USING SPATIAL ANALYSIS TO DETERMINE CRITICAL AREAS OF THE ENCROACHMENT OF SALTWATER FOR PLANNING

by

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(Under the Direction of Rosanna Rivero)

ABSTRACT

The purpose of this study is to analyze the current conditions of a south Florida coastal area, in Miami-Dade County, and identify environmental indicators of saltwater intrusion into the groundwater aquifer. In Miami-Dade County, the Biscayne Aquifer is a major source of freshwater. It is threatened by the encroachment of saltwater, thus impacting the freshwater supply. By identifying indicators and analyzing them using spatial analysis in ArcGIS, critical areas can be determined where over drafting may occur on the groundwater aquifer, leading to further inland movement of the saltwater and freshwater interface. Environmental indicators include elevation, depth to aquifer, land use, chloride concentration values, and distances from canals, supply wells, and the current delineated saltwater and freshwater interface line. Using spatial analysis to determine critical areas provides planners with knowledge of areas of over drafting and the potential threat of well contamination so that future conservation methods may be implemented.

INDEX WORDS: Saltwater Intrusion, Spatial Analysis, and Groundwater

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CHAPTER 1

INTRODUCTION

A current environmental phenomenon is occurring in coastal regions that vastly affect the amount potable water available to these regions. Although not a new phenomenon, saltwater intrusion is a growing problem for coastal regions, such as South Florida. Saltwater encroachment is the result of two factors that are commonly seen in coastal areas. The two main contributing factors are over drafting of the aquifer and sea level rise (Blanco et. al., 2013).

Sea level rise (SLR) is a constant factor contributing from climate change. Over drafting results from increased populations and land uses that are extensive in water use, such as residential and agricultural land uses. When water consumption in these land uses is not regulated, freshwater is withdrawn from the aquifer at a higher rate that it can be recharged. When this occurs, the cone of depression that forms around the pumping wells creates a negative pressure causing saltwater to intrude into the aquifer, as seen in figure 1.

The availability of safe drinking water is a vital factor for sustainable development. Planners can benefit from knowing critical areas where over drafting is occurring. By knowing these critical areas, planners can prevent overdevelopment and place water use regulations in place in these areas. This project uses different indicators of saltwater intrusion to determine critical areas where saltwater intrusion is most likely to occur. These indicators include elevation, depth to water, land use, chloride concentration results from monitoring wells, and distances from canals and pumping supply wells, and proximity to the current delineated saltwater intrusion line. These factors are ranked according to elevation, how close the aquifer is to the surface, their relative distance, concentration levels, and land uses that consume the most water. The rankings are added together to determine critical areas.

Over the years, Miami-Dade County has seen influx in its population, and it is expected to increase. Miami's 2013 population was 2,617,176 with a 4.8% increase in population from 2010 (United States Census Bureau, n.d.). With an increase in population comes an increase in water use. This increase in population is a major contributing factor in the saltwater intrusion issue that the region is facing. When addressing this issue, planners need to look at both contributing factors to successfully assess future water supply, and by focusing on the demand and reducing possible over drafts of the aquifer.

In Miami-Dade County, the issue of saltwater intrusion dates back to 1932, however research has been conducted on this issue since 1904 (Sonenshein, 1995). According to Sonenshein, in 1904, the saltwater interface was believed to be at the coast due to high levels of freshwater in the Biscayne Aquifer and the amount of freshwater in the Everglades. This, however, started to change in 1909 through the 1930's with the extension of the Miami River and the construction of the vast network of canals, which are still present today (Sonenshein, 1995). According to the South Florida Water Management District, there are approximately 2000 miles of canals, nearly 70 pump stations, and over 650 water control structures to date (SFWMD, 2014). These canals were built for drainage and contained no control structures. Their main function was to drain the Everglades and to prevent flooding, which kept such fragile ecosystems alive. This resulted in the lowering of the freshwater in the aquifer and thus allowing saltwater to intrude into the aquifer. Saltwater also crept further inland through the recently built canals, connected to the ocean, which directly recharge the aquifer (Sonenshein, 1995).

Starting in 1946, control structures were built to help prevent saltwater intruding from tidal changes in the canals. Control structures, being constructed more inland, also served to backup freshwater to retain a higher level of water in the aquifer. With the construction of additional canals in the 1960s and with the droughts of 1970 and 1971, the saltwater interface moved further inland (Sonenshein, 1995).

When saltwater moves inland it forms a wedge shape under the existing freshwater. This is due to the fact that saltwater is denser than freshwater. As freshwater is drawn from the aquifer, at a rate faster than it can be recharged, it lowers the level in the aquifer making it susceptible to the encroachment of saltwater. According to Miller, the inland movement of saltwater in the Biscayne Aquifer is directly related to development (Miller, 1990).

As saltwater continues to become a more urgent issue for the Miami area, as well as other coastal regions, proper planning is imperative to insure the population a sustaining supply of drinking water, such as waste water recycling and searching for alternative sources. This issue may become more difficult to plan for due to the increasing population in the area and the load that the urban centers put on the aquifer. According to Cruz and Hesler, the population in Miami as of 2011 is 2,554,766 people (Cruz & Hesler, 2013). Based on Census data 1,897.72 people live within a square mile on average in Miami-Dade County (US Census Bureau, 2014). This shows that population density is high and that water use may be concentrated in these developed areas. This is a problem for future generations as population grows in these coastal regions. The population in Miami is expected to grow by an estimated 21.9% between 2005 and 2020, (Zwick and Carr, 2006). Future population growth is illustrated in Figure 2.

The future population growth for coastal regions can lead to future water supply issues. With little or no regulation on water use, the aquifers that supply water to these regions can become contaminated with saltwater, thus leading cities and municipalities to look for alternative means to supply water to meet the ever-growing demand. Some of these alternatives can become costly; therefore, it is important for planners to monitor for over drafting of the ground water aquifer and thus inhibit the further encroachment of saltwater contamination.

With the use of Geographic Information Systems, or GIS, analysts and planners can identify critical areas where particular land uses and other environmental indicators can lead to potential saltwater encroachment. The purpose of this project is to combine environmental indicators to determine areas that are the most susceptible to over drafting of the ground water aquifers. By combining these environmental indicators, analysts can also see where multiple indicators may affect one particular area. With this information, planners can place water conservation measures or look for other water source alternatives.

Since saltwater encroachment is a concern for the future populations of these regions, many are looking at alternative sources of fresh water. Some of these alternatives include moving the supply wells further inland or even treating the seawater through desalination for safe drinking and use. Many of these alternatives can be costly and can lead to other possible negative impacts on the surrounding environment (Wiedenman, 2010).

Impacts and costs of using alternative water supply sources may differ based on the region and their surrounding environment. For this project, alternative sources for fresh water are discussed as well as their costs and impacts to the surrounding environment. Alternatives discussed are from previous literature published on the current issue in Miami-Dade County, which will be addressed further.

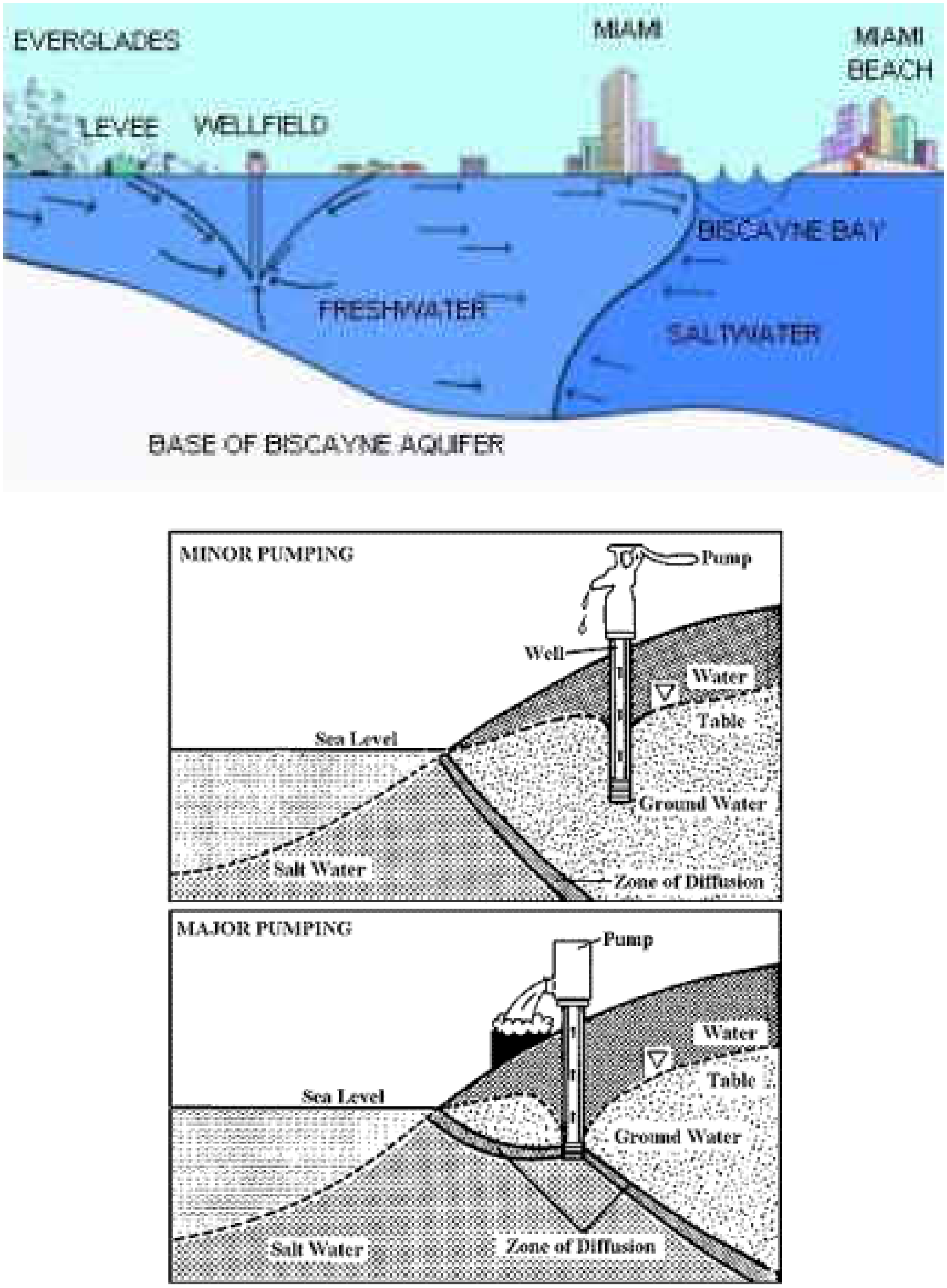


Figure 1: Freshwater and Saltwater Interface Under Normal and Current Situations**.** (Left) Higher pressure of freshwater keeps saltwater from intruding. (Right) Saltwater intruding due to over drafting of the freshwater in the aquifer. (Source: University of Florida IFAS Extension Miami-Dade County)

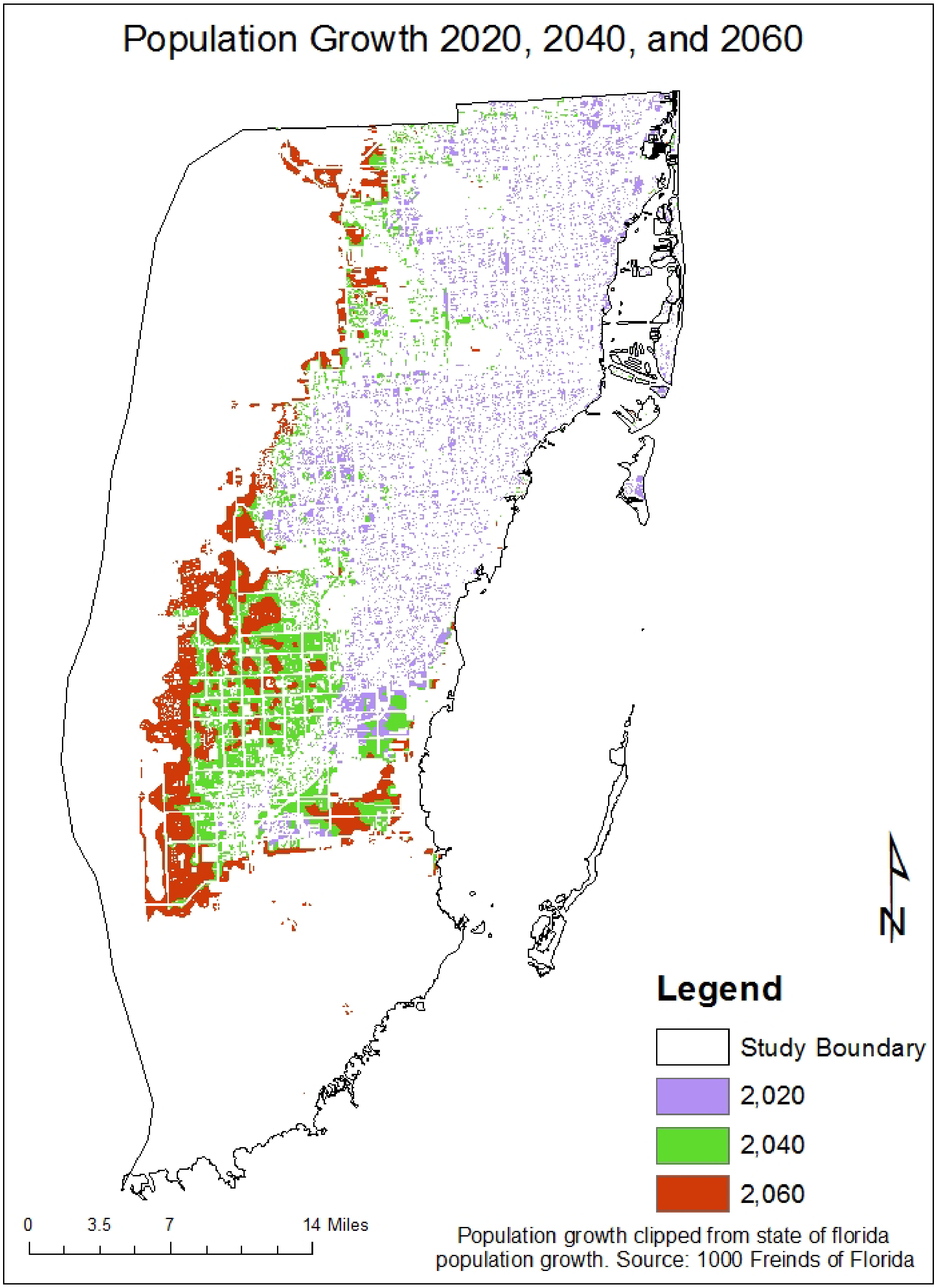


Figure 2: Population growth for year 2020, 2040, and 2060. Data is resourced from 1000 Friends of Florida.

CHAPTER 2

AQUIFERS

Biscayne Aquifer

The Biscayne Aquifer covers an area of about 4,000 square miles of the southern tip of Florida. It is the main source of water of Miami-Dade County, as seen if Figure 2. According to Jenkins (2009), it is also the source of water Broward, Palm Beach, and Monroe County. The Florida Keys Aqueduct Authority pumps water from the Biscayne Aquifer to residents over 100 miles away from the southern range of the aquifer to Key West. According to the United States Geological Survey, about 70 percent of the water pumped from the aquifer is for public use, and supplies water to about 3 million people in the south Florida region (Miller and USGS, 1990). This region is an area of major population growth, which creates an increasing demand on the already impaired water supply.

Due to its location near the shoreline, the Biscayne Aquifer is very close to the surface and very permeable. It is formed from highly permeable limestone and sandstone, which is less permeable. Being close to the surface makes the aquifer very susceptible to contamination from chemicals carried by runoff. In most areas, the aquifer is covered only by a thin veneer of porous soil. According to Jenkins (2009), the aquifer is only 35 to 40 feet thick near the southern part of the Everglades and thickens as it moves northeast. USGS records the wedge shaped aquifer to a depth of about 240 feet near the coast at Boca Raton, Florida, just north of Miami (Miller and USGS, 1990).

Historically the Biscayne Aquifer was recharged by precipitation that falls on it and by the overland sheet flow that supplies the Everglades. Southeast region of Florida receives an average of 52.3 inches of rainfall each year according to the Southwest Florida Water Management District hydrologic database (SWFMD, 2014). This precipitation is the main component of recharge on the aquifer. Precipitation levels are responsible for the fluctuation of water levels in the aquifer causing it to fluctuate as much as 2 to 8 feet (Jenkins, 2009). Even though precipitation is the main component of recharge, overland sheet flow is also a major contributing factor to recharge the aquifer.

The Everglades wetland ecosystems have always depended on this sheet flow for their existence. As Lake Okeechobee historically would overflow its shoreline, the water would flow southward across the southern tip of the state. Aquifers in this region, such as the Biscayne Aquifer and the Floridan Aquifer, a large deep aquifer with some of its area underlying the Biscayne Aquifer, also benefit from this overland sheet flow. Over the past decades, however, most of this overland flow has been captured and rerouted by canals in the name of flood control. These canals now crisscross the land and have drastically altered the hydrology of south Florida and thus negatively impacting the Everglades and aquifers, including the Biscayne Aquifer.

As mentioned previously, the canals also caused saltwater encroachment to occur and to move inland as the canals were cut into the highly permeable land which was already just above sea level. They also created an interchange connection between surface waters in the canals, which directly recharge the aquifer (Miller and USGS, 1990). With the aquifer being close to the surface, the water level in the canals directly affects the water level in the aquifer. If the water level decreases in the canal, so does the water level in the aquifer, making it susceptible for saltwater to intrude. One benefit of the canal's interconnection is that the groundwater can be immediately recharged by the canal system. This also allows water management to direct the water towards the coastal region of the aquifer to allow recharge in that region to help retard the encroachment of saltwater if aquifer levels get too low (Miller and USGS, 1990).

The SFWMD now control these canals and use them to help route water into conservation areas that can be used to recharge the aquifer during periods of drought or when the aquifer is overdrawn and water levels become low enough for saltwater encroachment to occur. The presences of control features in the canals along the coast are becoming increasingly important to prevent the encroachment of saltwater into the canals.

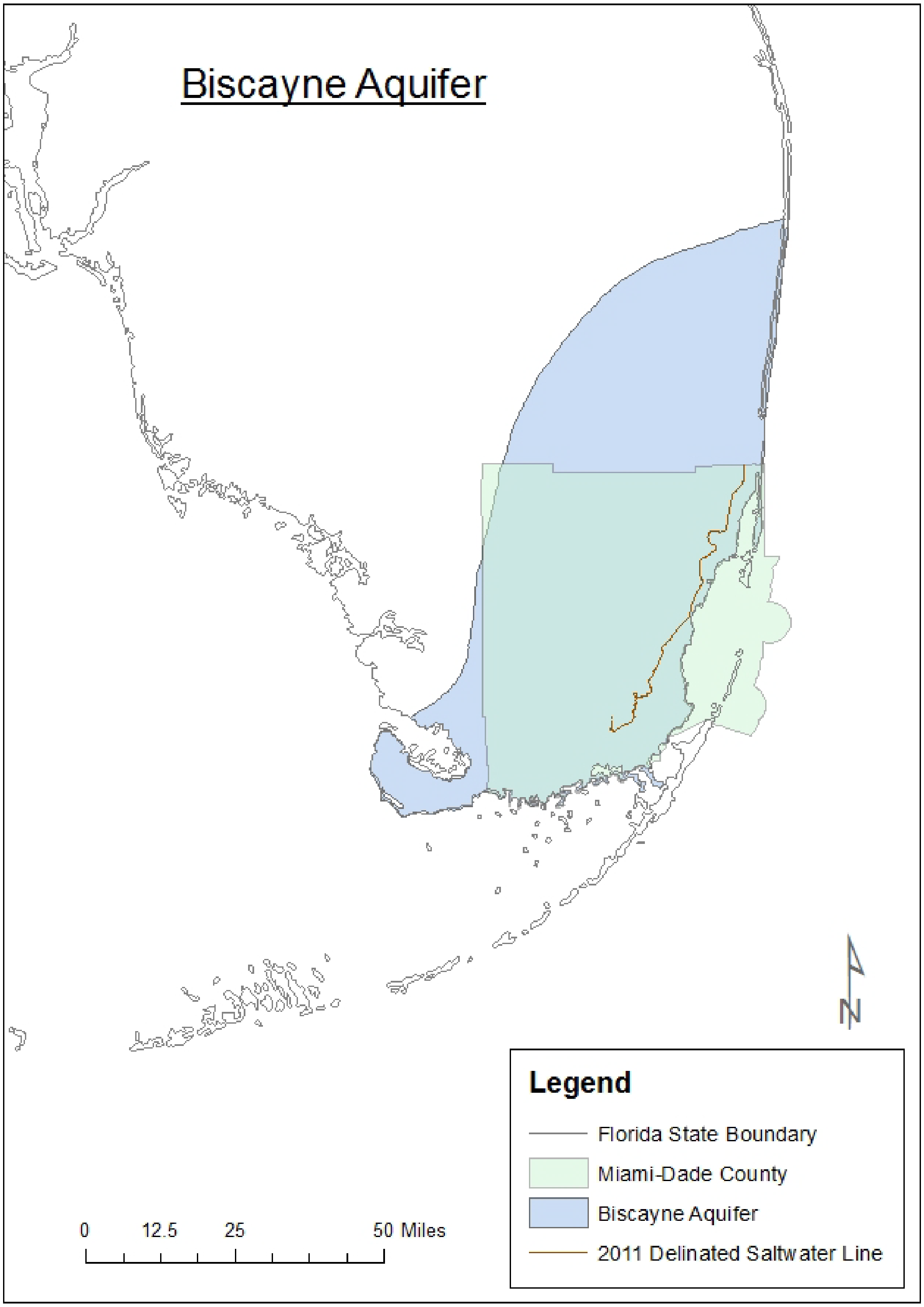


Figure 3: Map of Biscayne Aquifer in relation to Miami-Dade County Boundary. Delineated saltwater intrusion line in 2011 mapped to show current freshwater and saltwater interface.

Floridan Aquifer

Another aquifer in the region of great importance is the Floridan Aquifer. This aquifer is one of the most productive aquifers in the world and covers an area of about 100,000 square miles. It provides fresh water to cities in Florida, southern Alabama, southeastern Georgia, and even southern South Carolina, as seen in Figure 3 (USGS, 1990). The aquifer has evidence of some saltwater encroachment near the coastal regions resulting in brackish water in these areas of the aquifer system (USGS, 1990).

The Floridan Aquifer is deep and is overlaid by the Biscayne Aquifer in the southeastern Florida region. Therefore it is much deeper and predominantly hydrologically isolated from the Biscayne Aquifer (Wiedenman, 2010). The high productivity of the Floridan Aquifer makes it a potentially alternative source for water in parts of the region. Since the Floridan Aquifer in southeastern Florida, consists of mostly brackish water, additional treatment would be needed to allow for safe consumption (Wiedenman, 2010).

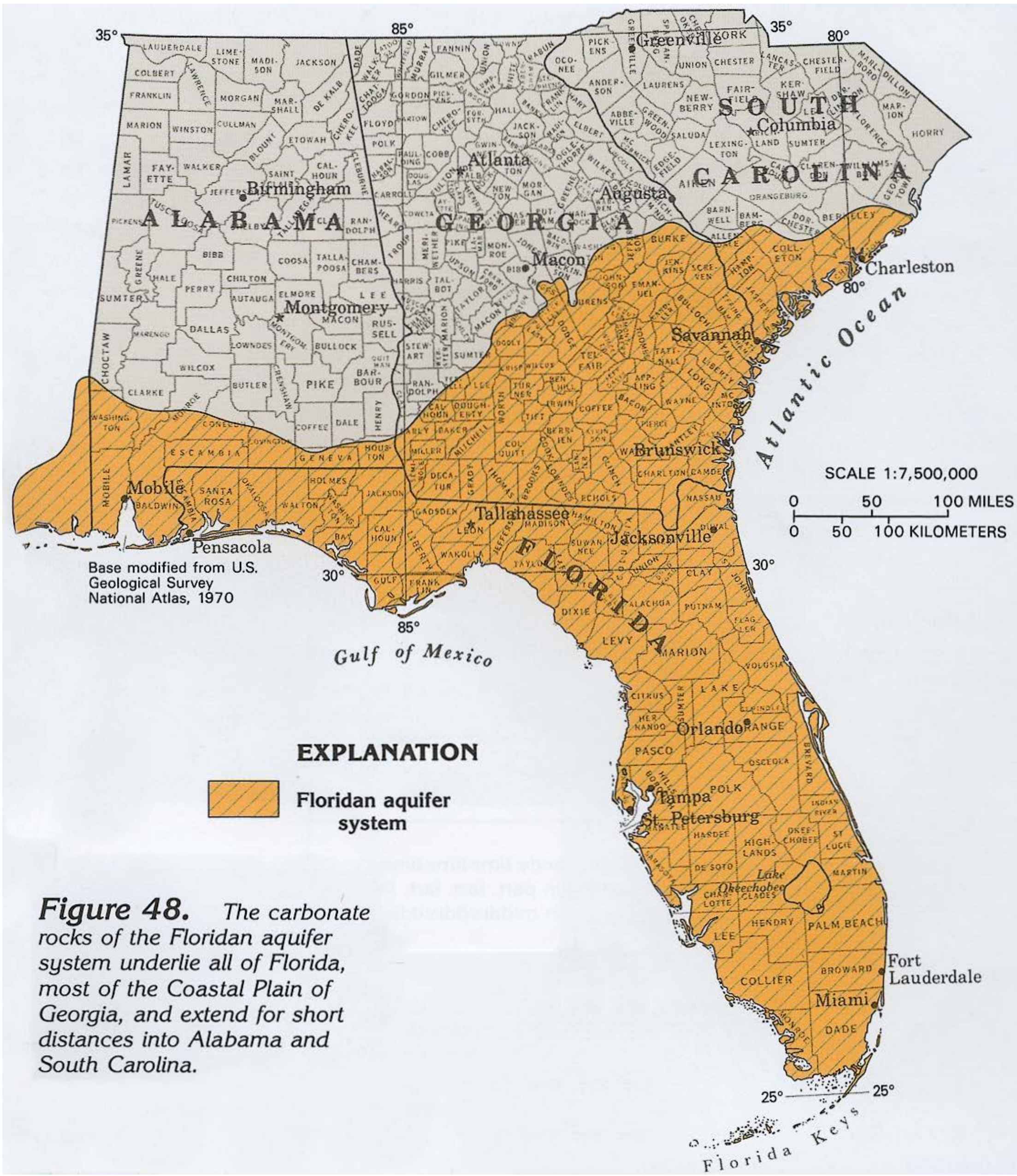


Figure 4: Map of Floridan Aquifer. (Source: USGS, 1990)

CHAPTER 3

LITERATURE REVIEW

The Miami region is facing an environmental phenomenon that will greatly impact the population, giving a challenge for future planning. This phenomenon is saltwater intrusion, which affect the availability of fresh water in the Biscayne Aquifer. Much of the Miami area, and other surrounding cities, and even the Florida Keys get their drinking water from the Biscayne Aquifer.

As water managers and planners start to face this issue, it is important to discover ways to decrease the amount saltwater intruding into the aquifer or to find additional sources of water. In a 2010 study, Ryan E. Wiedenman proposes to answer the question of "which adaptation strategy can provide the most cost-effective approach to providing freshwater supplies to human populations while minimizing the overall adverse impact to the environment given the expected rate of sea level rise induced saltwater intrusion into freshwater aquifer supplies?" (Wiedenman, 2010). In his paper, *Adaptive Response Planning for Sea-Level Rise and Saltwater Intrusion in Miami-Dade County*, Wiedenman poses three alternatives that can hopefully fulfill the increasing demands for water in the county.

Every alternative is going to have an impact both on cost to the people as well as a potential adverse impact to the environment. Wiedenman looks at each alternative with a cost-effectiveness approach as well as an environmental impact analysis. For our purposes, we will mainly focus on the environmental impact analysis that this study discusses for each alternative. He also views the issue and provides insight on the alternatives based on a 50-year time horizon. This will give planners and management districts a new way to look at saltwater intrusion, since Florida law only requires them to look ahead 20 years (Wiedenman, 2010).

The three alternatives mentioned by Wiedenman is to (1) move the pumping wells to new locations in the Biscayne Aquifer not yet affected by the saltwater intrusion, (2) using reverse-osmosis desalination to purify brackish waters from the deeper Floridan Aquifer under the Biscayne Aquifer, and (3) use the same reverse-osmosis desalination to purify water from the seawater (Wiedenman, 2010). An important factor that was not included in this study was the effect of the physical barriers placed in the canals to prevent saltwater intrusion from occurring. Prevention is important regardless of the alternative chosen. This author did not include physical barriers due to the fact that they would be implemented anyway as they are today and should be considered as a component of each alternative.

The first alternative mentioned in this study is the movement of the pumping wells to a less impacted area of the Aquifer. For the Miami-Dade County, the best implementation is to move the pumping wells westward or further inland towards the protected Everglades. This is a good alternative to consider since some pumping wells had to be closed in the past due to contamination of saltwater, ultimately reducing the supply of water (Wiedenman, 2010).

By moving the wells further inland, this will result in the construction of new wells and the acquisition of the needed land. In comparison, this is most likely to be the most cost-effective alternative for the county and for the supply of water consumed by the population. Treatment of water will likely be the same as is currently, it would just need to be piped further to the treatment facility or further from the treatment facility to the urban areas. However, this alternative does not come without any environmental impacts. If the wells are moved westward and the pumping rate is to be maintained, then the cone of depression formed in the water table may affect the hydrology of neighboring ecosystems, such as the Everglades. Based on the author's cost analysis, this alternative will most likely receive the most interest due to the fact that its present value cost is much lower than the other two alternatives (Wiedenman, 2010).

The next two alternatives, mentioned in the literature, involve a more complex and yet more expensive type of treatment to the water supply. The first of these two alternatives involves drilling deeper and tapping into the Floridan Aquifer below the currently used Biscayne Aquifer. This alternative requires additional treatment since the water in the Floridan Aquifer is brackish. Brackish water consists of a mix of freshwater and saltwater, so the need of advanced treatment will be necessary. Treatment would consist of using reverse-osmosis desalination in order to reduce the Cl^- concentration level to a consumable, save level. The state of Florida is the national leader in using desalination to treat brackish water as a fresh water source (Chen, 2014).

Another issue is the current use of the Floridan Aquifer by other areas in northeast Florida, as well as other major cities that withdraw from the aquifer. In 2008, according the St. Johns River Water Management District, more than the majority of water used in northeast Florida comes from the Florian Aquifer (SJRWMD, 2009). This use could result in other contamination, including dissolved solids and sulfates stirred up from deeper inside the aquifer, resulting in additional treatment on the water supply, thus resulting in additional costs. As mentioned earlier, the Floridan Aquifer is large and extends up to southern Alabama and Georgia. Several cities withdraw water from the aquifer already.

The environmental impacts of tapping into the Floridan Aquifer can have less of a negative impact on the small scale. Since the Floridan Aquifer is confined beneath the Biscayne Aquifer, withdraws would not affect the hydrology of other surrounding ecosystems. The negative environmental impact can be seen on a larger scale by the production of additional carbon emissions from the energy needed to run the desalination facilities. Another negative impact, and an additional cost would be the disposal of the highly saline concentrate produced as a byproduct of desalination.

The third and final alternative mentioned in the study is another desalination alternative (Wiedenman, 2010). Instead of tapping into the brackish, Floridan Aquifer, this method uses the ocean as a source. Saltwater has a concentration of 9,300 mg/L, which will take significant amount of treatment at a higher cost (Lehigh Environmental Initiative, 2011). This, however, will not lead to the construction of new wells, but will lead to the construction of a new desalination plant near the coast. There is also the possibility of the need to construct the desalination plant near an existing power plant or perhaps build an additional power plant to run the desalination plant. This is due to the amount of energy required to run the facility and that much energy would be lost in transmission if the power source were too far away.

This alternative has been implemented in other parts of Florida in the past. The city of Tampa uses a desalination plant on Tampa Bay, which can supply up to 25 million gallons per day of water to the residents of Tampa (Tampa Bay Water, n.d). This is a considerable amount of water since the per capita use in Miami Dade County was 139.6 million gallons a day in 2009. However, the county produced more than 312.5 million gallons day to serve more than 2.2 million customers that same year in 2009 (Miami Dade County, n.d.). The major advantage of using the ocean as a source for drinking water is the potentially limitless supply. The downfall of this alternative would be the extensive amount of energy required to treat the seawater, as well as, the additional cost for that energy. Amount of carbon emissions and costs would be much greater than treating the brackish water in the Floridan Aquifer. Also, there will be an even greater amount of saline concentrate that will be produced as a byproduct. Disposal of this byproduct would become a great concern and expense. Based on Wiedenman's cost analysis, alternative three would have a higher present cost value of an estimated $649,012,009, more than alternative one and two combined (Wiedenman, 2010). The higher cost is resulting from the higher water treatment cost which is contributed to the higher energy consumption required to operate the desalination plant.

Along with the alternatives mentioned, Wiedenman also discusses the environmental impacts of each. He also discusses three particular negative impacts that would be associated with the three previously mentioned alternatives. These negative impacts include the impacts to wetland and other aquatic ecosystems from, 1) the lowering of the water table, 2) the effect of saline and by-product discharge on marine and local aquatic ecosystems, and 3) the global impact created by the increased levels of carbon emissions required to generate power for the increased treatment. These impacts are important to discuss since they may majorly affect the ecosystems that are important to human populations. This in turn will affect the human population itself as it will affect the quality and the amount of freshwater available.

The impact on wetland ecosystems could be a major factor from all three alternatives mentioned, however, the first alternative, of moving the wells may have the greatest negative impact. Wetlands are very prevalent in south Florida, and the presence of the federally protected Everglades would be one of the wetlands most likely affected by this alternative. The benefits that wetlands provide to the human population are often more vast than most realize. Wetlands provide a natural buffer for storm surge, act as a natural water treatment facility to improve water quality, as well as provide a natural sink for the emissions of carbon dioxide. Wetlands also provide a habitat to several species of animals, some of which are endangered and thereby protected by the Endangered Species Act. This act is in place to prevent the taking of species that are listed as threatened or endangered, by any person or government agency (U.S. Fish and Wildlife Service, n.d.).

Another major environmental impact directly related to second and third alternative is the impact of the saline concentrate, which is a by-product of desalination. This will be a major concern for planners if one of these alternatives is chosen. Saline concentrate, if not properly managed, will have a drastic impact on water quality. The literature discusses primarily the effects related to deep-well injections of the concentrate. Although this alternative may be one considered for the disposal of the by-product, it is important to realize the impacts associated with it. If one of the injection wells fails, then the byproduct will enter the Biscayne Aquifer or enter the deeper Floridan Aquifer prematurely resulting in contamination (Wiedenman, 2010).

Environmental impacts also must be considered from other methods of disposal. If deep well injections are not used as a method of disposal, other methods would have to be utilized. One of the major concerns is that of storage of the saline by-product. Proper storage could become expensive as well as a potential hazard if the storage facility fails or is damaged by natural causes, such as storm. As mentioned earlier, this by-product can be very detrimental to the water quality as well as the quality of the nearby aquatic and marine ecosystems.

The third and final impact discussed by Wiedenman, are the environmental concerns related to the increased carbon dioxide emissions. This is a concern, which will counteract the goal of increasing the availability of fresh water. Carbon emission is one of the major contributing factors to sea level rise, which, in turn, is one of the major factors leading to saltwater intrusion. This impact will not only lead to increased levels of saltwater intrusion, but also to the degradation of wetland and marine environments which would affect water quality as a whole.

In order to determine the best possible alternative from the three discussed, a ranking system was used to rank the areas of impact and the rankings are then totaled to determine which alternative would have the least overall environmental impact. Alternative 1, moving the wells westward, would have the highest impact on wetlands ecosystems, especially the Everglades (Wiedenman, 2010). This is due to the cone of depression created from the pumping wells, which would lower the water table and the amount of water in the wetland systems. In turn reducing biodiversity, habitat, water quality, and available carbon sinks. This alternative, however, has zero ranking of impact for saline concentration pollution, since pumping will still be from the freshwater aquifer, and excess carbon emissions.

In terms of the rankings of alternative 2, which involves tapping into the Floridan Aquifer and use desalination to treat the brackish water. This alternative has very little if any impact on the wetland environments; however, it does have an impact on the saline concentration pollution issue as well as a slight increase in the carbon emissions to run the additional treatment. These extra emissions would only be slightly higher than that of moving the wells and to continue the current treatment process (Wiedenman, 2010). The additional emissions, however, would be sustained.

The final alternative, using the ocean as the supply of water, also ranked low on wetland impacts. This is due to fact that ocean would not be in direct relationship with the inland hydrology, which affects the wetlands. This alternative did however; rank higher in the categories of saline concentrate by-product pollution and carbon emissions. The ocean waters are more than twice the salinity of the brackish water being used in alternative 2. This would lead to an increase in the saline concentrate by-product. The largest environmental impact caused by alternative 3 would be the increased carbon emissions. The amount of power needed to treat the ocean water to a level safe to drink would be greater than the first two alternatives. There may also be a possible need for the desalination plant to have its own power plant to run the operation.

According to his ranking system, alternative 3, ocean water desalination, ranked the highest in environmental impacts over alternative 2 and alternative 1 (Wiedenman, 2010). This is due to the level of carbon emissions being greater than the first two alternatives. Since sea level rise is a major contributor to saltwater intrusion, a much higher weight was placed on the category of carbon emissions over wetland degradation and saline concentrate pollution possibility.

In the paper, *Adaptive Response Planning for Sea-Level Rise and Saltwater Intrusion in Miami-Dade County*, Wiedenman only discussed three alternatives and their economic and environmental impacts. There are other alternatives that could be analyzed for sustaining water supply for the increasing population in Miami-Dade County. Also, by using spatial analysis to discover critical areas as a method for response planning, one can further determine which alternative solution or solutions could be implemented to insure adequate water supply for the increasing population.

CHAPTER 4

CURRENT ISSUE

The southeast region of Florida is ranked as one of the ten most vulnerable coastal metropolitan areas in the world to climate change (Florida Center for Environmental Studies, n.d.). Some of the many reasons for this high ranking include low elevation and an open water system. The region is also exposed to periods of extreme droughts and periods of flooding. This results from extreme conditions in the region's wet and dry seasons. Since rainfall is the primary source of recharge for the Biscayne Aquifer, the different seasons directly affect the water level, or depth to water, in the aquifer (Langevin, 2001).

The canals can also play a role in the depth to water in the aquifer during the wet and dry seasons. During the dry season, the canals can help recharge the aquifer by routing water from further inland to the coastal areas. The redistribution of water aids in the prevention of saltwater intruding further inland during the dry season, when the depth to water is low. The opposite is true in the wet season, where the canals work to drain the aquifer into Biscayne Bay to prevent flooding in urban and agricultural areas. This is managed by allowing the control structures to be open during the wet season and closed during the dry season (Langevin, 2001).

As mentioned earlier, the Biscayne Aquifer is the main supply of freshwater for this region and Miami-Dade County. Since the aquifer is close to the surface, with many parts is only covered by thin veneer of topsoil, the extreme changes in wet and dry seasons drastically affect the water level in the aquifer as seen in figure 5 and 6. Notice the larger cone of depression forming around the pumping wells during the wet season when the canals are used to drain the aquifer to reduce flooding in urban areas. This shallow depth to the aquifer makes the region susceptible to further saltwater intrusion, and thus threatening the current fresh water source for Miami Dade County.

The main issue facing this region is saltwater intrusion from due to sea level rise and over drafting from the aquifer. Over drafting is a major concern that must be further assess to ensure adequate freshwater supplies for the region. Over drafting can be regulated by monitoring consumption rates and factors that influence fluctuations of levels in the aquifer. Of the roughly 2,000 miles of canals in south Florida reported by SFWMD, about 1,014.7 miles are located within Miami-Dade County as seen in Figure 7. This distance was calculated by generating statistics using ArcGIS on the mapped canals in our study area.

These canals drastically influence freshwater levels in the Biscayne Aquifer since it is located close to the surface. The water levels in the canals can fluctuate for controlled reasons as well as in seasons of flooding and drought. For this reason, it is important to use canals as an environmental indicator for the purpose of the study.

An equally important indicator is the location of water consumption to the supply wells and the current delineated interface line. As water is withdrawn from the supply wells, a cone of depression forms and creates a negative pressure. This negative pressure promotes the movement of the freshwater and saltwater interface further inland. Proximity to these locations is an environmental indicator used in this study.

Land use is a major component in all forms of planning. In the case of this study, determining which land use consumed the most water, or contributed the most to the demand of water, is important in identifying critical areas. Based on USGS, about 52 percent of groundwater withdraws in Florid in 2005 were for public supply. Followed by agricultural and irrigation uses being around 31 percent (Marella, 2008). By monitoring consumption based on land use, proper conservation measures and water use plans can be modified for each land use contributing to over drafting.

Miami is a major metropolitan area in the southeastern Florida region with a growth rate of 21.9 percent by the year 2020 (Zwick and Carr, 2006). For this reason, residential land use, was considered to be a major contributor to water consumption. Land use was categorized and ranked upon level of consumption and used as an environmental indicator for this study. The map of the categorized land use can be seen in Figure 8.

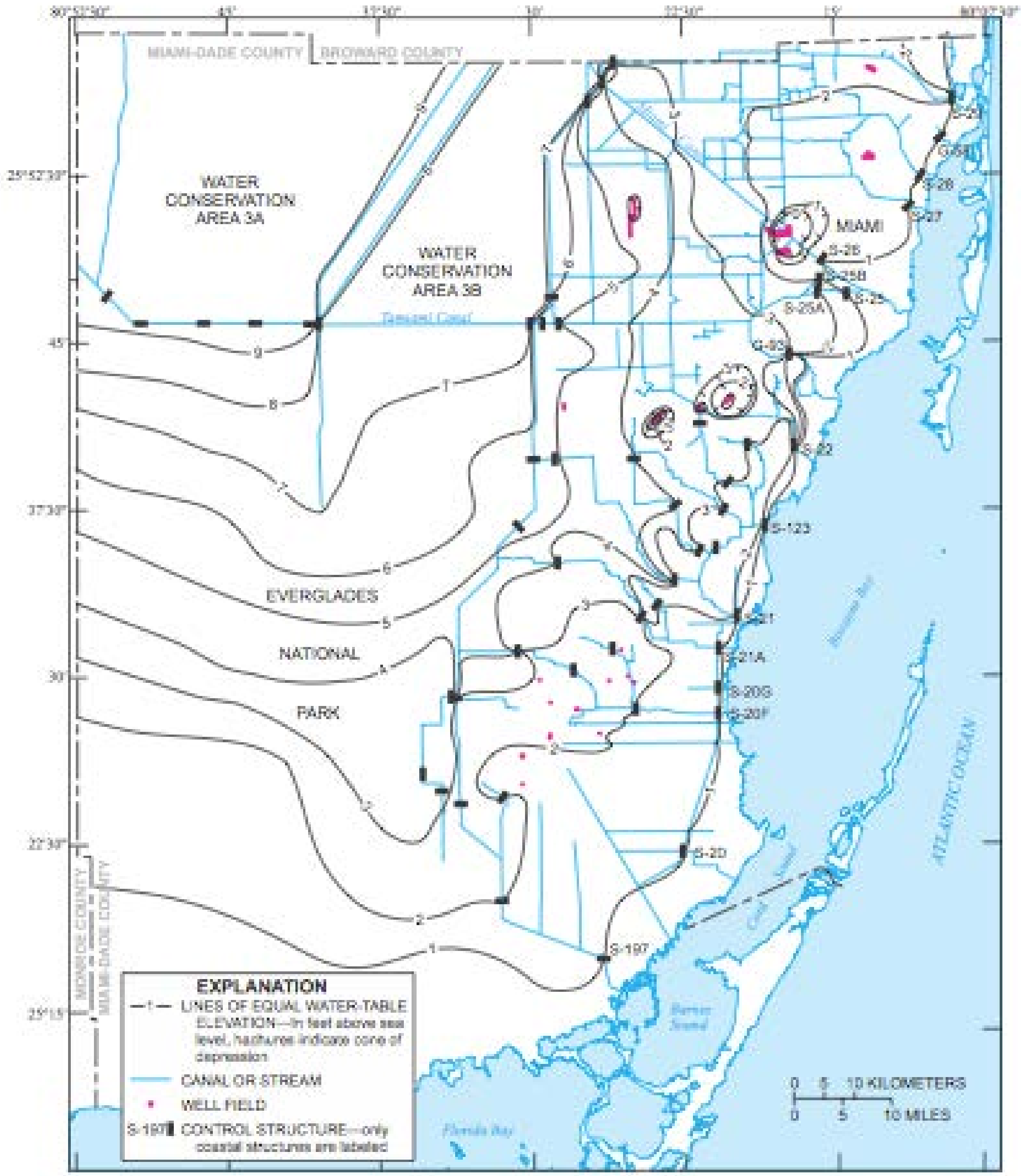


Figure 5: Depth to water in May of 1993 during the dry season (Langevin, 2001).

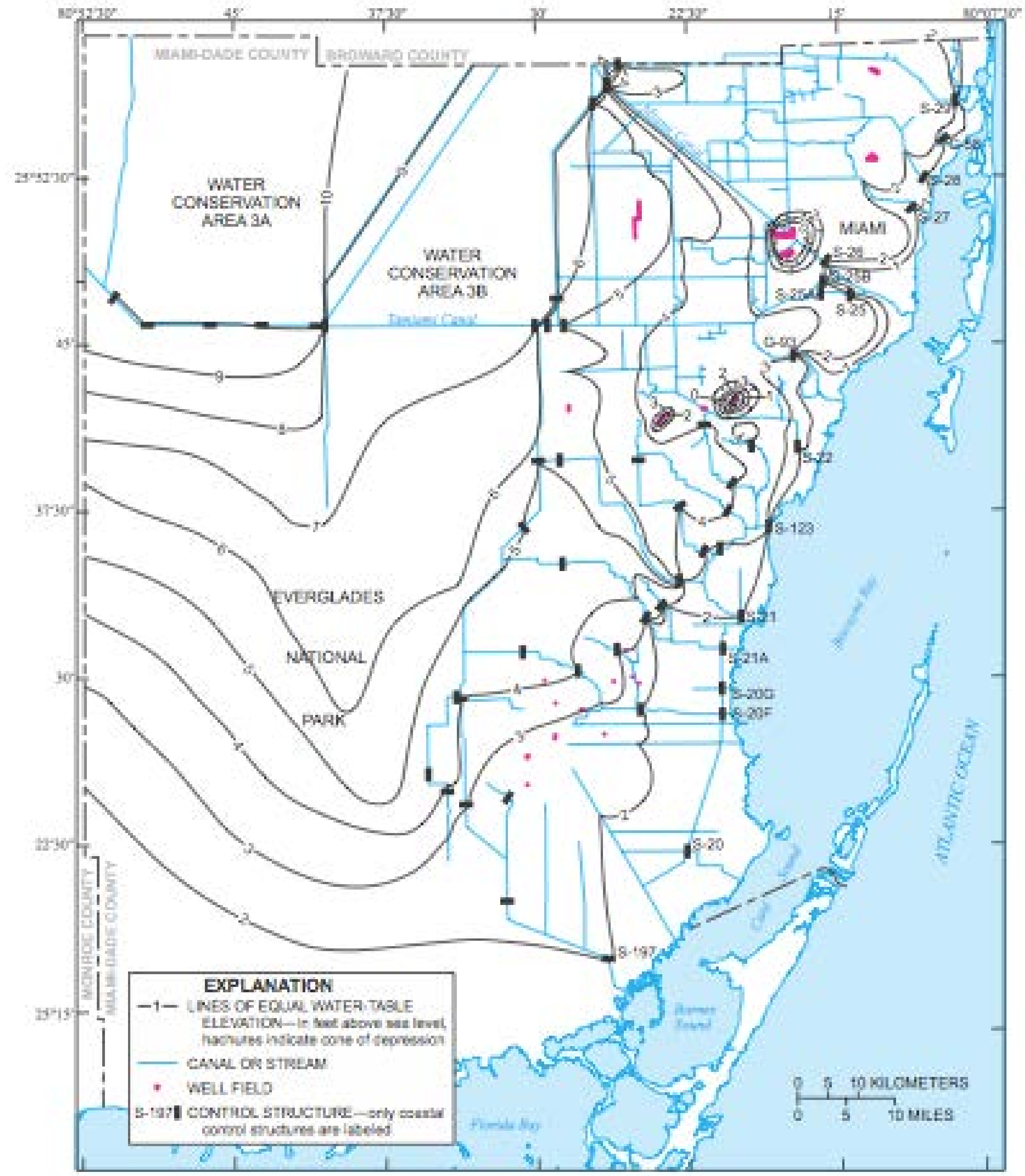


Figure 6: Depth to water in November of 1993 during the wet season (Langevin, 2001).

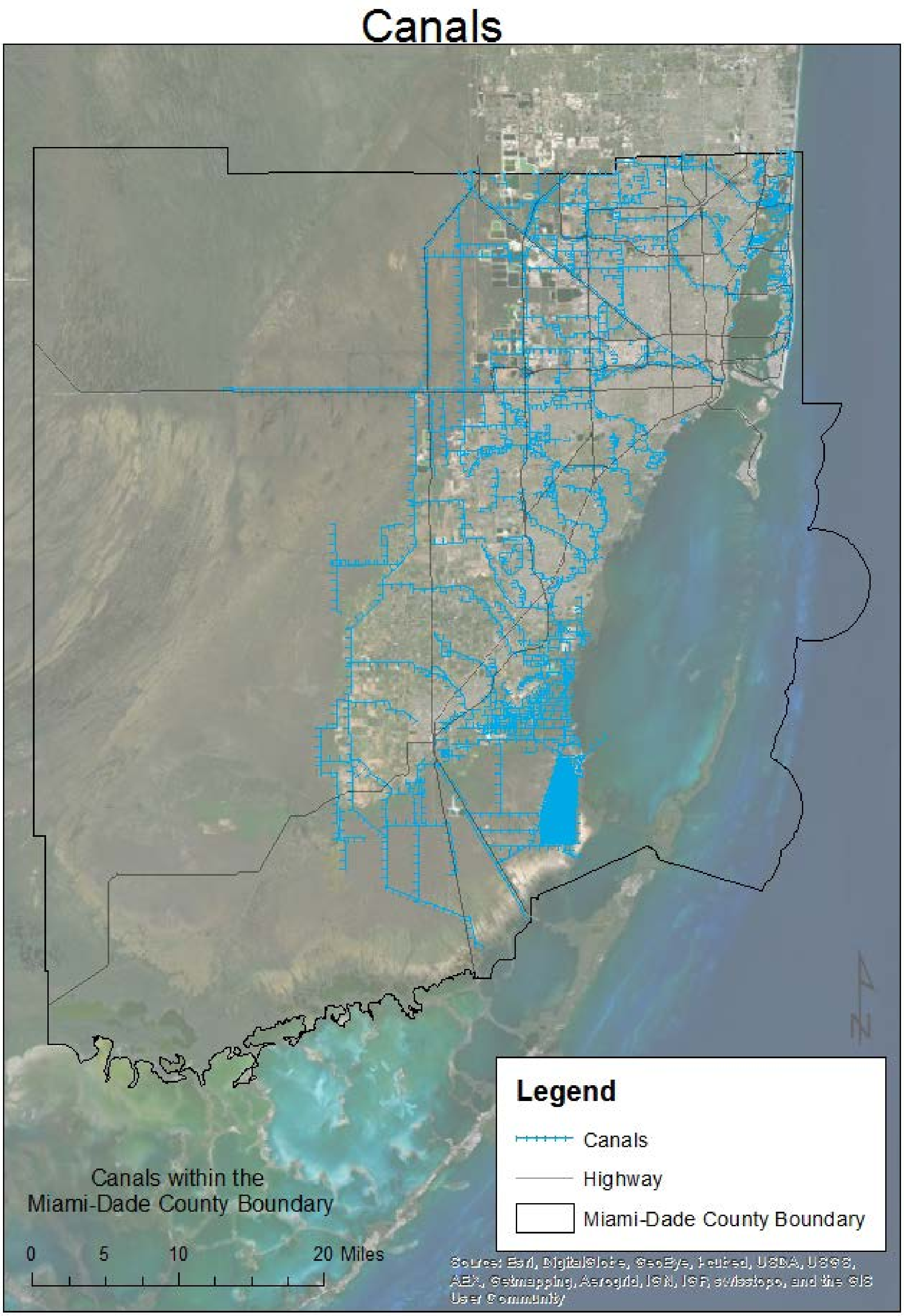


Figure 7: Canals in Miami-Dade County

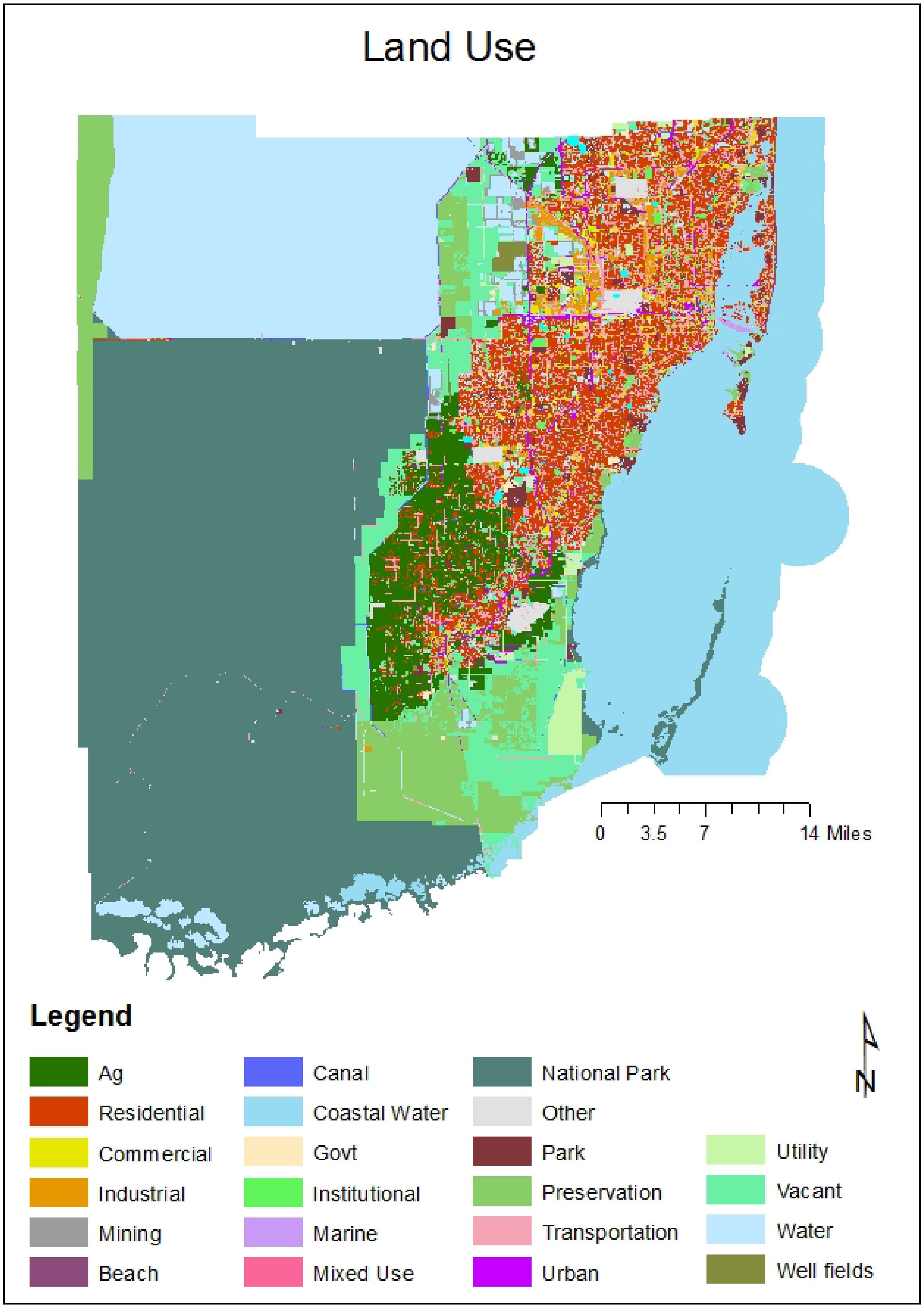


Figure 8: Land Use for Miami-Dade County

CHAPTER 5

METHODOLOGY

With the population growth expected in the future for Miami-Dade County, it is important to look at the impacts with in the county that may lead to the advancement of saltwater intrusion. In order to look at these impacts, first environmental indicators must be developed and used to conduct analysis. Extensive research was conducted to determine which environmental indicators were best to use for the study area in Miami-Dade County. These indicators may differ from region to region. The environmental indicators included in the analysis are based on elevation, depth to water, land use, distance from wells, both private and public, distance from canals, distance from the most recent delineated saltwater intrusion line, and the chloride ion concentration levels of wells.

Data was collected from a variety of sources, and in some cases, were created for the purpose of this study. Elevation levels were collected from remotely sensed LIDAR data from 2007 of Miami-Dade County. Depth to water was downloaded from Florida Department of Environmental Protection, and is also used in the Florida Aquifer Vulnerability Assessment conducted by FDEP for the entire state (Arthur et. al., 2005). The pumping wells were individually mapped based on permitting information from the South Florida Water Management District. This process was time consuming and required creating a new shapefile to add the points marking the pumping well sites. The 2011 delineated saltwater intrusion line used in the analysis was created after a 4-year study by USGS, Miami Dade Water and Sewer, and Miami-Dade County Department of Environmental Resources. This shapefile shows the best estimate of the current saltwater and freshwater interface.

After identifying indicators to use, a ranking system would be used to rank the features coupled with each indicator. For example, urban areas would be ranked as a 5 and a distance within .5-mile from the canals would be ranked a 5 as well. The higher the ranking placed on each individual indicator, the more susceptible in causing saltwater intrusion to occur. This ranking system would go from 1, being the lowest, to 5, being the highest, or most critical. Levels of ranking for each environmental indicator are listed in Table 1. The rankings for each indicator are based on their influence to saltwater intrusion and not in correlation with each other.

Ranking	Land Use	Cl^- Concentration Levels	Combined Distances
5	Residential	14600 mg/L	.50 mile
4	Agricultural	5000 mg/L	1.5 mile
3	Urban/Commercial	1900 mg/L	3 miles
2	Industry/Utility	600 mg/L	6 miles
1	Mining	250 mg/L	12 miles

Table 1: Ranking determinations for each environmental indicator.

These indicators will finally be grouped according to their ranking, using a raster calculator to add the rankings together, in order to determine possible critical areas to be further assessed. By using this form of spatial analysis, spatial relationships can be determined to look at areas where possible over drafting may occur in the Biscayne Aquifer and the possibility of saltwater intrusion to occur.

Data must first be collected and analyzed using ArcMap. A study area then had to be determined so that the analysis would only be focused in the area of interest, which was the area surrounding the city of Miami. Since Miami Dade County is large and contains some of the Everglades, the study area was determined by simply editing the county boundary to exclude the Everglades protected areas as well as other areas that are not a contributing factor to the study. The study area created can be seen in Figure 9 below.

Elevation levels were ranked critical for low-lying areas and areas that are actually below sea level in elevation. The depth to water was derived from elevation so areas were the water in the aquifer is close to the surface was ranked most critical while areas that had the greatest depth to water were ranked the lowest. Since depth to water was derived from elevation, their values and rankings had a high correlation. However they were individually assessed in the end to see the impact each had on determining critical areas.

A major indicator that leads to over drafting in the aquifer are particular types of land uses. Based on research of consumption rates, we determined which land use consumed or resulted in the largest withdraws from the aquifer. These land uses were then ranked according to their consumption of water; 5 for residential land followed by 4 for agricultural land uses, 3 for urban and commercial, then 2 for industrial, and 1 for mining and resource extraction, as seen in Table 1.

To properly rank land uses the most current land use had to be downloaded and then reclassified based on the scope of the project. To get the most current and accurate data, the 2013 land use was used from the Miami-Dade County GIS data database. The data contained multiple differing classes of land use, however we wanted to narrow them down by sub-classifying the existing classification. This process can be very time consuming based on the amount of detail the land use is mapped. However, the more detailed the initial classification the more accurate the classification and ranking will be. After reclassifying the land use, rankings were then added to the sub classes with 5 being the most critical and 1 being the least critical. By ranking the least critical as 1, prevents any non-contributing data from being calculated, as it will be given a value of 0 out of default. The resulting ranking was then rasterized for continued analysis.

Distances were determined by calculating the Euclidian distance from selected indicators. Euclidian distance from canals, current delineated saltwater intrusion line, and pumping wells were calculated. The results produced continuous distances in raster images from the three indicators. The distance could be symbolized on the map base on their distance in feet, however in order to properly rank the distances calculated, they first need to be added together using a raster calculator. Once the three continuous distances were added together, they were reclassified and then ranked based on proximity, with 5 being the closest and 1 being the furthest distance.

The distances from the three features including the canals, pumping wells, and saltwater intrusion line were added together to form a single combined distances map. This map was added to the other indicator maps to create the final image. This process was done due to issues related from adding them individually with the other indicators. When adding each ranked distance individually, the resulting map would appear to be a solid color and missing valuable information. Therefore, the distances needed to be combined and ranked before adding them to the other ranked indicators.

Distances were ranked accordingly; with 5 being within a .5 mile distance, 4 within a 1.5 mile distance, 3 within a 3 mile distance, 2 within a 6 mile difference, and 1 within a 12 mile distance, as seen in Table 1. Distance rankings were based on exponentially increasing distances from the already summed indicators. These distances can be mapped by symbolizing the rankings used in reclassification.

Monitoring wells are located throughout the region to monitor contaminate levels in the groundwater. The wells used in our analysis were clipped to our study area and ranked based on the chloride concentration levels recorded in the wells. Interpolation was initially used to predict groundwater concentration at unmeasured locations. To do this, an Inverse Distance Interpolation (IDW) was used. An IDW interpolation estimates the values, in this case concentration values, at unmeasured areas using the concentration levels taken at the known monitoring well location (Bolstad, 2012). The resulting interpolation produced a raster image, which can be then reclassified according to the determined ranking system with 5 being areas with the highest concentration and 1 being the areas of the lowest concentration.

The values were determined by the standard deviation of values in five classes and are listed in Table 1. A concentration over 250 mg/L is considered to be unsafe for human consumption based on the EPA safe level (EPA, 2013). Brackish water occurs between 500 mg/L and 5000 mg/L (Lehigh Environmental Initiative, 2011). The highest level recorded in the monitoring wells was 14,600 mg/L. A level of 19,400 mg/L is considered to be pure seawater (Lehigh Environmental Initiative, 2011).

The final stage of the analysis uses the raster calculator to add the ranked land use and ranked chloride concentration level interpolation to the already summed distance rasters, along with elevation and depth to water. This will produce a final map image that illustrates the summed rankings from all five indicators, which will illustrate the most critical areas where further saltwater intrusion is most likely to occur. Using a graduated color ramp, an analyst can symbolize the more critical area with the darker end of the color ramp.

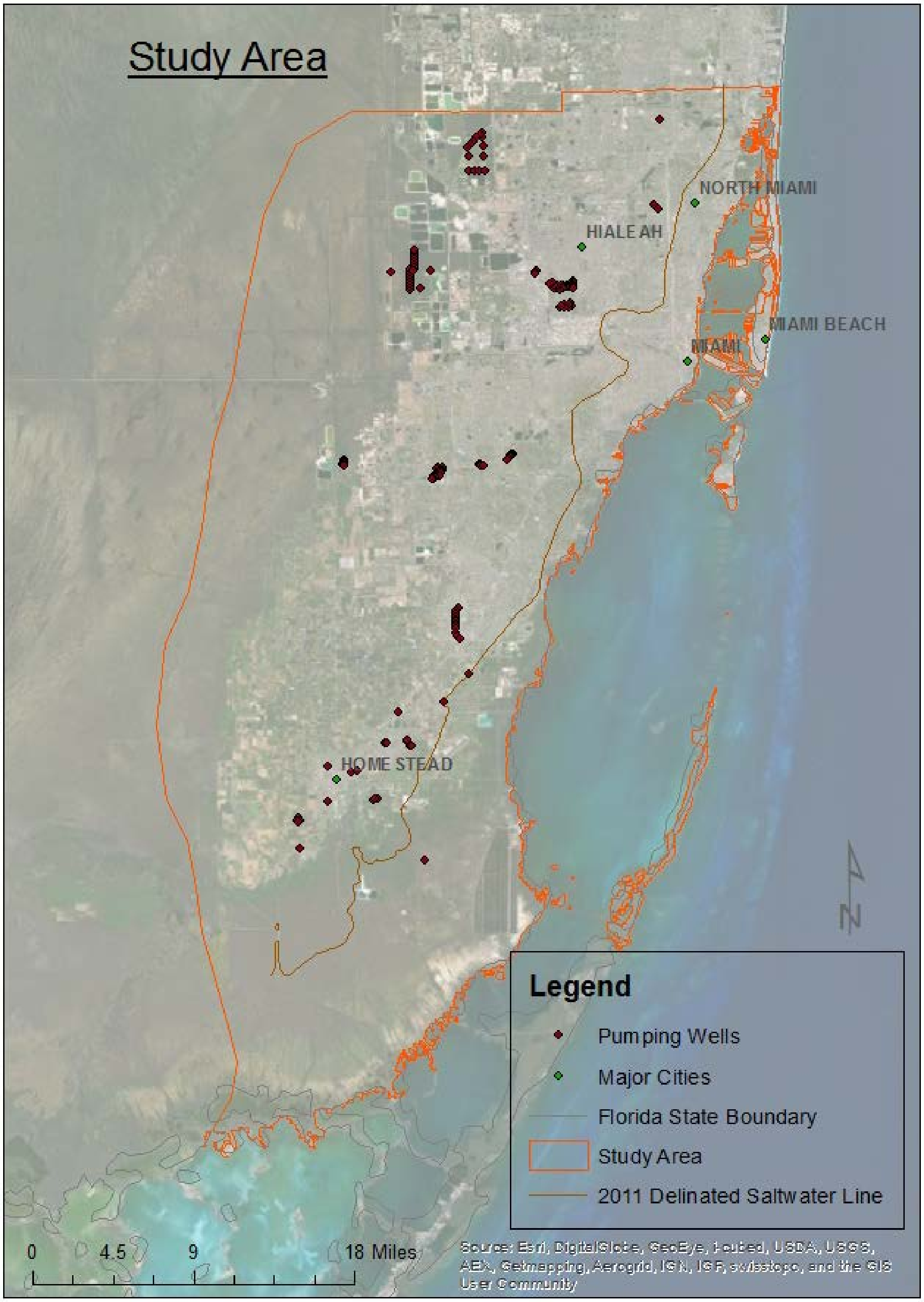


Figure 9: Map of Study Area including location of pumping wells and major cities. The 2011 delineated saltwater and freshwater interface is mapped.

CHAPTER 6

ANALYSIS AND RESULTS

The resulting images illustrate the critical areas by highlighting them as the darker parts of the image. The resulting map was symbolized using a graduated color ramp so that the darker regions illustrate the higher ranked areas as seen if Figure 10. The critical areas identified tended to be associated with high-populated areas as well as along the 2011 delineated saltwater and freshwater interface line. Some of the populated urban areas include Aventura, North Miami Beach, Miami, Miami Shores, and Homestead.

In order to analyze the impact of each environmental indicator used, additional weight was added to each and analyzed. Weights were added by creating a weighted overlay to the image to produce new maps. In each case, 60 percent weight was added to one indicator while only 10 percent weight was added to the other remaining indicators. This weighted percentage was derived from the fact that five indicators were added to the created the final image in Figure 10. When equal weight is given, each indicator would be given 20% weight. In order to show the influence of each indicator in the separate maps, 10% was taken from each indicator and added to the primary indicator being mapped. The impact of the three environmental indicator ranking can be seen in Figure 11.

In Figure 11a and 11b, the correlation between elevation and depth to water can be seen. Areas that are low in elevation are consistent with areas that the aquifer is close to surface. These areas are considered to be most critical, while the areas of high elevation and greater depth to water are ranked lowest. By adding additional weight to concentration values, as seen in Figure 11c, critical areas can be seen in relation to interpolated high concentration areas. Concentration values are mapped along with the rankings of the combined environmental indicators. The critical areas seen here are consistent to those found in the combined distance map. This shows how much impact the saltwater interface and canals have on depicting critical areas of saltwater intrusion.

Figure 11d shows the results of adding additional weight to the combined distance rankings. As mentioned earlier, distance to pumping wells, distance to canals, and distance to the current freshwater and saltwater interface line, were added together then ranked. Critical areas were identified with areas in proximity of the current saltwater and freshwater interface line as well as with the pumping wells.

Figure 11e illustrates the results of adding additional weight to the land use rankings. Land use was initially ranked with residential areas being ranked most critical, followed by agricultural areas. This is still evident in Figure 11e where the most critical areas illustrate densely populated urban areas and agricultural zones.

One critical area that is evident in all resulting images, regardless of the rankings is the dark area in the southeast section of the image. This area has a high concentration of canals due to the location of the Turkey Point Nuclear Generating Plant. When calculating the Euclidian distance from the canals, this area contained a high ranking since the canals were in close proximity to each other. This high concentration of canals can be seen in Figure 11c.

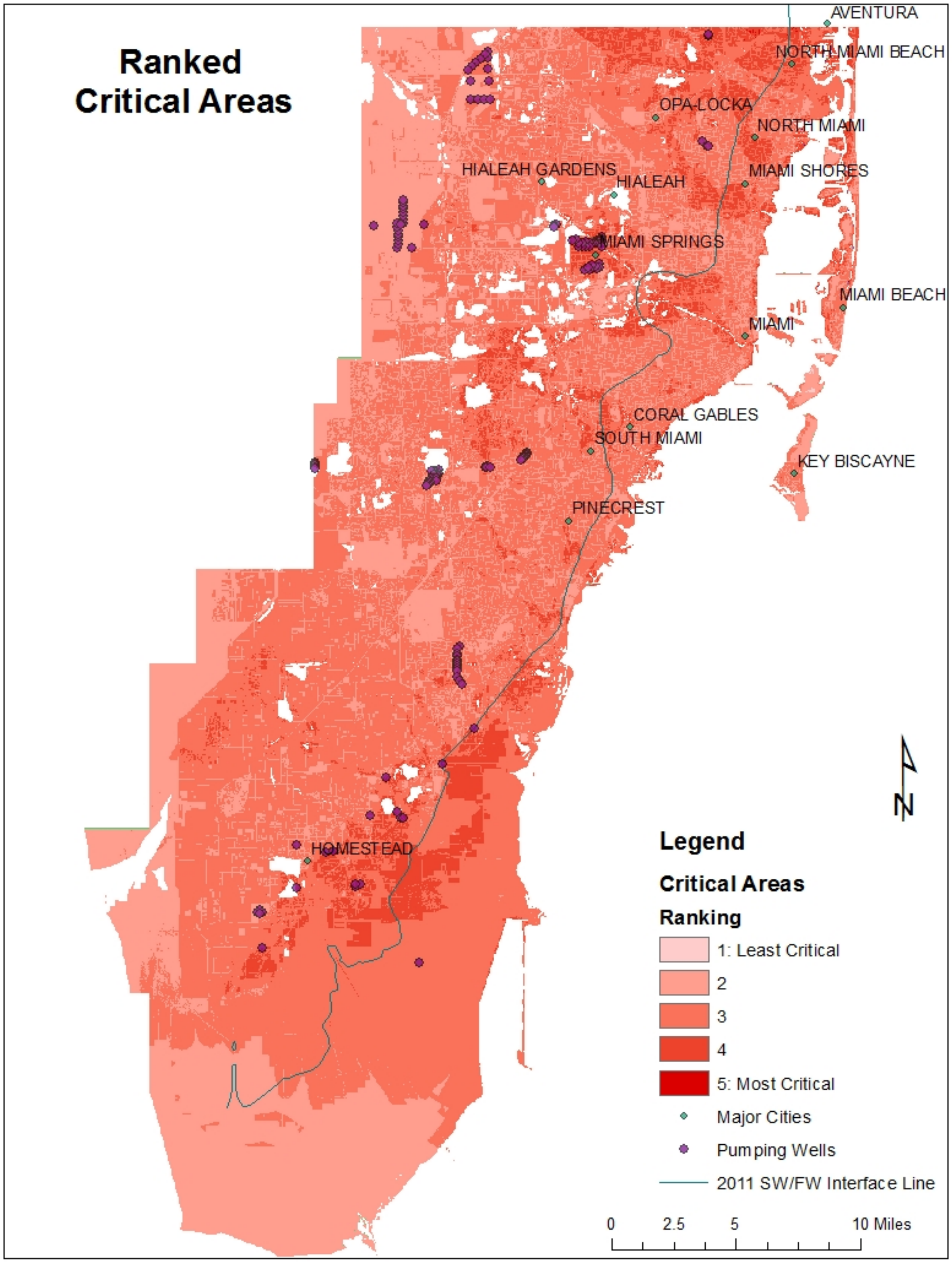
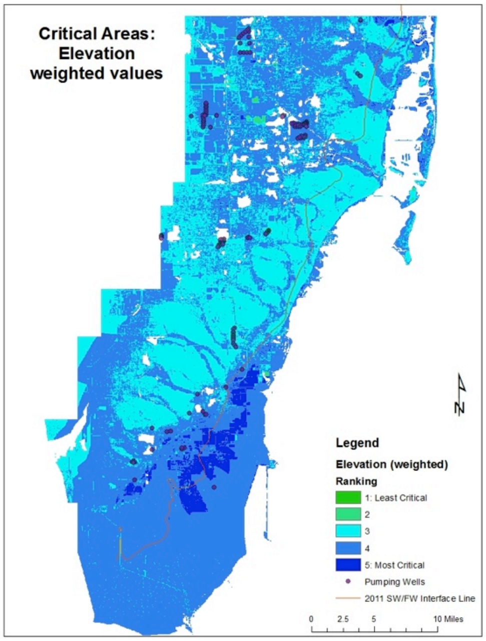
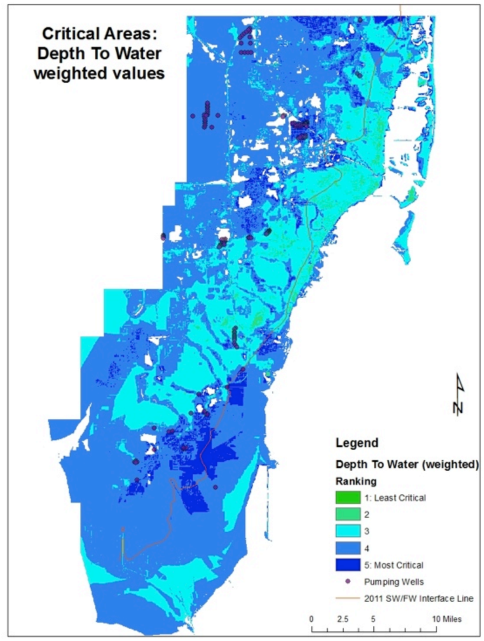


Figure 10: Combined environmental indicators to determine critical areas

a.


b.


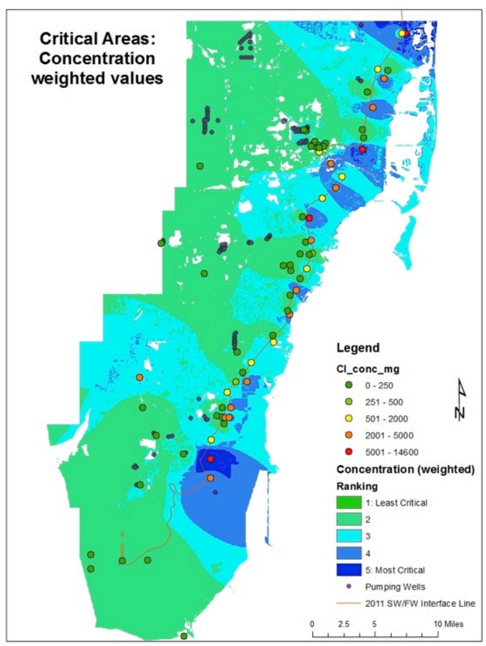
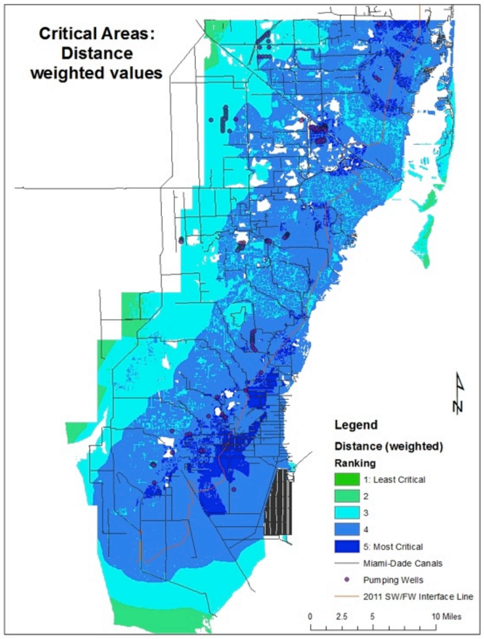
c.


Figure 11a: Map illustrating results from added weight to elevation rankings. **Figure 11b:** Map illustrating results from adding weight to depth to water ranking. **Figure 11c:** Map illustrating results from adding weight to concentration in mg/L rankings.

d. 

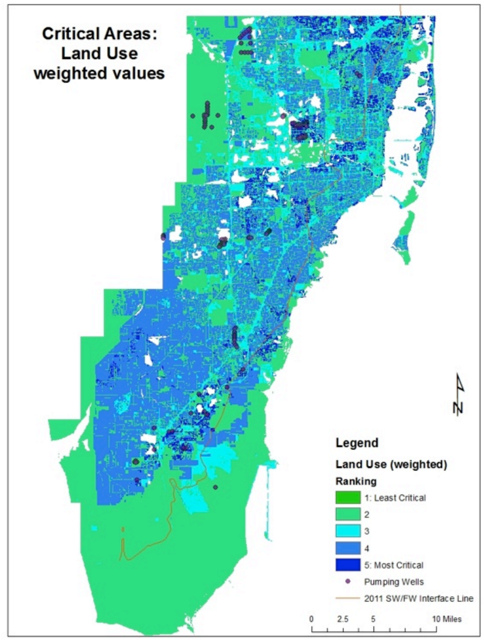
e. 

Figure 11d: Map illustrating results from adding weight to combined distance rankings.
Figure 11e: Map illustrating results from adding weight to land use rankings.

CHAPTER 7

LIMITATIONS AND FUTURE CONSIDERATIONS

This study uses a variety of indicators to create a spatial analysis that results in determining critical areas where over drafting is most likely to occur which leads to further saltwater intrusion in the Biscayne Aquifer. As previously discussed, these indicators include land use, chloride concentration values from the monitoring wells, elevation, depth to water, and distance from pumping wells, canals, and 2011 delineated saltwater intrusion line. With the study area being large, and since research was conducted remotely, an analyst has to rely on the most current published data.

Another major limitation to this project was the time line. With the amount of information, and the complexity of the models generated, a great deal of time should be allotted to the analysis. This can be difficult to achieve when other factors and commitments are present. Research had to be conducted on a variety of contributing factors that lead to saltwater intrusion, as well as the study area itself. Once the indicators to be used were determined, a ranking system had to be created for each indicator to be used in the analysis.

Determining the ranking scale for each can be daunting due to the limited amount of information regarding degrees of impact for each indicator chosen. In some cases, rankings were based off of natural breaks found in the histogram of raster images of individual indicators. This type of classification, although provides less consistent information for each ranking, does allow for the mode of different values to be used in the final analysis, and prevent any exclusion of important information. This classification was used for elevation and depth to water.

When other definite classifications were used, data appeared to be missing in the initial ranking images. In the case of elevation and depth to water, extreme values such as peaks and low areas were given more weight and the more subtle changes in elevation and levels were not factored. This could be due to the relatively flat terrain of the study area. This information is important to determine critical areas, since most of the south Florida region is relatively flat with very little changes in topography.

This is also true for indicators used in other vulnerability models, such as the DRASTIC model. These models are used to determine the vulnerability of aquifers to potential contamination. The DRASTIC model was created by the EPA as a standardized system for evaluating ground water pollution potential in aquifers (EPA, 1987). The model uses indicators including Depth to water, Recharge, Aquifer media, Soil, Topography, Impact to the vadose zone, and Conductivity to determine vulnerable areas of contaminations in the aquifer (Arthur et. al., 2005).

The DRASTIC model was developed with assumptions that the contaminant is introduced at the ground surface, the contaminant is flushed into the ground water by precipitation, the contaminant has the mobility of water, and the area is over 100 acres (EPA, 1987). Based on these assumptions, this model is not the best to use in the case of saltwater intrusion, since the contaminant is not introduced from the surface and is not flushed into the system from precipitation. The model also does not take in to consideration land use or current contamination levels of the aquifer. It also does not take in to account features such as canals and pumping wells, which play a role in water consumption.

The main reason the Biscayne Aquifer is vulnerable to saltwater intrusion is from over drafting, or over use of the freshwater. The DRASTIC does not show results from over drafting, but does show other environmental considerations. The purpose of this study was to determine critical areas where over drafting is most likely to occur, which is why this model was designed.

Future research on the use of this method to identify critical areas of over drafting may include, using alternative methods of data collection to achieve differing results, and incorporating other indicators such as soil. Instead of using IDW to interpolate concentration values, interpolation could be done using kriging methods. By using kriging instead of IDW, the analyst can choose to add weights to different values, thus possibly achieving differing, or more predictable, results.

Analyst can also experiment with different weights for each indicator in the production of the final map. In this study, the final map was created by assuming that all indicators had a similar impact on in determining critical areas, thus were given similar weight. Additional maps were also created by adding additional weights to each indicator in order to illustrate the influence each indicator had in determining critical areas.

The indicators chosen in this analysis are not the only environmental indicators of saltwater intrusion. Analyst can add other indicators into the model to see the influence that they have in predicting critical areas. Indicators such as soil characteristics may be considered since it affects recharge rates. In south Florida, the aquifer is very close to the surface and the soil characteristics are similar across the study area. This may be the case in other coastal regions where this method may be used.

This model was created based on research of influencing factors that lead to over drafting of the Biscayne Aquifer in Miami Dade County. In other coastal regions, different indicators may be implemented in to the model as well as the amount of influence these factors have on causing saltwater intrusion to occur. Models should be developed based on the environmental factors and impacts of each region being mapped.

CHAPTER 8

CONCLUSION

Saltwater intrusion is an ever-growing problem in coastal regions and coastal cities, such as Miami. As populations begin to increase, it is important that planners work to ensure a sustainable fresh water resource for future generations. By the year 2020, the Miami population is expected to grow by 21.9% (Zwick and Carr, 2006). Residential land use was ranked as the most critical land use for consumption from the Biscayne Aquifer, and the expected growth in population is only making this matter worse.

The south Florida region is also affected by wet and dry seasons that semi-annually affect the water levels in the aquifer. As the water level fluctuates, water consumption can remain constant resulting in creating a deeper cone of depression around the pumping wells allowing saltwater to further intrude. Proper water management can help to maintain the water levels during the two seasons. Not all regions, however, can manage depth to water fluctuations with canals, thus proper planning must be implemented to insure the coastal populations with a sustaining supply of fresh, drinking water.

By identifying and mapping critical areas based on contributing environmental factors, planners and government agencies can identify which areas of the county where over drafting is most likely to occur. The resulting maps created help identify these areas of concern, as well as the amount of influence each indicator contributed to this environmental issue. With this knowledge, water use plans can be put in place in these areas to reduce the overall demand and preventing the current saltwater and freshwater interface from moving further inland. This is important tool that could be implemented in other coastal cities as well.

Monitoring wells are important in these regions for monitoring the overall health of the groundwater aquifer, and freshwater supplies. In the Biscayne Aquifer, the wells showed a positive or negative correlation between the mean sea level and their chloride concentrations according to their proximity to the current saltwater and freshwater interface (Blanco, et. al, 2013). Cities such as Miami depend on the Biscayne Aquifer for their freshwater supply. For this reason monitoring the health of the Biscayne Aquifer is an important part of conserving this vital resource.

There are other alternatives, mentioned by Wiedenman, which could be possible for Miami-Dade County to consider. These alternatives, however, have there own impacts on the environment as well as cost to the population. Using spatial modeling in GIS, planners can work to sustain the current freshwater source for Miami, and further prevent saltwater intrusion. With proper planning, in the mapped critical areas, the amount of over drafting could be mitigated and thus keep the freshwater level high enough in the Biscayne Aquifer where the saltwater and freshwater interface stays in its current location or even reversed.

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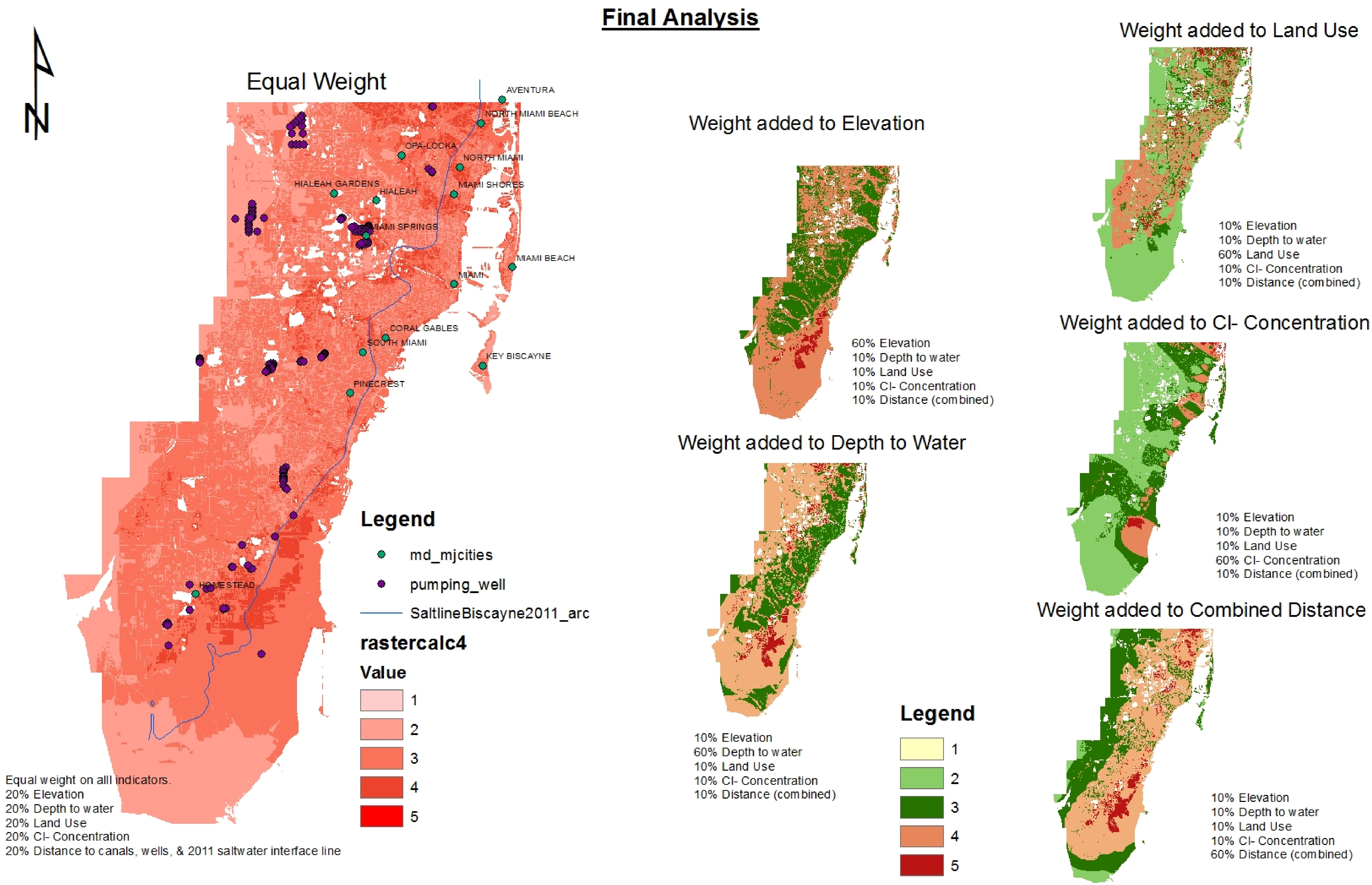

Final Analysis
N
Equal Weight
AVENTURA
NORTH MIAMI BEACH
OPA-LOCKA
NORTH MIAMI
HIALEAH GARDENS
HIALEAH
MIAMI SHORES
MIAMI SPRINGS
MIAMI BEACH
MIAMI
CORAL GABLES
SOUTH MIAMI
KEY BISCAYNE
PINECREST
HOMESTEAD
Legend
md_mjcities
pumping_well
SaltlineBiscayne2011_arc
rastercalc4
Value
1
2
3
4
5
Equal weight on alll indicators.
20% Elevation
20% Depth to water
20% Land Use
20% Cl- Concentration
20% Distance to canals, wells, & 2011 saltwater interface line
Weight added to Elevation
60% Elevation
10% Depth to water
10% Land Use
10% Cl- Concentration
10% Distance (combined)
Weight added to Depth to Water
10% Elevation
60% Depth to water
10% Land Use
10% Cl- Concentration
10% Distance (combined)
Legend
1
2
3
4
5
Weight added to Land Use
10% Elevation
10% Depth to water
60% Land Use
10% Cl- Concentration
10% Distance (combined)
Weight added to Cl- Concentration
10% Elevation
10% Depth to water
10% Land Use
60% Cl- Concentration
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Weight added to Combined Distance
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60% Distance (combined)