Effects of Sea Level Rise and Other Climate Change Impacts on Southeast Florida's Water Resources

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Southeast Florida, with a population of 5.5 million (U.S. Census, 2008) is among the ten coastal metropolitan areas in the world most vulnerable to climate change (Nicholls & OECD, 2008). The region is especially susceptible to sea level rise and expected changes in local weather patterns. Recent reports (Karl, etal, USCCSP, & NOAA, 2009; IARU, 2009, Vermeer & Rahmstorf, 2009) indicate that global average sea level may rise by approximately 2 to 5 feet or more by 2100, with similar expectations for Southeast Florida, an amount that will have significant effects on its coastal areas.

Southeast Florida's vulnerability derives from its geographic location, low elevation, porous geology, unusual groundwater 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 the region's habitability. Future sea level rise and other climate change impacts are likely to influence Southeast Florida's water resources.

Global Warming

Increasing concentrations of greenhouse gases in the atmosphere, especially carbon dioxide, methane and nitrous oxide, have been shown to be the primary cause of global warming (IPCC 2007). Over the past 100 years, worldwide surface temperatures have increased at an unprecedented rate, contributing to warming of the oceans, melting of ice fields and glaciers, and other climatic effects. After several millennia of stability prior to the 20th century, sea levels have been rising at accelerating rates due to thermal expansion of the oceans and from land-based ice melt (IPCC, 2007). Another significant effect is acidification of the oceans caused by increased dissolution of carbon dioxide. The early impacts of climate change are already adversely affecting the world's freshwater resources (AWWA et al., 2008). Other significant effects caused by global warming are heat waves, extremes in precipitation patterns (drought and intense rainfall), and more violent weather (hurricanes, severe thunderstorms, tornadoes, etc.). Details of how climatic effects have begun to deleteriously affect many components of the biosphere are described in many recent publications (IPCC, 2007; Karl, et al., USCCSP, & NOAA, 2009; IARU, 2009; UNEP, 2009).

Climate change is likely to threaten the integrity and availability of fresh water supplies and increase the risk of flooding, not only in the low-lying coastal areas, but also in Southeast Florida's interior flood plains. The water supply is in jeopardy because (a) saltwater intrusion is likely to intensify with sea level rise, (b) prolonged droughts may contribute to water shortages, and (c) heavier rains during the rainy season and hurricane storm surge may increase the risk of contamination of the Biscayne Aquifer from flooding (Heimlich et al, 2009).

More frequent and damaging floods during heavy rain events are likely as sea level continues to rise. What follows is a more detailed discussion of possible impacts as cli-

Table 1 - Summary of Climate Change Impacts on Southeast Florida's Water Resources (Heimlich et al., 2009)

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

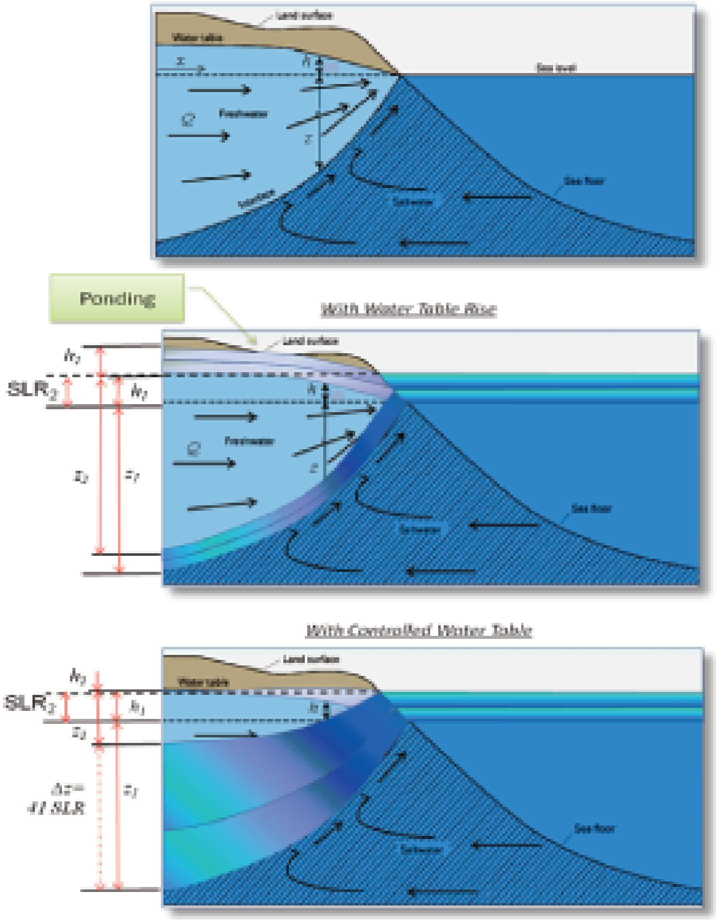

Figure 1 - Sea level rise will affect groundwater flow, water table height, and the extent of saltwater intrusion. If the water table is allowed to rise as shown in the second drawing above, saltwater intrusion can be offset. However, there would be increased risk of ponding in areas of low elevation, and reduced soil storage capacity increases the risk of flooding during heavy rain falls. Conversely, if water tables are maintained at current levels as shown in the bottom drawing, groundwater flow would be diminished that can contribute more serious saltwater intrusion threatening the integrity of fresh water supplies. At equilibrium, the saltwater interface would rise 41 feet for each foot of sea level rise according to the Ghyben-Herzberg Relation (Heimlich et al., 2009).

mate change progresses. Table 1 summarizes the potential impacts of climate change in Southeast Florida, the likely effects on its water resources, and other major effects.

Impacts of Sea Level Rise

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

1. Inundation of barrier islands and coastal property.

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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.

The hydrological effects on the region's water resources are likely to 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.

Saltwater Intrusion

As sea level rises, increased ocean hydrostatic head will cause the saltwater interface to migrate inland, especially if the water table is held constant, as has been historically assumed in hydrological modeling to date (Zygnerski & Langevin, 2007; Zygnerski M. , 2008). In addition to increased saltwater intrusion, groundwater flow and water table height will approach new equilibrium values that depend upon the extent of sea level rise 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. Sea level rise is also likely to compromise the effectiveness of the primary drainage canals and flood control structures (Obeysekera, 2009; SFWMD, 2009) unless engineering modifications are made (Heimlich et al., 2009).

The Ghyben-Herzberg relation governs equilibrium in an open coastal aquifer such as the Biscayne Aquifer (Todd & Mays, 2008). Assuming uniform aquifer transmissivity, the depth below sea level of the saltwater interface, *z*, will be approximately 40 times the height of the water table, *h*, at equilibrium. 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, the ratio,

$$\begin{aligned} z/h &= \rho_f\ (\rho_s - \rho_f) \\ &= \sim 1.0 / (1.025-1.000) \\ &= \sim 40. \end{aligned}$$

Figure 1 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 1 illustrates what would happen if the water table is allowed to rise by about the same amount as sea level, i.e., $h_2 = \sim h_1$. The extent of saltwater intrusion would be relatively small, but ponding could occur in areas of low elevation as illustrated. The lower diagram presents the case where the water table is controlled at current levels 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, i.e., $h_2 = h_1$ - SLR. 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 $(z_1 - z_2) / (h_1 - h_2) = (z_1 - z_2) / \mathrm{SLR} = 40$. Because sea level is displaced by the amount of rise, the saltwater interface rises by 41 times sea level rise. It is evident that holding the water table at current levels as sea level rise leads to substantial saltwater intrusion. If the rates of groundwater and surface water flow, sea level rise, aquifer transmissivity, and other hydrological factors are known, the timing of transition from one equilibrium state to another can be predicted using hydrological models.

The Challenge of Balancing Saltwater Intrusion and Stormwater Drainage

Southeast Florida's highly engineered stormwater drainage system of canals and control structures has enabled lowering of the natural water table to permit recovery of land for agriculture and urban development; saltwater intrusion has occurred as a result. Today, the challenge facing water managers is how to limit saltwater intrusion by holding the water tables at the highest levels possible while maintaining adequate flood control.

With few exceptions, canals drain stormwater to the ocean by gravity. Significant areas of the flood plains west of the coastal ridge that parallels the coast about one to three miles inland have been drained in this manner. With much of low-lying Southeast Florida

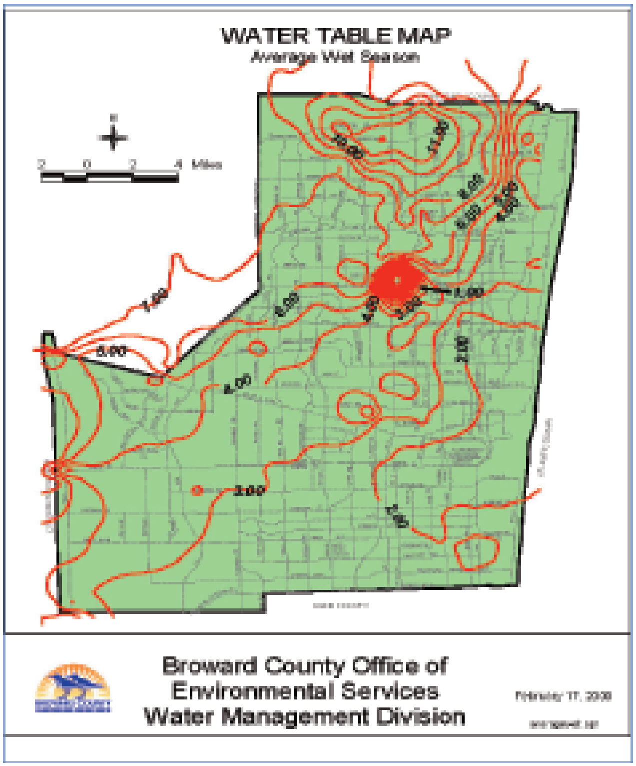

Figure 2 – Wet season water table map for Broward County (2000). Water table levels are 2 to 4 feet in south Broward County where most elevations are below 5 feet. (Broward County).

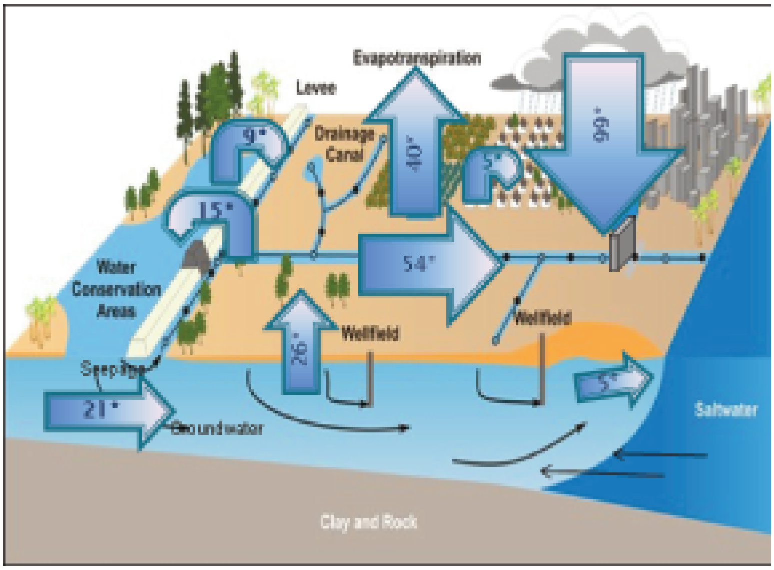

Figure 3 - Schematic water balance model (1965-2000 annual avg.). Based on data from Broward IWRP (2008) and Heimlich et al., (2009).

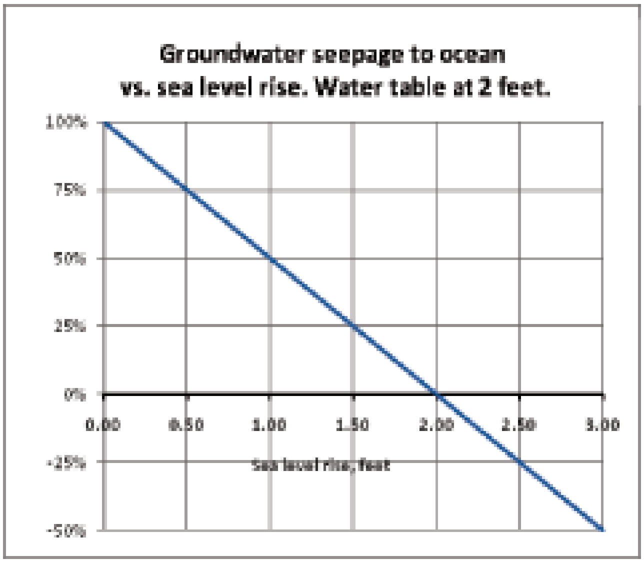

Figure 4 - Groundwater seepage to the ocean could decrease as sea level rises (Heimlich et al. 2009).

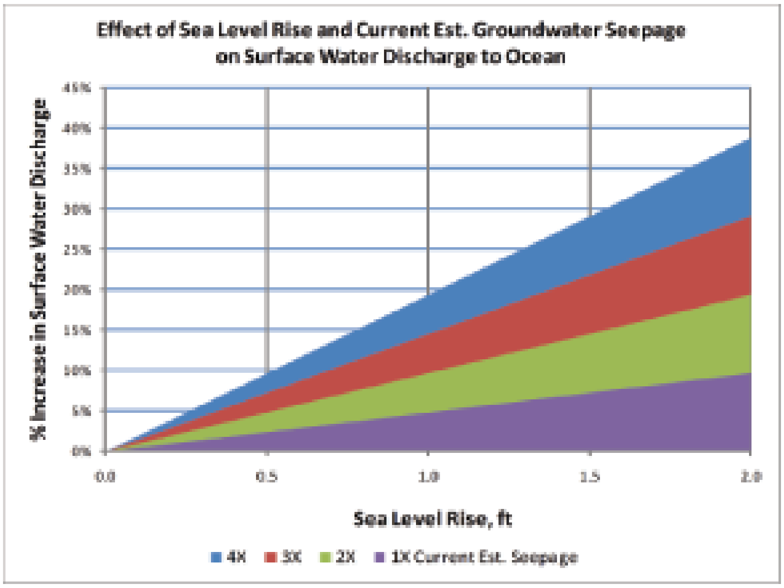

Figure 5 - If current groundwater flow is greater than currently estimated, there would be greater increases in stormwater drainage as a result of sea level rise (Heimlich et al. 2009).

Figure 6 – Typical coastal flood/salinity control structure of the sluice gate type. (Credit: SFWMD)

Figure 7 - S-13 Pump station located on C-11 canal in Davie, FL. It has a rated capacity of 540 cubic feet per second, equivalent to approximately 14.5 million gallons per hour (Credit: SFWMD).

at less than 5 feet above sea level, gradients for stormwater drainage are small. Water tables are already maintained as high as possible in order to counter saltwater intrusion. As a result, water managers in Southeast Florida have little latitude to raise water tables to counter sea level rise. As sea level continues to rise, gradients for drainage will be further reduced and forward pumping will likely be needed to maintain flood control. The unfortunate conclusion for Southeast Florida is that, since the water table cannot be allowed to rise, sea level rise will result in more extensive saltwater intrusion. Saltwater intrusion caused by sea level rise may eventually reduce the availability of raw fresh water for potable use. As sea level exceeds the water table level, hydrodynamic barriers, horizontal wells, relocation of salinity structures, and relocation of wellfields further from the coast will be required to protect fresh water supplies.

During the course of this research, it became evident that the effects of sea level rise on groundwater flow, stormwater runoff, water table levels, and flood control had not been adequately considered in hydrological modeling. Sea level rise will not only threaten saltwater intrusion in Southeast Florida and increase the risk of inundation of coastal areas, but it could substantially increase the risk of flooding during heavy rainstorms in the interior flood plains because of compromised stormwater drainage.

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

Maintaining water tables at current levels as sea level rise progresses is likely to become

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

Werner and Simmons (2009) modeled the effects of sea level rise on a hypothetical open coastal aquifer in two distinct cases: 1) where water table level is held constant and 2) with persistent flow of groundwater discharge to the sea despite increased sea level. In the constant water table case, reduced groundwater flow and increased saltwater intrusion is predicted. In the persistent flow case, rise of the water table is predicted and saltwater intrusion would be substantially avoided as is illustrated in Figure 1.

In southeast Florida, which receives approximately 57 inches of rainfall annually (Sherwood et al., 1973), high rates of aquifer recharge is inevitable and close control of the water table is essential to prevent flooding of the low terrain. Groundwater flow rates are relatively high due to the aquifer's permeability, which also makes the aquifer more susceptible to saltwater intrusion. Furthermore, water table levels and groundwater flows are very responsive to changes in rainfall, aquifer withdrawals, stormwater management, and sea level rise.

The water table near the coast is maintained at about 2 feet above mean tide to control saltwater intrusion, i.e., essentially the level of mean high tide. In the approximately 20 miles from the ocean to the Everglades conservation areas on the west side of the urban area, the water table gradually increases from about 2 feet to about 4 feet during the wet season as shown in Figure 2 for Broward County. The water table during the dry season has been shown to be only slightly lower. Much of southwest Broward County is below 5 feet elevation, so the water table is just below the surface in the lowest areas.

The water budget (Figure 3) for Broward County includes average annual precipitation of approximately 57 inches of rainfall annually (Sherwood et al., 1973), which is equivalent to 99 billion gallons per year per 100 square miles (99 BGY/ 100 sq. mi.) (Heimlich et al. 2009). Evapotranspiration accounts for approximately 40 BGY/100 sq. mi. The major share of the remaining water flows to the sea through the canals, i.e., the flood control system, and a lesser amount flows through the aquifer. Approximately 54 BGY/100 sq. mi. flow to the ocean through the canals and the coastal flood control structures, while groundwater seepage through the aquifer is estimated at 5 BGY/100 sq. mi.

Sea level rise may affect groundwater and surface water flow through the canals and flood control structures to the ocean. If 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 percent; 1 foot of sea level rise would reduce the head differential by about 50 percent as illustrated in Figure 4. According to Darcy's Law, flow through an aquifer is proportional to the pressure differential. As sea level rises, groundwater flow by seepage to the ocean would decrease and surface water discharge would have to make up the difference. Based upon the Broward County water budget, sea level rise of 1 foot would result in about a five percent 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 approach zero and could reverse if sea level rises above the water table (Todd and Mays, 2008). This will increase the burden on the canals and coastal flood control structures.

The estimate of groundwater seepage in the water budget is crude at best. If groundwater seepage is actually higher than the current estimate, the effect of reduced groundwater seepage due to sea level rise on stormwater discharge to the ocean could be greater, as shown in Figure 5. For example, if groundwater seepage is up to four times higher than the current estimate, a 1-foot sea

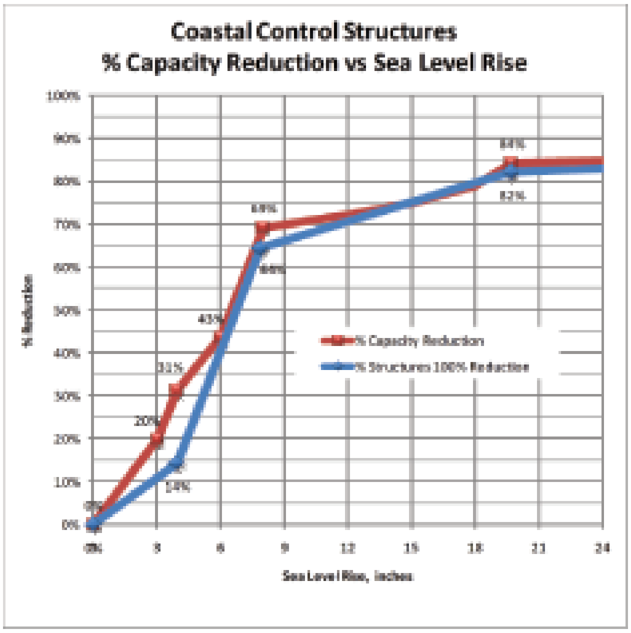

Figure 8 - Effect of sea level rise on capacity of coastal flood control (salinity) structures in Southeast Florida (Heimlich et al., 2009). Blue curve is from data by Obeysekera (2009).

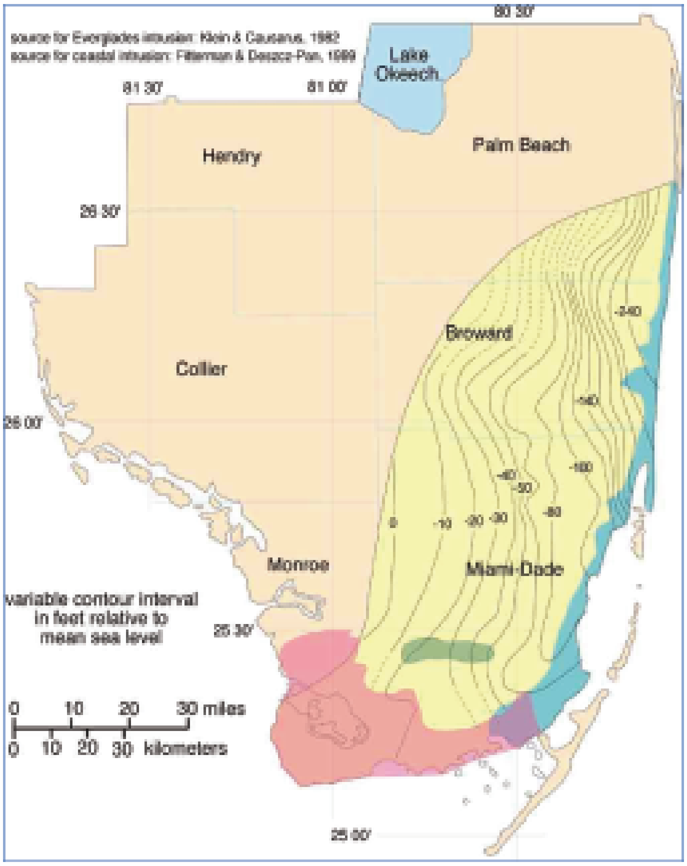

Figure 9 - Biscayne Aquifer lower contours in feet relative to mean sea level as of ca. 1999. Areas shown in blue and pink are the saltwater intrusion zones. (Credit: USGS)

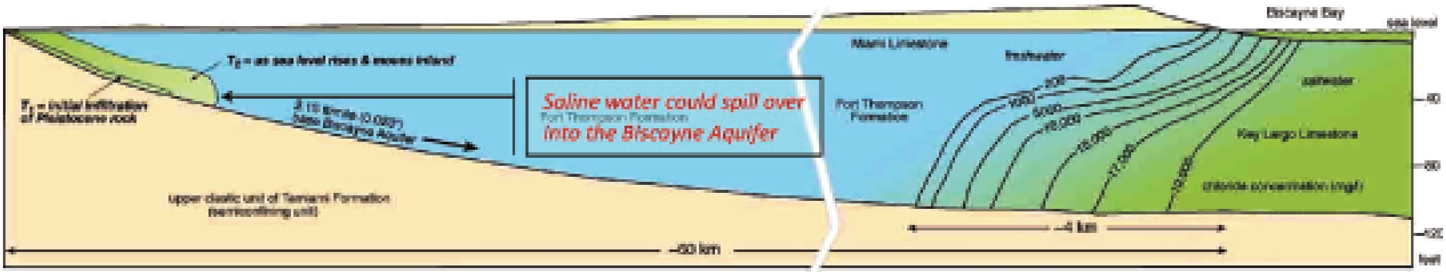

Figure 10- Cross section of Biscayne Aquifer in South Miami-Dade showing saltwater intrusion and potential spillover of saline water from Everglades as a result of northward migration of saltwater in southernmost Everglades due sea level rise (Credit: D.F. McNeill, U. Miami, 2008)

level rise would increase the volume of surface water discharge from the initial rate of 54 by up to 19 percent to 64 BGY/100 sq. mi. A 2-feet sea level rise would increase surface water discharge from the initial rate by 38 percent. This hypothetical estimate shows that surface discharge is very sensitive to sea level rise and the ratio of current groundwater seepage rate to surface water discharge. Since there is considerable uncertainty in the current rate of groundwater seepage, additional research is needed to estimate groundwater flow rates throughout the region more accurately. Furthermore, water budgets based on old data should be updated.

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

Impact on Coastal Flood Control (Salinity) Structures

The South Florida Water Management District is responsible for allocating water resources for the entire Everglades watershed, including the Kissimmee River, Lake Okeechobee, Big Cypress Swamp, and the Everglades. Coastal flood control structures in each of the primary drainage canals and rivers are used to control stormwater discharge to tide when there is a flooding threat, and to control saltwater intrusion. The coastal flood/salinity control structures are very effective for controlling saltwater intrusion, and the saltwater-freshwater interface aligns very closely with the locations of these structures. All but three of the coastal structures are spillways, either sluice gates similar to that shown in Figure 6 or gated culverts, and rely on gravity for flow. There are only three pumping stations: the S-13 located on

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the C-11 canal in Broward County and pictured in Figure 7, and the S-25B and S-26 on the C-4 canal and the Miami River in central Miami-Dade County.

As sea level rises, the flow capacity of sluice gates and gated culverts decreases. If sea level rises to the point that there is no longer any differential 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 reported by Obeysekera (2009) and SFWMD (2009). These results are shown in blue in Figure 8. These data indicate that almost two-thirds of the structures could become inoperable when sea level rises by 8 inches above 2000 levels, which is possible by as early as 2040 (Heimlich et al. 2009). The structures most at risk are those located in southern Miami-Dade County due to the extremely low elevations of that area.

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 in Heimlich et al. (2009), Appendix D. According to Bernoulli's law, flow rates for structures of these types vary approximately as the square root of the head differential across the structure.

The calculation results are shown by the red line in Figure 8. The two curves agree closely, except for the initial 6 inches of sea level rise. In this range, the contribution of partial capacity loss of higher structures is significant. For example, at 4 inches of sea level rise, which could occur by about 2030, total system capacity could decrease by approximately 30 percent (Heimlich et al., 2009, Appendix C). Forward pumping stations will be required to offset the loss of flood control structure capacity due to sea level rise. These facilities are costly to build, costly to operate, and consume substantial energy. Furthermore, there is a long lead time for design, environmental permitting, funding, and construction.

Table 2 - Interaction of Climate Change Impacts on Water Resources (Heimlich et al., 2009)

	Solo Effects	**Effects in Combination with Sea Level Rise**
Sea Level Rise	• Saltwater intrusion • Water table rise • Surface water level rise • Beach erosion • Coastal inundation • Encroach coastal wetlands and Everglades	**CELLS SHADED IN GRAY INDICATE AMPLIFIED EFFECTS**
Intense Hurricanes	• Storm surge • Flooding • Wind damage • Beach erosion • Power failures	• Severe beach erosion • Inundation/breaching of barrier islands • Increased storm surge • Increased wave damage to coastal property • Increased interior flooding
Severe Drought	• Water shortages • Less annual rainfall • Increased likelihood of multi-year drought • Increased evapotranspiration • Fire hazard in urban areas • Wildfire risk	• Increased saltwater intrusion • Reduced groundwater flow • Reduced water availability • Increased seawater encroachment in southern Everglades
Torrential Rains	• Shorter, wetter rainy seasons • Flooding and runoff • Contamination of ground and surface water	• Rise in water tables and canal levels • Reduced flow capacity of canal structures • Severe Interior and coastal flooding
Elevated Temperatures	• High evapotranspiration • Increased water demand • Heat stress • Dryness, fire risk • Severe thunderstorms • Possible tornados • Heating and hypoxia of shallow coastal waters	**Severe Drought** • Extreme water shortages • Increased risk of wildfires and urban fires • Damage to crops and landscaping • Increased water demand • Increased heat stress

Another question 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 percent, each inch of rainfall fills approximately 3 to 5 inches of soil. Soil storage capacity is reduced when the water table rises, increasing the likelihood of flooding during heavy rainfall events. If drainage rates do not keep pace with rainfall, stormwater can back up through the drainage system, causing primary canal levels to increase during periods of heavy rainfall. In order to prevent frequent widespread flooding, it may become necessary to install lift pumps to move stormwater from tertiary to secondary to primary canals if flooding begins to occur more frequently.

In the face of ever increasing sea level rise, it is reasonable to question how effectively the water table can be controlled by the drainage canals and flood control structures, with or without forward pumping. Ponding of groundwater could occur in low elevation inland areas as water tables rise, reducin soil storage capacity. The low-lying flood plains, such as west of the coastal ridge in Miami-Dade and southwest Broward counties where the water table is within 1 to 3 feet of the land surface, are especially vulnerable to these possibilities.

Saltwater Intrusion in the Southern Everglades

As sea level rises, the saltwater intrusion zone in the southern Everglades (pink area in Figure 9) will move northward. Saline water would inundate the surface waters of the southern Everglades watershed. As salinity levels in the ground and surface waters in the southern Everglades migrate northward, it would threaten the wellfields in southwest Miami-Dade County by contaminating the southern Biscayne Aquifer at its head waters in the Everglades. As shown in Figure 10, 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 best be accomplished by increasing fresh water flow to the southern Everglades, which is 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.

Other Climate Change Threats

Extreme Rainfall Patterns

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, Karl et al., 2009). Since the atmosphere's capacity to hold moisture is increased at elevated temperatures, global warming is 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, torrential rains, and more intense hurricanes. Extreme seasonal variations in precipitation patterns would become more problematic for south Florida since its flat topography limits storage of excess precipitation for use during the anticipated periods of drought. Extremes in weather phenomena are not new to Florida, where periods of increased hurricane activity have occurred about every 20 years, and periodic droughts are observed in roughly seven year cycles (SFWMD, 2009).

Climate models are less reliable 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 for Florida (Twilley, et al. 2001). The Hadley model projects a decrease in average annual rainfall, while the Canadian model projects an increase in rainfall, especially in south Florida. Both models predict that Florida will experience greater precipitation extremes, i.e., more intense rainfall events and more droughts.

Climate change may already be influencing weather in southeast Florida. Rainfall has decreased over the past 30 years, and the daily summer pattern of convective storm activity, which contributes over 70 percent of southeast Florida's annual rainfall, appears to be altered (Marshall, et al 2003). For July and August, from 1924 to 2000, wet season rainfall decreased while temperatures increased. 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." Marshall's modeling suggests that land use changes have reduced total rainfall by 12 percent since 1900, especially in the summer. Future changes in climate associated with global warming are likely to worsen these effects. Additional research and high resolution climate modeling for the Florida peninsula are being undertaken (SFWMD, 2009).

Hurricanes and Tropical Storms

Since 2005, there has been considerable research on the effects of climate change on future Atlantic tropical cyclone activity. A broad consensus of diverse groups concluded that high-resolution dynamic models consistently indicate that global average tropical cyclone intensity will increase by 2–11 percent by 2100, while the frequency will decrease by 6 to 34 percent (Knutson et al., 2010).

Hurricanes in southeast Florida are likely to be more destructive to coastal areas as a result of higher intensity exacerbated by higher sea levels. Aside from the disproportionate wind damage that would be inflicted by more intense hurricanes (Emanuel, 2005), higher sea levels will result in more severe flooding due to storm surge.

Elevated sea level will cause higher storm surge that can penetrate further inland, increasing the risk of property damage, flooding by seawater, and seawater contamination of the land, surface water, and ground water. There could be coastal flooding of most of the areas

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east of the coastal ridge and deep inland penetration along rivers and canals. Storm surge associated with Hurricane Andrew reached almost 17 feet in south Miami-Dade County. With elevated sea level, storm surge will be magnified because surge and wave action are accentuated on deeper waters (Alvarez, 2008). Storm surge model projections are needed to predict storm surge at elevated sea level. Storm surge could temporarily contaminate the water supply with saltwater and other contaminants. After Hurricane Andrew in 1992, storm surge in south Miami-Dade County did not cause significant or lasting contamination of the aquifer, since surge did not reach the vicinity of the water wellfields. Extreme flooding due to storm surge combined with heavy rains during tropical storms and hurricanes would be exacerbated by stormwater drainage systems compromised by elevated water tables and sea levels.

Elevated Temperatures

The 2007 Intergovernmental Panel on Climate Change (IPCC) report 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 percent 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, i.e., evaporation, transpiration, and atmospheric humidity, increase with increased atmospheric temperature, and all three contribute to increased urban and agricultural water demand. Increased evaporation from warmer water surfaces reduces surface water levels. Increased transpiration increases the amount of 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 would require higher levels of potable water treatment and increase the 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.

Higher air temperatures can decrease surface water quality. Increased water temperature reduces dissolved oxygen content. The combination of higher temperature and lower oxygen levels causes surface waters to be more sensitive 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 shallow estuarine waters can increase evaporation rates and concentrate salt concentrations, especially near the surface in coastal tributaries during periods of drought. 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.

Climate Change Impacts in Combination

Climate change impacts can be amplified synergistically when they occur in combination. For example, sea level rise amplifies storm surge, wave damage, and flooding due to hurricanes. An analysis of the combined effects of the most relevant climate change impacts when taken two at a time is shown in Table 2. The second column of Table 2 lists the most important effects of each impact when considered alone. Each cell in the third column lists the synergistic effects if the impact listed in the column title occurs in combination with sea level rise; the combination shown for elevated temperature is with severe drought. The total effects of each combination are the solo effects of each impact plus the amplified effects.

Increased sea level by itself will cause increased beach erosion, coastal inundation, seawater encroachment of coastal wetlands and the southernmost Everglades, rising water tables, and increased levels in surface waters, such as canals, retention ponds, lakes, etc.

Sea Level Rise with Hurricanes.

The combination of sea level rise and hurricanes can take a heavy toll on coastal areas and barrier islands, including severe beach erosion, coastal inundation, enhanced damage from storm surge and wave action, and possibly the breaching of barrier islands; this occurred on Captiva Island on Florida's Gulf Coast during Hurricane Charlie in 2004. Interior flooding can be more extensive with sea level rise because stormwater drainage would be compromised. The water supply could be threatened by hurricanes because surface waters, soils, and the aquifer can be contaminated with seawater from storm surge and contaminants in runoff from torrential rain and ensuing floods. On Aug. 24, 1992. for example, Hurricane Andrew struck southern Miami-Dade County as a Category 5 hurricane with gusts of over 170 mpg and a 17-ft. storm surge was measured along the coast of Biscayne Bay. Property damage across southeast Florida was estimated at $25 billion. Although no water wellfields were affected by storm surge during Hurricane Andrew, if a similar event occurred in North Dade or Broward County where there are wellfields that are relatively close to the coast, saltwater contamination would be possible.

Sea Level Rise with Drought

Saltwater intrusion in coastal wellfields during periods of drought and the winter/spring dry season could be intensified by sea level rise. Increased hydrostatic backpressure due to elevated sea level would result in landward migration of the saltwater front by reducing water table gradients; freshwater availability could be jeopardized as a result. In the southernmost Everglades, northward migration of saline surface water due to reduced freshwater sheet flow during periods of drought would be exacerbated by saltwater inundation caused by sea level rise.

Sea Level Rise with Torrential Rains

Summertime thunderstorms, tropical storms, and hurricanes are expected to be more intense as a consequence of climate change (Karl et al., 2009). Sea level rise is likely to reduce groundwater flow and/or elevate water tables, compromise the stormwater drainage system, and reduce flood control structure capacity (Heimlich et al., 2009). Sea level rise is expected to substantially increase the region's vulnerability to flooding due to more frequent and intense torrential rains.

Elevated Temperatures in Combination with Severe Drought

Elevated temperatures increase evapotranspiration. Higher temperatures combined with drought increase demand and reduce supplies for municipal water, agricultural irrigation, and the natural environment. Higher temperatures result in parched soil requiring more water for irrigation. When extreme drought is combined with heat waves, severe drying in the Everglades can set up conditions that encourage northward saltwater migration and increase the risk of wildfires. Furthermore, elevated temperatures, drought, and sea level rise present a triple threat to water supplies. These conditions will become more likely due to the combined impacts of climate change.

Addressing the Threats Posed By Climate Change

To protect southeast Florida's water resources, creative solutions will be required. These will fall primarily into five categories: 1) water conservation, 2) protection of existing water resources, 3) development of alternative water sources, 4) wastewater reclaim and reuse, and 5) new approaches to stormwater management. A toolbox of solutions is presented in the authors' assessment report (Heimlich et al., 2009). They are also the subject of a paper being prepared for publication in the water management literature.

Summary of 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 percent by 2030. By about 2040, 6 to 9 inches of sea level rise may reduce their capacity by 65 to 70 percent. Most of these early impacts will be felt in low-lying areas of southeastern Florida.
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 become progressively more saline and may 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.

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