen exposure.

Public access reuse systems, where irrigation areas are accessible to the public, include residential lawns, golf courses, cemeteries, parks, landscape areas, and highway medians. In this case, reclaimed water must be filtered to less than 5.0 mg/L of suspended solids before the application of the disinfectant to assure that disinfection inactivates viruses and other pathogens. Filtration also removes protozoan pathogens (*Cryptosporidium* and *Giardia*). Ground water monitoring and regular testing for pathogens is required adjacent to unlined storage ponds or lakes. Viruses are not efficiently removed by filtration or chlorine disinfection.

Southeast Florida's large centralized systems have not until now lent themselves to widespread irrigation since that would require extensive and costly reclaimed water distribution systems using "purple pipe" to distinguish them from potable water and sewer systems. Legislative mandates to eliminate ocean outfalls, requirements for beneficial use of reclaimed wastewater, and restrictions on raw water withdrawals from the Biscayne Aquifer have intensified efforts to reuse wastewater for irrigation and industrial cooling.

Shortcomings of wastewater reuse cited by some Southeast Florida utility directors include:

1. Most wastewater treatment plants generate substantially more treated wastewater than can be used for irrigation or hydrodynamic barriers, especially during the wet summer and fall months.
2. The Biscayne Aquifer, being one of the most transmissive aquifers in the world, may be more vulnerable to wellfield contamination by constituents present in irrigation quality reuse water.
3. Reclaimed water may be contaminated with low levels of pharmaceutically active substances (PAS), viruses, micro-constituents, and organic compounds which are difficult to remove and may pose environmental or public health concerns.
4. The chloride content of much of Southeast Florida's wastewater exceeds 1,000 mg/L as a result of sewer line leakage especially in communities close to the ocean, where there is saltwater intrusion. Therefore, it cannot be reused for irrigation without reverse osmosis treatment unless leakage can be substantially eliminated.

Figure 63 - Piping used for distribution of reclaimed wastewater is colored purple to distinguish it from potable water pipes. (SFWMD)

Furthermore, as sea level rises, controlling the water table and surface waters at acceptable levels are likely to require significant discharges of stormwater to the ocean and/or the Everglades by pumping. The challenge may become how to discharge excess ground and surface water to avoid flooding, which may become more problematic even without obligation to beneficially reuse tens of millions of gallons per day of reclaimed wastewater. As sea level rises, irrigation or groundwater or surface water recharge with reclaimed water may become a less viable option, especially during the rainy season.

Figure 64 - Use of reclaimed water for cooling two 1 gigawatt plants in Miami-Dade County can use a total of 70-90 MGD of cooling water.

5.4.2 Industrial Use of Reclaimed Wastewater

Reclaimed wastewater is a useful replacement for industries that can use low quality water. Examples applications are large commercial water-cooled air conditioning systems, cooling water for power plants and industrial processes. Miami-Dade Water and

Sewer Department is considering supplying about 70-90 MGD of treated wastewater to Florida Power and Light Company's Turkey Point nuclear power plant. FPL has two nuclear power plants at Turkey Point and two new ones are planned. Since over 60% of the water used in the cooling towers is evaporated, this could be a significant beneficial use of a substantial amount of treated wastewater.

Concurrent municipal and agricultural usage has increased demands on groundwater sources in many places. Water quality requirements for human and ecosystem use are typically higher than those needed for agricultural or industrial use. Wastewater reuse rules for agriculture, golf courses, lawns, etc. require matching evapotranspiration rates.

The cost of implementing reclaimed water use systems is $3-5/GPD in capital costs for standard filtration, enhanced disinfection, storage, and pumping. The cost to implement reuse at all large facilities in Southeast Florida could approach $2.5 billion and advanced wastewater treatment could increase capital costs by another $2 billion.

5.5 Regionalization of Alternative Water Supplies and Reclamation Projects

Regionalization can offer opportunities for development of advanced water treatment technologies while reducing the incremental impacts to water utility rate payers through sharing of costs and risks and taking advantage of economies of scale. Such projects are difficult to organize because of difficulties in deciding how responsibility and authority should be divided. Participating utilities, including small utilities, can substantially reduce investments and operating costs on a pro rata basis. Furthermore, it enables economies of scale through higher utilization of available resources and centralized management.

Examples of successful regional water supply partnerships are the large desalination facility at Tampa

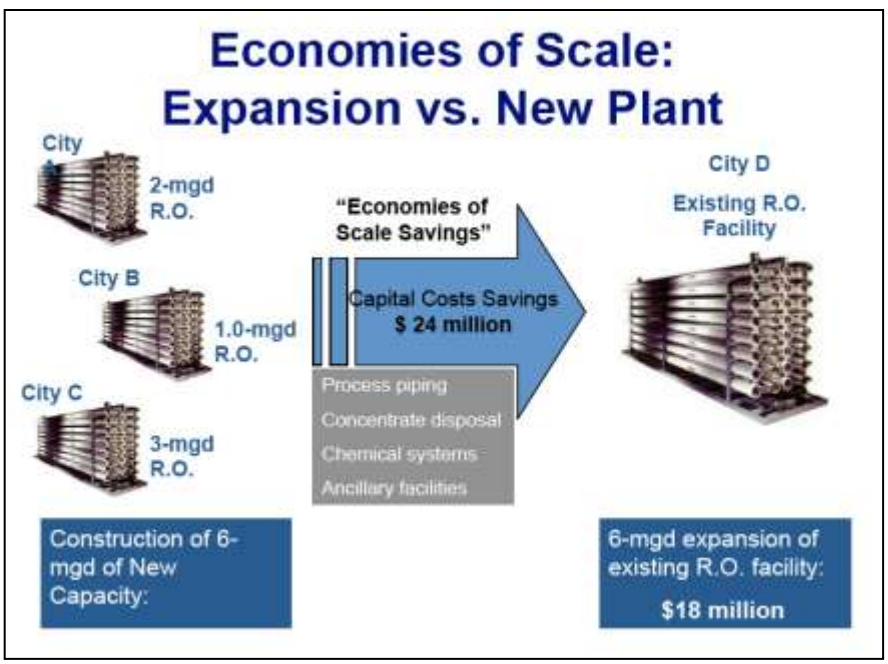

Figure 65 - Example of how regional partnerships can offer substantial economies of scale, especially when new capacity can be added onto an existing facility. (Perez, 2009)

Bay Water, the Peace River/Manasota Regional Water Supply Authority, and the Withlacoochee Regional Water Supply Authority, and others (refs). Currently, a number of local governments in central Florida are evaluating (1) the feasibility of a new desalination plant to be located on Florida's northeast coast and (2) the feasibility of taking surface water withdrawals from the upper St. Johns River. In addition, Polk County has established a new working relationship with its municipal governments to explore alternative water supplies and minimize competition for scarce remaining ground water resources.

In confronting the major challenges facing Southeast Florida water resources, managers will have to consider pooling resources to undertake major infrastructure projects.

5.6 Wastewater Alternatives

Climate change will present Southeast Florida with major challenges including a dilemma, which is how to simultaneously protect the region's freshwater supply, augment it with alternative water sources, control flooding, and dispose of its wastewater and stormwater, all in the face of sea level rise and with the desire to minimize energy usage that contributes to the underlying cause of climate change. Not the least of these will be what to do with the wastewater. To summarized the major issues and concerns:

1. The legislature has mandated discontinuing use of the ocean outfalls by 2025 and 60% of that must go to beneficial use.
2. As sea level rise reaches about 1 foot or more, flooding will become an ever-increasing problem, especially during the rainy season, during major rain events including hurricanes, and during spring and fall high tides. It is already a problem on the barrier islands during spring and fall high tides, during major rain events, and in certain very low-lying areas such as Sweetwater in Miami-Dade County.
3. As sea level rises, there will be an ever-growing challenge to protect the aquifers against saltwater intrusion and contamination from flooding.
4. As sea level rises, there will be an ever-growing challenge to guard against migration of seawater up the southern Everglades watershed.
5. As sea level rises significantly, several of the alternative water supply approaches currently under development may become of less value due to compromised stormwater drainage especially during the rainy season, such as reuse for irrigation and hydrodynamic barriers, and other more speculative approaches such as surface water recharge and direct Biscayne Aquifer injection.
6. Climate change is likely to result in more severe rainfall events and hurricanes, which will increase the likelihood of flooding and the need to discharge large volumes of stormwater while sea level rise is compromising stormwater drainage systems.
7. There is a need for more water storage but limited opportunities.

Options for disposing of treated wastewater are the following:

1. Deep well injection to the Boulder Zone
2. Reuse for irrigation, agriculture, industrial cooling.
3. Storage of treated wastewater by aquifer storage and recovery (ASR)

4. Aquifer recharge to hydrodynamic barriers, the Biscayne Aquifer, the Floridan, or the Everglades Conservation Areas.

Table 10 on the next page presents analysis of alternatives for utilizing treated wastewater in the face of climate change. Conclusions drawn from this analysis are:

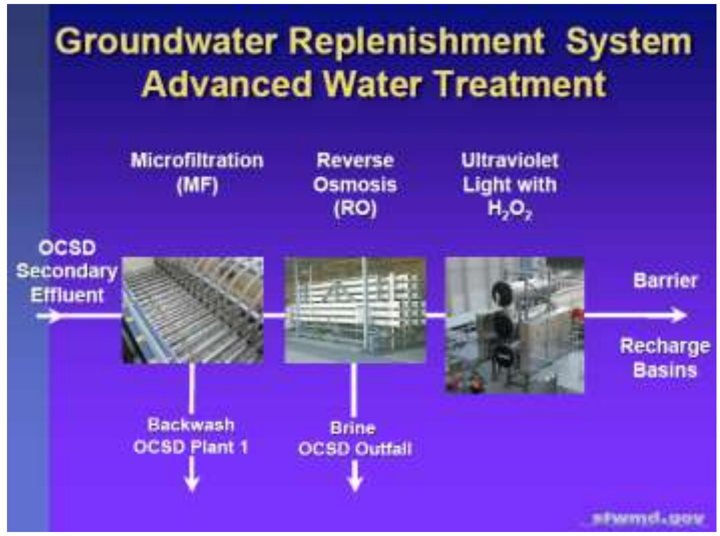

Figure 66 - Groundwater Replenishment - Advanced Water Treatment. Elsner, SFWMD, 2009)

1. **Deep well injection** is viable and economical for discharge of secondary treated wastewater with no anticipated adverse climate impacts. However, it provides no beneficial use of the wastewater. There will be a continuing need to discharge large volumes of wastewater, at the least as an emergency backup.
2. **Wastewater reuse for irrigation, agriculture, and industrial cooling** are relatively low cost, have high technical feasibility and offer important benefits as alternative water sources. However, their utility may be limited during the rainy season especially as sea level rises.
3. **Hydrodynamic barriers** offer the high benefit of protecting against saltwater intrusion in vulnerable wells. However, they are yet to be proven technically, would require high treatment and cost, and its utility may be limited to the dry season and before sea level rise becomes a serious concern.
4. **ASR** experience in Southeast Florida to date has been largely unsuccessful. There are concerns about yield losses, contamination, capacity limitations operating problems, and high capital and operating costs. If it could be an excellent alternative if the technical problems can be overcome.
5. **Recharge of the Biscayne Aquifer** through surface recharge or direct injection provides high beneficial use, but would require very high treatment and cost, and may contribute to flooding during the rainy season as sea level rises.
6. **Lower Floridan recharge** would be a high beneficial use with no anticipated adverse impacts from climate change. However, it requires high cost treatment, the technology is unproven, and there are potential environmental concerns.
7. **Recharge the Everglades** with highly treated wastewater may be an attractive long-term solution for reasons explained below.

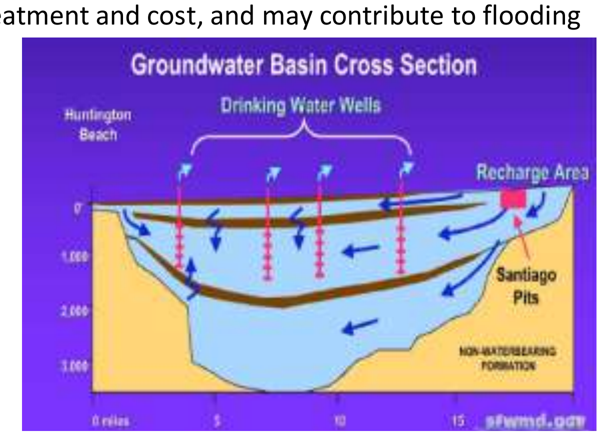

Figure 67 - Groundwater Recharge for Reuse by Potable Water (Elsner, SFWMD, 2009)

Table 9 - Wastewater Disposition Alternatives

	Wastewater Alternative	Additional Treatment	Purpose/ Benefits	Drawback	Effects of Climate Change	Cost Increase
Discharge	**Deep well injection to Boulder Zone**	None.	Disposal of wastewater. No beneficial use	No beneficial use.	None anticipated.	Moderate: injection pumping.
Reuse	**Reuse for irrigation**	None. Separate purple pipe infrastructure	Alternative water supply. AWS* credit. Most useful during dry season.	Requires separate piping system. Demand insufficient -during rainy season. May contribute to flooding.	Risk of flooding during rainy season.	Moderate operating cost. High capital cost for distribution systems.
Reuse	**Reuse for agriculture**	None, separate infrastructure.	Outlet for treated wastewater. Good where farms are near waste-water plant. AWS	Demand primarily in winter months. Low demand in wet season. Risk of flooding.	Minor. Increased risk of biological contamination.	Moderate operating cost. High capital cost for piping systems.
Reuse	**Industrial Cooling Water**	None, blow down deep well injected.	Reduces demand for raw or potable water. Possible AWS credit.	Limited demand except near power plants. May requires treatment depending on disposal method.	None	Minimal. High capital cost for piping systems.
Reuse	**Aquifer storage and recovery**	High treatment, maybe both ways.	Capture water during periods of excess for use during shortages. AWS.	Unproven technology. Yield loss, operating problems, capacity limits, possible contamination.	None	Very high capital and operating costs
Aquifer recharge	**Hydrodynamic barrier/ infiltration trenches**	High treatment required.	Protect wellfields from saltwater intrusion. AWS possible.	Raises local water table; risk of flooding in low lying areas during rainy season. Technology yet to be proven.	Risk of flooding due to water table rise during rainy season.	Very high capital and operating costs
Aquifer recharge	**Biscayne recharge for indirect potable water**	High treatment required.	Very high beneficial use. Recharge aquifer. AWS credit.	Political resistance. High environmental hurdle. Requires regional facilities. Losses to tide with canal recharge.	Risk of flooding due during rainy season	Very high capital and operating costs
Aquifer recharge	**Lower Floridan recharge**	High treatment required.	High beneficial use. Minimize risk of Floridan depletion.	Political resistance. High environmental hurdles. Requires regional facilities. Unproven technology.	None anticipated.	Very high capital and operating costs
Aquifer recharge	Recharging the Everglades	High treatment required.	Very high beneficial use. Recharge surficial aquifer. Hydrate southern Everglades. AWS.	Environmental Risk. High environmental hurdles. Requires regional facilities.	Can offset seawater migration in southern Everglades.	Very high capital and operating costs

Table Key:	Important Drawback	Neutral	Important Benefit

***AWS**: Possible allocation credit for Biscayne Aquifer recharge.

Every alternative for disposing wastewater has its benefits and its drawbacks. The viable long range beneficial solutions all involve high investment in development and capital equipment and high operating costs.

5.7 Recharging the Everglades

If water managers and the State believe that reuse is the answer to South Florida's water supply needs, there are over 800 MGD (Elsner, SFWMD, 2009) of treating wastewater generated daily in Southeast Florida that need to be disposed or reused. A comprehensive solution previously suggested by Bloetscher and Muniz (2008)may be to augment the Everglades restoration plan; provide regional advanced treatment facilities that bring wastewater to the quality level required for direct aquifer recharge; and discharge it into the Everglades Water Conservation Areas (WCAs) and/or recharge the aquifers as deemed best.

In addition, in order to facilitate flood control in the increasingly vulnerable low-lying areas west of the coastal ridge because of sea level rise and potential flooding due to climate change, the same concept could be applied to treating and delivering stormwater during the rainy season to the Everglades Water Conservation Areas (WCAs) where it could be stored and delivered as necessary to the southern Everglades. This would require reengineering the stormwater drainage system in order to collect and convey stormwater to advanced treatment facilities before pumping to the WCAs.

Figure 68 - Alligator in its nest hole in the Everglades. (Photo Credit: Barry Heimlich)

The suggested concept envisions a partnership between utilities and regulators to address technical, economic, environmental and regulatory issues to meet the growing demands of the region.

Concept:

1. Construct a piping network that delivers secondary treated wastewater to several regional 50-100 MGD advanced treatment facilities.

2. Advanced treatment facilities would consist of filtration, cartridge filtration, UV disinfection, reverse osmosis, and advanced oxidation, and other advanced treatment technology deemed appropriate after thorough engineering evaluation and design. The resulting water quality would approach distilled water, so post chemical stabilization might be needed. Anticipated capital cost would be in the order of \$10/gal treated.

3. High quality treated wastewater discharged directly to the WCAs would provide more consistent hydration year-round.

4. Treated wastewater could be directed to local recharge canals and areas as needed.

5. Existing canals and / or new necessary conveyance systems would be used to transfer stormwater to stormwater treatment facilities that would likely be located close to the edge of

the WCAs. Feeder canals would be used to recharge the surficial aquifer locally as deemed appropriate.

6. Adding water to the Everglades WCAs would recharge the Biscayne Aquifer at its head.
7. Recharging the Everglades and the Biscayne Aquifer would increase available water supplies.
8. Alternative water supply credits could be granted for all of the treated wastewater returned to the Everglades (or for local recharge) providing a huge boost in water available for municipal needs.
9. It may be possible to avoid development of other wastewater alternates, such as Floridan reverse osmosis, reclamation and reuse, thereby offsetting the cost of other approaches.
10. Current wells and treatment facilities would continue to operate as is, maximizing utilization of local infrastructure.

Benefits:

This option offers advantages that are far-reaching despite the potential costs:

1. Centralization of facilities would lower costs of operation and investment in capital equipment resulting from economies-of-scale
2. Reduction in the amount of secondary treated wastewater currently disposed by deep well injection or ocean outfall. (Injection wells at the regional advanced wastewater treatment plants would still be required to dispose of reverse osmosis concentrate.)
3. A major contribution to ecosystem restoration and restoring flows to the Everglades.
4. Increased efficiency in the utilization of local and regional water resources
5. Provide significant additional water to the Everglades to counter northward migration of saltwater in the southern Everglades caused by sea level rise.

The capital and investment and operating costs required to implement this approach would be partially offset by avoiding facilities that would be otherwise needed for alternative water supply and recharge facilities. Large regional facilities would be expected to have lower unit costs as a result of economies-of-scale.

Capital investment with piping would exceed $10 per gallon of capacity based on construction costs for the Water Factory 21 in Orange County California, shown in Figure 69 at right.

Figure 69 - Orange County, California Factory 21 Advanced Wastewater Treatment and Groundwater Replenishment.

5.8 Reengineering Canal Systems, Control Structures, and Pumping

Stormwater management during the rainy season and major rainfall events will become increasingly difficult as sea level continues to rise to levels approaching and exceeding current water table levels. As explained in Section 4.2, the risk of flooding will increase as sea level rise causes reduced groundwater flow, compromises the flow capacity of the storm drainage system and coastal structures, and may cause water tables to rise.

As sea level rises, beneficial use of treated wastewater for irrigation or hydrodynamic saltwater barriers during the rainy season may become less practical.

If seas rise by up to 3 feet or more, the southern Everglades are likely to be dramatically changed. There may be a point where freshwater flow alone will not prevent the southern Everglades from becoming a brackish environment. When that happens, Southeast Florida's primary water source may be progressively threatened from the west by saltwater contamination. In order to extend the habitability of the region for as long as possible, dramatic engineering solutions may be required. Hopefully, but only if early global mitigation of the causes of climate change is achieved, Southeast Florida can be spared from the worst consequences of ever-increasing sea levels of 3 to 4 feet and more.

Historically, the natural flow of water from the western floodplains of Southeast Florida was to the west. The major goal of CERP is to restore the sheet flow that took place in the Everglades prior to its being redirected through the primary canals to the Atlantic Ocean. Reengineering the canal systems west of the coastal ridge to direct stormwater to the Everglades Water Conservation Areas in a similar manner as discussed for treated wastewater in Section 5.7 may be worthy of serious consideration (Bloetscher & Muniz, Water Supply in South Florida - The New Limitations, 2008). Highly treated wastewater processed in large-scale regional advanced treatment plants could provide a reliable resource for Everglades hydration.

Because of Southeast Florida's porous geology, some believe that it may not be possible to armor its coasts and waterways against the rising sea. However, without detailed engineering analysis it is premature to jump to this conclusion. *Necessity is the mother of invention*. The word *ingenuity* is the linguistic root of the word *engineer*. The question of whether and how this might be accomplished is beyond the scope of this study, but this is a question that should be answered by civil engineers with the relevant expertise. Based on informal conversations with members of USACE, armoring Southeast Florida's coasts is not beyond possibility and it is worth evaluating when there is so much at stake. It may be possible to protect most of Southeast Florida's land and assets with coastal dikes, strategically locating sea gates, redesigned canals, levees and flood control structures, salinity barriers and locks, installation of high capacity stormwater pumps, and the like.

6 Case Study– Lessons Learned from a Model Municipal Water Utility

A Case Study of the City of Pompano Beach Water Utility was conducted in cooperation with the utility's management and staff by Frederick Bloetscher, Ph.D., Daniel Meeroff, Ph.D., faculty members of Florida Atlantic University's Department of Civil, Environmental and Geomatics Engineering, and Barry Heimlich, a senior fellow at the Center for Urban and Environmental Solutions at FAU. The Case Study, attached as Appendix A, describes the water utility's jurisdiction, governing agencies, raw water sources, water treatment process plant and processes, plans for growth, plans for development of alternative water sources, special situations, its expanding wastewater reclamation and reuse program using wastewater drawn from the County's ocean outfall line, its efforts to develop hydrodynamic saltwater barriers to protect its eastern water wellfield from saltwater intrusion, etc. The City does not operate its own wastewater treatment plant – its sewage is processed at Broward County's nearby regional wastewater treatment facility. The Case Study report should be referred to for detailed information including estimated costs.

The challenge for water suppliers is to determine how to manage the hydrologic cycle in providing water to service areas, in what quantities, and with what level of reliability (Bloetscher & Muniz, Defining Sustainabiity for Water Supply Purposes, 2006). The City of Pompano Beach was chosen for the case study because it is confronting many of the issues faced by utilities in Southeast Florida. Saltwater intrusion, flooding and storm events are common to all coastal areas of Southeast Florida. However, sea level rise was found to be the most significant climate change issue the City faces.

The City of Pompano Beach, FL is located in northeast Broward County, along the coast of the Atlantic Ocean. The City includes three miles of beachfront that extends from the intersection of State Road A1A and Terra del Mar to the Hillsboro Inlet. Water bodies within the City include the Intracoastal Canal, and minor canals for drainage. The per capita water usage is projected to be 191 gallons per day. As a result, the projected annual daily average water demand will increase by 4.96 MGD during the indicated 20 year planning horizon from 2005 to 2025. The City operates two wellfields. The eastern wellfield has had its permitted withdrawals reduced to a third of installed capacity due to the proximity of the saltwater intrusion interface. In addition, the City's overall permitted withdrawals from the Biscayne aquifer have been reduced after 2010 by over 2 MGD.

Based on an understanding of the City's service area, the following are the most vulnerable areas of the system as a result of encroachment from sea level rise:

1. Inundation of certain low-elevation areas with salt water.
2. Contamination of groundwater from sea water inundation and storm surge.
3. Higher water table throughout the service area, which means less capacity to store rainfall.
4. Inundated land on which septic tanks operate. Septic tanks will be jeopardized as the water table rises. Fortunately there are a limited number of septic tanks in the utility's service area.
5. Increased manhole leakage/inflow from saltwater intrusion and surface flooding.
6. An associated increase in chlorides in raw wastewater and hence added treatment required for reclaimed water for irrigation or aquifer recharge.

7. Saltwater migration toward eastern raw water wellfields.
8. Loss of soil capacity for stormwater storage, which means less potential for irrigation with reclaimed water or other sources as sea level and water tables rise.

These findings mean that the City may:

1. Be forced to rely less on its eastern wellfield due to the potential for increased saltwater intrusion potential or inundation from storm surge.
2. Need to convert septic tank areas to central sewers since they will likely not function correctly in the future due to sea level rise.
3. Need to harden the sewer system to prevent inflow that would be contrary to their reuse goals
4. Need to reconsider reuse efforts in light of lessened soil storage capacity
5. Need to consider infrastructure to protect the wellfields

These challenges bring opportunities for solutions and specific recommendations on action steps that the utility could consider for improving the resilience of their facilities. For the long-term the City has a number of efforts it can pursue to harden its water supply, and protect its vulnerable residents from the impacts of sea level rise. However, rather than dictate a timeline, it would appear to be more appropriate to match the implementation goals to milestones in the sea level elevation. There are four scenarios: minimal risk (under 1 foot), low risk (1-2 ft), high risk (2-3 ft), and critical risk (3 ft or more).

Minimal risk (less than 1.0 foot sea level rise, 2020-2060): A slight increase in sea level probably will create no significant impacts on the utility. Flooding in low-lying areas will increase but localized solutions like additional stormwater pump stations can alleviate much of these concerns. Increased inflow to the sewer collection system would indicate that solutions should be implemented to protect against sea level rise involving the wastewater system infrastructure – G7 program (see Appendix A for details), and added reclaimed water use to migrate private well users away from the Biscayne aquifer. Additional implementation of the City's water conservation program could be pursued immediately and probably should be to stay ahead of the issue.

Low Risk (1-2 feet sea level rise, 2040-2070): Once it is determined that sea level rise will reach the 1 foot stage within the foreseeable future, the utility should start reviewing desalination options using the Floridan aquifer, and those associated with salinity barriers. Aquifer recharge, salinity barriers, added reuse, and similar options would be appropriate actions.

High Risk (2-3 feet sea level rise, 2070-2100): By the time sea level rise is 2 feet, the appropriate steps should have been taken. Before sea level rise reaches 2 feet, low-lying areas in the east and along the beach will flood more frequently. While initially a nuisance, people will notice that very small rainstorms may create significant flooding. The problem will be exacerbated as storm intensities increase and as sea levels continue to rise.

Critical risk (3 feet or more sea level rise, 2080 or later): As sea level rise increases towards 3 feet, large areas of the utility service area may flood frequently during rainstorms. Small storms may cause localized flooding. Pump stations will probably be required to deal with the flooding problem. Reduced soil storage capacity may defeats efforts to utilize salinity barriers and reuse. As a result the utility may want to consider shifting from current reuse efforts toward aquifer storage and recovery (ASR) whereby the reclaimed wastewater could be stored in injection wells and withdrawn to produce potable water after applying advanced treatment. An alternative that deserves serious consideration is to pump treated wastewater to the Everglades. By the time sea level has risen to 3 feet, stage adjusted canal structures may be needed.

Table 10 - Summary of Measures Pompano Beach could implement to combat climate change effects on its water supply.

<table>
<tr><th>Trigger</th><th>Estimated Timeframe</th><th>Implementation Strategy</th></tr>
<tr><td rowspan="3">Immediate</td><td rowspan="3">2010-2010</td><td>Install pumping stations in low lying areas to reduce stormwater flooding</td></tr>
<tr><td>Water conservation</td></tr>
<tr><td>Armoring the sewer system (G7 program)</td></tr>
<tr><td rowspan="2">0 – 1 ft Sea Level Rise</td><td rowspan="2">2010-2060</td><td>Additional reclaimed water production</td></tr>
<tr><td>Aquifer recharge/salinity barriers</td></tr>
<tr><td rowspan="6">1 – 2 ft Sea Level Rise</td><td rowspan="6">2040-2070</td><td>Desalination</td></tr>
<tr><td>Control flooding west of the coastal ridge</td></tr>
<tr><td>Central sewer installation in septic tank areas</td></tr>
<tr><td>Closing of private irrigation wells</td></tr>
<tr><td>Relocating wellfields/installation of horizontal wells</td></tr>
<tr><td>Salinity/lock structures</td></tr>
<tr><td rowspan="2">Before 3 ft Sea Level Rise</td><td rowspan="2">2070-2100</td><td>Regional desalination/aquifer recharge/discharge to Everglades</td></tr>
<tr><td>Aquifer storage and recovery with waters of impaired quality</td></tr>
<tr><td>3 – 4 ft Sea Level Rise</td><td>Beyond 2080</td><td>Massive groundwater drainage, transfers of water supplies.</td></tr>
<tr><td>Beyond a 4 ft Sea Level Rise</td><td>Beyond 2100</td><td>Large areas of the City may have to be abandoned</td></tr>
</table>

7 Adaptive Management as Applied to Water Resource Resiliency

Adaptive management (AM) [Adapted from (SFWMD, 2001)] provides an alternative approach to traditional planning procedures for the design and implementation of programs and projects that seek to manage and/or restore complex systems fraught with uncertainly. AM is neither “trial and error” nor “managing adaptively”. Traditional “cookbook” protocols for project planning require high levels of predictability with respect to the performance of alternative plans, anticipated outcomes, and agreement regarding project goals. Numerical models are used to generate predictions of planned performance to

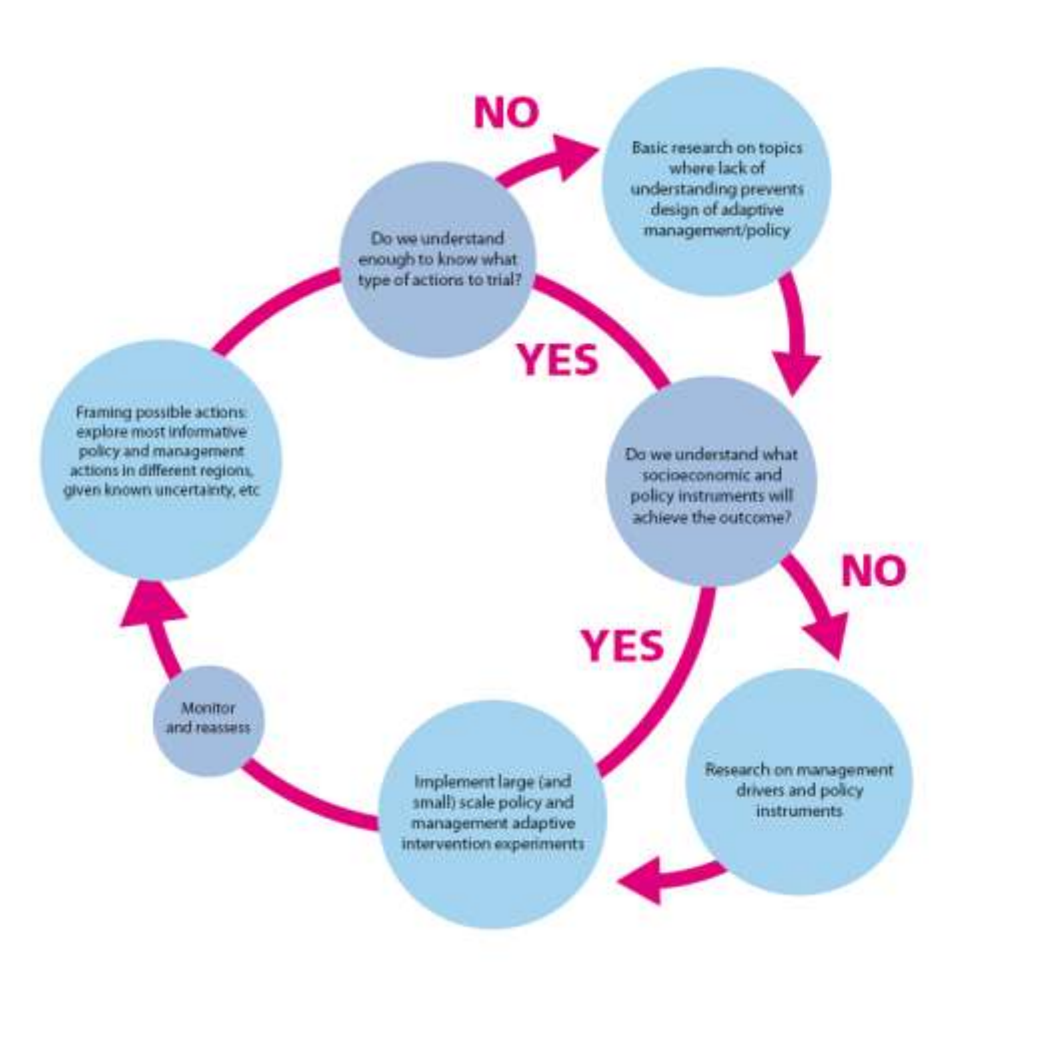

Figure 70 - A visual representation of active adaptive management, an iterative approach built around explicit, experimentally based development of plausible management options. This schematic diagram is from the recent report from the Copenhagen Congress on Climate Change recently issued by the International Association of Research Universities (International Alliance of Research Universities, 2009)

characterize the results of management actions at large spatial scales and to define program/project goals. For global climate change, however, although many numerical models are being used to predict global climate and related phenomena, the system is so complex, as is the uncertainty of what interventions may be employed by the human population, that it is widely appreciated that model predictions for IPCC and others cannot be relied upon with any high degree of certainty. Also, the global system has many feedback mechanisms that are not well understood and cannot be predicted accurately. This leads to uncertainty about what management decisions should be made and disagreement about what goals should be set and the most effective routes for achieving any set of project objectives.

Adaptive management is an adaptation of the scientific process, i.e. hypothesis, experimentation, measuring outcomes, comparison of observed results versus expectations, hypothesis revision taking into account the new observations, and experimenting again. Adaptive management is applied in environmental, sociological, economic, and political programs. It is used to manage actual undertakings where there is risk and uncertainty, not experimental research and hypothetical models. AM integrates goal setting, program design, planning, execution, systematic monitoring to test assumptions, learning from the new information and unanticipated results, adaptation, resetting goals and plans, and continuing the iterative process until the desired goals are achieved or abandoned as unachievable or no longer desirable.

To help address these uncertainties, and to improve the performance of a restoration project, AM has evolved to deal with the challenges inherent in predicting and restoring large-scale complex ecosystems. AM replaces the current dependencies on numerical models and traditional planning guidelines by applying a focused "learning-by-doing" approach to decision-making. The "learning-by-doing" approach is proactive – it is an iterative and deliberate process of applying principles of scientific investigation to the design and implementation of restoration projects to better understand the ecosystem and to reduce the key uncertainties, as a basis for continuously refining the program/project design and operation. New information that can guide a project plan can include results from scientific research and monitoring, new or updated modeling information gleaned from iterative project implementation and as input from managers and the public. Potential applications of this "learning by doing" AM approach include: (1) transfer of lessons learned from one program/project to another to avoid pitfalls; (2) use of physical models/modeling to test possible outcomes of management decisions; and (3) incorporation of flexibility and versatility into project design and implementation.

There are many reasons why AM is well suited for regional climate change adaptation programs since it improves the chance of success in meeting program/project goals in light of the large uncertainties associated with climate change and the wide range of opinions and options concerning desired outcomes. AM fosters the success of project planning, implementation, and assessment by applying the following principles:

1. Use of scientific inquiry to address the most important structural, operational, and scientific questions;
2. Incorporation of robustness (i.e., maintaining design and operational options) into project design;
3. Use of feedback loops that iteratively feed new information into the decision-making process for planning, implementation and assessment of project components;
4. Emphasis on an open, inclusive, and integrative process for design and implementation of adaptation programs/projects; and

5. Emphasis on collaboration and conflict resolution in order to reconcile competing scientific and socioeconomic objectives.

These principles maximize learning to address key uncertainties and disagreements and help build an expanding body of knowledge that will support both current and future decision-making. The continuously updated body of knowledge and open collaborative process facilitate consensus on the ultimate plan design and the desired endpoints. Because decision-making in an atmosphere of uncertainty can lead to an uninformed and distrustful public, AM incorporates active collaboration the purpose of creating an informed and contributing public, and for bridging gaps in communication and understanding among the public, the scientific community, and managers responsible for implementing the program.

In summary, the use of AM is essential for achieving program/project objectives in any situation where there are comparatively high levels of uncertainty and/or disagreement about: (1) the validity, complexity, and predictability of global climate change; (2) the most effective design and operation to achieve program/project goals; and (3) what constitutes program/project success. In these situations, applying the principles and guidelines of AM is a means of reducing the hurdles to planning and program/project implementation caused by uncertainty and a lack of consensus.

Table 11 - Adaptive Planning Framework: Protecting SE Florida's Water Resources

	ADAPTATION TOOL	SEA LEVEL RISE	MORE INTENSE HURRICANES	SEVERE DROUGHT	TORRENTIAL RAINS	SEVERE HEAT WAVES
Conservation		Counteract low water tables and saltwater intrusion, dry season		Conserve water supply		Counter water losses due to evapotranspiration
Protect Existing Water Supplies	Relocation of Wellfields	Locate wells away from saltwater intrusion zone	Locate wellfields away from surge zones	Locate wells away from saltwater intrusion zone		
	Hydrodynamic barriers w/treated wastewater or stormwater	Protect wells from saltwater intrusion Risk of flooding in injection zone during rainy season	Risk of flooding during periods of heavy rainfall	Protect wells from saltwater intrusion	Risk of flooding during periods of heavy rainfall	
	Redesign/Relocate Salinity Structures/ Locks and Pumps	Reengineer or relocate to counteract saltwater intrusion, sea level rise. and enhance stormwater drainage	To prevent storm surge penetration up primary canals and rivers enhance stormwater drainage		Reengineer or relocate to enhance stormwater drainage	
	Land Use Planning Protect High Recharge Areas	Counter low water tables and saltwater intrusion	Locate recharge areas away from surge zones	Counter low water tables and saltwater intrusion		Recharge to offset evapotranspiration
Alternative Water Supplies	Floridan Desalination	Replace supply threatened by saltwater intrusion	Not vulnerable to storm surge contamination	Supplement water shortages		
	Storage Reservoirs & Impoundments	Supplement supply of fresh water	Locate storage away from surge zones. Levee adequately for surge in reservoir.	Supplement water shortages	Storage of excess stormwater	Increases supply during hot, dry periods of high evapotranspiration
	Aquifer Storage & Recovery (ASR)	Store excess storm and waste water in rainy season for use during water shortages		Supplement water shortages	Storage of excess stormwater	Avoids evapotranspiration
Wastewater Recovery and Reuse	Irrigation	Conserve water supply Risks Flooding Heavy Rain		Conserve water supply	Risk of flooding during heavy rainfall	Conserve water supply
	Agriculture	Conserve water supply		Conserve water supply		Conserve water supply
	Industry/ cooling water	Conserve water supply		Conserve water supply		Conserve water supply
	Recharge aquifer for indirect potable use	Biscayne and/or Floridan recharge Biscayne recharge could contribute to flooding		Applicable to Floridan recharge. Also to Biscayne only during drought	Biscayne and/or Floridan recharge Biscayne recharge could contribute to flooding	Counter losses due to evapotranspiration
Reengineer Stormwater Systems	Forward Pumping to Ocean	Begin improving flood control systems immediately before sea level rises by 3-6 inches	Improve stormwater drainage as sea level rise exceeds 1-1.5 feet		Flood control, last resort	
	High Treatment and Discharge to Everglades WCAs.	Control flooding in low lying westerly flood plains due to sea level rise effects on drainage		Hydration of Everglades	Control flooding in low lying westerly flood plains due to sea level rise effects on drainage	

Contraindicated | Not Applicable | Applicable, unproven feasibility | Applicable | Highly Applicable

Increasing Applicability

8 Adaptive Planning Framework

Southeast Florida's water resources are seriously challenged by the prospect of climate change and its expected impacts in the region. In order to determine which tools would be most appropriate to use in response to those impacts, a matrix of impacts versus adaptation tools was developed (Table 11 on the previous page) in order to establish which tools would be most applicable for responding to each climate impact. The note in each cell describes the major reason or goal for application of that tool to that impact. The matrix is color coded to indicate degree of applicability as follows:

8.1 Issues to Consider

1. **Relating to Sea Level Rise and Saltwater Intrusion**
   1.1. There is uncertainty about the extent and rate of sea level rise. More reliable predictions of sea level rise are needed.
   1.2. Sea level rise will increase the threat of saltwater intrusion. Since water tables must be controlled at near current levels, hydrological theory predicts that significant inland migration of the saltwater interface is likely to occur.
   1.3. Sea level rise will reduce groundwater flow and compromise stormwater drainage and flood control systems.
   1.4. As sea level rise approaches the level of the water table, it may become impractical or impossible to prevent water tables from rising since the aquifer is recharged by heavy rainfall, especially during the wet season. Elevated water tables will reduce soil storage capacity and increase the risk of flooding.
   1.5. Sea level rise may reduce the amount of fresh water available for withdrawal as groundwater flow toward the ocean decreases and saltwater intrusion increases as a result of backpressure from the ocean.
   1.6. Desalination by reverse osmosis of supplies from the Biscayne Aquifer may become necessary as saltwater intrusion causes increases in salinity.
2. **Relating to Other Climate Change Impacts**
   2.1. Combinations of sea level rise with more severe or prolonged drought, torrential rains, and intense hurricanes will exacerbate impacts on water resources. Heat waves in combination with severe drought will intensify their impacts.
3. **Relating to Flooding**
   3.1. The flow capacity of coastal control structures will be adversely affected by reduced head differential between headwater and tailwater as sea level rises. Preliminary analysis (Section 4.2.3) indicates that there may be significant loss of coastal structure capacity with as little as 3 to 6 inches of sea level rise within the next 10 to 20 years. Engineering studies are needed at the earliest opportunity to confirm the magnitude of this threat and to plan appropriate responses.
   3.2. Comprehensive integrated regional surface and ground water modeling is needed to predict how water tables, groundwater flow, and saltwater intrusion will respond to increasing sea levels.

3.3. Hydrological model predictions of effects of sea level rise on stormwater drainage should be overlaid on topographical maps to predict where and how flooding may occur during major rain events.
3.4. Since sea level rise will exacerbate the effects of hurricane storm surge, storm surge modeling studies are needed to predict the magnitude of this effect.
3.5. During the dry season and periods of drought when water tables are low, treated wastewater reused for irrigation and hydrodynamic barriers may be a tool for offsetting saltwater intrusion. However, during the rainy season, water tables elevated by sea level rise and heavy rain may reduce or eliminate the utility of hydrodynamic barriers because of flooding risk.

4. **Relating to Adaptive Planning**
4.1. Adaptation strategies and policies are needed to protect water resources, land and property.
4.2. A dilemma will be created by the likelihood that there will be freshwater shortages during the dry winter and spring months and freshwater overabundance during the rainy season that will challenge capacity to store or discharge excess stormwater. This will call for major public works projects to convey, store, treat and discard excess stormwater.
4.3. Reengineering of primary canals system will likely be required to manage stormwater drainage.
4.4. Desalination and other advanced water treatment (AWT) methods will substantially raise the cost of potable water. It will also substantially increase energy usage and the carbon footprint for potable water treatment, wastewater treatment, stormwater management, and flood control.
4.5. As sea level rise exceeds 2 to 3 feet, there may be places where flood control may become impractical or impossible, and it may be necessary to consider various strategic alternatives including strategic retreat from indefensible areas.

5. **Relating to Application of Adaptation Tools**
5.1. The extent to which saltwater intrusion can be countered by raising the water table using conservation and wastewater reclamation and reuse alternatives is limited by flood control considerations and because reduced soil storage capacity will increase the risk of flooding.
5.2. The ability to reuse treated wastewater for irrigation and aquifer recharge is likely to be reduced as sea levels rises by 2 to 3 feet or more. The possibility of rising water tables and reduction of soil storage capacity increases the risk of flooding during the rainy season or during major rainfall events.
5.3. In the face of sea level rise and intensified rainfall events, high capacity pumps and advanced water treatment facilities may be needed to discharge stormwater to the ocean and/or the Everglades.

6. **Relating to the Everglades and CERP**
6.1. Saline surface water will migrate north in the southern Everglades as sea level rises, threatening ecosystems and the integrity of the Biscayne Aquifer in southern Miami-Dade County. This increases incentives for Comprehensive Everglades Restoration Plan (CERP).
6.2. More fresh water flow to the southern Everglades than currently planned may be needed to offset the threat of saltwater migration up the southern Everglades watershed.

6.3. Highly treated wastewater and stormwater could be supplied to the southern Everglades to help offset saltwater migration. The high cost for new infrastructure and treatment to levels suitable for discharge to the Everglades may be justified.

8.2 Major Questions

1. How to dispose of excess stormwater runoff during the rainy season and major rain events and hurricanes as sea level rise compromises the capacity of the stormwater drainage system?
2. How much stormwater forward pumping capacity will be needed as a function sea level rise?
3. How best to draw off, capture, and store stormwater?
4. How best to move, treat, and distribute stormwater to Everglades?
5. How to control flooding in the coastal areas and low-lying westerly flood plains?
6. How best to discharge water to tide or the Everglades during emergency flooding events?
7. How much freshwater flow is needed to offset migration of seawater up southern Everglades?
8. How to improve the resiliency of the barrier islands and low-lying coastal areas?
9. Is coastal armoring feasible for defense against hurricane storm surge?
10. How to moderate or adapt to coastal inundation due to sea level rise?
11. How to dispose of excess wastewater that cannot be used for irrigation and hydrodynamic barriers?
12. What should be the criteria and policy for land use in areas that will become more flood-prone?
13. What criteria and policy should be set for restricting development in areas vulnerable to sea level rise?
14. What criteria and policy should be established for deciding when and how to fortify or abandon vulnerable areas?

8.3 Major Conclusions

1. All of the freshwater sources that can be developed are needed.
    a. Fresh water is the primary tool for offsetting sea level rise and saltwater intrusion, for providing urban and natural area water supply needs, and for forestalling northward migration of seawater through the southern Everglades watershed.
    b. To the extent possible, loss of stormwater to tide during the dry season should be prevented, and capture and storage during the rainy season should be promoted.
    c. More capacity is needed to capture and store stormwater runoff during the rainy season for use in dry season, such as more stormwater treatment areas, impoundments (such as C-9 and C-11), reservoirs (such as C-51), and "River of Grass" U.S. Sugar land acquisition.
2. New approaches to augment flood control systems will be needed as sea level rise compromises existing systems.

3. As sea level rises and with the likelihood of more intense hurricanes, the engineering feasibility of coastal armor, such as dunes, dikes, seawalls, sea gates, pumping stations, etc. should be explored.
4. More clean, fresh water will be needed for the Everglades, probably more than currently anticipated in CERP, to forestall migration of seawater northward up the southern Everglades watershed as a result of sea level rise.
5. As sea level rise continues to about 2-3 feet or more, water flow alone may become inadequate for protecting the Everglades from becoming saline and jeopardizing headwaters of the water supply for urban Southeast Florida. At that time, it may become necessary to stem invasion of saline water northward through the Everglades watershed.

9 Strategic Recommendations

1. Considering the possibility that Southeast Florida's stormwater drainage systems, especially its coastal control structures, could be compromised by sea level rise of as little as 3 to 6 inches, which could occur by about 2020-2030, engineering evaluation and planning should begin immediately to assess their vulnerability and determine what steps are needed to improve their resilience.
2. Conferences and workshops should be convened where regional scientists, engineers, water managers, planners, policymakers and other stakeholders in Southeast Florida can be informed of the results of this study and related work being conducted by the South Florida Water Management District and other agencies, where knowledge can be exchanged and comprehensive recommendations can be developed for protecting Southeast Florida's water resources from the impacts of climate change.
3. Utilities and water resources agencies should develop comprehensive adaptive management plans that set short, intermediate, and long range goals and establish strategic implementation strategies for water resources under their jurisdiction that embody the likely impacts of climate change, and its operational, economic, and environmental effects.
4. The South Florida Water Management District, in cooperation with state universities, Southeast Florida local government agencies and water utilities and municipal utilities, should establish a comprehensive research program to develop scientific and technical knowledge relating to the impacts of climate change and adaptation solutions for the region's water resources to inform policy and decision makers.
5. Development of alternative water supplies should be continued to meet increased water demands of the urban community and the environment while offsetting saltwater intrusion and other impacts.
6. New approaches will eventually be needed to best utilize excess wastewater and stormwater as sea level and water tables continue to rise since current approaches for wastewater reclamation and reuse may become impractical during the wet season.
7. Feasibility studies of large scale regional advanced water treatment facilities should be undertaken to evaluate:
    a. Production if potable water from brackish water, treated wastewater, or stormwater.

    b. Advanced treatment of stormwater or wastewater for aquifer recharge and/or Everglades hydration.
    c. Potential for realizing economies of scale.
8. In the event that sea level rises by 1½ to 3 feet or more, innovative and aggressive approaches will be needed to protect the region's water resources and land from inundation.

10 Policy Recommendations

10.1 State and Local Government Policy Recommendations

1. Climate change should be formally incorporated in all planning and policymaking concerning the region's water resources.
2. Current water resource management plans should be reevaluated from the vantage point of climate change and revised as necessary.
3. State and local governments should reexamine all current and anticipated water resource development projects to explicitly address climate change and its anticipated impacts.
4. Florida Department of Environmental Protection (FDEP) should upgrade stormwater regulations, taking the effect of sea level rise and the likelihood of more intense heavy rainfall events and prolonged drought into consideration.
5. State and local water managers should end their reliance on historic ranges of sea level rise and climate patterns in water resource planning and establish guidelines that take into account projections that account for climate change in water resource planning, including potable water, wastewater treatment, reuse and disposal, stormwater management, and flood control.
6. Local governments should revise land use, zoning, building, and related codes and regulations in consideration of projected climate change impacts incorporating advanced planning strategies such as Smart Growth and Low Impact Development.
7. State and local government agencies should coordinate planning, policies, and regulations.
8. Prior to issuing new development permits, the effects of projected climate change impacts should be required to assure that adequate long-term capacity and infrastructure will be available for potable water, wastewater, and stormwater management.
9. SFWMD and local governments should collaborate to address advanced wastewater treatment upgrades and to identify reuse opportunities throughout the region.
10. State and local agencies should establish energy efficiency and greenhouse gas emissions reduction programs in water, wastewater, and stormwater treatment and distribution facilities. Consideration should be given to the tradeoffs between energy and water resource management requirements. Opportunities should be sought to utilize and produce renewable energy wherever possible.
11. State and local managers should continue emphasis on reducing water demand through conservation, reclamation and reuse; and fund strategies to make better use of reclaimed water.

12. FDEP, SFWMD and local governments in concert with the US EPA should set science-based numeric nutrient criteria for reclaimed wastewaters intended for recharge of both the Biscayne and Floridan aquifers, for recharge into surface waters, and for discharge to the Everglades.
13. SFWMD, the South Florida Everglades Restoration Task Force (SFERTF), relevant federal and local agencies should reevaluate CERP water requirements, determine the levels and flows required to rehydrate the Everglades and offset northward migration of saline water caused by sea level rise and incorporate projected changes in sea level, rainfall patterns, and other impacts in their planning.
14. USACE and SFWMD should continue to develop and apply adaptive management methods in the management of CERP with full consideration of climate change and its impacts in their planning.
15. SFWMD and local water managers should develop and apply adaptive management programs in their planning and decision making of water resources that take climate change and its impacts into account.
16. SFWMD and local water managers should develop and implement greenhouse gas emissions reduction programs in their operations.
17. The State of Florida in collaboration with local governments and agencies should develop and/or update long-term regional water management plans in order to incorporate climate change and take a more coordinated approach to water management, including water conservation and reuse, in order to meet the needs of people and the fish and wildlife they depend on for food, jobs, and recreation

10.2 Federal/Regional Government Policy Recommendations

1. Congress should require all federal water resource-related agencies to incorporate climate change and sea-level rise projections into their water resources planning procedures and programs.
2. Congress should provide incentives or pass regulations for all water related utilities to maximize energy efficiency and minimize direct and indirect greenhouse gas emissions including use and production of renewable energy wherever possible and feasible.

11 Recommendations for Future Research

1. Comprehensive study of water budgets for Southeast Florida with focus on establishing updated estimates of all components including those that are not directly measurable, such as groundwater seepage to the ocean, seepage from the Everglades to the urban areas, and evapotranspiration.
2. Comprehensive study of the effect of sea level rise on projected flooding during heavy rainfall events in the lower Florida peninsula through the development of hydrological models for surface and ground waters and topographical mapping.
3. Determine the energy requirements associated with alternative water supplies, wastewater treatment alternatives, and flood control systems modifications associated with adaptation to sea level rise and other climate change impacts.

4. Reevaluate projections of hurricane storm surge and its impacts taking into account sea level rise and future changes in the region's hydrology using integrated hydrological and storm surge models.
5. Stormwater drainage adaptation strategies to offset sea level rise induced changes in groundwater flow patterns, saltwater intrusion, rise of water tables, inundation, and flooding.
6. Address climate change impacts on barrier islands in order to propose and evaluate alternative adaptation strategies.
7. Evaluate the potential climate change impacts on coastal wastewater treatment plants and develop alternatives for enhancing their resilience.
8. Similar studies of other Florida coastal regions: Southwest Florida, Treasure Coast, Space Coast, Northeast Florida, Tampa Bay, Panhandle, etc.

Appendix A - Case Study of a City Water Utility

Improving the Resilience of a Municipal Water Utility Against the Likely Impacts of Climate Change

A Case Study: City of Pompano Beach Water Utility

By

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The Appendix is available online at:

http://www.ces.fau.edu/files/projects/climate_change/PompanoBeachWater_CaseStudy.pdf

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Appendix C – Method for Forecasting Sea Level Rise

By Barry N. Heimlich

Much of the literature on sea level rise forecasts focuses on 2100. Adaptation planners however require a timetable for reaching various thresholds of sea level rise. There is little guidance in the literature as to prediction of sea level rise at intermediate times. For this reason, the following method was developed. Recently, the U.S. Army Corps of Engineers issued guidelines for predicting sea level rise using a similar approach (USACE, 2009).

Church and White (2006) demonstrated that sea level rise data could be correlated using an acceleration model described by Quadratic Acceleration Equation I:

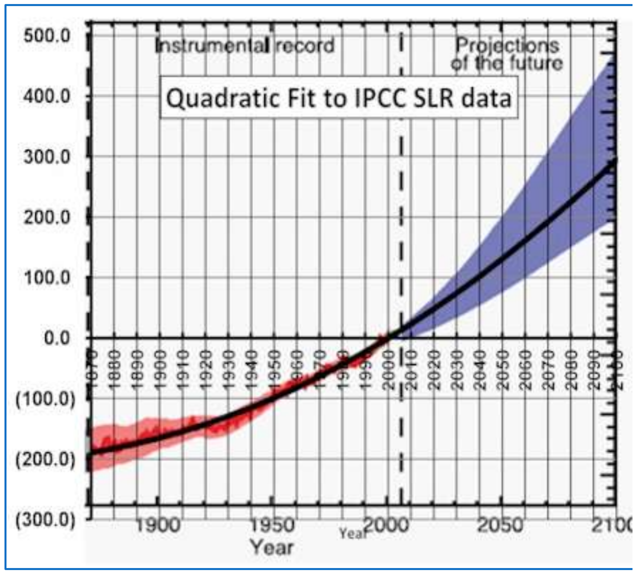

Figure C-A - Sea level rise has been accelerating at about 0.013 mm/yr^2 during the 20th Century. (Church and White, 2006)

Equation I - Quadratic Acceleration Equation

$$\Delta S = + v_0(t - t_0) + \frac{a\,(t - t_0)^2}{2}$$

Data for 1870 to 1990 was well correlated with an acceleration, a, of 0.013 mm/yr^2 and a velocity, v_0, of 2.0 mm/yr. The resulting acceleration equation predicts sea level rise of 295 mm (0.97 feet) in 2100, which agrees with the median IPCC (2007) prediction as shown in Figure C-A.

To provide a method of forecasting intermediate values of sea level rise corresponding to sea level rise in 2100, ΔS_{2100} , of 2 through 4 feet, a series of curves based on the Quadratic Acceleration Equation shown in Equation I was generated to derive sea level rise values. For any given value of sea level rise in 2100, ΔS_{2100}, velocity, v_0, for year t_0 = 2000, acceleration, a, can be calculated according to Equation II.

Equation II - Calculation of acceleration corresponding to ΔS_{2100}.

$$a_{\Delta S_{2100}} = \frac{2\left(\Delta S - v_0(t - t_0)\right)}{(t - t_0)^2} = \frac{2(\Delta S_{2100} - 3.1 * 100)}{100^2}$$

The initial velocity, v_0, in 2000 was set at 3.1 mm/yr, the latest rate estimate based on satellite data (Cazenave, Lombard, & Llovel, 2008). Figure C-B shows estimated values of sea level rise through 2100.

Superimposed on Figure C-B are horizontal timelines for sea level rise values at 0.5 foot intervals. Since topographical maps are developed at increments of elevation, usually 1 foot, it is useful for planning purposes to define timeframes for specific event horizons. For example, the planner would want to know the range of times when a given sea level might be reached. If a topographical map is available at 1 foot increments, the planner can determine the projected consequences at 1, 2 or 3 foot sea level rise with precision, but not for 1.3 feet, the approximate median value for 2060 in Figure C-B. The projected

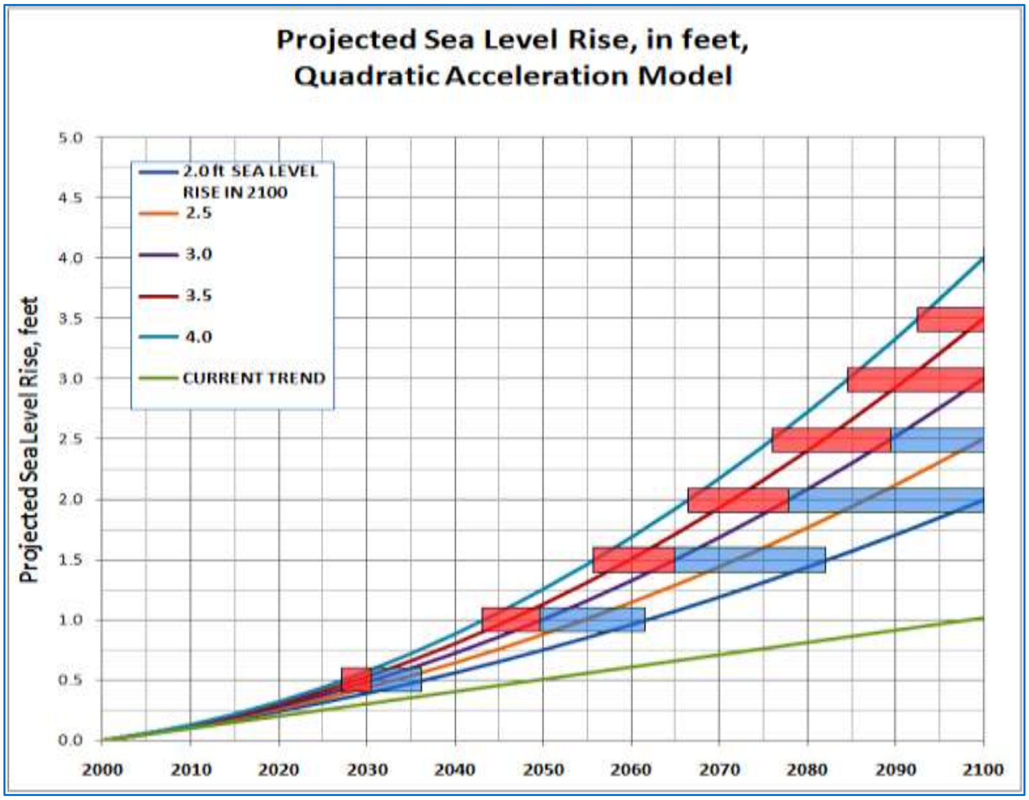

Figure C-B - Projected sea level rise, acceleration model.

years, T, at which any given amount of sea level rise might occur can be calculated using Equation III if one knows the initial velocity, v_0, and acceleration, $a_{\Delta S_{2100}}$ corresponding to the projected sea level rise in 2100, ΔS_{2100}, calculated using Equation II,

Equation III - Predicted time at which a given sea level rise might occur.

$$T = 2000 + \frac{-v_o + \sqrt{{v_o}^2 + 2 * \Delta S * \ a_{\Delta S_{2100}}}}{a_{\Delta S_{2100}}}$$

Table C-1a provides projected ranges of sea level rise at 10-year intervals beginning in 2020. Table C-1b shows dates for the indicated sea level rise thresholds assuming a 2100 sea level rise range of 2 to 4 feet. Table C-1c provides the projected date range for 3 to 4 feet in 2100. For planning purposes, it is recommended that the more conservative values in Table C-1c be used. These values appear as the horizontal red bars in Figure C-B. For example, for a projected sea level rise of 1.0 feet, it is recommended that the planner use a date range of 2043-2050 from Table C-1c. From Table C-1c, a 0.5 foot sea level rise is forecasted for 2027-2031, i.e. 18 to 22 years from 2009.

Table C-1 - Sea level rise projections

Table C-1a

Year	Sea level rise since 2000, feet		
2000	0.00	-	0.00
2010	0.11	-	0.12
2020	0.24	-	0.32
2030	0.39	-	0.57
2040	0.56	-	0.88
2050	0.75	-	1.25
2060	0.96	-	1.68
2070	1.19	-	2.17
2080	1.44	-	2.72
2090	1.71	-	3.33
2100	2.00	-	4.00

Table C-1b

Sea level rise, since 2000, ft.	Projected date ranges Sea level rise in 2100: 4 ft	3 ft	2 ft
0.00	2000	2000	2000
0.25	2017	2018	2021
0.50	2027	2031	2036
0.75	2036	2041	2050
1.00	2043	2050	2062
1.50	2056	2065	2082
2.00	2067	2078	2100
2.50	2076	2090	2116
3.00	2085	2100	2130
3.50	2093	2110	2144
4.00	2100	2119	2157

Table C-2 summarizes values of acceleration required to reach projected values of sea level rise in 2100. Also shown is the acceleration factor, f, which is a multiplier on Church's historical acceleration to obtain the indicated acceleration, $a_{\Delta S_{2100}}$ corresponding to projected sea level rise in 2100, ΔS_{2100} .

Table C-2 - Acceleration Factors

ΔS_{2100}, ft.	ΔS_{2100}, mm	$a_{\Delta S_{2100}}$, mm/yr^2	Acceleration Factor, f	Base Year
Church, 2006		0.013	1.0	2000
2.0	610	0.060	4.6	2000
2.5	762	0.090	7.0	2000
3.0	914	0.121	9.3	2000
3.5	1067	0.151	11.6	2000
4.0	1219	0.182	14.0	2000

It is significant that the acceleration would have to increase more than 4-fold during the 21st Century over the historical acceleration reported by Church and White (2006) to obtain a result of 2 feet in 2100 and acceleration factors of 9-fold and 14-fold are required to obtain results of 3 feet and 4 feet respectively in 2100. That sea level rise could accelerate by as much as 4- , 9- or 14-fold seems surprising. Nonetheless, it is a fact that Greenland and Antarctica have more than enough ice to raise sea levels by many times these amounts and that glacial melt appears to be increasing significantly. It is a question of how rapidly the ice sheets can melt or disintegrate and that answer cannot be determined with precision at this time. There is significant concern among the science community that a threshold could be reached at an uncertain time in the future when glaciers and ice sheets could suddenly collapse causing a dramatic increase in sea level rise.

Appendix D – Estimated Capacity Loss of Coastal Structures

Obeysekera (2009) reported the impact on Southeast Florida's coastal flood control structures in terms of the percentage of structures losing 100% of their operability as a function of sea level rise. Each structure would lose 100% of its operability when sea level rises to each structure's customary headwater level. It is possible that a structure could lose a significant percentage of its capacity when sea level rise is less than that required for 100% loss of operability. Determination of the capacity loss of each structure as a function of sea level rise would require analysis of the operating characteristics of each structure and would require complex calculations of non-linear equations. In order to estimate whether partial loss of capacity due to sea level rise could contribute significantly to system loss, assumptions were made to simplify the calculations.

Rating Development for Gated Spillways

Based upon a 1960-61 study on a 1:16 scale physical model of a typical SFWMD gated coastal control structure, the United States Army Corps of Engineers (USACE) developed theoretical flow equations for gated spillway coastal control structures. These equations are the basis of SFWMD calibration of each individual coastal control structure. Invalid source specified. Invalid source specified.

The following is excerpted from Tillis, Swain, & USGS (1998):

> "Orifice-flow equations are used where flows are controlled by gates, and weir-flow equations are used where flows are not controlled by gates. Whether the flow is free or submerged depends on the downstream stage. Free flow occurs when the downstream stage is low enough relative to the sill that it does not affect flows through the coastal control structure. Free-orifice and free weir flows are computed using only upstream water surface elevations and physical characteristics of the orifice or weir. Submerged orifice and submerged weir flows are common at the coastal control structures. Free flow is more common at the more northern coastal control structures, such as those in Palm Beach County, because the sill elevations are high with respect to sea level. The exact gate openings for the transition zone between orifice and weir flows are difficult to define. Collins (1977) considered submerged weir flow to exist if the gate opening is greater than two-

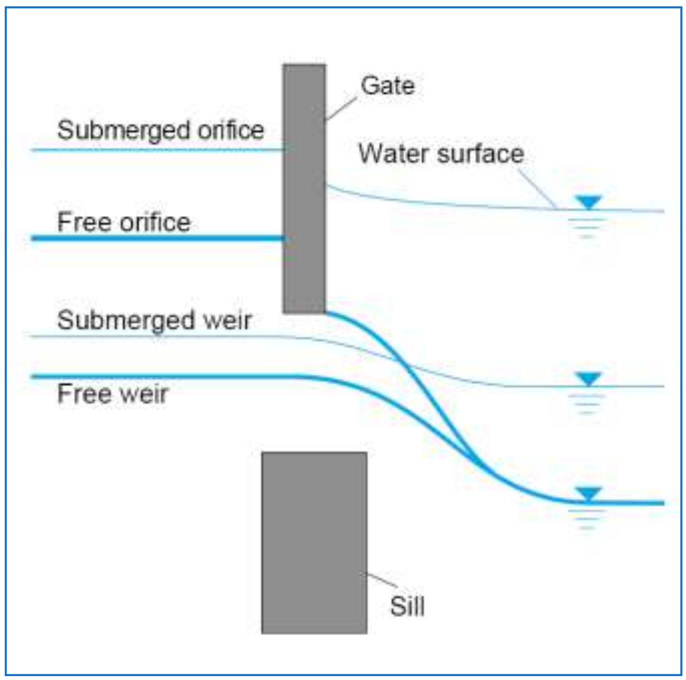

Figure D-1 - Schematic of various flow regimes of gated spillway such as those used in the coastal control structures in Southeast Florida.

thirds the height of the upstream water level over the gate sill. Otero (1994) considered a transition zone from gate openings three-fifths the upstream water level over the gate sill to a point where the gates were out of the water. This transition zone, which is neither orifice nor weir flow, was assumed to occur when the discharge coefficient no longer changed, in accordance with the orifice flow equation, with the gate opening. Weir flow is considered to be the flow regime when the flow is unaffected by the gate."

Submerged Orifice-Flow Equation *Invalid source specified.*
"Submerged orifice flow is expressed by the equation:

$$Q = C_{gs} Lh\sqrt{2g(H-h)} \quad (1)$$

where Q is discharge, in cubic feet per second; C_{gs} is the discharge coefficient relative to the function of a gate opening and submergence; L is length of gate sill, in feet; g is acceleration of gravity, in feet per second per second; H is headwater height above sill, in feet; and h is tailwater height above sill, in feet. …

"Because C_{gs} is considered to be both a function of gate opening and submergence, values of C_{gs} computed from field measurements are plotted against the dimensionless parameter h/G in a log-log plot and a linear scale plot, where G is the gate opening, in feet. The theoretical submerged orifice discharge coefficient most often used by the SFWMD is 0.75 times the inverse of h/G. A least squares regression analysis of available data points yields the rating curve, which is an estimate of the true relation. …"

It is assumed that the gate opening, G, would be at its maximum height when sea level rise is limiting flow through the spillway. Therefore, since $C_{gs} \approx C_s G/h$, where C_s is a constant that is theoretically equal to 0.75, and $A = LG$,

$$Q = AC_s\sqrt{2g(H-h)} \quad (2)$$

Submerged Weir-Flow Equation *Invalid source specified.*
"Submerged weir flow is expressed by the equation:

$$Q = C_{ws} Lh\sqrt{2g(H-h)} \quad (3)$$

where C_{ws} is a discharge coefficient for submerged weir flow. C_{gs} should approach C_{ws} as the gate opening approaches submerged weir flow conditions. …"

Most of the coastal structures operate in both the submerged orifice-flow and submerged weir-flow regimes. It is likely that at sea level rises when tailwater heights are high, these structures would be either operating in the submerged orifice-flow regime or close to it, i.e. $h \approx G$. Therefore, since $LG = A$, it is reasonable to make the simplifying assumption that the flow for all gated spillways can represented by equation (2).

Gated Culverts

Several of the coastal flood control structures in southern Miami-Dade County are submerged gated culverts. The following excerpt from Swain, et al, (1997) describes the equations for such structures:

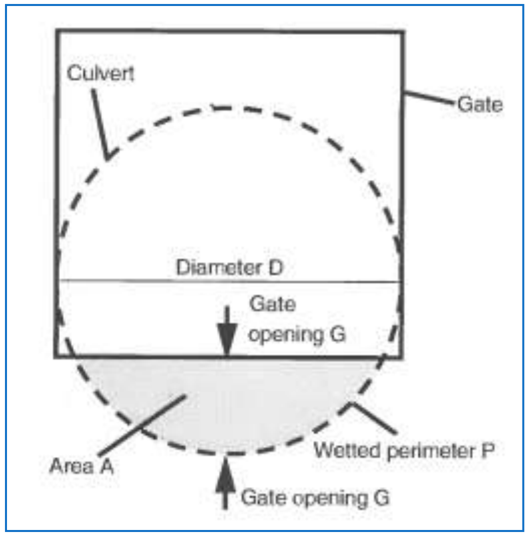

Figure D-2 - Schematic diagram of gated culvert.

> "… The standard rating equation for a submerged culvert used in southern Florida originates from the orifice-flow equation:
>
> $$H - h = K\frac{v^2}{2g} \qquad (4)$$
>
> where K is a flow coefficients which accounts for the entrance, friction, and exit losses; $v = Q/A$, the mean flow velocity; and A is the open area of the gate. With some manipulation, equation 5 becomes:
>
> $$Q = AC_c\sqrt{2g(H-h)} \qquad (5)$$
>
> *where C_c is a submerged culvert coefficient. …"*

Swain (1997) goes on to derive the complex equation for the open area of the culvert, A, as a function of culvert diameter, D, and the position of the gate. For the purpose of this analysis, however, the gate is assumed to be held at a constant position, arguably completely open when sea level rise limits the rate of flow, and therefore the open area, A, can be treated as a constant.

Simplifying Assumptions

For the purposes of this preliminary analysis to approximate the relative effect of sea level rise on the cumulative capacity of the 28 coastal structures in Southeast Florida, a simplifying assumption, in addition to those described earlier in this derivation, is made in equation (10), namely that the % initial capacity of each group of structures losing 100% of their capacity at each level of sea level rise is equal to the % of the number of the structures losing 100% of their capacity at that level of sea level rise. This is a very rough approximation, the significance of which is discussed at the end of this Appendix.

The equations describing the flow of each i^{th} spillway or culvert, i.e. equations (2) and (5), are of the same form:

$$Q_i = \left\{AC\sqrt{2g(H-h)}\right\}_i \qquad (6)$$

The headwater height above the sill of each gated spillway or the bottom of each culvert, H for each i^{th} structure, is a constant for that structure and equals the height at sea level relative to that structures spillway sill or culvert bottom at which that structure would lose 100% of its capacity or operability.

Therefore the cumulative capacity of the system of coastal structures as sea level rises is:

$$Total\ system\ capacity,\ Q_T = \sum Q_i = \sum_{\mathrm{i}} \left\{AC\sqrt{2g(H-h_i)}\right\}_{\mathrm{i}} \tag{7}$$

That the initial capacity of the system of coastal structures in Southeast Florida can be approximated for the purposes of this approximation, by the equation:

$$Q_{0T} = \sum Q_{0i} = \sum_{\mathrm{i}} \left\{AC\sqrt{2g(H-h)}\right\}_{0\mathrm{i}} \tag{8}$$

That the relative cumulative capacity, i.e. the fraction of the total system capacity remaining, can be approximated by:

Percent system capacity remaining =

$$\frac{Q_{total}}{Q_{0\ total}} = \frac{\sum Q_i}{\sum Q_{0i}} = \sum_i \left\{\frac{AC\sqrt{2g(H-h_0)}}{\sum Q_{0i}}\sqrt{\frac{(H-h_i)}{(H-h_0)}}\right\}_i \tag{9}$$

Since $\left\{\frac{AC\sqrt{2g(H-h_0)}}{\sum Q_{0i}}\right\}_i$ is the initial capacity of each structure as a fraction, f_i , of the total system capacity, equation (9) can be simplified to:

Percent system capacity remaining =

$$\frac{Q_{total}}{Q_{0\ total}} = \sum \left\{f_i\sqrt{\frac{(H-h)}{(H-h_0)}}\right\}_i \tag{10}$$

This is the simplifying assumption referred to previously. The % of the number of structures losing 100% of their capacity reported by Obeysekera (2009) is used as an estimate of f_i , the fraction of the initial capacity of all the structures. The significance of this assumption is discussed at the end of this Appendix.

As sea level rises, the tailwater level, h, increases according to:

$$h = h_0 + \Delta S \tag{11}$$

where ΔS , is sea level rise.

Therefore, percent system capacity remaining equals:

$$\frac{Q_{total}}{Q_{0\ total}} = \sum \left\{f_i\sqrt{\frac{(H-h_0-\Delta S)}{(H-h_0)}}\right\}$$

(12)

and:

$$\frac{Q_{total}}{Q_{0\ total}} = \sum \left\{ f_i \sqrt{1 - \frac{\Delta S}{(H - h_0)}} \right\}_i$$

(13)

The percent system capacity lost is calculated by:

$$100 \times \left\{ 1 - \frac{Q_{total}}{Q_{0\ total}} \right\} \tag{14}$$

The results presented by Obeysekera (2009) used as the starting point for this calculation are summarized in Table D-1.

Table D-1 - Percent structures losing 100% operability vs. sea level rise (Obeysekera, 2009)

Sea level rise, cm	Sea level rise, inches	Total # Structures losing 100% capacity	% of # Structures lost	Incremental % of # structures lost at each level of SLR
0	0.0	0	0.0	0.0
10	3.9	4	14.3	14.3
20	7.9	18	64.3	50.0
50	19.7	23	82.1	17.9
200	78.7	26	92.9	10.7
250	98.4	27	96.4	3.6
350	137.8	28	100.0	3.6

Table D-2 summarizes the calculation according to equation (13). Figure D-3 (also Figure 39 in the main report) presents two curves, namely:

1. According to Obeysekera (2009): The percent total structures that would loss 100% of their operability vs. sea level rise.
2. The approximate percent total capacity lost vs. sea level rise according to this derivation.

The results indicate that the contribution to capacity lost by those structures that will lose a portion of their operability as sea level rises may be significant, especially for sea level rise values of less than 9 inches. Percent capacity lost could be as much as about 15% to about 37% with a sea level rise of as little as 3 to 6 inches, which could take place within the next 10 to 25 years.

Equation (13) is an approximation of the effect of sea level rise on total system capacity. A significant simplifying assumption was made as discussed previously. This assumption is of course not rigorous and in fact the structures have a wide range of initial capacities, so the results of this estimation is at best a rough approximation. What is needed at the earliest possible opportunity is a rigorous analysis for each structure according to equations (1), (3), and (5). Such an analysis is beyond the scope of this study. It should be undertaken by engineers at the SFWMD and the USACE so that appropriate decisions can be made regarding modifications that may be required to increase the resiliency of the coastal flood control structures as sea level rises.

Table D-2 - Calculation of total % capacity remaining and total % capacity lost.

SEA LEVEL RISE									
In cm	**0**	**10**	**20**	**50**	**200**	**250**	**350**		
In inches	**0.0**	**3.9**	**7.9**	**19.7**	**78.7**	**98.4**	**137.8**		
% of # Structures Lost*	0.0%	14.3%	64.3%	82.1%	92.9%	96.4%	100.0%		
Incremental % Structures Lost	0.0%	14.3%	50.0%	17.9%	10.7%	3.6%	3.6%		
SEA LEVEL RISE, inches	**% Capacity remaining**							**Total % Capacity Remaining**	**Total % Capacity Lost**
0.0	0.0%	14.3%	50.0%	17.9%	10.7%	3.6%	3.6%	100.0%	0.0%
3.0	0.0%	7.0%	39.3%	16.4%	10.5%	3.5%	3.5%	80.3%	19.7%
3.9	0.0%	0.0%	35.4%	16.0%	10.4%	3.5%	3.5%	68.8%	31.2%
6.0	0.0%	0.0%	24.4%	14.9%	10.3%	3.5%	3.5%	56.5%	43.5%
8.0	0.0%	0.0%	0.0%	13.8%	10.2%	3.4%	3.5%	30.8%	69.2%
12.0	0.0%	0.0%	0.0%	11.2%	9.9%	3.3%	3.4%	27.8%	72.2%
15.0	0.0%	0.0%	0.0%	8.7%	9.6%	3.3%	3.4%	25.0%	75.0%
18.0	0.0%	0.0%	0.0%	5.2%	9.4%	3.2%	3.3%	21.2%	78.8%
19.7	0.0%	0.0%	0.0%	0.0%	9.3%	3.2%	3.3%	15.8%	84.2%
24.0	0.0%	0.0%	0.0%	0.0%	8.9%	3.1%	3.2%	15.3%	84.7%
36.0	0.0%	0.0%	0.0%	0.0%	7.9%	2.8%	3.1%	13.8%	86.2%
39.4	0.0%	0.0%	0.0%	0.0%	7.6%	2.8%	3.0%	13.4%	86.6%
48.0	0.0%	0.0%	0.0%	0.0%	6.7%	2.6%	2.9%	12.1%	87.9%
59.1	0.0%	0.0%	0.0%	0.0%	5.4%	2.3%	2.7%	10.3%	89.7%
78.7	0.0%	0.0%	0.0%	0.0%	0.0%	1.6%	2.3%	3.9%	96.1%
98.4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.9%	1.9%	98.1%
118.1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.3%	1.3%	98.7%
137.8	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%

*(Obeysekera, 2009)

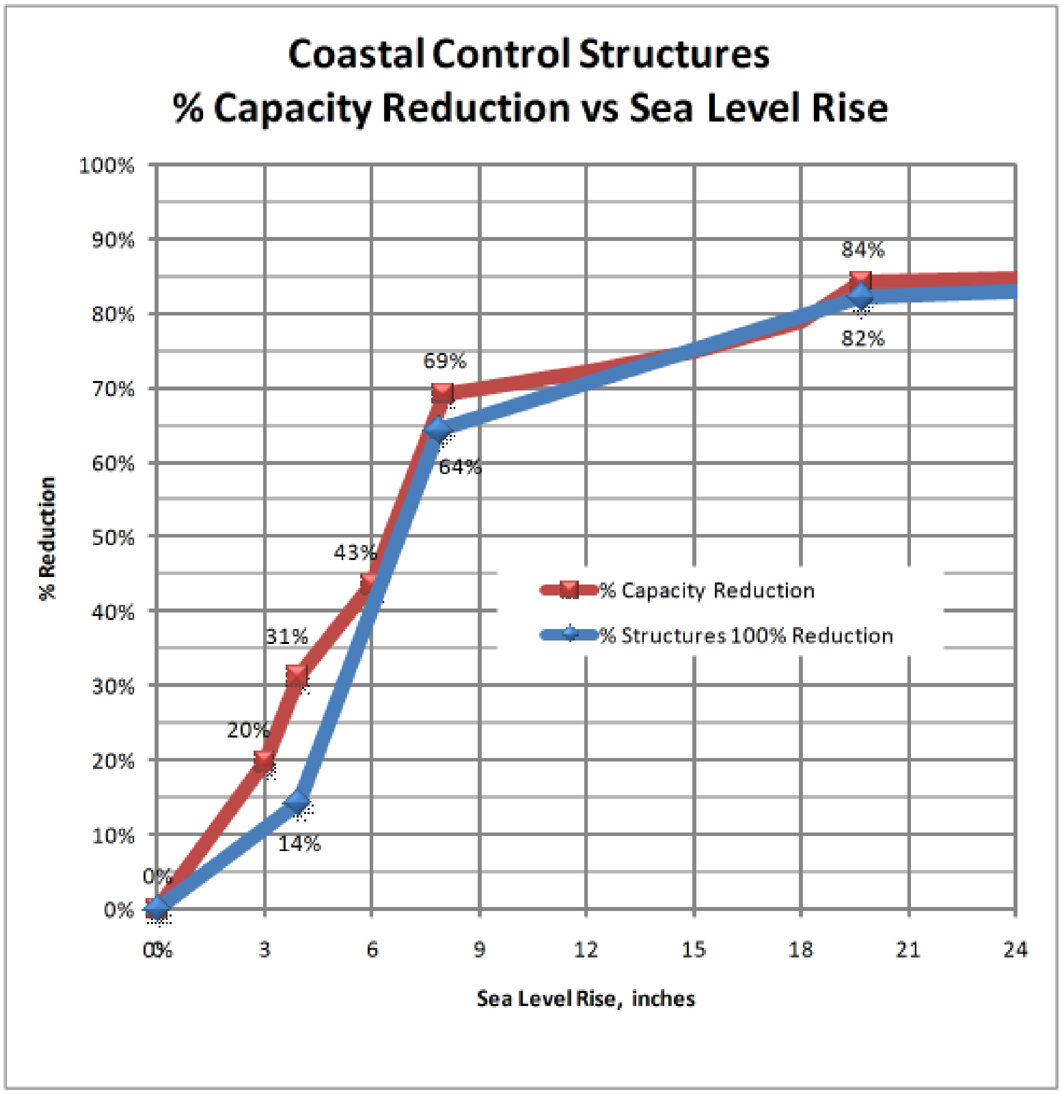

Figure D-3 - Effect of sea level rise on capacity of coastal control structures. Based on data from Obeysekera (2009).

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