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Application of the Method of Galdit for Groundwater Vulnerability Assessment: A Case of South Florida

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ABSTRACT

Saltwater intrusion is a growing concern for many coastal regions in Florida. Groundwater pumping in Florida has increased over the past years in order to meet the demand for fresh drinking water. Groundwater pumping is reducing freshwater flow toward coastal discharge areas and drawing saltwater toward the freshwater zones of the aquifer. In order to better prepare and mitigate the effects of saltwater intrusion, saltwater intrusion vulnerability maps can be created to indicate areas that may be highly susceptible. The creation of a saltwater vulnerability map, through application of the GALDIT method, allowed us to identify areas that are highly vulnerable to saltwater intrusion. The six factors incorporated into assessing saltwater intrusion vulnerability (groundwater occurrence, aquifer hydraulic conductivity, depth to groundwater level, distance from shore, impact of existing seawater intrusion, and aquifer thickness) allow us to numerically rank and map areas of low to very high vulnerability. The final vulnerability map clearly identified the south eastern portion of Florida as the most vulnerable region in Florida which includes the Miami-dade, Broward, palm beach areas. Strategies need to be defined to manage the long term sustainability of the ground water underneath these critical areas.

Key Words: GALDIT method, salinity intrusion, ground water, hydraulic conductivity

Source of Support: None, **No Conflict of Interest:** Declared

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INTRODUCTION

Saltwater intrusion is a growing concern in many of Florida's coastal regions. Under normal conditions, the saltwater is prevented to move towards seaward by the fresh ground water from encroaching coastal aquifers and thus near the coast or far below the interface between freshwater and saltwater is maintained. The interface between freshwater and saltwater is a diffuse zone in which freshwater and saltwater mix, and it is referred as dispersion zone (Barlow, 2013). Groundwater pumping in Florida has increased over the past years to meet the growing demand for fresh drinking water. Groundwater pumping can reduce freshwater flow toward coastal discharge areas and can draw saltwater toward the freshwater zones of the aquifer. Freshwater storage in the aquifers decreases due to saltwater intrusion and for extreme cases can cause abundance.

There are three different ways of saltwater intrusion. The first type of saltwater intrusion is the most common and in this type the fresh inland ground water is pushed back by the saline water. Excessive freshwater pumping causes the horizontal intrusion which lowers the aquifer piezometric head and allows for saltwater to creep in. The freshwater moves down toward the wellhead and allowing saltwater to rush in during drawdown. The saltwater is pulled in to replace the freshwater. The second type of saltwater intrusion occurs when drainage canals are dug with no salinity control structures. Florida is low, flat topographical region and the high water table, land cleared for development must be drained via canals. These canals must have control structures, such as dams. If not, then water will flow unimpeded until the surrounding groundwater levels are lowered to those of the canals. As the groundwater level is lowered tidal seawater can move further inland though these canals and penetrate into the groundwater. The third type of saltwater intrusion involves leftovers of seawater from when thousands of years ago South Florida was submerged. All the saltwater was not flushed out when the oceans receded and some quantity is still present in the surficial aquifer system. This form of saltwater contamination is known as Connate Sea Water (Terrazas, 2000).

In order to better prepare and mitigate the negative effects of saltwater intrusion, saltwater intrusion vulnerability maps can be created to indicate areas that may be highly susceptible. The focus of this research is on applying the GALDIT method to access saltwater intrusion vulnerability in regions of Florida. The most important factors controlling saltwater intrusion are groundwater occurrence (aquifer type; unconfined, confined, and leaky confined), aquifer hydraulic conductivity, depth to groundwater level above the sea, distance from the shore, impact of existing status of saltwater intrusion, and thickness of the aquifer. The acronym GALDIT is formed from the highlighted letters of the parameters previously stated (Ferreira et al., 2005). A numerical ranking system to assess saltwater intrusion in hydro geological settings has been done using GALDIT factors. The three significant parts of this system are weights, ranges, and ratings. Each GALDIT factor has been evaluated with respect to the other to determine the relative importance of each factor (Ferreira et al., 2005). The basic hypothesis made in the development of the model is that the bottom of the aquifer lies below the mean sea level (MSL).

Indicator weights depict the relative importance of the indicator to the process of saltwater intrusion. After identifying the indicators, they were weighed in the order of importance for saltwater intrusion. The most significant factors have weights of 4 and the least a weight of 1 indicating parameter of less significance to saltwater intrusion. Assigning of importance rates to indicator variables uses a scale of 2.5 to 10. Each of the indicators has some variables according to the specified attributes to determine the relative significance of the variable in question for saltwater intrusion. The higher the importance rating indicates higher vulnerability to saltwater intrusion (Ferreira et al., 2005). The following sections describe the methodology and application of the GALDIT method to create a saltwater intrusion vulnerability map for Florida.

METHODOLOGY

Analytical Procedure to Vulnerability Map Generation

To generate the salt water intrusion vulnerability map in selected portion of Florida region, a six step procedure was followed using the GALDIT method (Fig. 1).

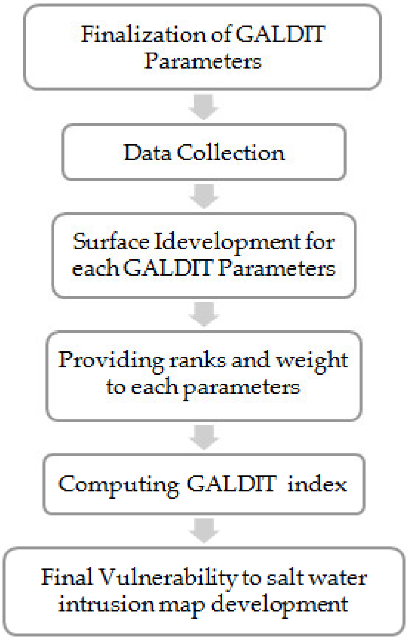


Fig. 1: Flow chart of methodology

Step 1: Finalization of GALDIT Parameters: The same parameters which Chachadi and Loboferreira (2001) used were kept in the present study without inclusion or deletion of any parameters. Identification of all the indicators was done through extensive discussions and consultations with the experts, academicians etc (Chachadi and Loboferreira, 2001). Therefore, under normal circumstance, present set of indicators should not be deleted. Because any addition of the indicators would require re-deriving of the weights and the classification of vulnerability.

Step 2: Data Collection on Each GALDIT Parameters: Data on six GALDIT method parameters were collected from different sources. The data of aquifers type was obtained from the website of Florida Department of Environment Protection (FDEP). The data was stored in vector format (in shape-file) which was used later to code according to saltwater vulnerability criteria. The aquifer hydraulic conductivity data was collected from a cartographic map from the United States Geological Survey (USGS). There may be more data on hydraulic conductivity that could be collected from lithological logs, but due to time limitation issues, the present study used the data from the cartographic map of Florida region. Ground-water level data with respect to MSL was obtained from USGS observation wells in Florida. Since, the well depth was measured from a national datum, NAVD88, we collected additional information from National Oceanic and Atmospheric Administration (NOAA) of tidal benchmark which corrected the height from MSL. Data for "distance from shoreline" was obtained from National Oceanic and Atmospheric Administration (NOAA) and it was stored in vector file format. The information required for the parameter "Impact magnitude of the existing seawater intrusion in the area" was gathered from historical reports and chemical analysis data from USGS website. There were 384 wells which had the chlorine concentration information and seventy nine (79) wells which had bicarbonate concentration information. Therefore, we interpolate the 79 points to 384 points to compute the parameter, "Impact magnitude of the existing seawater intrusion in the area" for 384 points. Aquifer thickness data was also collected from a cartographic map from the United States Geological Survey (USGS). There may be more point based aquifer thickness data that could be collected from lithological logs, but due to time limitation issues, the present study used the cartographic map of Florida region.

Step 3: Continuous Surface Development for Six GALDIT Parameters: Two of the GALDIT parameters, "height of ground water level from MSL" and "impact magnitude of the existing seawater intrusion in the area", had point based information such as elevation at well locations and chloride and hydro-carbon ion concentration at well locations. We used empirical "inverse distance method" to develop the continuous surface for these two parameters using the collected point based elevation and concentration information. For another parameter "aquifer media", the data was collected in vector format which gave the advantage to recode directly the vector file according to salinity intrusion vulnerability criteria and develop the surface for the parameter. Two other parameters "aquifer thickness" and "aquifer hydraulic conductivity", we developed raster based surface using ARCGIS digitization method using the cartographic map provided by USGS. For the final and sixth parameter "distance from shoreline", we developed continuous vulnerability surface using ARCGIS distance operator where we set the vulnerability according to the distance from shoreline.

Step 4: Providing Ranks and Weight to Each Parameters Using Map Algebra: Indicator weight is necessary to count the importance of each indicator towards seawater intrusion process. The weights were identified by a group of people consisting of environmentalists, Geologists, in house experts and hydro geologists. The feedbacks from all personnel were analyzed jointly and the final indicators weights were prepared (Table 1). "Height of ground water above sea level" and "Distance from the shore" is the most significant indicators which got weights of 4 and the lowest weight was 1 in a five- point scale pointing to less significance in the seawater intrusion process.

Table 1: GALDIT Indicator weights

Factors	**Weight**
1. Ground water occurrence	1
2. Aquifer hydraulic conductivity	3
3. Height of ground water level above sea level	4
4. Distance from the shore	4
5. Impact of existing status of seawater intrusion	1
6. Thickness of aquifer being mapped	2

Source: Adapted from Chachadi and Lobo Ferreira, 2001.

After proving weight, variables were assigned importance rates using a scale of 2.5 to 10. There are four (4) categories for each indicators and rates were given according to the relative significance of the variable in the seawater intrusion process (Table 2 for thorough rates to indicator variables).

Table 2: Ratings for GALDIT parameters

Parameters	Indicator variables		Importance Ratings
	Class	Range	
Groundwater occurrence/Aquifer type (G)	Confined Aquifer		10
	Unconfined Aquifer		7.5
	Leaky Confined Aquifer		5
	Bounded Aquifer		2.5
Aquifer Hydraulic Conductivity (A) (m3/day)	High	>40	10
	Medium	10 to 40	7.5
	Low	5 to 10	5
	Very Low	<5	2.5
Height of ground water level above MSL (L) (m)	High	<1.0	10
	Medium	1.0-1.5	7.5
	Low	1.5-2.0	5
	Very low	>2.0	2.5
Disatnce from shore/ high tide (D) (m)	Very small	<500	10
	Small	500-700	7.5
	Medium	750-1000	5
	Far	>1000	2.5
Impact status of existing seawater intrusion (I)	High	> 2.0	10
	Medium	1.5-2.0	7.5
	Low	1-1.5	5
	Very low	<1	2.5
Aquifer thickness (saturated) (T) (m)	Large	> 10	10
	Medium	7.5-10	7.5
	Small	5-7.5	5
	Very small	<5	2.5

Source: Adapted from Chachadi and Lobo-Ferreira, 2001

Step 5: Computing the GALDIT Index: At that point, each of the six indicators got a fixed weight which reflects its importance to the process of seawater intrusion. Next, the GALDIT Index was obtained by evaluating each indicator scores and summing them as per the following expression:

$$\text{GALDIT Index} = \sum_{i=1}^{6}\{(\text{Wi})Rj\}/\sum_{i=1}^{6} Wi \quad (1)$$

Where W_i is the weight and R_i are the importance rating of the ith indicator.

Step 6: Final Decision Criteria of Vulnerability to Salt Water Intrusion: By multiplying the values of importance ratings with the corresponding indicator weight we get the total sum of the individual indicator scores and on basis of this result the final decision is taken. The most salinity intrusion vulnerable aquifers referred to higher importance ratings for a variable. Once the GALDIT-Index has been calculated, it is possible to classify the area into various categories of seawater intrusion vulnerability. The ranges of the minimum and maximum GALDIT-Index scores started from 2.5 to 10 and was sub-divided into three groups (see Table 3). All the six indicators have 2, 5, 7.5, and 10 as their importance ratings.

Table 3: Vulnerability Classes of final GALDIT index

GALDIT Index Range	Vulnerability Classes
>=7.5	Very High Vulnerability
5 to 7.5	High Vulnerability
5 to 2.5	Moderate Vulnerability
<2	Low Vulnerability

Source: Adapted from Chachadi and Lobo-Ferreira, 2001

GALDIT Indicator Descriptions

Following is a description of all the six individual GALDIT parameters for our case study.

Groundwater Occurrence (Aquifer Type): In nature, groundwater exists in geological layers, which may be unconfined, confined, and leaky confined or limited by several boundaries. The extent of saltwater intrusion depends on this original nature of aquifer media. For example, a confined aquifer would be less affected by seawater intrusion comparing to an unconfined aquifer since confined aquifer holds more pressure in addition to atmospheric pressure. Similarly, a confined aquifer may be more vulnerable towards saltwater intrusion comparing to a leaky confined aquifer. Because, leaky confined aquifers maintain minimum hydraulic pressure from leakages of adjoining aquifers. Therefore, in assigning the relative weights to aquifer media, it requires careful understanding about the type of the aquifers in the study area. Again, confined aquifer is more prone to salt water intrusion due to the instantaneous release of water to wells during pumping and also the larger cone of depression further adds the vulnerability. If multiple aquifers are present in an area, the highest rating can be adopted. For example, the rating of 10 may be chosen if an area has all the three aquifer. (Chachadi et al., 2007).

Aquifer Hydraulic Conductivity: Aquifer hydraulic conductivity is a representative parameter to measure the rate of flow of water in the aquifer (Chachadi et al., 2007). The aquifer hydraulic conductivity is the ability to transmit water. The hydraulic conductivity is the result of effective porosity in the sediments and fractures in the consolidated rocks. The hydraulic conductivity of the aquifer influences the magnitude of seawater forward movement. The higher the conductivity, the more the seawater fronts inland movement. During well pumping, the high conductivity also results in wider cone of depression. In this case, the researcher need to take account for the hydraulic barriers like impervious dikes parallel to the coast and clay layers which may act as walls to seawater intrusion (Chachadi et al., 2007). The ratings for the GALDIT parameter A, are described in Table 2 and are modified from ALLER et al (1987).

The Level of Groundwater: The level of groundwater with respect to mean sea elevation is the most important factor of the seawater intrusion evolution in an area (Chachadi et al., 2007). Because the level determines the hydraulic pressure available to push back the seawater front. The ratings adopted for the parameter, L were described in Table 2.

Distance From the Shore: The impact of seawater intrusion reduces as one move inland at right angles from the shore (Chachadi et al., 2007). Close to the coast, we can get the maximum impact. Table 2 provides the general guidelines for rating of the GALDIT parameter D assuming the aquifer is under unrest conditions.

Impact of Existing Status of Seawater Intrusion: The study area has a potential to be under stress which can already modify the natural hydraulic balance between seawater and fresh groundwater. Therefore, this factor needs to be considered while mapping the aquifer vulnerability to seawater intrusion. Chachadi and Lobo-Ferreira (2001) recommended the ratio of Cl^{-} / [$HCO3^{-1}$ + $CO3^{2-}$] as an alternative criterion to evaluate seawater intrusion in a coastal aquifer. Chloride ion dominates in the seawater but available in small in groundwater. Bicarbonate is available in large quantities in groundwater but occurs in small quantities in seawater. This ratio can be used to assign the rating for the GALDIT parameter I. for the study area though chloride data was available for 384 well points.But the concentration information for bicarbonate was available for only 79 well locations. We interpolated data of 79 well points to 384 to compute the parameter in 384 points. Table 2 gave the ratings for a parameter, I.

Thickness of Aquifer Being Mapped: In determining the extent and magnitude of seawater intrusion in the coastal areas, aquifer thickness or saturated thickness of an unconfined aquifer plays an important role (Chachadi et al., 2007). The larger the aquifer thickness, the larger the extent of seawater intrusion and vice versa. Based on this understanding, table 2 supplements the ratings for various ranges of aquifer thickness.

RESULTS AND DISCUSSIONS

Identification of Critical Areas for Saltwater Intrusion

We applied the GALDIT method in Florida starting from South Florida up to Central Florida. We computed the vulnerability up to Central Florida because we could not collect information on sufficient numbers for wells in North Florida. Hence, the GALDIT scores for each of the six parameters were computed separately. Some of the findings from each of the six GALDIT parameter layers are the following.

- Biscayne aquifer got a rating of 7.5 since it was an unconfined aquifer, surficial Aquifer got a score of 7.5 since it was unconfined aquifer, Floridian aquifer system got a score of 5 since it was confined aquifer, Sand and Gravel got a score of 7.5 since it was unconfined aquifer and Intermediate confined aquifer got a 2.5 rating because it was a bounded aquifer. When we coded the aquifer media in 4 point scale, our study area was under three vulnerability region: high, moderate and low vulnerability (See Appendix: Figure 5 a and b).
- The hydraulic conductivity of the study area ranges from 10-7 to 1 centimeter per second. Therefore, the study area was classified into 4 classes of vulnerability- very high, high, moderate and low vulnerability (See Appendix: Figure 6 a and b).
- Depths above mean sea level of the study area ranges from -1 to 9 meters from MSL. Therefore, the study area was classified in 4 classes of vunerability- very high, high, moderate and low vulnerability (See Appendix: Figure 7 a and b).
- Distance from the coastline was classified in 4 classes of vulnerability. The criteria (see table 2) was very high if distance from shoreline <500 meters. The criteria is high if distance from shoreline ranges from 500-700 meters. The criteria is moderate if distance from shoreline ranges from 750-1000 meters. The criteria is less if distance from shoreline >1000 meters. Our study area was divided in- very high, high , moderate and low vulnerability (See Appendix: Figure 8 a and b).
- Impact of existing ground water intrusion has been computed in EPM and based on the criteria mentioned in Table 2, if the ratio between two parameters > 2.0, the area is very high vulnerable. If the ratio between two parameters ranges from 1.5-2.0, the area

is high vulnerable. If the ratio between two parameters ranges from 1.0-1.5, the area is moderate vulnerable.If ratio <1, the area is less vulnerable (Table 2). Our study area was divided in- very high, high, moderate and low vulnerability (See Appendix: Figure 9 a and b).

- In terms of thickness of aquifer, the value was very high in Florida and therefore all the study area was considered as very high vulnerable in terms of aquifer thickness (See Appendix: Figure 10 a and b).

Since we computed the GALDIT scores separately for all the six GALDIT parameters, we applied a final vulnerability equation (1) in all those six parameter layers, and produced a final salt water intrusion vulnerability map on a 4-point scale. In that measurement, the area was a very high vulnerable area which got score more than 7.5, and the area which got the score less than 2.5 was considered as the low vulnerable area to salt water intrusion. The final map clearly indicates that the south-eastern portion, some part of the south western part and west central part of Florida are most vulnerable to saltwater intrusion. The vulnerability is encroaching to central parts including Orange county, Osceola county, Seminole county. The mentioned counties and several others are under high vulnerable zone and require more research to prevent them from becoming highly vulnerable to salt water intrusion.

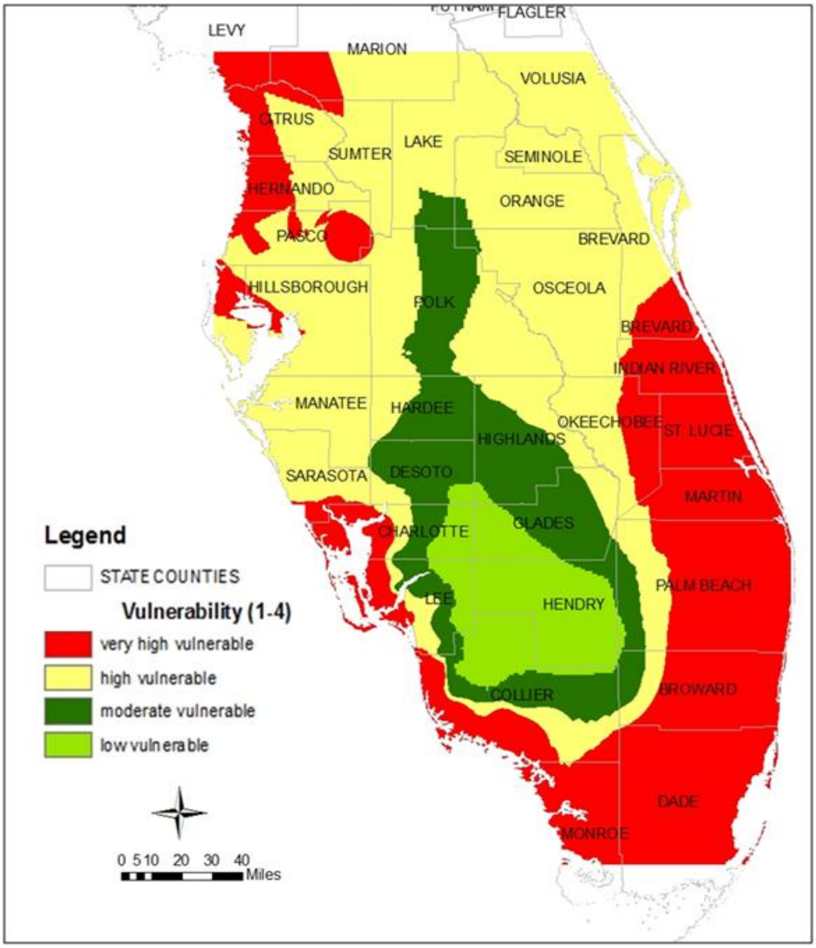
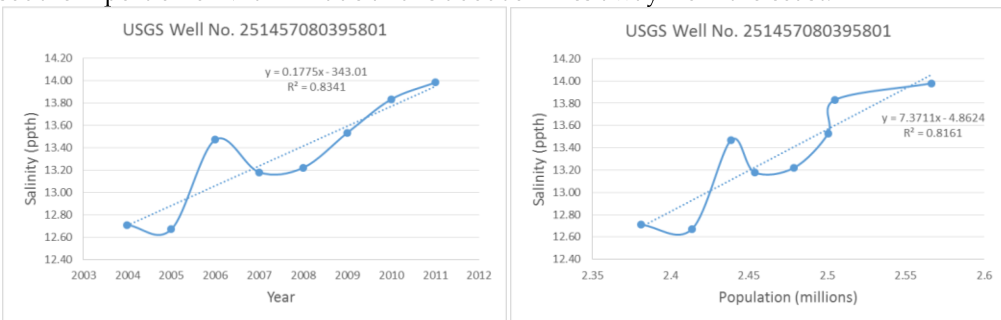


Fig. 2: Florida Aquifer Vulnerability Map

Interaction between Spatial and Demographic Factors for USGS Wells

To better understand saltwater intrusion at one of the highly vulnerable locations in Florida, a case study was conducted for wells located in the Miami-Dade area. For this study, a total of seven USGS wells were selected, and those were observed for the salinity concentrations over the past decade. The general trend of the wells showed an increase in salinity concentrations over the past decade. Population data for Miami-Dade was also obtained from the United States Census to see if there was an observable correlation between salinity concentrations and population growth. Another aspect that was studied for the Miami-Dade area was how the salinity concentration changes as a function of distance from the shore. It is general knowledge that the further one moves inland from the shore the lower the salinity concentration in the groundwater should be, but we wanted to be able to quantify this trend analytically.

The following graphs are for USGS well number 251457080395801and it is located in the southern portion of Miami-Dade and is about 5 miles away from the coast.



(a) (b)

Fig 3: Correlation Graphs, a) Salinity vs. Time b) Salinity vs. Population

The salinity concentrations for the two graphs are in parts per thousands. As seen in Fig, 3 a there has been a steady increase in the salinity concentration over the past decade. The salinity in 2004 was measured to be about 12.7 parts per thousand, and this value has enlarged to almost 14 parts per thousand in a time span of only seven years. In addition to looking at salinity concentrations, the correlation between population growth and salinity was also observed for this well and it is shown in Fig. 3 b. We can see that a positive correlation exists between salinity concentrations and population growth. The population in 2004 for the Miami-Dade area was about 2.38 million and increased to 2.57 million by 2011 (US Census Bureau, 2013). Over this time-span of population growth, the salinity concentration in the groundwater increased as well, which can be explained by a couple of factors? As the population of Miami-Dade continues to grow there is an increased demand for drinking water, which leads to increased groundwater pumping, and ultimately puts a strain on fresh groundwater supply in the aquifer. As this groundwater is pumped out for consumption, the aquifer piezometric head is lowered and allows for saltwater intrusion.

The last component of the Miami-Dade case study was to look at the relationship between salinity concentration and distance from the shore. To accomplish this, the salinity concentrations for the seven wells was documented on a yearly average and their respective distance from the shore was found using Google Maps. Next, the average salinity concentration for one year and each wells respective distance from the shore was graphed. The resultant salinity-distance from shore graph, shown below, allows us to estimate the salinity concentration in the groundwater by knowing a locations distance from the shoreline.

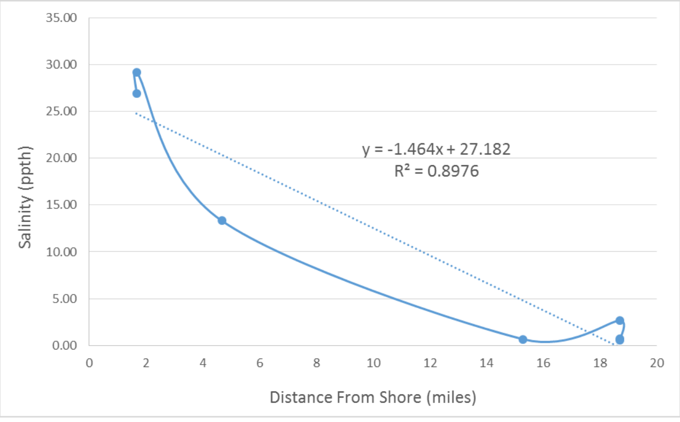


Fig 4: Salinity-Distance from Shore Graph

As expected the salinity concentration in the groundwater decreases as the distance from the shore increased. This trend can be explained by the saltwater intrusion process being relatively slow. However it is also dependent on soil properties, an amount of local groundwater pumping, and a presence of saltwater intrusion barrier wells. Saltwater intrusion barrier wells are one solution to the saltwater intrusion problem and will be discussed more in detail later. Possible uses of data similar to this could be sitting of groundwater pumping wells. Knowing where the salinity of the groundwater is at a minimum makes an area an attractive location for groundwater pumping and can also reduce future treatment expenses.

Conclusion

Saltwater intrusion is a growing concern for many coastal regions in Florida, however there are methods of slowing down or even controlling the process. One solution to saltwater intrusion is to diversify the source of drinking water. Due to the abundant supply of fresh groundwater in Florida, groundwater pumping has been our primary source of drinking water for many decades. However, with saltwater intrusion becoming a growing concern it may be time to look to other sources for drinking water. One source which is readily available is surface water. Water from rivers and lakes supplies a great majority of the United States drinking water supply and could be easily incorporated into Florida's drinking water supply. The only downside to surface water is that the cost of treatment is usually higher when compared to treatment of groundwater. Another source of water is brackish or seawater which can be treated with a reverse-osmosis process to produce extremely high quality drinking water. Similar to surface water, the major drawback with reverse-osmosis treatment plants is the high capitol cost.

One innovative solution to the saltwater intrusion problem is the use of saltwater intrusion barrier wells. These wells are used to inject water into a freshwater aquifer to prevent the intrusion of saltwater. The water of varying qualities is injected, including untreated surface water, treated drinking water, and mixtures of treated municipal wastewater and ground or surface water (EPA, 1999). Drilling of saltwater intrusion barrier wells are done to various depths depending on the depth of the aquifer being protected. They work by injecting freshwater into the aquifer, creating a ridge of freshwater, which acts as a hydraulic barrier against saltwater intrusion. The method is artificial recharge and raises the piezometric head of the aquifer, which prevents saltwater from moving inland (EPA, 1999).

The creation of a saltwater vulnerability map, through application of the GALDIT method, allows us to identify areas that are highly vulnerable to saltwater intrusion. The six factors incorporated into assessing saltwater intrusion vulnerability (groundwater occurrence, aquifer hydraulic conductivity, depth to groundwater level, distance from shore, impact of existing seawater intrusion, and aquifer thickness) allow us to numerically rank and map areas of low to very high vulnerability. By using this mapping model and the saltwater prevention techniques just discussed we can prepare for saltwater intrusion and mitigate the effects on fresh groundwater supplies. The creation of the saltwater vulnerability map for Florida has real world applications which include future siting of groundwater pumping wells, well areas that may need to be abandoned in the future, and strategic locations where saltwater intrusion barrier wells could be installed to prevent saltwater intrusion.

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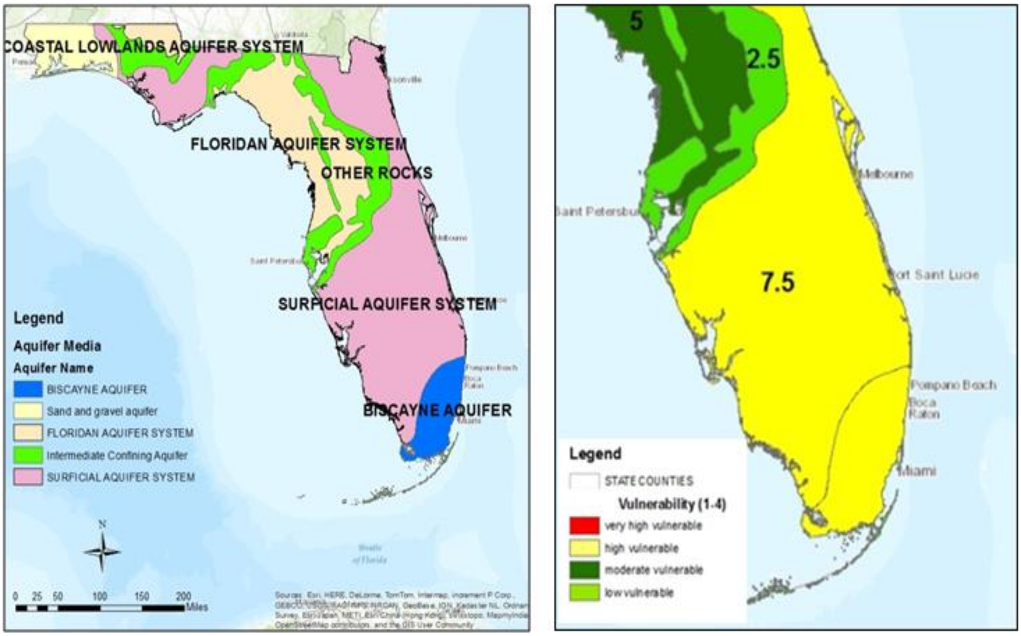
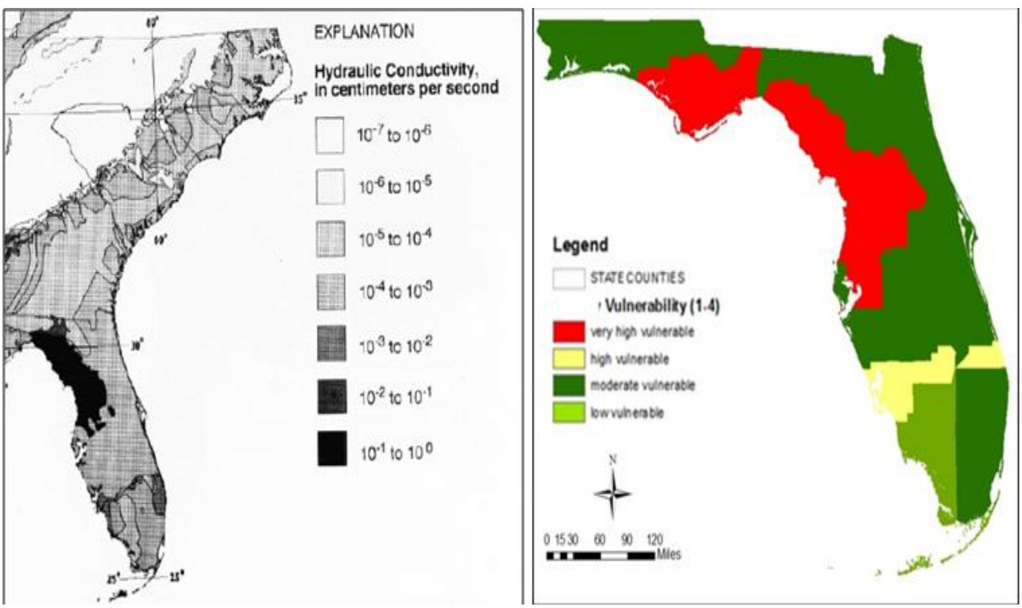
APPENDIX



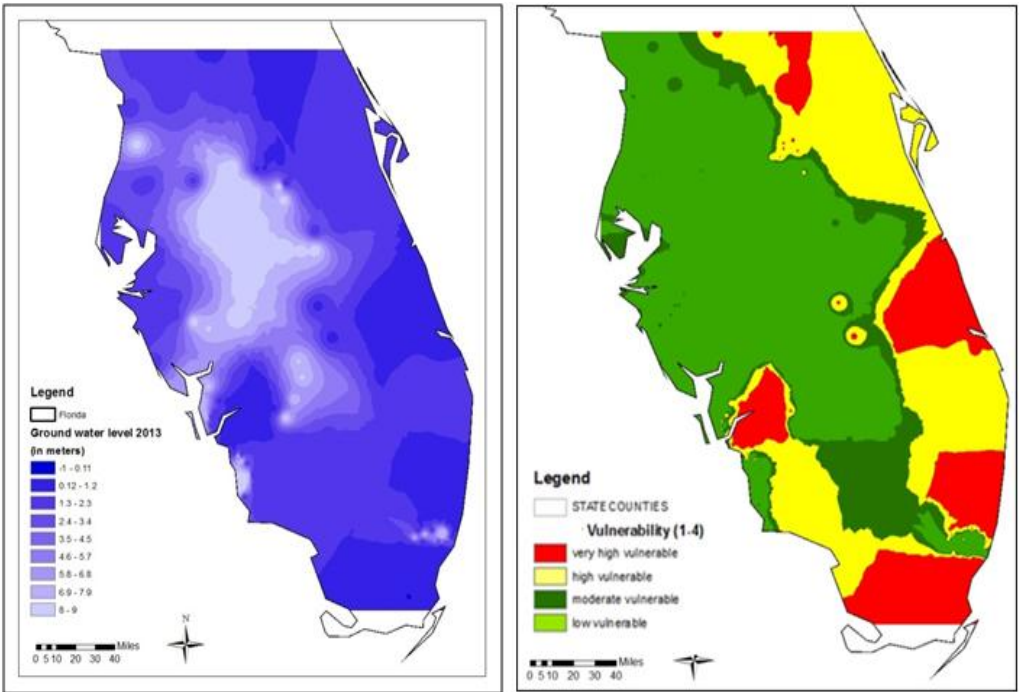
(a) (b)

Fig 5: Aquifer media, a) Real Data, b) Four Point Vulnerability Map



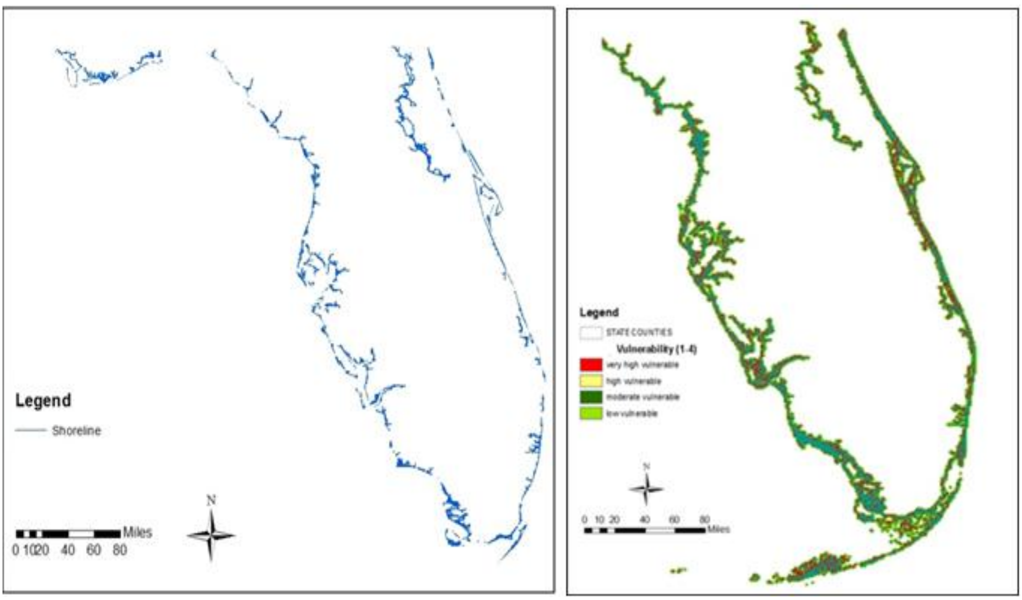
(a) (b)

Fig 6: Aquifer hydraulic conductivity, a) Real Data, b) Four Point Vulnerability Map



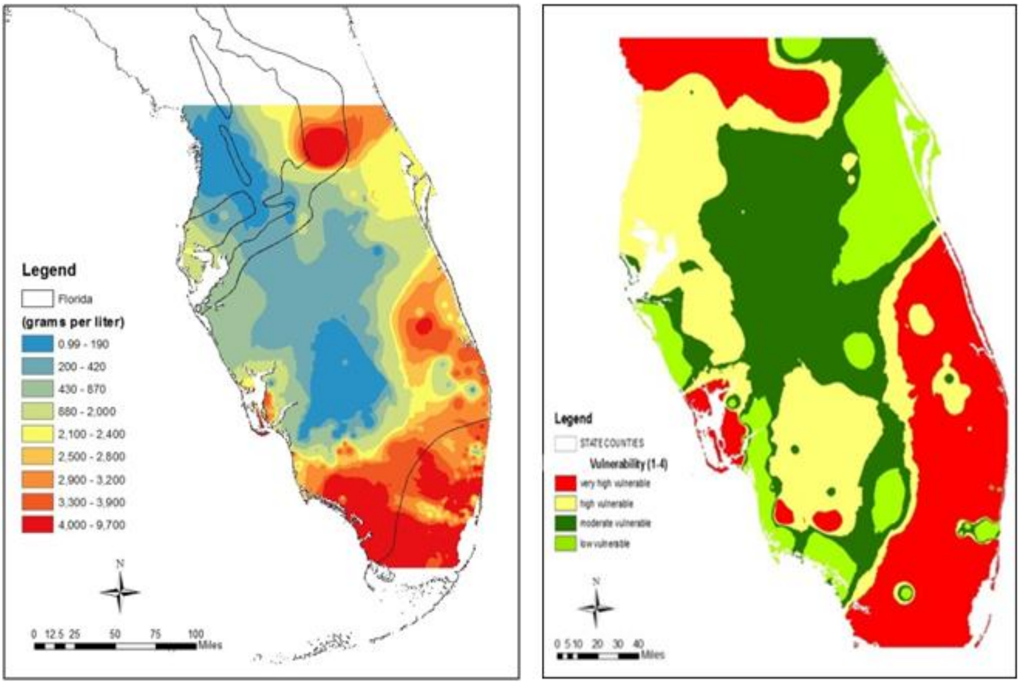
(a) (b)

Fig 7: Height of ground water level above MSL, a) Real Data, b) Four Point Vulnerability Map



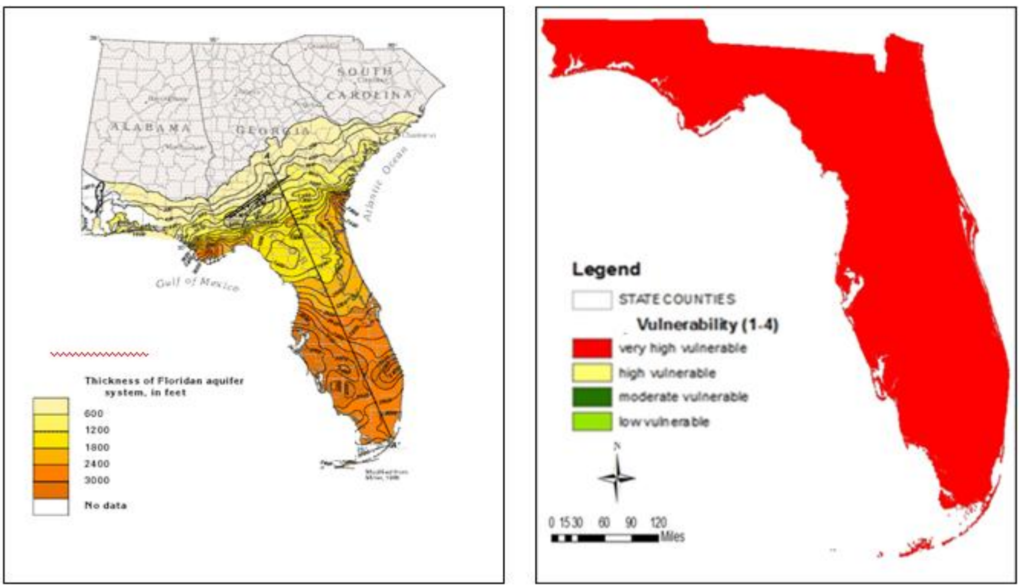
(a) (b)

Fig 8: Distance from shoreline, a) Real Data, b) Four Point Vulnerability Map



(a) (b)

Fig 9: Impact of Existing Status of Seawater Intrusion, a) Real Data, b) Four Point Vulnerability Map



(a) (b)

Fig 10: Aquifer Thickness, a) Real Data, b) Four Point Vulnerability Map

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