Water **2012**, *4*, 367-388; doi:10.3390/w4020367

OPEN ACCESS

water

ISSN 2073-4441
www.mdpi.com/journal/water

Article

Protecting People, Infrastructure, Economies, and Ecosystem Assets: Water Management in the Face of Climate Change

Frederick Bloetscher

Department of Civil, Environmental and Geomatics Engineering, Florida Atlantic University, 777 Glades Road, Boca Raton, FL 33431, USA; E-Mail: h2o_man@bellsouth.net; Tel.: +1-239-250-2423; Fax: +1-561-297-0493

Received: 22 February 2012; in revised form: 16 March 2012 / Accepted: 26 March 2012 / Published: 11 April 2012

Abstract: Recent literature outlines significant impacts from climate change on many areas of the world, with much focus on causes and impacts. However the long-term trends demand adaptation strategies. While a variety of solutions have been suggested, some politically viable, others not, perhaps the most significant barrier to a cohesive approach to climate adaptation is the failure from the public and policy-makers to realize that different areas will be affected differently and that "one-size-fits-all" policy solutions will not be successful. In addition, as one area may identify and respond to challenges in their location, others should be supportive of those efforts, realizing that while such actions may be neither desirable nor appropriate for them, they may need support for solutions in the future in their areas. This project was designed as a framework to identify solutions and demonstrate differences between small regions and locales based on field conditions. The State of Florida was used as a case example to outline these differences because Florida is faced with significant challenges in the coming years related to water resources, the use of funds and political capital, and the potential for economic disruption. The intent is that the results of this project will lead to a series of recommendations and action steps for policy makers to conserve the state's assets. A similar approach can be used in other states and countries to assess the likely policy and infrastructure needs for different locales.

Keywords: climate change; adaptation strategies; water supply

1. Introduction

There is strong evidence that global climate change is impacting the global water cycle and global water resources [1–5]. The global scientific consensus is that the climate system is warming, as is evident from rising global average air and ocean temperatures, increased and earlier snow and ice melt, shorter subtropical rainy seasons, as well as elevated rates of rising global average sea level and greater variations in temperature and precipitation. [1,6,7]. The National Oceanographic and Atmospheric Administration (NOAA) predictions are that the warming trend will create more intense rainfall events, such as more severe thunderstorms and tropical cyclones, greater variation in weather related events, and significant changes in precipitation patterns in many areas [5]. For example, the U.S. Climate Change Science Program suggests that there may be "slightly increased runoff in the southeast United States", but trying to identify where changes will occur, and to what extent, is an ongoing exercise in global system modeling [8]. Research to develop downscaling models for projecting regional changes has proven to be difficult because the global grid spacing is coarse and there are many uncertainties in the global models that obfuscate regional or local differences [9]. Yet, much of the adaptation needed to protect development will happen at the local and regional level. Efforts are ongoing at the regional and local scale as communities who believe they are susceptible to the impacts of climate change engage in activities to attempt address or clarify local uncertainties, but many efforts are either not coordinated with others, or consist of one-size-fits all solutions that may not be pragmatic at the local level. As a result the intent of this paper is to highlight a framework to discern the similarities and differences associated with climate change adaptation between subregions, with application to a case study.

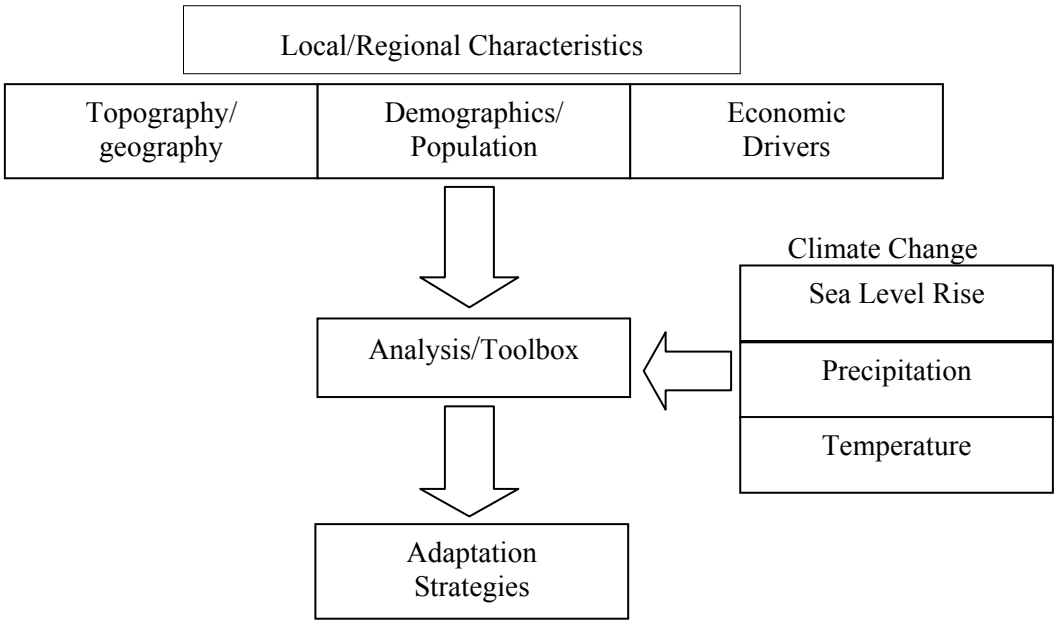
2. Methodology

Global climate discussions have focuses on three factors related to climate change that are of concern across the globe: warmer temperatures, alteration in rainfall patterns and sea level rise from thermal expansion of the oceans and glacial melt [10,11]. Accompanying these drivers are potential changes in storm frequency and intensity, desertification, population migration, ocean acidification and coastal flooding [1]. However, depending on whether you are located in the mountains, the coast or interior flatlands, the impacts will differ as may your attitudes toward climate change. For the majority of the world, sea level rise is not a factor since they are not located on a coast, but sea level rise is a permanent problem (with respect to human time). While changes to storm patterns may create temporal variations in weather patterns, areas expecting more rain are less concerned than those that are losing snowpack relied upon for summer water supplies [12]. As a result, different areas focus on different aspects of climate change depending on what their perceived vulnerabilities may be. The Pacific Northwest has focused on earlier snow melt and precipitation changes as a means to address water supplies and economic issues associated with fishing [12,13], while those in the Rocky Mountains have looked at earlier snowmelt and lesser total rainfall [14]. The southwestern US projects less rainfall, accompanied with increased pressure for development. Examples or this rapidly growing interest in this subject can be found in Florida [9,15,16], California [17], King County, Washington [18],

and New York City [19]. The common theme across all of these plans is water supplies and impacts of changes to water supplies on both the built and natural environments.

This project was designed to develop a framework to evaluate the impacts of climate change water resources and economic development (as they are intrinsically intertwined). The framework was developed in multiple steps to be readily transferrable to most communities. The first step focused on identifying: topography, economic drivers and population, compared to likely climate change impacts (precipitation, temperature and sea level rise). Figure 1 outlines a simplified flow chart used as a basis for the evaluation. Topographic and LIDAR data can be used for the terrestrial characteristics. The topographic, census and economic activity data were evaluated to determine how climate changes would impact the population and economy. Economic development requires appropriate management of water, sewer, storm water and transportation networks, which immediately identifies water resource management as a key issue for climate adaptation using the toolbox approach developed by Florida Atlantic University [9]. Where water supplies are disrupted or unreliable, it is difficult to sustain long-term economic activity. To illustrate the process, a case study was developed for the State of Florida.

Figure 1. Analysis tool.



3. Discussion of Florida Case Study

Florida has been identified as one of the most vulnerable areas in the world with respect to climate change because of its low-lying topography and porous geology [20], making it an excellent case study. Major challenges include both changes to the climate (precipitation volume and timing) and sea level rise. With 80 percent of the population living within 50 miles of the coast and significant economic value embedded in the coastal waters for tourism, fishing and recreation, sea level rise presents a significant risk to both the built and natural environment of the state. The interrelationship between these environments creates challenges for water resource utilization and protection, but

there are clear differences in adaptation needs and local attitudes of people to climate change throughout the state.

A comprehensive study of specific climate change impacts on the state has yet to be undertaken, although there are actions being taken by the State University System and locally (Dania Beach, Surfside, Miami-Dade County, Broward County, Monroe County, Coconut Creek, Punta Gorda, Charlotte County among others). Based on a review of the locales that have initiated climate studies, those that have taken the lead appear to be the more vulnerable areas. Meanwhile the climate change discussion is politically tenuous at the State level. As a result, the goal of this project was to outline the relevant issues to the State, and attempt to discern the differences in responses required. A side benefit was thought to be a means to align the effort cohesively, or to understand the barriers for same.

The project included a review of studies associated with Florida specific projected or observed climate changes [9,15–16,21–26], the 2010 census data, LiDAR topographic data developed by FAU via NOAA DEM data, current and historical maps of groundwater levels, and development patterns developed for each region of the state. As prior studies conducted by Florida Atlantic University and other agencies indicated, the major issues will be rising temperatures, less certain rainfall patterns and sea level rise [4,21–26]. Water is a common theme. Using the knowledge of the state from various references, the major economic factors were identified [21–26]. The natural environment, which requires specific timing and quantities of water, and the built environment that relies on the natural system for economic activity, storage and recharge, are closely connected throughout the state, so impacts on one affect the other. The potential climate impacts were used to identify overarching infrastructure needs and provide a series of localized strategies for climate adaption in various areas of the state [8].

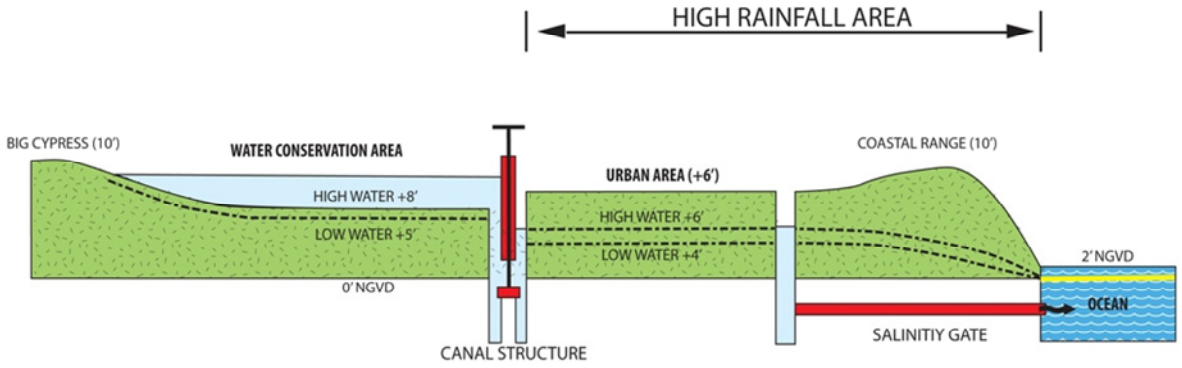
3.1. Description of the State Florida

The State of Florida is a 400 mile long, 100 mile wide, peninsula. FAU students have mapped most of the state using high quality LiDAR imaging developed from NOAA DEM data. By looking at the LiDAR imaging, and calibrating it to ground level data, the topographic characteristics of different parts of the state become clear, setting the stage for regional differences in climate adaptation approaches. For example, north Florida contains much topography in excess of 100 ft (30 m) NAV88, but southern Florida is low-lying [<15 feet (4.6 m)] with very little elevation change south of Lake Okeechobee. Hence for much of the northern half of the state, the sea level rise discussion has little consequence and garners limited interest. In contrast, because of the low elevation of southeast Florida, the water table is often located within 2–5 feet (0.6–1.5 m) of the land surface (see Figure 2a—cross section of SE Florida), which raises considerable concern by local officials already plagued with complaints of flooding during typical summer afternoon rainstorms.

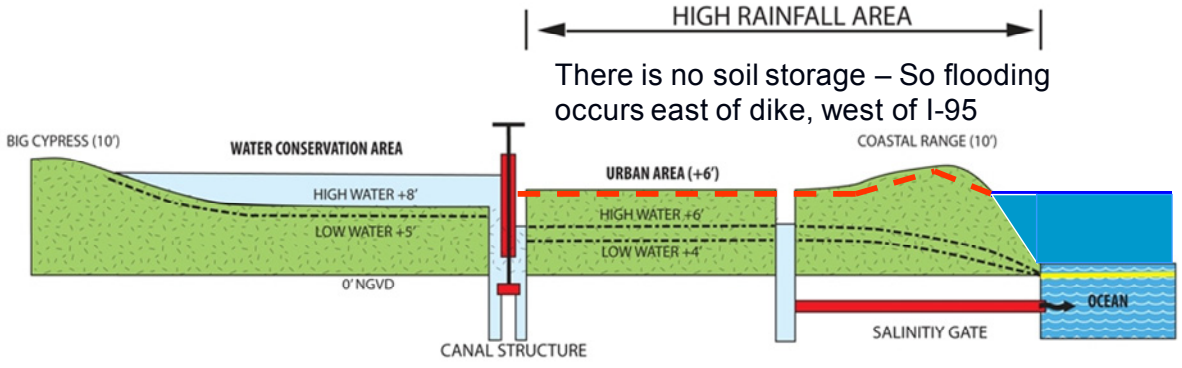
Florida is a water rich state, but rainfall is seasonal, and does not coincide with demand periods. Historically much of the 60 inches/year of annual rainfall that fell on Southeast Florida, occurred from June to September, and drained to the Everglades [4]. The Everglades watershed, a wide, shallow wetlands ecosystem and river flowing south from Lake Okeechobee to Florida Bay, recharges the Biscayne aquifer which is relied upon for surficial groundwater supplies by 5.5 million people in southeast Florida [15]. In contrast, much of central and north Florida relies on the Floridan aquifer as

the primary water supply for urban and agricultural users. While the Floridan aquiferis a productive water source, it is semi-confined, meaning recharge is not as efficient as the surficial Biscayne aquifer. Sinkholes and land subsidence are problems in areas where the Floridan aquifer is overdrawn [27]. The Floridan aquifer is an alternative water supply source only available to urban areas with reverse osmosis capability in south Florida. Such deeper aquifer systems are confined and represent unsustainable supplies despite their current, ongoing use.

Figure 2. (**a**) Cross-section of SE Florida prior to the canal systems and (**b**) post canal construction showing the impact of sea level rise on aquifer levels (thick, dashed line). Note I-95 is the main north-south highway located on the coastal ridge [9].



(a)



(b)

Excess surface water has been the State's historical issue. Florida's development began in the northern part of the state before the Civil War, but was primarily confined to agriculture. Swamps and flooded areas were primarily confined to the southern half of the state. Citrus farming occurred as far south as Vero Beach, but the primary hub was Orlando. Wetlands were used as water supplies or drained to obtain the fertile soils. The Everglades was a barrier to development south of Vero Beach. In the 1890s, Henry Flagler's Florida East Coast Railroad opened the southern tip of Florida to development. The railroad was constructed on the highest land, known as the Coastal Ridge, which is a narrow section of land running close to and parallel to the coast with an elevation of approximately 10 ft NGVD (3.3 m). However, the Everglades "swamp" was problematic in Florida's early history and efforts began almost immediately to drain and control the water, resulting in the Central and South Florida Drainage project, a network of 1800 miles of canals and over 50 pumping stations and other structures that control water flow, while lowering the water table throughout the region (see Figure 2b).

The lower water table permitted the development along the coast, especially in southeast Florida, but reduced the available water in the surficial aquifer system, and will complicate matters when sea level rise increases the groundwater table in the future. Flood control efforts to permit development has reduced the potential water supplies and aquifer levels throughout the region and disrupted the natural systems that stored water supplies for the dry winter season [15]. The reduction in surficial water supplies has pushed southeastern utilities to deeper, confined aquifers or alternative options (like reuse), that come with higher carbon footprints, as noted above.

Despite copious annual rainfall, an addition limitation for Florida is that water storage potential is virtually nonexistent throughout the state due to the shallow elevations, resulting in periodic droughts in an area that receives over 40 inches of rain on a severe drought year, and an average of 60 inches otherwise. Since these supplies cannot be retained with the current infrastructure, long-term water supply issues are serious concerns as weather patterns become more erratic and climate variations increase at the same time as population demands increase.

In 120 years, Florida has become home to nearly 20 million residents, and numerous part-time winter residents. Development of the state has occurred within three economic sectors: tourism, agriculture and construction, although they vary in intensity across the state [28]. Tourism and housing are major economic drivers along the coast, while agriculture is the major driver in the central portion of the state. Import/export businesses are significant in southeast Florida, Tampa and Jacksonville. From an economic perspective, construction and tourism are very subject to economic fluctuations, which has been an ongoing issue for the State since the 1920s. The three major economies can all be viewed all large water demands; construction because it leads to additional houses (base demands), tourism (which adds to peak demands) and irrigation for plants [26].

3.2. Separating differences Across Demographics and Economics

As a means to identify differences in climate impacts, and subsequent adaptation strategies, the state was divided into 10 areas. The boundaries were chosen to separate differences among the issues that are important to understand in dealing with any policy issues: demographics and population, geography and geology, and economic sectors are different throughout the state, so the impacts of climate change will impact regions less or more based on the number of people impacted, the geography and geology, and the economic disruption that could occur (see Figure 3 and Table 1). These criteria generally correspond to the top three boxes in Figure 1. While the exact boundaries could be argued, these areas were chosen because of commonalities in water resources and economic conditions, and include entire counties. Economic centers are mostly oriented toward three coastal regions and two inland areas. Water supplies vary, and economic development is based largely on the ability to provide water-related service infrastructure.

Figure 3. Areas of the State.

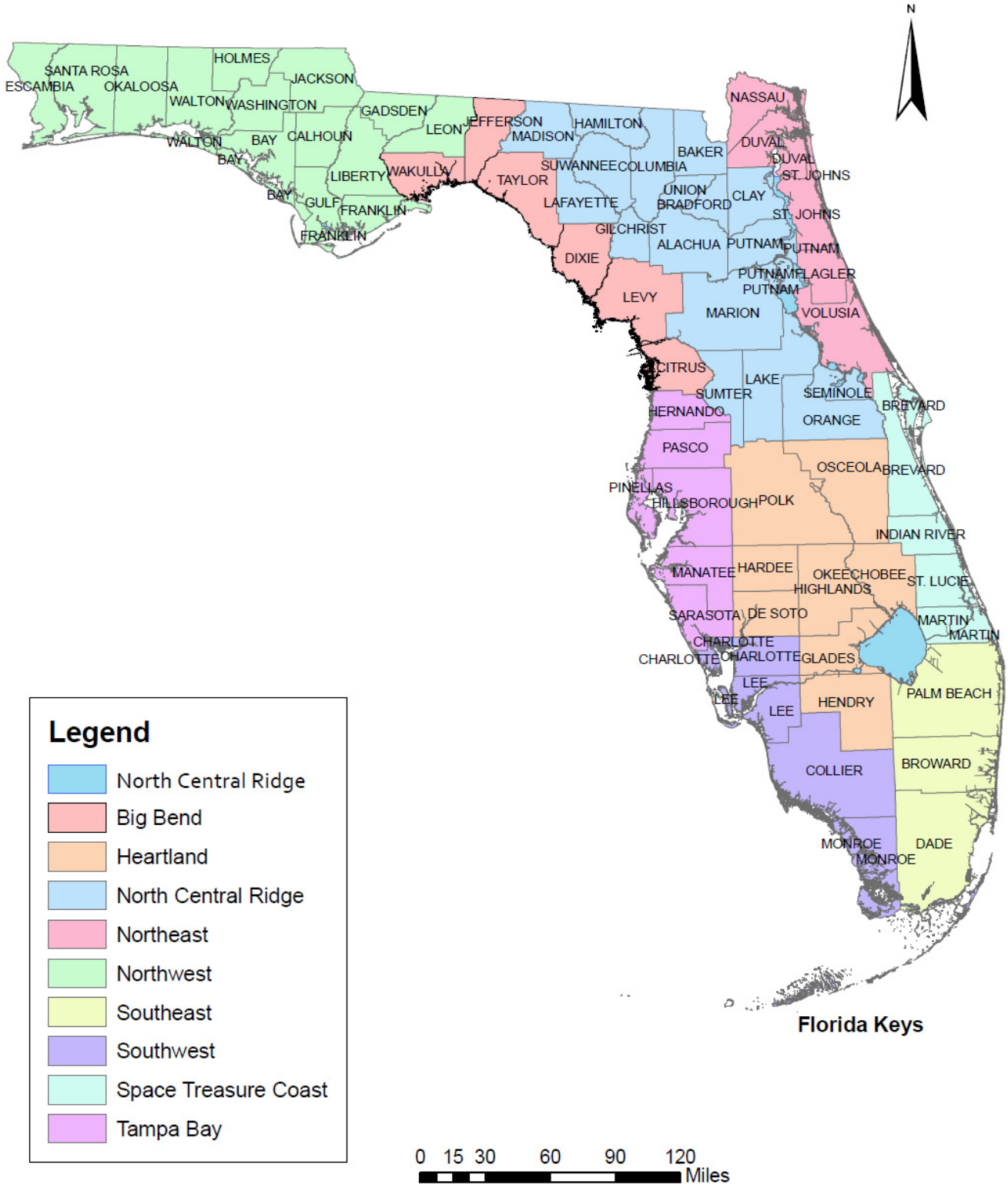


Table 1. Outline of the 10 areas of the state created for this project.

Region	Geography/Geology	Economic Drivers	Water Needs
SE Florida	Extremely low-relief topography, has coastal ridge, lower inland, porous, permeable limestone	Tourism, import/export to Latin America, Housing, agriculture, medical, fishing/reefs	Growing for Tourism, housing, decrease for Agriculture
Kissimmee River Valley	Low in Kissimmee River Valley, but contains among highest land in state on sand ridges	Agriculture, Mining	Agriculture increasing
Florida Keys	Flat, generally under 5 ft NAV 88	Tourism	Low growing for Tourism
Southwest Coast	Slight upward incline going inland, limited relief, no coastal ridge or barrier	Tourism, Housing, some Agriculture	Growing for Tourism, housing, less for Agriculture
Tampa Bay	Low coast, but steady incline inland	Tourism, Housing, Fishing , limited Agriculture, import/export	Growing for Tourism, housing, decrease for Agriculture
Space/Treasure Coast	Low coast, but steady incline inland	Tourism, Agriculture, Housing	Growing for housing, decrease for Agriculture
Northwest	Significant fast increase inland, limited coastal exposure	Tourism, Agriculture	Growing for Tourism, Steady for Agriculture
Big Bend/Suwanee	Flat coastal plain, higher relief inland, no barrier	Agriculture	Steady
NE Florida/St. John's River	Coastal ridge between St Johns River and Atlantic, slope decreases to near sea level both directions	Tourism, agriculture, some industry	Growing for housing, Agriculture
North Central Ridge	Higher elevation, no coastal exposure, sand and sandy clay ridge, reduced infiltration	Tourism, agriculture, Housing	Growing for Tourism, housing, Agriculture

Military bases include Pensacola Naval Air Station (home of the Navy's Blue Angels) Hurlburt Field, Eglin Air Force Base, Tyndall Air Force Base, Coastal Systems Station-Naval Surface Warfare Center, Corry Station Naval Technical Training Center.

3.3. Projected Climate Change Impacts.

Using Table 1, each of the 10 areas of the state were analyzed for impacts on the geography, economy and water as a result of the climate impacts of precipitation variations, sea level rise and temperatures (the latter will cause more power demands and increased water use). Table 1 shows that there are significant differences in the 10 regions of the state that create variations in regional vulnerability to climate change, and to particular components of climate change. The first area reviewed was sea level rise.

Flooding in low lying areas may be the first indication of climate change from sea level rise. Topography is an easy way to identify areas vulnerable to the impacts of climate changes, especially sea level rise. The coastal areas are very easy to evaluate if appropriate tools like high resolution LiDAR are in place because in Florida, the average tidal fluctuations are ±2 feet each day with annual fluctuate of 6 to 8 inches. Because of the speed of groundwater movement relative to the tidal cycle, groundwater will tend toward mean high tide, making it difficult to draw groundwater below 2 feet

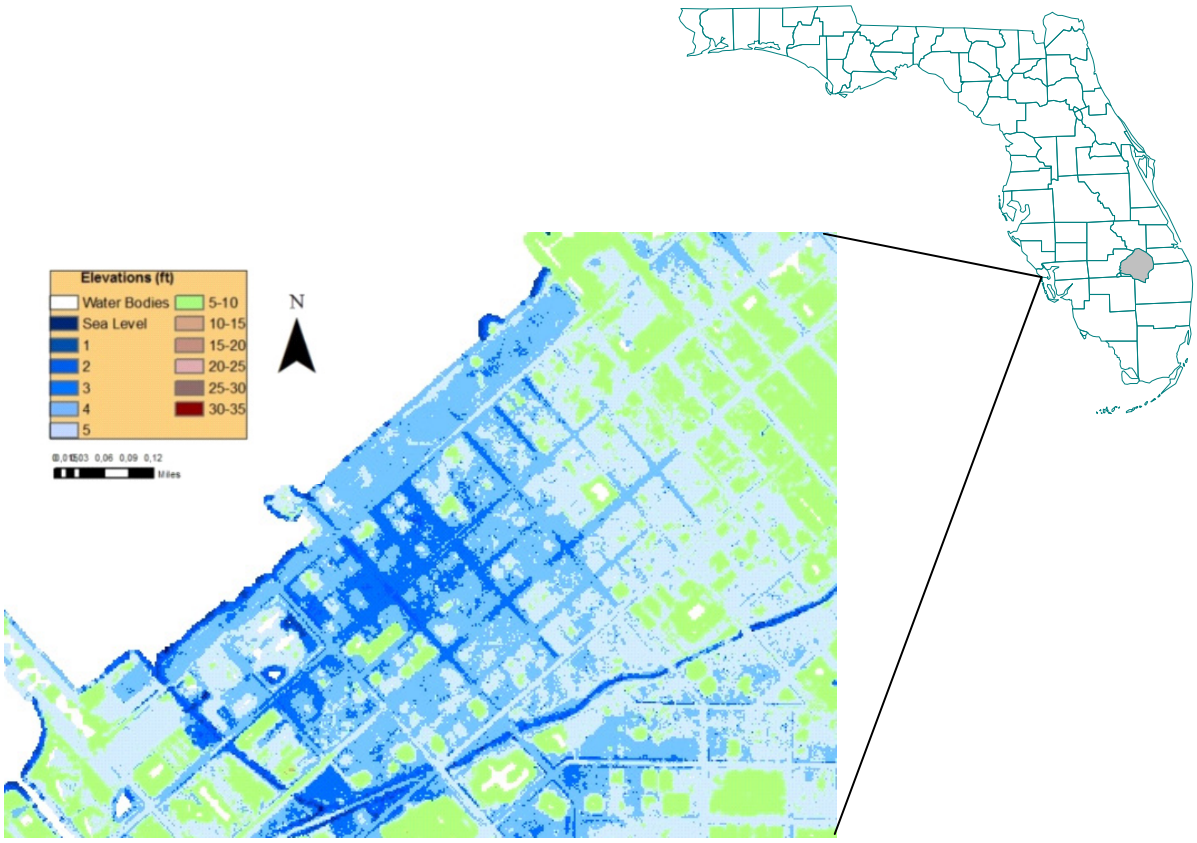
above sea level in a natural condition. Consequently, the actual groundwater table is never less than +2 feet except at the immediate coastline. Since the mean sea level is 0 using the NAV88 datum, if the SLR is 3 feet by 2100, most groundwater will not be able to be drawn below 5 ft above sea level. Therefore, it is reasonable to assume that if the projected SLR is 3 feet then any land lying below 5 ft NGVD will flood. Therefore, the initial assumption for identifying areas that are potentially vulnerable to SLR is where the ground elevation is below 5 feet NAV88. This is a protocol used by FAU for initial evaluation of FDOT roadways in Florida. All that is needed is useful, vertically calibrated datum information to perform raw analyses of the potential impacts of certain areas.

The southeast Florida region includes Miami Dade, Broward and Palm Beach County. As noted previously, this is an area with 5.5 million people, and much of the area below 5 ft NAV88. While the area is characterized by extremely low-relief topography, there is a coastal ridge within 2 miles of the coast that can act like a land-bridge. The lower land inland is underlain by porous, permeable limestone, however, that will increase the potential for flooding due to sea level rise and accompanying groundwater increases. Inland and coastal flooding due to sea level rise will adversely impact the transportation and water management/resource infrastructure systems that service the economy. Tourism, the Everglades, import/export to Latin America, housing, agriculture, medical services to an aging population, and fishing/reefs/diving are major economic drivers that may be impacted one way or another. An estimated $10 trillion in property values and $184 billion in annual economic activity occurs in the area, the largest percentage of the state's economy [28].

For comparison, inland from Southeast Florida is an area termed Heartland in this project. It includes the non-coastal counties south of I-4 that generally drain into the Everglades/Kissimmee River basin. While the land is low in Kissimmee River Valley, the area contains among highest land in state on sand ridges. Mining and agriculture, especially citrus, are the primary economic drivers of the area. Many of the wetlands have been drained for agriculture. Flooding is only an issue in low-lying or remnant swamp areas, both of which are generally agricultural properties today. The economic impact of sea level rise will be limited given that extensive drainage systems are in place. The impact on population is limited since the areas is sparsely populated compared to southeast Florida. South of these areas are the Florida Keys, an area of very low elevation, home to 80,000 people and predominantly tourism based, that is the most vulnerable area in the state to sea level rise. The other issues pale in comparison to the sea level rise threat when virtually all of the land is under 5ft. NAV88.

Southwest Florida is similarly situated to southeast Florida, minus the land bridge. The area has a slow steady incline, but elevations are generally under 20 ft. NAV88. Figure 4 is a topographic high resolution LiDAR image of downtown Punta Gorda on the southwest coast of Florida, created at FAU. FAU, and others have studied the impacts on Charlotte Harbor and the City of Punta Gorda which lies on Charlotte Harbor. Reconnaissance indicated that the LiDAR correctly represents the future impacts on the City. The figure shows that all areas in blue are below 5 ft NAV88, which includes much of downtown Punta Gorda. Naples, Fort Myers, Cape Coral, Sanibel Island and Marco Island are similarly situated cities on Florida's southwest coast. What is most noticeable is that the infrastructure systems, starting with roadways, but including the water, sewer and stormwater under those roadways, will be inundated in front of the buildings causing the buildings to be isolated. Because of the proximity to the coast, the city has limited options to overcome this threat. The future economic viability of similarly situated communities will require analysis.

Figure 4. Example of impact of sea level rise on low lying coastal communities. Blue is permanent inundation at 3 ft seal level rise.



Sea level rise creates another problem for the southern half of the state. Water managers in south Florida currently use the drainage canal network to reduce water table levels to prevent flooding. Excess rainfall is discharged to tide by gravity. Properly placed control structures can prevent the inland migration of seawater in the canals and provide physical boundaries for the saltwater intrusion front. By maintaining high water levels in the canals, the aquifer retains water that is otherwise discharged to tide by gravity, which protects against saltwater intrusion. The rising tides will cause much of the gravity drainage system to fail in the future. Obeysakera [25] presented an analysis for the 28 coastal structures in Miami-Dade, Broward, and Palm Beach Counties that indicated that approximately 13% of the structures would lose 100% of their capacity when sea level rise is about 4 inches, about 67% with an 8 inch sea level rise, and over 80% of the structures with a 1.5 foot rise in sea level. Projection models of sea level rise in the year 2060 are generally in agreement about projected sea level rise amounts averaging 1.5 feet [17]. The dilemma is that at the same time that control structure capacity is declining, stormwater runoff rates will be substantially increasing as sea level rises, resulting in the stormwater drainage system being significantly compromised.

Drainage is not the primary concern in north Florida, because there is more ground elevation and therefore more ability for the rainfall to runoff the surface to lakes and streams. The difference between the surface, groundwater and sea level are enough that sea level rise will not create major conflicts except right along the coast. However, because rainfall is less in north Florida (40–45 in/yr *vs.* 55–60 in/yr), a reduction in precipitation may prove difficult to manage as there are no storage areas. Supplies are limited in some areas already. Less rainfall means less surface water supplies for north

Florida, and less recharge in much of the state. Development potential will be limited in north Florida because the carrying capacity of the water supply region is far more limited that southeast Florida.

Precipitation patterns will affect the state, and may already be doing so. Freas, *et al.* [6] suggest 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 due to limitations in existing global climate models [21], and lack of topography [22]. Marshall *et al.* [7] showed a lesser trend in rainfall (11%) for the Florida peninsula based on historical trends from 1925 to 2003, with convective, summer rainfall being the most affected. This confirms the finding of Pielke [23] which reported that "it appears that development has exacerbated their severity, since landscape changes over south Florida have already appear to have reduced average summer rainfall by as much as 11%." The loss of wetlands has been implicated as the land use change most affecting rainfall [7]. These land use changes have been implicated in modifying regional seasonal temperatures as well as precipitation.

Marshall *et al.* [7] also identified increasing temperature trends from 1900 to date based on historical data (+0.6 C in 100 years). Similar results were found by Obeysakara *et al.* [24]. If global temperatures rise, it is reasonable to expect that Florida's existing climate zones will move northward and the zones of more tropical climate will enlarge, but this has not been the case as the citrus industry continues to move south, not north. The reason they have moved south is due to increased frost events; evidence in the past 30 years indicates that temperature variations may be greater—warmer summers, but more variation in winter temperatures—witness hard freezes in the lower part of the Florida peninsula that are not known in the historical record, which would appear to contradict the global warming tenet. Uncertainty in long-term predictions, resulting from short term observations, is of critical concern. Again loss of wetlands has been implicated.

Water is the linkage between the built and natural environments. Many of Florida's natural systems are linked from the upland forests, lakes, and rivers to the estuaries, marshes, and reefs on the coast through hydrologic basins. Most of these natural areas act as catchments for water supply and recharge purposes for agricultural and urban users. These linkages created a natural flow and connectivity from the upper central portion of the state to the coastal regions. Throughout the state, the natural systems historically absorbed the excess rainfall, which is why the loss of wetlands is significant. While changes to the terrestrial environment have brought significant changes to date, including significant economic advantages, the addition of excess water may create further changes, including some that will limit those economic advantages. For example, in south Florida, mangroves will push inland in direct competition with urban environments. Saltwater will migrate north in the Everglades.

Each region of the state has different ecologic issues in terms of providing water for human use and natural ecosystem functions, many natural system issues traverse political, water management and regional boundaries. Coastal wetlands provide habitat for wildlife, including nurseries for fish that are a multi-billion dollar economy for Florida [29]. Ways to integrate natural resource economies into overall adaptation strategies are among the more challenging issues facing the state. As a result of terrestrial changes to the state and the lack of storage venues, the cost to treat water will increase not only from a capital perspective, but also from an energy perspective. The cost for advanced treatment options is significantly more energy intensive than current treatment processes. For example, reclaimed wastewater (reuse) is twice the energy cost of conventional wastewater treatment—desalination is four

times as energy intensive as nanofiltration membranes. The power grid cannot support these demands in peninsula Florida, which is why FPL has proposed construction of two new nuclear power facilities in Miami in the coming 20 years [26]. All areas of the state will have increased costs to treat water, but low lying areas will also have costs to pump water. In areas that will pump water 24/7 in the future, the evaluation of this "waste product" should be considered in light of potable water supply demands, the offsets for more saline sources. At the same time, most large infrastructure planning projects take 15 to 20 years to come to fruition, so early planning is needed. As a result, it is clear that the management of water will need to vary across the state. From Figure 1, this is where adaptation strategies must be developed and evaluated for local and regional implementation.

4. Results

Most of Florida's economy (tourism, housing, and agriculture) is based on adequate water supplies. As a result much of the ensuing discussion will focus on how water issues associated with climate change will impact the different regions of the state similarly or differently. Climate change will create a need to morph adaptation/response strategies into a long-term program for protection of Florida's assets. Most of the impacts that can be expected locally from climate change will be water-related. These changes will occur slowly, but permanence is the key. Sea level rise is unlikely to retreat anytime soon. There are three water issues—water supply wastewater disposal and stormwater. Tables 2 to 4 were developed to look at each of the water issues as they related to the regions developed in Table 1. The options were developed from prior toolbox efforts [9]. The tables outline the application to each region.

Table 2 outlines the water supplies and challenges will affect the economic driver in each region of the state. As the table shows, Florida has five primary sources of potable water, the Biscayne and Floridan aquifers, a series of sand aquifers that have limited production, a few surface water bodies, and the Ocean. To understand the issues in the table, look at South Florida. There are three water supply options: Biscayne aquifer, Floridan aquifer and the ocean. Column 3 shows the volume and sustainability of each supply, along with some considerations (desalination is very costly). Column 4 outlines other challenges. The table shows that south Florida has more abundance and more sustainable water supplies than most of the rest of the state, primarily because the Biscayne aquifer is a phreatic system. However, the Biscayne Aquifer is the only source of fresh water in southeast Florida, and is a karst formation that has flow channels that make is susceptible to influxes of saltwater. However as sea level rises, groundwater level will rise, creating a potential additional supply—dewatering. This may improve the supply availability in south Florida but higher water tables complicate concepts like reclaimed water irrigation. The Floridan aquifer south of Lake Okeechobee is confined, brackish and unsustainable because there is no local recharge. Utilities using this source have experienced a degradation of water quality with time.

The areas north of I-4 appear to be reaching their sustainable yields despite significantly less population than southeast Florida. This means that water supply may be a barrier to future economic development in the northern half of the state. Reilly [27] has identified the overuse of this source, meaning it is not sustainable and less rainfall will exacerbate the problem. Sink holes are one component of this indication. Northern Florida has a few surface water systems, but they are mostly

small. Many of the streams in the panhandle originate from Georgia and Alabama, posing potential conflict points and a major barrier to future development. Less rainfall may create significant adverse effects on local agriculture and development. The northeast area of the state and Tampa Bay have seriously looked at or installed desalination capacity to deal with water supply limitations.

Table 2. Regions of the State, raw water supplies and water supply challenges.

Region	Potential Raw Water Supply Options	Water Supply Volumes	Water Supply Challenges
SE Florida	Biscayne Aquifer Floridan Aquifer Atlantic Ocean	High, sustainable Not sustainable High, cost concern	Higher Groundwater table, Everglades intrusion of saltwater may contaminate wellfields, balance storrmwater, wastewater disposal and water supply objectives, saltwater migration, lack of storage, less summer rainfall
Kissimmee River Valley	Floridan Aquifer (freshwater) Lake Okeechobee Surface waters	High, may be reaching limitations Very limited Limited	Level of Lake Okeechobee, sand aquifers, limited quantities, changes in rainfall patterns
Florida Keys	Floridan Aquifer Gulf of Mexico	Limited High, cost concern	Inundation
Southwest Coast	Surface waters Various aquifers Gulf of Mexico	High, reached limit? Sustainable High, cost concern	Alternative water supply options, changes in rainfall patterns
Tampa Bay	Biscayne Aquifer (Mainland) Gulf of Mexico	Not sustainable High, cost concern	Higher groundwater tables, Alternative water supply options, saltwater migration, lack of storage, less summer rainfall
Space/Treasure Coast	Floridan Aquifer Gulf of Mexico	Currently sustainable High, cost concern	Higher groundwater tables, Alternative water supply options, lack of storage, less summer rainfall
Northwest	Surface waters Surficial aquifer Gulf of Mexico	High, climate sensitive Low High—limits on access, disposal options, cost	Supply, changes in rainfall patterns
Big Bend/Suwanee	Surface waters Floridan aquifer Atlantic Ocean	Medium, climate sensitive High—reached limits? High—limits on access, disposal options, cost	Supply, changes in rainfall patterns
NE Florida/St. John's River	St John's River/ Surface waters Floridan aquifer Atlantic Ocean	Medium, climate sensitive Medium—reached limits? High—limits on access, disposal options, cost	Saltwater migration up St Johns River contaminates wellfields from west, supply, Alternative water supply objectives, changes in rainfall patterns, storage
North Central Ridge	Floridan Aquifer Surface waters	Limited, may be reaching limitations	Alternative water supply options, changes in rainfall patterns

Table 3 focuses on alternative water supply strategies. The problem with these strategies is that they are all expensive, and are unlikely to be pursued except in the urbanized areas by regional utilities. They are also large power draws. Only coastal areas can do desalination of the ocean, but many of these areas have more than sufficient amounts of water so pursuing desalination is unnecessary. The inland areas that are limited do not have access to the ocean. Aquifer storage and recovery has not been successful in southeast Florida or north Florida due to what appears to be confinement/formation issues, but seems to be successful on the west coast. While useful for utilities, agriculture is unlikely to pursue ASR as a water management strategy due to cost and uncertainly and the South Florida Water Management District's regional ASR program to store billions of gallons of water has been significantly scaled back due to a lack of success in test programs. Storage potential and surface water systems are virtually non-existent in much of the state. Hence the potential for increases in conflicts over water resources will persist. Interestingly, south Florida is well poised in many of these areas despite is topographic disadvantage.

Table 4 focuses on water strategies related to wastewater and stormwater for each region of the state. Reuse is a solution for irrigation demands in many areas of the state, but it simply does not work as irrigation in parts of southeast Florida and the Keys due to topography, density and groundwater levels. Water quality is a barrier for a variety of reuse options. Recharging water conservation areas with reclaimed water treated to higher standards might be applicable in southeast Florida, but not other parts of the state which lack these large land areas. Indirect potable recharge (IPR) may work in several regions—targeted IPR may be a solution to many for southeast Florida's needs, but the cost and public perception make it unattractive. Agricultural users can use reclaimed water, if they are located in proximity to urban users, which is rarely the case except in north and central Florida.

Previous discussion noted that drainage is primarily a south Florida and coastal issue. Table 4 indicates that more management of the stormwater will be required in the future in south Florida. Salinity structures are site specific in coastal areas, but local and regional systems will be required. Far more management will occur in the future to balance the urban, natural, water, wastewater and groundwater level needs of the regions. Most of this infrastructure comes with a cost of construction and operations. In all cases, the underlying theme, in addition to increased capital costs, it is a huge demand for power. Power use to manage the system will increase by several gigawatts. That power capacity is currently not in place.

Based on the data developed in Tables 1–4, Table 5 was developed to suggest an estimate of the risk posed by climate change to the 10 regions of the state with respect to protection of the infrastructure, economy and natural systems. The higher the population (column 2) the more potential risk may exist, given other factors. Combine this with sea level rise and surge (storm) risk, low lying, high population areas will have significant risks. A lightly populated area that is low, like the Big Bend has far less property, people and economic value at risk than south Florida. It is evaluated as having low risk. Columns 5–7 summarize the water supply and treatment options supplies based on the data generated from Tables 2 to 4. The final two columns in Table 5 estimate the potential for, and cost of, protecting the infrastructure and property in these areas.

Table 3. Water supply options/alternative water supply options.

Region	Move Wellfields	Storage	Aquifer Storage and Recovery (ASR)	Horizontal Well/Infiltration gallery potential?	Desalination	Surface water
SE Florida	Yes—avoid impacts form sea level rise on west in Miami Dade County	limited	Has not been demonstrated to work	Yes, need demonstration of effort combined with surface/stormwater	Yes, cost and power limitations	no
Kissimmee River Valley	No	limited	Has not been demonstrated to work	Limited sites available	No access	Some potential may exist
Florida Keys	No, need desalination or mainland	no	Has not been demonstrated to work	No	Yes, cost and power limitations	no
Southwest Coast	Yes, inland and to brackish water sources with Reverse osmosis plants	limited	Operational	Yes, need demonstration of effort combined with surface/stormwater	Yes, cost and power limitations	yes
Tampa Bay	No, Currently reducing aquifer use, desalination option	limited	Potential projects, arsenic issues	Yes, need demonstration of effort combined with surface/stormwater	Yes, cost and power limitations	yes
Space/ Treasure Coast	Yes, but conflicts with Agricultural, ecosystem, supply limits	limited	Has not been demonstrated to work	Yes, need demonstration of effort combined with surface/stormwater	Yes, cost and power limitations	No
Northwest	Yes, but limited supply, conflicts with Agricultural	yes	Has not been demonstrated to work	No	Limited, cost and power limitations	Current supply
Big Bend/ Suwanee	Yes, but limited supply, conflicts with Agricultural	Limited near coast	Has not been demonstrated to work	No	Limited, cost and power limitations	yes
NE Florida/ St. John's River	Yes, but conflict with St Johns River, ecosystems, limited supply	Some potential exists	Has not been demonstrated to work	Yes, need demonstration of effort combined with surface/stormwater	Yes, cost and power limitations	Partial current supply, limited availability
North Central Ridge	no	limited	Has not been demonstrated to work	Limited sites available	No access	Some potential may exist

Ag = Agriculture.

Table 4. Waste and stormwater supply options.

Region	Seal Sewers	Sewer Service	Reuse	Aquifer Recharge	Recharge Water Conservation Areas s	Deep Wells	Salinity Structures	Local pumping of SW
SE Florida	Yes, needs to be done to protect other wastewater disposal options	500,000 septic tanks to sewer creates major treatment and disposal need	Yes, north of Broward & Miami-Dade Co., limited sites Broward and Miami-Dade, need other options; flooding likely to prevent wholesale solution in future	Yes, need RO/AOP/UV cost and power limitations	Yes, need RO/AOP/UV cost and power limitations	Yes, limited issues	Needed, political and property rights issues in play	Yes, environmental permitting issues will arise.
Kissimmee River Valley	Yes not related to wastewater quality	Limited need for change	Yes, current practice	Yes, need RO/AOP/UV cost and power limitations	No	No	Not an issue	Not a major issue
Florida Keys	Yes, needs to be done to protect other wastewater plants	Septic conversion ongoing	No	No	No	No	Not an issue, area too vulnerable for this to matter	Not solving problem
Southwest Coast	Yes, needs to be done to protect other wastewater disposal options	Convert septic tanks to sewer creates major treatment and disposal	Yes, current practice	Yes, need RO/AOP/UV cost and power limitations	No	Yes	Needed, but inundation will render them useless with time	Yes, environmental permitting issues will arise; limits as sea level inundates areas

Table 4. *Cont.*

Region	Seal Sewers	Sewer Service	Reuse	Aquifer Recharge	Recharge Water Conservation Areas s	Deep Wells	Salinity Structures	Local pumping of SW
Tampa Bay	Yes, needs to be done to protect other wastewater disposal options	Convert septic tanks to sewer creates major treatment and disposal need along coast	Yes, current practice	Yes, need RO/AOP/UV cost and power limitations	No	No	Needed for saltwater intrusion	Yes, environmental permitting issues will arise.
Space/ Treasure Coast	Yes, needs to be done to protect other wastewater disposal options	Convert septic tanks to sewer creates major treatment and disposal need along coast	Yes, current practice	Yes, need RO/AOP/UV cost and power limitations	No	Yes	Not a major issue	Yes, environmental permitting issues will arise.
Northwest	Yes, needs to be done to protect other wastewater system	Convert septic tanks to sewer creates major treatment and disposal need along coast	Yes, may require more treatment, cost, power limitation	No	No	No	Not a major issue	Not a major issue
Big Bend/ Suwanee	Yes, needs to be done to protect other wastewater systems and disposal options	Convert septic tanks to sewer creates major treatment and disposal need along coast	Yes, may require more treatment, cost, power limitation	No	No	No	Needs more evaluation	Not a major issue
NE Florida/St. John's River	Yes, needs to be done to protect other wastewater disposal options	Convert septic tanks to sewer creates major treatment and disposal need along coast	Yes	Probably not, geology limitation	No	No	Yes, needs more evaluation, political and property issues in play	Limited to coastal areas, permits may be an issue
North Central Ridge	Yes not related to wastewater quality	Limited need for change	Yes, current practice	Yes, need RO/AOP/UV cost and power limitations	No	No	Not an issue	Not a major issue

RO/AOP/UV = reverse osmosis, ultraviolet light and Advanced oxidation processed.

Table 5. Summary of risks of climate impacts to various regions of the state based on analysis of Tables 1–4.

Region	Population	Sea Level Rise Risk	Surge Risk	Water Supply Availability (Excl desalination)	Available Water Treatment Options	Economic Risk of Climate Change	Opportunity to Protect Property	Cost to Protect
SE Florida	H	H	H	H	H	H	M	H
Kissimmee River Valley	L	L	L	M	M	L	H	L
Florida Keys	L	H	H	L	H	H	U	U
Southwest Coast	M	H	H	H	M	M	L	U
Tampa Bay	H	H	H	M	H	M	M	U
Space/Treasure Coast	M	L	H	M	L	L	H	L
Northwest	L	L	M	L	L	L	H	L
Big Bend/Suwanee	L	M	M	L	L	L	L	L
NE Florida/St. John's River	M	M	M	M	L	M	H	L
North Central Ridge	L	L	L	M	L	L	H	L

H= high; M = medium; L = low.

When looking at this table, it is clear that south Florida, the Florida Keys and southwest Florida are far more vulnerable to sea level rise than the rest of the state. All three have population, low topography and are at high risk for climate change (specifically sea level rise and surges). Based on the prior Tables 2–4, Table 5 shows that there is potential to spend money to delay impacts with significant infrastructure improvements in southeast Florida, but it is highly unlikely the Sate of federal governments will fund the solutions.

At the same time, certain areas cannot be saved in the long-term (the "U" in the last column), such as the Keys, which are predominantly below 5 ft NAV 88, and the southwest coast where no coastal ridge exists. Both low lying areas that lack the economic engine of southeast Florida. Public policy-makers need to take this into account and make plans to address these lost properties and economic opportunities.

For the northwest, Northeast, North Central Ridge and Kissimmee River Valley regions, there is limited population and significant topography, so the climate changes risks are not viewed with concern, but future water supplies (due to precipitation changes) may be a driver. Hence the risks are low and any needed infrastructure costs are limited, so the costs are shown as low.

While Tables 2–4 showed there are difference strategies that can be pursued, utilizing the toolbox approach developed by FAU, Table 5 shows is that different areas will experience climate impacts and risks differently even in a place as small globally as the State of Florida. Within the state, adjacent regions will see different risks and one-size-fits-all policies will not be successful. Even within regions, the same actions will not be equally successful as many solutions are local. Others will require cooperative efforts from multiple levels of government and the private sector. Climate adaptation and risk are both a global and local phenomenon.

Table 5 provides insight to another phenomenon. For the southeast coast, the Florida Keys and some areas in southwest Florida or along the coast, the sea level rise issue will be a significant future concern. It is therefore not surprising to see that these areas have most of the activity in the state. It is also not surprising to see that climate discussions have gained little traction in the rest of the state (either among the public or politically), as the water issues are far more related to supply limitations on development than associated with climate change. Given that climate change risks are low outside south Florida, few residents outside south Florida expect to be paying for any adaptations made in the future, and therefore may believe there are far more important issues to invest time and political capital on. Unfortunately this sets a bad precedent for the future because the state's largest economic driver is southeast Florida, so impacts in one part of the state could have future impacts on the state as a whole. Despite the lack of risk in much of the state, and despite the political climate surrounding climate change, state officials should be supportive of local and regional efforts that local officials believe are needed to address their particular needs. This may include modifications to state infrastructure (Florida Department of Transportation), regional drainage systems (water management districts) and a number of regulations concerning environmental protection (where Nature is reclaiming the urban areas). Permits for constructing storage and dealing with stormwater are concerns. Funding to research water supply options is a need for certain areas, as is continued efforts in changing irrigation practices for agriculture.

5. Conclusions

There are three issues identified as drivers with climate change in Florida: changes in precipitation patterns, temperature increases and sea level rise. These three factors appear to be the perfect scenario to create disruption to the state's long-term economic growth and development. Understanding climate variability and sea level rise are important to understanding the potential impacts on Florida. Separating the state into regions reveals that different areas of the state will be affected more or less than other areas. With respect to climate change vulnerability across the state, as water issues will significantly affect economic, natural and built environmental systems. Protection of developed land is almost certain for most of the coastline to protect the economic value of coastal resources. While apparently Florida-centric based on the case study, all of these concerns apply outside Florida as well. The framework, toolbox of options and analysis of regional and local conditions should be pursued by local, regional and national policymakers to create that cohesive climate change strategy that has been so elusive to date.

References

1. IPCC. Intergovernmental panel on climate change. In *Climate Change 2007: The Physical Science Basis*; Cambridge University Press: Cambridge, UK, 2007.
2. UNEP. *Climate Change Science Compendium 2009*; United Nations Environmental Programme: New York, NY, USA, 2009.
3. Karl, T.R.; Melillo, J.M. 2009. *U.S. Global Change Research Program, Global Climate Change Impacts in the United States*, Peterson, T.C., Eds.; Cambridge University Press, Cambridge, UK. 2009. Available online: http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts/full-report (accessed on 26 March 2012).
4. Heimlich, B.N.; Bloetscher, F.; Meeroff, D.E.; Murley, J. *Southeast Florida's Resilient Water Resources: Adaptation to Sea Level Rise and other Climate Change Impacts*; Florida Atlantic University: Boca Raton, FL, USA, 2009. Available online: http://www.ces.fau.edu/files/projects/climate_change/SE_Florida_Resilient_Water_Resources.pdf (accessed on 26 March 2012)
5. Risk and Vulnerability Assessment Tool (RVAT); NOAA Coastal Services Center: Charleston, SC, USA, 2011. Available online: http://www.csc.noaa.gov/rvat/ (accessed on 26 March 2012).
6. Freas, K.; Bailey, R.; Muneavar, A.; Butler, S. Incorporating climate change in water planning. *J. Am. Water Works Ass.* **2008**, *100*, 93–99.
7. Marshall, C.H.; Pielke, R.A.; Steyaert, L.T.; Debra, A.W. The impact of anthropogenic land—Cover change on the Florida Peninsula sea breezes and warm season sensible weather. *Mon. Wea. Rev.* **2004**, *132*, 28–52.
8. Backlund, P. *Synthesis and Assessment Product 4.3: The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States*; 27 May 2008. Available online: http://www.climatescience.gov/Library/sap/sap4-3/final-report/default.htm#EntireReport (accessed on 22 February 2012).
9. Bloetscher, F.; Heimlich, B.N.; Meeroff, D.M. Development of an adaptation toolbox to protect Southeast Florida water supplies from climate change. *Environ. Rev.* **2011**, *19*, 1–21.

10. Grinsted, A.J. Reconstructing sea level from Paleo and projected temperatures 200 to 2100 AD. *Clim. Dyn.* **2009**, *34*, 461–472.
11. Rahmstorf, S. A semi-empirical approach to projecting future sea-level rise. *Science* **2007**, *315*, 368–370.
12. *Portland Climate Change Efforts*; Office of Sustainable Development: Portland, OR, USA, 2003. Available online: http://www.portlandonline.com/bps/index.cfm?a=112117&c=41917 (accessed on 26 March 2012).
13. Palmer, R.N.; Hahn, M. *The Impacts of Climate Change on Portland's Water Supply: An Investigation of Potential Hydrologic and Management Impacts on the Bull Run System*; Portland Water Bureau: Portland, OR, USA, 2002. Available online: http://cses.washington.edu/db/pdf/palmerhahnportland111.pdf (accessed on 26 March 2012).
14. RMCO. *Colorado Climate Scorecard: The Implementation Status of the Colorado Climate Action* Plan *and RMCO's Climate Action Panel Recommendations*, Rocky Mountain Climate Organization: Denver, CO, USA, 2009. Available online: http://www.rockymountainclimate. org/images/CO%20Scorecard%20Update.pdf (accessed on 26 March 2012).
15. Bloetscher, F.; Meeroff, D, Heimlich, B.N., Brown A.R., Bayler D. Loucraft M. *Improving the Resilience of a Municipal Water Utility against the Likely Impacts of Climate Change—A Case Study*; Florida Water Utility: Pompano beach, FL, USA, 2009.
16. Murley, J. *Charting the Course, Where is South Florida Heading*; Florida Atlantic University: Boca Raton, FL, USA, 2006.
17. *2009 California Climate Adaptation Strategy: A Report to the Governor of the State of California in Response to Executive Order*; *S-13-2008*; California Natural Resources Agency: Sacramento, CA, USA, 2009.
18. Littell, J.S.; M. McGuire, L.C.; Whitely B. *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate*; Climate Impacts Group, University of Washington: Seattle, WA, USA, 2009. Available online: http:// www.cses.washington.edu/db/pdf/ wacciaexecsummary638.pdf (accessed on 26 March 2012).
19. *Assessment and Action Plan—A Report Based on the Ongoing Work of the DEP Climate Change Task Force*; Department of Environmental Protection: New York, NY, USA, 2008.
20. Nicholls, R.J. *Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes*; OECD Environment Working Papers: Paris, France, 2008.
21. Mulkey, S. Climate change and land use in Florida: Interdependencies and opportunities. Presented at *Century Commission for a Sustainable Florida*: Tallahassee, FL, USA, 2007.
22. Bloetscher, F.; Heimlich, B.N.; Romah, T. Counteracting the effects of sea level rise in Southeast Florida. *J. Environ. Sci. Eng.* **2011**, *5*, 1507–1525.
23. Pielke, R.A.; Steyaert, L.T.; Vidale, P.L.; Liston, G.E.; Lyons, W.A.; Chase, T.N. The influence of anthropogenic landscape changes on weather in south Florida. *Weather Rev.* **1999**, *127*, 1663–1673.
24. Obeysakara, J.; Park, J.; Irizarry Q.M.; Trimble, P.; Barnes, J.; van-Arman, J.; Said, W.; Gadzinski E. *Past and Projected Trends in Climate and Sea Level for South Florida, Hydrologic and Environmental Systems Modeling Technical Report*; The South Florida Water Management District: West Palm Beach, FL, USA, 2011, p. 171.

25. Obeysekera, J.S. Climate change and water management: Planning for sea level rise. Presented at *Broward Climate Change Task Force, Science and Technology Subcommittee*, Broward County, FL, USA, 2009.
26. Bloetscher, F.; Muniz, A. Climate Change Impacts on Florida Water Supplies. Presented at *America Water Works Association Annual Conference and Exposition Proceedings*, Denver, CO, USA, 2009.
27. Reilly, T.E.; Dennehy, K.F.; Alley, W.M.; William L.C. *Ground Water Availability in the United States*; USGS: Reston, VA, USA, 2009.
28. Global Insight. The role of metro areas in the US Economy; Reported for The United States Conference of Mayors, Washington, DC, USA, 1 March 2006. Available online: http://usmayors.org/metroeconomies/Top100_2006.pdf (accessed on 14 February 2012).
29. Johns, G.; Leeworthy, V.R.; Bell, F.W.; Bonn, M.A. Socioeconomic Study of Reefs in Southeast Florida: Final Report; Hazen and Sawyer: Hollywood, FL, USA, 2003.