Development of an adaptation toolbox to protect southeast Florida water supplies from climate change

Frederick Bloetscher, Barry Heimlich, and Daniel E. Meeroff

Abstract: Sea level rise and changes in precipitation patterns due to climate change present a challenge to water resources engineers and planners in southeast Florida with regard to sustainable water supplies and Everglades restoration. Because over half of the urban areas of Miami–Dade and Broward counties, as well as portions of Palm Beach County (home to 5 million people), are at an elevation below 5 ft national geodetic vertical datum (ngvd), protection against sea level rise and coastal migration presents a challenge. Current approaches to water supply will not protect the resilience and prolong the sustainability of the region's water resources. In this paper, the authors outline the potential effects of sea level rise scenarios for coastal southeast Florida and develop a toolbox of options for adaptation for water, wastewater, and stormwater utilities to apply. Any given option may not be appropriate for all utilities, and any given utility may deem there to be benefits to pursuing multiple strategies on a timeline in keeping with the latest estimates of sea level rise. The authors also developed milestones to trigger infrastructure investments, as climate changes may occur more rapidly or more slowly than currently projected. While applied to southeast Florida, many of these same toolbox items may be useful for other utilities located in coastal areas with low elevation, high water tables, and significant wet and dry seasons.

Résumé : Le relèvement du niveau de la mer et les modifications dans les patrons des précipitations dues aux changements climatiques constituent un défi pour les planificateurs et les ingénieurs des ressources en eau dans le sud-ouest de la Floride, relativement aux ressources durables en eau et à la restauration des Everglades. Parce que plus de la moitié des territoires urbains de Miami-Dade et du comté de Broward, ainsi que des portions du comté de Palm Beach (où habitent 5 millions de personnes), une grande partie du sud-est de la Floride se trouvant ainsi située au-dessous de 5 pieds du système géodésique national (SGN), une protection contre l'élévation du niveau de la mer et la migration côtière vont présenter un défi. Les approches actuelles pour l'approvisionnement en eau ne vont pas protéger la résilience et prolonger la durabilité des ressources en eau de la région. Les auteurs soulignent ici les effets potentiels de scénarios d'élévation du niveau de la mer pour la côte sud-est de la Floride et développent un choix d'options applicables aux services d'eau, d'eaux usées et d'eaux pluviales. Une option donnée peut ne pas être appropriée pour tous les services, et on peut imaginer qu'un service donné gagnerait à utiliser des stratégies multiples selon une séquence en tenant compte les dernières estimations de l'élévation du niveau de la mer. Les auteurs proposent des étapes à suivre pour déclencher les investissements en infrastructures étant donné que les changements climatiques peuvent survenir plus ou moins que les projections actuelles. Bien qu'appliquées au sud-est de la Floride, plusieurs de ces mêmes options pourraient s'avérer utiles pour les services d'autres localités des régions côtières à faible élévation, avec des nappes phréatiques élevées et des saisons humides et sèches marquées.

Mots-clés : élévation du niveau de la mer, options adaptées, approvisionnement en eau, services dégout.

[Traduit par la Rédaction]

Introduction

In southeast Florida, abundant water supplies are present as a result of an average of nearly 60 in (1 in = 2.54 cm) of rain each year. The historical hydrologic cycle for southeast Florida was dominated by the Everglades, which is a large subtropical wetland that starts with the Kissimmee River near Orlando, Fla., and flows south to Lake Okeechobee and then south as a shallow, slow moving river 40–60 mi (1 mi = 1.61 km) wide that discharges into Florida Bay. The Everglades system is dominated by evaporation and transpiration, with surface runoff into Florida Bay comprising a relatively small percentage of the annual rainfall. Historically, the Everglades ecosystem was driven by rainfall; during the rainy wet season (May–October), sheets of water would move down the state from Orlando, through the Kissimmee River, to Lake Okeechobee, then south to the Everglades National Park (see Fig. 1 — hence the moniker, "River of Grass"). Because the land was so flat (less than 1 in per mile of slope), water would spread across the entire Everglades (40–60 mi) and flow through natural river channels and sawgrass prairies, which are the recharge areas for the shallow Biscayne Aqui-

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F. Bloetscher and D.E. Meeroff. Florida Atlantic University, Department of Civil, Environmental, and Geomatics Engineering, Boca Raton, FL, USA.
B. Heimlich. Florida Atlantic University, Florida Center for Environmental Studies, Jupiter, FL, USA.

Corresponding author: F. Bloetscher (e-mail: h2o_man@bellsouth.net).

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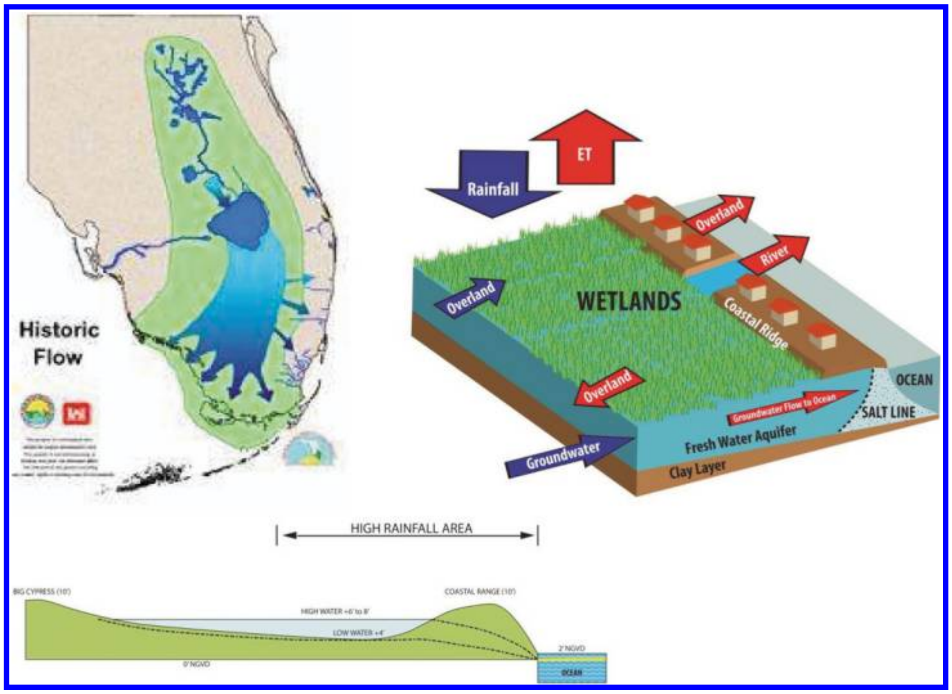
Fig. 1. Historical Everglades flow pattern. Clockwise from top: map view of the historical Everglades flow pattern; the original area to be developed showing the coastal ridge; a cross section from west to east highlighting that the high point in southeast Florida is only a few miles from the ocean. West of the high point, the topography slopes downhill to the east bank of the Everglades "river of grass." Upper left map from SFWMD.



fer. Prior to 1850, there were no barriers or canals to direct or control the path of water. In the aftermath of tropical storms, water could stand for weeks or months with no adverse effects on the ecosystem. When few people lived in the area, standing water was not a problem.

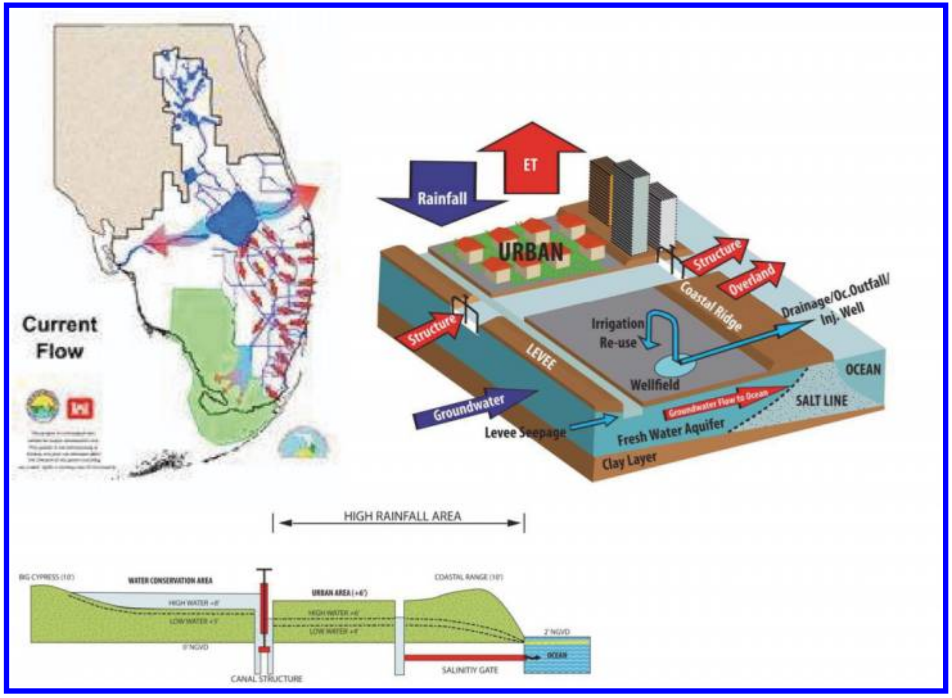
However, by 1882 efforts began to drain the Everglades and create habitable property. From 1850 to 1950, incremental dredging and draining began to control the water levels and open south Florida for agriculture and urban development. In the 1920s and then the late 1940s, after years of severe hurricanes, followed by droughts, and then more storms, Florida asked the federal government for a master plan to control the water (SFWMD 2008). In 1948, Congress authorized the Central and Southern Florida (C&SF) Flood Control Project, stretching from just south of Orlando to Florida Bay (200 mi). Construction began in 1949 and continued for over 20 years. Today, the system consists of a channelized Kissimmee River, Lake Okeechobee, 1800 miles of canals and levees, 200 water control structures, and 16 major pump stations to send water south and through man-made waterways eastward and westward to both coasts (where this water never used to flow). This network is managed by the US Army Corps of Engineers and the South Florida Water Management District (SFWMD 2008). The changes have enabled over 4.5 million people to live in southeast Florida in prior swampland (see Fig. 2).

As a result of this new system, almost half of the original Everglades was turned into agricultural or urban centers. North of Lake Okeechobee, large-scale cattle ranches and milk operations sprang up, and runoff from these operations, containing significant nutrient loading, has degraded the water quality of the Kissimmee River and Lake Okeechobee (SFWMD 2008). South of the lake, the Everglades Agricultural Area (EAA) was turned into hundreds of thousands of acres of sugarcane and other vegetable farming operations. Until a recent federal court decision ordered the practice to cease (SFWMD 2004)), highly nutrient laden summer flood water was being diverted from agricultural property back into the lake.

While these projects have prevented flooding in the urban corridor and agricultural areas, there are other impacts, including dramatic effects on the ecosystem health of the Everglades and on the quality of south Florida's potable water supplies. By the 1980s, it was obvious that a number of critical species (e.g., Everglades kites, apple snails, most heron and ibis populations) were declining and that changes in the ecosystem had likely caused these impacts (SFWMD 2008). At the same time, problems with unimpeded saltwater intrusion, drawdown impacts along the eastern edge of the Everglades, greater urban populations, and an inability to consistently recharge canals from Lake Okeechobee created water supply reliability issues for southeast Florida residents (Bloetscher and Muniz 2008).

The State of Florida, through the SFWMD, has committed billions of dollars to reversing the impacts of these defunct drainage projects in an effort to restore the natural flows and levels in an agreement with the federal government called the Comprehensive Everglades Restoration Plan (CERP) (USACOE 1999). The SFWMD are investing billions of dollars toward CERP, including projects to improve Everglades water quality and Lake Okeechobee and Estuary Recovery Plans. In October 2004, the SFWMD announced an initiative to expedite the funding, design, and construction of a series of critical Everglades projects to restore 100 000 acres of wetlands, expand water treatment areas, and provide 428 000 acre–feet of additional storage and reduce phosphorus loads.

Fig. 2. Current Everglades flow pattern depicting land-use changes made in the past 80 years. Clockwise from top: map view of the current Everglades flow pattern depicting that the historical flow pattern has been severed by a series of canals; urban development of the original eastern edge of the Everglades made possible by the construction of canals; a cross section from west to east depicting that although the topography has not changed, water management changes are evident. However, as sea level rises, the current hydrological improvements that have been made will be negated. Upper left map from SFWMD.



To date, over 40 000 acres of constructed treatment wetlands have been built to capture and treat nearly 488 billion gallons of water to improve the quality of water flowing into the Everglades. The SFWMD estimates that phosphorus loadings to the water conservation areas ahead of the Everglades have been reduced by 70% already (SFWMD 2008).

Beneath the Everglades are native sediments that are highly permeable and capable of absorbing significant percolation into the soil and porous, surficial limestone. This limestone is the outcropping of the Biscayne Aquifer, which flows toward the coast underneath much of mainland Monroe, Miami–Dade, Broward, and Palm Beach counties (see Fig. 3). The Biscayne Aquifer is a surficial aquifer system that extends from land surface to approximately 200 ft (1 ft = 0.3 m) in depth in southeast Florida. As can be seen in Fig. 3, it is clear that the Everglades is the recharge area for the Biscayne Aquifer, which is the water supply for much of the southeast coast of Florida (Bloetscher and Muniz 2008).

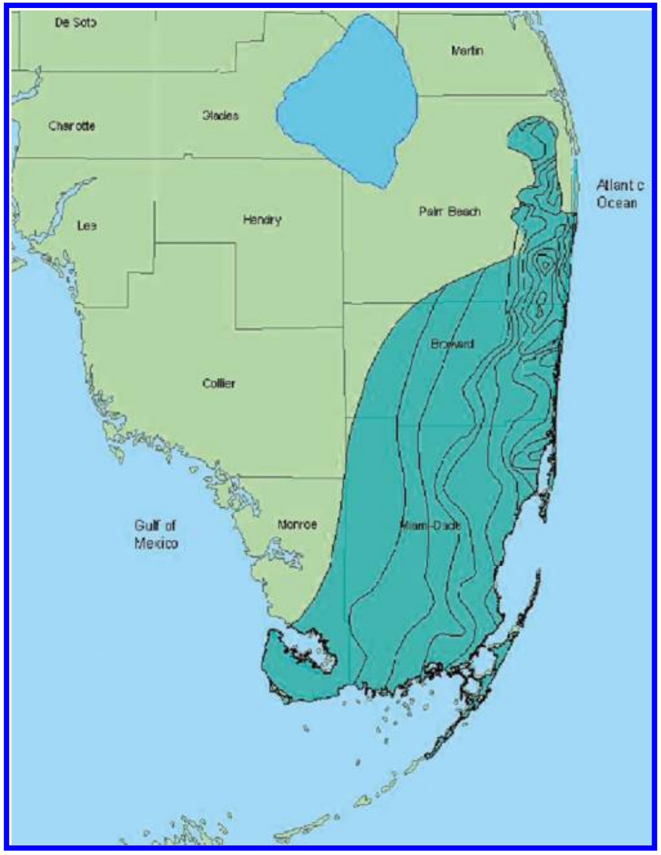
Climate change

Much of the current focus on climate change is directed at changes in precipitation and loss of water storage in snow pack. There has been significant discussion on the potential for greenhouse gases to accelerate a natural warming trend on the Earth (IPCC 2007). The Earth's climate undergoes constant changes. On a large timescale, climate fluctuations vary from hundreds of millions of years to decades or less (Huggett 1991; Goudie 1994; Issar 2005; Lamy et al. 2006; Yang et al. 2006; Dragoni and Sukhija 2008).

The scientific literature shows that there is strong evidence that global climate change is having an impact upon the world's water resources (IPCC 2007; Karl et al. 2009; UNEP 2009). The 2007 IPCC report on global scientific consensus is that the "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, and rising global average sea level" (IPCC 2007). Of the 12 years from 1995–2006, 11 rank among the 12 warmest years in the instrumental record of global temperature data (since 1850). This rapid warming is expected to cause more intense rainfall events, such as more severe thunderstorms and tropical cyclones (IPCC 2007; USCCSP 2008; Karl, et al. 2009; NOAA 2007). The data demonstrate that climatological variations alter the hydrologic cycle, and the current data indicate that hydrological cycles are already being impacted (Strzepek and Yates 1997; Buffoni 2002; Labat et al. 2004; Huntington 2006; Di Matteo and Dragoni 2006; IPCC 2007; Dragoni 2008; Dragoni and Sukhija 2008). The US Climate Change Science Program (USCCSP 2008) suggests that there may be "slightly increased runoff in the southeast [United States]." Such a trend may not apply to the flat Florida peninsula, as Marshall et al. (2003) showed a lesser trend in rainfall (12%) for the Peninsula based on historical trends from 1925 to 2003, with convective, summer rainfall (which contains the most runoff potential) being the most affected. Freas et al. (2008) also suggest that there is a potential for lower overall annual average precipitation in subtropical areas similar to peninsular Florida, but the direction and magnitude of precipitation changes for the Florida peninsula are more uncertain than other sections of North America owing to limitations in existing global climate models (Mulkey 2007).

Marshall et al. (2003) also showed increasing temperature

Fig. 3. Natural water movement of the Biscayne aquifer. The blue–green colour in the lower right of the map in the figure depicts the Biscayne aquifer, highlighting that it underlies the eastern Everglades. The Biscayne aquifer comes to the surface in the Everglades (recharge area) and deepens to the east (see contours in the blue–green area): although surface waters flow south as shown in Fig. 1, groundwater flows east (Bloetscher and Muniz 2008).



trends from 1950 to date based on historical data (0.6 °C). Rising temperatures make it reasonable to expect that Florida's existing zones of subtropical climate will extend further north. Uncertainty in long-term predictions resulting from short term observations, is of critical concern because the predictions that the temperature will rise by several degrees and the warming trend will last for centuries may portend consequences that cannot be predicted today (Dragoni and Sukhija 2008). Temperature changes will have two effects: (*i*) uncertainty in the amount and timing of precipitation, and (*ii*) sea level rise resulting from melting glaciers and land-based polar ice fields.

Climate change in Florida

The effects of climate change may already be influencing weather patterns in southeast Florida. Marshall et al. (2003) found a long-term increasing trend in temperature. If temperatures rise, it is reasonable to expect that Florida's existing climate zones will migrate northward, and zones of more tropical climate will enlarge, but the opposite has been the case despite record temperatures and warm periods in the state because, while temperatures are higher, extremes are greater, which explains why, despite higher temperatures, the citrus industry has moved south, not north.

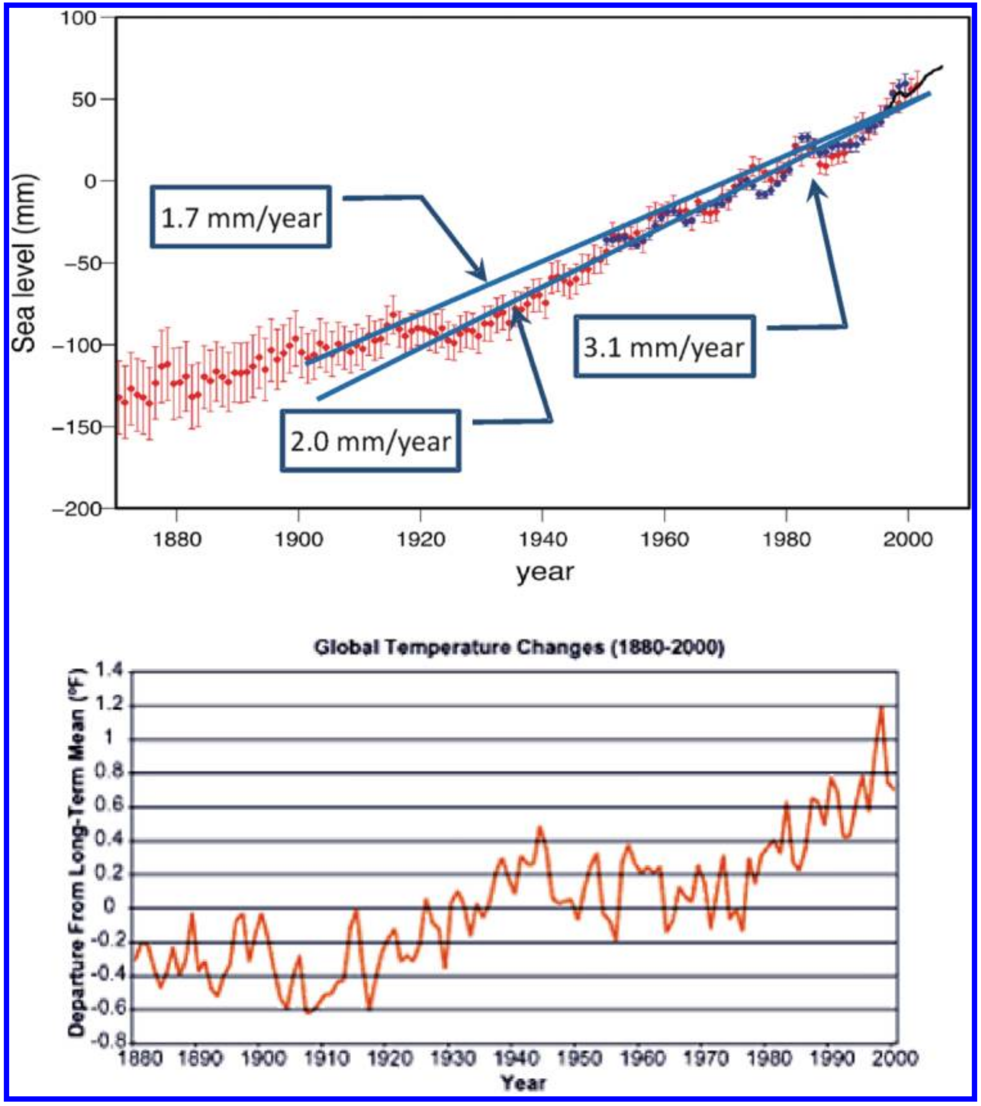
Marshall et al. (2003) also reported a decrease of 12% in convective (summer) rain, which supports the prior findings of Pielke (1999). The daily summer pattern of convective storm activity appears to be the most affected "because sea breezes are driven primarily by contrasting thermal properties between the land and adjacent ocean, it is possible that alterations in the nature of 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% of the annual rainfall, which is the source of the standing water in the Everglades. Less standing water means less recharge, which limits potable water supplies and future growth. Expected changes in climate will likely worsen these effects; however, additional research and high-resolution climate modeling for the Florida peninsula is needed.

Sea level rise

Much of the focus on climate change issues has been directed at the scientific understanding of causes and on projecting future climate patterns. More recent attention has been paid to coastal adaptation for coping with anticipated sea level rise. There is clear scientific evidence that sea levels have risen steadily over the past 100 years, and sea levels are presently rising at an increasing rate (see Fig. 4). Global average sea level has risen at 3.1 ± 0.70 mm/year since 1993 (Cazenave et al. 2008) with contributions from thermal expansion and melting of glaciers and ice sheets. Rapidly growing interest in this subject can be found in Florida (Murley 2006), California (California Natural Resource Agency 2009), King County, Washington (Littell et al. 2009), and New York City (NYCDEP 2008), which are areas with infrastructure vulnerable to sea level rise.

Of interest was whether the trends identified by IPCC (2007) and others since are different than those of Florida. Measurements in Florida (Maul 2008) show 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 is the Western Hemisphere's longest sea level record. From 1913–1999, sea level in Miami, Fla. has risen 2.39 ± 0.22 mm/yr (USEPA 2009). Barrier islands in the Tampa Bay (2.3 mm/yr) region are experiencing significant beach erosion due to sea level rise, compounded by high storm surge. Table 1 summarizes some of the existing sea level rise projections from numerous researchers. Figures 5 to 7 show the changes in sea level at stations on Florida's Atlantic Ocean coastline, the Gulf of Mexico coast, and Florida Panhandle coastlines. In all cases, the stations show an increase in the level of the sea. Combining these, Fig. 8 shows that (*i*) 95% confidence limits were developed based on the full record of observations of tide gauges in Florida (95% occur within the light blue interval shown on Fig. 8); (*ii*) Florida's average sea level rise is 2.10 ± 0.49 mm/yr for 14 Florida locations; (*iii*) the average for all but one location is within the 95% confidence interval (the exception is Panama City, Fla.); and (*iv*) the average global sea level rise for 1920–2000 was 2.0 mm/yr, which is within the 95% confidence interval for Florida locations. The result is that global projections of sea level rise of 2–4 ft by the year 2100 (Grinsted 2009; Rahmstorf 2007; IPCC 2007), are in line with the results seen for the Florida stations. Nicholls et al. (2008) note

Fig. 4. Present rate of both global and local sea level rise is approximately 12 in per century (1 in = 25.4 mm). This chart reflects the rise of sea levels since the 19th century and the accelerated pace over the last few decades. Red points show reconstructed data since 1870, blue points show coastal tide gauge measurements since 1950, and the blue curve is based on modern satellite altimetry. 50 mm is approximately 2 in. (Adapted from Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, figure 5.13. Cambridge University Press.)



that these factors, and the significance of Florida's economy to the state and the nation, place South Florida among the world's most vulnerable coastal regions to climate change, especially as it relates to sea level rise.

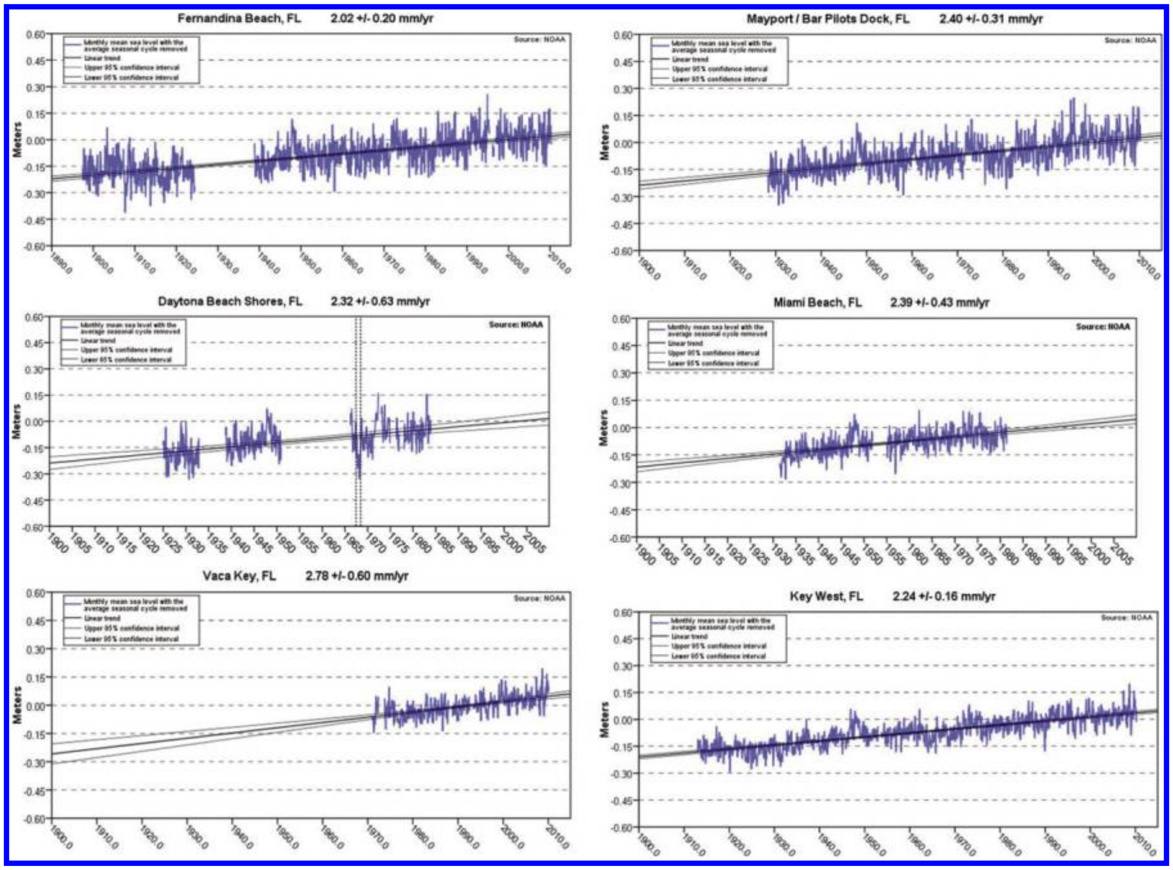
In Southeast Florida, with its low-lying topography and porous geology, much of the land elevation is under 5 ft ngvd (which would be mean high tide with 3 ft sea level rise by 2100) and could be subject to tidal inundation (Fig. 9). As a result of sea level rise, coastal areas will see migration of seawater into previously fresh aquifers that will threaten the integrity and availability of fresh water supplies, but the physics of groundwater dictates that the rise in sea level will be accompanied by an increase in groundwater levels. As southeast Florida has developed only by reducing groundwater levels, sea level rise has the potential to undo much of the C&SF project goals. Rising seas also mean rising groundwater, so more intense rainfall will increase the risk of flooding, not only in the low-lying coastal areas, but also in the interior flood plains due to the loss of soil storage capacity for percolation. More frequent and damaging floods are likely to become an ever-increasing problem as sea level continues to rise because of: (*i*) increasing levels of interior ground and surface waters; (*ii*) reduced groundwater seepage through the aquifer to the ocean; (*iii*) increasingly compromised stormwater drainage systems; and (*iv*) more frequent inundation of barrier islands and coastal areas. Greater inundation and subsequent runoff is of particular interest in a region where 93% of water used comes from groundwater sources (Bloetscher 2008).

As sea level rises, the saltwater will migrate into the southern Everglades (Fig. 9) and begin to inundate the surface waters of the southern Everglades watershed with high salinity levels. This saltwater contamination of the southern Biscayne Aquifer at its head waters in the Everglades will threaten the wellfields in southwest Miami-Dade County, which supply potable water to the county's 2.5 million resi-

Table 1. Model result of projected sea level rise (1 ft = 0.3 m).

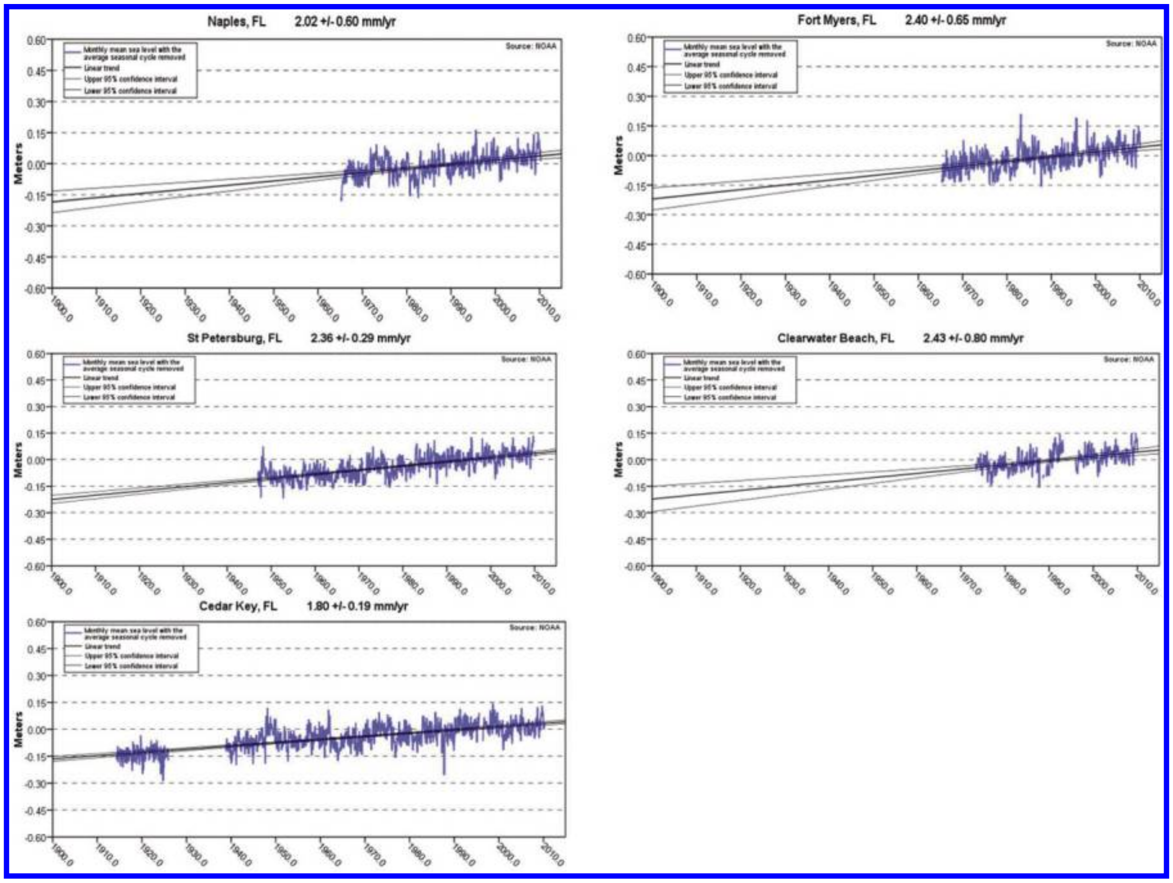
Region	Sea level rise projections (ft)	Time frame	Data source	Date published	Model(s) and (or) method used
Global	0.26–2	2100	IPCC	2007	Hierarchy of several models
Global	1.9–5.25, with confidence limits of 1.93 and 5.9	2100	Jeverjeva, Moore and Grinstead	2010	Inverse statistical model
Global	1.6, 3.2, and 4.9	2100	USACE	2009	Modified NRC curves with modified equations and IPCC projections
Global	4.27–20.67	Not given	Mitrovica	2008	Modified calculations and models (Fingerprinting, IPCC)
Global	2.5–6.2	2100	Vermeer and Rahmstrof	2010	Semi-empirical dual model
Global	2.6–6.5	2100	Pfeffer et. al.	2008	Calculation of ice sheet dynamics
Global	1	2100	Church and White	2006	Statistical analysis of historic sea level data/trends
Global	3.12–3.94	2250	MIT–IGSM	2009	Integrated global systems model
Florida	In-progress	In progress	Gulf Coast Alliance	2014	
Florida	3–5	2100	Heimlich et. al.		Quadratic equation
Florida	3–5	2100	Miami-Dade Climate Change Advisory Task Force	2008	Modified IPCC
Florida	0.59–4.4	2100	SWFRPC	2010	Modified EPA and Stanton and Ackerman

Fig. 5. Trends in monthly mean sea levels recorded for Florida stations located on the Atlantic Ocean showing a rise in sea level over the last ~100 years at all stations.



dents. As shown in Fig. 3, the Biscayne Aquifer is wedge-shaped; its bottom surface slopes downward from the Everglades toward Biscayne Bay and the Atlantic Ocean. Because of density differences, the saline water will travel downward along this slope as illustrated. To protect these vulnerable water supplies from saltwater intrusion, the fresh water flow to the southern Everglades must be increased. The primary goal of CERP is to restore the natural freshwater flow to the Everglades, which becomes even more imperative in light of potential sea level rise impacts. Thus, CERP will have the added benefit of assisting with adaptations to climate change and protecting potable water supplies for the future.

Fig. 6. Trends in monthly mean sea levels recorded for Florida stations located on the Gulf of Mexico showing a rise in sea level over the last ~100 years at all stations.


Naples, FL 2.02 +/- 0.60 mm/yr

Fort Myers, FL 2.40 +/- 0.65 mm/yr

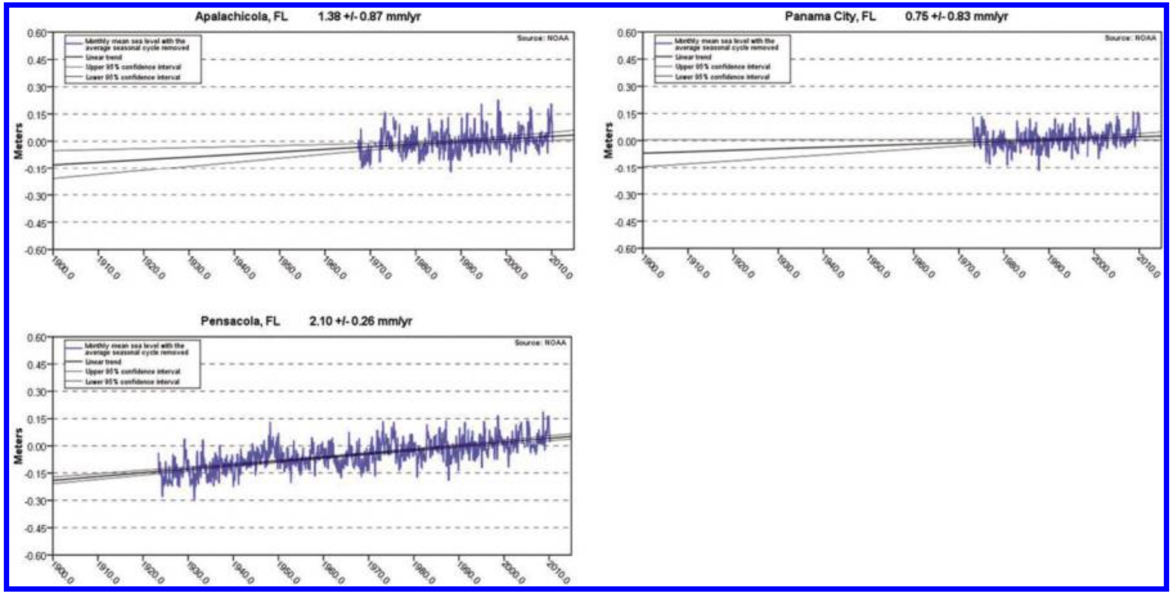
St Petersburg, FL 2.36 +/- 0.29 mm/yr

Clearwater Beach, FL 2.43 +/- 0.80 mm/yr

Cedar Key, FL 1.80 +/- 0.19 mm/yr

Source: NOAA

Fig. 7. Trends in monthly mean sea levels recorded for Florida stations located on the Gulf of Mexico in the Panhandle showing a rise in sea level over the last ~100 years at all stations.


Apalachicola, FL 1.38 +/- 0.87 mm/yr

Panama City, FL 0.75 +/- 0.83 mm/yr

Pensacola, FL 2.10 +/- 0.26 mm/yr

Source: NOAA

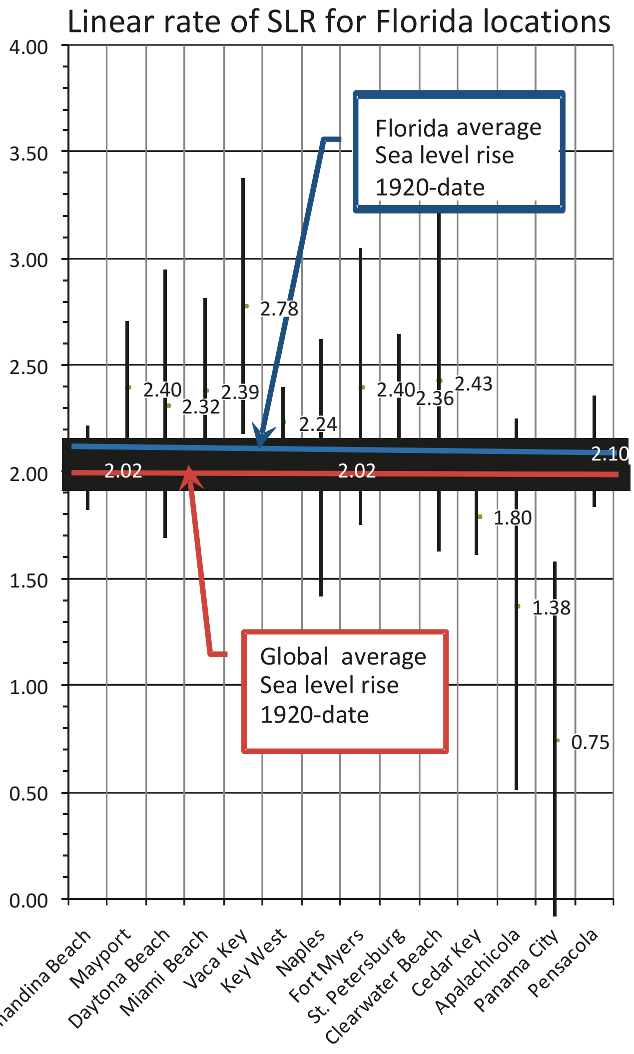
Toolbox for protecting water resources

A number of strategies can be considered for utilities to safeguard future water supplies, although the applicability of these options will vary according to local issues, topography, and vulnerability assessments. Table 2 summarizes a selection of tools for water resource protection from the impacts of climate change. The timing to pursue these options is also discussed.

Install local stormwater pumping

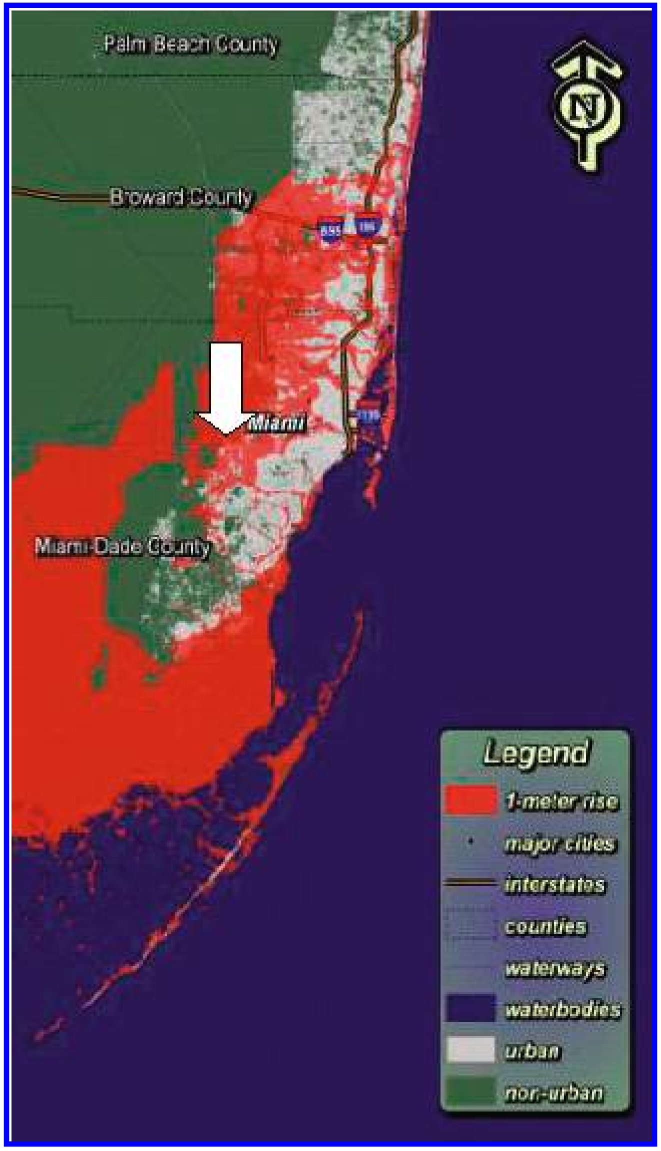
Approximately 70% of southeast Florida's rain falls from mid-June through September, on a nearly daily basis; the sub-

Fig. 8. Sea level rise (SLR) data from all 14 Florida tidal stations measured over the last ~130 years.The average sea level rise for Florida (blue line) is 2.10 ± 0.49 mm/yr and is consistent with the global average sea level rise of ~2.00 mm/yr (red line) and the IPCC projection of 1.00 mm/yr.



tropical summer rainy season. Average storms deliver up to 0.5 in in a 30–60 min period. Localized accumulations in excess of 2 in are common. This ignores hurricanes and tropical storm events that can deliver far more rain in a 24 h period. Stormwater management during the wet season and major rainfall events will become increasingly difficult as sea level rises. Because groundwater levels are tied to sea levels in coastal regions, any amount of sea level rise will cause a corresponding increase in groundwater levels. Increased groundwater levels diminish soil storage capacity (i.e., the amount of rainfall that can percolate into the soil) and compromise the flow capacity of storm drainage systems and coastal structures. Modest increases in sea level could lead to the potential for severe flooding of large areas after typical summer rainstorm events (0.5–1.0 in). Currently, some communities in southeast Florida have areas that already flood after most storms. The problem will worsen with time as more areas will have issues associated with reduced soil storage capacity. In low-lying areas, exfiltration trenches will cease to function, and dry retention will become wet retention.

Fig. 9. Approximate susceptibility of Southeast Florida to 1 m (3.25 ft) sea level rise The highlighted area is at an elevation equal to 1 m 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. Note that southeast Florida has a coastal ridge that follows I-95 (see white arrow). The result is vulnerable areas on the west side of the developed (light-colored) areas, which is not what people expect (Image credit: Weiss and Overpeck, 2010).



Localized pumping stations will need to be installed to rapidly drain this extra water to reduce ponding. As the water table rises, ever smaller storms will create flooding as soil storage capacity is lost. These stations will range in capacity depending on the rain event and drainage basin (watershed), but could range from US$1.5 to over US$5 million for each pump station depending on drainage basin size. For southeast Florida, dozens of these pumping stations may be needed in large communities along the coast. Permits will be a major challenge because of contaminants in the runoff as regulated by MS 4 Stormwater permits, and the inability to treat this water under the current structure. The cost and energy re-

Table 2. Summary of water supply benefits and climate change benefits from various tools in toolbox (after Heimlich et al. 2009).

Tool	Benefit to water supply	Climate change benefit
Install local pumping stations	None – reduces aquifer levels	Reduce flooding in low lying areas
Water conservation	Lowers per capita use, stretched current supplies	Reduces stress on vulnerable water supplies
Armoring the sewer system	Protects water quality and supply	Protect reclaimed water option but protecting water quality
Wastewater reclamation	Replaces use of fresh water for irrigation and industrial use	Replaces vulnerable water supplies
Aquifer recharge	Reduces raw water requirements	Recycles existing water to increase available fresh water
Protection of existing water sources	Protects water quality and supply	Reduces stress on vulnerable water supplies
Strategic well relocation	Reduce impact of coastal supplies	Increased fresh water available for countering impacts
Horizontal wells	Skims fresh water	Increased fresh water available for countering impacts
Re-engineering canal systems	Controlling water tables and protecting against contamination	Flood control
Hydrodynamic barriers	Controlling water tables and protecting against contamination	Reduce saltwater intrusion
Capture and surface storage of excess runoff	Storage mechanism for existing	Increased fresh water available for countering impacts
Septic tank closure	Protect groundwater quality	Increased fresh water availability
Close private wells	Protect groundwater quality	Increased fresh water availability
Desalination	New water source	Replaces vulnerable water supplies
Aquifer storage and recovery	Storage mechanism for existing	Increased fresh water available for countering impacts
Regionalization of alternative water supplies	Shared risks of water supply options	Economies of scale for wastewater and stormwater recovery and reuse

quired to treat this water also is a major concern going forward. Communities will need to perform additional stormwater modeling and collect LIDAR topography and ground truthing to prioritize areas in need of added drainage (pumping) improvements. Stormwater utilities will see dramatic increases in capital construction and operations that currently do not exist and time will be needed to secure and comply with these new permits.

Water conservation

Water conservation programs, which have many short- and intermediate-term benefits not related to climate change, are useful in reducing the need for expansion of water supplies because they encourage reduced per capita water usage. From the utility perspective, water use efficiency 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, such as in southeast Florida prior to the 2008 economic turndown, immature water conservation programs were not be able to provide timely gains in water supply needed to keep up with increasing demand.

Water conservation programs require funding for staff, incentives, outreach, etc. The most successful measures in southeast Florida are outreach and toilet retrofits, which require significant investments (Bloetscher et al. 2009). Other ordinances have been implemented to restrict irrigation, require installation of rain sensor devices, promote xeriscaping, or require the use of ultra low volume plumbing, implement water use restrictions, and provide incentives for reuse of reclaimed water to offset irrigation usage. All are required by the SFWMD for the renewal of water use permits. Rate structure modifications can also encourage water conservation. Inverted rate structures, where rates increase at high-use levels, can be a strong incentive for conservation and are required by permit for all utilities in southeast Florida (Bloetscher and Meeroff 2009)

However, water plants have significant fixed costs such as debt service, amortization of capital, lean operating staffs, and administrative expense. Capacity under-utilization can cause budgetary problems because of reduced revenues that can only be partially offset by reduction of variable costs for electric power, maintenance, and chemicals consumed, for example. Therefore, effective conservation programs may require rate increases or surcharges to balance budgets and meet bond covenants. This can cause negative public response to the perception that good behavior is penalized. Furthermore, capacity under-utilization can cause operational 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.

Armoring the sewer system (G7 program)

Inflow reduction is important not only from the cost savings in the operation of the wastewater treatment plant, but because a portion of the collection system may be inundated as a result of sea level rise. Therefore, the inflow is largely saltwater, which will reduce options for use of reclaimed wastewater because the chloride levels will be too high for land application. In this case, treatment with reverse osmosis to reduce the total dissolved solids (TDS) would become necessary for reuse. An effective infiltration and inflow (I/I) reduction program will combat the need for expensive membrane treatment for water reclamation in the short term. This tool has the following components:

- inspection of all sanitary sewer manholes for damage, leakage, or other problems;
- smoke testing of sanitary sewer system for leaks;
- low flow inspection events;
- documentation of all problems, locations, and recommended repairs;
- repair of components (manholes, benches, etc.) in poor condition or exhibiting substantial leakage;
- repair and (or) sealing of manhole chimneys to reduce infiltration from the street during flooding events;
- installation of dishes in all manholes to prevent infiltration;
- installation of plugs where manholes in the public right-of-way or other portion of the utility's system may be damaged; and
- manhole inspection and dish replacement — this is for manholes where the repairs have previously been made and only the inspection and dish replacement occurs.

The costs for this type of program will be on the order of US$500 per manhole (plus repairs to an estimated 15% of service laterals at a cost of up to US$500 each based on recent pricing and experience). Repairs to pipes and laterals are estimated be US$2000 per manhole based on experience in southeast Florida. Reinspection should occur every 5 years. The benefit of this program is that it would keep excess water out of the sewer system, especially saltwater from inundated areas. This program also has a low initial cost and high rate of return compared to other options. If inundation of roadways occurs as a permanent issue, those affected areas would likely need to be abandoned, as there is no fail-safe way to prevent water from seeping into sewers under flood conditions.

Wastewater reclamation and reuse

Presently, most of the treated wastewater generated in the US is discharged to surface waters. In California, Florida, Texas, Arizona, and Nevada, substantial reclaimed water programs exist because of limited water supplies. Public access reuse systems can provide irrigation for residential lawns, golf courses, cemeteries, parks, landscape areas, and highway medians as well as agricultural irrigation, cooling water, and other industrial uses. Reclaimed water must be filtered to further remove suspended solids before application of disinfectant to assure adequate deactivation of viruses and other pathogens (i.e., *Cryptosporidium* and *Giardia*).

Water quality requirements for human and ecosystem use are typically more stringent than those needed for agricultural or industrial use. Most southeast Florida utilities do not have these facilities installed, so capital must be expended to pursue reuse options. The cost of implementing reclaimed water use systems is US$3–5 per gallon (1 gallon = 3.78 L) of treatment capacity in capital costs for standard filtration, enhanced disinfection, storage, and pumping. The operations cost is on the order of US$1–2 per 1000 gallons above the cost of supplying secondary (conventional biological) treatment. The cost to install the distribution network is on the order of US$0.5–1 million per mile of pipe, and the cost to connect to the distribution network is on the order of US$10 000 or more per household for delivery to individual homes.

However, the purpose of irrigation with reclaimed water is to keep the soil moist, but as sea level rises, controlling the water table in low-lying areas and surface waters at acceptable levels to permit the application of reclaimed water without flooding becomes more of a challenge. As a solution on how to discharge excess ground and surface water to avoid flooding will become more problematic, the additional obligation to beneficially reuse tens of millions of gallons per day of reclaimed wastewater will be a tipping point. As a result, as sea level rises, the application of reclaimed water may become less feasible, particularly during the rainy season.

Aquifer recharge

There are various methods of recharging surficial aquifers using stormwater or treated wastewater to augment fresh water supplies. These include: (*i*) stormwater diversion to impoundments located on permeable land; (*ii*) treated water discharge into surface waters for aquifer recharge; (*iii*) direct injection of treated stormwater or surface water from reservoirs; (*iv*) percolation ponds or wetlands using tertiary treated wastewater; (*v*) direct injection of highly treated wastewater using reverse osmosis; and (*vi*) other similar variations of these approaches.

Artificial recharge with stormwater is an option used in many regions of the country, but has not yet been pursued in southeast Florida. Aquifer recharge with treated wastewater has been employed for decades at the Orange County, Calif., Water District's Water Factory 21. Water Factory 21 began operation in 1976 and has continuously met or exceeded the USEPA drinking water standards. Purified reclaimed water is produced for industrial use and irrigation using various advanced processes, including reverse osmosis and ultraviolet disinfection (US Water News Online 1988). Based on Water Factory 21 experience, construction costs for similar facilities in southeast Florida would approach US$12 per gallon of treatment plant capacity (CDM 2009) with operational costs over US$10 per 1000 gallons treated (Heimlich et al. 2009). Application sites are needed, which can limit opportunities. Also as sea level rises, the aquifer recharge systems will tend to increase groundwater levels, increasing potential flooding. As a long-term option, this loses viability.

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 to saline contamination. Limiting wellfield withdrawals is an obvious strategy to prevent saltwater intrusion, but meeting increasing demand would necessitate drilling of new wells that are further from the coast. Other solutions worthy of consideration are coastal salinity structures, horizontal wells, and hydrodynamic barriers.

Strategic well relocation

The highly managed water control system in southeast

Florida has permanently reduced groundwater levels along the coast, which has enabled urban development. During the winter months, the Biscayne aquifer's water level usually declines unless some form of supplemental recharge is provided to prevent the aquifer from draining. As the level of water in the Everglades is related to the water available in the Biscayne aquifer, reduced groundwater levels, combined with lessened historical rainfall in the Everglades, results in less standing water in the Everglades during the summer months. The net result is a reduction in available fresh water supplies during the dry season, which coincides with the increased winter population and peak irrigation season.

To counteract the impacts of sea level rise, strategic relocation of wells to areas where water supplies are plentiful and reliable is one of the more attractive options to be considered. Site selection is critical and should take into account variations in local geology, recharge capacity, groundwater flow, ecosystem impacts, and potential vulnerability to future climate change threats. 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. With regard 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 in the Everglades. 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. Well costs include piping, pumps, and wellhead protection zones. To secure additional Biscayne water, the wells will need to be smaller in capacity, possibly shallower, and spread further apart. Costs are estimated on the order of US$1 million per MGD (million gallons per day) of capacity.

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. Because saltwater has higher density than fresh water, the fresh water in the aquifer tends to float above the saltwater in a shallow lens as it approaches the coast (Fig. 10). A vertical well causes a steep drawdown cone while a horizontal well spreads the region of influence over a much wider area. Horizontal wells enable drawing fresh water in the same location where a vertical well might be intruded by saltwater. One drawback is that most horizontal wells would be in sand, which has much lower transmissivity than the deeper geology of the Biscayne aquifer, so yield is unclear. In addition, because the horizontal wells are placed in a shallow location, the water they draw may be considered "groundwater under the influence of surface water" according to the Surface Water Treatment Rule (USEPA 2005). Consequently, the permitting process may be more challenging, and the water may require a higher level of treatment for removal of pathogens, nutrients, and other contaminants. Nonetheless, this tool may be an attractive alternative for extending wellfield life when saltwater intrusion becomes a threat.

At this time, there are no horizontal wells in the region, but a test project was proposed by one of the authors in Dania Beach, Fla. The project is included in the City's water supply plans, commencing prior to 2015, but the current economic conditions and lack of economic development may delay this project. A horizontal well is anticipated to be about twice the cost of a vertical well, and careful consideration of entrance velocities is required to prevent fouling of the well screen, but the potential to capture additional water is higher because more of the aquifer is exposed.

Re-engineering canal systems, control structures, and pumping

Water managers in southeast Florida use the drainage canal network to control water table levels to prevent flooding by discharging stormwater to tide in coastal areas. Properly placed control structures can also prevent the inland migration of seawater in the canals and provide physical boundaries for the saltwater intrusion front (Fig. 11). There is fresh water on the inland ("headboard") side of the structures; whereas, waters on the ocean ("tailboard") side are tidal and brackish. By maintaining high water levels in the canals, the aquifer retains water that is otherwise lost to tide, which protects against saltwater intrusion.

The SFWMD is the responsible authority that maintains the primary canal system. According to their estimates, approximately 13% of the control structures would lose 100% of their capacity with sea level rise above 4 in, about 67% with an 8 in sea level rise, and over 80% of the structures with a 1.5 ft rise in sea level (Obeysekera 2009). However, these estimates ignore the additional losses in design capacity due to the increased groundwater elevation from sea level rise. The dilemma is that as control structure capacity is declining, stormwater runoff rates will increase substantially from increased surface water ponding. Thus, the stormwater drainage system will be significantly compromised. As a result, 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 elevations. The SFWMD is evaluating solutions to this issue. Open ocean access, private property rights, inverse condemnation, and a variety of public interests will resist the construction of salinity structures closer to the ocean, and such construction may accelerate inundation and flooding of low-lying coastal areas. But not only is low-lying property along the coast an issue, so are communities much farther inland that were previously part of the Everglades.

Hydrodynamic barriers

The hydrodynamic barrier works by raising the water table with waters of lower quality (i.e., stormwater or wastewater treated with reverse osmosis and advanced oxidation). A hydrodynamic barrier increases hydraulic head between the saltwater interface and the wellfield and pushes back the saltwater intrusion front (Fig. 12). A preferred method for protecting a large wellfield is to use shallow horizontal injection wells or infiltration trenches. Both methods are viable for countering saltwater intrusion and increasing available water supplies by recycling water.

Capital costs for hydrodynamic barriers are in the range of US$10–12 per gallon of treated water capacity, which does not include the high energy consumption and operating costs (up to US$10 per 1000 gallons treated). Economic justification may depend upon the utilities receiving an allocation

Fig. 10. Interface between fresh and saltwater lenses in groundwater (the Ghyben–Herberg principle). A balance of pressure is created between the less dense freshwater and the denser saltwater, resulting in the freshwater rising above the saltwater intrusion. This relationship depends upon the level of the water table compared to sea level. Note the freshwater will try to rise over the top of the saltwater because of the density difference.

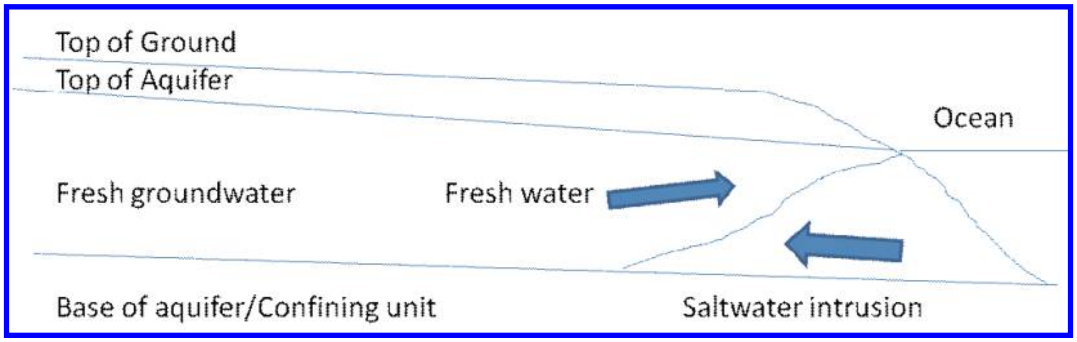


Fig. 11. Location of salinity structures in southeast Florida (the small arrows depict canals that drain by gravity, the large arrows are canals that require pumping; structures denoted in the U-shapes on each canal – one is circled in red in Boca Raton). The migration of saltwater intrusion matches these salinity structures. Source: SFWMD 2010.

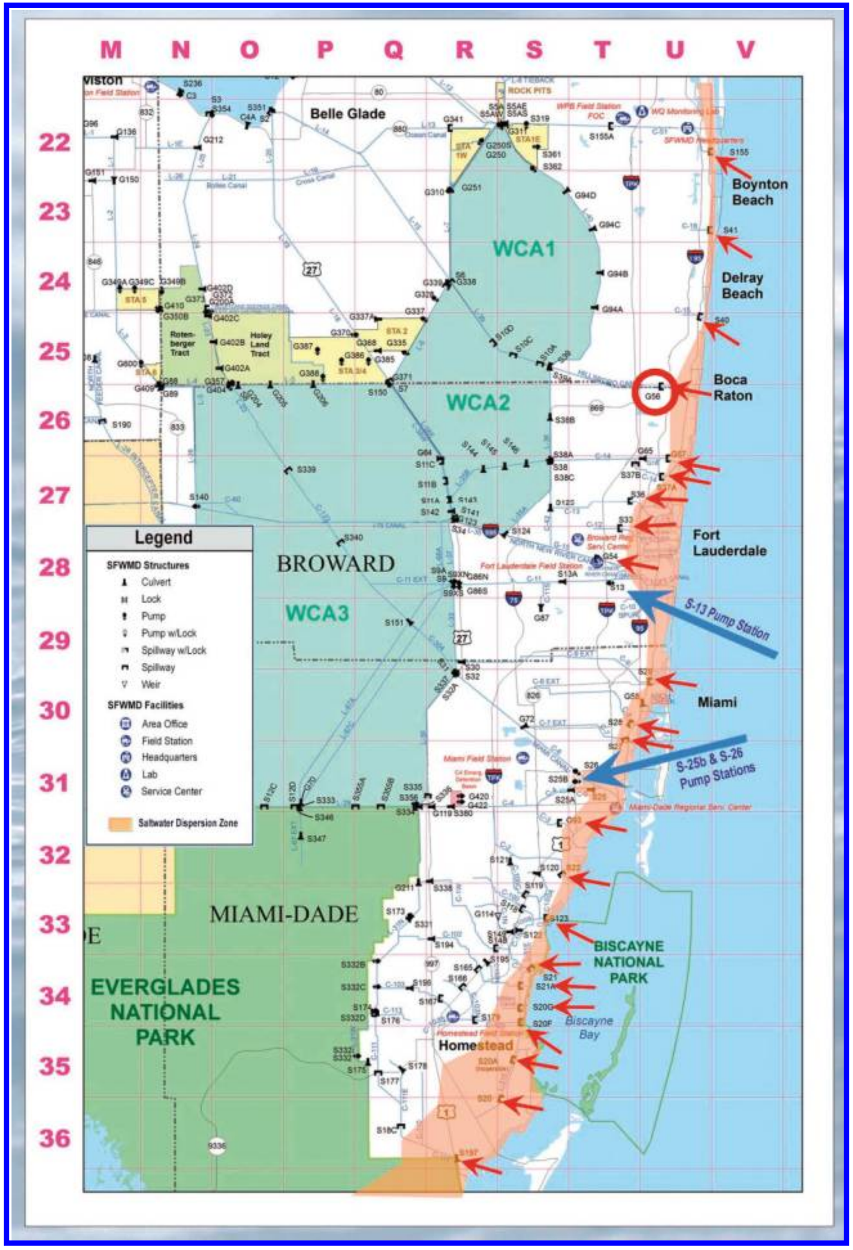
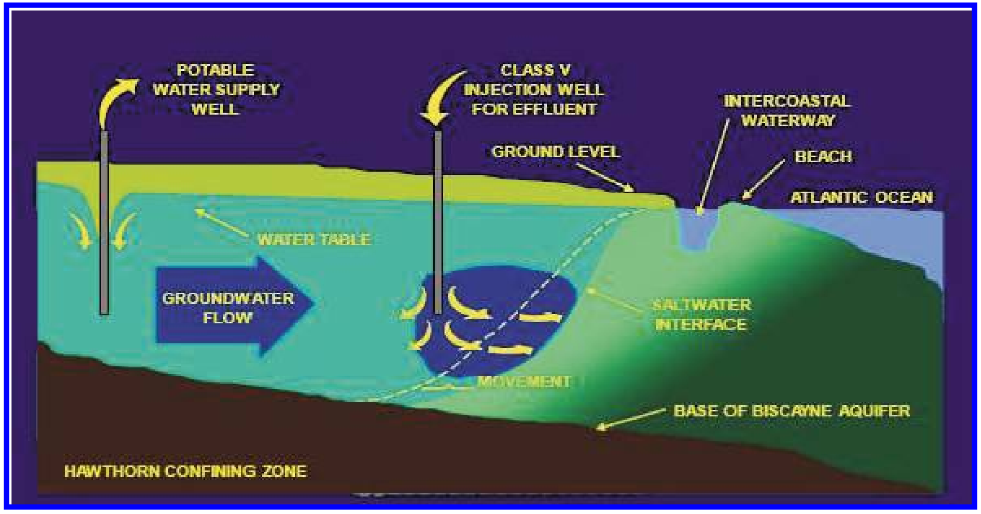


Fig. 12. Schematic of a potential salinity barrier project. The potable water supply well is shown. Saltwater intrusion threatens it (dashed line). The dashed line continues westward as development retards groundwater recharge thereby necessitating the construction of the class V injection well. High-quality reclaimed effluent is then pumped into the class V injection well for effluent, upstream of the saltwater front (see blue bubble with arrows showing how water moves). The resulting increase in groundwater levels would push the front back towards the sea (see difference between dashed line and saltwater interface ("movement" is caused by injected high-quality effluent).



credit to potable water supplies from the aquifer recharge so that the utility can increase raw water withdrawals. Another concern is that raising the water table will likely reduce soil storage and lead to more localized flooding as sea level rises. To prevent property damage from increased flooding, computer simulations must be undertaken to predict the extent of flood prone areas. Interface between models is an emerging process. Implementation of hydrodynamic barriers may not be beneficial in the long term because rising groundwater levels will limit opportunities for injection without increasing the risk of flooding.

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 for water resource planning, but because southeast Florida has such flat topography, surface water storage reservoirs may not be technically feasible. South Florida utilities have proposed constructing the C51 reservoir project to intercept 160 MGD of drainage water that would otherwise be sent out to tide. The proposed reservoir would exploit abandoned rock pits in an area with low groundwater permeability in southern Palm Beach County. The cost for this project is estimated at US$2.50–3.00 per gallon of treated water capacity, which is less than some other alternative water supply approaches. The proposed reservoir would represent a significant portion of southeast Florida's projected water supply shortfall of approximately 250 MGD by 2025 (Hazen and Sawyer 2009). Although property acquisition and permitting challenges threaten to derail the proposed reservoir, the concept remains valid.

Septic tank closure

As sea level rises, operation of existing septic tanks and on-site sewage treatment and disposal systems (OSTDS) will not work properly as rising water tables submerge drainfields. An FAU study (Meeroff et al. 2008) quantified the pollutant loading contributions with regard to nutrient and pathogen indicators from a single family residential neighborhood served by OSTDS located adjacent to coastal canals in Dania Beach, Fla. Pollutant loading was compared to that in a similar residential area serviced by sanitary sewers in Hollywood, Fla. Field studies of the paired sites were conducted during the seasonal high water table (SHWT) and seasonal low water table (SLWT) events. During the SHWT, the coastal waters were impacted by OSTDS contributions, but the OSTDS appeared to work effectively during the SLWT because there was more area for treatment in the vadose zone between the drainfield and the water table. The study suggests that once sea level rise reaches a certain threshold, septic tanks will no longer work properly under any conditions. Over 500 000 OSTDS exist in southeast Florida (FDEP 2001). The cost of transferring OSTDS to sewers would average US$10 000 per household and would likely be assessed against the property owners. Wastewater treatment plants would also need to be expanded to handle the additional flow at a cost of another US$10 000 per household.

Closing of private irrigation wells in the Biscayne aquifer

Private residential and agricultural water use (primarily for irrigation needs) exceeds urban water consumption in southeast Florida. Presently, wells on private property are not regulated unless they exceed 100 000 gallons perr day. Many residents use private wells for irrigation because it is "free" water. These wells are typically 20–30 ft deep. Water at this level is currently fresh, but if sea level rises, there is potential for saltwater intrusion, especially for wells located near the coast. Politically, closing private wells is difficult to implement because operating a private well is considered a property right and would be unpopular to impose. In southeast Florida, utilities cannot acquire the water use rights from private wells. However, closing private wells will create increased potable or reclaimed water demands for the utilities. As a result careful implementation of this concept is needed to ensure reclaimed water could replace these new irrigation demands without impacting limited potable water supplies.

Fig. 13. A typical large-scale reverse osmosis desalination installation in Hollywood, Fla. The use of reverse osmosis in southeast Florida has increased to address water quality concerns in brackish water aquifers. This same technique could also be applied to seawater and reclaimed water but at a high power cost.

Development of alternative water sources

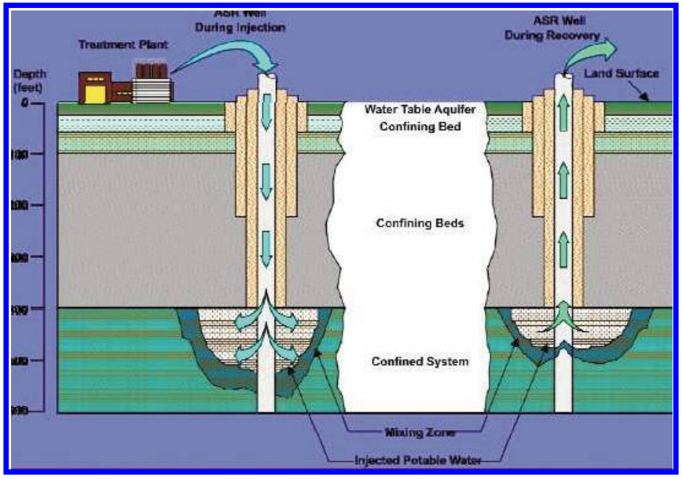
Development of alternative water sources is an important strategy for conserving raw water resources, assuring sufficient water supplies to meet municipal demand, and also to provide water needed for ecosystems. The use of reclaimed water for irrigation and aquifer recharge are two alternative source options that have already been discussed. Desalination is another.

Desalination

Recovering fresh water from seawater or brackish water using reverse osmosis membranes is a preferred option in southeast Florida where fresh water is in limited supply (Bloetscher and Muniz 2008). Where more dilute brackish waters are available, they would be preferable to seawater desalination in terms of operating costs (US$10–13 per 1000 gallons). Reverse osmosis membrane systems could also be used to reclaim treated wastewater and stormwater. Major technological improvements have significantly improved membrane performance, reduced costs, and lowered energy requirements. At the current state of development, 50% recovery is achievable from seawater and up to 85% for brackish water sources.

Figure 13 is a photograph of a typical large-scale desalination installation. Southeast Florida has access to the ocean as a water supply as well as the brackish Floridan aquifer. In either case, raw water is prefiltered to remove suspended solids and then pumped under pressure to the first stage reverse osmosis membrane cartridges. High-purity water permeates through the membranes and is collected in holding tanks. The dissolved solids are retained in the "concentrate." The combined permeate is collected in storage tanks for further treatment by chemical stabilization and final disinfection before use as potable water. Disposal of concentrate is an issue. Fortunately, utilities in southeast Florida have access to class I injection wells for concentrate disposal. New injection wells cost around US$6 million per well, which is an expensive option for a small utility.

Fig. 14. In an aquifer storage and recovery (ASR) well, water is injected into an aquifer formation during periods when there is plenty of water available and water is retrieved from the system during periods when water supplies are stressed (Heimlich et al. 2009). The well on the left shows the injection condition — water moves into the aquifer. On the right is the withdrawal condition. Note the clear water bubble diminishes with recovery.



Desalination requires substantial electrical energy to drive the pumps and other equipment required. The capital cost for a reverse osmosis treatment facility is site specific, typically on the order of US$5–7 per gallon capacity. Operating costs are likely to be in excess of US$3 per 1000 gallons for the Floridan aquifer and up to US$13 per 1000 gallons for ocean desalination. The latter is more than three times the amount for conventional water treatment. The power grid is a major concern because at this level of energy consumption, the local energy company will need to add additional power generating capacity to meet demands (Bloetscher et al. 2010).

Aquifer storage and recovery

Aquifer storage and recovery (ASR) is not an alternative water supply, but a management tool used to store excess water underground where the geologic formations allow water managers to capture and store water that would otherwise go to tide or would be lost to evapotranspiration if stored in open aboveground reservoirs. For ASR to work, a confined aquifer is used to store water during times of excess to be recovered to meet peak demand during times of shortage (Fig. 14). ASR can be applied to potable water, treated wastewater, or treated stormwater as deemed applicable. During the wet season 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 flow conditions rather than peak demand, with the ASR water only requiring disinfection and blending with the newly treated water. Considerable investment in expansion of treatment capacity can be saved and more efficient overall operation can reduce operating costs while conserving energy, provided that the partially treated water can be recovered efficiently. The economics are especially attractive for more costly reverse osmosis facilities, which need to operate at constant speed to optimize efficiency. For an ASR system to satisfy the requirements of regulatory agencies, the injected water must be treated to meet the applicable water quality standards for the aquifer selected for storage. For southeast Florida, this requires treatment to potable water standards to store water in a G-2 aquifer.

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 the 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. An advantage of ASR over surface water storage is that it avoids evaporation losses. However, full recovery of water stored underground is not achievable. 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. In southeast Florida, several ASR projects (Broward County, Fort Lauderdale Sunrise, SFWMD) have been unsuccessful for a number of reasons including heavy metals contamination (arsenic leaching from the formation) and leakage of the injectate to other zones. As a result, efforts to apply the method have been given a lower priority. Instead, more emphasis is being directed to surface water storage such as the proposed C51 reservoir in Palm Beach County to store excess stormwater runoff that would otherwise be discharged to tide. This water would be rerouted through the secondary canal system to recharge wellfields in the future (post 2020).

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 (or) risks and taking advantage of economies of scale through higher utilization of available resources and centralized management. Such projects are difficult to organize because of complications in deciding how responsibility and authority should be divided among the regional partners and customers. Participating utilities, including small utilities, can substantially reduce investments and operating costs on a pro rata basis.

Regional solutions are available in many places, but must be tailored to the locale. For example, if water managers and the state believe that reuse is the answer to southeast Florida's water supply needs, there are over 800 MGD (Elsner 2009) of treated wastewater generated daily in southeast Florida that must either be disposed of or reused. A comprehensive solution previously suggested by Bloetscher and Muniz (2008) is to augment the Everglades restoration plan by providing regional advanced treatment facilities that bring wastewater to the quality level required for direct aquifer recharge. This water would then be discharged to the Everglades Water Conservation Areas (WCAs) and (or) regional recharge areas, as needed.

More specifically, a regionalization plan would consist of the following components: a piping network to deliver secondary treated wastewater to several regional advanced treatment facilities and a network of 50–100 MGD advanced treatment facilities using media filtration, cartridge filtration, ultraviolet disinfection, reverse osmosis, advanced oxidation, and other advanced treatment technologies deemed appropriate. The high-quality treated wastewater produced in this option could then be discharged directly to the WCAs providing more consistent hydration year-round for ecosystem restoration. This would also recharge the Biscayne aquifer at its headwaters and increase the available water supplies for the region. 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. The treated wastewater could also be directed to local recharge canals and areas as needed. Under this scenario, current wells and treatment facilities would continue to operate as designed, maximizing utilization of local infrastructure, and it may be possible to delay development of other water supply alternatives. The capital investment and operating costs required to implement this approach would be partially offset by avoiding facilities that would otherwise be needed for alternative water supplies and groundwater recharge. Capital investment with piping would exceed US$10 per gallon of capacity based on construction costs for the Water Factory 21 in Orange County, Calif. (GWRS 2011).

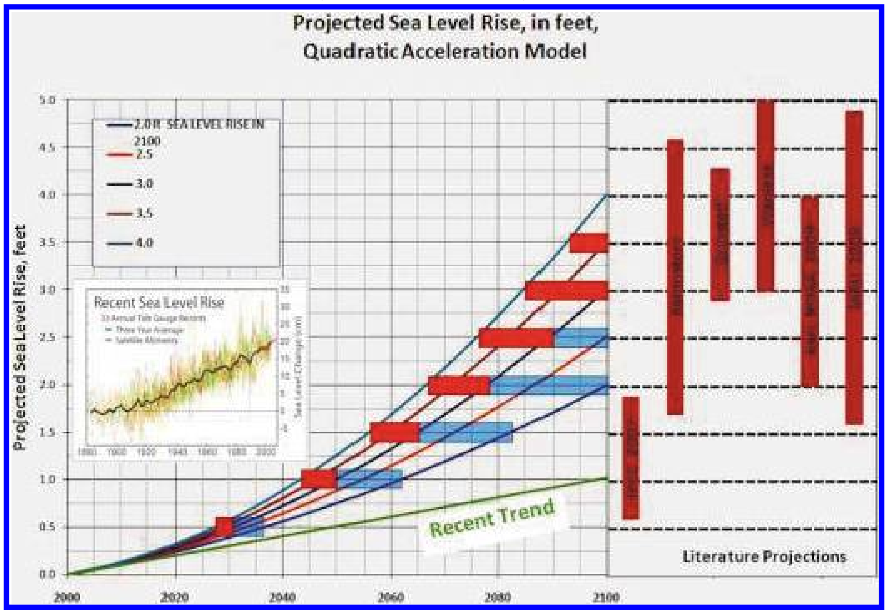
This option offers advantages that are far-reaching despite the potential costs. Centralization of facilities would lower costs of operation and investment in capital equipment resulting from economies of scale. In addition, the amount of secondary treated wastewater disposed by deep well injection and ocean outfalls would be reduced. The concept would provide a major contribution to ecosystem restoration by providing the water needed to counteract the northward migration of saltwater in the southern Everglades caused by sea level rise.

In addition, to facilitate flood control in the increasingly vulnerable low-lying areas west of the coastal ridge, the same concept could be applied to treating and delivering stormwater during the rainy season to the Everglades WCAs, where it could be stored and delivered as necessary to the southern Everglades. This would require reengineering of the stormwater drainage system to collect and convey stormwater to advanced treatment facilities before pumping to the WCAs. The proposed concept envisions a partnership between utilities and regulators to address technical, economic, environmental, and regulatory issues to meet the growing demands of the region. It is possible that existing canals could be modified to transfer stormwater to treatment facilities located close to the edge of the WCAs. Feeder canals would then be used to recharge the surficial aquifer locally as deemed appropriate.

Timing

The sea level rise challenge brings opportunities for solutions and specific recommendations on action steps that utilities could consider for improving the resilience of their facilities. For the long-term, there are a number of efforts to

Fig. 15. Prediction of sea level rise using a Quadratic Acceleration Equation (Heimlich et al. 2009). The graph outlines the average, and 1 and 2 standard deviations from the average, of the current models (Table 1). The horizontal bars outline the ranges when the sea level rise could occur. The shading changes before and after the medial prediction so that the viewer can understand whether infrastructure should be accelerated or can be delayed. These data are used in Table 3 (Heimlich et al. 2009).



harden water supplies and protect vulnerable residents from the impacts of sea level rise. However, due to uncertainties in the predicted rate of climate change impacts, rather than dictate a timeline, it is more appropriate to match the implementation goals to milestones in the sea level elevation. Accordingly, there are four scenarios: (*i*) minimal risk (under 1 ft), (*ii*) low risk (1–2 ft), (*iii*) high risk (2–3 ft), and (*iv*) critical risk (3 ft or more — see Fig. 15).

The minimal risk scenario corresponds to less than 1 ft of sea level rise. This situation will probably not create significant impacts to a southeast Florida utility. Flooding in low-lying areas will increase, but localized solutions such as additional storm water pump stations can alleviate much of these concerns. Increased inflow into the sewer collection system would necessitate wastewater system infrastructure armoring (G7 program), and added reclaimed water use to migrate competing users away from the Biscayne aquifer. Water conservation implementation is another tool that could be pursued immediately to stay ahead of the issue.

Once it is determined that sea level rise will exceed the 1 ft stage, the utility should start seriously reviewing the desalination option for alternative water supplies using the Floridan aquifer. In addition, changing the location of salinity structures should be evaluated as well. Aquifer recharge, salinity barriers, increased reuse capacity, and similar options would be appropriate actions under these conditions. Before sea level rise reaches 2 ft, low-lying areas will flood more frequently or become persistently flooded during daily irrigation. 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 toward 3 ft (critical). In the critical scenario of sea level rise in excess of 3 ft, large areas served by the area will flood consistently during rainstorms and many low-lying roads will be permanently flooded. Small storms will cause much localized flooding. Pump stations can be implemented to deal with the flooding problems, but this will also reduce groundwater storage, which defeats the purpose of salinity barriers, groundwater recharge, and irrigation with reclaimed wastewater. As a result, utilities should consider migration away from current reuse efforts towards a reuse ASR system, whereby the reuse water could be withdrawn as a raw water supply. Although the State of Florida promulgated a moratorium on ocean outfall discharge, at this stage of sea level rise, the outfalls may be absolutely necessary to assist in draining large portions of the urban corridor (at enormous cost — the issue remains an ongoing topic with the Legislature) or as an alternative to discharging treated wastewater to the Everglades. Canal structures need to have been constructed, and water level stages on other structures adjusted by the time sea level has risen 3 ft.

Ultimately, the worst case scenario for significant sea level rise is a retreat or evacuation, which is beyond the scope of this evaluation. If sea level rise exceeds 3–4 ft, large areas of the region will have to be abandoned. Water supply issues for the utility will be of limited concern at that point.

Case study results

Four utilities in Broward County, Fla. (one large, two medium, and one small) were evaluated according to the toolbox, based on the authors' familiarity and prior work with the utilities. All four utilities are similarly situated along the southeast Florida coast, treat predominantly fresh water, and are primarily retail providers, but are of different sizes and service areas. Table 3 outlines each tool's benefits and barriers for each of the participating utilities. Cost estimates for each utility to harden its water supply infrastructure and protect its residents from the impacts of sea level rise were evaluated. These estimates were based on professional judgment during specific planning for three of the utilities, status of

Table 3. Implementation program — four utilities. (All dollar amounts are in USD.)

Implementation strategy	Barriers to implementation	Point when action may need to be abandoned	Cost: pompano Beach, Fla., 120 000 served	Cost: Dania Beach, Fla., 16 000 served	Cost: Hollywood, Fla., 400 000 served	Cost: Broward County, Fla., 1 million served
Trigger: Immediate 0–0.5 ft SLR by 2030						
Install stormwater pumping stations in low lying areas to reduce storm water flooding (requires study to identify appropriate areas, sites and priority	NPDES permits, cost, land acquisition	When full area served is inundated (>3–5 ft SLR)	Start at $1.5–5 million each, number unclear without more study but exceeds 20	Start at $1.5–5 million each, 5–10 minimum, to find exact number needs more study	Start at $1.5 to 5 million each, number unclear but may exceed 20, to find exact number needs more study	Limited service area east of coastal ridge, to find exact number needs more study
Water conservation	Budget, staff time, cost, political will	Not available	Start at $30 million + $1 million/yr	Start at $1 million + $.05 million/yr	Start at $50 million + $2 million/yr	Start at $50 million + $2 million/yr
Armoring the sewer system (G7 program)	Budget, recurring expense	When area served is inundated	$12.5 million start, plus annual cost allocation	$0.5 million start (complete), plus annual cost allocation	$15–20 million service area to start, plus annual cost allocation	$20 million start, plus annual cost allocation
Trigger: 0.5–1 ft SLR2031–20						
Additional reclaimed water production	Budget, lack of application sites in the city; long term frustrates sea level rise protection efforts	Before 3 ft SLR makes soil saturation a problem	Over $25 million depending on permit requirements (10 MGD)	Not available	Over $500 million depending on permit requirements, needs RO treatment (50 MGD)	Over $500 million depending on permit requirements (100 MGD)
Aquifer recharge and (or) salinity barriers	Regulations for indirect potable reuse, public perception	Before 3 ft SLR makes soil saturation a problem	up to $200 million depending on permit requirements	Not available	up to $500 million depending on permit requirements	Available north serve area only
Trigger: 1–2 ft SLR2043–20						
Relocate wellfields westward and (or) horizontal wells (based on current capacity and very rough estimates of costs)	Cost, concern over saltwater intrusion east and west, inundation of wellfields, permitting by SFWMD	When well is inundated	$20 million assuming locations can be permitted in Biscayne aquifer	$3.5 assuming locations can be permitted in Biscayne aquifer, horizontal well investigation proposed	$30 million assuming locations can be permitted in Biscayne aquifer	$30 million assuming locations can be permitted in Biscayne aquifer
Control flooding west of the coastal ridge	Cost, discharge location for water	When full area served is inundated	Start at $1.5 to 5 million each, number unclear without more study; dozens would be needed	Start at $1.5 to 5 million each, number unclear without more study; greater than 10 needed	Start at $1.5 to 5 million each, number unclear without more study: dozens would be needed	Mostly a municipal issue
Central sewer installation in OSTDS areas	Cost, assessments against property owners	When full area served is inundated	$10 000 per household: less than 150 households	$10 000 per household times 400 households	$10 000 per household; greater than 20 000 households	$10 000 per household; greater than 20 000 households
Closing of private wells	Private Property rights	Not available	Cost unknown	Cost unknown	Cost unknown	Cost unknown
Desalination	Disposal of concentrate, power grid, cost	none	$20 million for plant conversion	Concentrate disposal option not available	Already in place	Would need membrane facilities; est $30–50 million

Table 3 (*concluded*).

Implementation strategy	Barriers to implementation	Point when action may need to be abandoned	Cost: pompano Beach, Fla., 120 000 served	Cost: Dania Beach, Fla., 16 000 served	Cost: Hollywood, Fla., 400 000 served	Cost: Broward County, Fla., 1 million served
Salinity/lock structures (based on canal presence)	SFWMD, western residents, private property rights arguments	Not available	3–5 at $10 million, may require ancillary stormwater pumping stations	1 at $10 – 20 million, may require ancillary stormwater + pumping stations	2 at up to $10 million, plus ancillary stormwater pumping stations	Millions
Trigger: Before 3 ft SLR 2070- 2100						
Regional desalination and (or) aquifer recharge and (or) Everglades (est based on wastewater generated or plant capacity)	Perception, nutrients, cost	Not available — solution to retard sea encroachment	$200 million	$30 million	$1 billion	>$1 billion
Aquifer storage and recovery with reclaimed water	Regulations for indirect potable reuse, public perception, assumes desalination in place	Not available	Wells are $30 million, unknown treatment requirements	Not an option — no waste water treatment plant	Millions. Unknown wells, unknown treatment requirements	Test ASR well not successful
Trigger: 3–4 ft SLR2085 – 2100						
Massive groundwater dewatering, send to Everglades	Regulations for redirection of stormwater that likely has high phosphorus levels, public perception, cost	Not available — solution to retard sea encroachment	$ billions	$ billions	$ billions	$ billions
Trigger: Beyond 4 ft SLR After 2100						
Large areas of the city must be abandoned	Public perception; worst case scenario, likely greater than 100 years out	Not available	$ billions	$ billions	$ billions	$ billions

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the toolbox concepts based on familiarity with utility operations, and applicability to each utility .

In the immediate future, each utility has the need to evaluate localized flooding during rain events and install appropriate infrastructure. The use of a stormwater utility is in place to fund and maintain such infrastructure. However, as the sea level rises, studies of flood-prone areas will dictate a series of improvements that should be prioritized.

All currently pursue a water conservation program. Most residents in the utilities studied use 70 gpcd, and have limited large irrigation uses. Plumbing retrofits have been started by Broward County. Dania Beach has instituted complete armoring of their sewer system. The others have instituted some parts of the program.

Reclaimed water production is not possible in Dania Beach because they do not have a wastewater plant. Pompano and Hollywood have active reclaimed water programs to irrigate golf courses. Hollywood's program was started in 1994. Both Hollywood and Broward County are evaluating options to expand reclaimed water as a result of a legislative requirement to cease use of the current outfalls by 2025. Pompano Beach is currently looking at a salinity barrier near their golf course. Hollywood looked at this in the late 1990s, but the project was not pursued because of permit issues. All three may need to look at this option further.

Broward County initiated inland wellfields 20 years ago. They have managed the wellfields to provide raw water to many utilities, including Dania Beach and Hollywood. Pompano Beach and Hollywood have second wellfields that were pursued at least 10 years ago. Hollywood pursued Floridan (brackish) wells in 1994. Pompano and Broward County are looking at brackish water supplies in the next 20 years.

Pompano Beach and Dania Beach have limited septic tank areas. Broward County is aggressively converting septic tanks to central sewers, but Hollywood has nearly 20 000 septic tanks to convert in the future and no current plan to pursue. This is potentially a billion dollar issue as it affects the homeowners, wastewater plant, and disposal options. Thousands of private wells for irrigation purposes exist in all four areas, but the number and cost to close them is unknown.

As sea level rise exceeds 1–2 ft, the communities need to address salinity structures with the SFWMD, who is in charge of the primary canal system. Because the primary canal system is regional, it affects many communities at once, and no single community can make improvements to the canals without impacts up and downstream. Because the structures have decreasing capacity, pumps and relocations will be required. It may take 20 years to site, design, acquire property, and build new structures. The SFWMD is currently evaluating this problem, but the communities need to be engaged in the conversation today.

Reuse will no longer prove palatable in the future as the soil becomes saturated at the surface. A new wastewater disposal pattern, as discussed previously, would appear to be the most likely because it resolves wastewater disposal, treatment, and the outfall issue. This issue is not on the radar of any of the utilities of the SFWMD at this time. It is a major engineering effort that should be evaluated to determine the potential issues that will need to be resolved so that current improvements to not detract from future improvements.

The Table 3 comparison of the four utilities is based on the data gathered and familiarity with operations. These steps are needed to protect water supplies — existing as well as future allocations. The utilities will need to determine timing, based on the model described in Fig. 15. The goal of the method presented in Fig. 15 is to spend money on infrastructure when needed, not before or after it is too late. Milestone sea level rise will indicate when the expense is needed. Table 3 shows a 100 year projection. Many things can change, but the table is designed to provide a picture of the magnitude of the infrastructure needs that are forthcoming. Each of the utilities will need to generate revenue from user rates to pay for many of these projects, as few are general fund tax revenue expenses — all are enterprise fund type projects. The table also shows that, as time progresses, the costs become much more significant, but specifics are less certain. More study is needed on these ramifications, which are beyond the scope of this project.

Summary and conclusions

Southeast Florida water managers must optimize water supplies to accommodate the sometimes incompatible goals of water supply, flood control, and ecosystem protection. Water managers need to evaluate how climate change will affect the hydrologic cycle and how to mitigate impacts on water transmission and sewer systems and the risk of flooding. Additional water will be needed during dry periods to retard saltwater intrusion in the open coastal aquifer and migration of saltwater migration in the lower Everglades as a result of sea level rise.

This project was performed to create a toolbox of options that southeast Florida utilities could pursue to meet water management needs, but the toolbox has wider application to most coastal communities. Each of the tools offered in the previous discussion must be adapted to local conditions. Some may not be locally available, such as ASR and places to dispose of saline membrane concentrate. Seasonal weather patterns may limit reclaimed water use, while availability of land may limit other options. Some tools could apply to each utility (although some additional study is needed in most cases).

Some work was already done by the four utilities studied, such as sewer hardening and desalination. The horizontal well option is being considered in Dania Beach. However, much more infrastructure will need to be designed and installed. Extra pumping will be needed in the wetter periods to limit flooding, with no current storage to accept this extra water. Long-term planning will have to focus on the toolbox options (Tables 2 and 3).

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