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Characterizing Temporal Dynamics of Isotope and Ion Chemistry in Groundwater Across a Barrier Island as Influenced by Rainfall and Tidal Cycles.

by

Subhashi Karunarathne

Under the Direction of Luke Pangle, PhD

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 2022
ABSTRACT

Saltwater intrusion into coastal aquifers poses a threat to drinking water sources. We evaluate the plausibility of saline-water intrusion into the Surficial Aquifer of a barrier island on Georgia’s coastal plain. Using a transect of shallow wells, we monitored groundwater levels, specific conductivity, chloride concentration, and the $\delta^{2}H$ and $\delta^{18}O$ within groundwater. We sampled precipitation and water in an adjacent tidal creek to evaluate the mixing of components. We test a conceptual model that predicts enhanced saline water intrusion along island margins and lesser saline water intrusion toward the island interior. This conceptual model was not completely verified. Instead, specific conductivity and chloride concentrations in groundwater were greatest at an inland location, not at the island margin. Overall, the isotope composition of all groundwater samples paired with hydrometric and tidal data seems to suggest marginal water delivery from the coastal rivers into the terrestrial aquifer, except in areas proximal to a relic drainage ditch that apparently serves as a preferential flow pathway for highly saline water into the island interior.

INDEX WORDS: Coastal aquifer, isotope study, groundwater
Characterizing Temporal Dynamics of Isotope and Ion Chemistry in Groundwater Across a Barrier Island as Influenced by Rainfall and Tidal Cycles.

by

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May 2022
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1 INTRODUCTION

Groundwater is the largest source of global freshwater, providing potable water for more than two billion people worldwide (Taylor, et al., 2013). The Upper Floridan Aquifer (UFA) system provides potable fresh water to more than half of the combined population in Georgia, Alabama, Florida, and South Carolina. Nearly 22% of the total freshwater demand of Georgia is obtained by pumping 1.45 billion gallons of groundwater per day from the UFA (Priest, 2007; Fanning, 2003).

Coastal aquifers are under much stress due to long-term, extensive utilization of the aquifers, construction of irrigation systems manipulating the surface and groundwater, and saltwater intrusion due to sea-level rise (Ajami, 2021). Such factors impose changes on the sensitive balance of the freshwater-saltwater boundary (Krause, 1997; Ataie-Ashtiani, et al., 2001; Conrads, et al., 2013), contribute to declining groundwater levels (Clarke, et al., 1990), and negatively impact groundwater quality (Priest, 2007). However, Global Climate Models show that over-extraction of groundwater has resulted in more saltwater intrusion and groundwater quality deterioration in coastal aquifers than projected sea-level rise (Ferguson & Gleeson, 2012). Ferguson and Gleeson (2012) utilized a modified analytical model of how much the coastal aquifer is vulnerable to saltwater intrusion by sea-level rise or groundwater extraction. Their study shows that aquifers with very low hydraulic gradients are more likely to be impacted by saltwater intrusion due to sea-level rise.

The most productive aquifer systems for groundwater supply in Georgia are found in the coastal region. Groundwater is mainly pumped from the UFA and Brunswick aquifer systems, both considered confined over much of their extent, and an unconfined aquifer colloquially named the
Surficial Aquifer (Miller, 1990; Randolph, et al., 1991; Clarke J. S., 2003). The primary issue with pumping water from these aquifers is that saltwater intrusion can happen horizontally and vertically through the aquifer systems. Heavy groundwater pumping forms cones of depression in the aquifer, which can change groundwater flow directions and alter groundwater quality (Taylor & Alley, 2001). In places with a downward hydraulic gradient, along with either discontinuities or relatively high permeability areas of aquitards, the Surficial Aquifer recharges the UFA (Randolph, et al., 1991). Therefore, if the Surficial Aquifer gets salinized, the UFA experience saline water intrusion through these flow pathways (Figure 1.1). Chloride concentrations increase in Southern Georgia with a downward gradient, and shallow groundwater infiltrates the underlying aquifer systems locally due to the construction of wells and local geology (Clark, et al., 1997). However, Reichard, et al., (2012) shows that the Surficial Aquifer on St. Catherines Island has [Cl⁻] of two to four times greater than in the UFA, which raises the question of whether the Surficial Aquifer is the source of saltwater intrusion to the UFA in all locations. Reichard, et al., (2012) also shows through Piper diagram analysis that modern sea-water is not plotting along the observed mixing line of the UFA, yet chemical data from mainland Lower Floridan aquifer plot on the upgradient side of the observed mixing line. This could mean saltwater intrusion in the UFA on St. Catherines Island occurs through upward saline water movement more from the Lower Floridan aquifer and vertical fractures or faults.

However, as the UFA provides nearly 59% of the total groundwater demand of Coastal Georgia (Water Plan, 2020), saltwater intrusion can impose a threat to the freshwater supply (Reichard et al., 2014).
Figure 1.1: Illustration of submarine groundwater discharges and sea-water intrusion in Savannah Georgia adapted from the study (Foyle & Henry, 2002). According to Foyle et al., (2002), the study area shows a landward hydraulic gradient promoting sea-water intrusion.

In addition to pumping, other conditions such as tides (Ataie-Ashtiani, et al., 1999; Ataie-Ashtiani, et al., 2001; Park & Aral, 2008), precipitation (Almanaseer & Sankarasubramanian, 2012), and evapotranspiration (Condon, et al., 2020) could have an impact on the groundwater dynamics in coastal aquifers. Groundwater level fluctuation in Georgia generally shows a cyclic and seasonal pattern. Higher water levels are observed in winter and spring due to decreased evapotranspiration and increased recharge by precipitation. During summer and fall, the groundwater level drops as evapotranspiration and pumping decrease further recharge (Peck, et al., 2011).

1.1 The objective of the study

The study’s main objective is to identify relationships between tidal fluctuations and salination of the Surficial Aquifer at Wormsloe State Historic site on the Isle of Hope. Because of the marshy and wetland conditions of the site, there could be a higher effect on the Surficial Aquifer by the
tides. If salination of the aquifer occurs due to the tidal effect, that can pose a disadvantage to the water quality of the UFA in places with a downward hydraulic gradient from the Surficial Aquifer to the UFA. We hypothesize that groundwater’s ion and isotope chemistry will change systematically from the island margins to the interior, becoming less saline and isotopically akin to the tidally influenced water surrounding coastal rivers. The anticipated contribution of this research is an empirical test of this general conceptual model, which will inform efforts to identify areas with varying risks of saline water intrusion to the underlying UFA. The study also aims at identifying any changes occurring in the salination of the aquifer because of historical landscape alteration by human activities in the study area.
2 LITERATURE REVIEW

2.1 Coastal hydrogeology of Georgia

Geography on the coast of Georgia between the mainland and the barrier islands consists of alternating series of riverine and ocean-dominated bar-built systems with salt marshes and tidal creek networks (Dame, et al., 2000). The subsurface houses a series of aquifers, variably separated by aquitards (Figure 2.1) named the Surficial, Brunswick, Upper Floridan, Lower Floridan, Gordon, Claiborne, Clayton, and Cretaceous. The Surficial Aquifer is a shallow, unconfined aquifer with unconsolidated, sand-textured, marine-terrace deposits of Pleistocene age as aquifer material and Holocene sandy, terrestrial deposits, and less pervasive silt- to clay-textured materials (Miller, 1990; Randolph, et al., 1991; Clarke J. S., 2003). The finer-textured sediments in the Surficial Aquifer may act as aquitards and result in local semi-confined conditions (Miller, 1990). Figure 2.1 (b) shows the thicknesses of the Surficial Aquifer, reaching a maximum thickness of 200 ft in Glynn County and a 100 ft in Chatham County. The Surficial Aquifer has an average yield of about 2-25 gal/min and a maximum yield of 75 gal/min (Peck, et al., 2011). The permeability of the Surficial Aquifer is variable due to the lithological variations laterally and vertically. The Surficial Aquifer has a transmissivity of about 100 – 1000 ft²/day (Clarke, et al., 1990).

The UFA is a highly productive aquifer pumped for the water necessities in the coastal regions of Georgia. Heavy pumping of the UFA causes a decline in water levels in Savannah (Krause & Randolph, 1989; Payne & Voss, 2006). Studies conducted in the coastal region of Georgia, South Carolina, and Florida have shown that there is leakage of saltwater into the UFA (Figure 1.1) from the overlying aquifer systems through flow paths, highly permeable paleochannel material, and
small-scale fault conduits in the confining layers in between the aquifer systems (Foyle, et al., 2002; Payne & Voss, 2006; Jasechko, et al., 2020; Project, 2007; Bush, et al., 2016; Vance, et al., 2016; Reichard, et al., 2012). Sea-water encroachment in the Surficial Aquifer is more prominent during drought because of lower water levels (Foyle & Henry, 2002).

2.2 Tidal impact on the groundwater levels and saltwater intrusion

Furthermore, coastal aquifers have complex groundwater dynamics with flow variability in space and time due to changes in hydraulic gradient (Li et al., 1999; Li and Jiao, 2003), waves, and tides (Taniguchi et al., 2002; Burnett et al., 2003), dispersive circulation along the freshwater-saltwater boundary (Kohout, 1960), and changes in upland recharge (Michael et al., 2005). Even the impact of these forces changes from one location to the other. The Surficial Aquifer also has a water level that fluctuates in response to weather patterns and tidal cycles (Bush, et al., 2016) as the aquifer is mostly unconfined (Peck, et al., 2011). The water table along the coastal region varies around 5 ft below the land surface and increases gradually towards inland regions.

Groundwater levels in the aquifers rise and fall as sea-water penetrates in and out of the aquifer material, respectively, in response to the tidal cycle. Depending on the permeability of the aquifer material and the distance of the aquifer from the coast, the response to the tidal rise and fall in the water level can have a delay from the rise and fall of tide in the ocean (Jiao & Post, 2019; Ataie-Ashtiani, et al., 2001; Ataie-Ashtiani, et al., 1999). Clarke and others 1990 composed a map (Figure 2.2) on the extent of the tidal effect in the Eastern coastal region. The region to the east and southeast of the 20 ft contour line in the map shows the highest impact on groundwater from the tidal cycle (Clarke et al., 1990).
Figure 2.1: (a) is a model of geological units and hydrogeological units in Coastal Georgia (b) is a map of the Surficial Aquifer thickness using data published by U. S. Geological Survey (Gill, et al., 2011). (c) principal aquifers found in Georgia
Figure 2.2: Estimated water-table level in the coastal region of the Surficial Aquifer. The approximate limit of tidal influence is indicated with the single dashed line (Clarke, et al. 1990)
Tidal fluctuation impacts groundwater from a diurnal temporal scale to spring and neap tide scale controlled by the lunar calendar (Burgess, et al., 2017). Previous studies show that diurnal fluctuations of tides result in saltwater intrusion into the aquifer at Isle of Hope (Bush, et al., 2016). As the saltwater-freshwater interface at the intertidal zones is highly dynamic due to the tidal fluctuations and groundwater flow conditions, it is difficult to quantify the saltwater intrusion with a numerical solution. Generally, the seawater-freshwater interface shows dynamic seawater-freshwater fingering because of density differences (Park & Aral, 2008).

Groundwater mixing between the saltwater and freshwater occurs when saltwater from the tide intrudes on the aquifer. Groundwater mixing can happen on different scales, with different recharge sources and flow paths. Mixing models techniques can quantify and identify the sources and sinks of saltwater intrusions. The variables measured in mixing models are concentrations of conservative tracers like Cl\(^-\), δD, and δ\(^{18}\)O measured in the aquifers and suspected sources. (Gregg, 1966; Ataie-Ashtiani, et al., 1999). Tracers are used as markers that follow the water flow; thus, they could give information about hydraulic conductivity, porosity, dispersity, etc., by identifying and quantifying the phase changes like evaporation, condensation, and sublimation (Davis, et al., 1985; Leibundgut et al., 2009). End member mixing model results obtained by Williams, (2019) at the study area show a mixing gradient of saline water and freshwater of the groundwater near the coast to the groundwater inland (Figure 2.3). In Figure 2.3, MW-01, MW-02, MW-03, and MW-04 are the monitoring wells of the well transect. Saltwater intrusion occurs with lateral intrusion greater on the eastern edge of the Isle of Hope, governed by diurnal tidal pumping (Williams, 2019; Bush, et al., 2016). During an end-member mixing analysis, it was found that MW04 has 39% marine water, MW03 has 30% marine water, MW02 has 4% marine water, and
MW01 has entirely freshwater (Figure 2.3). The samples for the analysis were collected on 1/22/2016, four days after the neap tide, and the model in Figure 2.3 shows conditions under the neap tide.

![End Member Mixing Analysis (EMMA): Chloride](image)

**Figure 2.3:** End member mixing analysis of chloride samples from the wells MW-01, MW-02, MW-03 and MW-04 (Williams, 2019).

### 2.3 Precipitation and evapotranspiration impact groundwater

In the Southeastern U.S., the recharge and discharge of groundwater are influenced by winter precipitation in January, February, and March and summer precipitation in July, August, and September (Almanaseer & Sankarasubramanian, 2012). Groundwater tables show fluctuations corresponding to evapotranspiration in riparian wetland and semi-arid regions. When the trees are metabolizing under sunlight, trees transpire and pull soil moisture during the daytime. In an area with dense tree coverage or specific plant species that transpire, more groundwater level depletion can be observed. In contrast, groundwater rises back to the original piezometric level when the
trees do not transpire during the night. Due to evapotranspiration, this rise and fall create a diurnal pattern in the groundwater level (Condon, et al., 2020; White, 1932; Gribovszki, et al., 2008).
3 METHODOLOGY

3.1 Study area

The study area is in the Wormsloe State Historic site located at the Isle of Hope, Savannah. Wormsloe Historic site is a monument of the initial Euro-American colonialization of Georgia. It is in the southeast portion of Chatham County, Georgia. The Isle of Hope is a marsh island between Skidway Island and the Georgia mainland. The average elevation (Figure 3.1) of the island is 16 ft above the mean sea level (MSL) (Bush, et al., 2016).

A monitoring well network located in the Isle of Hope was used for the sample collection and water level monitoring for the study. The well network consists of 4 monitoring wells located in an east-west transect. A human-made canal is located close to MW-03, bringing brackish water inland from the tidal creek to the east of the well transect.

Figure 3.1: Digital Elevation Model of the study area; four monitoring wells are in an East-West transect (Williams, 2019). MW-01 and MW-02 are on the margin of a grass field next to a forested land in the lowest elevated region of the study area. MW-03 is located by an endpoint of a manmade canal from the tidal creek to the east (a distributary of Skidway River). The canal directs tidal water about 100 m inland during high tide but does not reach the well. MW-04 is located closest to Jones creek at the highest elevation of the four wells.
Williams (2019) conducted ground-penetrating-radar (GPR) surveys on the island and reported that there are small-scale faulting and discontinuities in the confining layer in the subsurface of the study area. Figure 3.2 shows the discontinuation of the aquitard found below monitoring well 03 (MW-03). Discontinuities like this could serve as vertical conduits among the aquifer systems conducting water from one aquifer to another, otherwise disconnected (Foyle, et al., 2002).

![Figure 3.2: Hydrogeological Conceptual Model, based on GPR survey, showing the discontinuity in the confining aquitard in the subsurface below MW-03 (Williams, 2019).](image-url)
Figure 3.3: Cross section along the well transect adapted from Williams (2019). (Not to scale).
3.2 Monitoring well network

Groundwater levels were measured, and samples were collected utilizing a network of four wells installed along an approximately west-to-east transect at Wormsloe Historic Site in the Isle of Hope, GA (Figure 3.3). The wells have 1” PVC pipes inserted in them. The average depth of the wells is 18.3’ below the surface, and the well screening runs to an approximate height of 10’ from the bottom of the wells. The wells were completed as flush-mounted wells. MW-01 is situated at the west-most end of the transect close to Moon River, and MW-04 is the east most located close to Jones Creek, a tributary of Skidway River. The underlying geology at the well transect includes well-sorted quartz sand (fine to very fine) and low amounts of heavy mineral sand.

Groundwater levels and temperature were recorded hourly with Solinst, Inc. Model 3001 LT Junior level loggers at the four monitoring wells (Although the level logger in MW-01 malfunctioned and the recordings were not obtained). The downloaded data of the water level were corrected according to the following equation (Williams, 2019);

\[
\begin{align*}
    h_c - h_m &= h_{wt} \\
    h_l - h_{wt} &= f_c \\
    h_l - f_c &= h_{wl}
\end{align*}
\]

(1)

Where, \(h_c\) is the height to the top of the casing (ft), \(h_m\) is the manually measured water level (ft), \(h_{wt}\) is the water table elevation (ft), \(h_l\) is the logger “raw” level, \(f_c\) is the correction factor, and \(h_{wl}\) is the water level (ft). The datum of the measurements is the mean sea level.
3.3 Data and sample collection

The data on the tidal levels were obtained from the USGS Fort Pulaski tide gauge (Figure 3.4), with the mean sea level as the datum in 1-hour time intervals. The linear distance between the tidal gauge and the well transect is 17.4 km.

Groundwater samples from the wells and water samples from the tidal creek were collected for 11 days in January and June, during high and low tide periods. In the January sampling period (01/12/2021 – 01/22/2021), samples were collected from the Jones Creek, MW-01, and MW-04 to establish a groundwater mixing model to assess the saline water intrusion using isotope analysis. During the June sampling period (06/01/2021 – 06/11/2021), all four wells, Jones Creek, and rain events were sampled to study the groundwater dynamics of the study area more broadly. During

Figure 3.4: Google satellite image location map of the well transect at Wormsloe Historic Site and Fort Pulaski Tidal Gauge.
the January sampling period, the spring tides prevailed, with the maximum tidal height on 01/13/2021, and during June, the neap tide prevailed with the maximum tidal height on 06/03/2021. The samples were collected with a low-flow peristaltic pump and autosamplers. In addition, rainwater samples were collected during the rain events with a Stratus rain gauge in the late-spring sampling period. Daily rainfall data was collected from the Skidway station (Figure 3.5) of the University of Georgia Weather Network (University of Georgia Weather Network, 2022).

Figure 3.5: Google satellite image location map of the UGA Weather Station – Skidway

The specific conductivity was measured while sampling groundwater at three depths in the screened interval of wells by utilizing a low flow peristaltic pump with measurements read through
a YSI 600 XL multiparameter water quality sondes. The specific conductivity values were converted into salinity with the following equation (UNESCO, 1983):

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

(2)

where \( C \) is the conductivity of sea-water, \( S \) is salinity (ppt), \( t \) is the temperature (°C) and \( p \) is pressure in decibels, and \( C(35, 15, 0) \) represents the conductivity of standard sea-water at salinity 35 (ppt), at 15°C, and atmospheric pressure. The obtained salinity values were used to assume the \( \text{Cl}^- \) concentration in the samples to dilute the samples for laboratory analysis. Using ion chromatography, laboratory analysis was conducted on selected samples to determine the actual \( \text{Cl}^- \) concentrations. A correlation (Figure 3.6) was developed with the obtained results between the measured specific conductivities and the \( \text{Cl}^- \) concentrations to determine the \( \text{Cl}^- \) concentrations of all the samples.

Groundwater samples were taken from the monitoring wells and tidal marsh for the isotope analysis. The samples were collected to avoid evaporation in 4 mL glass bottles with tight screw caps, labeled, and placed in the dark at room temperature (to avoid algal growth) before laboratory
analysis. The abundance ratios of $^2$H: H and $^{18}$O:$^{16}$O, expressed in delta notation as $\delta^2$H and $\delta^{18}$O, were quantified with Off-Axis-Integrated-Output-Cavity Spectroscopy using a Los Gatos Research IWA-45EP Isotope Water Analyzer (LGR IWA). As a result of kinetic meteorological processes, water molecules containing heavy and light oxygen and hydrogen isotopes are fractionated throughout the hydrological cycle (Craig, 1961). Fractionation occurs due to the thermodynamics of a system resulting in different rates of reactions, where one isotope is proportionating in the greater or lesser amount on one side of the reaction relative to the other isotope. Therefore, signature values of $^{18}$O and $^{16}$O can be found in the reservoirs of the hydrological cycle driven by two major driving forces of the hydrological cycle; evaporation and condensation, which are dependent on vapor pressure and temperature. The variation of the isotopic ratio of a sample and a standard of a species can be indicated with the mathematical expression of the Delta notation (Clark & Fritz, 1997).

$$Isotopic\ ratio = \frac{Apparent\ abundance\ of\ heavy\ isotope\ (X^h)}{Apparent\ abundance\ of\ heavy\ isotope\ (X^l)}$$

(3)

$$Delta\ notation\ (\delta X^h)_{Sample} = \frac{(X^h/X^l)_{Sample} - (X^h/X^l)_{Standard}}{(X^h/X^l)_{Standard}}$$

(4)

Because fractionation happens in minor concentrations, $\delta$ values are expressed in parts per thousand or permil (‰) (Clark & Fritz, 1997).

$$Delta\ notation\ (\delta X^h)_{Sample} = \left(\frac{(X^h/X^l)_{Sample} - (X^h/X^l)_{Standard}}{(X^h/X^l)_{Standard}}\right) \times 1000‰$$

(5)
4 RESULTS

4.1 Influence of rainfall and seasonality on groundwater level in the wells

The average groundwater levels recorded in the wells showed seasonal fluctuations (Table 4.1). Water levels in MW-02 and MW-03 were higher during the January sampling period. Although MW-04 had a higher water level during June than in January. Figure 4.2 shows the hourly fluctuations of water levels in MW-02, MW-03, and MW-04 from 1/1/2021 to 11/10/2021.

Table 4.1: Summary of groundwater levels (ft) from the mean sea level in wells MW-02, MW-03, and MW-04 in winter and summer sampling periods.

<table>
<thead>
<tr>
<th>Groundwater levels (ft) in January (1/11/2021 – 1/22/2021)</th>
<th>Groundwater levels (ft) in June (6/1/2021 - 6/11/2021)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>Minimum</td>
</tr>
<tr>
<td>MW-02</td>
<td>5.07</td>
</tr>
<tr>
<td>MW-03</td>
<td>4.83</td>
</tr>
<tr>
<td>MW-04</td>
<td>3.25</td>
</tr>
</tbody>
</table>

In the January and June sampling periods, the maximum hourly precipitation amounts recorded at the University of Georgia Skidaway Weather Station were 0.07 inches and 0.17 inches, respectively (UGA Weather Network, 4/10/2022). Precipitation during the sampling periods did not immediately impact groundwater levels in MW-03 and MW-04 (Figure 4.1 b and c). In MW-02, the rain event that occurred on 1/15/2021 (0.07 in) and 6/3/2021 (0.17 in) caused an increase in the groundwater level (Figure 4.1 (a)).

Table 4.2: Daily precipitation totals (in) recorded at the University of Georgia Skidaway Weather Station during winter and summer sampling periods.

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1/11/2021</td>
<td>0.01</td>
</tr>
<tr>
<td>1/12/2021</td>
<td>0</td>
</tr>
<tr>
<td>1/13/2021</td>
<td>0</td>
</tr>
<tr>
<td>1/14/2021</td>
<td>0</td>
</tr>
</tbody>
</table>
Rainfall events increase the groundwater level if the rainfall is 1 inch or more (Figure 4.1 and Figure 4.2). Further rainfall events of less magnitude seem to be affecting the groundwater levels more slowly. After rain events, the groundwater levels showed less fluctuation for some time or increased before the gentle decline in the water levels was resumed. This pattern can be observed in Figure 4.1 for MW-02, MW-03, and MW-04 for both sampling periods. MW-02 and MW-04 showed an increase in the water-table elevation from mid-September to March and rain events. The greatest water level fluctuations (3.1 ft increase) were observed in MW-02 during rain events from 7/7/2021 to 7/9/2021 (5.09 in), and the second-highest water level fluctuation (2.92 ft increase) happened on 9/18/2021 to 9/22/2021 (5.51 in). Compared to MW-04, MW-03 had a higher water level throughout the year. Moreover, compared to MW-02, MW-03 had a higher water level in the summer months if not for the rain events. MW-03 had a relatively constant water level without major impacts from seasonal changes or rain events.
Figure 4.2: Annual groundwater level fluctuation (GWLF) of three monitoring wells during and daily rainfall 01/01/2021 – 11/10/2021. MW-01 data was not recorded due to a faulty level logger.

4.2 Influence of tidal level fluctuations on groundwater levels in the wells

To determine the influence of tidal level fluctuations on the groundwater, tidal levels recorded at the Fort Pulaski tidal gauge (nearest tidal gauge to the well transect) and the water levels recorded in the wells were plotted in a line graph against time (Figure 4.3). The tidal levels showed diurnal fluctuations, and summer groundwater levels of MW-03 and MW-04 showed a diurnal pattern.
Figure 4.3: Comparison of water levels in monitoring wells and the fluctuation of tidal levels in January and June 2021. The water levels of MW-03 (a) and MW-04 (b) are represented in the graph, considering the relatively high proximity to the tidal creek. The water levels were recorded hourly with level loggers installed in the monitoring wells. The level logger in MW-04 was malfunctioning and was replaced on 01/12/2021. MW-03 has a relatively constant water level (~4.8 ft above MSL), and MW-04 water levels show fluctuations depending on seasonality (~3 ft in January and ~3.5 ft in June). Tidal data was obtained from the Port Pulaski tidal gauge in Savannah (https://tidesandcurrents.noaa.gov/stationhome.html?id=8670870). In June, the high tide reaches up to 7.5 ft above MSL; in January, the high tide rises to about 8 ft above sea level.

The water levels of MW-03 and MW-04 in the winter showed deviations from the diurnal pattern. However, plateauing was observed in the water table elevation during the high tide in the daytime (Figure 4.3) in both wells MW-03 and MW-04 in summer. The correlation plot between tidal levels and the water level had an $R^2$ value of less than 0.01 for summer and winter in wells MW-03 and MW-04 (Appendix A).
4.3 Water isotope chemistry of the study area

Abundance ratios of $^2$H:$^1$H and $^{18}$O:$^{16}$O, expressed in delta notation, were relatively depleted within the aquifer compared to the tidal creek water and the rainwater. Further, the isotope values were more depleted in January than during June (Figure 4.4). This is also indicated from the isotope values in the tidal creek as they were generally more depleted in the January than in June.

![Graph showing isotope chemistry variation](image)

*Figure 4.4: Isotope chemistry variation in the monitoring wells, tidal creek, and rainwater during the sampling periods in January (01/12/2021 – 01/22/2021) and June (06/01/2021 – 06/11/2021). Rainwater, MW-01, and MW-03 were not sampled in January for isotope analysis. MW-04 water is much more depleted than the other wells, although MW-04 is the closest to John’s tidal creek.*

<table>
<thead>
<tr>
<th></th>
<th>$\delta^{18}$O/‰</th>
<th>$\delta^2$H/‰</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Median</strong></td>
<td><strong>Average</strong></td>
<td><strong>Median</strong></td>
</tr>
<tr>
<td>MA</td>
<td>5.00E-02</td>
<td>2.55E-02</td>
</tr>
<tr>
<td>MW01</td>
<td>-3.82E+00</td>
<td>-3.79E+00</td>
</tr>
<tr>
<td>MW02</td>
<td>-3.95E+00</td>
<td>-3.95E+00</td>
</tr>
<tr>
<td>MW03</td>
<td>-3.79E+00</td>
<td>-3.74E+00</td>
</tr>
<tr>
<td>MW04</td>
<td>-4.45E+00</td>
<td>-4.41E+00</td>
</tr>
<tr>
<td>Rain</td>
<td>-5.73E-01</td>
<td>-5.41E-01</td>
</tr>
</tbody>
</table>

*Table 4.3: Summary of isotope signatures of the samples collected in June 2022*
Table 4.4: Summary of isotope signatures of the samples collected in January 2022

<table>
<thead>
<tr>
<th></th>
<th>$\delta^{18}$O/%</th>
<th>$\delta^2$H/%</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median</td>
<td>Average</td>
<td>Median</td>
</tr>
<tr>
<td>MA</td>
<td>-8.14E-01</td>
<td>-7.21E-01</td>
<td>-3.73E+00</td>
</tr>
<tr>
<td>MW02</td>
<td>-3.86E+00</td>
<td>-3.88E+00</td>
<td>-1.77E+01</td>
</tr>
<tr>
<td>MW04</td>
<td>-4.39E+00</td>
<td>-4.42E+00</td>
<td>-2.22E+01</td>
</tr>
</tbody>
</table>

As shown in Figure 4.4, the groundwater of MW-04, which is nearest to the tidal creek, had the most depleted isotope signature of all the wells. Next to MW-04, MW-03 is the closest well to the tidal creek. Samples of MW-03 collected in June (median $\delta^{18}$O/% = -3.79E+00, median $\delta^2$H/% = -1.64E+01 (Table 4.3)) had more enriched isotope values than MW-04 (median $\delta^{18}$O/% = -4.45E+00, median $\delta^2$H/% = -2.20E+01) (MW-03 was not sampled in January). MW-02 is situated much more inland when compared to MW-03 and MW-04. MW-02 isotope values were slightly more depleted than MW-03 (Table 4.4). However, the observed isotope signatures of MW-02 (median $\delta^{18}$O/% = -3.95E+00, median $\delta^2$H/% = -1.75E+01) were more enriched than of MW-04. MW-01 was not sampled in January, yet MW-01 had similar isotope values compared to MW-03 (Table 4.3).

### 4.4 Chloride ion concentrations in the groundwater

The specific conductivity (SPC) and Cl\(^-\) concentrations in all the wells and tidal creeks were higher in summer than in winter (Table 4.2). For each sampling period, the monitoring wells did not show a daily fluctuation in [Cl\(^-\)]; only seasonal variation was observed (Figure 4.5 and Figure 4.6). The highest SPC and [Cl\(^-\)] values were recorded at MW-03. The SPC and [Cl\(^-\)] concentrations of MW-01 and MW-04 showed similar values, indicating that these two wells had the least impact from the brackish water of the tidal creeks.
Table 4.5: Average specific conductivity and Cl$^-$ concentrations of the four wells and tidal creek in the January and June sampling periods.

<table>
<thead>
<tr>
<th></th>
<th>MW-01</th>
<th>MW-02</th>
<th>MW-03</th>
<th>MW-04</th>
<th>Tidal Creek</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific conductivity (µs/cm)</td>
<td>504.7</td>
<td>200.8</td>
<td>30372.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[Cl$^-$] (ppm)</td>
<td>92.2</td>
<td>17.4</td>
<td>9988.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jun</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific conductivity (µs/cm)</td>
<td>228.5</td>
<td>540.8</td>
<td>2867.4</td>
<td>225.6</td>
<td>39303.6</td>
</tr>
<tr>
<td>[Cl$^-$] (ppm)</td>
<td>24.2</td>
<td>101.3</td>
<td>675.8</td>
<td>23.5</td>
<td>12958.9</td>
</tr>
</tbody>
</table>

Figure 4.5: [Cl$^-$] concentration (ppm) variation in the monitoring wells in high tide and low tide conditions during the June sampling period. [Cl$^-$] in the wells do not fluctuate depending on the tidal cycles. MW-03, in the island’s center, has higher [Cl$^-$] than the other three wells.
Figure 4.6: $\text{[Cl]^-}$ concentration (ppm) variation in the monitoring wells in high tide and low tide conditions during the January sampling period. $\text{[Cl]^-}$ in the wells do not fluctuate depending on the tidal cycles.
5 DISCUSSION

The obtained results show that the hypothesized initial conceptual model of declining saltwater intrusion from the island margins to the interior of the island (from MW-04 to MW-01) needs to be modified. Instead of this anticipated trend in saltwater intrusion, a more complex saltwater intrusion pattern and groundwater dynamics were observed in the study area. The modified conceptual model is illustrated in Figure 5.1.

5.1 Influence of rainfall and seasonality on groundwater level in the wells

It was observed that rainfall accumulations greater than one inch per day induced immediate and marked increases in water-table elevation within MW-02, MW-03, and MW-04 (Figure 4.2). This increase in the groundwater table proves that the groundwater in the study area is recharged from rainfall. The lower groundwater levels of the wells in the summer could result from higher evapotranspiration during the summer (White, 1932; Lewis, et al., 2002). Additionally, higher groundwater levels could result from spring tides that prevailed during the January sampling period, while lower groundwater levels in June could result from the neap tide that prevailed during the June sampling period (Optaz & Dinicola, 2018). Although the reason for MW-04 showing higher water levels in June than in January is unclear, further studies are required to confirm its reasons. When more than 1-inch of rainfall occurred, a simultaneous increase in the water levels in MW-02 and MW-04 was observed (Figure 4.2). The relatively less fluctuating water levels in MW-03 can be explained in two ways (Figure 5.1 and Figure 4.2). One is the hydraulic connectivity of the Surficial Aquifer to the tidal creek through the canal, and two is the hydraulic connectivity of the Surficial Aquifer to the underlying aquifer through the discontinuity underneath MW-03.
Figure 5.1: The dark blue dashed line indicated the interpreted groundwater level during 01/12/2021 – 01/22/2021 and the dark blue dashed line indicated the interpreted groundwater level during 06/01/2021 – 06/11/2021. The water level fluctuation might have been affected by the tidal cycles and seasonal precipitation. The white arrows indicate the flow directions to the East and West of the island away from a topographic height in between MW-02 and MW-03, with the description of subsurface geology (Williams, 2019). The yellow line indicates the interpreted groundwater level in summer of 2021. The depression marked on the right of MW-03 is the manmade canal that brings water inland from the John’s creek. According to the specific conductivity (SPC) data of the wells MW-03 has the SPC out of the four wells, MW-04 has the lowest SPC. During the summer 2021 sampling the groundwater level was found shallowest in MW-04 and the deepest was in MW-02. Groundwater level of MW-03 dropped down much faster during 15-minute pumping time from around 4 ft to 7 ft. The groundwater level showed no significant changes from high tide to low tide. When comparing the groundwater level and flow direction in the previous study in 2019 and current study in 2021, groundwater level has depleted, and the flow direction is towards MW-03 rather than away from MW-03.
In previous studies conducted by Reichard, et al. (2012), Vance, et al., (2016), and Bush, et al., (2016), discontinuities resulting in connections between otherwise separated aquifer systems were observed. Based on Clark, et al. (1997), the estimated UFA hydraulic head at Wormsloe was approximately -38 ft MSL. Moreover, from 2016 to 2021, the mean water level of MW-03 was recorded as +5.76 ft from the MSL. Therefore, it can be concluded that there is a downward gradient of water around MW-03 if there is a connection between the underlying aquifers and Surficial Aquifer through the discontinuity. Because of the down gradient, the groundwater level of MW-03 should be lower than the other wells, although MW-03 shows a higher groundwater level than the other wells. These observations indicate that the more stable water table at MW-03 is most likely caused by the hydraulic connection between the tidal creek and the unconfined aquifer through the human-built canal. Therefore, the Surficial Aquifer in the study area may have recharge from the rainfall depending on the rainfall amount, and the aquifer around MW-03 has greater and consistent recharge through the canal during high tides.

5.2 Influence of tidal level fluctuations on groundwater levels in the wells

The tidal level rise and fall could be imposing pressure on groundwater resulting in the water levels in the wells rising and falling (Ataie-Ashtiani, et al., 1999). The June groundwater levels in MW-03 and MW-04 showed a daily rising and falling pattern, which also had a plateau in the middle of the rising peak (Figure 4.1). Even though the water levels of MW-03 and MW-04 in the winter showed an irregular pattern that is hard to explain with the data obtained in this study. The southeastern U.S. generally has declines in shallow groundwater storage (55-59%) occurring consistently with the increase in evapotranspiration (85-86%) (Condon, et al., 2020). This plateauing of the water table elevation in MW-03 and MW-04 could result from evapotranspiration
affecting against the high tide pressure during the daytime. Even though the groundwater level increases with the high tide, evapotranspiration decreases the groundwater level during the daytime. Moreover, the net effect of the two processes might result in the water level plateauing effect. The lack of correlation between daily tidal and groundwater levels could be because there are other variables like evapotranspiration governing the groundwater level of the study area.

Further, MW-03 and MW-04 did not show a diurnal pattern in the groundwater level in January (Figure 4.3), possibly because the aquifer had higher recharge in winter due to precipitation. A greater tidal effect could be there in summer because the hydraulic head in the aquifer was relatively low compared to the tides (Table 5.1). This indicates a possible seasonal influence of tides on the aquifer. The diurnal pattern was not prominent in MW-02, indicating that tidal influence’s seasonal effect may be limited to island margins.

| Table 5.1: Average groundwater levels (ft) in MW-02, MW-03, and MW-04 in winter, spring, and summer of 2021 |
|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|
| Average groundwater level (ft) in winter | Average groundwater level (ft) in spring | Average groundwater level (ft) in summer |
| MW-02 | 5.01 | 4.18 | 4.15 |
| MW-03 | 4.99 | 4.94 | 4.88 |
| MW-04 | 3.70 | 4.20 | 3.54 |

In addition, the times when the peaks and troughs of the water level graph occur shift from when the tidal level graph peaks and troughs occur (Figure 4.3 b). The tidal effect is more direct on a surface water body than on groundwater as groundwater flow and groundwater level fluctuation has resistance to the tide from the pressure of the subsurface material. Such resistance may result in a lag in the peak high and peak low water levels (Gregg, 1966; Davidson, et al., 2011). The effect of tidal lag might explain why no diurnal fluctuation is observed in MW-02 when compared
with MW-03 and MW-04 in both winter and summer. According to the hypothesized initial conceptual model, the tidal effect on the groundwater should decrease due to the increasing tidal lag from the island’s margins toward inland. Furthermore, the observed groundwater levels agree with this hypothesis. In future studies, if the water levels of MW-01, the canal, and the two tidal creeks can be monitored in addition to water levels of MW-02, MW-03, and MW-04, a better understanding of the tidal lag on groundwater in the study area could be modeled.

5.3 Water isotope chemistry of the study area

The range of the isotope values of $\delta^{18}O$ in the four wells (-3.4 to -4.8‰) falls in the range similar to what is reported by Clark, et al., (1997) for $\delta^{18}O$ values measured at the UFA (-3.0 to -4.8‰). Clark, et al., (1997) also report an inland gradient of $\delta^{18}O$ (0.60 ± 0.15‰/100km) in the UFA. They also observed a similar gradient in shallow groundwater wells in the UFA’s recharge areas and in the Surficial Aquifer near Brunswick, Georgia. These observations might indicate regional groundwater flow paths of the UFA that discharge in the coastal region which at some locations flow via vertical upward groundwater flow paths of faults and joints.

Isotope chemistry of water in the study area was analyzed to understand the sources and movement of the groundwater. Based on the initial hypothetical model, it was expected to have a gradient in mixing fresh groundwater from inland sources and saline water from the tidal creek in the aquifer around MW-03 and MW-04 (Krause, 1997; Kohout, 1964; Williams, 2019). In this model, MW-02 was predicted to have relatively depleted isotopic signatures of $\delta^{18}O$ and $\delta^2H$, representing fresh water as it is located most inland in the well transect. The tidal creek was predicted to have relatively enriched isotopic signatures of $\delta^{18}O$ and $\delta^2H$ representing saline water. And MW-04,
which is between the freshwater end-member and saline water end-member, was predicted to have a mixture of saline and fresh water. Therefore, the hypothetical model assumed that isotopic signatures of $\delta^{18}$O and $\delta^2$H in MW-04 would fall between $\delta^{18}$O and $\delta^2$H values of MW-02 and the tidal creek.

The obtained results (Figure 4.4, Table 4.3, and Table 4.4) showed that the initial hypothetical model must be modified greatly depending on the isotope chemistry of the groundwater. Abundance ratios of $^2$H:$^1$H and $^{18}$O:$^{16}$O, expressed in delta notation, were relatively depleted within the aquifer compared to the tidal creek water and the rainwater. $\delta^{18}$O and $\delta^2$H isotope values in the tidal creek were generally depleted in the winter than in summer. The thermodynamics of isotope fractionation can explain this observation. The ocean water and the precipitation are enriched with heavy isotopes when the evaporation is high due to high temperatures in the summer (Urey, 1946; Clark & Fritz, 1997). Therefore, generally, the water in the tidal creek, surface water, and groundwater would have enriched isotope signals in the summer than in the winter.

When considering the proximity to the tidal creek, the isotope signatures of groundwater in the wells should deplete in the order of MW-04, MW-03, MW-02, and MW-01. Because the well closest to the tidal creek would most probably have the water with an enriched isotope signature resembling the mixing with the tidal creek, and wells more inland would have more depleted water (Nachiappan, et al., 2003). Although, as shown in Figures 4.4 and 5.1, the groundwater of MW-04, which is nearest to the tidal creek, had the most depleted isotope signature of all the wells. This observation indicates that there is no mixing of tidal creek water in the groundwater of MW-04. One reason for the depleted isotope signature could be the groundwater source of MW-04 being
the recharge of the isotopically depleted winter precipitation (compared to isotopically enriched summer precipitation). The aquitard (Williams, 2019) in the subsurface below MW-04 might provide ideal conditions for the winter precipitation accumulation and block saline water intrusion.

MW-03 had a relatively enriched $\delta^{18}$O and $\delta^2$H isotope signature that is anomalous when considering the expected groundwater and saline water mixing gradient. Because MW-04 should have had an enrichment value higher than MW-03, that resulted from groundwater and saline water mixing due to the proximity of MW-04 to the tidal creek. The enriched isotopic signature in MW-03 could be due to the flow of the tidal creek water along the man-made canal constructed closer to the well (the distance between MW-03 and the canal terminal is about 25 m). Furthermore, the combination of natural depression and the man-made construction might bring the flow of tidal creek water to the groundwater at MW-03, resulting in a more enriched isotopic signature resembling tidal creek water.

MW-02 is situated inland when compared to MW-03 and MW-04. Therefore, theoretically, the isotope signature of MW-02 should be more depleted than MW-04 and MW-03. Instead, the isotopic values of MW-02 fell between MW-03 and MW-04 (Table 4.3). MW-02 might have recharged from summer precipitations (Figure 4.1a), resulting in these enriched isotope signals. To describe the exact reason for this observation, further studies are required. MW-01 was not sampled in January, yet the samples collected in June showed that MW-01 had similar isotope values compared to MW-03. These similar values could result because MW-01 groundwater is mixed with the brackish water flowing in the Moon River’s distributaries west of the study area.
The $\delta^{18}$O and $\delta^2$H isotope signatures in the groundwater and tidal creek water of the study area indicate complex mixing paths of isotopically enriched and depleted water instead of the linear mixing from the island margin to the interior as hypothesized in the initial conceptual model. Moreover, the results show that there could be local zones with $\delta^{18}$O and $\delta^2$H depleted groundwater in coastal unconfined aquifers despite the proximity to isotopically enriched saline water bodies. Further sampling and testing of water from the tidal creek, the canal, the four wells and the rain events should be done to understand the seasonal variation of isotope chemistry, which would give more insight into the mixing paths of groundwater in the study area.

5.4 Chloride ion concentrations in the groundwater

The initially hypothesized conceptual model for the study area with linear saline intrusion needs to be modified with the obtained SPC and [Cl$^-$] values. Because the highest SPC and [Cl$^-$] values are observed in MW-03, and the lowest SPC and [Cl$^-$] values are observed in MW-04 for both sampling periods.

The overall SPC and [Cl$^-$] of groundwater and tidal creek water in June were higher than SPC and [Cl$^-$] in January (Table 4.5). The reason for the observed higher values of June SPC and [Cl$^-$] values could be the increased concentration of ion species and more conductivity resulting from high temperature increasing water evaporation (Table 4.3). When comparing the [Cl$^-$] results of the current study with the [Cl$^-$] of the UFA by the coastal region by Savannah (average [Cl$^-$] = 22.33
mg/L) (Clark, et al., 1997), MW-03 shows a significantly higher \([\text{Cl}^-]\) (average \([\text{Cl}^-]\) = 675.75 mg/L). This comparison is illustrated in Figure 5.2.

![Figure 5.2: (a) Comparison of Cl\(^-\) concentrations reported by Clark et al. (1997) with those observed in the study area. The average \([\text{Cl}^-]\) of the wells GA 02 and GA 01 is 22.33 mg/L (b) locations of wells utilized by Clark, et al., (1997) for their study. The wells utilized by Clark et al., (1997) have a depth range of 50 - 100 m into the UFA, and the wells are cased from the top of the ground to the top of the aquifer.](image)

The anomalous increase of \([\text{Cl}^-]\) in MW-03 water could be its hydraulic connection to the tidal creek through the manmade canal (Figure 3.1) which brings the saline water close to MW-03. Similar observations were made by Reichard, et al., (2012) at St. Catherines Island where the Surficial Aquifer had two to four times more \([\text{Cl}^-]\) than the UFA. Therefore, it can be assumed that the higher \([\text{Cl}^-]\) or the saltwater intrusion at MW-03 is not due to groundwater conductance from underlying aquifer systems through vertical conduits but rather through the man-made canal bringing in saltwater from the tidal creek at high tide. The second highest SPC and \([\text{Cl}^-]\) values were observed in MW-02. When pumping water from MW-02 to collect samples, the water had a distinct pungent smell, possibly due to \(\text{H}_2\text{S}\) emission. To confirm the presence of sulfur species in the groundwater, further sample analysis should be conducted. SPC and \([\text{Cl}^-]\) concentrations in MW-01 and MW-04 indicate that these two wells have the least impact from brackish water of the
tidal creeks. These observations were very different from what is observed by Williams, (2019), where there was a gradual decrease of saltwater from MW-04 to MW-01 from the east to the west of the well transect (Figure 5.1). This could mean that the groundwater dynamics along the well transect can change within a short time, governed by tides, geology, and human activities.
6 CONCLUSION

The initial conceptual model of the study hypothesized a regular decrease of saltwater intrusion from the island margins to the interior of the island, with the greatest saltwater intrusion at MW-04. From the results obtained the conceptual model is not supported. There is a dynamic variability in aquifer physical and chemical properties across an 850 m well transect on the Isle of Hope. Therefore, the initial conceptual model should be modified according to the results and observations to describe the complex hydrogeological flow paths of fresh water and saline water.

The four monitoring wells had a slow recharge by infiltration of meteoric water from rain events less than 1 inch and faster and greater recharge by rain events of more than 1 inch. The water levels of MW-01, MW-02, and MW-03 were higher in January than in June because of increased recharge by precipitation in January and decreased water table due to evapotranspiration in June. The water levels of MW-03 remained relatively constant throughout the year (with less seasonal fluctuation) due to the hydraulic connectivity of the tidal creek through the man-made canal, which brought in high tide water towards MW-03. The daily conductance of high tidewater through the canal may also overrule the decrease of groundwater level by the downward gradient of water flow that might happen around MW-03. The downward water flow may be due to the discontinuity in the aquitard underneath MW-03 that might act as a conduit for water flow between Surficial Aquifer and the underlying UFA.

Groundwater levels observed during June in MW-03 and MW-04 showed a diurnal oscillation that may occur due to the increase and decrease in the water level by the high and low tide, respectively. The plateauing in the water level may result from evapotranspiration lowering the water table and
working against the high tide, which increases the water table elevation. The chemistry data seem to support the conclusion that the man-made canal was the preferential flow pathway for water from the tidal creek to infiltrate the aquifer during high tide and cause saltwater intrusion. The high [Cl⁻] and enriched water isotope signatures were proof of the salinization and tidal water and freshwater mixing at MW-03. If there is a downward gradient of groundwater flow, this may result in saltwater intrusion into the underlying aquifers through the discontinuity in the aquitard beneath MW-03. MW-04 had the most depleted isotope signatures of δ¹⁸O and δ²H and the least Cl-concentrations, proving that MW-04 has fresh water. This shows that in coastal unconfined aquifers, there could be local zones with fresh water despite the proximity to isotopically enriched saline water bodies.

In conclusion, the landward transition of the saline water – freshwater boundary is not uniform along the island margin. Instead, saltwater intrusion is governed by factors such as rainfall, tides, and man-made structures with varying temporal and spatial differences. And the greatest influence on saltwater intrusion at the study area is from the canal that brings high tide water into the interior of the island. This observation proves that historically made drainage structures in coastal regions can act as sources of saltwater intrusion even after they no longer serve their initial purpose.

Many results found in this study raise further questions about the groundwater flow paths of the study area, the influence of the canal conducting high tide water from the tidal creek to the interior of the island, and the influence of the subsurface geology in creating conduits of groundwater flow between aquifers. Therefore, in addition to the existing monitoring wells, more monitoring wells should be installed in Surficial Aquifer and UFA to monitor saline water flow paths in the
proximity of the canal and the suspected discontinuity in the confining unit that lies beneath. Increasing the time of the sampling periods and the number of samples is suggested to monitor the seasonal and daily groundwater behaviors over longer periods. Further sampling and testing of water from the tidal creek, the canal, the four wells and the rain events to understand the seasonal variation of isotope chemistry would give more insight into the mixing paths of groundwater in the study area and the seasonality of groundwater recharge by precipitation.
REFERENCES


Williams, M. D. (2019). *Controls on Saltwater Intrusion in a Shallow Coastal Aquifer: Wormsloe Historic Site, GA (Thesis)*. Atlanta: Georgia State University.
APPENDICES

Appendix A

The following graphs show the correlations between tidal level and water levels in MW-03 and MW-04 for June to identify the effects of tidal lag on the groundwater dynamics. The correlation plots do not show any correlation between the tidal and groundwater levels with or without tidal lag times. The $R^2$ value of the plots are less than 0.01 for summer and winter in wells MW-03 and MW-04. The tidal lag times shown here are zero hours, one hour, three hours, six hours, and twelve hours for both wells MW-03 and MW-04.
Tidal and water level correlation considering 1 h tidal lag

\[ y = 0.0005x - 0.0002 \]

\[ R^2 = 0.0015 \]

Tidal and water level correlation considering 3 h tidal lag

\[ y = 0.0005x + 0.0005 \]

\[ R^2 = 0.0032 \]
Tidal and water level correlation considering 6 h tidal lag

\[ y = 0.001x - 0.0005 \]
\[ R^2 = 0.0119 \]

Tide level (ft) vs. MW-03 water level (ft) in June

Tidal and water level correlation considering 12 h tidal lag

\[ y = -0.001x - 0.001 \]
\[ R^2 = 0.0002 \]

Tide level (ft) vs. MW-03 water level (ft) in June
Tidal and water level correlation without considering tidal lag

\[ y = 0.0033x + 2E^{-05} \]
\[ R^2 = 0.0158 \]

Tidal and water level correlation considering 1 h tidal lag

\[ y = 0.0032x - 0.0001 \]
\[ R^2 = 0.0148 \]
Tidal and water level correlation considering 3 h tidal lag

\[ y = 0.0012x - 0.0003 \]

\[ R^2 = 0.002 \]

Tidal and water level correlation considering 6 h tidal lag

\[ y = -0.0004x - 0.0007 \]

\[ R^2 = 0.003 \]
Tidal and water level correlation considering 12 h tidal lag

\[ y = 0.003x - 0.0023 \]

\[ R^2 = 0.013 \]