Spring 5-10-2019

Controls on Saltwater Intrusion in a Shallow Coastal Aquifer: Wormsloe Historic Site, GA

Marshall D. Williams

CONTROLS ON SALTWATER INTRUSION IN A SHALLOW COASTAL AQUIFER: WORMSLOE HISTORIC SITE, GA

by

MARSHALL WILLIAMS

Under the Direction of Brian K. Meyer, PhD

ABSTRACT

The Wormsloe Historic site is situated on a barrier island located off the Georgia Coast. Four shallow monitoring wells were installed in an east-west transect to monitor the surficial aquifer for saltwater intrusion and to find what factors were most strongly controlling it. Previous studies have found strong indications for saltwater intrusion along the east coast, particularly in areas where the underlying Floridan aquifer has been extensively pumped. Temperature and conductivity data gathered show evidence for the lateral movement of saltwater into the surficial aquifer moving inland from a saline marsh, while tidal, precipitation, and Ground Penetrating Radar data reveal the timing and controls of it. Integration of the multiple lines of evidence indicates risks whereby lateral saltwater intrusion could eventually be conveyed downward under continued sea level rise, with the potential to impact the Upper Floridan aquifer or the regions potable water aquifer in the future.

INDEX WORDS: Saltwater Intrusion, Hydrology, Tidal, Shallow Aquifer, Conductivity, Groundwater

CONTROLS ON SALTWATER INTRUSION IN A SHALLOW COASTAL AQUIFER: WORMSLOE HISTORIC SITE, GA

by

MARSHALL WILLIAMS

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science

in the College of Arts and Sciences

Georgia State University

2019

CONTROLS ON SALTWATER INTRUSION IN A SHALLOW COASTAL AQUIFER:

WORMSLOE HISTORIC SITE, GA

by

MARSHALL WILLIAMS

Committee Chair: Brian Meyer

Committee: Brian Meyer

Luke Pangle

Jeremy Diem

Electronic Version Approved:

Office of Graduate Studies

College of Arts and Sciences

Georgia State University

May 2019

DEDICATION

I would like to dedicate this work to my wife Sarah Williams for her constant support and love throughout my studies.

ACKNOWLEDGEMENTS

I would like to thank Brian Meyer for his generous sharing of time, data, and advice to help my project. I would also like to thank my committee members Luke Pangle and Jeremy Diem as well as the Department of Geosciences at Georgia State University.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

The southeastern coastal areas of the United States are almost completely dependent upon groundwater for their freshwater supplies (Barlow, 2003). This reliable source of freshwater may be the most important resource at risk in the region due to over pumping of coastal aquifers and the risk of saltwater intrusion (USGS, 2000). Based on 2010 U.S. Census data, coastal counties account for 39% of the nation's population and also include many of the largest cities and fastest growing counties (Wilson and Fischetti, 2010). Saltwater intrusion is defined as the disturbance of freshwater aquifers by the vertical or horizontal movement of saline (above 1,000 ppm NaCl) water (UGSS, 2000). This contamination into coastal aquifers is becoming an increasingly large problem as more groundwater is continually being withdrawn for human use (Klassen and Allen, 2017). Saline levels can also be impacted by sea level rise, as historical rise has been documented at around 1mm a year, while current estimates are as high as 3mm a year (Milne et al, 2009). The reduction of useable fresh groundwater supplies could greatly affect freshwater drinking sources for coastal areas in the United States. Coastal areas contain over a quarter of the world population, but less than 10 percent of the world's groundwater supplies (Kundzewicz et al, 2007). Critical freshwater aquifers in the southeast have begun to experience saltwater intrusion and reduced hydraulic head from aggressive groundwater withdrawals (Clarke et al, 2011).

1.1 Climate Change

Climate change and associated Sea Level Rise (SLR) is also a cause of coastal saltwater intrusion via lateral flow. SLR can both increase pressure in areas that already contain conduits for saline intrusion, as well as covering near-coast areas with overflow of saltwater for direct intrusion during predicted more intense storm events and rainy seasons (Nicholls and Cazenave, 2010). Conversely, it is also possible that increased precipitation could have a mitigating effect on shallow groundwater aquifers by flushing out the saltwater. However, higher droughts during dry months could render this effect moot (Payne, 2010). When applying a climate change model to the Pee-Dee River basin in South Carolina it was estimated that with a reduction in streamflow and a 1-foot rise in sea level, saline conditions could occur as often as 16.6 percent of the time, a frequency that far surpasses the current occurrence of saline water within the river basin of approximately 11 percent (Conrads et al, 2013). Although climate change and rising sea levels are affecting salinity groundwater levels in the southeast, a greater regulation of withdrawals will likely be most effective at diminishing saltwater intrusion (Kentel et al, 2005).

1.2 Tidal Controls

Tides can have a significant effect on both near shore surficial groundwater and lower aquifer saltwater levels due to their connection to both. The difference between high and low tides in coastal areas can average over 10 feet; this large variation also affects the groundwater system (Westbrook et al, 2003). In the Upper Floridan aquifer, the fluctuation in groundwater levels that follow high and low tides shows a large response to tidal energy (Gawne, 1997). At Hilton Head Island, also connected with the Floridan aquifer, the hydrostatic pressure change in groundwater levels (6.3 ft) from the loading effect of tidal energy (9 ft) was found to be matched up to 70% in the Upper Floridan, and the surficial system would most likely be affected to an even greater degree than that of the Floridan (Falls et al, 2005). Due to the effects of over pumping causing structural changes and exacerbating fault development in the sediment and underlying rock, water density inversions could promote mixing of saline water with freshwater, possibly even from surficial origin into the Upper Floridan (Landmeyer and Belval, 1996).

1.3 Seasonal and Precipitation Controls

Climate variation associated with coastal areas affects the surficial aquifer system and saline levels. As precipitation is a large majority of groundwater recharge in coastal areas, it follows that it would also act as a control on chloride levels (Clarke et al, 2011). Significant seasonal controls on groundwater levels and discharge from precipitation into tidal sediments at Chesapeake Bay, Virginia were found by Robinson et al. (1998). A model based on seasonal fluctuation data was able to accurately predict changes in both near-shore groundwater levels and saline levels from the 1998 study. Rainfall levels were also found to have an effect on saltwater concentrations into surficial coastal aquifers by a flushing out of the denser saltwater during wet months (Westbrook et al, 2003).

1.4 Structural Controls

Structural irregularities can serve as conduits for saltwater intrusion, particularly vertically. Through a study of wells in southeastern Florida, chloride concentrations anomalies were found that were not associated with pumping areas or mapped depressions in the potentiometric surface (Spechler, 1994). Features including fractures, joints, and faulting can allow saline water to move upward and downward where it is then free to spread laterally to other areas (Vance et al, 2011). Depression features such as sinkholes in karst areas can also allow the direct intrusion of saline water (Vera et al, 2012). Water quality issues due to saline intrusion were also discovered in northeastern Florida where two buried faults were found to be the source of excessive saltwater in the Upper Floridan aquifer (Leve, 1983).

1.5 Evapotranspiration Controls

In a shallow aquifer system that is devoid of plant life the effects of evapotranspiration on groundwater need not be taken into account, however in a marshes and wooded environments, plants can have an effect on groundwater levels. It was found that Eucalyptus trees derived between 40-100% of their transpired water from groundwater sources, with groundwater fluxes as the result of this between 1-4mm a day by using stable isotope data (Thornburn et al. 1993). The study surmised that these fluxes could be impacting chloride levels in the groundwater. This diurnal fluctuation of groundwater use of plants could have a small effect on both groundwater and saline levels (Gribovski et al, 2008).

1.6 Purpose of the Study

This project has evaluated the evidence for and controls on saltwater intrusion into the surficial aquifer at the Wormsloe State Historic site using a combination of specific conductance (SC) and temperature readings, chloride concentrations, tide and precipitation data, and subsurface topography analysis. These controls will help to determine if saline water could be conveyed downward through similar means at other nearby areas that rely on groundwater for their freshwater supplies. The Wormsloe site is located in southeastern Georgia on the Isle of Hope in Chatham County south of Savannah. Although currently minimal, withdrawals for non-potable home irrigation use occur on the northern portion of the Isle of Hope, and the potential exists for greater use, thereby decreasing reliance on the Upper Floridan aquifer for non-potable withdrawals. To date, no formal studies of the water quality or water availability of the surficial aquifer have occurred on the Isle of Hope or other islands in a similar physical setting in the area (Wilmington Island, Skidaway Island, Burnside Island, etc.). The Wormsloe site, located on the southern portion of the Isle of Hope, affords the unique opportunity to evaluate the shallow groundwater system on a barrier island in an undeveloped setting. The establishment of a groundwater monitoring network at the Wormsloe site in 2016 indicates elevated chloride concentrations in shallow groundwater as the result of saltwater intrusion. Although vertical saltwater intrusion occurs on the Georgia Coast, lateral saltwater intrusion was assumed to be the likely mechanism and an initial hypothesis was formed.

The project will evaluate the research question of: What is the source of saltwater intrusion occurring in the shallow groundwater system at Wormsloe? The objectives for examining the source are; 1) What is the source of the saltwater intrusion occurring in the surficial aquifer system, 2) What are the magnitude of the processes or controls (i.e. tidal forcing, evapotranspiration, etc.) on saltwater intrusion in the surficial aquifer system, and 3) Is there the potential for of saltwater reaching the underlying potable aquifer(s)?

2 STUDY AREA

The historic Wormsloe site (Figure 1) is located on the southern portion of the Isle of Hope in southeastern Chatham County, Georgia.

Figure 1: Location of Study Area (Isle of Hope, GA): Data from ArcGIS On-Line

The Isle of Hope is situated between the mainland of Georgia and Skidaway Island and surrounded by intertidal marsh. The average elevation for the barrier island is 13 feet above sea level. These low-lying areas have been occupied for hundreds of years and records exist of historical wells dug for drinking water sources and artesian wells (Bryan, 1753). While the Wormsloe site does not presently use its shallow aquifer for drinking water, there does exist a sustainable amount of withdrawals for non-potable use such as irrigation. If managed properly, the aquifer could supply a large percentage of needs for the island's non-potable use.

2.1 Geological Setting

The geology of the Georgia coast mostly consists of a sequence of variably compacted sand and clay layers overlying limestone and dolomitic beds with ages spanning the Paleocene to the present (Clarke et al, 2011.) The topmost sediments are largely unconsolidated Pleistocene and Holocene sand. The shallow aquifers present are generally unconfined but can sometimes have confining layers within the sediments that largely consist of interspersed sand, clay, limestone, and dolomitic bands. Clay layers may be present in variable thickness, leading to surface aquifers being both confined and unconfined (Reichard et al, 2014). Beneath the surficial aquifer lies the Floridan aquifer system, composed primarily of Paleogene carbonate rocks that dip eastward. Due to the karst nature of Floridan, joints and fractures are common and can affect the overlying stratigraphic layers (Leve, 1983). The Paleozoic crystalline basement rock that underlies the surficial sediment underwent faulting during the Miocene (Dillon, Klitgord, and Paull, 1983). At the Wormsloe site, there is typically a surficial layer of peat and sand lying overlying a clay confining layer at 20-25' depth.

2.2 Floridan Aquifer

Underlying the surficial aquifer at Wormsloe is the Floridan aquifer system, which consists of the Upper Floridan and Lower Floridan aquifer units. The Upper and Lower Floridan aquifers are confined beneath the coastal region and overlain by unconfined shallow aquifer systems. The Floridan aquifers are both highly laterally extensive and diverse in structure, consisting of highly permeable layers that have confining units throughout (Vance et al, 2016). The Upper and Lower Floridan layers are connected more prominently at areas of higher permeability and lower thickness of layers in between them (Williams and Gill, 2010). Although thickness varies across the aquifer, the layers thicken towards the east coast in the direction of groundwater flow (Reichard et al, 2014). The Upper Floridan has begun to experience saltwater intrusion and reduced hydraulic head from aggressive groundwater withdrawals (Clarke et al, 2011).

A nearby research effort that monitored chloride concentrations in the Upper and Lower Floridan aquifers near Savannah, Georgia from lateral seawater intrusion was conducted by Leeth et al. (2005). This research revealed that chloride levels generally increase as depth below the surface also increases, indicating another possible source of saline intrusion vertically into the Upper Floridan. At both Skidway and Tybee islands, substantial chloride levels were found in the Lower Floridan aquifer by using a combination of both SC data and ion readings from grab samples, most likely from relict seawater that can move upwards. The Upper Floridan aquifer water was fresh at both sites, with very low concentrations of chlorides. Chloride levels tend to be higher in both the surficial and Lower Floridan than the Upper Floridan (Falls et al, 2005).

2.3 Water Withdrawals and Cone of Depression

One of the largest causes of saltwater intrusion into coastal aquifers comes from groundwater pumping that creates a cone of depression. If pumping continues, this cone can eventually have the effect of reversing the natural groundwater flow paths and allowing saltwater to fill the cone either by lateral or vertical movement (Spechler, 1994). Both the surficial and Floridan aquifer systems in the southeastern United States are recharged mostly by precipitation, with recharge to the Floridan generally occurring in the upper Coastal Plain of Georgia and across Florida. Flow gradients are generally eastward towards the coast (Clarke et al, 2011). The eastward prevailing flow direction causes issues when cones of depression develop as saltwater is free to flow into the freshwater aquifer. A cone of depression has occurred as the result of over-pumping from Savannah (Figure 2). The cone has a diameter of over 70 miles and has greatly altered groundwater flow and recharge dynamics in the area. Recharge is now occurring from vertical intrusion in many parts of the aquifer due to decreased hydraulic head, which often leads to saline water becoming mixed within. The Savannah-centered cone of depression extends nearby to St. Catherine's Island. Recharge to the Upper Floridan was found to have come largely from vertical movement through unconsolidated sediment and through a fracture and dissolution network already present in the bedrock (Figure 3) at St. Catherine's Island (Reichard et al, 2014).

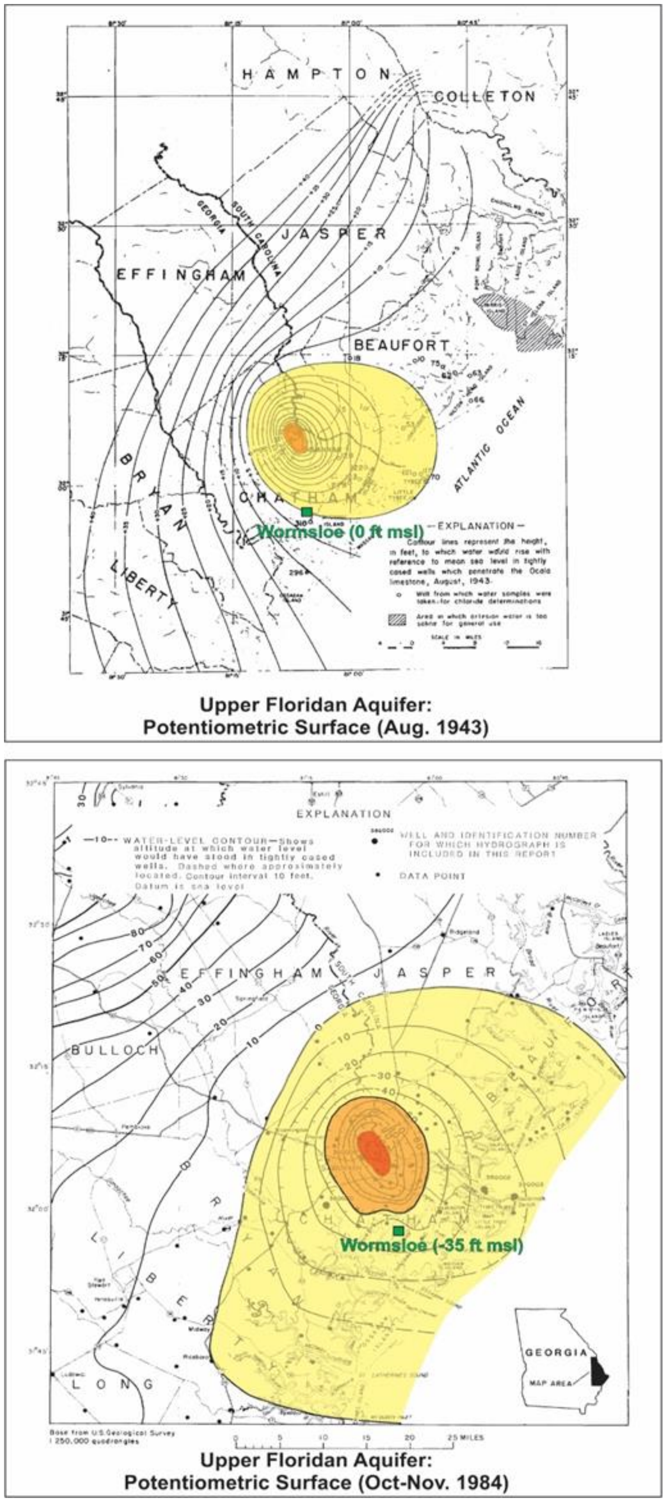

Figure 2: Upper Floridan Aquifer Cone of Depression Growth 1943-1984, adapted from Krause and Randolph (1989)

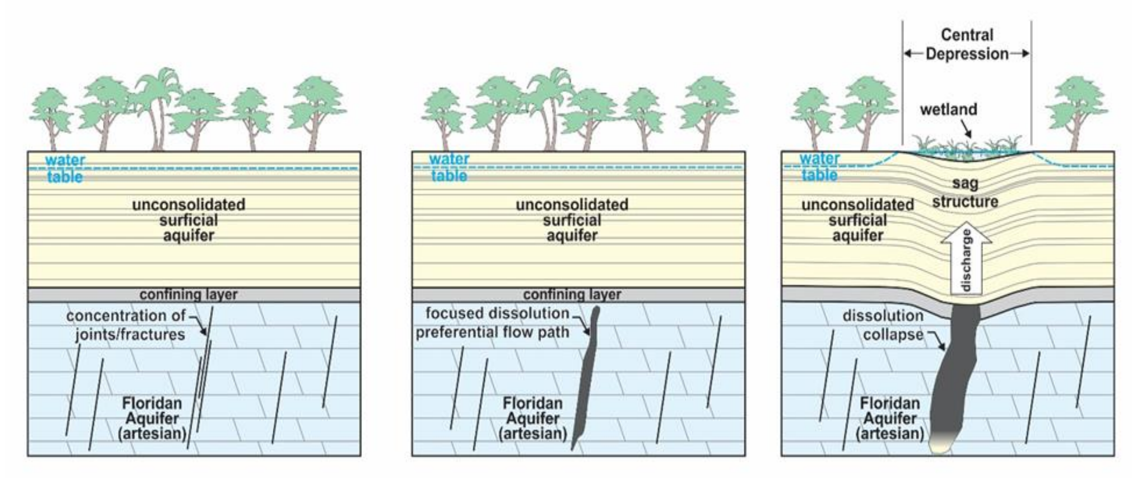

Figure 3: Illustration Showing Development of Karst Features and Sag Structures on St. Catherines Island, GA (adapted from Reichard et al, 2014)

Georgian shallow aquifers, as seen from Ground Penetrating Radar (GPR) mapping of Georgian coastal areas (Vance et al. 2011) seem to be highly influenced by underlying bedrock structures such as faults, and over-pumping from the Upper Floridan aquifer could be causing the shallow aquifers to lose hydraulic pressure and become contaminated with saltwater. Basement faults originating from Mesozoic rifting and underlying the Floridan aquifer can become reactivated and propagate upwards, creating vertical groundwater pathways and allowing saline water to intrude downwards (Leve, 1983). While these vertical groundwater pathways most likely used to serve as a conduit for freshwater under pressure to move upwards and create coastal wetlands, they can now have the opposite effect and allow saline water to move downwards (Chowns & Williams, 1983). Another concern for shallow aquifers that arises from over-pumping is saltwater contamination flowing vertically from underlying aquifers. The Lower Floridan aquifer contains a blend of very high concentration saline water of both modern and ancient origins; this saline water can move upwards through the system of fractures and joints into the permeable layers of the Upper Floridan aquifer and possibly surficial aquifers (Reichard et al, 2014). When a significant cone of depression is developed, this saline water can move upwards through hundreds of feet of rock and contaminate freshwater aquifers (Jones et al, 2002).

2.4 Shallow Aquifer System and Site History

The Wormsloe shallow aquifer system has experienced great change in the last three centuries (Figure 4). Descriptions of the surrounding barrier islands depicted these near-surface systems as near perennial wetlands (Bryan, 1753). The Upper Floridan had not yet experienced heavy water withdrawals and the settings were artesian, with multiple springs flowing with great pressure. A GGS Bulletin (B-7, 1898) revealed artesian systems nearby on Tybee Island and on the mainland at Bonaventure and Thunderbolt, with the first reported well drilled in the Savannah area in 1885. At late as 1912 groundwater levels were still high, with a USGS topographic map showing artesian wells at Wormsloe, but non-artesian conditions developing in Savannah. However, wells drilled into the nearby surficial aquifer overlying the Floridan at Parris Island had been abandoned as early as 1903 due to the presence of saltwater (Provost et al, 2005).

Following this time, we begin to see strong evidence for the loss of hydraulic head Upper Floridan, and any previously existing wetlands on the island become seasonal. An Isle of Hope well (#269) was found to be at near sea level (5/9/1939), while a Bethesda well (#138) was documented as having a water level at 8 feet below the surface (GGS B-49A, 1945), showing the effects of the Savannah cone of depression. By 1957, a USGS mapping effort found zero remaining artesian wells on or nearby Wormsloe, and saltwater levels had exceeded the recommended EPA drinking water standards in well BFT-315 on Hilton Head Island. In 1962, chloride concentrations mapped from the Upper Floridan in Brunswick, Ga were lower than 500 mg/L. However, by 1988, extensive withdrawals had caused them to contain over 2,400 mg/L chloride in some wells. The extensive groundwater withdrawals in the 20th century to present from the Upper Floridan Aquifer seems to have reversed groundwater flow directions, leading to the loss of year-around wetlands and complete loss of artesian wells. It is likely that even if pumping were strictly reduced and regulated, saltwater levels would remain high for many decades (Provost, 2005).

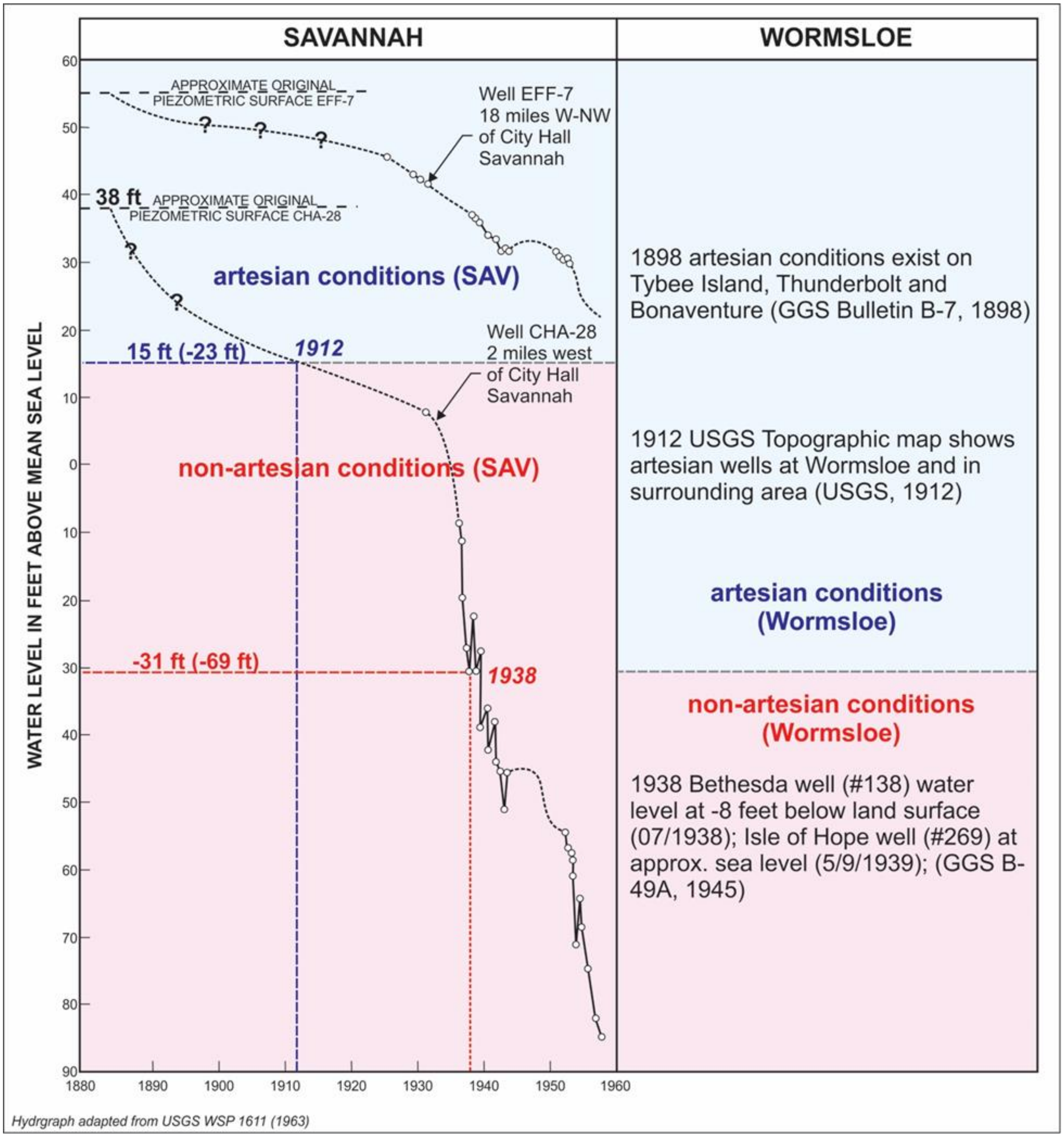

Figure 4: Artesian Conditions vs Time at Wormsloe Site and Savannah, GA (Meyer, 2016)

3 METHODOLOGY

3.1 Monitoring Well Locations and Construction

Four monitoring wells constructed of 1” PVC pipe were installed in an east-west transect in November of 2015 with the direct push technology method (Figures 5 and 6). These wells extend from the eastern margin to the central portion of the island. They were drilled to approximately 18’ below the surface with a top screen depth of 8’ on ground elevations ranging from 7-11’above mean sea level, and were completed as flush mounted wells. The drill cores revealed an underlying geology of well sorted quartz sand (fine to very fine) and displayed low heavy mineral sand amounts. Solinst, Inc. Model 3001 LT Junior leveloggers were installed in all of the wells in February 2016, providing hourly monitoring of temperature and water levels. After base readings showed significant levels of chloride in only MW’s 03 and 04, Solinst, Inc Model 3001 Junior Edge loggers were installed in those wells to monitor SC hourly. Data were downloaded semi-monthly and the loggers were calibrated with a manual water level taken for each well using Solinst water level meters during calibration. The downloaded data was placed into Excel and corrections to the water levels were calculated using the following equation: (Top of Casing - Manual Water Level = Water Table Elevation), (Logger “Raw” Level - Water Table Elevation = Correction Factor), (Logger “Raw” Level – Correction Factor = Water Level).

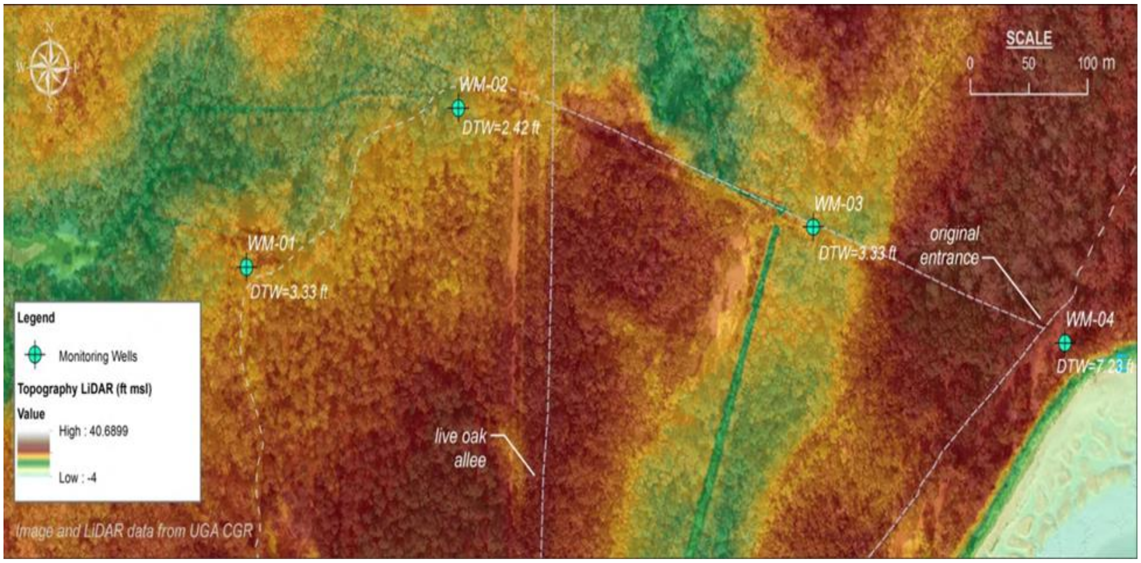

Figure 5: Location of Monitoring Wells Across East-West Transect; saline intrusion occurring via tidal activity most strongly seen at MW-04 and decreasing moving inland

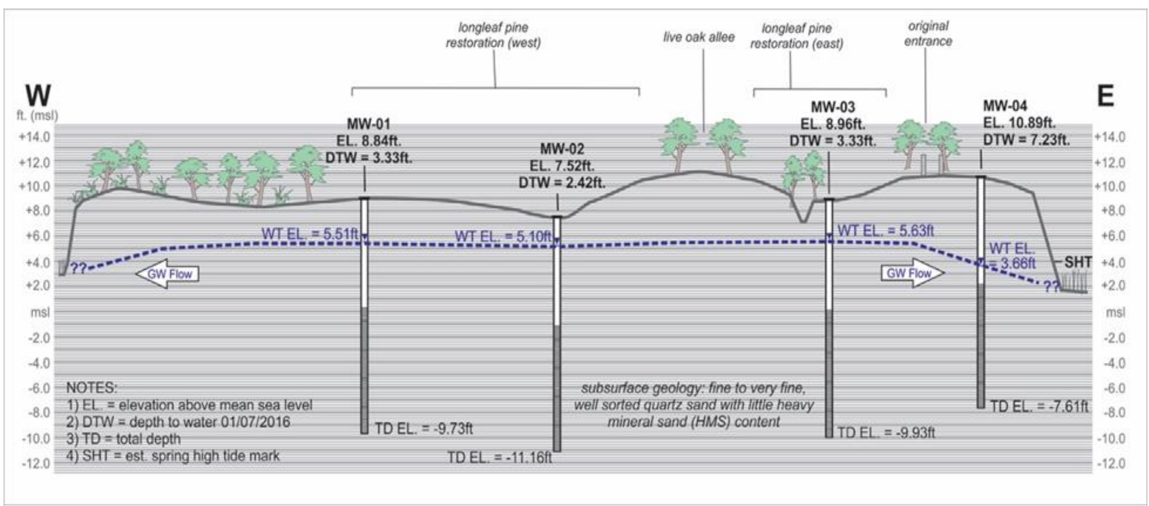

Figure 6: Interpreted Groundwater Flow Directions to the East and West of the Island, away from a topographic high in between MW-02 and MW-03, with description of subsurface geology

3.2 Geochemical Sampling

Initial groundwater samples were collected at site in January 2016 employing low flow peristaltic pumping with measurements read continuously through a YSI 600 XL for temperature, pH, oxidation-reduction potential (ORP), and conductivity sampled at three different lengths inside of the screened interval of the wells (Figure 7). These samples were compared to those collected from the local tidal marsh surface water to evaluate the source of saltwater intrusion. All sampling procedures followed USEPA Region IV operating procedures. A laboratory analysis was ordered to detect chloride, sulfate, calcium, potassium, magnesium, sodium, alkalinity, and total dissolved solids (TDS). This data was plotted on Piper Trilinear diagrams utilizing GW_Chart, public domain software from the USGS to characterize groundwater facies and evaluate geochemical trends, and an End Member Mixing Analysis (EMMA) was used to compare the quantity of mixing fresh and saline water for each of the wells using total chloride as a tracer.

Figure 7: 2016 sampling event employing Peristaltic Pump and YSI 600XL

3.3 Temperature and Specific Conductivity for Calculating Salinity

Temperature and SC can be used as an analogue for evaluating salinity in waters. Utilizing a method found in 1983 UNESCO report, salinity can be calculated by the following equation:

$$R = \frac{C(S,t,p)}{C(35,15,0)}$$

where C (S, t, p) is the conductivity of seawater at salinity (S), temperature (t) and pressure (p) in decibars, and C (35,15,10) represents the conductivity of standard seawater at salinity 35 (ppt), at 15°C, and atmospheric pressure. This is equal to the conductivity of a reference mixture of potassium chloride at the same temperature and pressure. An excel template for this calculation was taken from Douglas (2010), utilizing a reference conductivity of 42,900 (uS/cm) at 35 practical salinity units (psu) and 15°C. Applying the derived salinity to water classifications by the USGS in (Table 1), water is classified in one of four ways.

Classification of Water Based on Salinity	
Classification	psu
Freshwater	0-1
Brackish	1-10
Moderately Saline	10-35
Saline	>35

Table 1: USGS Classification of Water Based on Salinity (USGS, 2000)

3.4 Precipitation and Tide Data

In order to help determine the controls on saltwater intrusion, daily precipitation and temperature data were taken from the closest weather station operated by the University of Georgia Environmental Monitoring Network at the Landings on Skidaway Island in Chatham County, GA. Tide data were taken from the USGS Fort Pulaski tide gauge at 1-hour intervals with the datum as mean sea level. In order to approximate the distance of tidal timing between the tide gauge and the study area, a lag of 2 hours was set in between the gauge and the monitoring well data to compensate for the arrival of the tide at the inland location. Due to the failures of SC probes following hurricane events and flooding, the time scales for wells MW-03 and MW-04 are different due to data availability. There was also a loss of data in 2017 for MW-02 following Hurricane Irma. The time scale for tidal influence was lowered to show the relationship more clearly as opposed to precipitation.

Water table fluctuations in MW-02 were plotted for a three-day period in both the summer and winter of 2017 against tidal data to determine a possible diurnal effect of transpiration on groundwater. Although MW-01 is not experiencing saltwater intrusion, its location inland farther away from tides and its proximity to live oak vegetation made it ideal to examine this process. A plot of both summer and winter for water table fluctuations was used to look for any seasonally derived influence.

3.5 Ground Penetrating Radar

GPR transects were performed at Wormsloe in 2016 and 2018 (Figure 8) by GSU Geosciences faculty (Meyer) and students (Jessie Hughes, Albert Killingsworth, and Tim Herold). Data were collected using MALA GeoExplorer systems utilizing 100, 160, and 250 MHz antenna. Velocity of the subsurface material was determined by using the parabola fit method and the known depth to the water table. The GPR data were processed using RadExplorer software Version 1.42 for DC removal, Time-Zero adjustment, spatial interpolation, background removal, 2D spatial filtering, amplitude correction and bandpass filtering. GPR profile locations were recorded using a Trimble GeoExplorer XH handheld GPS device accurate to within 0.15m.

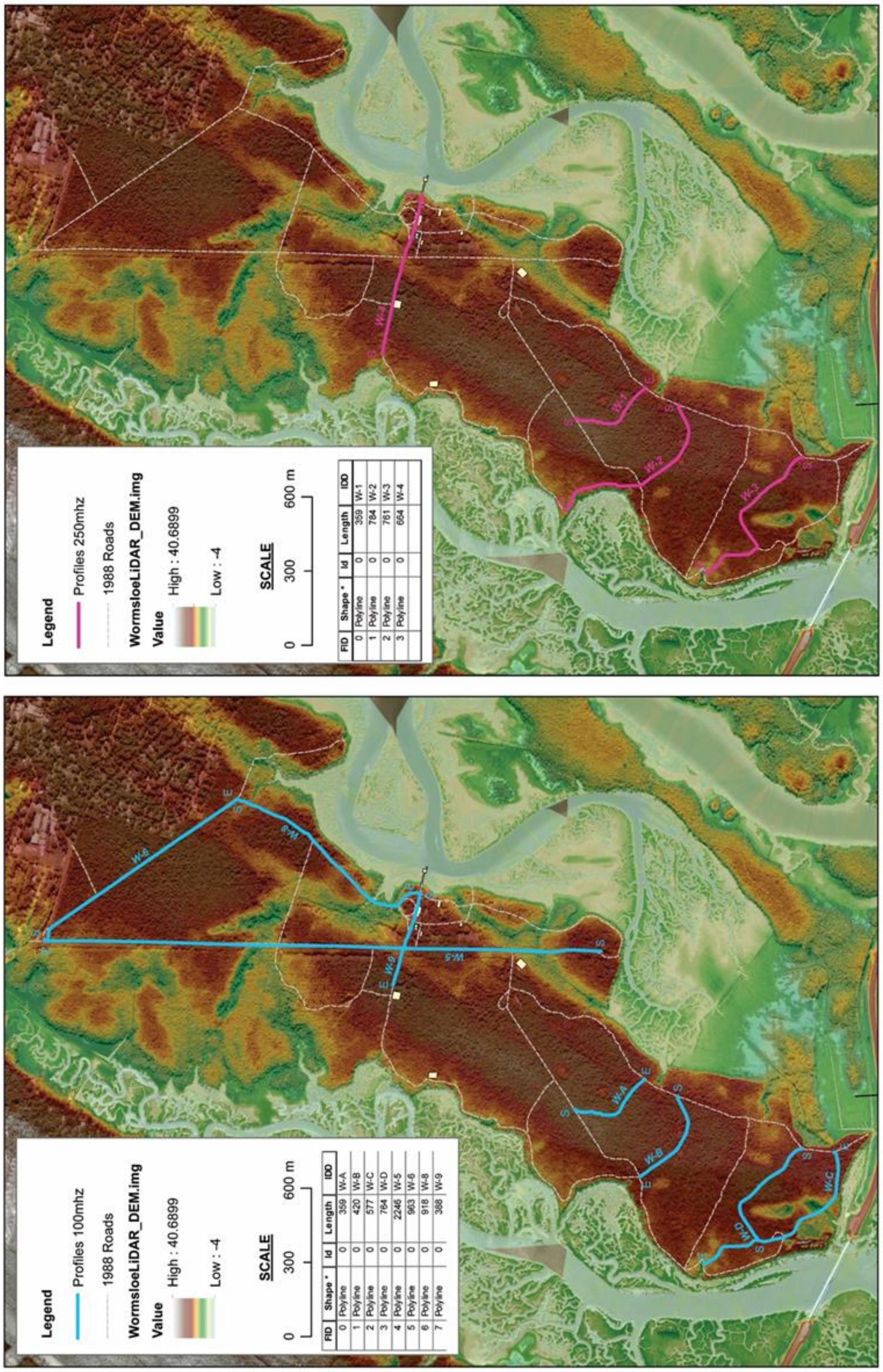

Figure 8: 2016 and 2018 GPR Survey Locations

4 RESULTS

4.1 Calculated Salinity

The results show both a presence of salinity and a clear decrease from the coast inward from MW-04 to MW-01. The following section shows the derived salinity levels utilizing temperature and conductivity for the wells using the method described in section 3.3. As only MW's 03 and 04 showed a saline solution of water based on preliminary readings from January of 2016 (Table 2), they are the wells that had permanent conductivity meters installed and have time-series uS/cm data displayed. MW-02 revealed only a slightly brackish mixture of 0.057-0.63 psu.

In Figure 11, MW-03 shows a range of salinity values from 0-5 psu mirroring those of the conductivity values derived from temperature (Figure 9) and SC (Figure 10). The average value for salinity levels is 6907 uS/cm from a period of 2/28/16 through 2/25/17. In Figure 14, MW-04 shows a range of salinity values from 1-7 psu also mirroring those of the conductivity values (Figure 13) and temperature (Figure 12). The average salinity level is 7.63 psu from a period of 2/28/16 through 10/8/16. The results from MW-04 are higher than MW-03 as expected due to its closer proximity to the shoreline from ocean-derived marsh saltwater. Both of these wells show strong evidence of ocean-derived saline intrusion. MW-03 shows low salinity anomalies that are most likely the result of freshwater rapidly infiltrating the shallow aquifer or penetrating the well casing following strong precipitation.

Well ID	Calculated Salinity (psu)	Classification
Global Seawater	35	Saline
MW-01	0.1	Freshwater
MW-01	0.11	Freshwater
MW-01	0.11	Freshwater
MW-02	0.57	Freshwater
MW-02	0.63	Freshwater
MW-02	0.63	Freshwater
MW-03	4	Brackish
MW-03	4.2	Brackish
MW-03	4.41	Brackish
MW-04	4.91	Brackish
MW-04	5.31	Brackish
MW-04	5.51	Brackish

Table 2: Derived Salinity from 2016 Readings

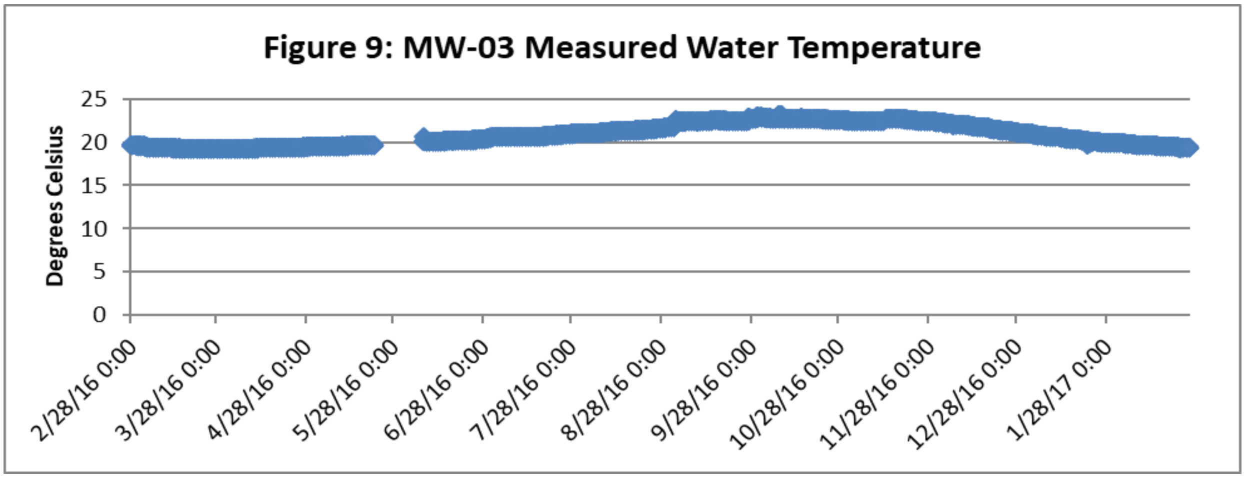

Figure 9: MW-03 Measured Water Temperature

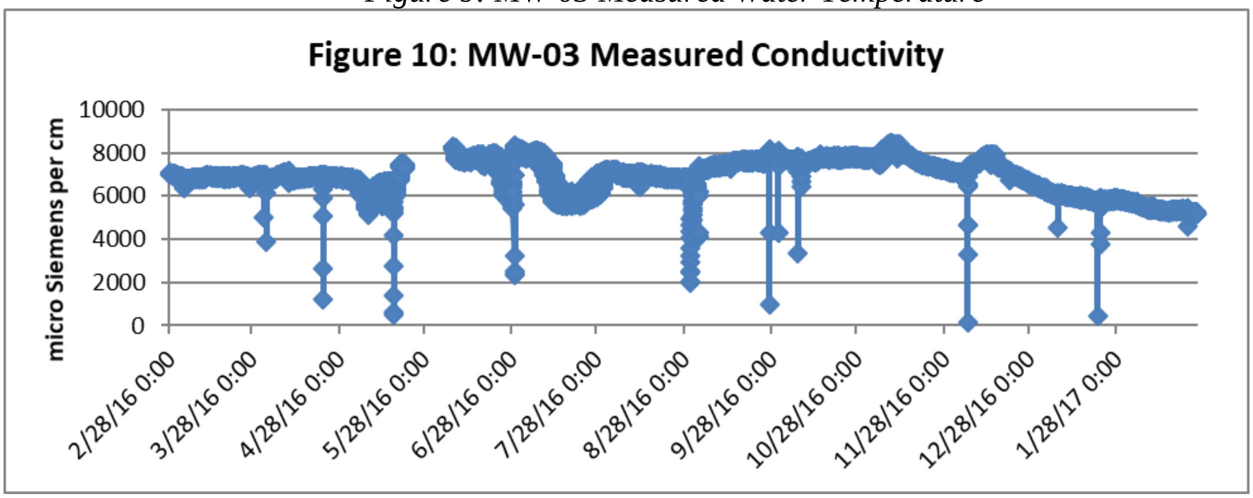

Figure 10: MW-03 Measured Conductivity

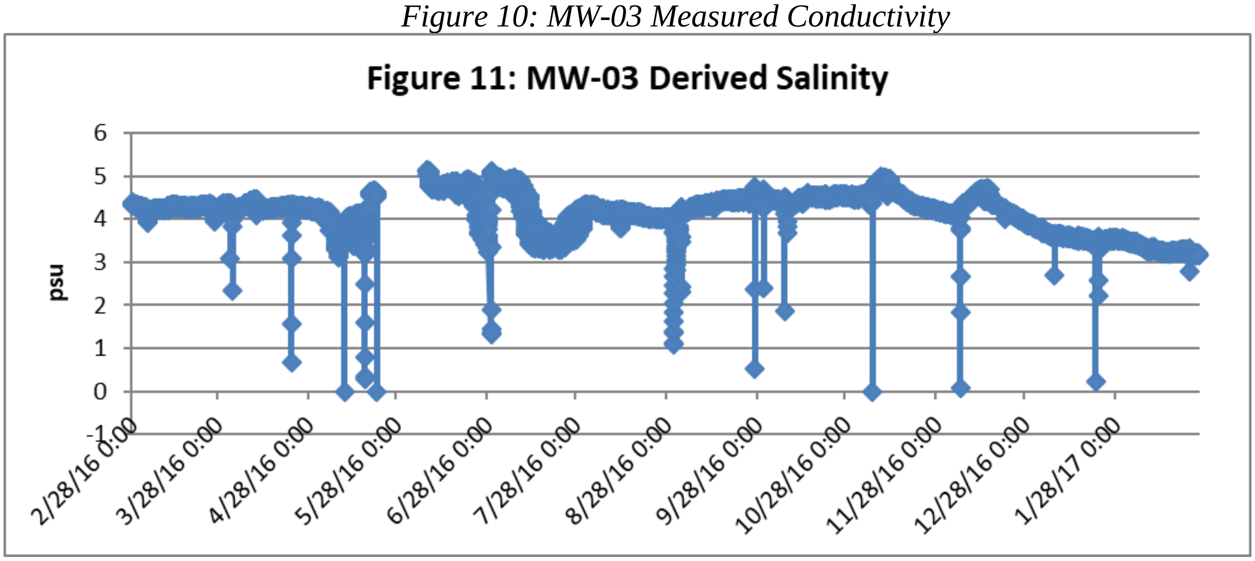

Figure 11:MW-03 Derived Salinity from Figures 9 and 10

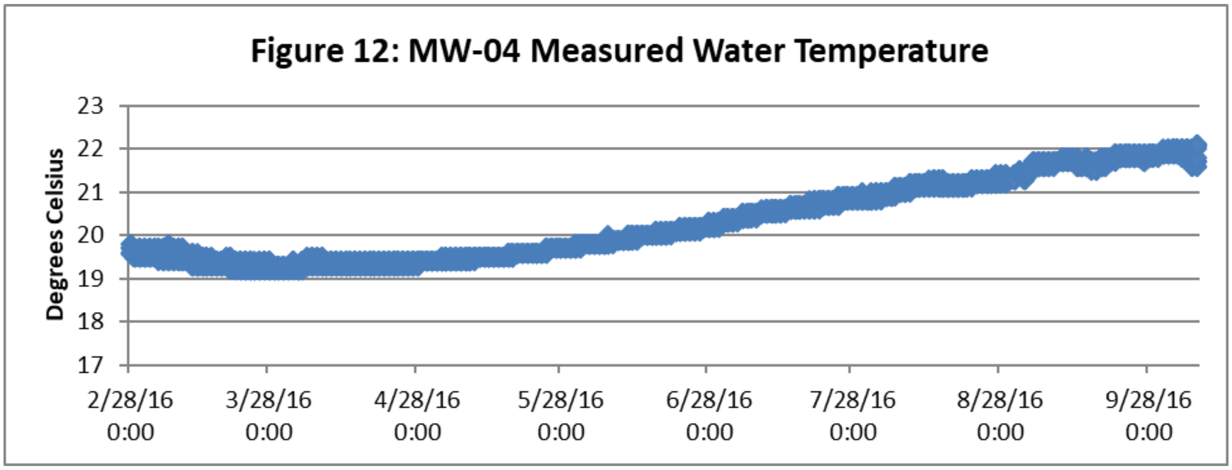

Figure 12: MW-04 Measured Water Temperature

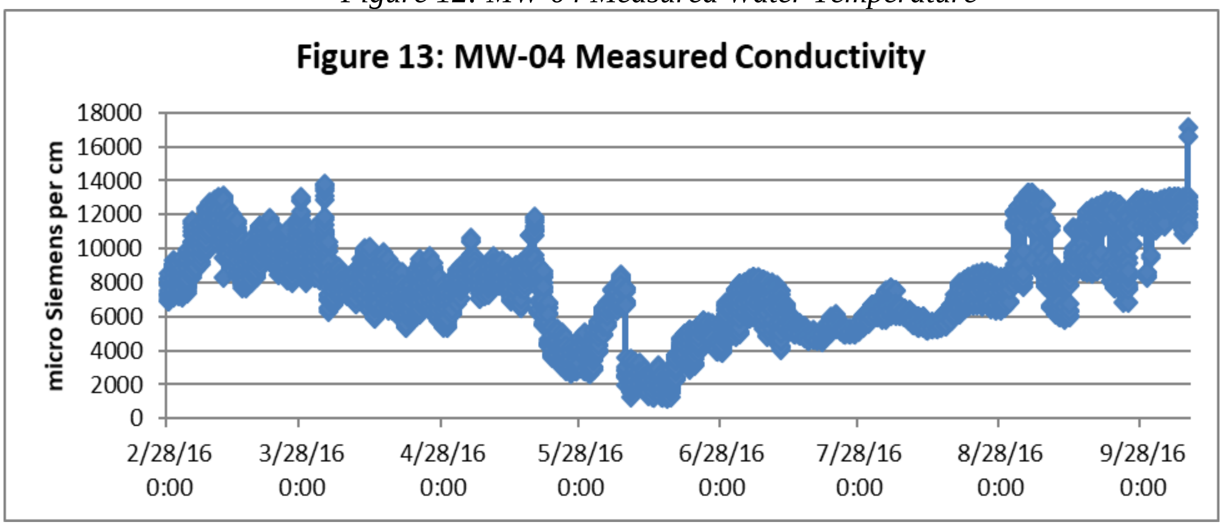

Figure 13: MW-04 Measured Conductivity

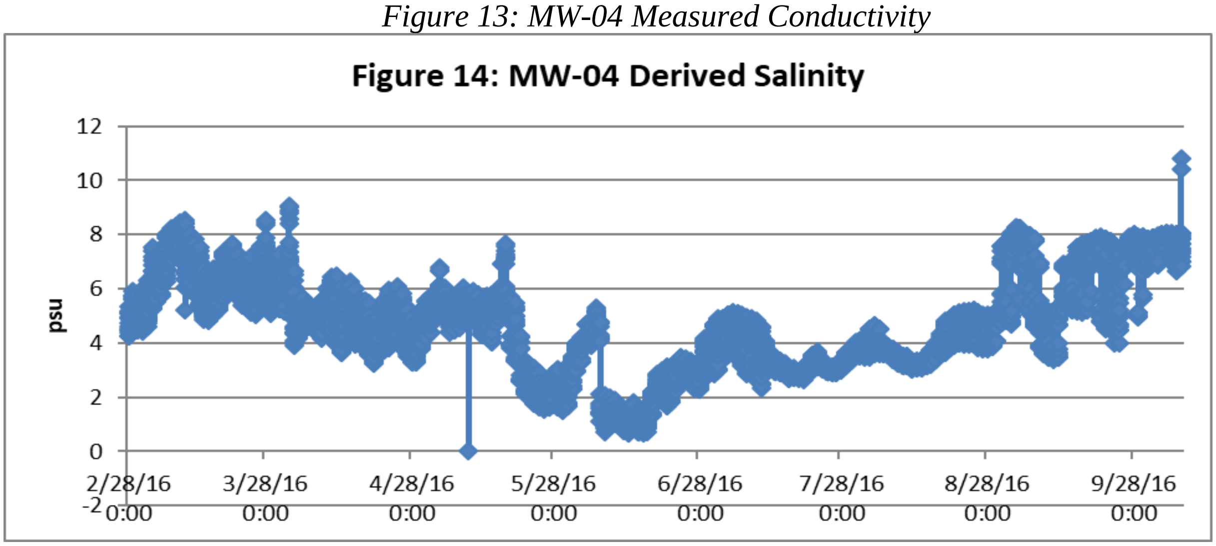

Figure 14: MW-04 Derived Salinity from Figures 13 and 14

4.2 Precipitation and Tidal Controls

As seen in Figures 16-19, both MW's 03 and 04 display tidal controls on conductivity through a strongly positively correlated relationship, but MW-04 displays a higher tidal response than does MW-03 as expected by its closer distance to the ocean. The tidal size change in the study area at Wormsloe averaged 6-9 feet, sometimes exceeding this during the twice-daily high and low tide periods

There is also a seasonal control exhibited strongly in MW-04 and to lesser extent in MW-03, where the water table levels are higher and the SC readings are lower in June-September (increased precipitation, Figure 15), and the SC readings are higher during the rest of the year. Both monitoring wells reached a peak of conductivity around September to November of 2016, and a low reading in June for MW-04 (1,266 uS/cm) and July for MW-03 (5,536 uS/cm).

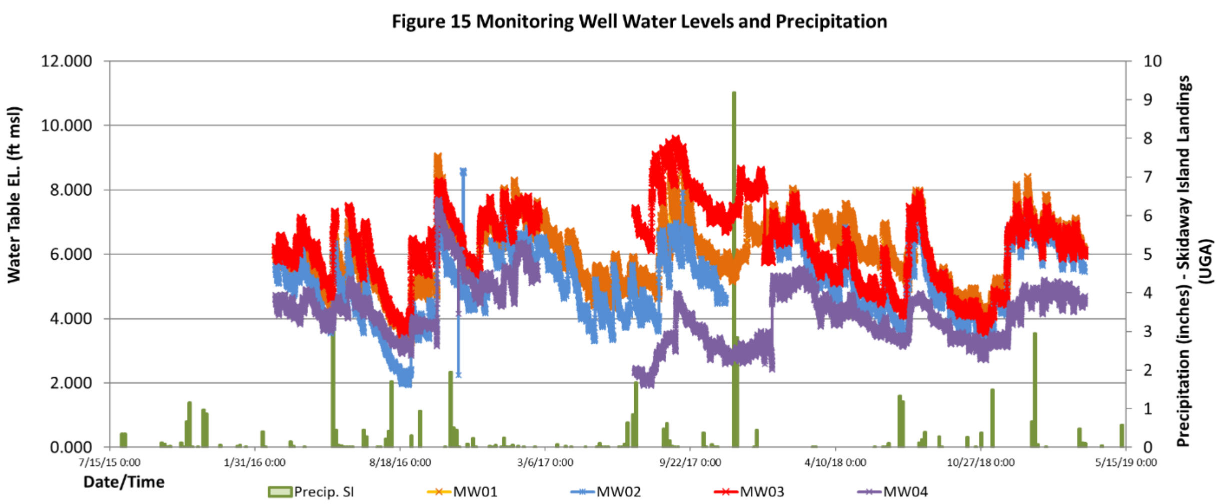

Figure 15: Monitoring Well Water Levels and Precipitation, note effects of Hurricanes Matthew (2016) and Irma (2017) on groundwater levels and slightly higher water levels during the Winter season

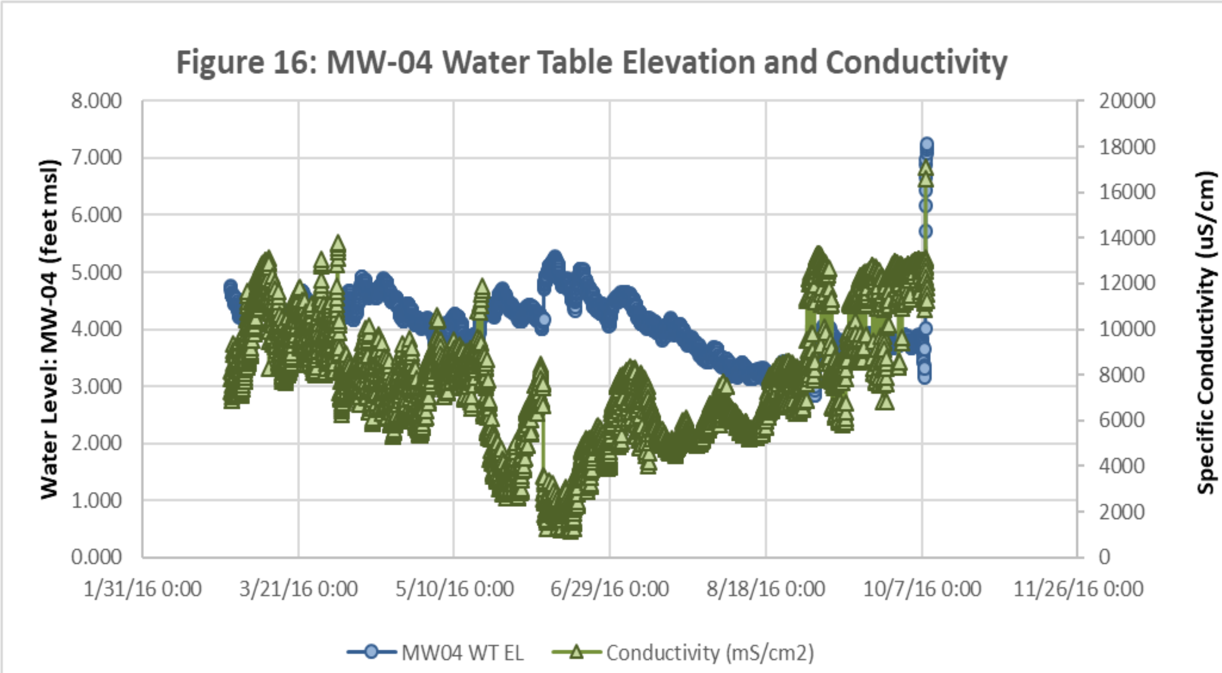

Figure 16: MW-04 Water Table Elevation and Conductivity, generally showing an inverse relationship

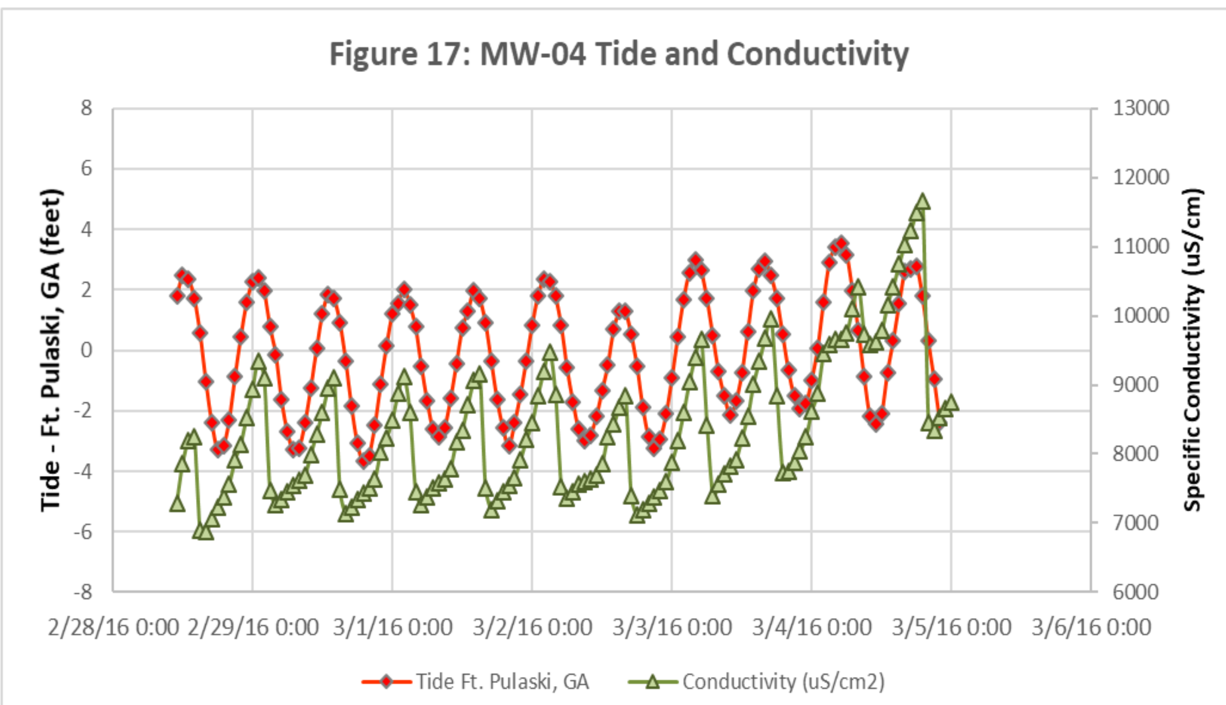

Figure 17: MW-04 Tide and Conductivity showing strong correlation

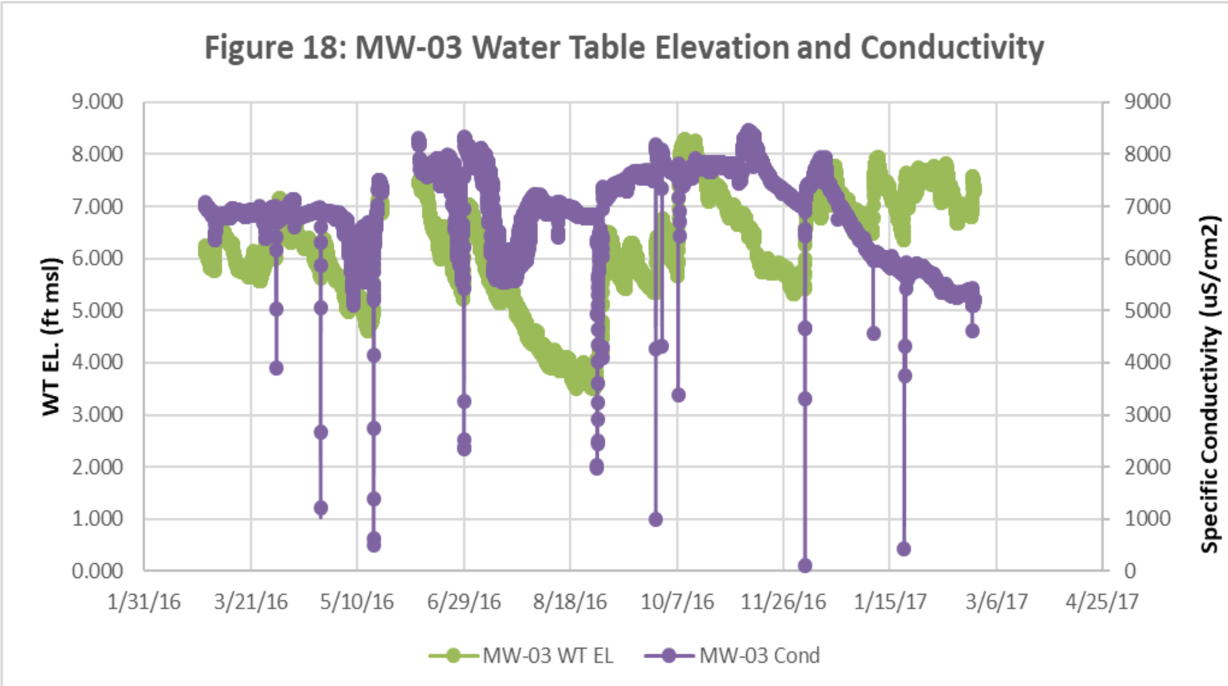

Figure 18: MW-03 Water Table Elevation and Conductivity, generally showing an inverse relationship

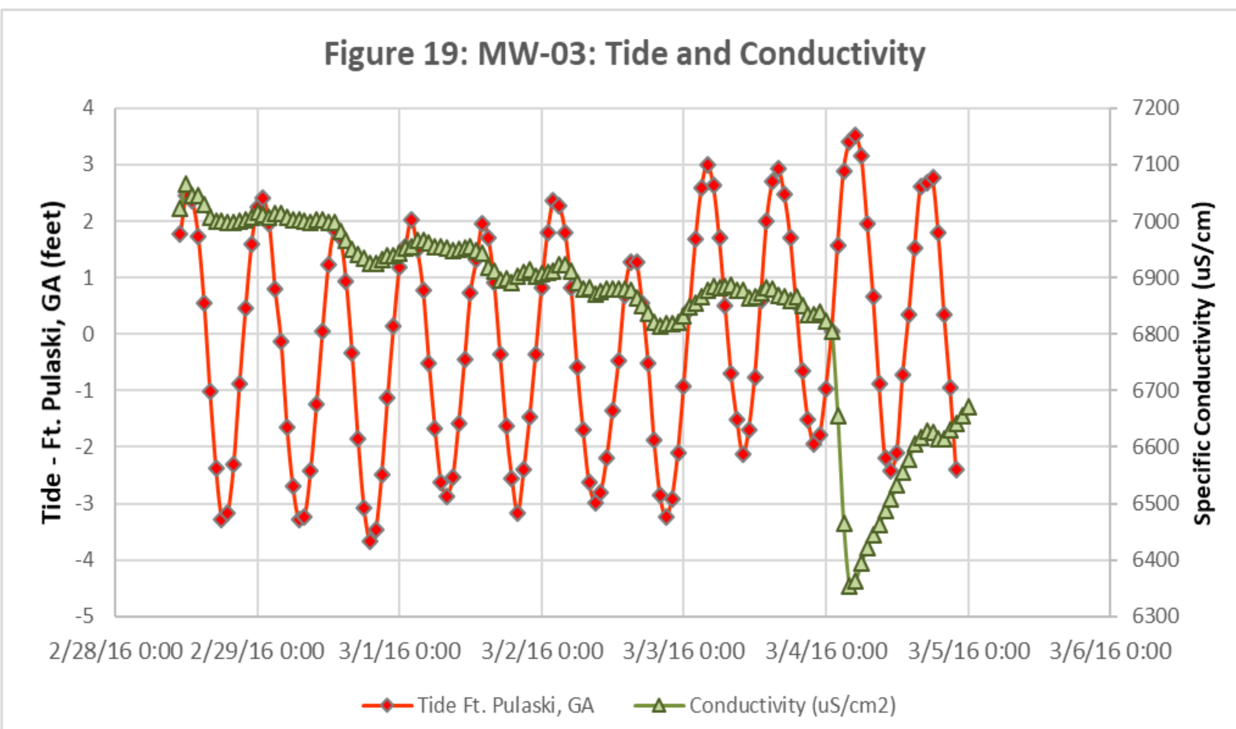

Figure 19: MW-03 Tide and Conductivity, correlation still present but less pronounced than MW-04

4.3 Geochemical

Figures 20 and 21 show evidence of saline water moving across a lateral path from the more saline waters of MW-04 to the relative freshwater MW-01. This is indicated by the decreasing (east-west) salinity (psu) and sulfate concentrations. Concentrations in salinity range from 5 psu in MW-04 to nearly 0 in MW-01.

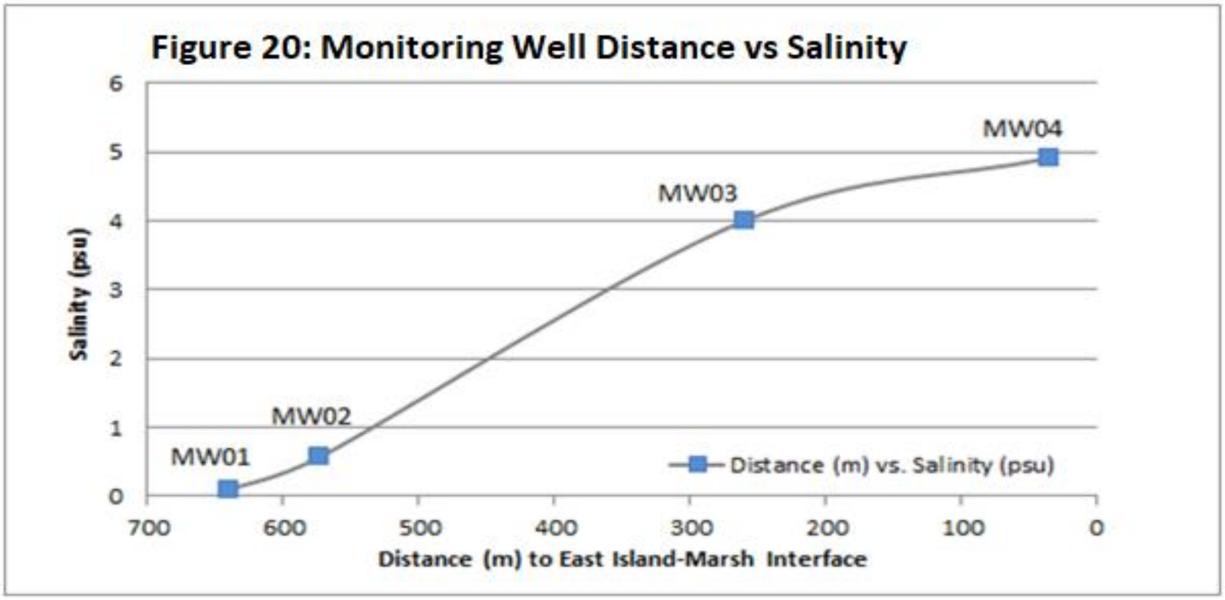

Figure 20: Monitoring well distance vs salinity relationship, with salinity values decreasing from MW-04 inland toward the west, indicating a saline source to the east

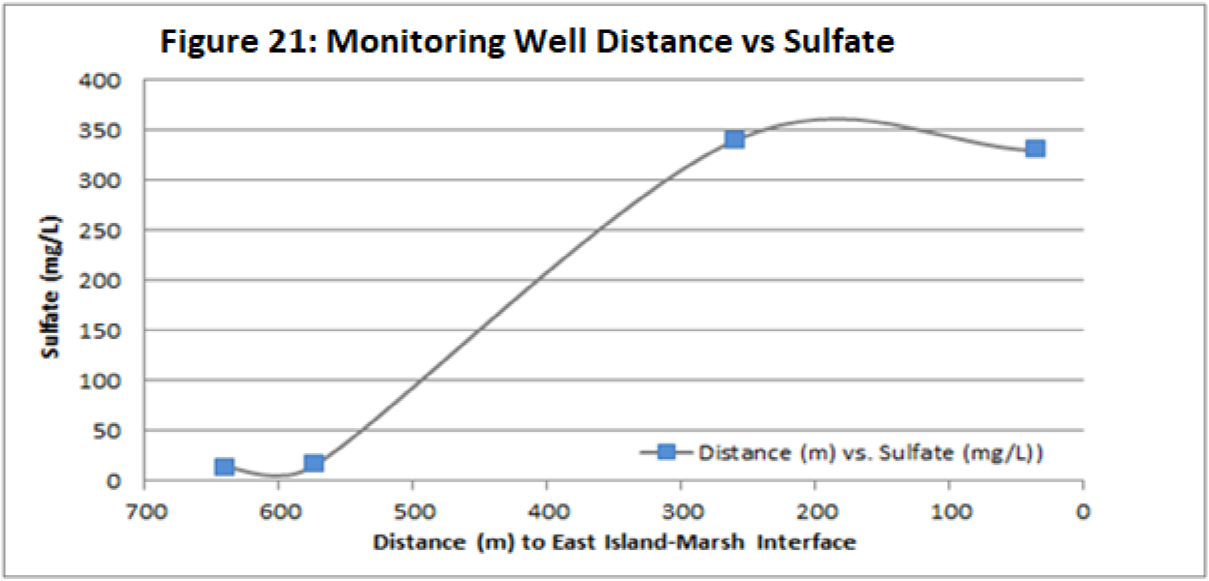

Figure 21: Monitoring Well Distance vs Sulfate, with sulfate levels decreasing from MW-04 inland toward the west, indicating a sulfate source to the east

The results of the monitoring well analyses (4) were plotted with the results of a surface water sample collected from Jones Creek, the intertidal surface water body to the east. The results are provided in Figure 22 and indicate the intertidal waters as the source of the saltwater intrusion by producing a classic linear mixing line. MW-04 nearly contains the same geochemistry as that of seawater. This is contrasted with the water sample from the underlying Upper Floridan aquifer, which is magnesium-bicarbonate dominated water.

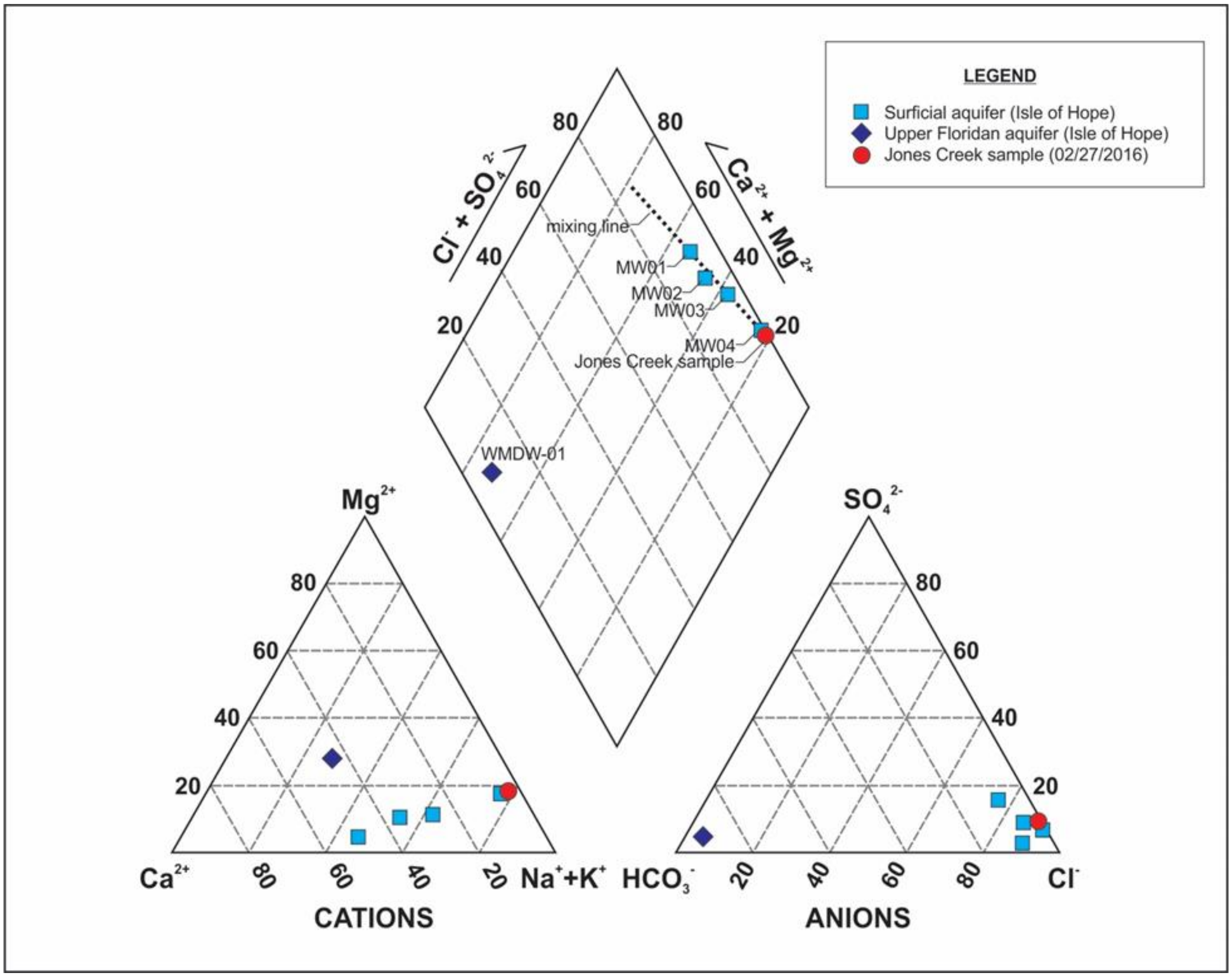

Figure 22: Piper Diagram Source Analysis

The EMMA shows further evidence of ocean derived saltwater as the chloride line trends from saline levels much closer to those of the marsh in chloride levels to freshwater at MW-01 from east to west. The results (Figure 23) indicate that MW04 is composed of 39% marine water, MW03 is composed of 30% of marine water, MW02 has 4% marine water, and MW01 is composed entirely of freshwater. The trend is that of pure seawater to brackish to freshwater as you move inland.

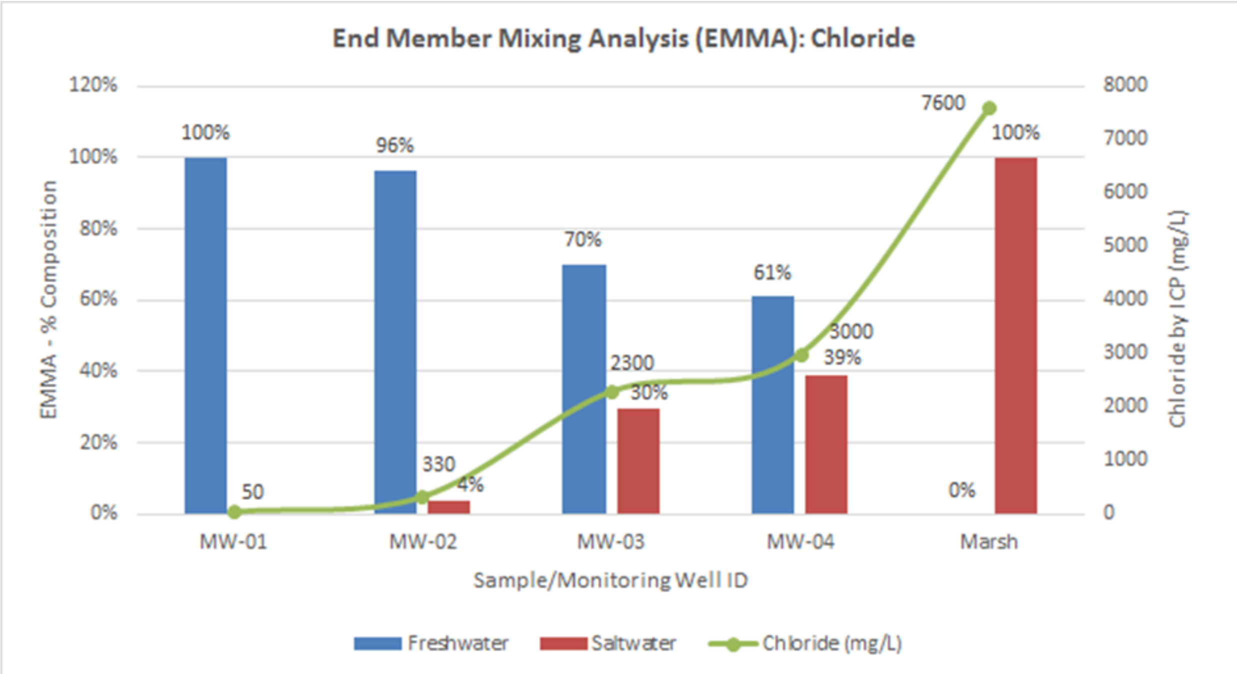

Figure 23: End Member Mixing Analysis (EMMA)

4.4 Aquifer Framework

GPR results give an indication of both the site history and pathways for saline intrusion. GPR transects indicate a clay confining layer or aquitard that is continuous beneath most of the surficial aquifer at a depth of approximately 20-24 feet below land surface, except in specific areas (Figure 24), and the presence of saline water near a large part of the island-marsh boundary where the GPR signal is significantly attenuated along the margins of the island as a result of saltwater intrusion. Synformal distortions can be seen in some areas in the aquitard.

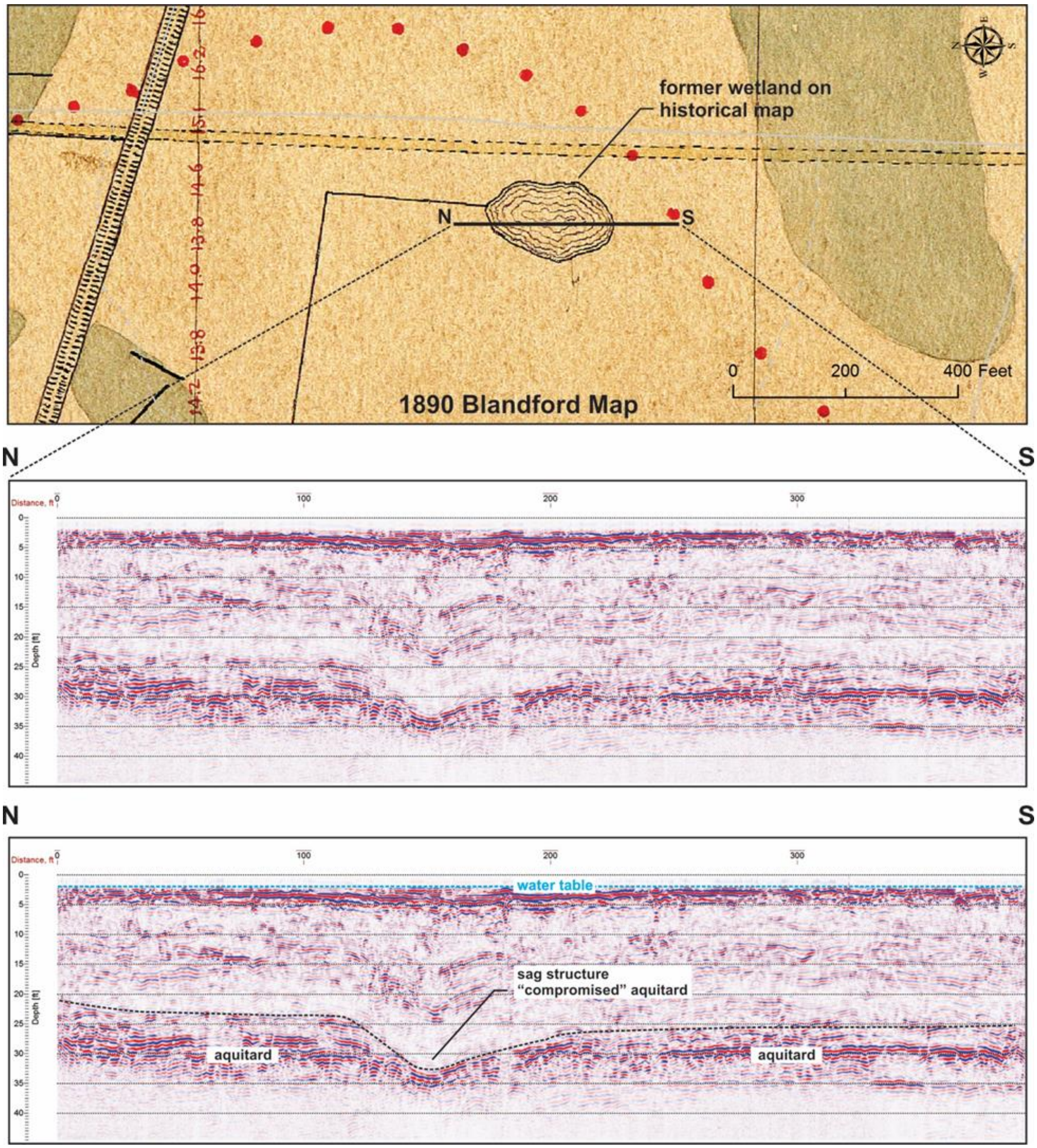

Figure 24: GPR Transect across the location of a former wetland at Wormsloe and 1890 map of site where sag structure location mirrors that of historical flowing wetland and the compromised clay aquitard

4.5 Evapotranspiration

Figures 25 and 26 show a diurnal change in groundwater levels, with that change being more pronounced in the summer than in the winter. The diurnal change in the water table of 1-3" (Figure 25) shows a clear evapotranspiration derived influence. MW-03 and MW-04 displayed too strong of a daily tidal flux in water levels to observe the trend as clearly. This effect is most likely occurring at the wells with saline intrusion as well, but further research is needed to conclude this.

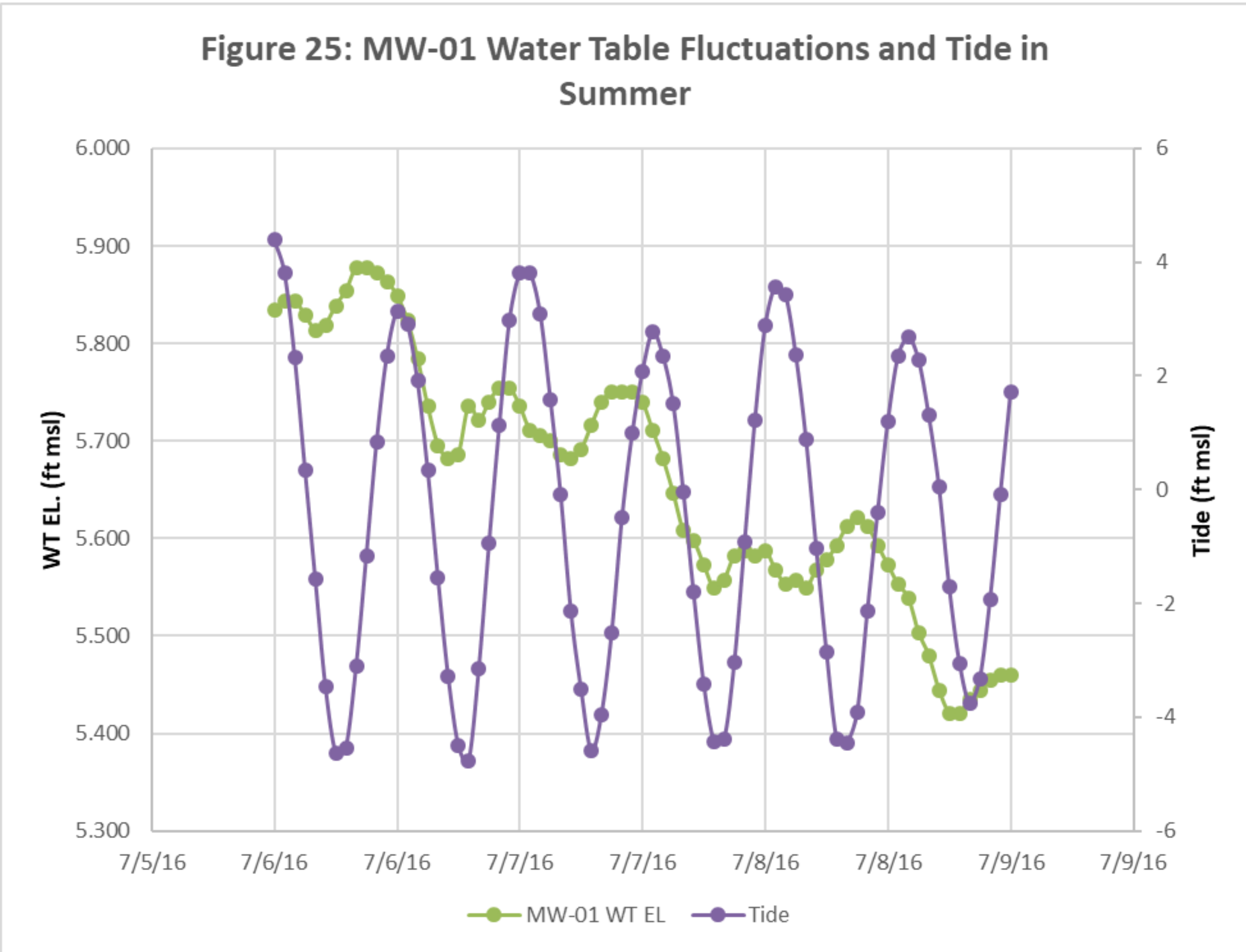

Figure 25: MW-01 Water Table Fluctuations and Tide in Summer, showing diurnal fluctuations

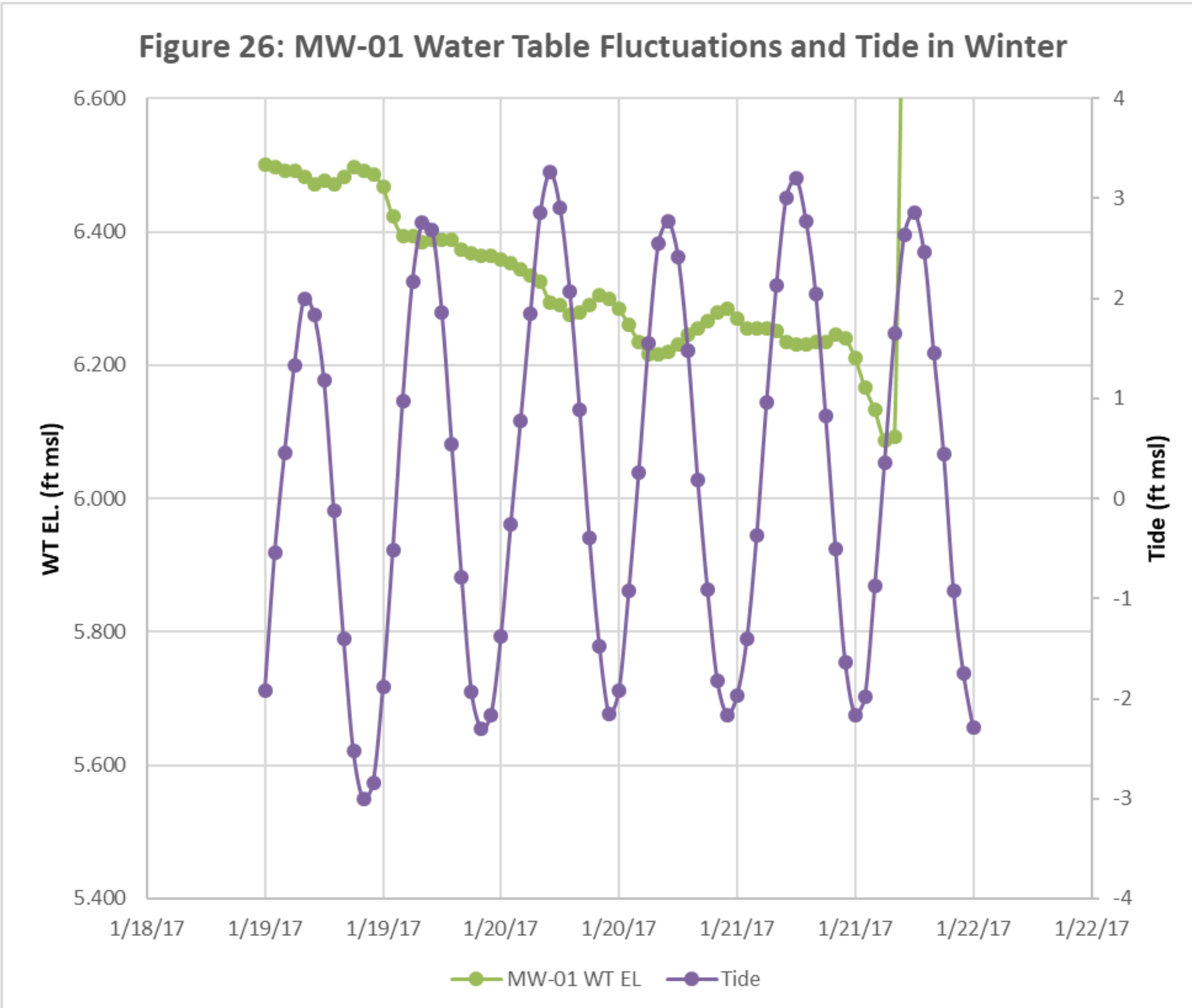

Figure 26: MW-01 Water Table Fluctuations and Tide in Winter, showing diurnal fluctuations, but less pronounced than in Summer

5 DISCUSSION

5.1 Evidence for Saltwater Intrusion

Since the mid twentieth century a cone of depression has developed around the Floridan aquifer due to aggressive pumping of the Upper Floridan aquifer centering around Savannah (Reichard et al, 2014). Baseline geochemical samples in the Wormsloe surficial aquifer showed brackish water present in the surficial aquifer and the EMMA also revealed a mixing of marsh derived saline water in MW's 03 and 04 that decreased further inland. Utilizing a 1983 UNESCO method where conductivity and temperature are used to derive salinity, saline intrusion was proven to be occurring year around with conductance as a reliable proxy for chloride levels, and definitive fluctuations were observed in the conductance levels over time.

5.2 Controls on Saltwater Intrusion

The monitoring wells revealed both strong tidal and precipitation controls on the timing and magnitude of saline intrusion. Conductivity readings move upwards when the tide arrives and fall back down when it moves out, showing a lateral preferred pathway originating at MW-04 for seawater through the surficial sedimentary layer. As the tide moves inward, the wells closest to the sea are inundated with saline water that replaces the freshwater due most likely to structures and depressions in the sedimentary layers containing the surficial aquifer that were previously under pressure (Westbrook et al, 2003). As the tide retreats, this effect dissipates, but a reduced chloride level remains in both wells. This provides strong evidence for coastal derived and tidal controlled saltwater intrusion.

As the recharge of the Upper Floridan aquifer and to a larger extent, the surficial aquifer is mostly controlled by precipitation (Clarke et al. 2011) we can see that rain events show a somewhat delayed but generally negative effect on conductivity and salinity while quickly raising water levels. The effects of Hurricane Matthew can be seen around 10/7/16 by the high-water level response and subsequent drop in conductivity for both wells (Figures 16 and 18). The low topography and shallow nature of the wells (all are between 7.6’-11’ above sea level) is another factor disposing them towards saline intrusion and overland flooding. There is a pronounced seasonal control visible in MW-04 and to a lesser extent MW-03 where conductivity is lower in the summer and higher in the fall and winter that mirrors decreased and increased precipitation amounts, respectively. The saltwater is most likely moving along openings derived from sagging structures (Vance et al, 2011) and Mesozoic basement fault reactivation (Dillon, Klitgord, and Paull, 1983) that is revealed by GPR. As observed in MW-01, changes in diurnal groundwater levels (Gribovski et al, 2008) could be causing saline intrusion flux from evapotranspiration as the Wormsloe site is covered in grasses, live oak, and pine which are active year around. Finally, Climate change and associated Sea Level Rise (SLR) could provide further pressure on the shallow aquifer system at Wormsloe by exacerbating the effects of over pumping.

5.3 Hydrogeological Framework

GPR results indicate that the confining layer underlying the surficial aquifer is compromised in select areas containing synformal distortions or sag structures with small-scale faulting, or the confining layer may be completely absent. These areas correlate strongly with wetlands that were formerly flowing from artesian wells during historical times, indicating a connection with the underlying Upper Floridan aquifer (Figure 27). Previous investigations regarding the connectivity between the surficial aquifer, Upper Floridan and Lower Floridan Aquifer systems along the Georgia Coast, including St. Catherines Island, have indicated that deep-seated fault systems have compromised the integrity of the confining layers that separate the various systems allowing for aquifer mixing (Krause and Clarke, 2001; Vance et al, 2016). These areas would have most likely served as areas of upward flow and there is a strong correlation between these areas and the occurrence of wetlands on historical maps (Figure 24 – Blandford Map).

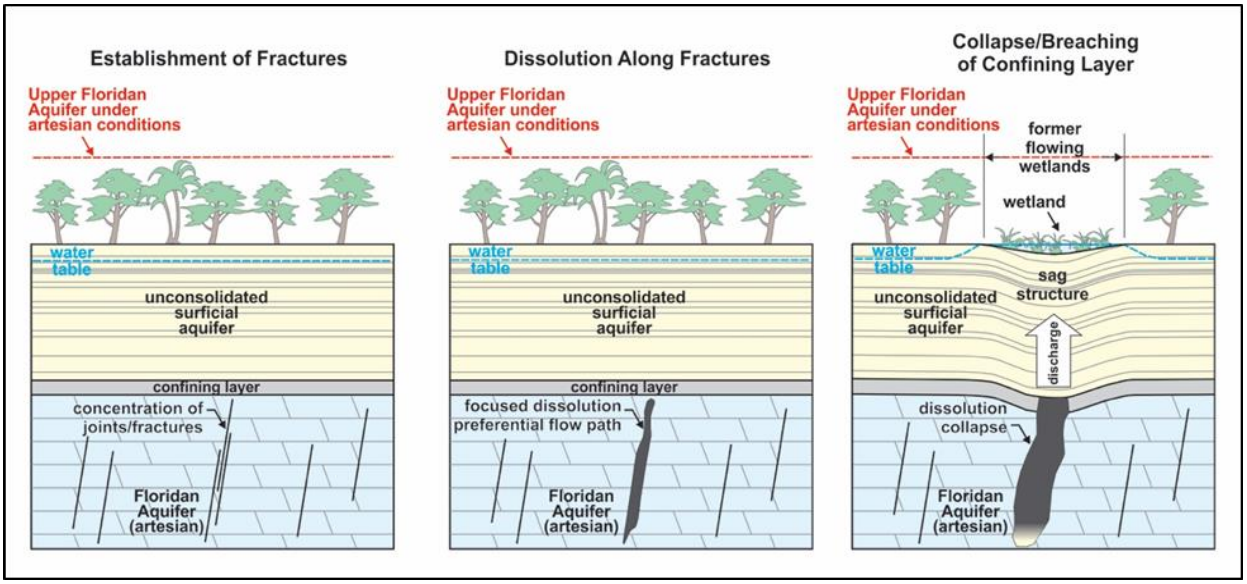

Figure 27: Development of Flowing Wetlands- Working Hypothesis

The trends of the formerly flowing wetlands at Wormsloe and at St. Catherines Island follow a strong N30°E or azimuth N210° trend (Figure 28). This trend is congruent with Triassic aged faults and joints (Tr3), thus preferential flow along these reactivated faults or fractures may have led to the development of karst features in the carbonate rocks of the Upper Floridan aquifer and compromising of the overlying confining layer (Vance et al, 2016).

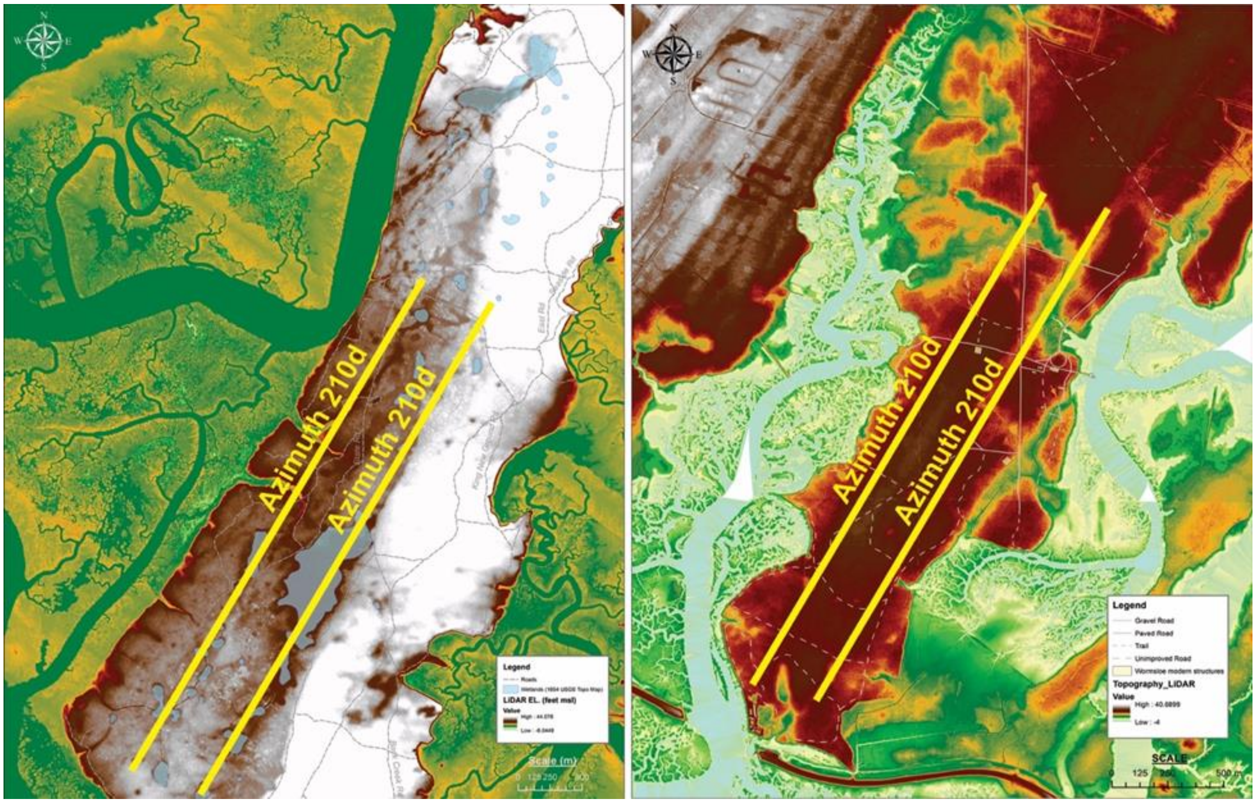

Figure 28: Formerly Flowing Wetlands- Spatial Trends: St. Catherines Island (left) and Wormsloe (right)

By integrating the GPR, hydraulic head and salinity data, a working hydrogeological conceptual model is created that demonstrates the relationship whereby lateral saltwater intrusion could be conveyed downward with the potential to impact the Upper Floridan aquifer (Figure 29 – Salinity and Hydrogeology; Figure 30 - Hydrogeological Conceptual Model).

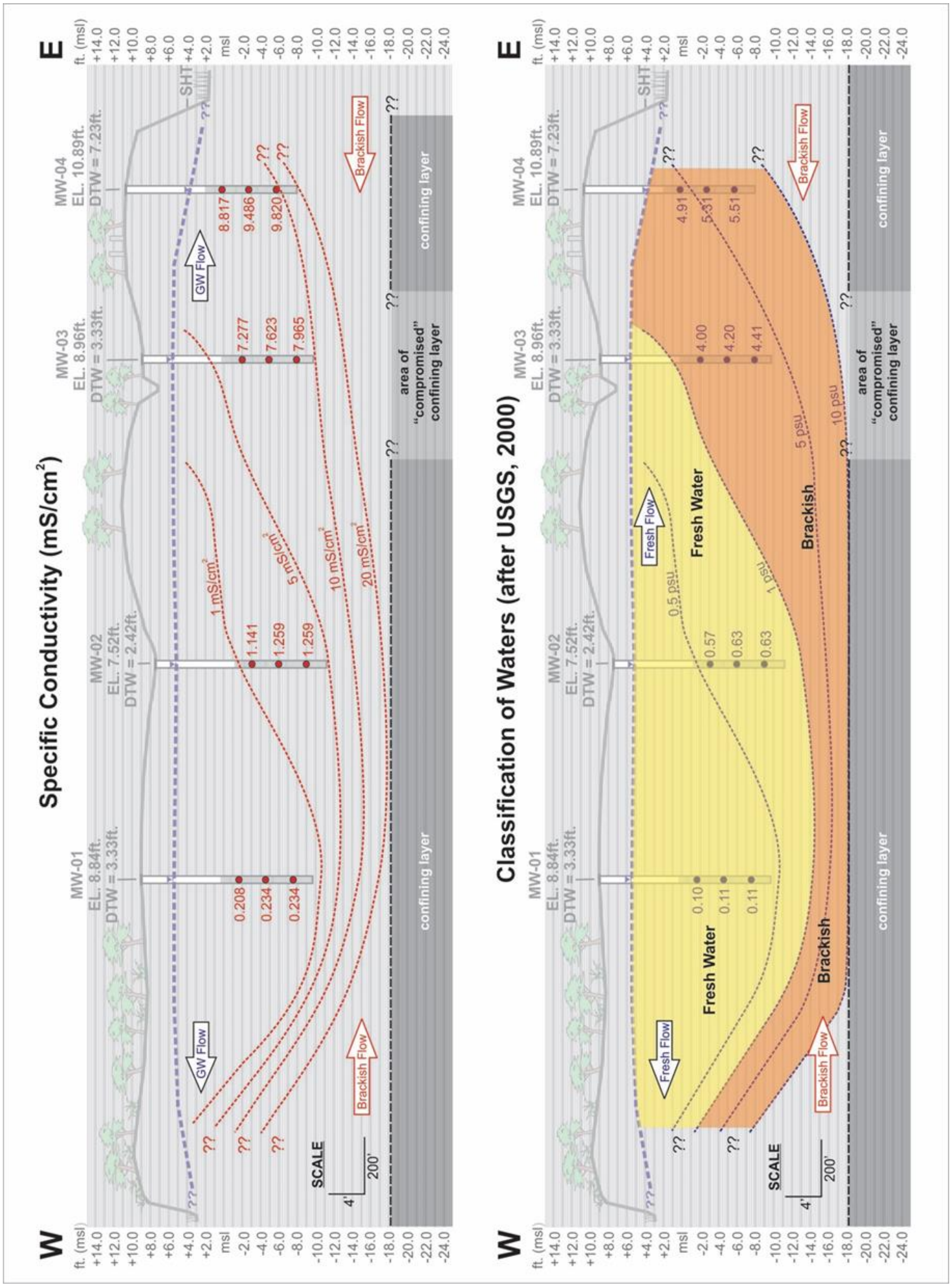

Figure 29: Salinity and Hydrogeology -

Created from water samples taken at 3 discrete depths for each well. Shows brackish flow moving inland from marsh environments and freshwater flow moving in opposite direction

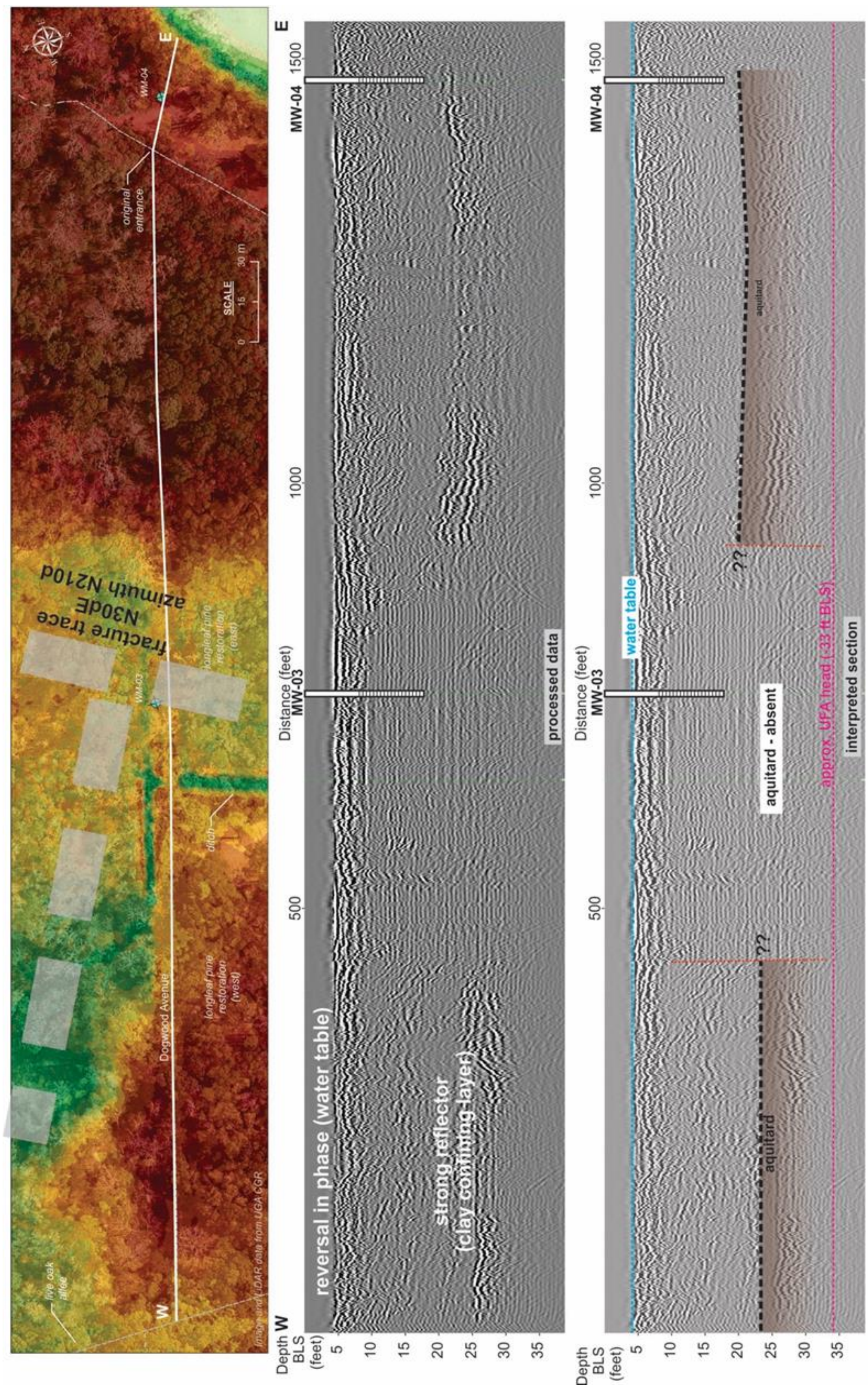

Figure 30: Hydrogeological Conceptual Model showing confining aquitard completely absent under MW-0, head relationships and potential downward conveyance of brackish water.

5.4 Potential for Future Research

The collection of water level, temperature, and SC reading should continue to assess changes over time and in response to additional hurricane events. A method for protecting the conductivity probes from sediment and corrosion should be considered to achieve more continuous data from them. An additional 1-2 monitoring wells on the western side of the island would complete a transect and allow a more complete picture of saline water movement from both sides. A study of the transpired water of the plants of the isle could combine both groundwater levels and isotopic reading to get an idea of the effect of evapotranspiration on saltwater levels, and the impact that this might have on plants in the future as available freshwater is reduced. To continue assessing the hydrogeologic history of the site, shallow cores could be taken and analyzed for both sediment content as for their palynology to obtain a greater understanding of the transition from artesian conditions and constant wetlands to near almost year- around dryland. Continued monitoring and expansion of the monitoring network should be performed to evaluate the impacts of SLR on the salinity of the surficial aquifer. Interconnections between the surficial and UFA systems indicate risks whereby lateral saltwater intrusion could ultimately infiltrate downward (Figure 31)

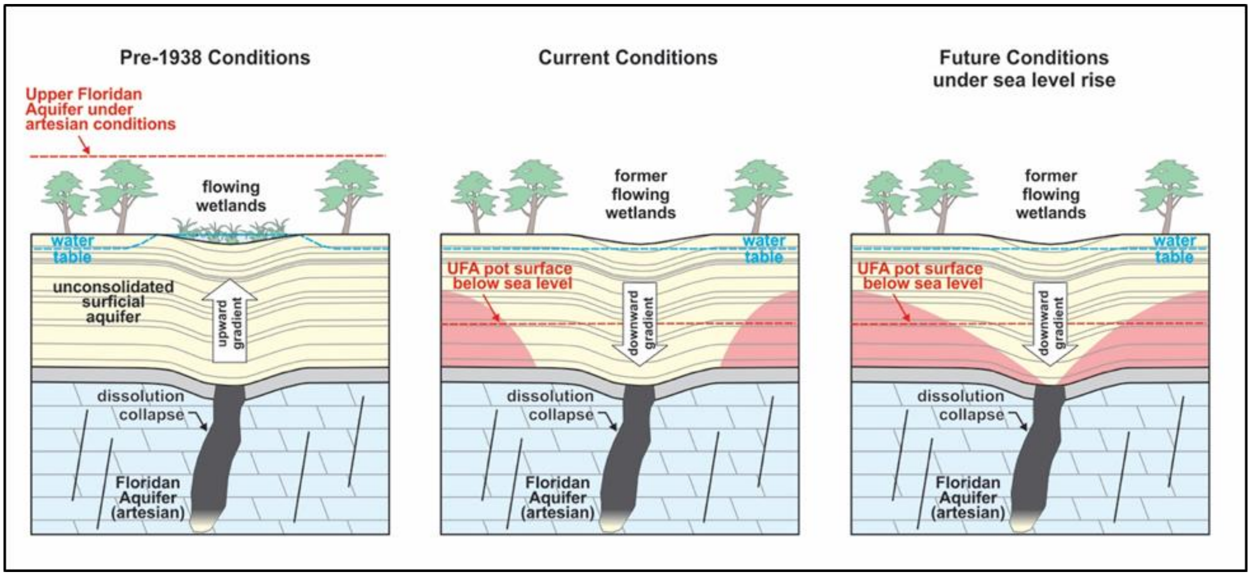

Figure 31: Potential Future Risks of Lateral Saltwater Intrusion under Sea Level Rise

6 CONCLUSIONS

The purpose of this study was to show evidence for lateral saltwater intrusion and find out what the controls on it are. Four shallow monitoring wells were installed on an east-west transect of the island and measurements of conductivity combined with temperature data showed strong evidence of ocean derived saltwater intrusion. These data were corrected and plotted to be compared with tidal, precipitation, and structural information. These comparisons showed a strong tidal influence from marsh derived coastal water moving inward, as well as precipitation controls, where the saline intrusion levels were higher during months of less rainfall. Structural findings from GPR showed the possible conduits for this intrusion that were previously under artesian pressure and created flowing wetlands have most likely been reversed from over pumping near Savannah. Integration of the multiple lines of evidence indicate risks whereby lateral saltwater intrusion could eventually be conveyed downward under continued SLR, with the potential to impact the Upper Floridan aquifer, or the regions potable water aquifer in the future.

REFERENCES

Barlow, P.M., 2003. Ground Water in Freshwater-Saltwater Environments of the Atlantic Coast. USGS Circular 1262, U.S. Geological Survey, pp. 113.

Bryan, Jonathan, Virginia S. Wood, and Mary R. Bullard. Journal of a Visit to the Georgia Islands of St. Catherines, Green, Ossabaw, Sapelo, St. Simons, Jekyll, and Cumberland, with Comments on the Florida Islands of Amelia, Talbot, and St. George, in 1753. Vol. 22. Mercer University Press, 1996.

Bush, Chelsea E., Lori A. Farley, and Tim J. Herold. "Evidence for Shallow Saltwater Intrusion: Wormsloe State Historic Site, Chatham County, Georgia." (2016).

Chowns, T. M., and C. T. Williams. "Pre-Cretaceous rocks beneath the Georgia coastal plain." US Geological Survey Professional Paper (1983): 1-42.

Clarke, John S., and Richard E. Krause. "Use of ground-water flow models for simulation of water-management scenarios for coastal Georgia and adjacent parts of South Carolina." Georgia Institute of Technology, 2001.

Conrads, Paul A., et al. Simulation of salinity intrusion along the Georgia and South Carolina coasts using climate-change scenarios. US Department of the Interior, US Geological Survey, 2013.

Douglas, Jim, 2010 Conductivity-to-salinity-conversion for html http://jimbodouglass.blogspot.com/2010/11/conductivity-to-salinity-conversion-for.html

Clarke, J.S., Cherry, G.C., and Gonthier, G.J., 2011, Hydrogeology and water quality of the Floridan aquifer system and effects of Lower Floridan aquifer pumping on the Upper Floridan aquifer at Fort Stewart, Georgia: U.S. Geological Survey Scientific Investigations Report 2011–5065, 59 p.

Dillon, William P., Kim D. Klitgord, and Charles K. Paull. Mesozoic development and structure of the continental margin off South Carolina. US Department of the Interior, Geological Survey, 1983.

Falls, W.F., Ransom, C., Landmeyer, J.E., Reuber, E.J. and Edwards, L.E., 2005. Hydrogeology, water quality, and saltwater intrusion in the upper Floridan aquifer in the offshore area near Hilton Head Island, South Carolina, and Tybee island, Georgia, 1999 - 2002, US Geological Survey, Scientific Investigations Report.

Gawne, C.E., 1997, Correction for tidal effects on water-level measurements in Floridan aquifer wells, southern coast of South Carolina, in Contributions to the hydrology of South Carolina: South Carolina Department of Natural Resources, Water Resources Division Report 14, p. 1–17.

Gribovszki, Z., P. Kalicz, J. Szila´gyi, and M. Kucsara (2008), Riparian zone evapotranspiration estimation from diurnal groundwater level fluctuations, J. Hydrol., 349, 6 – 17.

Jones, L.E., Prowell, D.C., and Maslia, M.L., 2002, Hydrogeology and Water Quality (1978) of the Floridan Aquifer System at U.S. Geological Survey Test Well 26, on Colonels Island, near Brunswick, Georgia: U.S. Geological Survey Water-Resources Investigations Report 02-4020, 46 p.

Kentel, Elçin, Harold Gill, and Mustafa Mehmet Aral. "Evaluation of groundwater resources potential of Savannah Georgia region." (2005).

Krause, Richard E., and Robert B. Randolph. Hydrology of the Floridan aquifer system in southeast Georgia and adjacent parts of Florida and South Carolina. Department of the Interior, US Geological Survey, 1989.

Kundzewicz, Zbigniew W., et al. "The implications of projected climate change for freshwater resources and their management." Hydrological sciences journal 53.1 (2008): 3-10.

Landmeyer, J.E., and Belval, D.L., 1996, Water chemistry and chloride fluctuation in the Upper Floridan aquifer in the Port Royal Sound area, South Carolina, 1917–93: U.S. Geological Survey Water-Resources Investigations Report 96-4102, 106 p.

Leeth, D.C., Clarke, J.S., Wipperfurth, C.J., and Craigg, S.D., 2005, Ground-Water Conditions and Studies in Georgia, 2002– 03: Reston, Va., U.S. Geological Survey Scientific Investigations Report 2005-5065, 128 p.

Leve, G.W., 1983, Relation of concealed faults to water quality and the formation of solution features in the Floridan aquifer, northeastern Florida: Journal of Hydrology, v. 61, no. 1/3, p. 251-264.

Meyer, Brian K., 2016. Insights into the Hydrologic History of Wormsloe. Wormsloe Institute for Environmental History, 2016 Research Symposium, Athens, Georgia, 07 April 2016.

Milne, G.A., Gehrels, W.R., Hughes, C.W. and Tamisiea, M.E., 2009. Identifying the causes of sea-level change. Nature Geoscience, 2(7), p.471.

Nevada, Hydrology Piper Plot for Excel (2005).
https://nevada.usgs.gov/tech/excelforhydrology/.../PiperPlot-QW.XLS

Nicholls, Robert J., and Anny Cazenave. "Sea-level rise and its impact on coastal zones." science 328.5985 (2010): 1517-1520.

Payne, Dorothy F. (2010), Effects of climate change on saltwater intrusion at Hilton Head Island, SC. U.S.A., SWIM21 - 21st Salt Water Intrusion Meeting, 21-26 June 2010, Azores, Portugal, pp. 293-296.

Provost, A. M., Payne, D. F., and Voss, C. I. (2005). "Simulation of saltwater movement in the Upper Floridan aquifer in the Savannah, Georgia-Hilton Head Island, South Carolina, area, predevelopment-2004, and projected movement for 2000 pumping conditions." Scientific Investigation Report 2006-5058.

Reichard, J.S., Nelson, B.R., Meyer, B.K. and Vance, R.K., 2014. Evidence for Saltwater Intrusion in the Upper Floridan Aquifer on St. Catherines Island, Georgia. Southeastern Geology, 50(3).

Robinson, M.A., Gallagher, D.L., Reay, W.G., 1998. Field observations of tidal and seasonal variations in ground water discharge to estuarine surface waters. Ground Water Monitoring and Remediation 18 (1), 83–92.

Smith, A.J., Turner, J.V., 2001. Density-dependent surface water– groundwater interaction and nutrient discharge in the SwanCanning Estuary. Hydrolological Processes 15, 2595–2616.

Spechler RM (1994) Saltwater intrusion and quality of water in the Floridan aquifer system, northeastern Florida. US Geol Surv Water-Resour Investigation Report 92-4174

Thorburn PJ, Hatton TJ, Walker GR. 1993. Combining measurements of transpiration and stable isotopes of water to determine groundwater discharge from forests. J. Hydrol. 150:563–87.

UNESCO (1983). Algorithms for computation of fundamental properties of seawater. UNESCO Technical Papers in Marine Science No. 44.

USGS, 2000. Hydrogeology and the Distribution of Salinity in the Floridan Aquifer System, Palm Beach County, Florida. Water-Resources Investigations Report 99–4061, 59 pp.

Vance, R. Kelly, Meyer, Brian K., and Reichard, James S., 2016. Structural Controls on the Hydrology of Two Georgia Barrier Islands. Southeastern Section Geological Society of America, 65th Annual Meeting, Columbia, SC.

Vance, R. K., Bishop, G. A., Meyer, B. K., Rich, F., and Reichard, J.S., 2011a, St Catherines Island, Georgia: Sag Structures, Hydrology and Sea Level Rise: Geological Society of America Abstracts with Programs, Southeastern Section Meeting, v. 43, n. 2, p. 81.

Vera, Irany, Ismael Mariño-Tapia, and Cecilia Enriquez. "Effects of drought and subtidal sea-level variability on salt intrusion in a coastal karst aquifer." Marine and Freshwater Research 63.6 (2012): 485-493.

Westbrook SJ, Rayner JL, Davis GB, Clement TP, Bjerg PL, Fisher SJ. 2005. Interaction between shallow groundwater, saline surface water and contaminant discharge at a seasonally- and tidally-forced estuarine boundary. Journal of Hydrology 302: 255–269.

Williams, L.J., and Gill, H.E., 2010, Revised hydrogeologic framework of the Floridan aquifer system in the northern Coastal area of Georgia and adjacent parts of South Carolina: U.S. Geological Survey Scientific Investigations Report 2010–5158, 103 p., 3 pl.

Wilson, S.G. and Fischetti, T.R. (2010). Coastline Population Trends in the United States: 1960 to 2008. U.S. Census Bureau, U.S. Department of Commerce, Publication P25-1139, pp.1-27.