A VARAIBLE-DENSITY MODEL TO DETERMINE POSSIBLE SOURCES OF ELEVATED TOTAL DISSOLVED SOLIDS IN SUWANNEE RIVER BASIN SPRINGS, NORTH-CENTRAL FLORIDA

by

THEAR KIRK FRALEY

(Under the Direction of John F. Dowd)

ABSTRACT

This work models the depth of the freshwater-saltwater interface in the Floridan aquifer system to determine its relationship to springs in the Suwannee River Basin using the SEAWAT model. During drought conditions with large withdrawals, spring water quality displays elevated dissolved constituents derived from limestone. Due to lack of data, previous investigations in the study area utilized the Ghyben-Herzberg Principle and do not model the full depth of the aquifer and associated higher dissolved constituents at lower depths. Using a variable-density, finite difference, transient, groundwater model, this work simulates the aquifer within range of drought and normal flow conditions. Results show that most of the interface is below the base of the Floridan aquifer system, the middle confining unit controls the position of the interface through differences in velocity, and springs are the only surficial feature that influence how dissolved constituents move vertically.

INDEX WORDS: Suwannee River, Floridan Aquifer System, Variable Density Model

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THEAR KIRK FRALEY

B.S., UNIVERSITY OF GEORGIA, 2010

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2015

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May 2015

DEDICATION

This work is dedicated to James D. and Demeris Kirk, my grandparents who taught me the beauty and wisdom of learning throughout life.

ACKNOWLEDGEMENTS

My fiancé, Claire Northcutt never gave up her faith and understanding in what I was working to accomplish, although there were moments when there was much distance and time between us. My family also provided much foundation and support for this endeavor. My Thesis Advisor, John Dowd's constructive criticism, intuition, and reasoning was always on point. I also would like to thank my committee members: Adam Milewski, Todd Rasmussen, and Rob McDowell. Wondwosen Seyoum, Micahel Durham, and everyone else in the UGA Water Resources and Remote Sensing Lab was always there with advice and a helping hand. And of course a thank you to Lester Williams (USGS) for providing and helping with salinity and hydrologic data. Trey Grubbs (SRWMD) for helping with model advice and design. Thank you to everyone at the U.S. Geological Survey and the Suwannee River Water Management District who either directly or indirectly helped by providing water data and information. And finally my dog, PJ; she gave up many walks at Dudley Park so that this work could be accomplished.

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CHAPTER 1

INTRODUCTION

Saltwater intrusion has been a concern in Florida since the 1940s when Parker and others (1944) began investigations in the area around Miami-Dade County in southwestern Florida. Since then, many studies have been conducted throughout Florida, most of which have taken place in proximity to metropolitan areas such as Miami, Jacksonville, and Tampa (Dauseman and Langevin, 2004; Mahon, 1989; Spechler, 1994).

During the historical 1998-2002 drought in northern Florida, natural springs contributing to the Suwannee River Basin saw a decrease in discharge (Copeland et al, 2009). Throughout this period of severe drought, pumping and development of the Floridan aquifer system increased, resulting in a drawdown of the potentiometric surface. Recent work by the Florida Geological Survey has shown that as a prolonged drought causes a decrease in spring discharge, the amount of saline and rock analyte constituents increase.

After crossing into the Gulf Coastal Lowlands, the Suwannee and Santa Fe river systems interact with the Upper Floridan aquifer system in a dynamic flow system and are hydrologically connected through a multitude of karst features (Katz et al, 1997). A model of this extensive interaction in the Lower Suwannee River Basin was developed by Grubbs and Crandall (2007) for the U.S Geological Survey (USGS) and the Suwannee River Water Management District. This work incorporated the Ghyben-Herzberg Principle to define the bottom boundary of the model and associated base of freshwater overlying a wedge of saltwater as a sharp interface. Past groundwater models in the Suwannee Basin and elsewhere in Florida use the Ghyben-Herzberg principle where a lack of data exists for assigning the saltwater-freshwater boundary (Dausman and Langevin, 2005)

The Ghyben-Herzberg Principle is defined where, in an unconfined aquifer, for every foot of fresh water above sea level, there is an associated forty feet of fresh water below sea level (Fetter, 1988). This is defined mathematically as:

$$z_{x,y} = \frac{\rho_{fw}}{\rho_s - \rho_{fw}} \cdot h_{x,y} \qquad (1.1)$$

Where:

$z_{x,y}$ is the depth to the saltwater interface below sea level at location $(\mathrm{x},\mathrm{y})(\mathrm{L})$

$h_{x,y}$ is the elevation of the water $-$ table above sea level at point $(\mathrm{x},\mathrm{y})(\mathrm{L})$

ρ_{fw} is the density of fresh water $(1\mathrm{kg}/L)$

ρ_{sw} is the density of saltwater $(1.025kg/L)$

(Fetter, 1988)

The use of the Ghyben-Herzberg Principle, and its assumed sharp interface, adequately represents the freshwater-saltwater interface in some hydrologic systems such as sandy barrier islands isolated from coastal aquifers. Conditions in the Suwannee River Basin of the Floridan aquifer system do not follow such a simplified approach. Miller (1986) and Williams (2013) noted that the area around the Suwannee River Basin acts as a continuous system, where the highest salinity is found at the greatest depths of the aquifer, and decreases in concentration as it shallows upward through a transition zone. Mahon (1989) observed that the interface is gradual merging of two waters and is dependent on pore characteristics. Bush and Johnston (1988) found water chemistry in the Upper Floridan aquifer system is dependent upon flow and proximity to the freshwater-saltwater interface. Where the Floridan is semiconfined or unconfined and the flow is highest, as in the Suwannee River Basin, the concentrations of dissolved solids are less than 0.25 g/L. However, in tightly confined areas where flow is less, concentrations are greater than 0.25 g/L (Bush and Johnston, 1988). Mahon (1989) further noted that a drawdown of the potentiometric surface in the Floridan aquifer system increases the potential for saltwater intrusion. These conditions for the saltwater-freshwater interface have not been simulated in any previous model in the study area (Sepúlveda, 2002; Planert, 2007; Grubbs and Crandall, 2007; Schneider et al., 2008).

1.1 Objectives of the Study

The goal of this work is to incorporate the freshwater-saltwater interface into a multi-variable density, transient, groundwater flow model that simulates both drought and wet periods, while investigating increases in rock constituents recorded in springs discharging into the Suwannee River Basin. To more accurately simulate the interface, this research involves recent work by the USGS, which further defines the regional location of the freshwater-saltwater interface through the use of data gathered from geophysical logs from former petroleum test wells combined with other studies (Williams, personal communication 2013). Using the boundary extents of the Grubbs and Crandall (2007) model, the newly defined transition zone was placed into Schlumberger Water Service's Visual MODFLOW program, which combines the USGS multivariable-density simulation code of SEAWAT and groundwater modeling code from MODFLOW 2000 (McDonald and Harbaugh, 1988; Guo and Langevin, 2002).

1.2 Limitations of the Study

The development of a transient model requires extensive continuous data that is not often available in a watershed. Fortunately, due to the efforts of the Suwannee Water Management district and USGS, there exists a sizable collection of data for springs, rivers, water quality, and ground water levels in the Suwannee River Basin. However, there is a limit to spatial coverage of groundwater data as well as gaps in the collection periods. The extent of groundwater quality data is also limited to seasonal sampling and depth at which these samples can be obtained.

The Floridan aquifer system is an extensive and highly productive water source for Florida and the Southeastern United States. The high productivity can be attributed to the large amount of dissolution channels that bisect the carbonate rock. This work is an attempt at simulating groundwater movement for a field area located within the Floridan aquifer system that assumes surficial watershed boundaries apply horizontally as well as vertically for the entire depth of the aquifer. Because of the large amount of karstification and dissolution channels, it is impractical to assume all surficial boundaries and watershed divides will bisect the entire depth of the Floridan aquifer system.

Multiple studies in the Floridan aquifer system as well as the Suwannee River Basin have utilized the MODFLOW program to model groundwater flow (Sepúlveda, 2002; Planert 2007; Grubbs and Crandall, 2007). However, the MODFLOW program is based on Darcy’s Law and the assumption that flow is laminar in a heterogeneous, system. In an aquifer that has extensive karst development and dissolution channels, flow is often turbulent and Darcy’s Law does not apply. With these limitations in mind, this work is an attempt at better understanding a complex system of rivers, springs, and surface water features that have a dynamic connection with the groundwater system underneath.

CHAPTER 2

STUDY AREA

The Suwannee is a unique river that crosses two physiographic provinces in Florida and Georgia. Upon entering the Gulf Coastal Lowlands, the river is augmented by numerous springs that vent water from the Floridan aquifer system.

2.1 Geologic History of the Suwannee River Basin

The Florida Peninsula and Coastal Plain of Florida and Georgia are underlain by a fragment of the African craton abutting the Appalachian Orogeny of North America and sutured during the Paleozoic Era (Chowns and Williams, 1983). These rocks form an assumed graben complex consisting of plutonic, metamorphic and sedimentary rocks that are Triassic in age or older. The Triassic rocks are truncated above by the Fall Line unconformity, which marks the bottom of Cretaceous and younger sediments of the Coastal Plain. Prior to the Mesozoic, the Appalachian Mountains were the primary source of siliciclastic sediment but had eroded to a point where sediment supply was now restricted to more proximal regions (Scott, 1992). The combination of restricted siliciclastic sediments, and a shallow platform that experienced little tilting or subsidence, and allowed the formation of very pure carbonates on the Florida Peninsula such as the Upper and Lower Floridan aquifers (Denizman and Randazzo, 2000; Scott, 1992).

Carbonates that comprise the Floridan aquifer system in the Suwannee River Basin, Figure 2.5, are Oligocene and Eocene that were deposited in warm, shallow waters during a regional sea level highstand beginning in the Paleocene and continuing through the Oligocene (Denizman and Randazzo, 2000; Miller, 1986). The circulation of water was restricted in these carbonate environments, allowing evaporates such as anhydrite, gypsum and occasionally halite to accumulate (Scott, 1992). These evaporate deposits later formed the confining and semi confining units of the Floridan aquifer system. During the Oligocene, renewed uplift in the Appalachians provided a new episode of siliciclastic deposition in northwest peninsular Florida coinciding with carbonate suppression and a major sea level drop (Denizman and Randazzo, 2000; Scott 1992).

In the Miocene, the Florida Platform was again inundated during a sea level high (highstand), which led to the deposition of the Hawthorne group, a sedimentary sequence that ranges from a weakly cemented argillaceous, phosphatic sandstone to a well-indurated phosphatic dolomite interbedded with silicicalstic and argillaceous sediments (Denizman and Randazzo, 2000). Where present, the sediments of the Hawthorne signify where the Floridan aquifer system is confined (Miller, 1986). Sea level dropped and retreated in the Pleistocene forming a succession of marine terraces (Cooke, 1945). At the boundary of the Sunderland and Wicomico physiographic provinces lies the Cody Scarp, the most significant of these marine terraces in north central-Florida (Denizman and Randazzo, 2000; Vernon, 1951). The Wicomico physiographic province corresponds to the Sangamon Interglacial Stage, which topped at a height of 30 m (98.4 ft) and eventually fell to three meters above present sea level (Cooke, 1945). Below the Cody Scarp, the carbonates of the Ocala Platform are exposed and the Floridan aquifer system is unconfined (Miller, 1986).

The overburden of the Hawthorne Group covered the underlying Oligocene carbonates of the Ocala Platform preventing the development of extensive limestone dissolution (karst) until removal following sea level drop in the late Miocene (Denizman and Randazzo, 2000). The development of karst is largely controlled by preferential dissolution along fracture and joint patterns that formed during uplift associated with formation of the Ocala Platform during the early Miocene. Frequent changes resulting from eustatic sea level fluctuations allowed for repeated exposure of the permeable carbonate platform to vadose and phreatic conditions at separate elevations following the Miocene.

The lowest position of Pleistocene sea level (lowstand) controlled much of the post-Miocene karstic evolution as seas retreated and exposed the Florida Platform (Denizman and Randazzo, 2000). It was during this period that younger karst landforms developed underground as terraces were subjected to increasing subaerial exposure on the surface. The increasing amount of exposure allowed for the progression of larger and more frequent karst landforms.

2.2 Suwannee River Geomorphology

The Suwannee River flows for approximately 390 km (242 mi) from its headwaters in the Okefenokee Swamp in southeastern Georgia and continues southward through north-central Florida where it reaches the Gulf of Mexico at the town of Suwannee (Figure: 2.1) (Katz et al, 1997). On its course to the Gulf, the Suwannee River drains a total area of 28,567 km^2 (11,030 mi^2) of Florida and Georgia (Crane, 1986). The upper reaches of the Suwannee River lie in the Northern Highlands physiographic region where the channel meanders through alluviul deposits while increasing in size through a dendritic system (Denizman and Randazzo, 2000). Once reaching the Cody Scarp in north-central Florida, the Suwannee enters the Gulf Coastal Lowlands where the channel is underlain by karst bedrock (Figures 2.4 and 2.10).

Here, a subsurface network of artesian springs contribute to overall discharge as the river flows south and sedimentary features such as point bars and islands become smaller and less frequent as the elevation slope decreases gradient.

At White Springs, the Suwannee changes course from a north-south direction to an east-west, a characteristic that is due to the stratigraphy and structure of the area (Ceryack, 1983). Above the town of White Springs, the river flows through sediments of the Hawthorne Formation. The lower beds of the Hawthorne in this location are more durable and are comprised of dolomitized and or silicified sediments that control the direction of the channel and the river to the west. It is here that the river cuts down through the dolomite bedrock while exposing high, overhanging ledges (Figure 2.9). The Suwannee River reaches the Cody Scarp below the town of White Springs. Here, many streams that drain the Northern Highlands disappear and resurges as a "rise" below the escarpment (Katz et al, 1997). The Suwannee River and its tributary the Withlacoochee are an exception and continue flowing on the surface as they incise through the escarpment that divides the two provinces (Denizman and Randazzo, 2000). The lithology changes to Oligocene Suwannee Limestone upon passing the Cody Scarp (Vernon 1951). When the river intersects the Suwannee Limestone, the channel aligns parallel to major lineaments and begins a northwestern course.

Rivers in Florida began incising their valleys in response to Pleistocene sea level changes (Vernon, 1951). However, rivers draining watersheds on the carbonate bedrock responded in a different manner. These fluvial systems found it easier to drain through existing fractures and dissolution channels in the underlying bedrock instead of forming deep valleys.

2.3 Karstic Geomorphology in the Suwannee River Basin

Carbonic acid is the primary dissolvent of limestone and forms from dissolved carbon dioxide (Jennings, 1985). The predominant source of carbonic acid is plant-root respiration and bacterial decay of organic matter. The downward movement of meteoric water drives this dissolution and forms karstic topography at or near the surface (Johnston and Bush 1988). Extensive dissolution within the epikarst, the boundary between soil and carbonate bedrock, can be attributed to diffuse autogenic recharge through soil layers and the transport of aggressive soil gasses (Denizman and Randazzo, 2000). Extensive karstification can be found in the marginal zone between the Gulf Coastal Lowlands and the Northern Highlands and is caused by allogenic recharge from the covered limestone of the Northern Highlands.

Overall, the topography of epikarst at the surface is not easily reshaped due to the high rate at which meteoric water drains underground (Jennings, 1985). Regions with extensive karst topography have streams further apart with less drainage in between. This kind of system allows more of the interfluve to survive for longer periods. Denizman and Randazzo (2000) note that subsoil solution is evident in the limestone and dolomite banks in the form of bleached-white, vuggy, dissolution. They are comprised of erratic vugs and cavities present from intervals of lower river stage up through the epikarst zone and terminating at the basal layer of soil.

2.4 Characteristics of Springs in the Suwannee River Basin

In the karstic, unconfined areas, spring flow augments the Suwannee River's discharge Figure 2.10) (Katz et al, 1997). Surficial streams are less common in karst and therefore, watersheds in karstic areas normally containing less drainage density than a watershed draining a differing geologic type (Jennings, 1985). The majority of the springs contributing discharge to the lower Suwannee River are drawing from an unconfined aquifer and therefore not artesian (Crane, 1986). The lower Suwannee River has incised downward through the limestone that hosts the unconfined aquifer while bisecting solution conduits of groundwater creating vents in proximity to the river's channel. Some springs discharge directly into the river channel while others form a head pool (Figure 2.8) that is connected to the river channel via a spring run. Five springs in the Lower Suwannee River Basin are first magnitude and have discharges of 2.83 cubic meters per second (100 cfs) or greater (Figure 2.2 and Table 4.2). While 22 second order streams discharging at 0.283 to 2.83 cubic meters per second (10-100 cfs) also make contributions to the Lower Suwannee River Basin. Most of the large springs in Florida lie in or along northwest and northeast trending lineaments associated with the Ocala uplift (Vernon, 1951).

Springs in the vicinity of the Suwannee River have the ability to reverse flow and become sinks (Katz et al, 1997). During high flows, the elevated river stage and hydraulic gradient flows away from the river due to pressure, and into the Upper Floridan aquifer system.

2.5 Hydrogeology of the Floridan Aquifer System in the Suwannee River Basin

The Floridan aquifer system is an extensive and hydrologically connected structure that is comprised largely of carbonate rocks underlying 100,000 square miles of the southeastern United States (Johnston and Bush 1988). Miller (1986) notes that units in the Upper and Lower Floridan aquifers are determined by either low or high permeability and do not directly correspond to named formations or time stratigraphic boundaries. Hydrostatagraphic units pertaining to this study begin with late Paleocene to early Eocene rocks of the Cedar Keys Formation and form the lower confining unit (Figure 2.5). The Cedar Keys are partially or completely dolomitized with intergranular gypsum filling much of the pore space. Above the Cedar Keys lie the early to late Eocene rocks and some Oligocene units that make up the extensive and thick carbonate sequences of the Floridan aquifer system. With exception of the middle confining unit, these units are characterized with highly developed primary and secondary porosity that is found throughout the Floridan aquifer system. Most prolific of these units are the upper Eocene and Oligocene, which are more extensively developed for water supply then lower units. The hydraulic conductivity of the basal units of the Upper Floridan aquifer is typically two orders of magnitude less than those above.

The Oligocene aged strata are associated with the Suwannee Limestone and rocks of the middle Eocene correspond with the Ocala Limestone. The middle confining unit consists of seven discontinuous, low permeability strata that divide the upper and lower Floridan aquifer units. Two of the seven middle confining units partially exist in the study area and have been designated middle confining units II and III by Miller (1986). Where the middle confining unit is absent, the Upper and Lower Floridan aquifers behave as one continuous system.

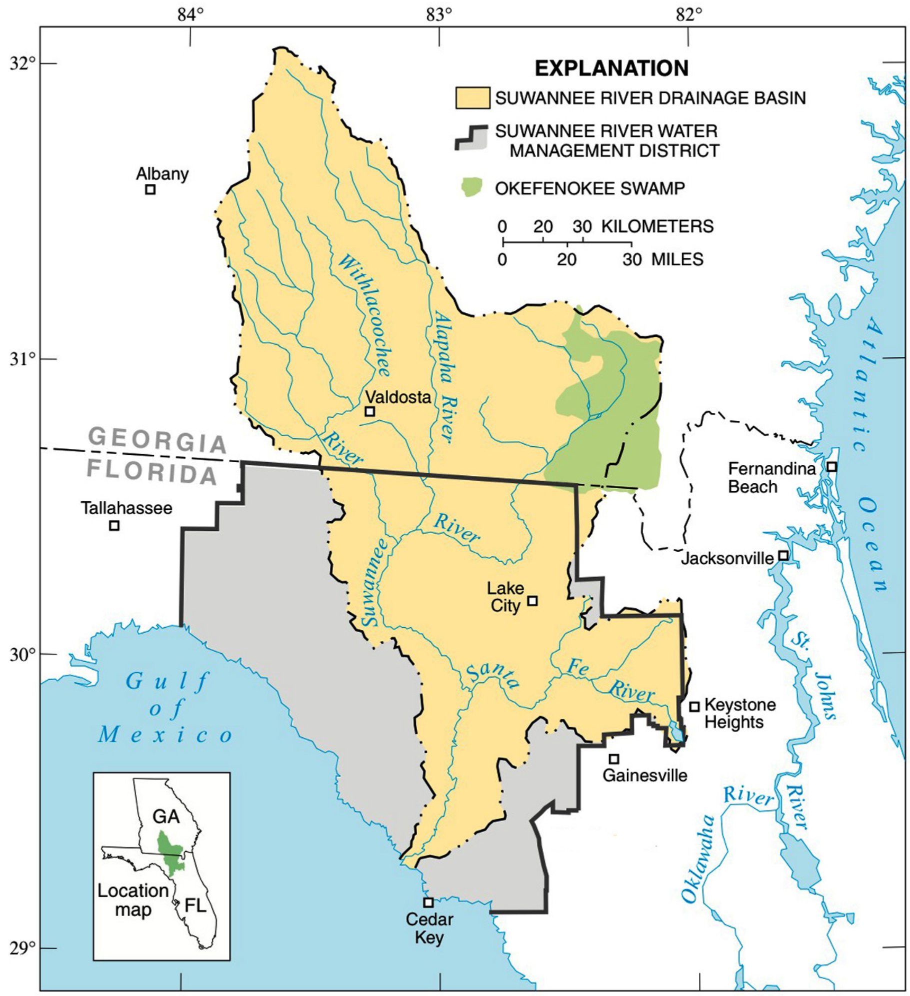
Occurrence and depositional history of sediments comprising the Floridan aquifer system were controlled by underlying structural features (Scott, 1992). For areas with positive features, such as the Ocala Platform located in the study area, the Floridan aquifer system exists at or near the surface and is unconfined (Miller, 1986; Scott, 1992). Negative features, such as the Apalachicola Embayment located northwest of the study area, are associated with the well-confined portions of the Floridan aquifer system. The Intermediate aquifer system exists primarily in regions with negative features and is less defined to non-existent in areas with positive structural features (Scott, 1992).

Above the Floridan aquifer system lie the poorly consolidated Coastal Plain sediments of the Hawthorne formation (Johnston and Bush 1988). These sediments erode easily in areas where carbonate rocks are exposed or within proximity of the surface such as the Lower Suwannee River Basin (Johnston and Bush 1988).

Hydraulic conductivity calculated by Schneider et al. (2008) ranges from 7.62 m/day to 2,743 m/day. Previous modeling studies produced values for transmissivity ranging from 3,048 m^2/day to 1,88,800 m^2/day (Sepulveda, 2002; Grubbs and Crandall, 2007). Where some of the largest flows are commonly associated within springsheads including Manatee and Fanning springs (Sepulveda, 2002; Grubbs and Crandall, 2007; Schneider et al. 2008).

2.6 Land Use and Climate in the Suwannee River Basin

Climate in the Suwannee River Basin is humid subtropical with mild winters and long, warm summers (Grubbs and Crandall, 2007; Katz et al, 1997). Average rainfall per year is 132 cm with half occurring between the months of June and September (Katz et al, 1997). However, the highest flows for the Suwannee and its tributaries occur during late February through late April. Localized thunderstorm activity is the primary source of precipitation in the summer months whereas, the occurrence of cold fronts in winter evenly distribute rainfall more regionally (Grubbs and Crandall, 2007). Land use in the basin primarily consists of silviculture, the manufacture of forest products, agriculture, livestock, and poultry farms Figures (2.6 and 2.7).



Base from U.S. Geological Survey digital data, 1972
Albers Equal-Area Conic Projection,
Standard parallels 29°30′ and 45°30′, central meridian -83°00′

Figure 2.1: The watershed of the Suwannee River in Georgia and Florida.

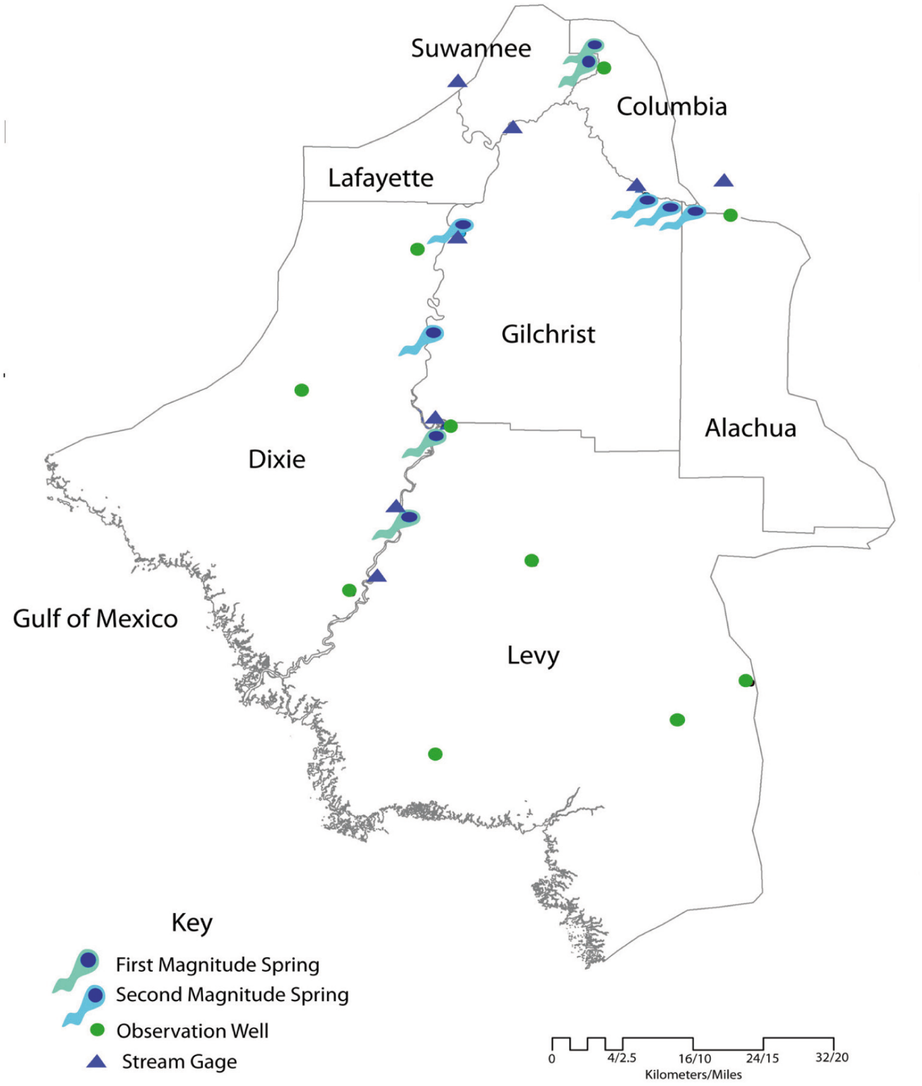


Figure 2.2: Springs modeled in the study area and their proximity to other hydrologic features.

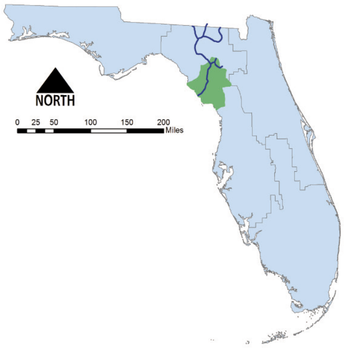


Figure 2.3: Right, The Suwannee River Basin in Florida. The study area is in green.

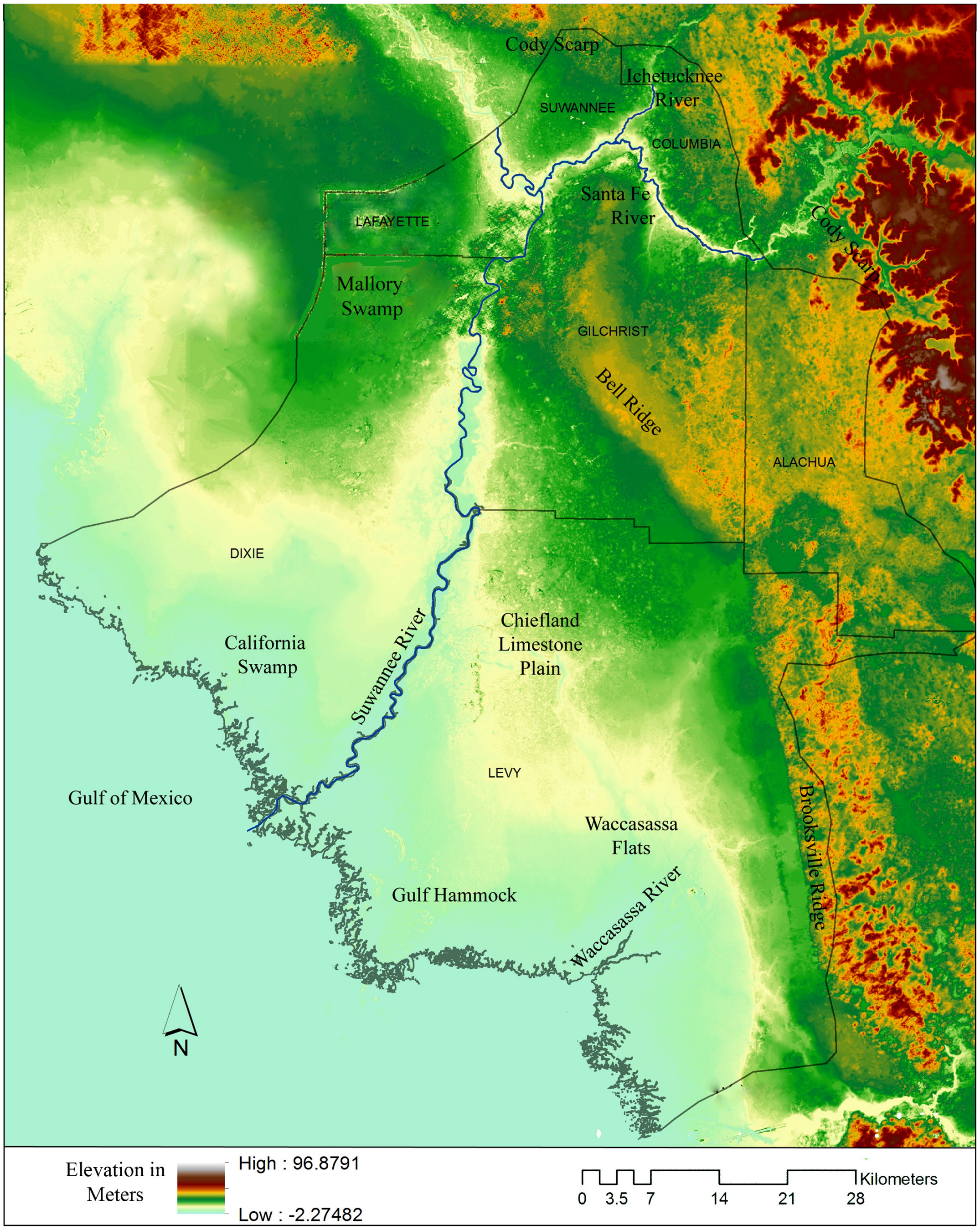
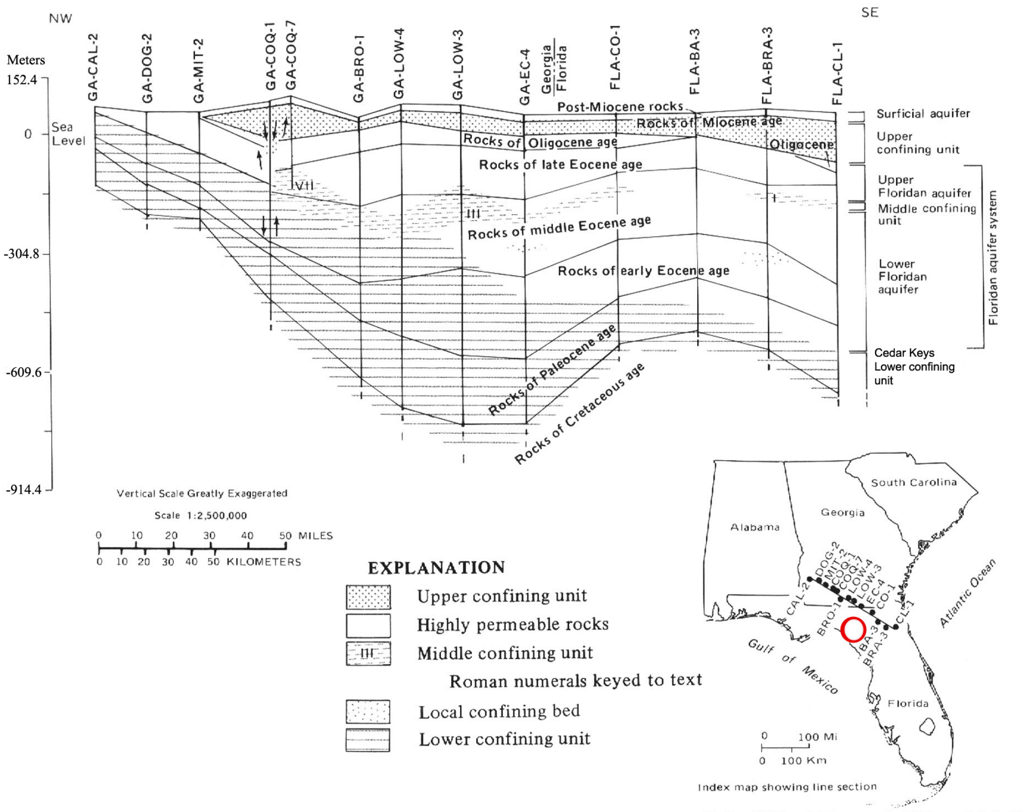


Figure 2.4: Surface feature map of the Lower Suwannee River Basin. After crossing the Cody Scarp the Suwannee River enters the Gulf Coastal Lowlands that overlie the unconfined Floridan aquifer system.



(Modified From Miller 1986)

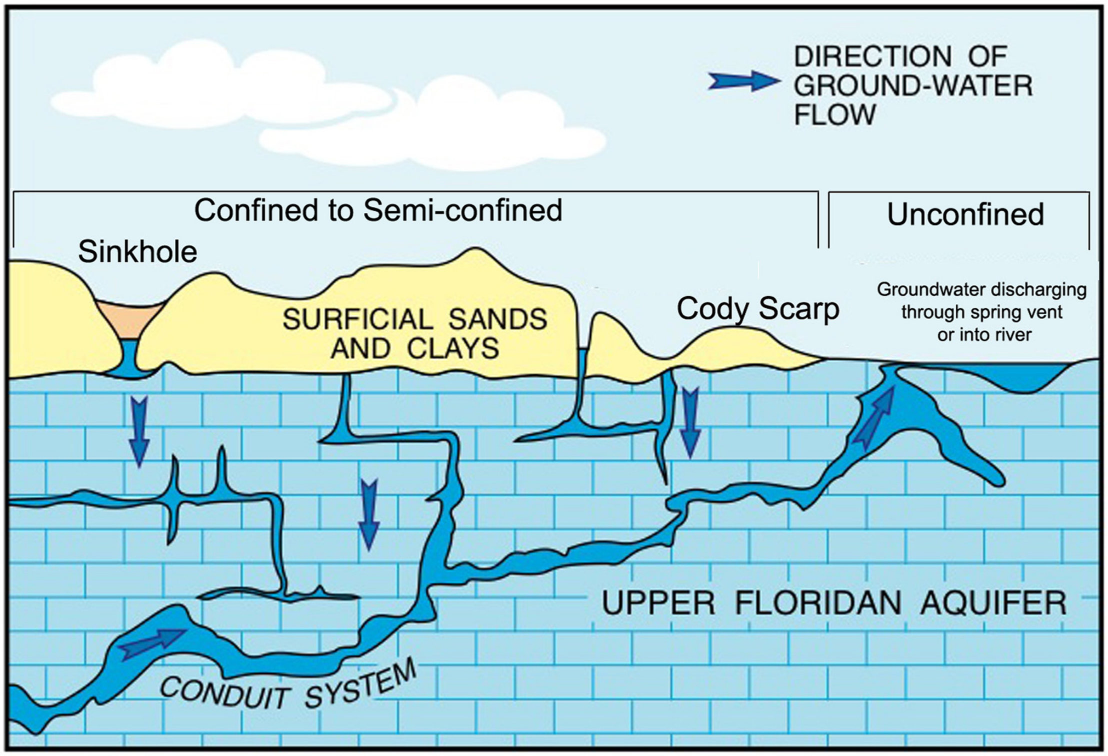
Figure 2.5: General cross section of litho and hydrostratgraphic units in Northern Florida and Southern Georgia. The study area is circled in red.

Figure 2.6: Central pivot irrigation withdrawing from the Floridan aquifer near the town of Branford, Florida. Photo by the author.

Figure 2.7: A stand of pine trees near Branford, Florida. The cultivation and manufacturing of forest products is an important industry in the Suwannee River Basin. Photo by the author.

Figure 2.8: The eye of Ginnie Springs in Gilchrist County. The site and adjacent park is a popular spot for swimming and paddling. Photo by the author.

Figure 2.9: Vuggy limestone outcrops along the Suwannee River. Photo by the author.



(Modified From Katz et al, 1997)

Figure 2.10: Simplified illustration of karst in the Floridan aquifer system.

CHAPTER 3

LITERATURE REVIEW

The highly productive Floridan aquifer system has been the subject of numerous studies by authors from many disciplines. Below is a selection of work pertaining to the Suwannee River Basin and previous investigations of saline intrusion in other Florida locations.

3.1 Previous Investigations in the Floridan Aquifer System

Starting in 1978, the USGS began producing a series of reports as part of the Regional Aquifer System-Analysis (RASA) (Johnston and Bush, 1988). This volume of work described the regional geology, hydrology, and geochemistry of the major groundwater systems located in the United States including the Floridan aquifer system (Bush and Johnson, 1988). The RASA publications pertaining to this study area include Miller (1986), and Johnston and Bush (1988)

Miller's (1986) Hydrologic Framework of the Floridan Aquifer System in Florida, parts of Georgia, Alabama, and South Carolina identified the regional extent of the aquifer in both hydrologic and geologic terms (Figure 2.3). This work also determined the control of geologic structure on groundwater flow in the Floridan aquifer system and investigated variations in the regional permeability based on rock composition, texture, and secondary porosity. Miller also identified the regional stratigraphic units and correlated the framework that connects surface and subsurface logs, which utilized 662 wells and corresponding data from cores, cuttings, and geophysical logs. This technique was used in order to determine the top and bottom of the stratigraphic units. In Florida, the use of geophysical logs, well cuttings, and cores for data is especially important due to the limit of surface exposure for much of the units that make up the Floridan aquifer system (Scott, 1992).

Bush and Johnson (1988) expanded the work of Miller by describing groundwater hydraulics and regional flow, along with pre-development and modern development on the aquifer system. For their work, they constructed a quasi-three dimensional, steady-state model covering the entire Floridan aquifer system in Florida, Georgia, Alabama, and South Carolina. The model consisted of four layers in a coarse finite difference grid structured in 65 rows by 80 columns, each representing an area of 165.8 km^2 (64^2 mi). The lower boundary for the model was placed where the concentration of chloride reached 10 kg/L, and determined to be a midpoint in the transition zone between the saltwater-freshwater interface. Water greater than 10 kg/L was deemed to be static and set as a Neumann Type II boundary. Due to a lack of groundwater development in the area at the time of model construction, less emphasis was placed on the Suwannee River Basin and adjacent unconfined Floridan aquifer.

3.2 Previous Investigations in Salinity in the Floridan Aquifer System

South of this study area in West-Central Florida, Hickey (1990) focused on the probability of saline water moving vertically from the middle confining unit into the overlying Floridan aquifer system due to freshwater development. Further, Hickey (1990) wanted to evaluate the common assumption that the middle confining unit acts as a Neumann Type II boundary. For this study, geothermal gradients and water quality tests were used to determine the possible extent and degree of movement of saline and brine waters from the middle confining unit. The middle confining unit contains relatively high sulfite and chloride concentrations, and primarily consists of limestone, and dolomite with inclusions of anhydrite and gypsum.

Sites used for this work showed variable amounts of salinity along with differing elevations where saline or brine waters were located. Three sites indicated chloride concentrations resembling that of seawater occurring in wells proximal to the coastline. Spatially, a saltwater-freshwater transition zone was evident in these sites where decreasing concentrations were observed further inland, coinciding with highest concentrations found at lowest sampled intervals. However, chloride concentrations at one location near the bottom of the Floridan aquifer system reached 21 kg/L. The amount recorded in the adjacent middle confining unit was 25 kg/L. These elevated amounts indicated a brine/seawater mixture and brine's potential movement vertically from the middle confining unit. Moving inland, chloride levels decreased greatly in the lowest regions of the Floridan aquifer system. However, chloride levels in the middle confining unit showed variability as the unit pinched out in the north and west further inland. The northern extent of Hickey's (1990) report borders this study. Approximately 103 km (64 mi) from the lower Suwannee model area a value for salinity of 54 kg/L was recorded in a well in proximity to the middle confining unit. Wells immediately adjacent to the model area recorded lower values of chloride at 0.0072 kg/L and sulfate at 0.002 kg/L in the middle confining unit. Temperature profiles indicated that vertical flow from the middle confining unit is minimal to non-existent.

Previous literature in West-Central Florida has placed the middle confining unit's conductivity to that of a compact clay bed, and assumed that evaporates in the middle confining unit are laterally continuous and extensive. Hickey (1990) argued the evaporates were originally deposited as thin, fragmented beds that eventually became inclusions in the carbonate host, and concluded that as nodules with limited lateral extent, vertical conductivity was on the order of 0.003 to 0.03 m/day (0.01-0.1 ft/day). This vertical conductance value was closer to that of very fine-grained sandstone than a compact clay bed as commonly assumed in studies in west central Florida. This range of conductivity was hardly within the range of conductivity found in the overlying Floridan aquifer system, but still higher than conductivity found in a traditional confining unit (Hickey, 1990).

Countryman and Stewart (1997) utilized Electromagnetic and electrical geophysical methods to locate the saltwater-freshwater interface along the mouth of the Suwannee River and the surrounding coastal boundary. An interface elevation map was constructed using Harmonic Electromagnetic (EM-34), DC resistivity, and Transient Electromagnetic (TEM) data. The top layer of the interface was determined to be a recording of 10 ohm-n or less and a sharp interface.

In their work, Countryman and Stewart (1997) found the elevation of the saltwater-freshwater interface was largely controlled by three geologic conditions in the Lower Suwannee Basin. First, where the Floridan aquifer system was unconfined, there existed a very high freshwater discharge and associated head forcing the interface deeper underground resulting in a saltwater-freshwater interface sloping in a shallow geometry away from the coast. The second scenario was controlled by the presence of the middle confining unit. Where present, such as in Levy County, the interface was determined to be shallow and the unit restricts the downward flow of freshwater causing vertical flow to become lateral at shallower depths within the aquifer. In Dixie County, the middle confining unit was absent and the more permeable Floridan still existed. Here, less head loss due to high permeability allowed the groundwater to descend further into the aquifer resulting in a deeper saltwater-freshwater interface. Finally, the authors found that surface elevations relating to geomorphic sub-zones such as coastal marshes approximately coincided with elevation changes in the interface. Observations in this study area indicate that, the saltwater-freshwater interface does follow the presumption of the Ghyben-Herzberg but only loosely follows the 40-1 ratio (Countryman and Stewart, 1997).

Increased demand for freshwater from the Floridan aquifer system in Northeast Florida has resulted in the upward migration of water from lower saline zones into developed freshwater zones (Spechler, 2001). Spechler (1994), Spechler (2001), and Phelps and Spechler (1997), have published recent studies for the USGS and St. Johns River Water Management District that attribute the occurrence to structural anomalies, combined with increased permeability, provide vertical conduits and pathways for localized saline intrusion. Structural anomalies include joints, fractures, faults, and collapse features that increase permeability through secondary porosity that has developed preferentially along these fractures (Phelps and Spechler, 1997) Salinity research was expanded in northeast Florida and Duval County through analysis of geophysical well logs. Where, wells in Duval County deeper than 274.32 m (900 ft) determined the most likely source of brackish water to the Lower Floridan is the underlying Fernandina Permeable zone, a hydrostratgraphic unit that contains fresh water in western Duval County and saline in the east. Other explanations for the origin of the saline water included a landward shift of the freshwater-saltwater interface, unflushed pockets of connate seawater, or a regional upconing of saltwater below pumped wells (Spechler, 2001). The lateral movement of the freshwater-saltwater interface in the area is unlikely since, saline water has been observed in more than 70 wells located 22.5 km (14 mi) inland from the Atlantic Ocean, while wells located between these locations and the coast do not show such a trend. The highly permeable zones present in the Lower floridan aquifer make connate water an unlikely source because it is normally associatiated with less permeable units. Finally, geophysical logs used in this study do not show trends that would indicate a regional upconing. If this scenario occurs regionally through upconing, then salinity values would be present in wells sampled throughout the study area. In contrast, the salinity is observed as individual zones with lenses of freshwater above and below which is indicative of being conduit controlled (Spechler, 2001).

Dausman and Langevin (2005) conducted a study to evaluate the dynamic relationship between water-level fluctuations and the saltwater-freshwater interface in the surficial aquifer and Biscayne aquifer in Broward County, Florida. Data for this study was collected as part of the USGS salinity-monitoring program. Where most of the wells were sampled quarterly or semiannually, six were monitored continuously and utilized for shorter term modeling of tidal influence on the interface.

To model the Biscayne aquifer, Dausman and Langevin (2005) used the USGS's three-dimensional finite difference modeling program, SEAWAT to simulate 15 layers that range from 7.5-10.5 m (24.6-34.4 ft) in thickness. Discretization of the model consisted of a 150 x 150 m (492 x 492 ft) grid simulating 23 rows and 152 columns in 78.7 km^2 (30.3 m^2). Calibration for the Biscayne aquifer model was achieved through adjusting parameters until simulated results matched observed values. Calibration parameters included horizontal and vertical conductance, porosity, specific yield, and transverse and longitudinal dispersivities.

Dausman and Langevin (2005) assigned multiple boundaries including Cauchey Type III, Dirichlet Type I, and Neumann Type II. Cells representing canals and the Intracoastal Waterway were designated constant head in layer one. A Dirichlet Type I boundary was also assigned to the sea floor of the Atlantic Ocean and allocated according to bathymetric data. Canals were also considered a hydraulic divide and assigned two different head values allowing for simulation of the upper and lower salinity control structures present in the field area. The bottom of the surficial aquifer was assigned a Neumann Type II boundary. A general-head boundary was assigned where the Everglades border the western extent. Dirichlet Type I cells were assigned a constant concentration where, those cells representing the Atlantic Ocean were given a value of 35 g/L, canal reaches above control structures were assigned a value of 0 g/L, reaches below control structures were assigned 12 g/L, and 23 g/L was assigned to cells representing the Intracoastal Waterway (Dausman and Langevin, 2005).

Two different temporal scales sharing the same model parameters and aquifer properties were used for modeling the surficial and Biscayne aquifer (Dausman and Langevin, 2005). The first temporal scenario consisted of a one-month simulation with 15-minute stress periods investigating diurnal fluctuations for both water-level and specific conductance . The second model simulated a 10-year period between the years 1990-1999 and consisted of monthly stress periods allowing for evaluation of long-term effects on water-level fluctuations on the saltwater-freshwater interface and intrusion.

Short-term model results show that water levels and saltwater interface movement were affected by rainfall, well-field demand, canal stage, tides, sea level rise, and evapotranspiration (Dausman and Langevin, 2005). In the model, factors affecting groundwater heads were different than those affecting movement of the saltwater interface. Changes in head proximal to the well field were affected by change in head from upstream to downstream in canals, rainfall, and pumping. However, regression analysis of the short-term model indicated precipitation had the greatest regional effect on the vertical movement of the interface except in areas proximal to canals, where the difference between upstream and downstream stage had the greatest effect on movement of the saltwater-freshwater interface. Results from the short-term model indicate that movement of the saltwater-freshwater interface was more affected by groundwater movement in the vertical direction rather than horizontal.

Data analysis showed similar results to those of the short-term model where precipitation did affect vertical movement of the interface but only in proximity to the well field (Dausman and Langevin, 2005). Data analysis also indicated that upstream canal stage had the greatest effect on movement of the saltwater-freshwater interface in the area of the canal and a combination of well field demand and canal stage had an effect on the interface in proximity to the municipal well field.

Model simulations indicated that short-term droughts, consisting of three years or less, have little effect on the long-term position of the saltwater-freshwater interface in the Biscayne aquifer (Dausman and Langevin, 2005). However, short-term droughts could be responsible for saltwater intrusion into the base of the surficial aquifer system.

Long-term model results indicated that canal stage played the most important role in the position of the saltwater-freshwater interface, and interface movement could be reversed by raising the stage of the canal for an extended period of time (Dausman and Langevin, 2005). The 10-year model run also indicated a relationship between changes in head level near the well field and the movement of the saltwater-freshwater interface.

3.3 Previous Groundwater Models in the Suwannee River Basin

In 2002 Sepúlveda constructed a model of the Floridan aquifer system, which covered peninsular Florida and included the central and eastern part of Suwannee Water Management District. The intent for this model was to improve the regional conception and understanding of the ground-water flow system of the Intermediate aquifer system and the Floridan aquifer system, while ultimately creating a projected scenario for future ground-water withdrawals and build a database for future ground-water models.

Sepúlveda’s (2002) work consisted of uniform 464 m^2 (5,000 ft^2) cells in a steady-state, quasi three-dimensional MODFLOW-96 model, where separate layers are utilized to simulate each individual unit of the groundwater system. Specifically, the quasi three-dimensional model, also known as vertical discretization, specifies that each single layer represent a hydrologic unit where storage release only occurs in the aquifer where flow is horizontal, whereas in the confining units, conductance is represented as vertical flow (Harbaugh and McDonald, 1996). To simulate confining units, the model utilized a leakance term between the aquifers. The program MODFLOW-96 simulates flow in the Floridan aquifer system by utilizing the three-dimensional ground-water flow equation finite-difference approximation and block-centered grid defined by Harbaugh and McDonald (1996)(Sepúlveda, 2002).

The Peninsular Florida model incorporates 156 springs along with rivers in the unconfined areas of the Floridan aquifer system (Sepúlveda, 2002). The model was calibrated to selected observation points including measured and estimated spring and river flows during the period of August 1, 1993, through July 1, 1994.

Four layers were created to simulate hydrologic units Surficial aquifer system; Intermediate aquifer system, Intermediate confining unit (where the Intermediate aquifer system is absent), Upper Floridan, and Lower Floridan that simulated ground-water flow in the aquifer horizontally, while flow in confining units was simulated vertically (Sepúlveda, 2002). Layer 1 began with the surficial aquifer system as the top most unit, and was designed to be a source-sink layer where Dirichlet Type I constant heads were used to define the elevation of the water table. As a simulated layer, the Dirichlet Type I constant heads permit the Upper Floridan aquifer to discharge to the Surficial aquifer or the Upper Floridan aquifer to receive leakage from the Surficial aquifer. Rates of exchange between the two layers are determined by the relative head difference between the water table and Upper Floridan. In areas where the intermediate confining unit is present, vertical leakance is accounted for between the intermediate confining unit and Upper Floridan. Sepúlveda (2002) used the River Package in MODFLOW to simulate rivers and springs inside the river's cells. For springs outside of the river cells, Sepúlveda (2002) used springs simulated as drains using the Drain Package in MODFLOW. For ground-water withdraw and injection, the author used the Well Package for MODFLOW.

Lateral boundary conditions used for the Upper Floridan included a combination of Neumann Type II and Dirichlet Type I conditions. Areas along the Gulf of Mexico, specifically in Citrus, Hernando, Pasco Counties, Sepúlveda (2002) concluded most of the lateral flow to be discharged by springs observed in the vicinity and applied a Neumann Type II boundary to the Upper Floridan in those areas. Dirichlet Type I boundaries were used for the Upper Floridan and set equal to the equivalent freshwater head off the coast of Georgia and Florida and ranged from 112.6 km (70 mi) offshore from Camden County, Georgia to 32.2 km (20 mi) offshore from St. Johns County, Florida. This boundary condition limited water exchange along these boundary cells between the simulated Surficial aquifer system and Upper Floridan. For the remaining lateral boundaries of the Upper Floridan, Sepúlveda (2002) assigned both interpolated and extrapolated specified heads derived from the 1993-1994 potentiometric surface.

For the Lower Floridan, Sepúlveda (2002) used either Neumann Type II or Dirichlet Type I boundaries. Sepúlveda (2002) placed the eastern and western Neumann Type II boundaries of the Lower Floridan where chlorine concentration exceeded 0.005 kg/L. The bottommost boundaries were designated where the Intermediate aquifer, Upper Flordian, and Lower Floridan contain chloride concentrations that exceed 0.005 kg/L and were designated Neumann Type II boundaries. Sepúlveda (2002) specifies that this approach prevented potential errors associated with modeling variable density fluids. Furthermore, the author suggested the freshwater-saltwater interface is relatively sharp, occurs laterally, and that groundwater flow across the interface is negligible.

Sepúlveda (2002) compared the observed groundwater withdrawal rates from 1993-1994 to the projected rates of Year 2020 and found demand to reach $1.285\text{x}10^{10}$ l/day, an increase of 36% over the entire model area. Projected drawdown for the Year 2020 ranged from 1.82 m (6 ft) in Duval County to 3.05 m (10 ft) in Orange County for the Upper Floridan. In Osceola and Seminole Counties, the drawdown from the UFA was eight feet. In Glades County, the projected drawdown reached 6.10 m (20 ft) in the Intermediate aquifer system. Finally, projected drawdown in the Lower Floridan reached 3.05 m (10 ft) in Orange County. Significant drawdown was not recorded in either the Upper or Lower Floridan in the Northwest and West-Central parts of the model area.

A steady-state model of the Suwannee River Basin was developed by Planert (2007) for the Suwannee Water Management District in cooperation with the USGS with the purpose of understanding the regional ground-water flow system, specifically the exchange of water between the Upper Floridan aquifer system and the Suwannee River in both Georgia and Florida. To simulate steady-state conditions, the model was developed to run during a period of record low-flow during September 1990 when the system was assumed to have reached a point of equilibrium. The model was constructed using Waterloo Hydrogeologic Incorporated's Visual MODFLOW software and consisted of a rectangular grid made up of 163 rows and 148 columns with a uniform spacing of 1,524 m (5000 ft) for the width of each row and column.

Like Sepúlveda, Planert (2007) modeled the Surficial aquifer and Upper Floridan as a single flow system due to similar patterns observed simultaneously in the two hydrostratagraphic units. This combined system approach was used wherever the intermediate confining unit was absent. The base of the fresh ground-water flow system in the Upper Floridan was not defined by Planert, who references Miller's work as not clearly defining the base of freshwater and attributed this to a lack of fully penetrated wells in the study area (Miller, 1986; Planert, 2007). For model calibration, 190 wells, five rivers, and seven springs were simulated for ground-water discharge targets (Planert, 2007). The Suwannee Basin Model was calibrated to within a residual mean error of five percent or less which, came within 1.46 m (4.8 ft) of the potientiometric head values (Planert, 2007). Simulated discharge fell within four percent or less of observed values for the five river reaches and seven springs used in the calibration process.

Planert designated five boundaries in the model area beginning with a diffusive boundary in the southwest where the Gulf of Mexico meets the thinning freshwater portion of the Upper Floridan (Planert, 2007). A Neumann Type II boundary forms the northwestern edge of the model where it follows a flow-line near the St. Marks River in the counties of Wakulla, Leon, and Jefferson. This boundary continues further northeastward into Georgia along the same flow-line. In the northern section of the model, a specified head boundary coincides with the Valdosta potentiometric high in Lowndes County, Georgia. A Neumann Type II boundary was placed in the eastern section of the model area and runs simultaneous with the flow-line and potentiometric high south of the specified head boundary. Finally, the southeastern extent of the domain is defined by a Cauchey Type III that coincided with low potentiometric heads attributed to ground-water flow to the Oklawaha River.

Planert's (2007) simulated transmissivity values range from 304.8 to 6,096,000 m^2/day (3,280- 65,616,797 ft^2/day). The elevated values of transmissivity were associated with springs with the highest value found in proximity to Wacissa Springs. The lowest areas of transmissivity generated were associated proximal to wetland areas. Values for model-simulated recharge ranged from 12.7 mm/yr (.5 in/yr) in the confined areas of the Upper Floridan in the northern and the eastern sections of the model and 508 mm/yr (20 in/yr) near Wacissa Springs. Planert's (2007) initial estimate of 177.8 mm/yr (7 in/yr) was determined to be appropriate for most of the unconfined portions of the model area.

In 2007 the USGS developed a model for the Suwannee River Water Management District that simulated exchanges between the Upper Floridan aquifer and the lowest reaches of the Suwannee and Santa Fe Rivers (Grubbs and Crandall, 2007). The primary goal of this work was to use current and historical data to model the exchange of water from aquifer to river over a range of hydrologic conditions, hypothetical water use scenarios, and evaluate timing of these exchanges in a variable flow model for water years 1998-1999. A total of three models were created; two of which models were uncoupled and simulated ground-water and surface-water flow independently, and a third that coupled the two individual models as one. Calibration for the model was conducted over the period between October 1997 through September 1999.

The uncoupled ground-water flow model utilized MODFLOW 96 to simulate the Upper Floridan as one continuous hydrostratigraphic layer in the same manner as Planert in the Suwannee Basin Model (Grubbs and Crandall, 2007). Vertical flow was assumed to be negligible in comparison to horizontal flow with a two-dimensional (vertically averaged) representation of ground-water flow. The model design consisted of 163 rows and 148 columns, with a uniform spacing of 1,524 m (5000 ft) for the height and width of each column. Grubbs and Crandall (2007) set the bottom boundaries of the ground-water model at the surface of the middle confining unit where present, and the boundary was set at the saltwater-freshwater interface following the Ghyben-Herzberg Principle where the middle confining unit was absent.

Hydrologic conductivity was used as a calibration and transmissivity was assigned to groups of cells through arrays of zones

Continuous ground-water divides including potentiometric highs and divergence points were chosen as the lateral boundaries for the Lower Suwannee model domain, with the exception of a Dirichlet Type I boundary located where the Gulf of Mexico's coastline intersects the freshwater-saltwater interface and the top layer of the Floridan aquifer system (Grubbs and Crandall, 2007). The northern Neumann Type II boundary originated in high areas beginning in the east and west, and terminates where it intersects the Suwannee River in Branford . The western extent of the northern Neumann Type II boundary was defined by a potentiometric surface and gradient of the Upper Floridan aquifer system and can be traced southeast through Dixie County where it intersects the Gulf of Mexico. The eastern Neumann Type II began at the Suwannee River in Branford and continued up-gradient along a flow line where it reaches the extent of the unconfined Floridan aquifer system. A head dependent Cauchey Type III was placed where the Floridan aquifer system is overlain by the intermediate confining unit. The Cauchey Type III boundary transitioned into a Neumann Type II boundary near the point where Alachua, Levy, and Marion Counties come together . The Neumann Type II boundary follows a flow path down-gradient from the potentiometric high and terminates at the Gulf of Mexico.

The surface-water model BRANCH was used to simulate open-channel flow in selected areas and was calibrated through adjusting the roughness parameter for channel and floodplain until simulated values matched measured values during May and August 1997, August 1998, and September 1999 (Grubbs and Crandall, 2007). For the Suwannee River, a total of 85.29 km (53 mi) was simulated between the Branford and Old Town gages. A total of 28.96 km (18 mi) of the Santa Fe was simulated from the Fort White gaging station to the confluence with the Suwannee River near Branford, Florida.

Grubbs and Crandall (2007) used MODBRANCH to combine both the surface and groundwater models and simulations were made starting on October 1, 1997, and ran through September 30, 1999. The coupled model allowed for simultaneous simulation of changes in river stage and discharge and ground-water flow in response to changing ground-water levels. Measured and calculated results correlated well with an average residual level of 60.9 mm (2.40 in) for ground-water and ranging from –7.3 to + 3.35 m (-24 to +11 ft).

Grubbs and Crandall (2007) used two variables in an approach to evaluating spring contribution to the Suwannee and Santa Fe Rivers due to the lack of surface-water drainage and the large contribution springs provide to river discharge in the model area.

The first variable was locating springs and corresponding median discharge rates along two specified river reaches. The second involved acquiring measured streamflows upstream and downstream of the two river reaches. Then, the total spring-flow was computed and compared to total average pickup measured in the two reaches. This approach provided an estimate of the total exchange between ground and surface-water through known springs and the likely contribution from unknown springs and regular diffusive exchange in the river channel.

The first of the two reaches used for spring contribution evaluation included the Santa Fe, Ichetucknee, and Suwannee Rivers (Grubbs and Crandall, 2007). The Santa Fe was measured below the Fort White gaging station and the Suwannee was measured from the Branford gaging station. The first measured stretch ended downstream of the confluence of the three rivers at the Wilcox gaging station on the Suwannee River. A total of 36,811 l/s (1,300 cfs) was calculated for the first reach, which comes to 85 percent of long-term average net ground-water flow during water years 1942 through 1999. The second reach began at the U.S. Highway 441 gaging station and ended at the Fort White gaging station downstream. A total of 19,821 l/s (700 cfs) accounted for ninety percent net of ground-water outflow during water years 1942 through 1971.

From the data derived from both reaches, Grubbs and Crandall (2007) determined that springs are the primary source of ground-water contribution to the Lower Suwannee and Lower Santa Fe Rivers. Furthermore, reaches with clustered springs contributed more ground-water flow than reaches with springs that were evenly spaced along the river channel.

Schneider et al., (2008) developed a model of Northern Florida for the Suwannee River Water Management District with the purpose to construct a regional use permit evaluation tool for determining minimum flows and levels and environmental resources while investigating water resource availability and the hydrologic properties of the region.

The North Florida Model was fully three-dimensional and covered the hydrostratigraphic units of the Surficial aquifer systime, Intermediate aquifer system, confining units, and the Floridan aquifer system (Schneider et al., 2008). This model was developed using USGS's MODFLOW 2000 and was constructed and calibrated through Environmental Modeling System Incorporated's Ground Water Modeling System (GMS) 6.0 graphical user interface. Each model cell was uniformly spaced at 1,524 m (5,000 ft) covering 7,620 m^2 (82,021 ft^2) with a grid that consisted of 190 rows by 245 columns.

Previous models in this region have been quasi three-dimensional, where, the simulated flow in confined portions is transferred through a vertical leakance term (Schneider et al., 2008). This model was designed through the GMS 6.0 program, which requires that each hydrostratagraphic unit, aquifer, and confining unit, be explicitly represented in the design, making this a fully three-dimensional model. One of the primary functions of the model was to simulate the close interaction of unconfined Floridan aquifer system with the many springs and rivers that lie within the it. The large amounts of springs (145) and siphons in the study area were modeled using the Drain package in MODFLOW.

Like Planert's Suwannee Basin Model, Schneider et al. (2008) designed and calibrated a steady-state model that would simulate an observed regional low-flow and dry period. The model was designed around a drought occurring during the 2001 Florida water year and calibrated to drought conditions from June 1, 2001, through May 31, 2002. Calibration was achieved through targeting 47 continuously monitored wells in the region including 22 in the confined aquifers and 25 in the unconfined aquifers. The RMS level for all 47 wells was .283 m (.928 ft) Further, the RMS difference for unconfined wells was .329 m (1.08 ft) and wells located in confined units had a level difference of 0.228 m (0.75 ft). Calibration also included all 145 springs simulated and most of the major rivers in the model area (Schneider et al., 2008).

The model's extent goes well beyond the Suwannee River Management District's borders and was created with the intent of having little or no influence on the hydrologic processes within the domain (Schneider et al., 2008). These extents are made up of Cauchey Type III Boundaries that begin north of Valdosta, Georgia, turn southeast and cross the counties of Leon and Wakulla. The eastern Cauchey Type III is extend east towards the Atlantic Ocean turning south, and running through St. Johns, Flagler, Marion, and Citrus Counties. The Gulf of Mexico is the primary western boundary for The North Florida Model where the layer representing the Floridan aquifer system was given a constant head of zero and the depth to saltwater was set according to previous work of Countryman and Stewart (1997) (Schneider et al., 2008). As for the eastern extent, Schneider et al. (2008) followed the same model domain as the Sepúlveda (2002), where specified heads were used for the Upper Floridan aquifer system and set equal to the equivalent freshwater head off the coast of Georgia and Florida ranging from 113 km (70 mi) offshore from Camden County, Georgia to 32.2 km (20 mi) offshore from St. Johns County, Florida. In the Suwannee River Basin, Schneider et al. (2008) designated the bottom of the freshwater system where the middle confining unit was present. Where absent, the saltwater-freshwater interface was designated at the bottom of the Lower Floridan aquifer or the calculated transition zone depending on which of the two was higher (Schneider et al., 2008). In either case the saltwater-freshwater interface was designated as a Neumann Type II boundary. Other boundaries for the Floridan aquifer system were modeled using the general head boundary package in MODFLOW and were designed to be distant enough from the investigated area that there was limited impact assumed.

Results from the North Florida Model matched closely to the observed values from wells, springs, and gaging stations in the model area (Schneider et al., 2008). Total simulated spring discharge was calculated to be approximately 135,637 l/s (4,790 cfs), which was greater than 99% of observed spring discharge with a maximum percent discrepancy of 8% between observed and simulated values. Furthermore, a majority of the springs have a percent discrepancy that was less than 1% . As for rivers, Schneider et al. (2008) utilized 38 rivers or river reaches in calibration that matched the observed baseflow value of 46,722 l/s (1,650 cfs). The maximum discrepancy between observed and simulated baseflows was 6.5% while 38 of the reaches had a maximum discrepancy that was less than 1% .

For observation wells in the surficial aquifer system, the average residual head was –3.66 m (–0.12 ft) and the average residual mean was 2.95 m (9.68 ft), which accounted for less than 5% of the aquifer's total head range of approximately 60.96 m (200 ft) (Schneider et al., 2008). For wells in the Upper Floridan aquifer system, the average residual head was 0.167 m (0.55 ft).

Absolute residual mean was 1.31 m (4.30 ft) for wells in the Upper Floridan, which is less than 5% of the approximately 30.48 m (100 ft) of the aquifer's head range.

In summary, all four models that simulated the Suwannee River Basin used some version of the USGS's MODFLOW program and the governing equation design of Harbaugh and McDonald (1988). Schneider et al.'s North Florida Model utilized a full three-dimensional model for discrtetization, whereas the other three models used a quasi-three dimensional design for simulation (Sepúlveda, 2002; Planert 2007; Grubbs and Crandall, 2007; Schneider et al., 2008). Schneider et al. (2008) modeled each hydrostratagraphic layer individually, while Sepúlveda (2002) combined the Floridan aquifer system and Surficial aquifer system as one unit and separated the lower hydrostratagraphic units in the Peninsular Florida Model. Planert (2007) and Grubbs and Crandall (2007) simulated one continuous unit layer for the unconfined Floridan aquifer system including areas overlain by the Surficial aquifer system and placed lower boundaries at the middle confining unit or saltwater-freshwater interface.

Sepúlveda (2002), Planert (2007) and Schneider et al. (2008) used steady-state models simulating low-flow conditions as opposed to Grubbs and Crandall (2007), who utilized a transient model covering a range of hydrologic scenarios. Grubbs and Crandall (2007) placed the bottom boundary of their model at the middle confining unit, where present, or the saltwater-freshwater interface as determined by the Ghyben-Herzberg Principle. Sepúlveda (2002) placed his bottommost boundary where chloride concentrations exceed 0.005 kg/L and considered this to be a Neumann Type II boundary, while Planert (2007) determined there was not enough data available to locate the saltwater-freshwater interface. Schneider et al. (2008) used a combination of Sepúlveda's (2002) work and Countryman and Stewart (1997) to define the saltwater-freshwater interface for the North Florida Model.

Springs and rivers were also handled differently for the four Suwannee Basin models. The majority of the models used the River Package for channel flow with the exception of The Lower Suwannee Model, which utilized the BRANCH package in both uncoupled and coupled simulations (Grubbs and Crandall, 2007). Also, springs were largely simulated through MODFLOW's River and Drain packages with the exception of The Lower Suwannee Model simulation (Sepúlveda, 2002; Planert 2007; Grubbs and Crandall, 2007; Schneider et al., 2008). In the Lower Suwannee Model the overall contribution of spring flow to the Suwannee and Santa Fe Rivers was determined through collecting discharge measurements at gaging stations along multiple river reaches and subtracting known spring discharge from those observed values.

CHAPTER 4

METHODS AND MATERIALS

This chapter is an overview of the collection and formatting of data input as well as how parameters in the model were designed around the data input. This chapter also describes the ground water and multi-variable density model development, calibration, and verification, as well as the mathematical basis for the two models.

4.1 Software Programs

Multiple software programs were used for formatting, input, and computation of the groundwater model. Microsoft Excel was utilized for formatting and metric conversion. Values were then converted to text format for placement into Visual MODFLOW. For data formation in respect to spatial assignments, ArcGIS 10.1 was used. The groundwater and multivariable-density transport models were developed and run in Schlumberger Water Services' Visual Modflow Pro 2011.1. Output and graphs for groundwater levels were viewed in the Kirk Compare program developed by John F. Dowd in C++.

4.2 Design and Discretization of the Model

The groundwater flow model was developed as a transient model spanning five years from May 1, 2007, through April 30, 2012 and coordinate with the Florida Department of Environmental Protection's designated water year. The design, build, and calibration of the transient groundwater model were completed in USGS MODFLOW 2000 with Visual MODFLOW (Harbaugh, 2005; Schlumberger Water Services). Upon completion, the model was then converted to the variable-density program SEAWAT, an option in Visual MODFLOW.

A daily time step simulating 1,825 days was used for the five-year run. Visual MODFLOW does not differentiate between time steps and stress periods; therefore the model simulated 1,825 stress periods as well. Problems arose when attempting to run the complete model with this amount of data over a five-year time span. To address the limited model capacity for data over the allotted time, the model was halved between two time spans. The first half was assigned two years, 2007-2008, with 730 time steps, and the second comprised of the remaining three years, 2009-2012, with 1,095 time steps.

The model domain includes six layers to simulate the upper Floridan aquifer system, middle confining unit (where present), and the lower Floridan aquifer system (See Figure 4.1). The additional layers were arranged specifically for assigned initial concentrations of total dissolved solids. Discretization of the grid was set up with 200 rows by 190 columns where each column is 631 m (2070 ft) wide and each row is 742 m (2438 ft) high.

4.3 Governing Equation for the Groundwater Model

The calibration model for this study was developed using MODFLOW 2000 and was later converted to SEAWAT for the variable density scenario. Developed by McDonald and Harbaugh (1988), the MODFLOW program assumes Darcy's Law is valid in that flow is laminar and simulates three dimensional movement of groundwater through porous earth material that is a heterogeneous, isotropic aquifer can be described in the partial-differential equation:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_y \frac{\partial}{\partial z}\right) + W = Ss \frac{\partial h}{\partial t} \quad (4.1)$$

Where K_x, K_y, and K_z are values of hydraulic conductivity along the x, y, and z, coordinate axes, h is the potentiometric head (L), W is a volumetric flux per unit volume of water and represents sources and/or sinks of water, Ss is the specific storage of the porous material, and t is time in days

4.4 Boundary Conditions

Three boundaries were used in the groundwater model, Dirichlet Type I, Neumann Type II, and Cauchey Type III (Figure 4.2).

Dirichlet Boundary Condition

The shore of the Gulf of Mexico was assigned a Dirichlet Type I boundary, where the boundary is simulated by setting the head at boundary nodes that are equal or relevant to known head values and often represent surface water bodies (Anderson and Woessner, 2002). The Gulf of Mexico was assigned a value of zero (m) for mean sea level. This was stated mathematically by Bear (1979) as:

$$h = f(x, y, z) \; on \; \Gamma \qquad (4.2)$$

Where Γ is the boundary surface

Neumann Boundary

Much of the boundaries enclosing this model are assigned as a no flow boundary (Neumann Type II) where groundwater flow lines begin up gradient and flow towards the Suwannee and Santa Fe Rivers (Grubbs and Crandall, 2007). No flow boundaries are prescribed flux boundaries (Neumann) and are written mathematically as:

$$q_n = f(x, y) \; on \; \Gamma \qquad (4.3)$$

Where q_n is the outward normal flux. For this work the NeumannType II boundary was designated a no flow boundary where $q_n = 0$

Cauchy Boundary

A Cauchey Type III (General Head Boundary) is based on the linear relationship between level of the boundary's head and its distance to the head level in an observation well placed beyond the model's boundary (McDonald and Harbaugh, 1988). This relationship can be further described where flow is simulated proportionally out of a cell i, j, k to the difference between the two heads by way of boundary conductance (Harbaugh, 2005).

$$C_n = Q_n \left(H_n - h_{ijk}\right) \qquad (4.4)$$

Where:

C_n is a constant flow boundary

Q_n is the flow to the cell i,j,k from the boundary (L^3T^{-1})

H_n is the head assigned to the external source (L); and

h_{ijk} is the head in cell ijk (L)

Cauchey Type III Boundaries were assigned by Grubbs and Crandall (2007) where the Floridan aquifer system is overlain by the intermediate confining unit. The northern Cauchey Type III Boundary begins in Suwannee County northeast of Branford and runs east before arcing southeast prior to its termination on the north side of the Santa Fe River near the intersection of Columbia, Alachua, and Gilchrist Counties. The second Cauchey Type III Boundary forms the eastern extent of the model beginning near the towns of Alachua and High Springs and traveling south to where it terminates near the borders of Levy, Alachua, and Marion Counties. During model design, Grubbs and Crandall (2007) interpolated seven potentiometric surface maps of the Floridan aquifer system to determine the general shape of the groundwater levels and where to assign their Cauchey Type III Boundaries for years 1998 through 1999. The continuous wells assigned to the two Cauchey Type III Boundaries for this study were observation well Alachua

S081806005 for the eastern boundary, and observation well Columbia S051621002 for the northern boundary north of Ft White.

Recharge

Recharge data was obtained from the USGS National Map Viewer and converted to individual zones in ArcGIS before importing into the model (Figure 4.6). The Recharge Package was used for aerially distributed recharge for each zone where a yearly amount (mm) was applied to a corresponding cell and divided over 365 time steps (Harbaugh, 2005). The Recharge Package is defined as:

$$R_{i,j} = I_{i,j} DELR_j DELC_i \qquad (4.10)$$

Where:

$R_{i,j}$ is the recharge flow rate applied to the model at horizontal cell location (i,j) expressed as fluid volume per unit time (L^3T^{-1}).

$I_{i,j}$ is the recharge flux (in units of length per time, L^3T^{-1} applicable to the map area, $DELR_jDELC_i$ of the cell).

Rivers

The River Package in MODFLOW is designed to simulate the flow of water from the ground water system into a surface-water feature (Harbaugh, 2005). The River Package does not simulate flow in the river, rather it simulates river-aquifer seepage for each individual cell that is assigned (Harbaugh, 2005). An assumption is made that losses for the measurable head between the river and the aquifer are limited to a loss from the riverbed itself, and no head loss between the riverbed's bottom layer and the point represented by the underlying node (Harbaugh, 2005).

Secondly, another assumption says that the underlying cell remains fully saturated (Harbaugh, 2005). The River Package can be defined mathematically by:

$$-Qr = Kr\left(Hr - h_{ijk}\right) \tag{4.8}$$

Where:

Qr	is the flow between the river and the aquifer (L^3T^{-1})
Hr	is the river's stage (L)
Kr	is the hydraulic conductance of the river aquifer interconnection (L^3T^{-1}) and
H_{ijk}	is the head at the node of each cell underlying the river reach

The Suwannee River is the main surface water feature in this model and flows north to south with two primary tributaries, the Santa Fe and Ichetucknee Rivers, which join the Suwannee in the northern section of the model (See Table 4.4 and Figure 4.2). Stream sections were assigned using Visual MODFLOW's River Package where reaches were divided by gaging station. Variables required for the River Package were the start and stop times for each day, the mean river stage for that day (m), the elevation of the riverbed bottom (m), riverbed conductance (m^2/day), the thickness of the riverbed (m), and the vertical conductance of the riverbed (m/s). The default conductance formula was assigned for each river reach. The default conductance formula is defined as (Schlumberger Water Services, 2011):

$$Kr = \frac{Lr \cdot w \cdot Kz \cdot C}{Tr - Br} \tag{4.9}$$

Where:

Kr	is the streambed conductance
Lr	is the reach length of the stream line in each cell

w	is the stream width in each grid cell
Kz	is the vertical stream bed conductance
C	is the conversion factor for converting the Kr value to the same L and T units used by Kr
Tr	is the streambed top
Br	is the streambed bottom elevation

For this model, the Suwannee River begins at the Branford gage near the town of Branford, Florida. This section of river joins with the mouth of the Santa Fe and ends at the Bell gage near the community of Bell. After Bell, the river is assigned values at the Wilcox, Manatee, and Fowler gages. The Gopher River gage was not used due because it did not have data available for the entire model.

The Santa Fe River begins at the High Springs gage near High Springs, Florida. From Fort White the river flows to the Hildreth gage near the community of Hildreth. The mouth of the Santa Fe lies shortly beyond the Hildreth gage. The Three Rivers gage near the mouth of the Ichetucknee was not used due to lack of data available during the model's specific data range. Only the Ichetucknee near Hildreth gage was used for the Ichetucknee River. For the Wacassasa, only the gage near Gulf Hammock was used. A table of gaging stations used is in Table 4.6.

4.5 Governing Equation for the Variable-Density Groundwater Model

The following equations and assumptions review the governing equations that describe variable-density flow and the solute transport in porous media. For a more detailed derivation of these equations, readers are encouraged to examine Bear (1972) as well as Guo and Langevin (2002). The SEAWAT program is based on the concept of freshwater head, or equivalent freshwater head, in a saline groundwater environment, where the variable-density ground water flow equation is developed in terms of fluid density and freshwater head.

The governing equation for SEAWAT further assumes the diffusive approach to dispersive transport is based on Fick's Law and can be applied, isothermal conditions prevail, and a single, fully miscible liquid phase of very small compressibility is also assumed (Guo and Langevin, 2002). The equation is written as…

$$\frac{\partial}{\partial x}\left(\rho K f_x \frac{\partial h_f}{\partial_x}\right) + \frac{\partial}{\partial y}\left(\rho K f_y \frac{\partial h_f}{\partial_y}\right) \qquad (4.5)$$

$$+\frac{\partial}{\partial_z}\left(\rho K f_z \left[\frac{\partial h_f}{\partial_z} + \frac{\rho - \rho_f}{\rho_f}\frac{\partial Z}{\partial z}\right]\right) = \rho S_f \frac{\partial h_f}{\partial_t} + \theta \frac{\partial_p}{\partial C}\frac{\partial C}{\partial t} - \bar{\rho} q_s$$

Where K_{fx}, K_{fy}, and K_{fz} are hydraulic conductivities for freshwater in three coordinate directions [LT^{-1}], ρ is the fluid density $\left[\frac{g}{L}\right]$, $\bar{\rho}$ is the density of water entering from a source or sink [ML^{-3}], q_s is the volumetric flow rate per unit volume of aquifer representing sources and sinks [T^{-1}], θ is porosity, t is time, K_f is the freshwater hydraulic conductivity, h_f is the freshwater head, ρ_f is the density of freshwater, S_f is the specific storage in terms of freshwater head, C is the NaCl concentration in total dissolved solids (TDS) [g/L].

Groundwater flow naturally causes a redistribution of solute concentration resulting in density variation within the aquifer. Guo and Langevin (2002) wrote that the movement of groundwater and the transport of solutes are a coupled process and the two equations must be solved together. Constituents such as NaCl are transported by groundwater flow through the process of advection and dispersion described in the partial differential equation and defined by Zheng and Bennett (1995) as:

$$\frac{\partial C}{\partial t} = \nabla \cdot (D \cdot \nabla C) - \nabla \cdot (\overrightarrow{vC}) - \frac{q_s}{\theta} C_s + \sum_{k=1}^{N} R_k \qquad (4.6)$$

Where:

D is the hydrodynamic disperssion coefficient $[\mathrm{L}^2\mathrm{T}^{-1}]$,

$\vec{v}$ is the fluid velocity $[\mathrm{LT}^{-1}]$

C_s is the solute concentration of water entering from sources or sinks $[\mathrm{ML}^{-3}]$

R_j $(i = 1{:}N)$ is the rate of solute production or decay in reaction k of *N* different reactions $[\mathrm{ML}^{-3}\mathrm{T}^{-1}]$

4.6 Adjustments for Boundary Conditions for the Variable-Density Model

The Cauchy Type II Boundary is not analogous for the SEAWAT simulation in the possibility the boundary conditions may require advective and dispersive components (Gao and Langevin, 2002). The head is specified for a normal Cauchy Boundary, but will exist at some hydraulic separation from the boundary where the relationship between the two is calculated in the simulation. It is here that the control on the head is linked through a conductance term. During salute transport the Cauchy Boundary depends on the specification of both concentration and concentration gradient (Zheng and Bennett, 1995). This indicates that dispersive flux across the boundary is specified (Gao and Langevin, 2002). However, as flow across the boundary during a transport simulation varies, the advective flux will also vary. Therefore, the flow, Q_b, into or from a Cauchy head dependent boundary can be calculated as:

$$Q_b = C(h_c - h_{ijk}) \qquad (4.6)$$

Where:

C is the conductance term

h_c is the specified control head

h_{ijk} is the calculated head at the boundary cell, which is linked through the conductance term.

As stated in section 4.4, a Dirichlet or specified head boundary, requires a relevant or known value for head specified along boundary nodes representing a surface body of water (Anderson and Woessner, 2002). The boundary simulates flow toward or away from the boundary and responds to a proportional relationship between the specified head at the boundary and calculated heads adjacent to the boundary (Gao and Langevin, 2002). Dispersive flux responds to this relationship between specified boundary and adjacent heads by also moving toward or away from the boundary. However, dispersive flux also responds and is affected by the assigned boundary and calculated concentration at points in proximity to the boundary. Finally, calculated concentration will determine the flux of the advective solute adjacent to as well as flowing toward the boundary (Gao and Langevin, 2002).

4.7 Data Collection

Hydrologic data was collected from the Suwannee River Water Management online Water Data Portal at http://srwmd.org. The Water Data Portal provides easy access to data that has been collected by the USGS and the Suwannee River Water Management District. Collected data includes gage height elevations for the Suwannee, Ichtucknee, and Santa Fe Rivers, discharge data for springs that contribute to the rivers, head values for observation wells used in the model, and water quality data used for springs and wells in the model. This hydrologic data was downloaded in Microsoft Excel format and converted for use in the modeling and spatial software packages. Data for the research and petroleum test wells was collected and provided by Lester Williams from the USGS.

4.8 Digital Elevation Model

All data points were formatted in ArcGIS 10.1 and converted to North American Datum 1983 UTM 17N. Two Digital Elevation Models (DEMs) were used for land surface elevation. The primary DEM was obtained from the USGS National Map Viewer and consists of a 30 m (98.4 ft) resolution. In a few locations the USGS DEM was distorted. To remedy this, a 90 m (295 ft) DEM acquired from NASA's Advanced Spaceborne Thermal Emission and Reflection Radiometer was added to the existing USGS 30 m DEM in these locations. Eventually, the 30 m data was found to be too detailed and the entire data set was resolved to a coarser 90 m.

4.9 Aquifer Properties

Initial values for hydraulic conductivity were acquired from Schneider et al. (2008). The hydraulic conductivity values were digitized and assigned to layers beginning with the Upper Floridan aquifer system and were then used as the starting point for calibration. The same values were used for the Lower Floridan aquifer system but assigned a value two orders of magnitude lower according to Miller (1986). The middle confining unit was assigned a single value of $3.52x10^{-7}$ m/s (0.01 ft/d) according to Hickey (1990), where values for storativity were required for input on the account that this is a transient simulation (Anderson and Wossener, 2002). The layers representing the Lower Floridan aquifer system and middle confining unit were assigned a value of $S= 0.001$ and the Upper Floridan aquifer system was assigned a value of $S= 0.05$. These values fall within the range of previous works by Grubbs and Crandall (2007), who assigned storage values that ranged from $S= 4x10^{-4}$ to $S= 0.5$ and Sepulveda (2002) who, used values of $S= 0.1$ for the unconfined aquifers to $S= 0.001$ for the confined aquifers. Sepulveda (2002) notes that storage in unconfined vs. confined has a difference of two orders of magnitude.

The USGS's 2010 potientiometric surface of the Floridan aquifer system was used to assign initial heads in the model (Kinnaman and Dixon, 2011). The surface was imported into ArcGIS as a shapefile and converted a point shapefile.

4.10 Observation Wells

Only continuous head observation wells were chosen as calibration points for this transient model (See Table 4.3). Well data for the model area was acquired from the SRWMD Water Data Portal. Coordinates for each well were converted to UTM in ArcGIS and imported into Visual Modflow as a text file. Daily values were assigned to individual stress periods for the two consecutive model runs of 0-730 and 0-1,095 days when combined made 1,825. If the well had a head value of zero and was not a likely value, then the associated stress period was skipped in the order. During the selection process, wells were chosen on data extent leaving four wells that were omitted due to gaps in recorded data that persisted for months to years.

Ten continuous observation wells (Table 4.3) were chosen for this study, all of which are monitored by the Suwannee River Water Management District. Wells were largely selected due to the extent of their data range as well as their location within the model. For instance, Columbia S061618003 has a limited amount of data available for the first two years of the model run but was used due to a lack of wells in the northern sector of the model. Descriptions of the observation wells are listed below beginning with the northern most well in Ichetucknee River State Park in Columbia County, and ending with the southernmost well in Levy County near the town of Cedar Key on the Gulf of Mexico

Located in Ichetucknee Springs State park, Columbia S061618003 is a shallow well at -10.97 m (-36 ft). The well is adjacent to Ichetucknee Head Spring and Blue Hole Spring, which are both classified as first magnitude as well as the Ichetucknee River **(**Hornsby and Ceryak, 1998). A number of other smaller springs, both named and un-named, also are in proximity to this well **(**Hornsby and Ceryak, 1998). The surrounding geology is karstic with extensive secondary dissolution, which facilitates the multitude of springs in the area. Well S061618003 is also surrounded on all sides by irrigated agricultural land, and is 6.5 km (4 mi) from the Santa Fe River to the south.

Located in the City of High Springs, Well S081703001 is a deep well at -87.47 m (286.97 ft). Encircling the town of High Springs are irrigated fields and as well as few industrial and mining sites. The well is located 5.8 km (3.6 mi) from the Santa Fe River and is drilled into a highly karstic portion of the unconfined upper Floridan aquifer.

Observation well Dixie S081313005 is located on the western side of the model on the edge of the Mallory Swamp, and is situated below the confluence of the Suwannee and Santa Fe Rivers. A shallow well at -10.68 m (-35 ft), it is approximately 2.2 km (1.4 mi) from the Suwannee in a narrow strip of irrigated agricultural land that runs parallel to the river. Numerous small ponds are located amongst the fields and timberlands that comprise of these high grounds.

Observation well Dixie S101210001is located in Cross City near the Cross City Airport. The well is relatively deep at -65.53 m (215 ft) and is located 13.5 km (8.4 mi) west of the Suwannee River. To the south and west of Cross City are the extensive low-lying areas of the California and Pumpkin Swamps that extend to the Gulf of Mexico 27 km (17 mi) away. Major withdrawals from the Floridan aquifer include Cross City, where it is used for municipal and industrial supply. To the east and north of Cross City lies a strip of agricultural land that parallels the Suwannee River's north-south course.

The Levy S101429020 well is approximately 1.2 km (0.75 mi) from the Suwannee River and in proximity of Fanning Springs in Fanning Springs State Park. This is a shallow well at -

9.75m (31.98 ft) and is also near the town of Fanning Springs. To the east of the well lies the Chiefland Limestone Plain that runs parallel to the Suwannee River. These elevated plains host the second largest extent of irrigated land in the model domain.

The City of Chiefland is one of the larger cities in the model and is close to the Levy S121508005 well. This is a shallow well at -10.05 m (35.26 ft) and is approximately 16 km (10 mi) from the Suwannee River. Both the well and city are situated on the Chiefland Limestone Plain, which runs parallel to the Suwannee River and hosts well-drained soils for irrigated farmland (Grubbs and Crandall, 2007). There are a few lakes in proximity, the largest being Long Pond, which is adjacent to Levy S121508005.

On the western bank of the Suwannee River, near its southern terminus at the Gulf of Mexico, is well Dixie 21330002. Relatively shallow at -12.192 m (-40 ft), this well is only 1.2 km (0.75 mi) from the west bank of the river and is surrounded to the north, south, and west by the California Swamp in Dixie County.

Observation well Levy S131736001 is a deeper well at -86 m (282 ft). Located on the edge of the model domain, this well is on Brooksville Ridge near the town of Williston. The Brooksville Ridge is largely covered with agricultural fields, which surround Levy S131736001. Approximately 3 km (2 mi) to the west and south, Brooksville Ridge is bordered by the edge of the Devils and Gulf Hammocks, which are low lying swampy areas where the water table lies at or near the ground surface (Grubbs and Crandal, 2007).

Lying entirely in the Devils and Gulf Hammocks and 582 m (1909 ft) from the Waccasassa River, Levy S141707004 is a relatively deep well drilled to -73.76 m (241.99 ft). This area is primarily a low-lying swampy area approximately 20km (12 mi) from the shores of the Gulf of Mexico.

Levy S141429001 is a deep well at -134.7 m (441 ft) and is located in the low- lying coastal Gulf Hammock. The well is near the communities of Rosewood and Sumner at the southern extent of the model, approximately 8 km (5 mi) from the Gulf of Mexico and approximately 17 km (10.5 mi) east of the Suwannee River.

4.11 Pumping Wells

The Well Package in MODFLOW simulates wells that withdraw water at constant rates during each time step or period (McDonald and Harbaugh, 1988). For this work, the Well Package was used to simulate withdraw from the Upper Floridan aquifer for irrigation, municipal, and industrial wells and also to simulate spring discharge. During the simulation, four values were needed for each well including the row, column, and layer number of the cell where the well is located and the specified discharge. The Well Package in MODFLOW redefines the well for each stress period (McDonald and Harbaugh, 1988). This can be mathematically defined as:

$$-\frac{Q_n}{Q_w} = \frac{T_i}{\mathrm{T}} \qquad (4.7)$$

Where:

Q_n is the discharge from layer n to a particular well in a given stress period (L^3T^{-1})

Q_w is the total discharge for the well in that stress period (L^3T^{-1})

T_i is the transmissivity of layer n (L^3T^{-1}), and

T is the sum of the transmissivities of all layers penetrated by the well (L^3T^{-1})

Groundwater withdrawals from agricultural, industrial, and municipal pumping for the 2007-2012 simulation period was gathered from the SRWMD's 2010 Water Supply Assessment. All municipalities that withdraw from the Floridan aquifer system were included in the model (See Table 4.1 and Figure 4.3). A single value for daily withdraw was assigned for each stress period between 0-1,825 days. The location of the pumping well was determined through the use of Google Earth and assigned wherever a municipality had a water tower located and an assumed well field. Industrial sites were located on Google Earth and assigned to the corresponding location in the model domain.

For agricultural demand, total withdraws for each county were determined from the percentage of how much area the county is represented within the model boundaries. Levy and Gilchrist counties lie completely within these boundaries. Withdrawals from the aquifer corresponds to yearly climate; in years with less rainfall, pumping and from the aquifer was greater. As for years with more rainfall, pumping was less. This amount was further subdivided for individual wells and dispersed to multiple agricultural areas that had multiple central pivot irrigation such the Chiefland Limestone Plain. These areas were located using Google Earth.

Nine springs of first and second magnitude were simulated as pumping wells (See Table 4.2 and Figure 4.3). Screen depth was set between two meters and 60 m (197 ft) to simulate the depth of the capture zone of potential fractures that contribute to the outflow. The majority of first magnitude springs in the lower Suwannee Basin are continuously gaged and include Fanning, Ichetucknee, Blue Hole, and Manatee Springs. Other springs represented in the model had measurements that were monthly or quarterly.

To determine when a spring was flowing at normal discharge or under drought conditions, and to alleviate data gaps found in the smaller magnitude springs, all available data was collected and analyzed through the use of box plots in R (Figures 4.4 and 4.5). When, the spring was deemed to be experiencing average or greater flows, the median discharge was assigned for that month. In months where the spring had less than average flow, the 25 percent quartile was assigned for discharge.

The Ichetucknee River drains an area that consist of multiple springs, most notably the first magnitude vents of Ichetucknee Head Spring and Blue Hole Spring (Hornsby and Ceryak, 1998). Other springs along the Ichetucknee include Devils Eye, Missing, Grassy Hole, Mill Pond, and Coffee Springs (Scott et al., 2004). Discharge data varies for this spring group where Ichetucknee had continuous daily discharge from February 2002 until May 2010 and stage data beginning in February 2002 until present. Blue Hole Spring had continuous stage and discharge data from February 2002 until present. Other springs along the Ichetucknee did not have frequent stage or discharge measurements. An analysis of stage and discharge data from Blue Hole and Ichetucknee Head Spring showed a correlation of 0.75 when compared to the discharge and stage data recorded at the USGS gage at U.S. 27 near Hildreth, FL. Therefore, instead of using a pumping well to simulate the spring's drain on the Upper Floridan aquifer, the drainage was represented by the Ichetucknee River. When both springs and river were included in the model a consistent under representation of observed versus simulated heads were recorded for the Columbia S061618003 well. An under-representation was observed throughout calibration and was corrected only after the drains representing the springs were turned off during model runs. Once turned off, the observed versus simulated heads matched and indicated that the springs were being duplicated through the river and well.

4.12 Calibration of the Transient Solution

Anderson and Wossener (2002) state that calibration of the flow model refers to the demonstration that the model is capable of producing field-measured heads and flows, which are calibration values. Further, the calibration is achieved by producing simulated heads and fluxes through variables including parameters, boundary conditions, and stresses all matching field-measured values within a pre-established range of error.

Calibration of the transient solution was achieved manually through the adjustment of parameters until simulated head matched observed head to within an acceptable range (Table 4.6). The primary calibration parameter was hydrologic conductivity (m/s) with secondary adjustments in boundary conditions including the Cauchey Type III Boundary (m^2/day) and river boundaries. Riverbed conductance (m^2/day) and vertical riverbed conductance (m/s) were both targets in the calibration of the groundwater model. Calibration was very sensitive to riverbed conductance and not very sensitive to vertical riverbed conductance.

Initially, the transient model produced heads that were largely out of acceptable range. For most wells, this period would stabilize around the end of the second year of the five-year simulation. Values produced during the first two years were not used in analysis for this reason. Some wells, such as Levy S141707004, would not fully stabilize until fourth year of simulation.

4.13 Evaluation of the Transient Solution

To confirm that the model accurately simulates field conditions in the natural setting, a evaluation process must be performed (Anderson and Woessner, 2002). This procedure involves the use of parameters and hydrologic stresses that the transient simulations were not previously calibrated to. To evaluate the calibrated output for this simulation, two years of head data (May 1, 2013-April 30, 2014) replaced the five years of data that the model was calibrated to and given the same parameters such as hydraulic conductivity and boundary types and widths. The two simulations were then compared.

4.14 Sensitivity Analysis

The objective of a sensitivity analysis of the calibrated groundwater model is to quantify any uncertainties that lie in estimated factors involving aquifer parameters, stresses, and boundary conditions (Anderson and Woesnner, 2002). Variables such as conductivity, boundary conditions, storage, and recharge proved to be sensitive when values were adjusted during 474 calibration runs. It was determined that after the large amount of model runs there was a general understanding of what variables were most and least sensitive. A general rating of sensitive variables can be seen in Table 4.6. The sensitivity analysis for this study focused on the calibration of the observation wells through changes in assigned horizontal conductivity, as opposed to variations in boundary conditions.

To evaluate sensitivity in the wells, three wells were removed in three separate schemes labeled A, B, and C found Tables 4.8 through 4.10 and Figure 4.11. Each well in the sensitivity analysis was measured at the initial, middle, and final time step. Prior to removal, the observation well's head levels were noted along with the simulated head levels. Following removal, the model was run again and the head levels were observed in the locations where the observation wells were removed. The relative percent difference was calculated between the value from the fully calibrated model and the value for the removed observation well. The model was then re-calibrated and the relative percent difference was calculated for the observed head value and the head value where the observation well was removed.

4.15 Salinity Data

Data for the multivariable-density simulation was acquired from the USGS's Saline Aquifer Mapping Project as well as ground water quality data from the Suwannee Water Management District. Data was acquired for intervals between 3 g/L and 35 g/L and were derived using the Resistivity Method (Table 4.5) from oil and gas test wells drilled throughout Northwestern Florida (Table 4.7) (Williams in communication, 2013). The data was used to map the extent of salinity in the bottom of the Upper and Lower Floridan aquifers, and consisted of 22 wells where four were within the boundaries of the model and 18 were outside. See Figures 4.7, 4.8, 4.9, and 4.10 for maps of the petroleum and research wells.

Initial values for Total Dissolved Solids were assigned as a gradient beginning at the top most layer (layer one) and gradually increasing towards the bottom (layer seven). For initial concentration in the top layer, the Total Dissolved Solids data from 19 water quality wells was averaged and converted to individual zones with the Theissen Polygon Tool in ArcGIS. The elevation for the 3 g/L and 10 g/L Total Dissolved Solids elevations were interpolated through the Empirical Bayesian Kriging tool in ArcGIS. The elevation of the 3 g/L and 10 g/L Total Dissolved Solids levels were then assigned to one of seven corresponding elevation layers in the model. The 5 g/L TDS elevation fell within a few meters of the 3 g/L and was not assigned.

For examining the salinity data output, four periods of dry and normal conditions were chosen from the spring data. Cells were then examined with Visual MODFLOWS Cell Inspector Tool to determine the Total Dissolved Solids concentration at that time step. Each time step was also examined in map view as well. Total Dissolved Solids concentration with depth was also recorded for municipalities and industries with the highest withdraw rate. After present conditions were sampled, future demand scenarios were examined based on the Suwannee River Water Management’s 2010 Water Supply Assessment. A sensitivity analysis was also performed where withdraw rates were doubled for five cities and one industrial site.

Table 4.1: Modeled Municipal and Industrial Groundwater Withdrawal Rates.

Name	Use	2010 Withdrawal kL/day	2010 Withdrawal mgd	Expected Increase for 2030 kL/day	Expected Increase for 2030 mgd
City of Archer	Municipal	537	0.142	666	0.176
City of Bronson	Municipal	863	0.228	1,242	0.321
Town of Cedar Key	Municipal	601	0.159	795	0.212
City of Chiefland	Municipal	1,589	0.42	1,885	0.498
Town of Cross City	Municipal	4,368	1.15	5,731	1.514
Town of Fanning Springs	Municipal	530	0.14	727	0.192
City of High Springs	Municipal	1,768	0.467	2,169	0.573
City of Newberry	Municipal	2,347	0.620	3,074	0 .812
Town of Suwannee	Municipal	378	0.10	379	0.10
Suwannee Lumber	Industrial	416	0.11	416	416.4
Town of Trenton	Municipal	874	0.231	874	0.231
Vulcan Materials	Industrial	4,997	1.32	4,997	1.32

Table 4.2: Springs Simulated in the Groundwater Model.

Spring Name	Latitude/ Longitude	Magnitude	Station Number	County
Blue Hole Spring	29° 58’ 49” 82° 45’ 31”	1	02322688	Columbia
Fanning Spring	29° 35’ 14” 82° 56’ 07”	1	02323502	Levy
Gilchrist Blue Spring	29° 49’ 46” 82° 40’ 59”	2	02322350	Gilchrist
Ginnie Spring	29° 50’ 08” 82° 42’ 00”	2	02322400	Gilchrist
Hart Springs	29° 40’ 28” 82° 57’ 05”	2	02323150	Gilchrist
Ichetucknee Head Spring	29° 59’ 02” 82° 45’ 43”	2	02322685	Columbia
Manatee Spring	29° 29’ 21” 82° 58’ 37”	1	02323566	Levy
Poe Springs	29° 49’ 33” 82°38’ 58”	2	02322140	Gilchrist
Rock Bluff Spring	29° 47’ 55” 82° 55’ 07”	2	02322997	Gilchrist

Table 4.3: Observation Wells Used in the Groundwater Model.

Observation Well	**County**	**Surface Elevation (m above sea level)**	**Depth to Top of Screen (m)**	**Well Depth (m)**	**Unit**
S081703001	Alachua	22.19	52.42	87.47	Upper Floridan
S061618003	Columbia	13.57	4.87	10.97	Upper Floridan
S081313005	Dixie	12.19	4.57	10.67	Upper Floridan
S121330002	Dixie	4.36	6.09	40.0	Upper Floridan
S101210001	Dixie	13.18	32.30	65.53	Upper Floridan
S101429020	Levy	7.92	3.65	9.75	Upper Floridan
S131736001	Levy	27.93	21.03	26.21	Upper Floridan
S121508005	Levy	10.22	6.09	10.05	Upper Floridan
S141429001	Levy	N/A	128.62	134.72	Upper Floridan
S141707004	Levy	10.83	30.17	73.76	Upper Floridan

Gaging Station Name	Latitude / Longitude	Elevation Above MSL (m)	Gaging Station Number	Bed Elevation (m)	Riverbed Thickness (m)	Riverbed Vertical Conductance (m/s)
Santa Fe River at High Springs	29° 55’ 18” 82° 25’ 35”	18.28	02321500	9.14	0.5	0.001
Santa Fe River at Fort White	29° 50’ 55” 82° 42’ 55”	7.01	02322500	5.79	0.5	0.001
Santa Fe River at Hildreth	29° 54’ 41” 82° 51’ 38”	2.74	02322800	2.74	1	0.0001
Ichetucknee at Hildreth	29° 55’ 57” 82° 47’ 57”	3.35	02322703	5.18	1	0.001
Suwannee River at Branford	29° 57’ 20” 82° 55’ 40”	6.10	02320500	3.35	1	0.0001
Suwannee River at Bell	29° 47’ 28” 82° 55’ 28”	5.18	02323000	2.13	1	0.0001
Suwannee River at Wilcox	29° 35’ 22” 82° 56’ 12”	2.13	02323500	2.10	1	0.0001
Suwannee River at Manatee Springs	29° 29’ 19” 82° 58’ 50”	0.61	02323567	.609	3	0.001
Suwannee River at Fowlers Bluff	29° 23’ 47” 83° 01’ 40”	0.61	02323590	.914	3	0.00001
Waccasassa River Near Gulf Hammock	29° 12’ 14” 82° 46’ 09”	0.61	02313700	.304	2	0.00001

Table 4.5. Conversions for Total Dissolved Solids and the Approximate Equivalent to Chloride Concentration and Specific Conductance.

Category	Dissolved Solids (g/L)	Approximate Equivalent	Chloride Concentration (g/L)	Fluid Specific Conductance (μS/cm)
Freshwater	0-1.5		0-.5	0-1,500
Brackish Water	1.5-10		.5-5	1,500-15,000
Saltwater	10-100		5-50	15,000-150,000

Modified from Mahon, 1989

Table 4.6. General ranking of a model input's sensitivity during the calibration process.

1. Horizontal Conductivity (m/s)
2. Riverbed Conductivity (m^2/s)
`3. Cauchey Type III Conductance (m^2/s)
4. Recharge
5. Storage
6. Dirichlet Type I Boundary
7. Riverbed Conductance z (m/s)

Table 4.7: Oil and Gas and Research Wells with Geophysical Logs Surveys included in the Variable-Density Simulation.

Well Name (Bold= within model boundary)	**County**	**Year**	**FAS Base (m)**	**Depth to 3 g/L TDS (m)**	**Depth to 5 g/LTDS (m)**	**Depth to 10 g/L TDS (m)**	**Depth to 35 g/L TDS (m)**
#1 Putnam Lumber	Dixie	N/A	-460	-228.60	-230.12	-452.93	N/A
#2 J.W. Gibson	Madison	N/A	-430	-393.19	-402.34	-463.30	-539.50
BCC #1	Perry	1963	-510	-265.18	-289.56	-321.56	-457.20
BCC #2A	Perry	1963	-560	-210.31	-249.94	-277.37	-341.38
BCC #5-1	**Dixie**	**1983**	**-390**	**-243.84**	**-295.66**	**-323.09**	**-414.53**
BROOKS-SCANLON INC BLOCK #42 #1	Lafayette	1949	-410	-466.34	-475.49	-573.02	-588.26
CONTAINER CORP OF AMERICA-E W PECK #1	Alachua	1971	-470	-624.84	-627.89	-640.08	-679.70
CRAPPS #1	Lafayette	1974	-380	-426.72	-426.72	-429.77	-539.50
FLORIDA STATE 224-A #1-B	Levy	1967	-590	N/A	N/A	-426.72	-560.83
FRANCES EXUM #34-15	Perry	1980	-420	-630.94	-633.98	-637.03	-685.80
FRED S DONALDSON ETAL #1	Alachua	1973	-480	-536.45	-638.56	-650.75	-669.04
GILMAN PAPER CO #22-2	Madison	1980	-440	-350.52	-377.95	-454.15	-557.78
HOLMES-MORRISON-MELTON #21-8	Columbia	1973	-440	-499.87	-521.21	-585.22	-588.26
HOWES #1	Suwannee	1974	-470	-323.09	-326.14	-335.28	-560.83
HURST #1	Suwannee	1974	-450	-320.04	-326.14	-356.62	-576.07
JCMarshSons_1	Columbia	1973	-430	-512.06	-518.16	-563.88	-606.55
JAMES B & JULIAN P RAGLAND #1	**Levy**	**1947**	**-560**	**-414.53**	**-426.72**	**-585.22**	**-594.36**
J P CONE ETUX #1	Hamilton	1948	-430	-481.58	-548.64	-579.12	-618.74
J T GOTHE #1	**Levy**	**1946**	**-530**	**-566.93**	**-569.98**	**-579.12**	**-624.84**
OWENS ILLINOIS GLASS CO #1	Columbia	1978	-440	-527.30	-563.88	-609.60	-612.65
P C CRAPPS #1	Lafayette	1981	-380	-426.72	-432.82	-454.15	-609.60
PERPETUAL FORESTS INC #1	**Dixie**	**1946**	**-460**	**-231.65**	**-234.70**	**-246.89**	**-249.94**
BRUNSWICK PULP & PAPER CO #1	Columbia	1968	N/A	N/A	N/A	-441.96	N/A
VINING #2-11	Suwannee	1950	N/A	N/A	N/A	-423.67	N/A

Source: Florida Department of Environmental Protection/ Williams (USGS)

Table 4.8: Sensitivity Group A. Column III is the calculated percent difference between columns I and III. Column V is the percent difference Between the observed value and column IV.

Observation Well Removed	Observed Value	I Calibrated Model Value	II Removed Well	III % Difference
Levy S141429001i	3.03	2.90	0.10	0.97
Levy S141429001m	3.04	2.80	2.21	0.21
Levy S141429001f	3.04	2.96	2.97	0.00
Dixie S101210001i	9.58	9.60	9.58	0.00
Dixie S101210001m	10.20	9.69	9.69	0.00
Dixie S101210001 f	9.20	9.75	9.87	0.01
Columbia S061618003 i	7.09	6.53	6.21	0.05
Columbia S061618003 m	7.09	6.98	7.00	0.00
Columbia S061618003f	6.80	6.69	6.67	0.00

Obsevation Well Removed	Observed Value	IV Calibrated with Removed Well	V % Difference
Levy S141429001i	3.03	0.02	0.99
Levy S141429001m	3.04	3.58	0.18
Levy S141429001f	3.04	3.41	0.12
Dixie S101210001i	9.58	9.58	0.00
Dixie S101210001m	10.20	9.74	0.05
Dixie S101210001 f	9.20	9.83	0.07
Columbia S061618003 i	7.09	6.21	0.12
Columbia S061618003 m	7.09	7.00	0.01
Columbia S061618003f	6.80	6.67	0.02

Table 4.9: Sensitivity Group B. Column III is the calculated percent difference between columns I and III. Column V is the percent difference between the observed value and column IV.

Obsevation Well Removed	Observed Value	I Calibrated Model Value	II Removed Well	III % Difference
Dixie 21330002 i	1.80	1.83	3.97	1.18
Dixie 21330002 m	2.26	2.59	1.51	0.42
Dixie 21330002 f	1.47	1.98	1.51	0.24
Dixie S081313005 i	5.68	6.07	6.07	0.00
Dixie S081313005 m	5.89	5.23	5.49	0.05
Dixie S081313005 fl	4.58	4.82	4.82	0.00
Levy S141707004 i	7.38	7.40	7.40	0.00
Levy S141707004 m	7.38	7.62	7.15	0.06
Levy S141707004 f	7.22	7.23	7.62	0.05

Obsevation Well Removed	Observed Value	IV Calibrated with Removed Well	V % Difference
Dixie 21330002 i	1.80	2.89	0.61
Dixie 21330002 m	2.26	1.51	0.33
Dixie 21330002 f	1.47	1.89	0.29
Dixie S081313005 i	5.68	6.04	0.06
Dixie S081313005 m	5.89	5.41	0.08
Dixie S081313005 f	4.58	4.53	0.01
Levy S141707004 i	7.38	7.39	0.00
Levy S141707004 m	7.38	7.23	0.02
Levy S141707004 f	7.22	7.91	0.10

Table 4.10: Sensitivity Group C. Column III is the calculated percent difference between columns I and III. Column V is the percent difference between the observed value and column IV.

Obsevation Well Removed	Observed Value	I Calibrated Model Value	II Removed Well	III % Difference
Levys 131736001i	13.28	13.30	13.28	0.00
Levys 131736001m	12.86	13.07	12.94	0.01
Levys 131736001f	11.37	12.77	13.82	0.08
Levy S101429020 i	0.97	1.24	2.12	0.71
Levy S101429020 m	1.18	0.69	0.69	0.00
Levy S101429020 f	1.24	0.81	2.12	1.62
Alachua S081703001i	9.72	9.70	9.80	0.01
Alachua S081703001m	9.60	9.94	9.94	0.00
Alachua S081703001f	9.27	9.68	12.87	0.33

Obsevation Well Removed	Observed Value	IV Calibrated with Removed Well	V %Diff Calibrated w/o Well
Levys 131736001i	13.28	13.28	0.00
Levys 131736001m	12.86	13.17	0.02
Levys 131736001f	11.37	9.64	0.15
Levy S101429020 i	0.97	2.12	1.20
Levy S101429020	1.18	0.69	0.41
Levy S101429020 f	1.24	0.81	0.35
Alachua S081703001i	9.72	9.80	0.01
Alachua S081703001m	9.60	9.98	0.04
Alachua S081703001f	9.27	9.67	0.04

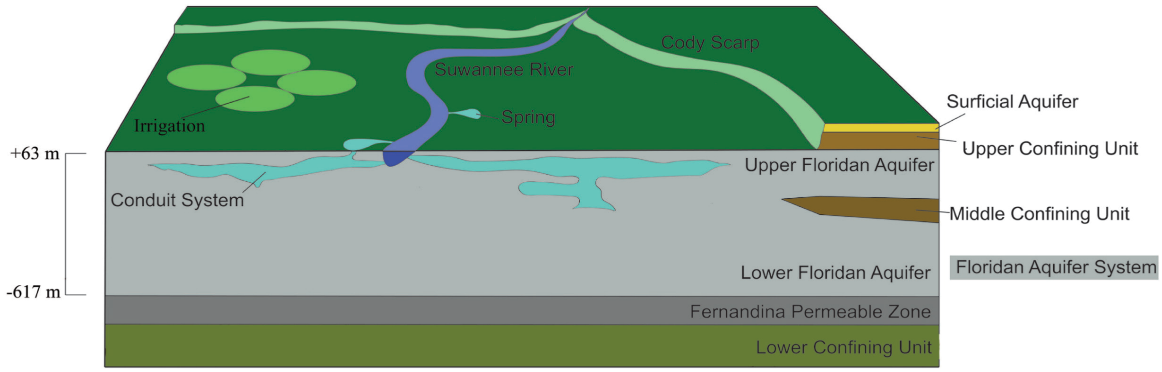


Figure 4.1: Conceptual model of the Lower Floridan aquifer system and the Suwannee River Basin. The Cody Scarp marks the boundary where the Floridan aquifer system transitions from confined to unconfined.

(Miller, 1986)

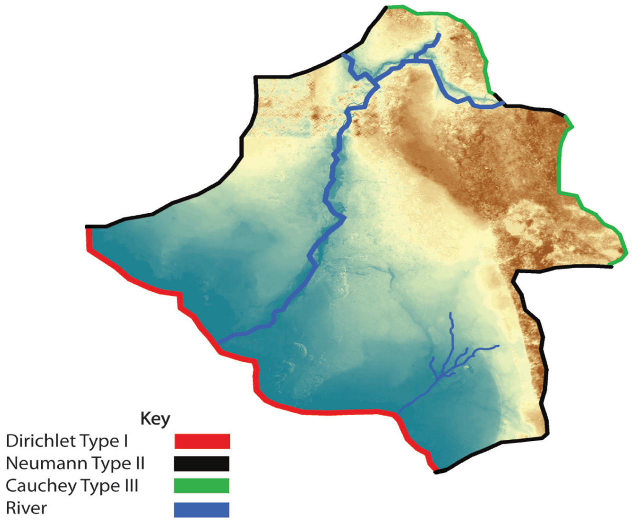


Figure 4.2: Map of the study area and associated boundaries used in the groundwater model.

(Modified from Grubbs and Crandall, 2007)

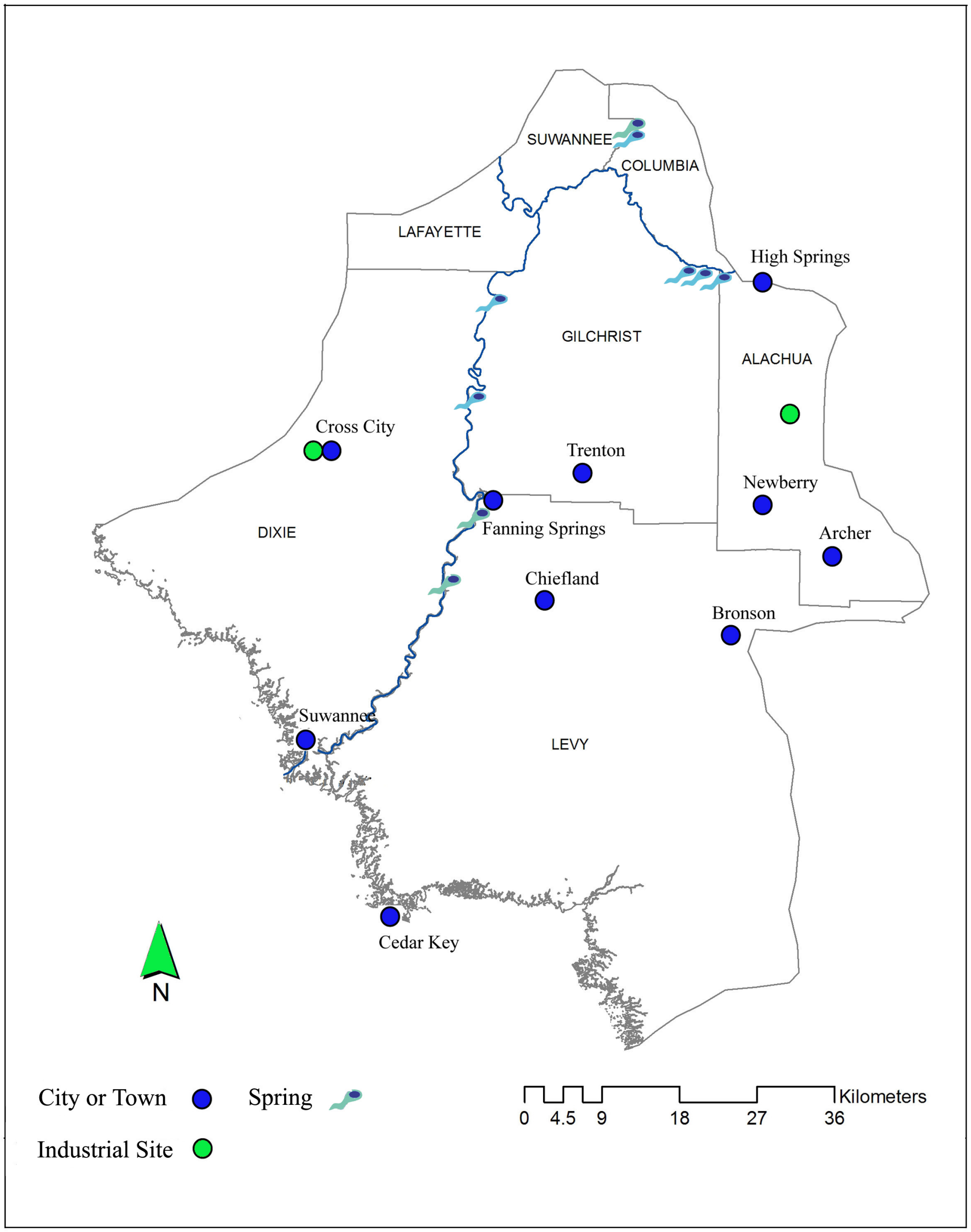


Figure 4.3: Cities and industrial sites, and springs where withdrawal was simulated in the groundwater model.

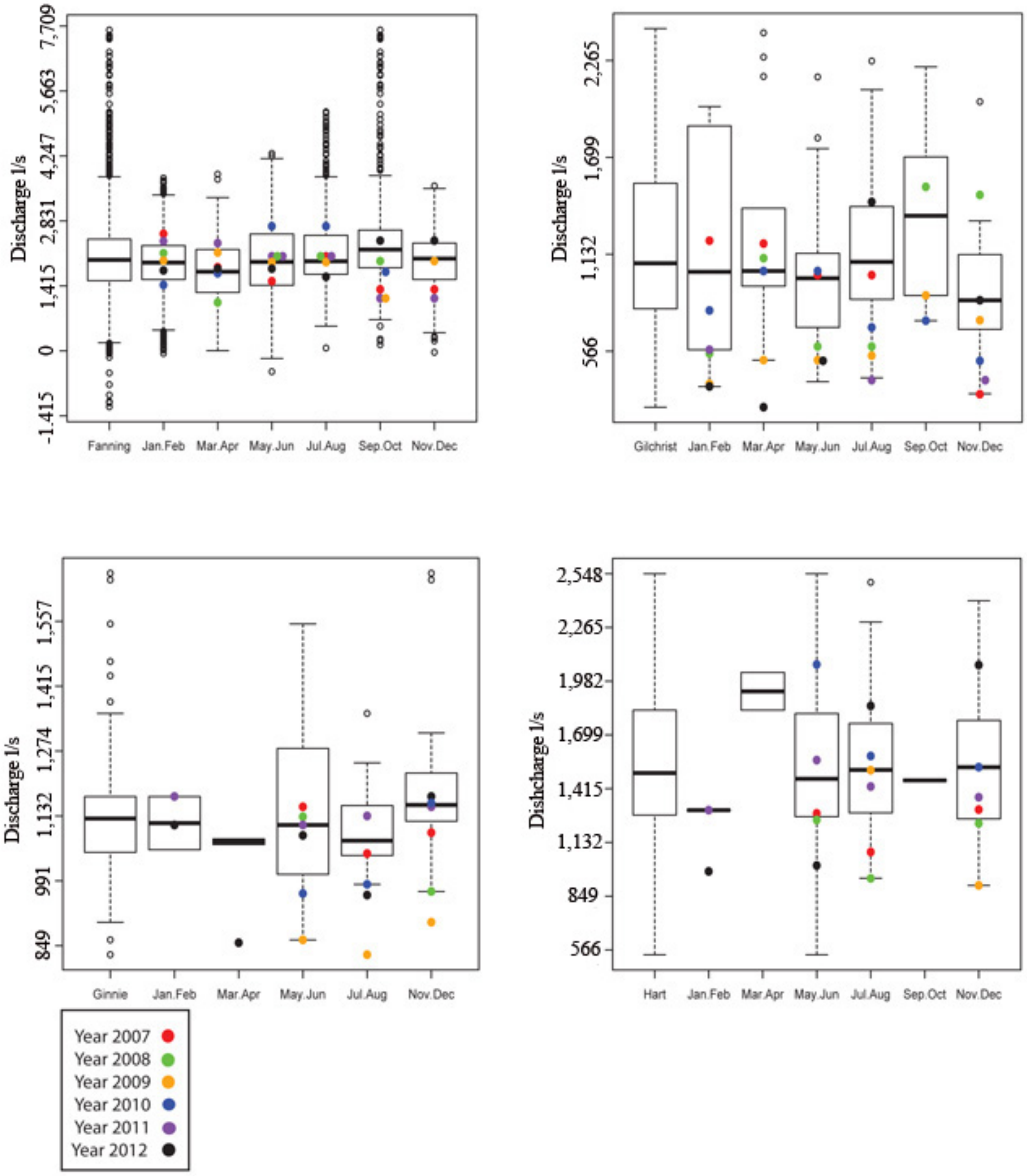


Figure 4.4: Box plots for Manatee, Poe, and Rock Bluff Springs with bi-monthly discharge data for each site. The data was combined in a bi-monthly scheme to fill in data gaps in an attempt to assign a daily discharge value in the groundwater model. Where, the 25 percentile for each bi-month period was assigned to springs during low discharge periods and the median percentile was assigned to periods of average of greater flows. All available data for the spring is plotted on the left of each diagram for comparison.

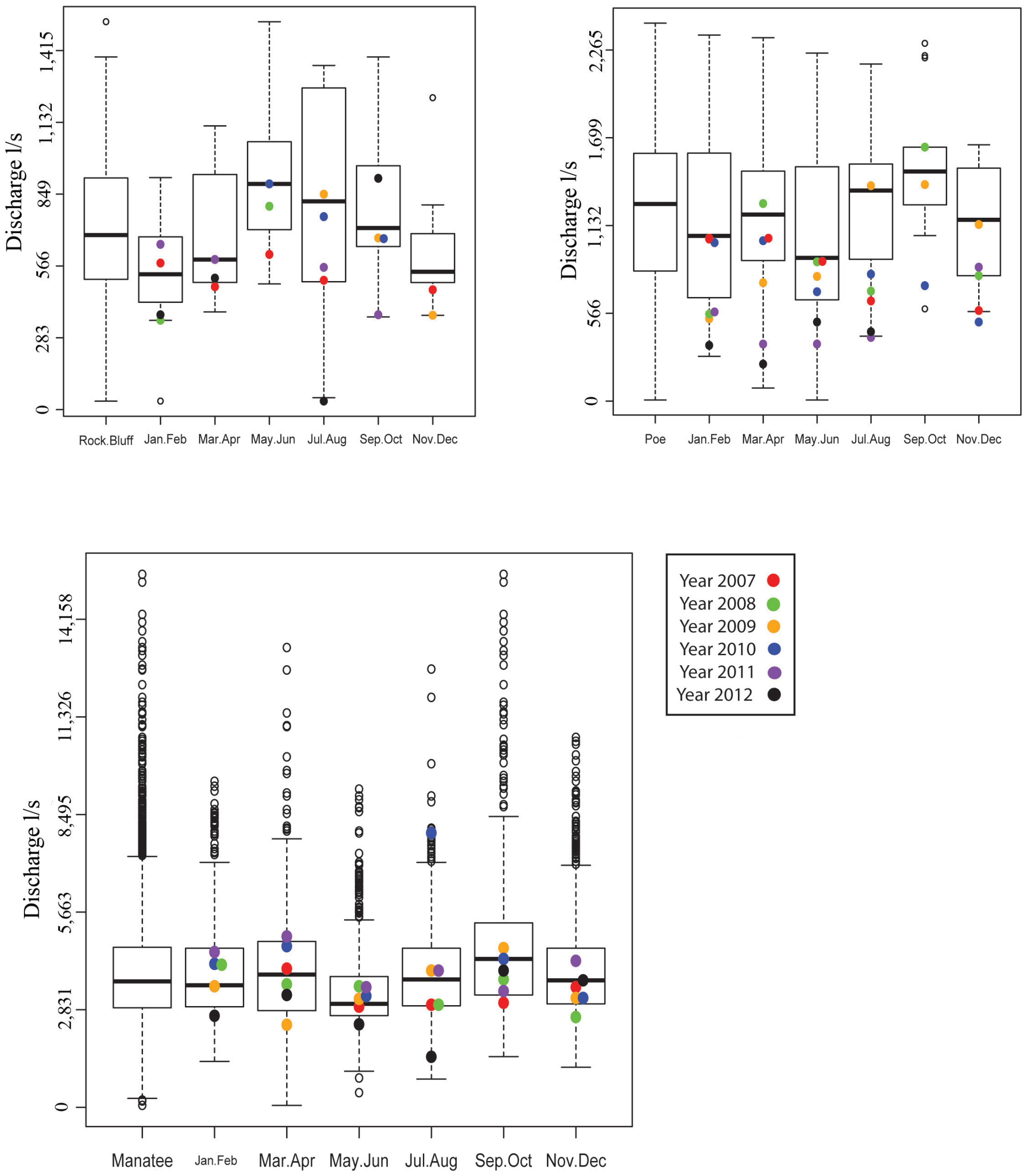


Figure 4.5: Box plots for Fanning, Gilchrist, Ginnie, and Rock Bluff Springs with bi-monthly discharge data for each site. The data was combined in a bi-monthly scheme to fill in data gaps in an attempt to assign a daily discharge value in the groundwater model. Where, the 25 percentile for each bi-month period was assigned to springs during low discharge periods and the median percentile was assigned to periods of average of greater flows. All available data for the spring is plotted on the left of each diagram for comparison.

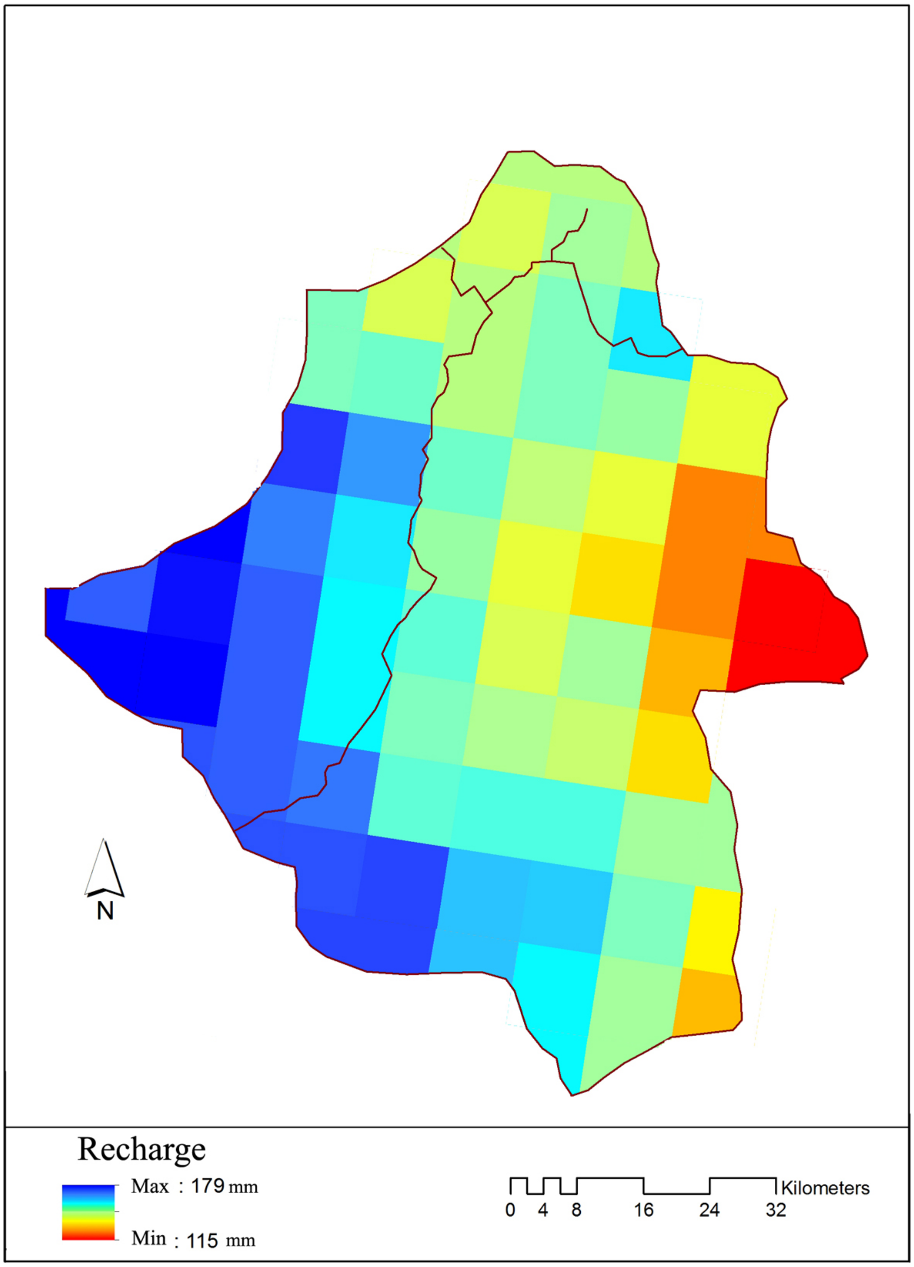


Figure 4.6 Aerially distributed recharge values. Recharge to the aquifer was assigned over 365 time steps simulating mm/Year in the groundwater model using the Recharge Package.

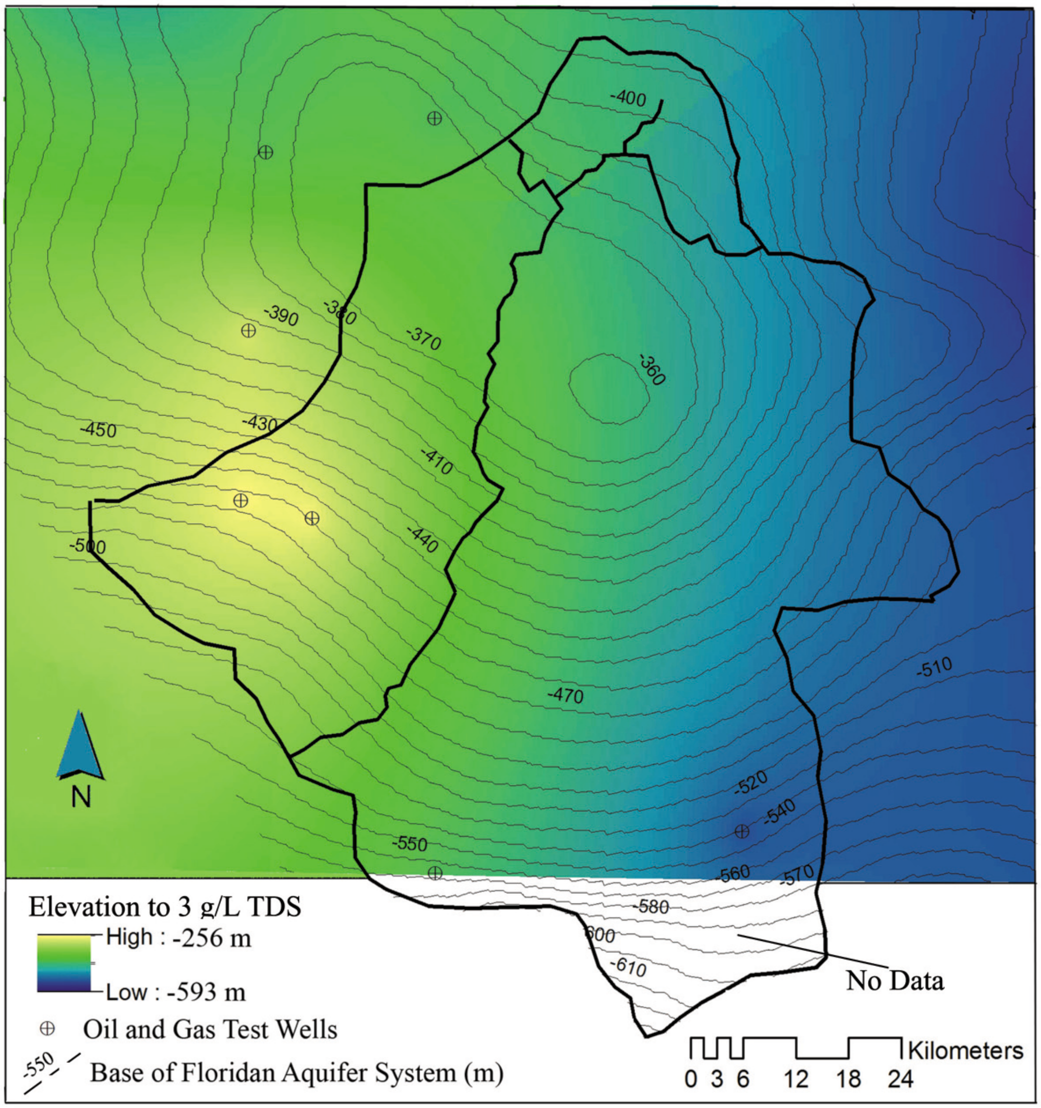


Figure 4.7: Depth to 3 g/L Total Dissolved Solids. Values were interpolated through Empirical Bayesian Kriging where the 3 g/L level is shallower by ~ 337 m in the western half of the study area.

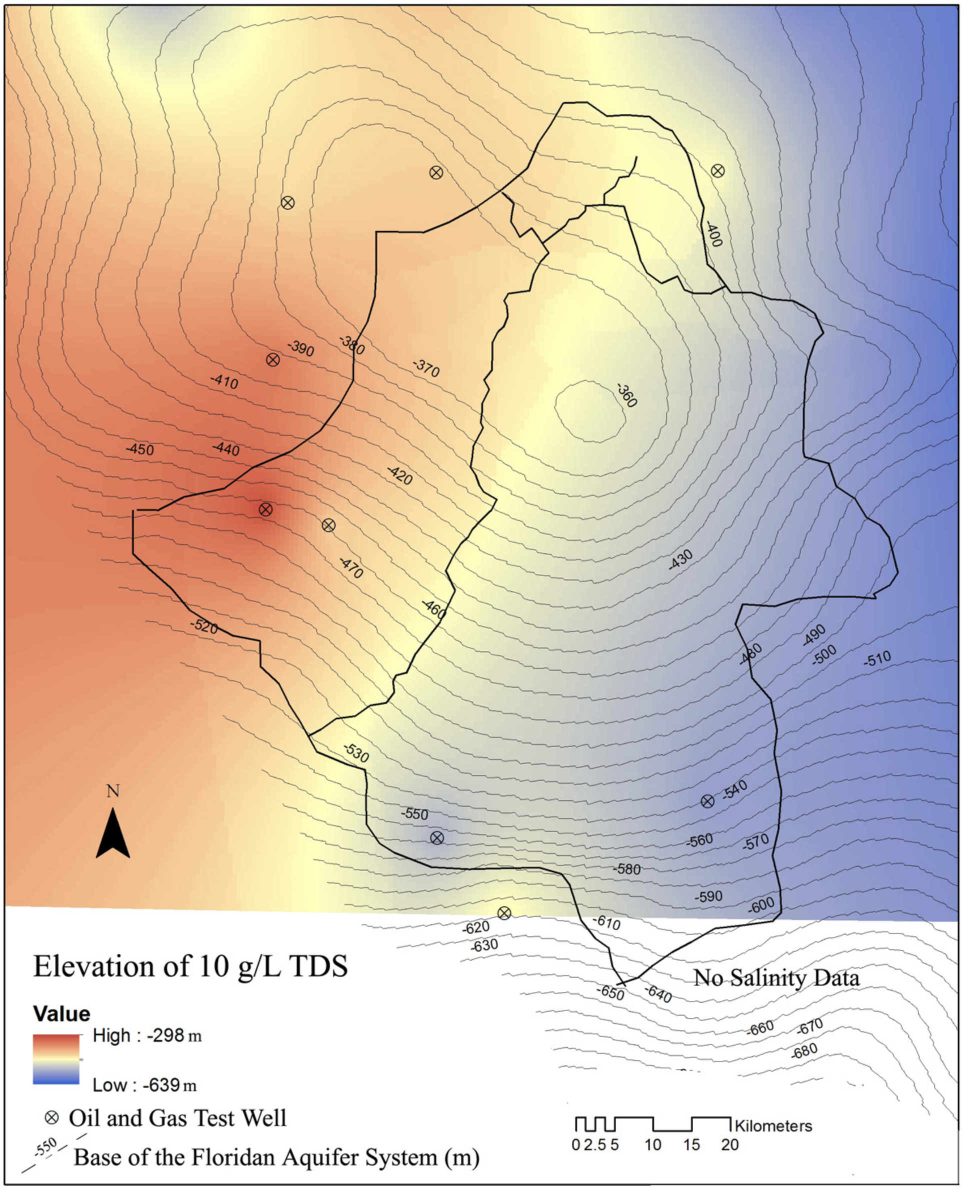


Figure 4.8: Depth to 10 g/L Total Dissolved Solids. Values were interpolated through Empirical Bayesian Kriging where the 10 g/L level has a noticeably smaller footprint then the 3g/L surface in Figure 4.5.

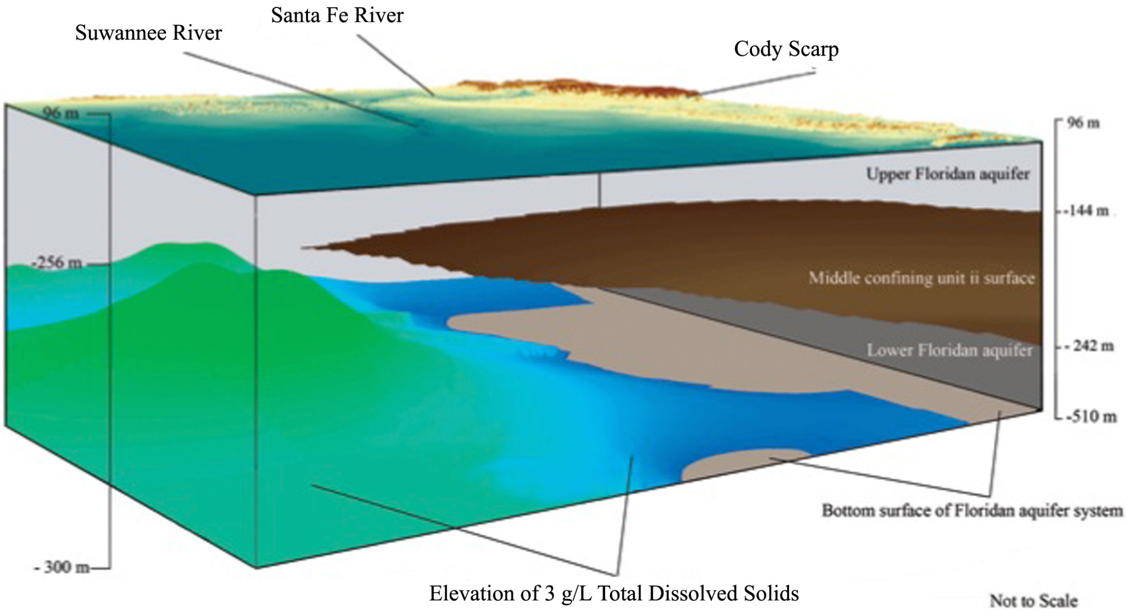


Figure 4.9: Three-dimensional view of 3 g/L assigned elevation for Total Dissolved Solids. The graphic depicts the surface's relationship to the Lower Floridan aquifer, middle confining unit, and land surface. This perspective is looking from southeast along the Gulf of Mexico to the northwest.

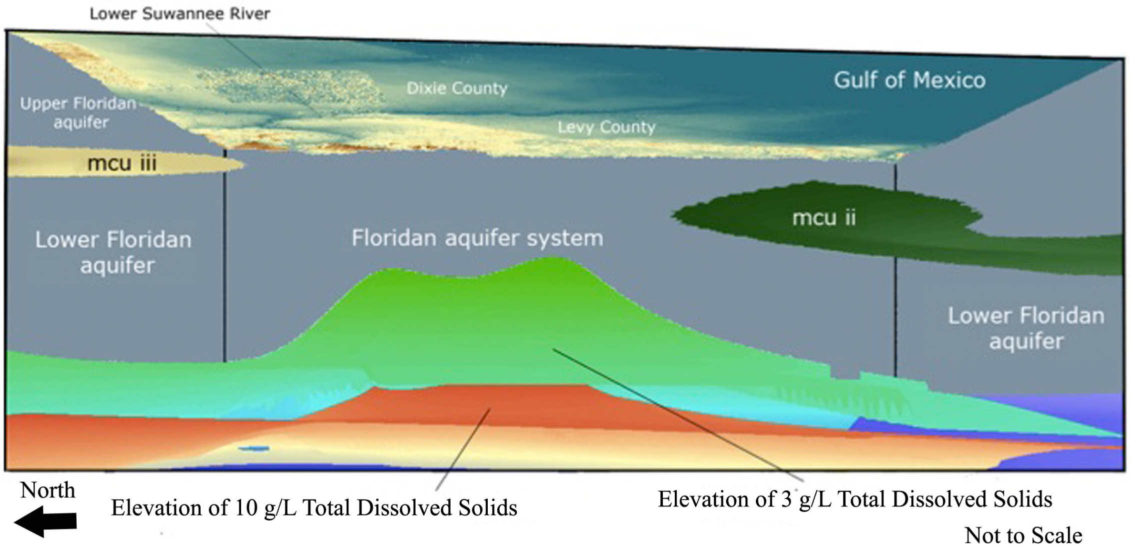


Figure 4.10: Three-dimensional view of the 3 g/L and 10 g/L assigned elevations for Total Dissolved Solids. The graphic depicts the surface's relationship to the Floridan aquifer system, middle confining unit, and surficial features in the Lower Suwannee River Basin. This perspective is looking from the western edge of Dixie County to the east.

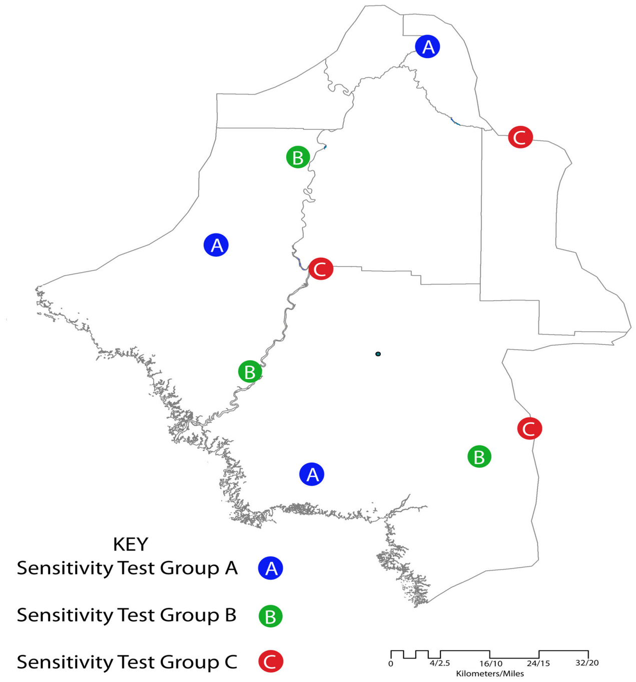


Figure 4.11: Wells selected by groups of three for the sensitivity analysis.

CHAPTER 5

RESULTS

The model was determined calibrated through adjustments such as hydraulic conductivity (Figure 5.1) after a total of 474 complete runs (948 total for the divided time scenarios). As stated in section 4.13, the model was considered stable after two years into the simulation and the heads of calibrated wells were reasonably simulating those of the observation wells. Figures 5.3 through 5.12 feature the comparison of observed and simulated heads for three of the ten wells used for calibration. Figures 5.14 through 5.26 display the results of the SEAWAT simulation for springs and municipalities modeled.

5.1 Results for Individual Observation Wells

Calibration of the groundwater model consisted of 474 simulations that involved adjustments of parameters such as hydraulic conductivity through a trial and error approach. Once calibrated, wells S01618003 (Figure 5.4), S081313005 (Figure 5.3), S101210001, and S101429020 (Figure 5.5) displayed the greatest results with R^2 values of 0.737, 0.800, and 0.744, respectively. Other wells resulted in poor values, such as observation well S121508005 (Figure 5.12) with an R^2 of 0.033 and S141707004 (Figure 5.8), which had an R^2 of 0.141 between simulated and observed values. Statistical results for all of the groundwater observation wells are summarized in Table 5.1.

5.2 Results of Sensitivity Analysis

Results for the sensitivity analysis were derived by calculating the relative percent difference between the simulated value of an observation well from the calibrated model, and the value for the location where the observation well was removed specifically for the analysis. The model was then re-calibrated and the relative percent difference was calculated for the observed head value and the head value where the observation well was removed. This process was repeated three times; A, B, and C. and are summarized in Tables 4.8 trough 4.10 and Figure 4.11.

Observation well Levy S141429001 had the greatest percent difference during the initial and middle simulations for Sensitivity Group A when the three observation wells were removed. The initial percent difference was 0.97 and mid-simulation value was 0.21. However, Dixie S101210001 had the greatest percent difference at the end of the model run with 0.01. Following calibration, the observation well with the highest percent difference was again Dixie S101210001 with a final value of 0.07.

Observation well Dixie 21330002 had the largest percent difference when removed from Group B with initial, middle, and final values of 1.18, 0.42, and 0.24 respectively. Once calibrated, Dixie 21330002 was again the observation well with the largest prevent difference with an initial value of 0.61, middle value of 0.33 and final value of 0.29.

The well with the largest percent difference for Sensitivity Group C. before and after calibration was Levy S101429020. The well's initial and final values after removal were 0.71 and 1.62. Values for calibration without Levy S101429020 were 1.20 for initial, 0.41 for the middle, and 0.35 for the percent difference.

5.3 Results for the Potentiometric Surface

A potentiometric map (Figure 5.2) was produced for periods when heads were the highest in February 2010 and lowest in April 2012. Potentiometric highs are greatest at 16 m (52.5 ft) in northeastern Dixie County near the Mallory Swamp. The Brooksville and Bell Ridges had the second and third highest potentiometric surfaces at 14 m (45.9 ft) and 12 m (39.4 ft) respectively. Potentiometric lows between 0 to 2 m (0 to 6.6 ft) were primarily found along the coast and follow the Suwannee River north to the town of Fanning Springs. Potentiometric lows in the range of 0 to 4 m (0 to 13 ft) divided the center of the study area north of Fanning Springs and continued up the Suwannee River and the mouth of the Santa Fe. In the vicinity of the Santa Fe and Ichetucknee Rivers, the potentiometric surface ranged from 6 to 8 m. (19.6 to 26.2 ft) during the simulated months February 2010 and April 2012.

The greatest drawdown in the model exists at Manatee Springs, where the heads reach -25 m (82 ft) for February 2010 and -35 m (114.8 ft) for April 2012. Lesser drawdowns existed at Hart and Fanning Springs and reach a head loss of -6 m (19.7) for Hart and -4 m (13.1 ft) for Fanning during both time periods. No significant cones of depression exist at the industrial or municipal locations for either date. A large lateral shift in potentiometric head can be found in the vicinity of the Santa Fe River around the White Springs Gage and the mouth of the Ichetucknee. There, a lateral shift of ~ 3.7 km (2.30 mi) between the 6 m head contour and ~3.5 km (2.17 mi) lateral shift along the 8 km contour occurs between the simulated period of February 2010 and April 2012.

5.4 Movement of Total Dissolved Solids

Freshwater is determined to be in the range of 0 to 1.5 g/L Total Dissolved Solids and brackish water in the range of 1.5 to 10 g/L Total Dissolved Solids Table 4.5 (Mahon, 1989).

The approximate equivalent in TDS for chloride concentration in freshwater is 0 to 0.5 g/L and 0.5 to 5 g/L for brackish. The threshold for saline water is considered to be 10 g/L Total Dissolved Solids and 5 g/L for chloride concentration. The U.S. Environmental Protection Agency has set water quality limits for surface waters at 0.5 g/L for Total Dissolved Solids, and chloride concentrations are limited to < 0.25 g/L.

Overall levels of Total Dissolved Solids in the first layer were highest in Dixie and Levy Counties with a range of 0.35 to 0.499 g/L. For the northern extent of the model, the dissolved solids level was at a lower range of 0.205 to 0.240 g/L. Layer two showed the same trend compared to layer four, which had a uniform Total Dissolved Solids level close to its assigned initial concentration of 0.5 g/L. Layers four through seven also showed little variation beyond their initial values. Model simulations did not indicate a lateral movement of Total Dissolved Solids, but a small vertical component is evident and was present in each time step after the initial start of the model.

Wells were assigned the withdrawal rates that reflected current use, the projected use for year 2030, and, for some wells, a doubled amount that surpassed the projected 2030 amount. For each increased amount, the Total Dissolved Solids would increase slightly as well. However, for industrial and municipal wells there was very little variation in Total Dissolved Solids concentration between time steps at each individual model run. Assuming this was a possible result of setting the municipal and industrial wells at a constant daily rate, the rates were varied for two test wells at The City of High Springs and Town of Fanning Springs. Varied pumping rates for the two cities did not show any change in the levels of dissolved solids during runs.

Springs however, showed a larger difference between samples taken during each model run (Figures 5.14 through 5.26). Variation between time steps was largest in the springs with the greatest discharge. For each spring simulated in the model, there was an associated zone of lower Total Dissolved Solids nearby. This anomaly was usually upstream of the simulated spring and varied in size that correlated with the size of the spring's discharge. Manatee Spring (Figure 5.16 and 5.18) had the largest of these anomalies, whereas Poe, Ginnie, and Gilchrist (Figures 5.14, 5.15, 5.20, 5.21, and 5.22) shared a smaller zone of lower Total Dissolved Solids.

Table 5.1: Statistical results for each observation well from May 1, 2009 through the end of the simulation on April 30th 2012.

Well ID	County	R^2	Root Mean Square	Mean Absolute Error	Nash-Sutcliffe
S081703001	Alachua	0.61	0.22	0.18	0.23
S01618003	Columbia	0.74	0.11	0.08	0.001
S081313005	Dixie	0.8	0.39	0.31	0.4
S101210001	Dixie	0.74	0.63	0.55	-0.75
S121508005	Levy	0.03	0.6	0.45	-0.11
S141429001	Levy	0.2	0.41	0.36	-0.42
S131736001	Levy	0.34	0.62	0.51	-0.15
S101429020	Levy	0.63	0.35	0.4	-0.09
S141707004	Levy	0.14	0.16	0.10	-2.22
S121330002	Dixie	0.13	0.43	0.36	-0.32

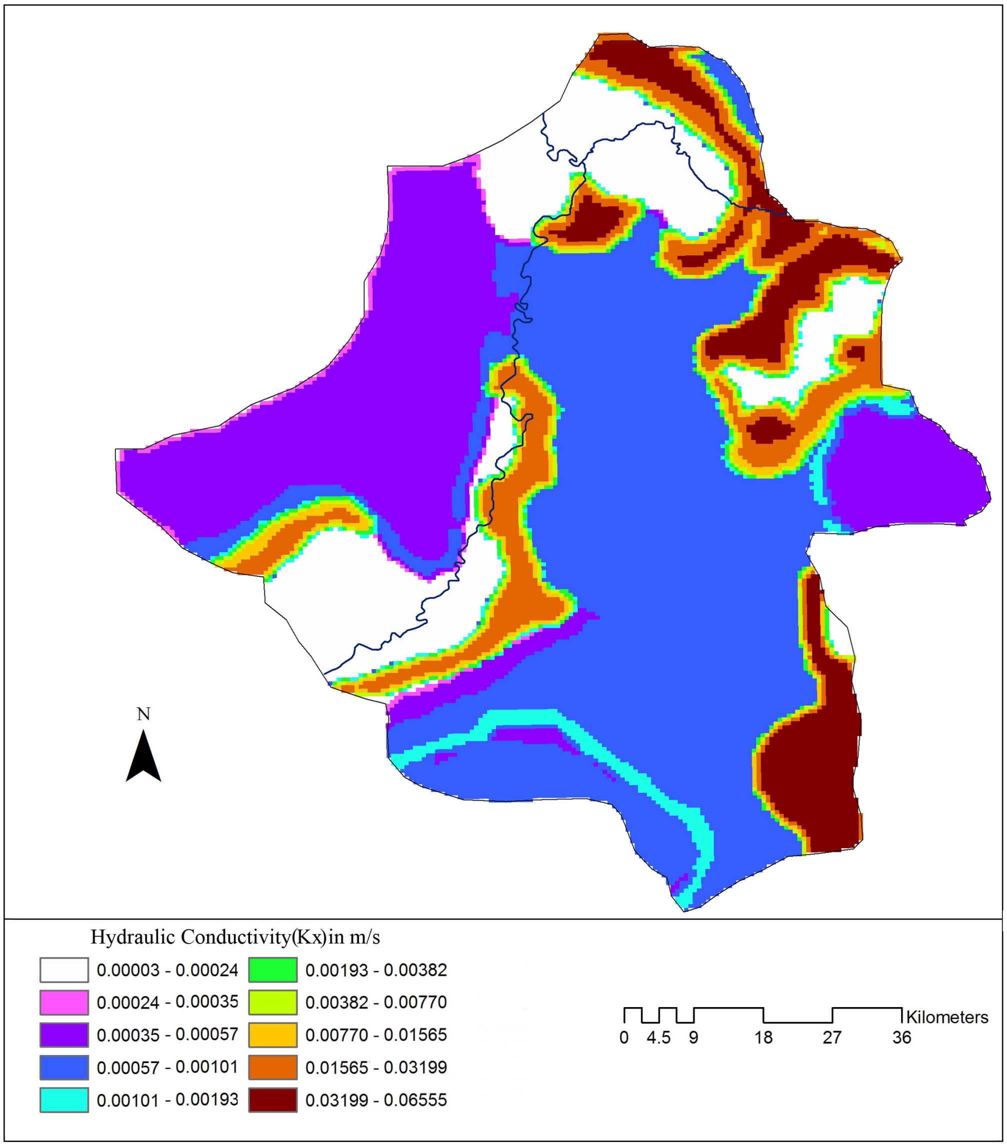


Figure 5.1: Map of hydraulic conductivity in m/s for the Upper Floridan aquifer system after model calibration.

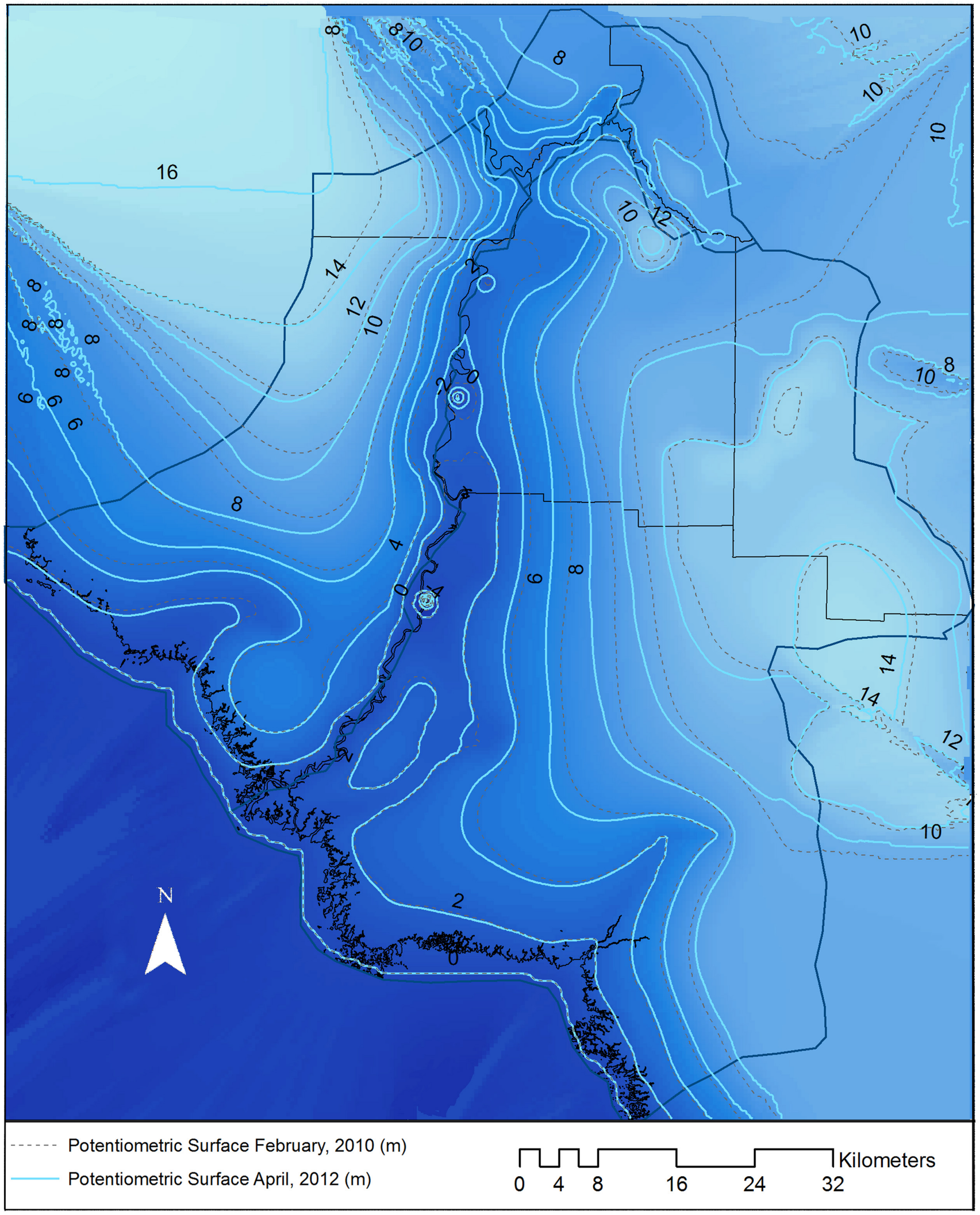


Figure 5.2: Map of the potentiometric surface for February 2010 and April 2012. Drawdown for Manatee, Fanning, and Hart Springs is visible along the Suwannee River.

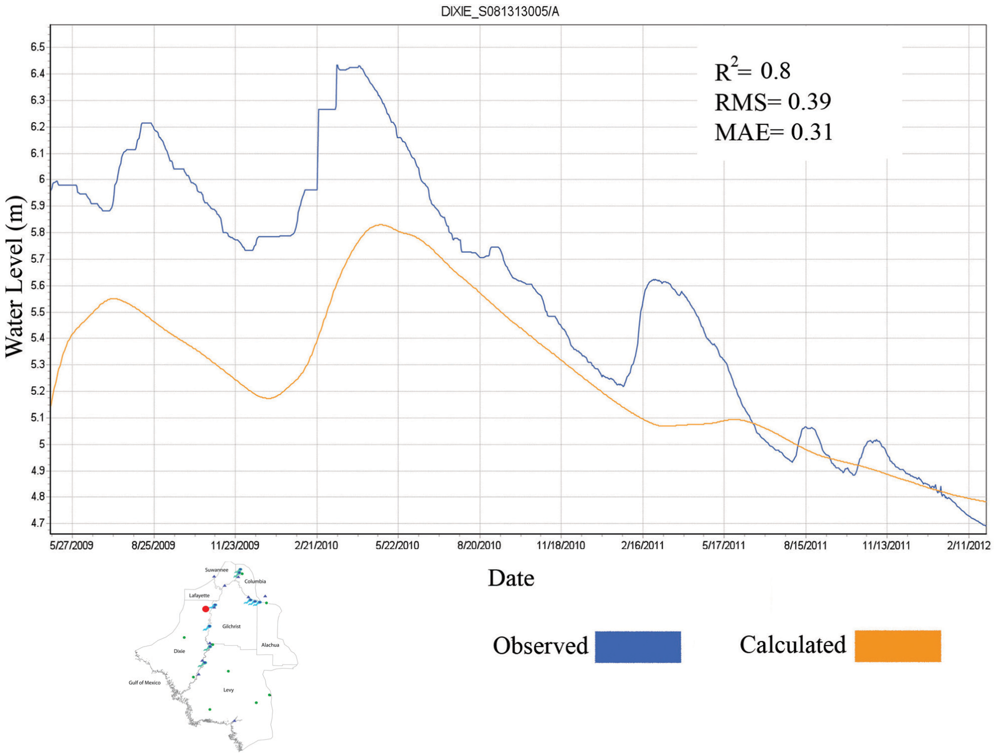


Figure 5.3: Observation Well Levy S081313005 (red circle) for the period of May 1, 2009 through April 30, 2013 after calibration of the transient model.

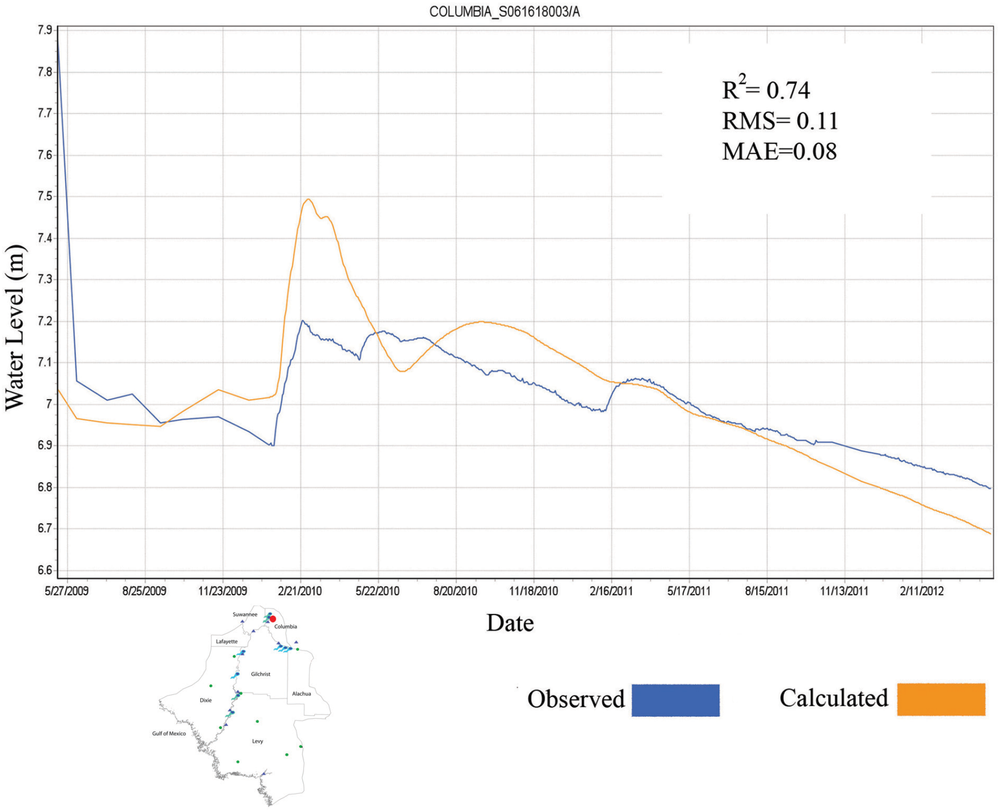


Figure 5.4: Observation Well Columbia S06168003 (red circle) for the period of May 1, 2009 through April 30, 2013 after calibration of the transient model.

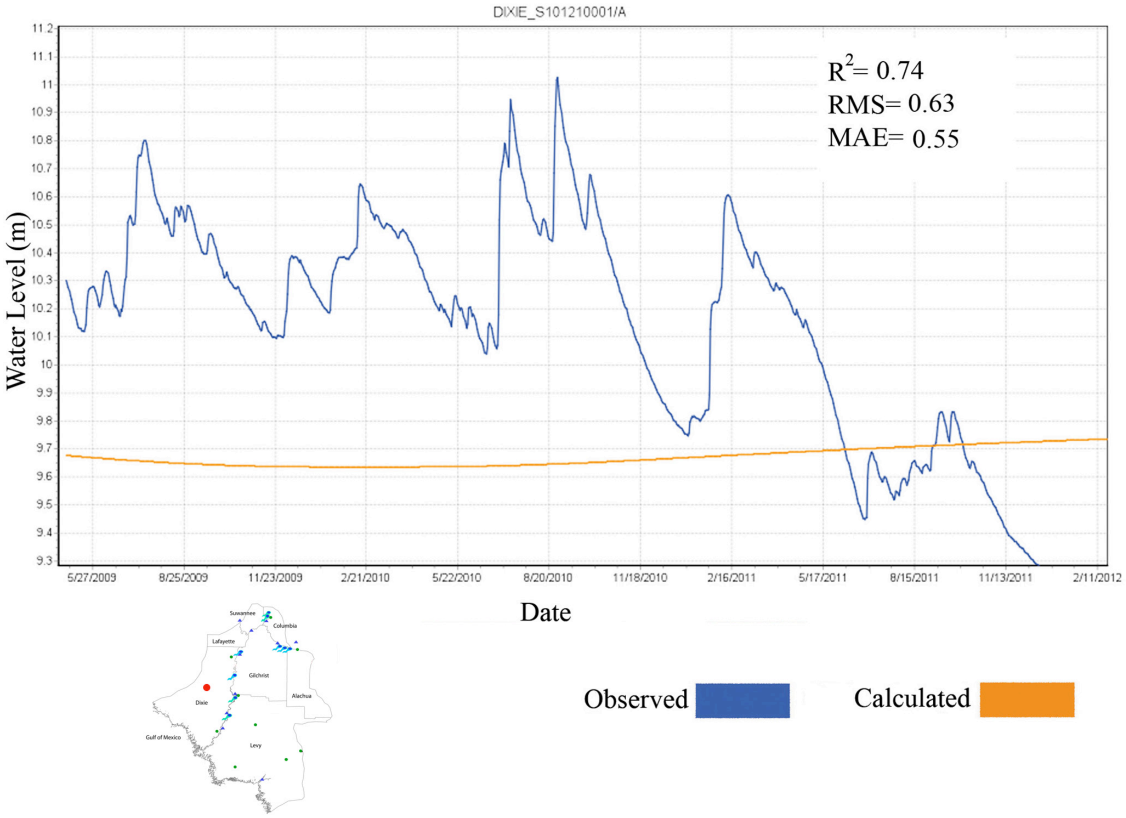


Figure 5.5: Observation Well Dixie S10121001(red circle) for the period of May 1, 2009 through April 30, 2013 after calibration of the transient model.

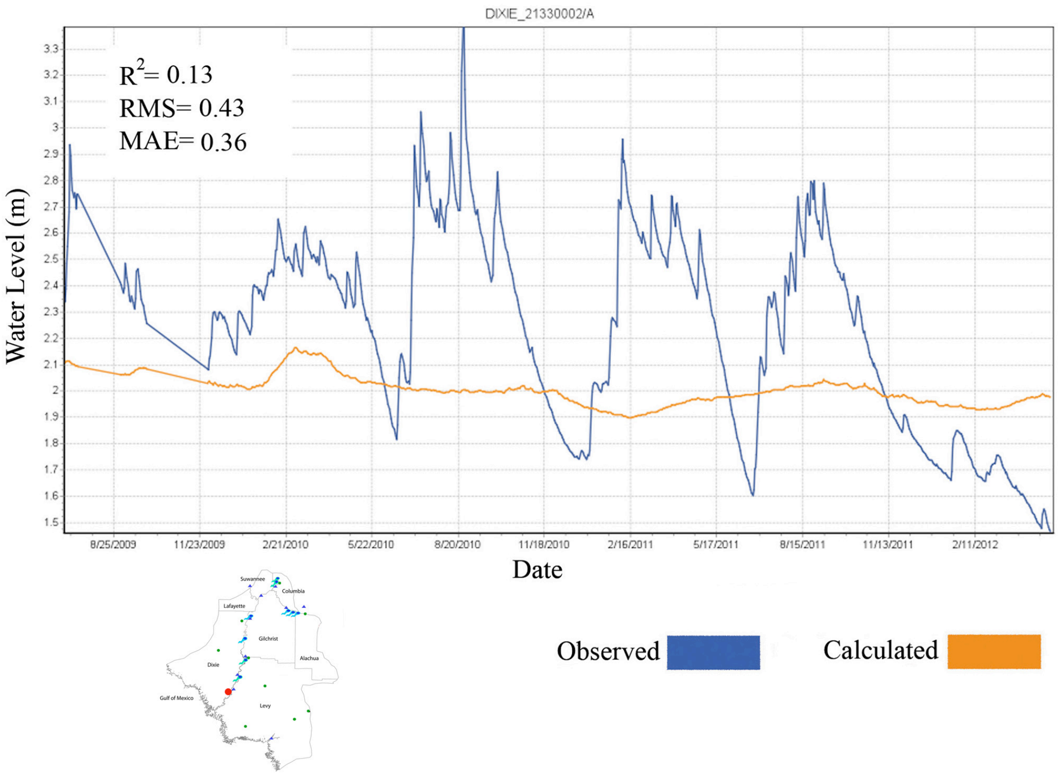


Figure 5.6: Observation Well Levy S21330002 (red circle) for the period of May 1, 2009 through April 30, 2013 after calibration of the transient model.

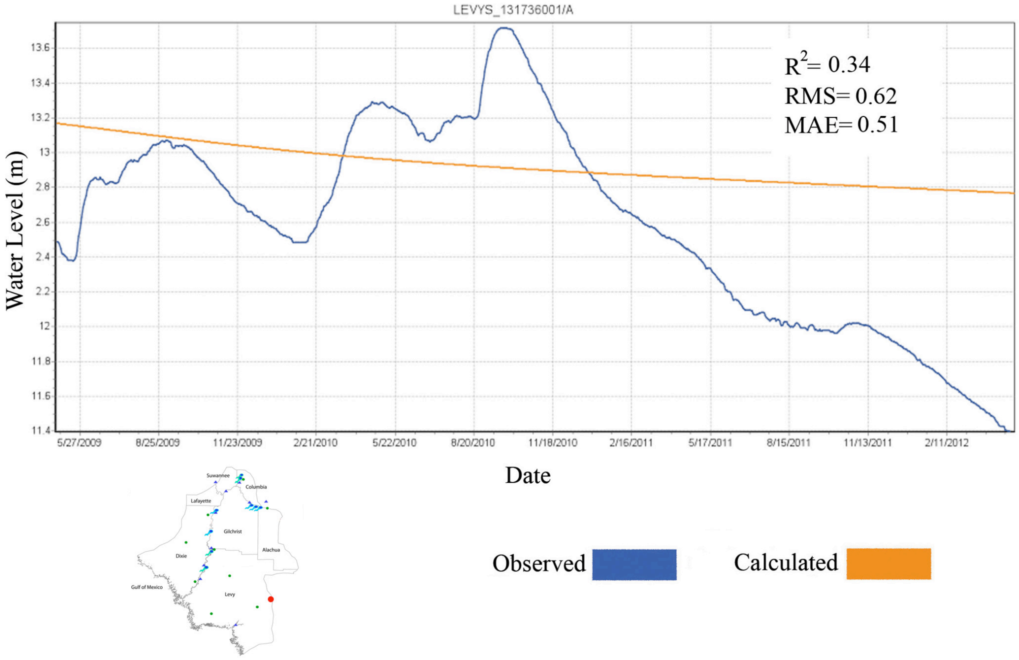


Figure 5.7: Observation Well Levy S13176001 (red circle) for the period of May 1, 2009 through April 30, 2013 after calibration of the transient model.

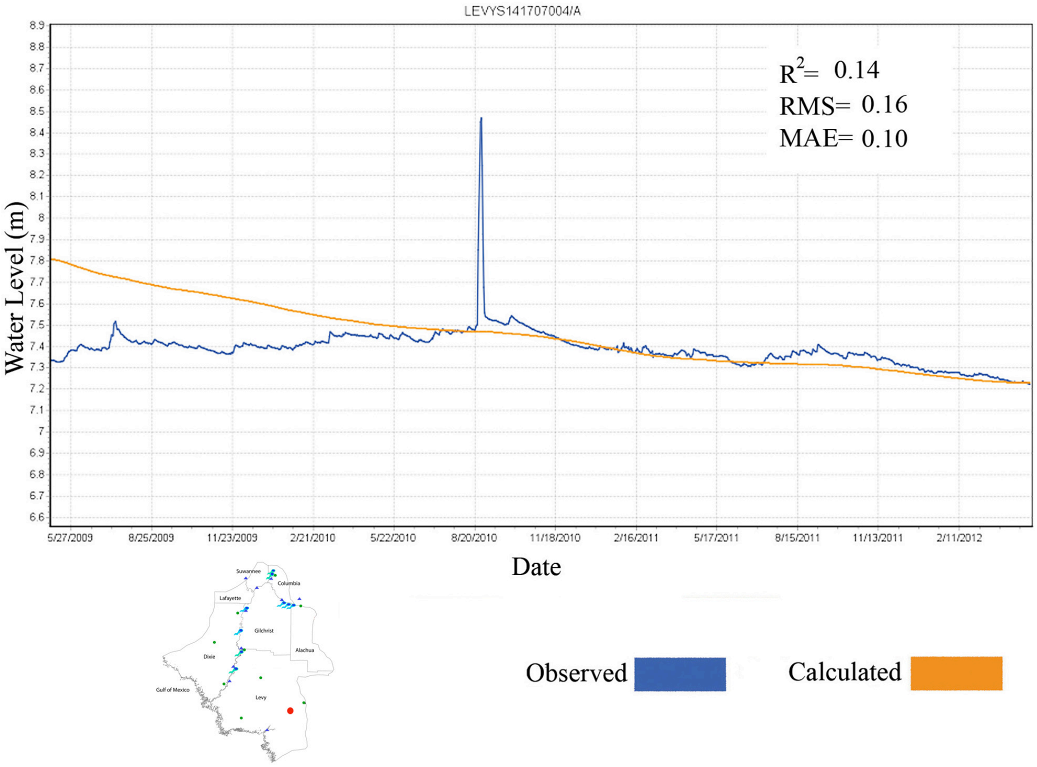


Figure 5.8: Observation Well Levy S141707004 (red circle) for the period of May 1, 2009 through April 30, 2013 after calibration of the transient model.

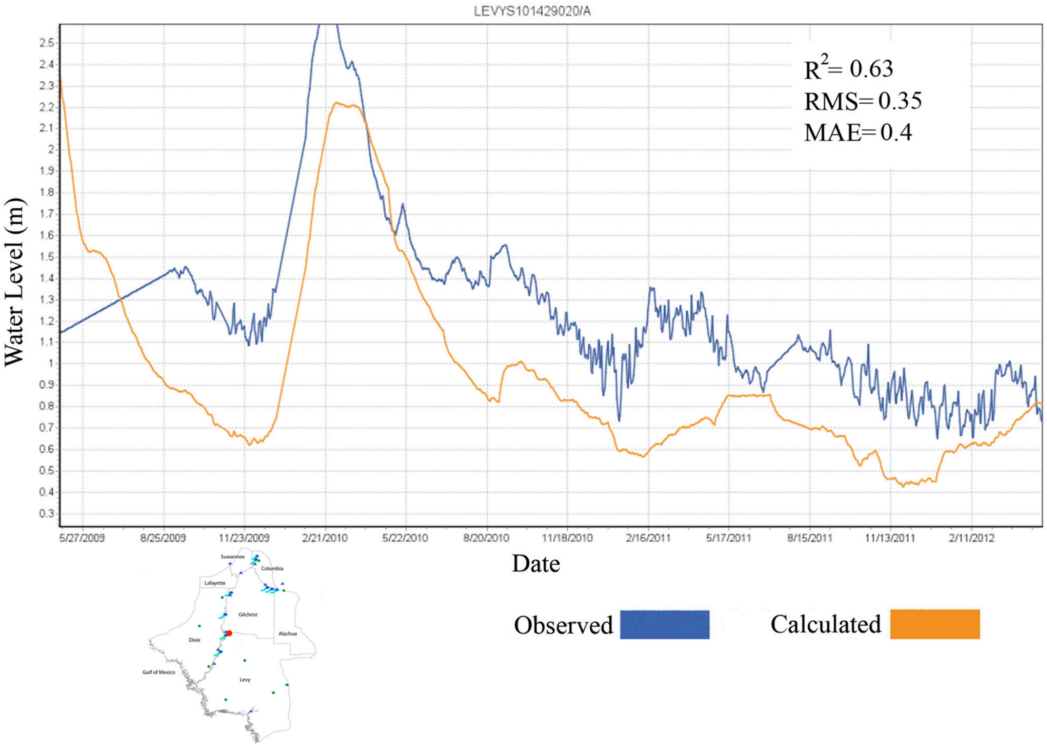


Figure 5.9: Observation Well Levy S101429020 (red circle) for the period of May 1, 2009 through April 30, 2013 after calibration of the transient model.

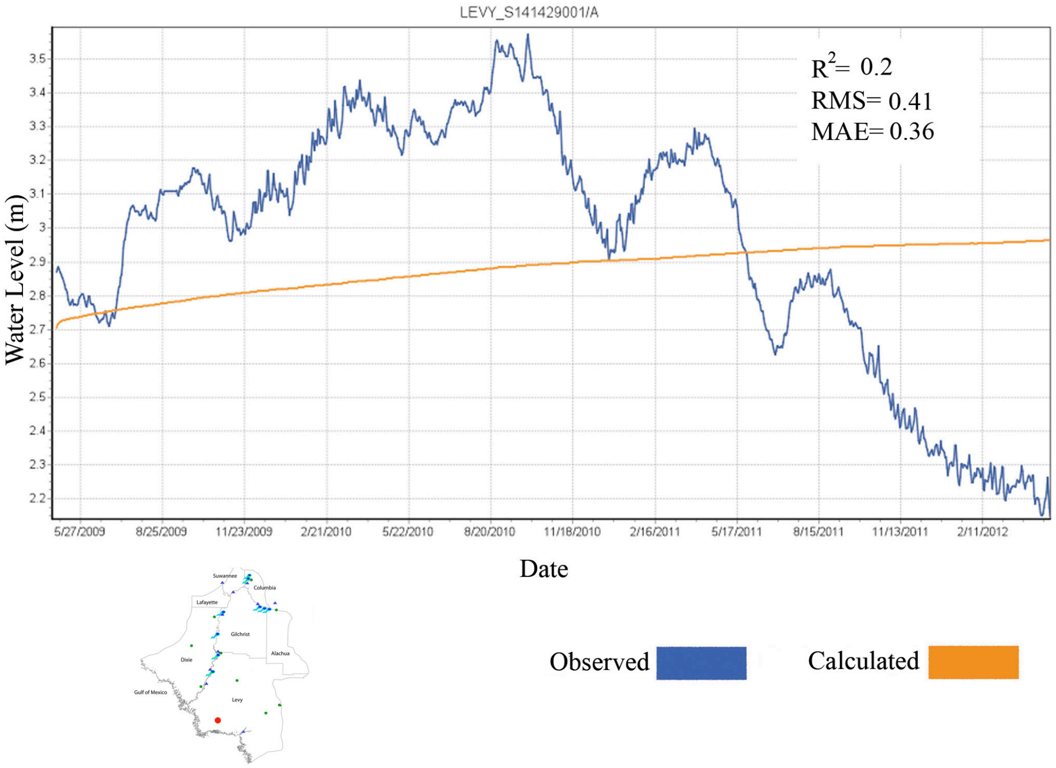


Figure 5.10: Observation Well Levy S141429001 (red circle) for the period of May 1, 2009 through April 30, 2013 after calibration of the transient model.

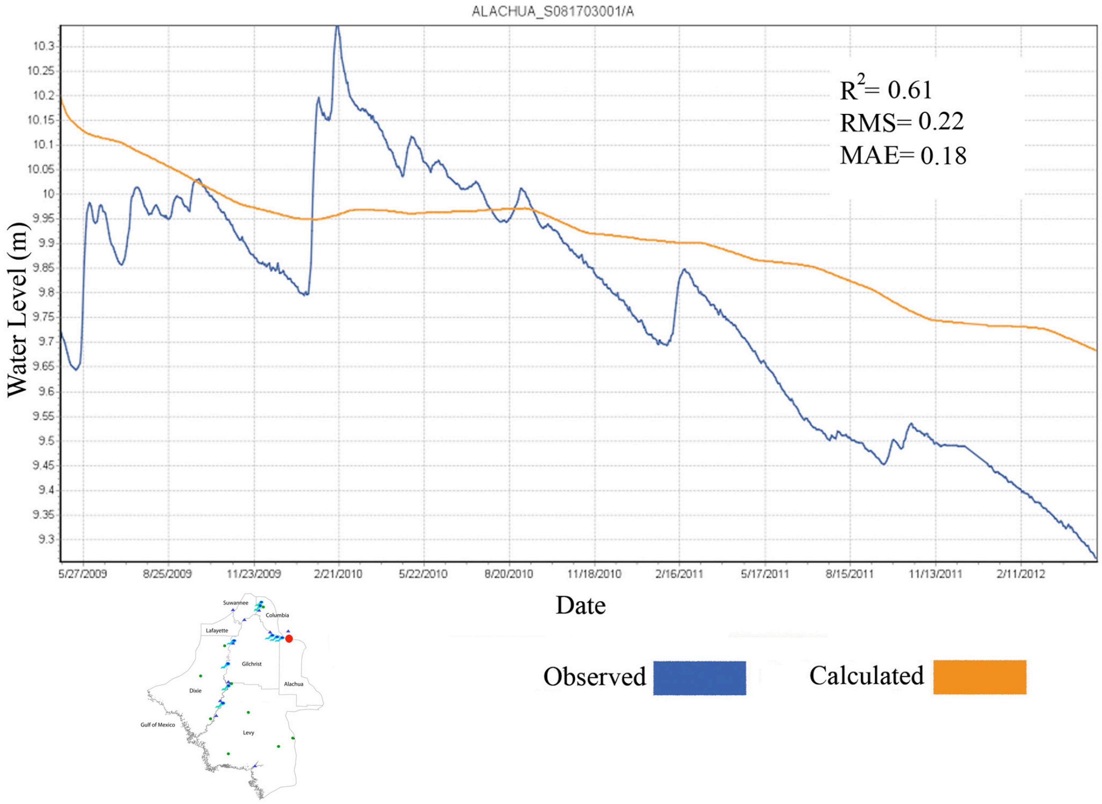


Figure 5.11: Observation Well Alachua S081703001 (red circle) for the period of May 1, 2009 through April 30, 2013 after calibration of the transient model.

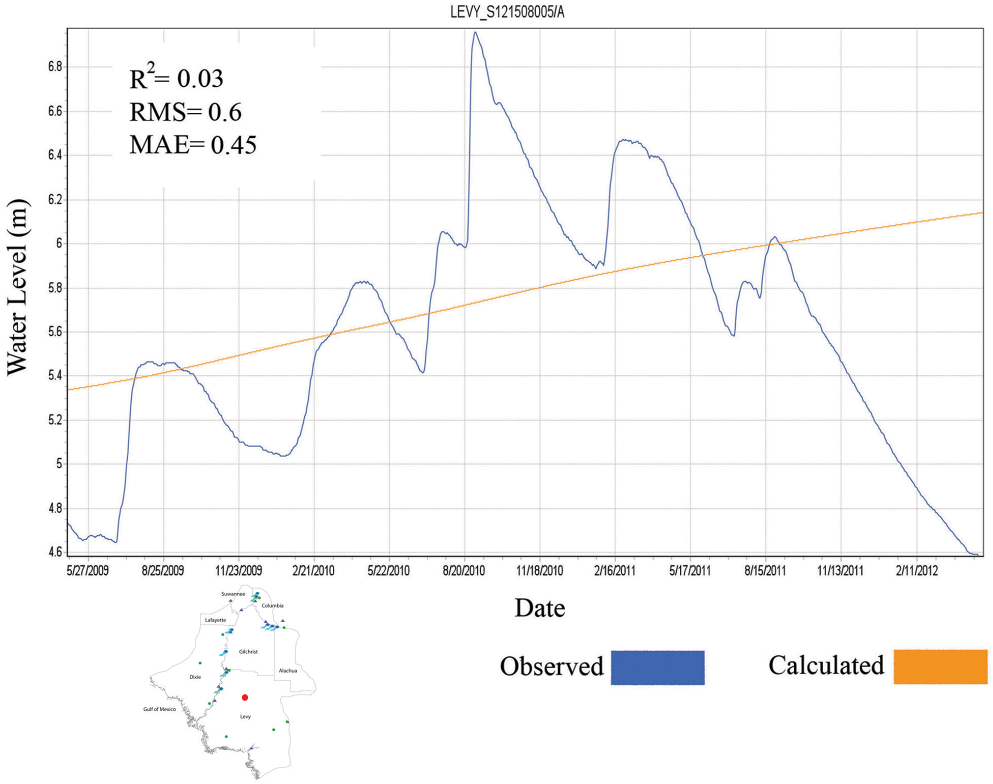


Figure 5.12: Observation Well Levy S121508005 (red circle) for the period of May 1, 2009 through April 30, 2013 after calibration of the transient model.

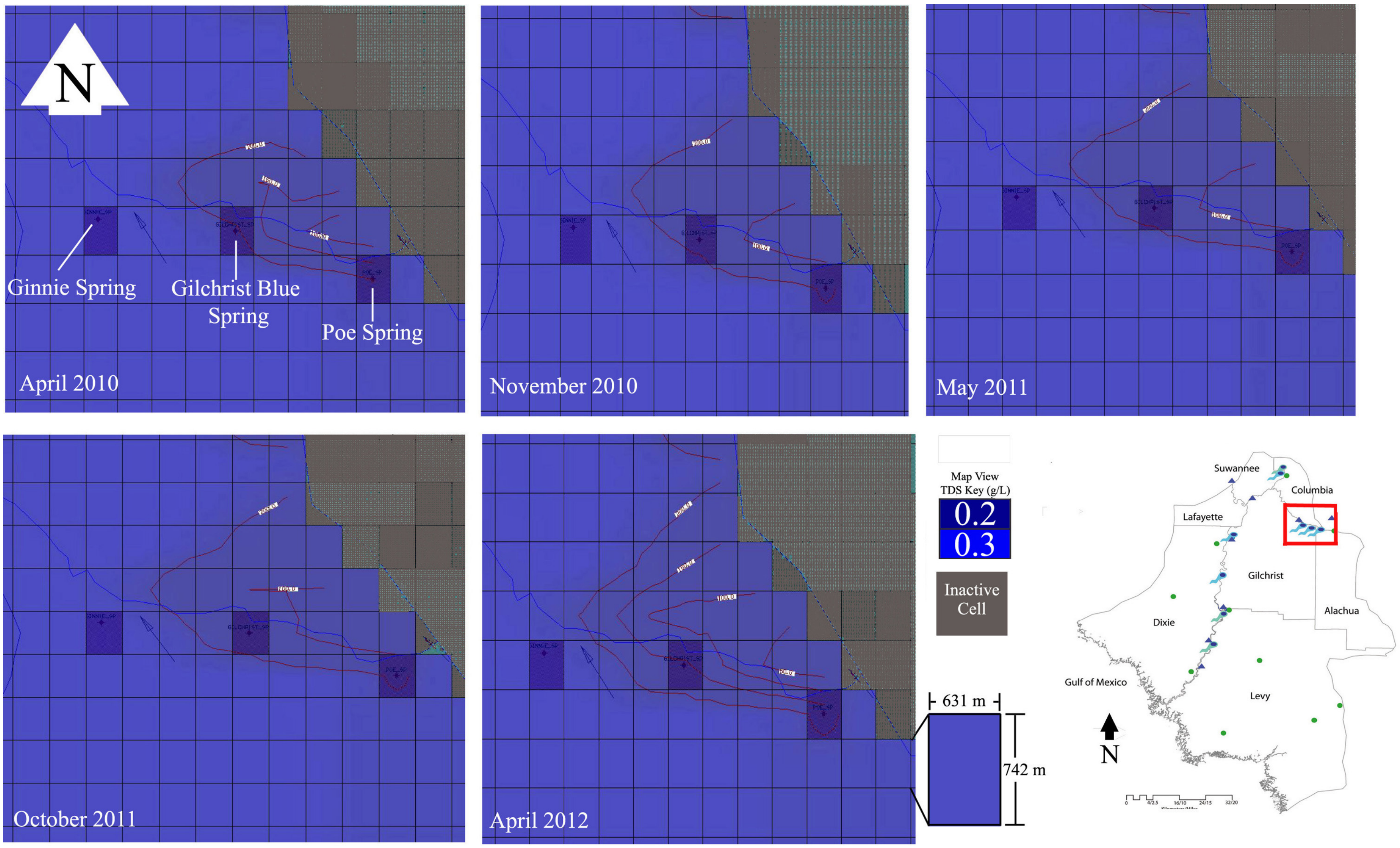
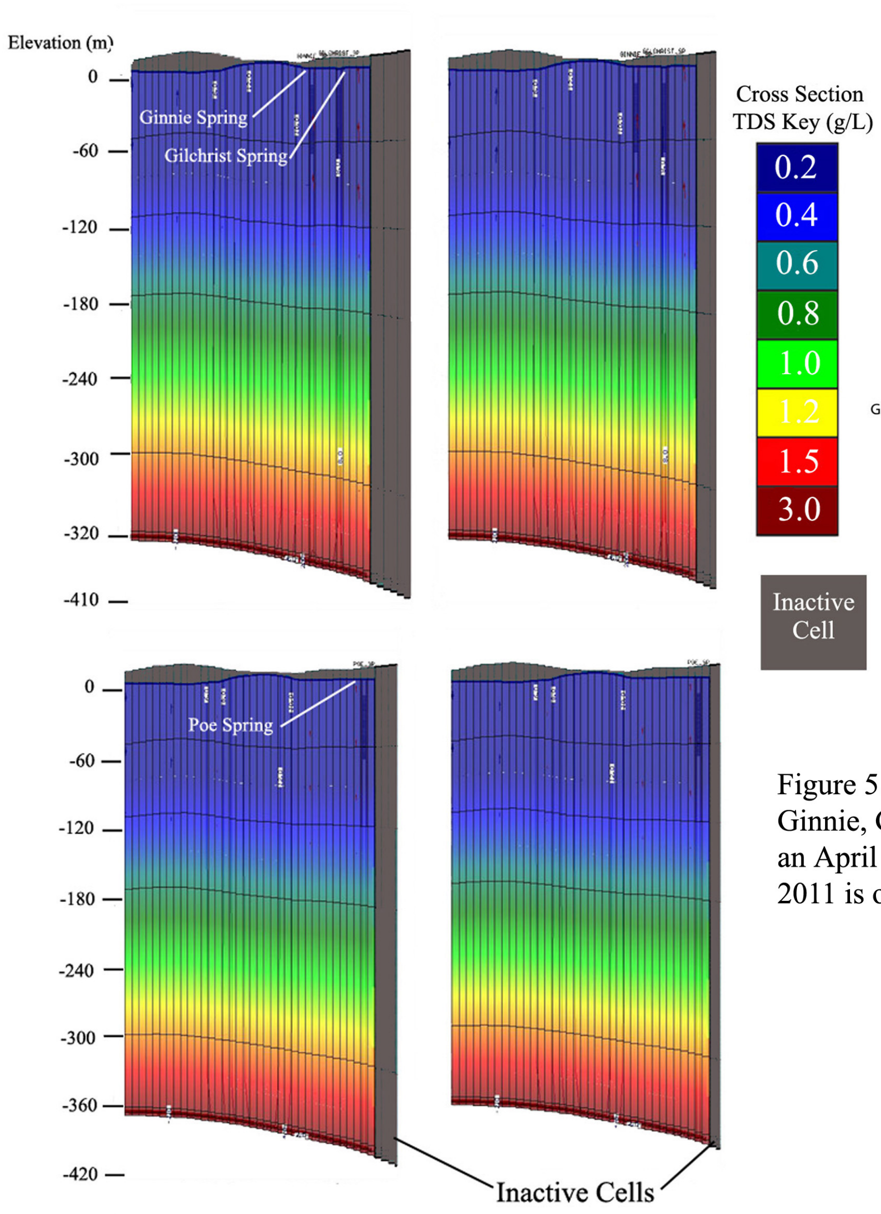


Figure 5.13: Map view of SEAWAT output for Ginnie, Gilchrist Blue, and Poe Springs. Sampled time steps from months left to right, April 2010, November 2011, May 2011, October 2011, and April 2012.



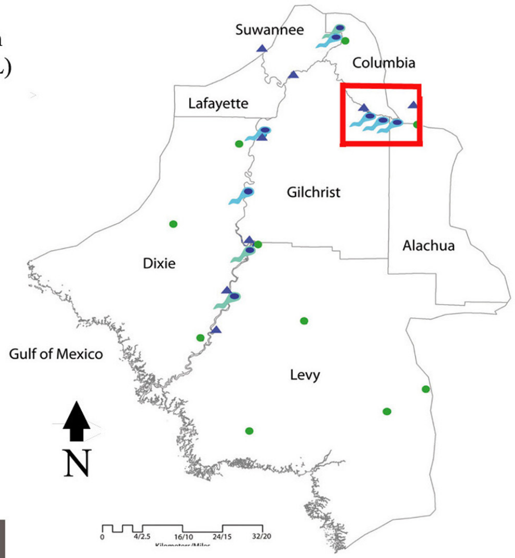


Figure 5.14: Cross section of SEAWAT output for Ginnie, Gilchrist Blue, and Poe Springs. A sample of an April 2010 time step is on the left and October 2011 is on the right.

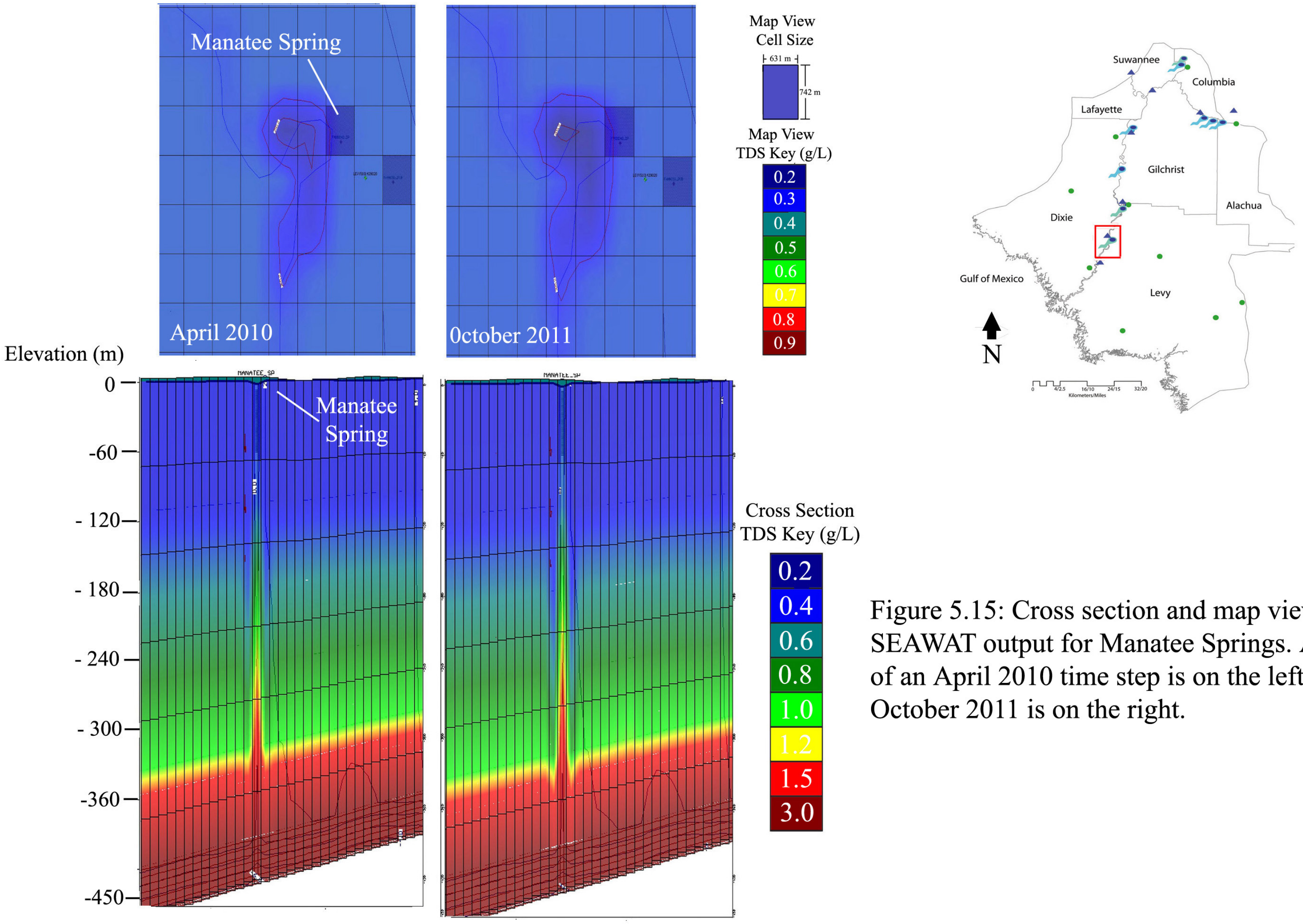


Figure 5.15: Cross section and map view of SEAWAT output for Manatee Springs. A sample of an April 2010 time step is on the left and October 2011 is on the right.

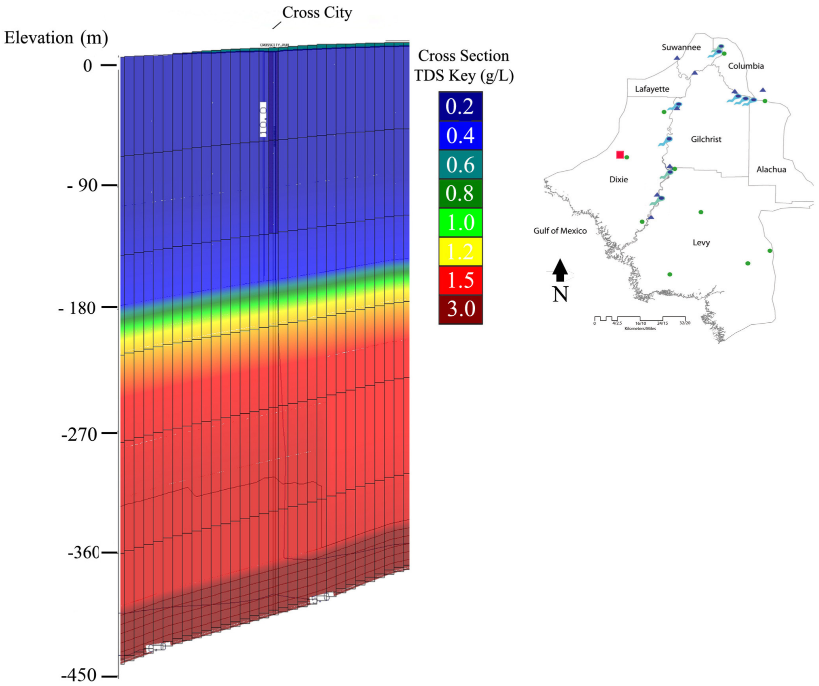


Figure 5.16: Cross section of SEAWAT output for Cross City. Results for the movement of Total Dissolved Solids for municipalities were minimal.

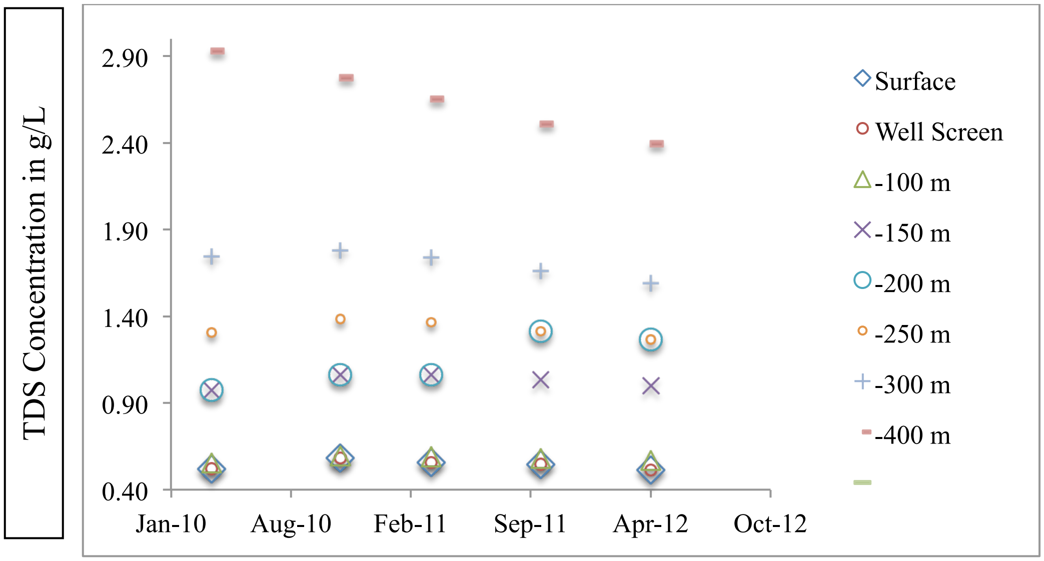


Figure 5.17: Plot of measured points for Total Dissolved Solids for Manatee Springs. Measurements were taken at multiple depths during the simulated time periods of April 2010, November 2010, May 2011, October 2011, and April 2012. Manatee Springs withdrew the greatest amount of water during the simulation and showed the greatest variation between time periods sampled.

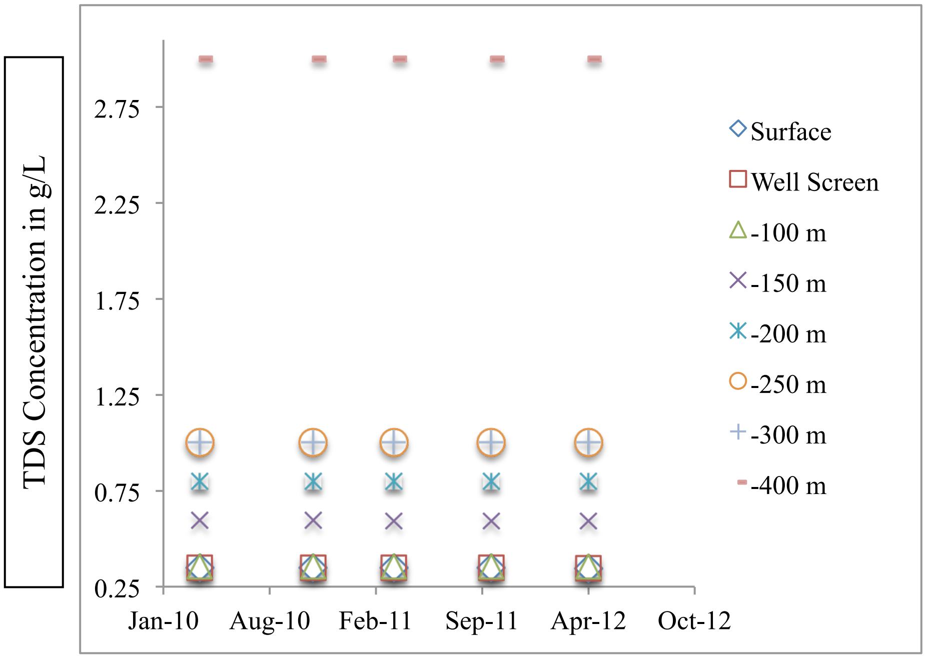


Figure 5.18: Plot of measured points for Total Dissolved Solids for Fanning Springs. Measurements were taken at multiple depths during the simulated time periods of April 2010, November 2010, May 2011, October 2011, and April 2012.

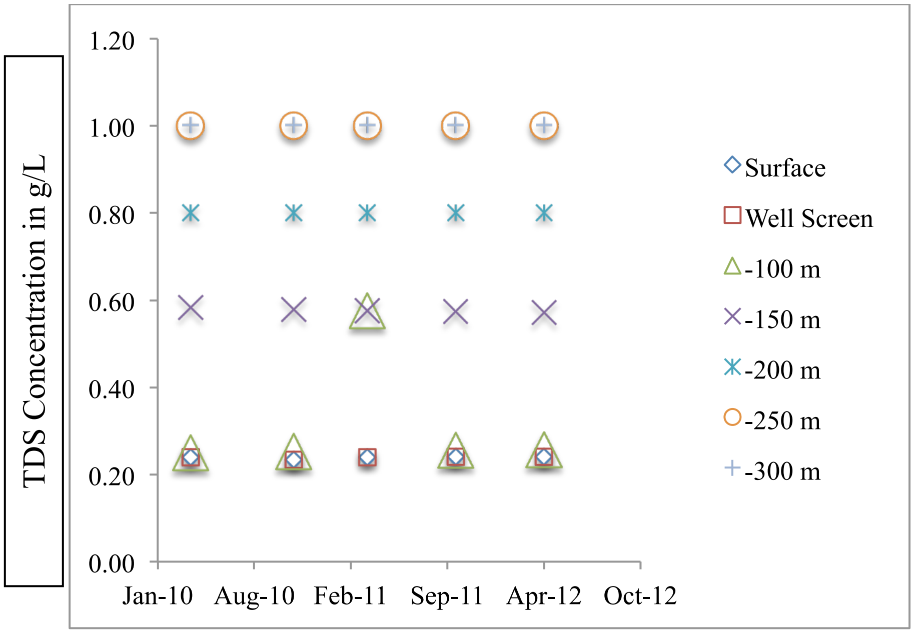


Figure 5.19: Plot of measured points for Total Dissolved Solids for Gilchrist Blue Springs. Measurements were taken at multiple depths during the simulated time periods of April 2010, November 2010, May 2011, October 2011, and April 2012.

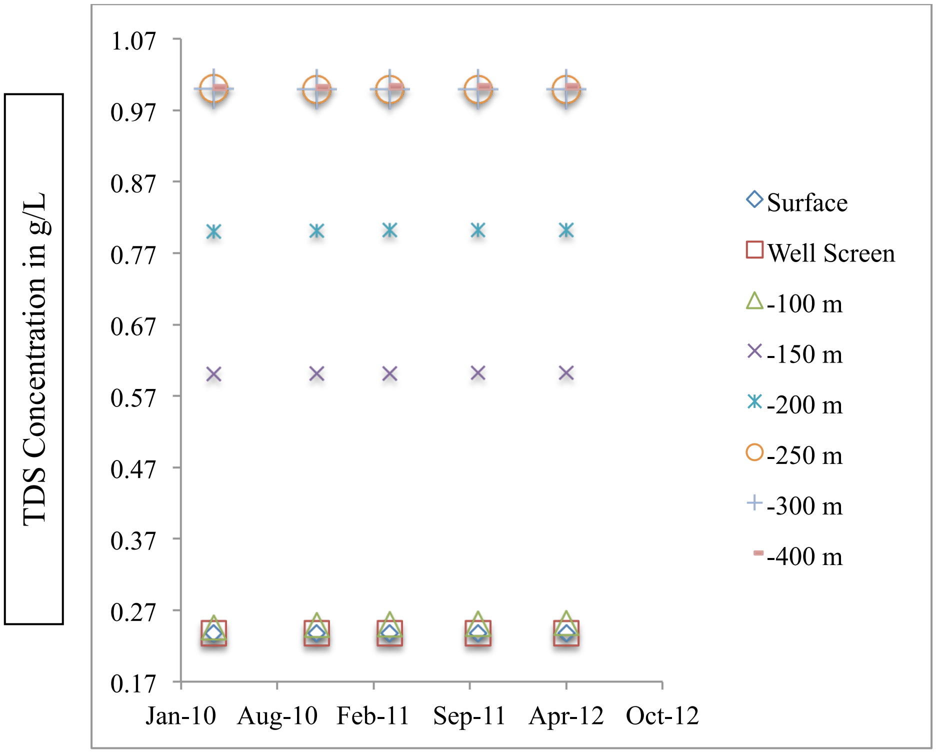


Figure 5.20: Plot of measured points for Total Dissolved Solids for Ginnie Springs. Measurements were taken at multiple depths during the simulated time periods of April 2010, November 2010, May 2011, October 2011, and April 2012.

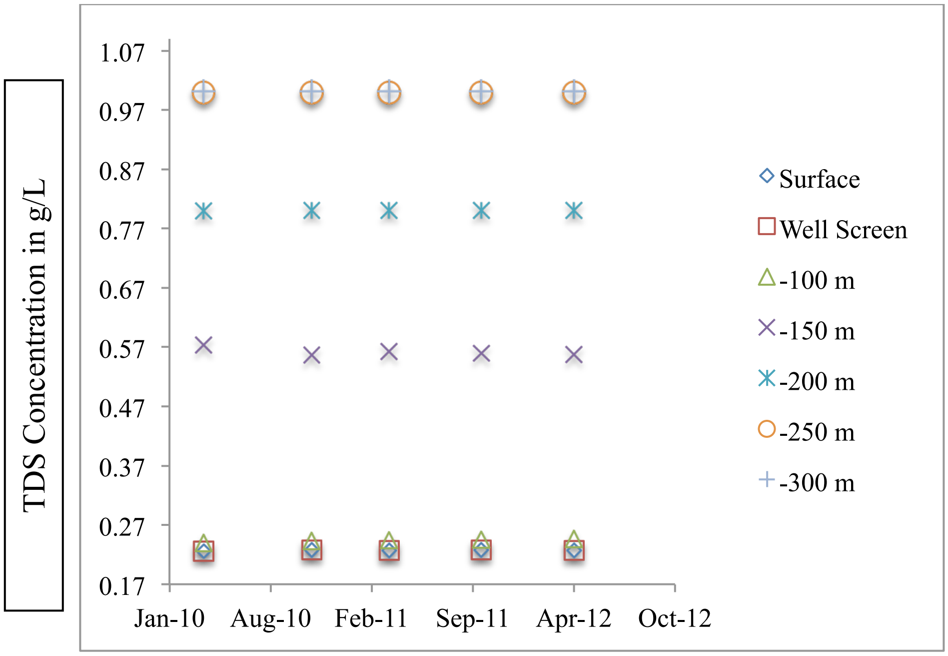


Figure 5.21: Plot of measured points for Total Dissolved Solids for Poe Springs. Measurements were taken at multiple depths during the simulated time periods of April 2010, November 2010, May 2011, October 2011, and April 2012.

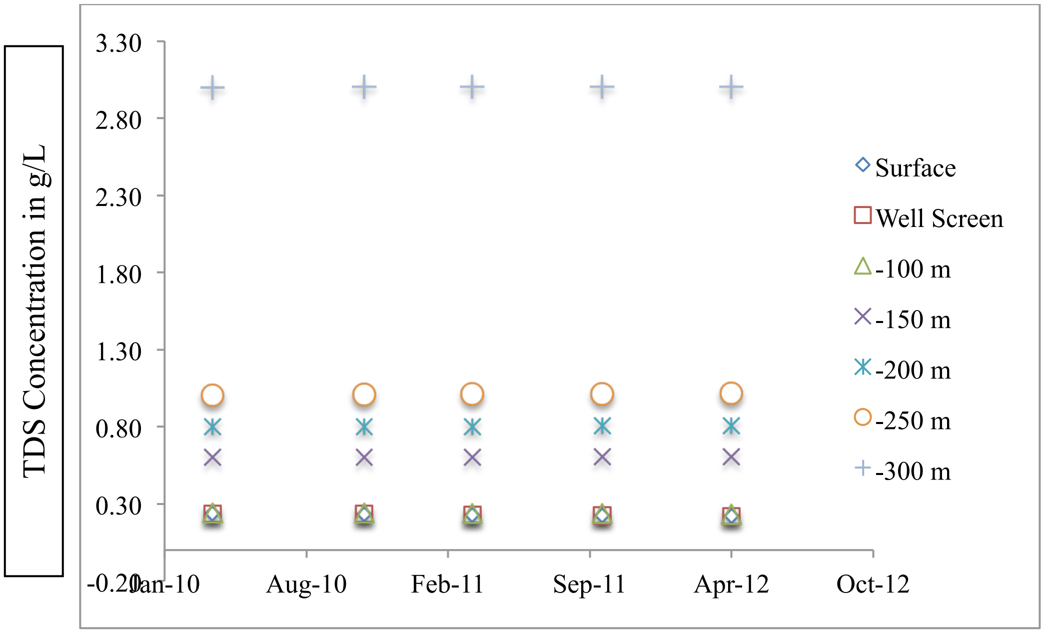


Figure 5.22: Plot of measured points for Total Dissolved Solids for Rock Bluff Springs. Measurements were taken at multiple depths during the simulated time periods of April 2010, November 2010, May 2011, October 2011, and April 2012.

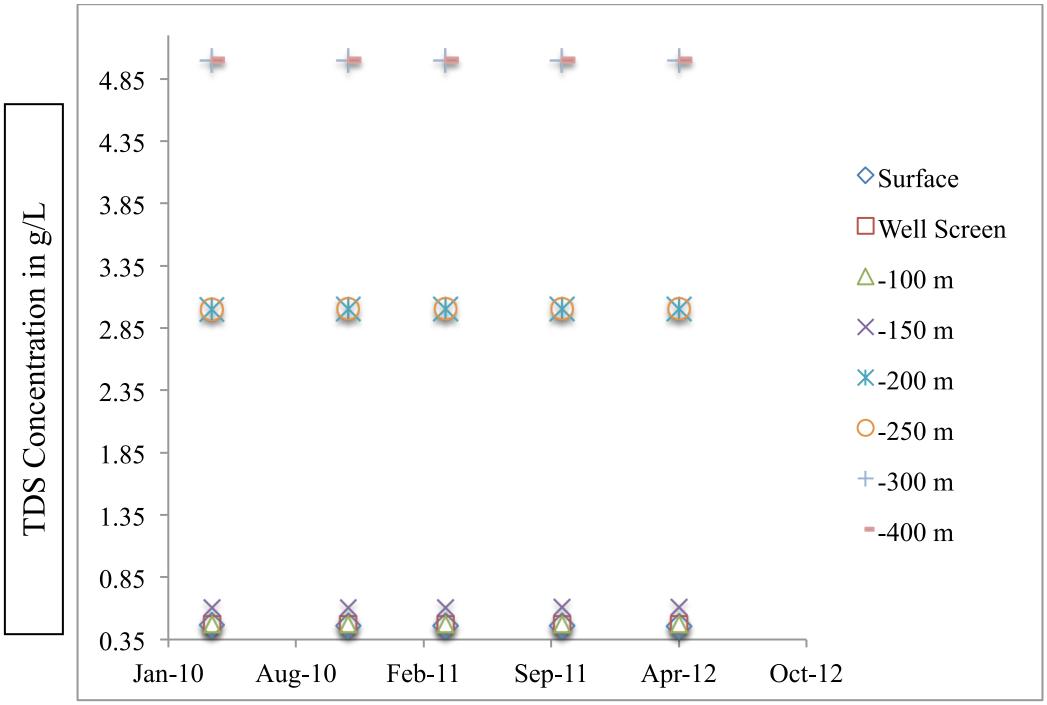


Figure 5.23: Plot of measured points for Total Dissolved Solids for Cross City. Measurements were taken at multiple depths during the simulated time periods of April 2010, November 2010, May 2011, October 2011, and April 2012. Cities showed very little change in Total Dissolved Solids between time periods sampled.

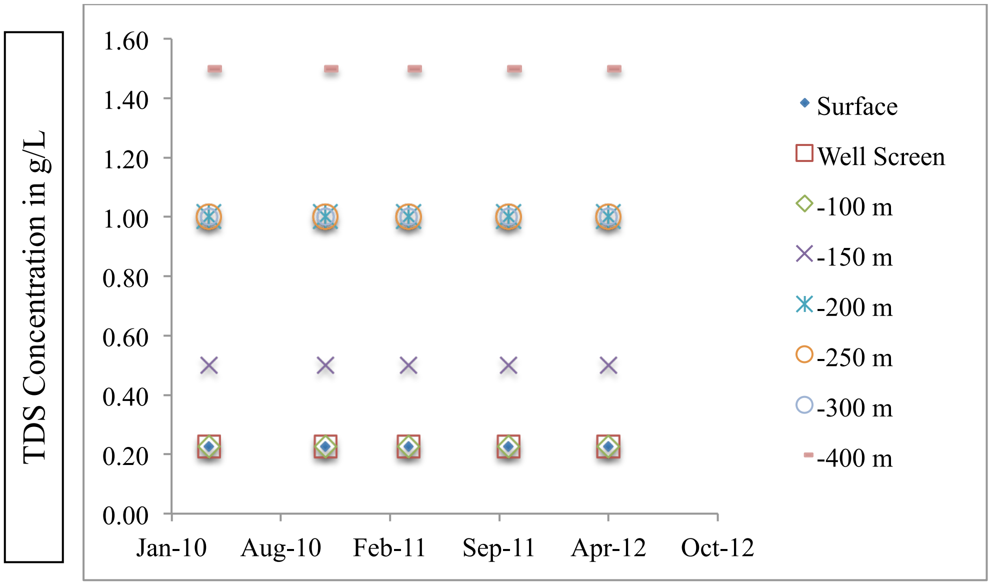


Figure 5.24: Plot of measured points for Total Dissolved Solids for the City of High Springs. Measurements were taken at multiple depths during the simulated time periods of April 2010, November 2010, May 2011, October 2011, and April 2012.

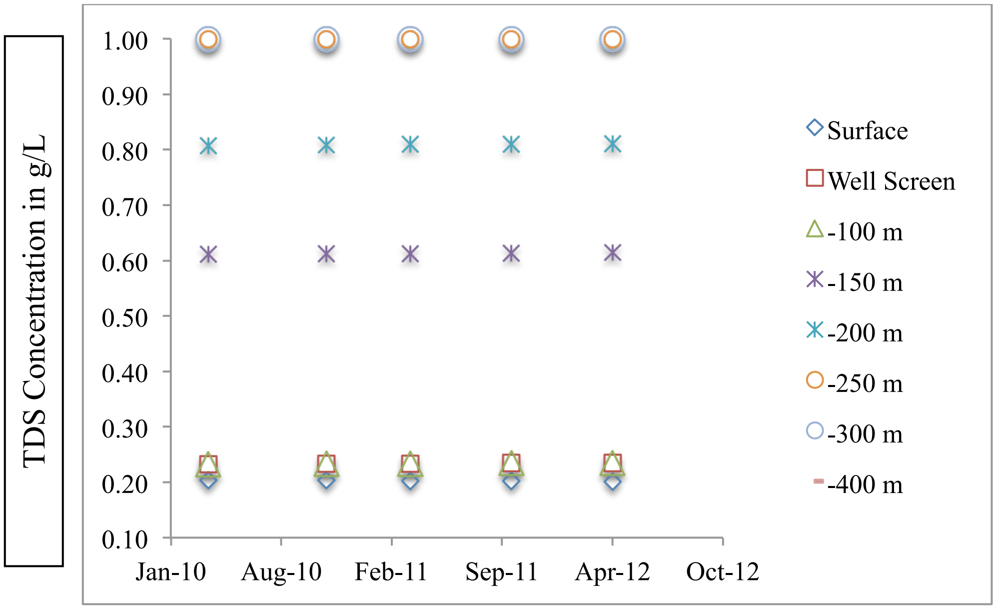


Figure 5.25: Plot of measured points for Total Dissolved Solids for the City of Newberry. Measurements were taken at multiple depths during the simulated time periods of April 2010, November 2010, May 2011, October 2011, and April 2012.

CHAPTER 6

DISCUSSION

6.1 Groundwater Flow Model

In the development and calibration of the groundwater model, the primary difficulty was matching simulated groundwater levels with the levels observed in groundwater wells. This complication is attributed to using the MODFLOW program to model groundwater flow in an aquifer that has extensive secondary porosity in the form of dissolution voids. The program MODFLOW assumes Darcy's Law in that the aquifer is heterogeneous and flow is laminar (McDonald and Harbraugh, 1988). Whereas flow though the Upper Floridan is turbulent throughout much of the aquifer which is attributed to the extensive dissolution.

This complication was amplified in areas such as levy County where there is a heavy agricultural presence and a lack of seasonal withdrawal data. Wells such as Levy S121508005 (Figure 5.12), Levy S131736001, (Figure 5.7) and Alachua S081703001 (Figure 5.11) have water levels that consist of cyclical fluctuations and vary by season. Observed values were also difficult to simulate for wells that were near municipalities such as Dixie S101210001 where seasonal pumping is also evident (See Figure 5.5).

6.2. Comparison of Calculated Transmissivity with Previous Groundwater Models

Compared to previous studies, the calculated transmissivity values vary greatly in some locations of the Upper Floridan aquifer system (Figure 5.1). Whereas other locations match one another well (Table 6.1). The differences are likely due to variables used in each model such as saturated thickness and/or the depth of the layer simulated, yet some differences could be attributed to scaling effects from the size of the different models. Only Grubbs and Crandall (2007) had transmissivity values that were calibrated within the same boundaries as this work as well as a transient model as opposed to steady-state.

High transmissivity values found in the area around High Springs and the adjacent Santa Fe River were calculated in three previous models by Sepúlveda (2002), Planert (2007), Grubbs and Crandall (2007), as well as this study. Grubbs and Crandall (2007) calculated the highest overall value at 1,828,800 m^2/day, and Sepúlveda (2002) calculated a range of 304,000 to 1,219,000 m^2/day. Planert (2007) calculated the lowest transmissivity values in a range of 18,288 to 70,104 m^2/day. This study calculated a range of 123,000 to 258,700 m^2/day.

In the far northwestern extent of the model, where there are numerous springs and the Ichetucknee River, the transmissivity values were also high. In this area, Planert (2007) calculated a range of 457,200 to 1,524,000 m^2/day and is comparable to Sepúlveda's (2002) range of 304,000 to 1,219,000 m^2/day. Grubbs and Crandall (2007) calculated a value of 142,000 m^2/day with a small area of 5,400,000 m^2/d in the vicinity of the largest springs that feed the Ichetucknee. This study produced a slightly lower range of 123,000 to 258,700 m^2/day.

The highest values calculated in this study were adjacent to the Brooksville Ridge and Waccasassa Flats at a range of 4,774 to 415,200 m^2/day. Other authors calculated high transmissivity values as well, including Planert (2007), with a range of 3,000 to 457,200 m^2/day and Grubbs and Crandall (2007), with a range of 27,000 to 469,400 m^2/day.

The lower Suwannee River, in the vicinity of Manatee and Fanning Springs, is also an area of very high transmissivity. Where Sepúlveda (2002) calculated a range of 152,400 to 2,438,200 m^2/day and is comparable to Planert's (2007) range of 457,200 to 1,524,000 m^2/day.

Grubbs and Crandall (2007) determined an overall value of 515,112 m^2/day and this study a range of 123,000 to 258,700 m^2/day.

The largest difference in calculated transmissivity was found in the center of the study within the Chiefland Limestone Plain and Waccassasa Flats provinces. Where Sepúlveda (2002) and Grubbs and Crandall (2007) calculated the largest ranges at 914 to 152,400 m^2/day and 914 to 152,400 m^2/day, respectfully. Much narrower ranges were calculated by Panert (2007) at 18,288 to 70,104 m^2/day and this study at 1,000 to 12,987 m^2/day.

In Dixie County, Grubbs and Crandall (2007) calculated the highest transmissivity range of 43,281 to 539,400m^2/d for the area. The other studies calculated smaller values of 914 to 30,480 m^2/d for Sepúlveda (2002) and 2,600 to 4,700 m^2/d for this study. Planert (2007) had a value of 18,288 m^2/d for the western half of the model, including Dixie County.

Large variations in calculated transmissivity were found at the mouth of the Suwannee River at the Gulf of Mexico, where this study produced a range of 6,010 to 258,700 m^2/d. Other ranges included 3048 to 457,200 m^2/d for Planert (2007), 15,240 to 152,400 m^2/d for Sepúlveda (2002), and 99,060 to 515,000 m^2/d for Grubbs and Crandall (2007).

Finally, the mean calculated for transmissivity in the Upper Floridan aquifer was 16,314 m^2/d, which is less than the calculated mean of 609,600 m^2/d for Schneider et al. (2008). This is possibly due to Schneider et al. modeling a much larger area and taking the calculated mean from a larger range of conductivity zones. For their model, Schneider et al. (2008) calculated a transmissivity range in the Upper Floridan of 185.8 m^2/d to 929,030 m^2/d.

Sepúlveda (2002) calculated transmissivity in portions of the Lower Floridan aquifer as well. In Dixie County, a range of 929 m^2/d to 1,858 m^2/d was calculated, yet for this work, the transmissivity calculated for the Lower Floridan in Dixie County ranges from 50 to 180 m^2/d. In eastern Levy County, Sepúlveda (2002) calculated the transmissivity for the lower Floridan between 929 to 4,645 m^2/d. Again, the calculated amount for this work is lower at 50 to 180 m^2/d. The differences are most likely due to a lower initial conductivity assigned to the Lower Floridan aquifer system coinciding with Miller's (1986) observation that the deepest Floridan units typically have a conductivity two orders of magnitude lower than those at shallower depths. Whereas Sepúlveda (2002) statistically calculated transmissivity by identifying the values of control points in discrepancy areas that decreased the absolute value of residuals, as well as using conductivity values from adjacent models.

6.3 Hydrologic Controls on the Saltwater-Freshwater Interface

The saltwater-freshwater interface forms an asymmetrical mound where the 3g/L surface rises to a depth of -256 m (-840 ft) in the western half of the study area under Dixie County (Figures 6.1 and 6.2). In the eastern half, the front dips east passing under the middle confining unit where the 3 g/L Total Dissolved Solids interval intersects the bottom of the Lower Floridan at approximately -500 m (-1,649 ft).

The middle confining unit's isolated presence under Gilchrist and Levy Counties controls the elevation of the interface. In this area, the unit's lower conductivity forms a divide which halves groundwater flow into the Upper and Lower Floridan as it moves parallel with the Suwannee River on its way to the Gulf of Mexico. This channeling of flow increases velocity as groundwater is forced to flow from an area of larger volume to that of smaller volume. Where the middle confining unit is absent underneath Dixie County, groundwater movement spreads vertically over a greater area resulting in decreased velocity while conserving flow. This decrease in velocity allows the diffusive front to rise to a shallower elevation. This is defined where $\vec{v}$ is the fluid velocity in equation 4.6.

It should be noted that using a small number of sampling points and interpolating them through kriging may not be adequate for characterizing the aquifer as a whole.

The extensive dissolution and heterogeneity that typifies the Floridan aquifer may contain pockets of connate water in some areas while preferential flow paths along features such as joints are actively flushing away constituents.

6.4 Movement of Total Dissolved Solids

The SEAWAT model helped to illustrate the vertical movement of Total Dissolved Solids in the Suwannee River Basin and the Floridan aquifer system. However, Total Dissolved Solids movement was minor under current conditions. The greatest points of withdrawal, such as Manatee and Fanning Springs, are the few locations that show a change through time in respect to the saltwater-freshwater interface (Figure 5.14 through 5.17). The larger cities such as High Springs, Cross City, and Newberry, showed little influence on the interface even when demand was increased past Year 2030 expectations (Figures 5.24 through 5.26).

Variation in level of Total Dissolved Solids is most evident in springs such as Manatee and Rock Bluff, where withdrawal is greatest. However, these variations do not reflect an increase in Total Dissolved Solids recorded in the field during droughts, but a decrease during the simulated low water events. There are two possible reasons for this outcome: the first being that the springs were assigned lower discharge rates during drought periods, and this in turn created less pull on the underlying interface. Second, with less water in the aquifer from which it was withdrawing water, the springs responded with induced recharge from the nearby river channel. This second scenario would explain the zones of lesser Total Dissolved Solids found in proximity of the spring. These zones increased in size and had decreased levels of Total Dissolved Solids during drought events indicating the spring was increasing the amount of induced recharge. The somewhat proximal location from of the decreased zone of Total Dissolved Solids from the spring and its elongated shape is indicative of the non-uniform hydrologic conductivity of field area.

Cross section views show a central plume of Total Dissolved Solids rising primarily through the cells assigned as wells where levels cut off sharply in adjacent cells. This phenomenon is not representational of aquifer conditions but is the result of coarse spacing in the model grid. A finer mesh is expected to have a more even gradation of constituents spreading from the well but would be computationally taxing.

6.5 Comparison of Saltwater-Freshwater interface with Previous Works

In the Suwannee River Basin, a limited amount of direct observations exist to help delineate the location of a saltwater-freshwater interface (Grubbs and Crandall, 2007). Past researchers have struggled with this lack of data in their construction of groundwater flow models (Sepúlveda, 2002; Planert, 2007; Grubbs and Crandall, 2007).

Countryman and Stewart (1997) conducted an extensive study utilizing surface electromagnetic and electrical geophysical methods to determine the position of the saltwater-freshwater interface. They determined that within 20 km (12.4 mi) of the mouth of the Suwannee River, the saltwater-freshwater interface loosely follows the Ghyben-Herzberg Ratio. They presumed that in locations where the middle confining unit was present, the interface was shallow and the unit restricted the downward flow of freshwater forcing vertical flow to become lateral at shallower depths. They also concluded that where the middle confining unit was absent, and as a result the Floridan is much deeper, decreased head loss due to the high permeability allows the groundwater to descend further into the aquifer resulting in a deeper interface. These ideas do not coincide with the current findings from the USGS Saline Aquifer Study (Williams in communication, 2013). Through a more direct geophysical method, the shallowest top of the 3 g/L Total Dissolved Solids level was found in Dixie County, and the deeper surfaces were found in Levy where the middle confining unit is still present. The availability of data with more direct method of measurement also conflicts with previous groundwater models, such as Schneider et al. (2008), who based their saltwater-freshwater interface along the Gulf Coast according to the work of Countryman and Stewart (1997).

Another previous modeling work limited by the lack of available data was Sepúlveda (2002), who assigned a Neumann Type II boundary at an estimated threshold of 5 g/L chloride concentration. The location of the interface was determined by using data from outside of the field area resulting in a determined depth of -304.8 m (-1,000 ft) lying within proximity of the northern extent of this study (Sepúlveda, 2002). The shallowest depth was determined to be at -152 m (499 ft) near the community of Bell in the center of this study (Sepúlveda, 2002). Along the Suwannee River and near the community of Bell, the 3 g/L Total Dissolved Solids was determined to be at a depth ranging from -300 to -400 m (984 to 1,312 ft). On the northern border of the study area, the depth of the 3 g/L Total Dissolved Solids interval has been determined to be at a depth that ranges from -400 m to -480 m (1,312 to 1,575 ft). This would conclude that the 5 g/L chloride concentration is at a lower elevation.

Finally, Grubbs and Crandall (2007) set the bottom of their model at the top of the middle confining unit or, if non-existent, the bottom of the Lower Floridan. Where the Lower Floridan was determined to be below the saltwater-freshwater interface, calculated by Ghyben-Herzberg Principle, the boundary was then set at the interface. Data acquired for this work shows that the saltwater-freshwater interface is situated below the middle confining unit and the bottom of the Lower Floridan as well. The highest amounts of Total Dissolved Solids recorded in the field area were 10 g/L located in the western extent of Dixie County. At 10 g/L that amount of Total Dissolved Solids approaches brackish water and not the 35 g/L Total Dissolved Solids threshold of saline water (Mahon, 1989).

Table 6.1: Comparison of transmissivity values calculated by different groundwater flow models in the Suwannee River Basin. (All values are in m^2/day.)

Author	**North High Springs and Santa Fe River**	**North Ichetucknee Springs**	**Central Suwannee River/Manatee & Fanning Springs**	**Central Chiefland Plain**	**South Mouth of Suwannee River**	**West Dixie Co. & Mallory Swamp**	**East Brooksville Ridge & Waccassasa Flats**
This Study	123,000-258,700	123,000-258,700	123,000-258,700	1,000-12987	6,010-258,700	1,100-12,900	4,774-415,200
Grubbs and Crandall (2007)	1,828,800-	142,000-5,400,000	515,112	27,035-181,600	99,060-515,000	43,281-539,400	27,000-469,400
Planert (2007)	18,288-70,104	457,200-1,524,000	457,200-1,524,000	70,104-18,288	3048-457,200	18,288	3,000-457,200
Sepúlveda (2002)	304,000-1,219,000	304,000-1,219,000	152,400-2,438,200	914-152,400	15,240-152,400	914-30,480	30,480-152,400

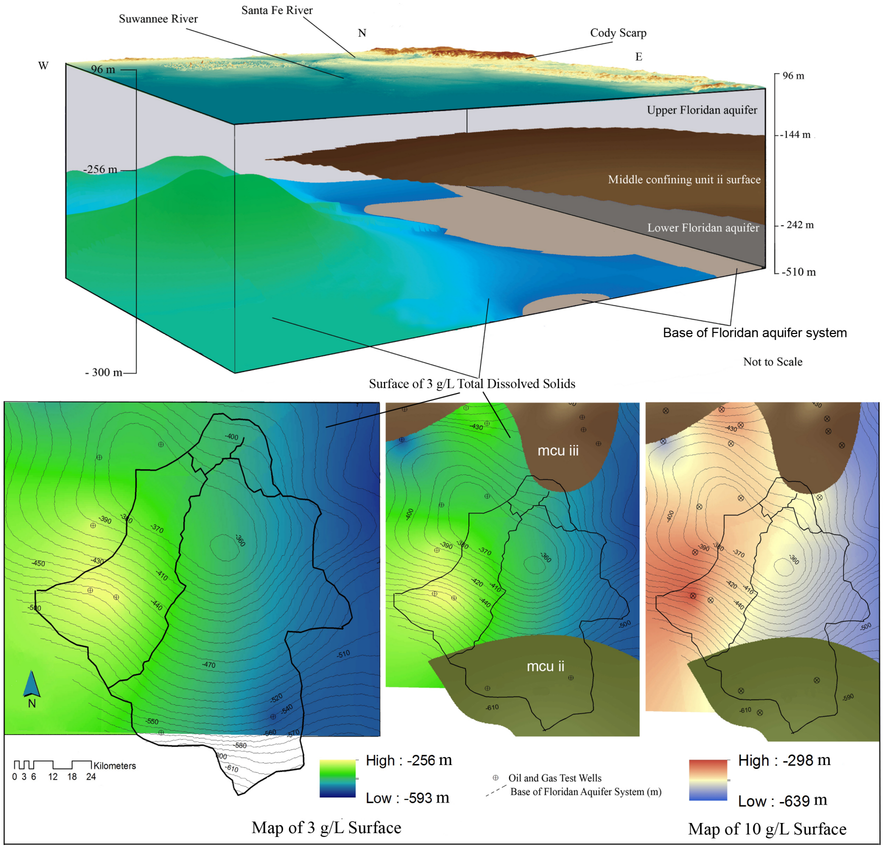


Figure 6.1: Map and cross section view of interpreted relationships between the 3 g/L and 10 g/L Total Dissolved Solid surfaces, Floridan aquifer system, and middle confining unit.

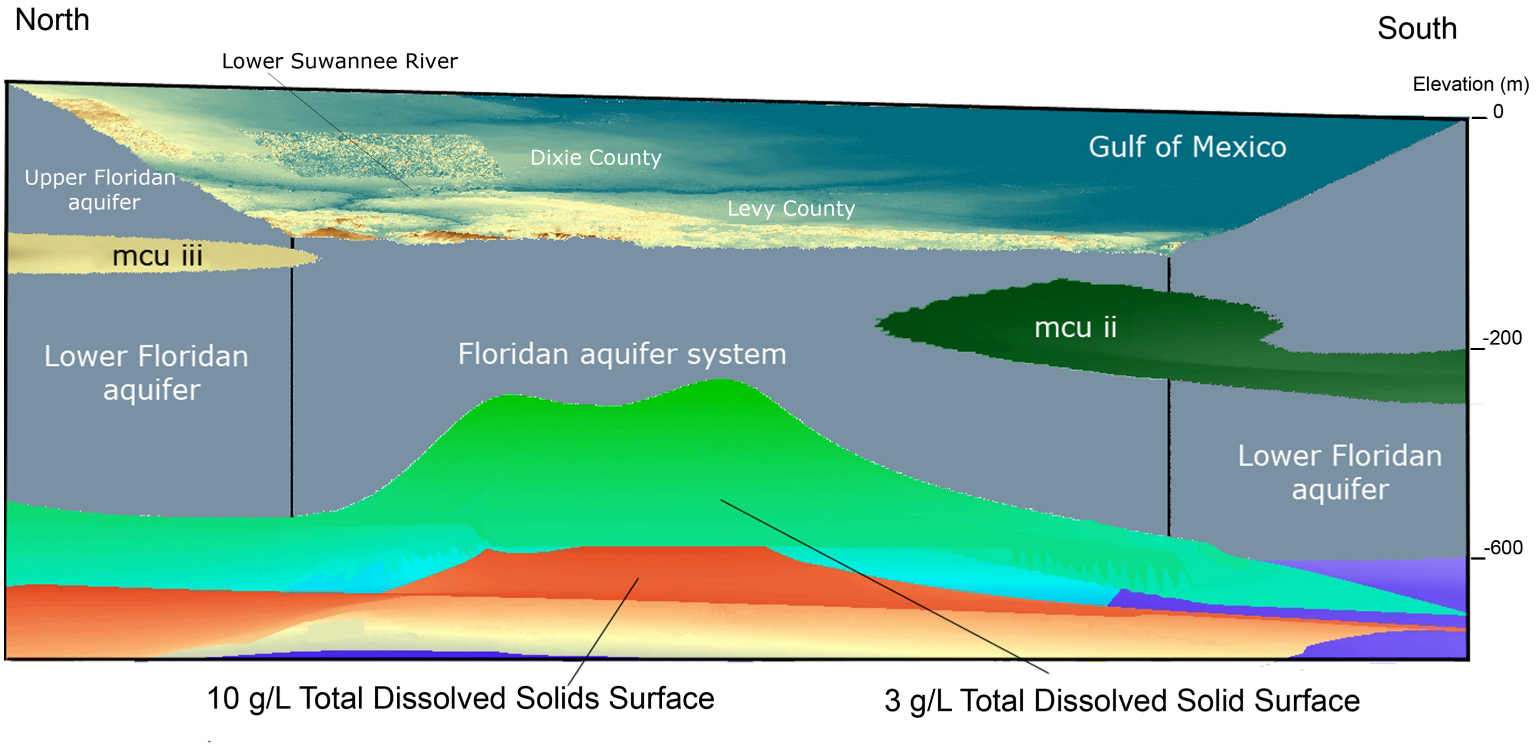


Figure 6.2: Cross section of interpreted relationships between 3 g/L and 10 g/L Total Dissolved Solid surfaces, Floridan aquifer system, and middle confining unit. Where the two halves of the middle confining units are absent, the 3 g/L and 10 g/L Total Dissolved Solids surfaces are shallower due to less hydraulic head.

CHAPTER 7

CONCLUSIONS

The goal of this work was to take recent well data from the USGS's Saline Aquifer Mapping Project and re-define the saltwater-freshwater interface in an existing transient groundwater flow model through conversion of the model into a multi-variable density simulation and ultimately examine the interface's relationship to discharging springs.

Interpolated surface data indicates that the saltwater-freshwater transition zone was shallower in Dixie County than Levy County to the east. This is due to the presence of the middle confining dividing groundwater flow and increasing velocity in the eastern half of the study area. However, on the western side of the Suwannee River area, the middle confining unit is non-existent and aquifer's volume increases resulting in decreased velocity. The velocity decrease allows concentration of Total Dissolved Solids to rise vertically to a shallower elevation in comparison to the east. With the exception of far western Dixie County, the saltwater-freshwater transition zone is below the base of the Floridan aquifer system.

During simulations, springs proved to be the largest influence on the vertical movement of Total Dissolved Solids and responded to seasonal fluctuations. However, under drought conditions, springs displayed lower Total Dissolved Solids concentrations than normal conditions or wetter periods. This phenomenon was likely attributed to induced recharge from the springs, which appeared as near-surface asymmetrical zones of lower Total Dissolved Solids within proximity of the spring. Finally, there was no observed lateral movement in the concentration of Total Dissolved Solids during simulations.

The groundwater model proved difficult to calibrate and achieve a reasonable solution. Simulated values were a poor to fair match to values from observation wells due to the nature of the Floridan aquifer system's extensive dissolution and secondary porosity, as well as lack of data involving groundwater demand. Future efforts are encouraged to use a groundwater model that explicitly handles the unique nature of karst and groundwater flow that does not adhere to Darcy's Law, as well as solving a multi-variable solution.

Recently, the Suwannee River Water Management District has expanded their continuous collection of groundwater data as well as continuous collection of specific conductance. Maintaining this continuous data will aid in future efforts of modeling the saltwater-freshwater data. Furthermore, increasing the number of wells and geophysical logs that fully penetrate the Floridan aquifer system will further aid in the understanding and extent of dissolved constituents and their variations both laterally and vertically in the dual porosity environment.

REFERNCES CITED

Anderson, M.P., Woessner, W.W., 1992, Applied Groundwater Modeling: Simulation of Flow and Advective Transport: San Diego, California, Academic Press, 381 p.

Bear, J., 1972, Dynamics of Fluids in Porous Media: New York, Dover Publications, Inc., 764 p.

Bush, B.W., Johnston, R. H., 1988, Summary of the hydrology of the Floridan Aquifer System in Florida and in Parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403-C. p. 80.

Chowns, T.M., Williams, C.T., 1983, Pre-Cretaceous Rocks Beneath the Georgia Coastal Plain – Regional Implications: U.S. Geological Survey Professional Paper 1313-L

Cook, C.W., 1945, Geology of Florida: Florida Geological Survey: Bulletin 29, p. 339.

Copeland, R., Doran, N. A., Aaron, J.W., Upchurch, S.B., 2009, Regional and statewide trends in Florida's spring and well groundwater quality (1991-2003): Florida Geological Survey. Bulletin No. 69, Tallahassee, Florida. 164 p.

Ceryak, R., Knapp, M.S., Burnson, T., 1983, The geology and water resources of the Upper Suwannee River Basin, Florida: Florida Bureau of Geology Report of Investigation No. 87. 165 p.

Countryman, R.A., Stewart, M.T., 1997, Geophysical delineation of the position of the saltwater surface in the Lower Suwannee Basin. [M.S. thesis]: University of South Florida, Tampa, Florida. 538 p.

Crane, J.J., 1986, An investigation of the geology, hydrogeology, and hydrochemistry of the Lower Suwannee River Basin, Florida: Florida Geological Survey Report of Investigations 96. 205 p.

Denizman, C., Randazzo, A.F., 2000, Post Miocene subtropical karst evolution, lower Suwannee River Basin, Florida: GSA Bulletin, v.112, p. 1804-1813.

Dausman, A., and Langevin, C. D. 2004, Movement of the saltwater interface in the surficial aquifer system in response to hydrologic stresses and water management practices, Broward County, Florida: U.S. Geological Survey Scientific Investigations Report 2004-5256. 73 p.

Fetter, C.W., 1988, Applied Hydrology: Columbus, Ohio, Merril Publishing Co., 592 p.

Grubbs, J. W., Crandall C. A., 2007, Exchanges of water between the Upper Floridan Aquifer and the Lower Suwannee and Lower Santa Fe Rivers, Florida: U.S. Geological Survey Professional Paper 1656-C. p. 83

Guo, W., Langevin, C.D., 2002, User's Guide to SEAWAT: A computer program for simulation of three-dimensional variable-density ground-water flow: U.S. Geological Survey Techniques of Water-Resources Investigations 6-A7. 77 p.

Harbaugh, A.W., and McDonald, M.G. 1988, A modular three-dimensional finite-difference groundwater flow model. U.S. Geological Survey, Techniques of water resource investigation of the United States Geological Survey, Book 6, Chapter A1, 586 p.

Harbaugh, A.W., McDonald, M.G., 1996, User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference groundwater flow model: U.S. Geological Survey Open-File Report: 96-485, 56 p.

Harbraugh, A.W., 2005, MODFLOW-2005, The U.S. Geological Survey modular ground-water model-the ground-water flow process: U.S. Geological Survey: Techniques and Methods Book 6, chap 16. p. 253.

Hickey, J.J., 1990, An Assessment of the flow of variable-salinity ground water of the middle confining unit of the Floridan Aquifer System, West Central Florida: U.S. Geological Survey Water-Resources Investigations Report 89-4142 13 p.

Hornsby, D., and Ceryak, R., 1998, Springs of the Suwannee River Basin in Florida: Suwannee River Water Management District Water Resources Publication 99-02, 178p.

Jennings, J.N., 1985, Karst Geomorphology: Oxford, Basil Blackwell Ltd, 293 p.

Katz, B. G., and DeHan R., Hirten J.J., Catches J.S., 1997. Interactions between ground water and surface water in the Suwannee River Basin, Florida: Journal of the American Water Resources Association, no 33. p. 1237-1254.

Kinnaman, S.L., and Dixon, J.F., 2011, Potentiometric surface of the Upper Floridan aquifer in Florida and parts of Georgia, South Carolina, and Alabama, May – June 2010: U.S. Geological Survey Scientific Investigations Map 3182, Scale: 1:100,000, 1 sheet.

Mahon, G.L., 1989, Potential for the saltwater intrusion into the Upper Floridan Aquifer, Hernando and Manatee Counties, Florida: U.S. Geological Survey Water-Resources Investigations Report 88-4171, p. 47

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations Book 6, chap A1. p. 586

Miller, J. A., 1986, Hydrogeologic framework of the Floridan aquifer system in Florida and in parts of Georgia, Alabama, and South Carolina: U.S. Geological Survey Professional Paper 1403-B. p. 91.

Nash, J. E. and Sutcliffe, J. V., 1970, River flow forecasting through conceptual models part I, A discussion of principles: Journal of Hydrology no 10. p. 282-290.

Parker, G.G., Ferguson, G.E., Love, S.K., 1944, Interim report on the investigations of water resources in South-Eastern Florida with a special reference to the Miami area in Dade County: Florida Geological Survey Report of Investigations 4, p. 39.

Phelps, G.G., Spechler, R.M., 1997, The relation between hydrogeology and water quality of the Lower Floridan Aquifer in Duval County, Florida, and implications for monitoring movement of saline water: U.S. Geological Survey Water-Resources Investigations Report 96-4242. p. 58.

Planert, M., 2007, Simulation of regional ground-water flow in the Suwannee River Basin, Northern Florida and Southern Georgia: U.S. Geological Survey Scientific Investigations Report 2007-5031. p. 50.

Schlumberger Water Services, 2012, Visual Modflow Flex user documentation.

Schneider, J.W., Upchurch, S.B., Jian, C. Cain, C., 2008, Simulation of groundwater flow in North Florida and South-Central Georgia, A three dimensional model of groundwater flow in the surficial, intermediate and Floridan aquifer systems: Suwannee River Water Management District p. 98.

Scott, T.M., Means, G.H., Meegan, R.P., Means, R.C., Upchurch, S.B., Copeland, R.E., Jones, J., Roberts, T., Willet, A., 2004, Springs of Florida: Florida Geological Survey Bulletin No. 66. p. 658.

Scott, T.M., 1992, A Geologic overview of Florida: Florida Geological Survey Open File Report No. 50. p. 78.

Sepúlveda, N., 2002, Simulation of ground-water flow in the Intermediate and Floridan Aquifer Systems in Peninsular Florida: U.S. Geological Survey Water-Resources Investigations Report 02-4009. p. 130.

Spechler, R.M., 1994, Saltwater intrusion and quality of water in the Floridan Aquifer system, Northeast Florida: U.S. Geological Survey Water-Resources Investigations Report 92-4174. 78 p.

Spechler, R.M., 2001,The relation between structure and saltwater intrusion in the Floridan aquifer system, Northeastern, Florida, *in* Kuniansky, E.L., ed. Karst Interest Group Proceedings: U.S. Geological Survey Water Resources Investigations Report 01-4011. p. 25-29

Suwannee Water Management District, 2010, Water Supply Assessment 2010. p. 109.

Suwannee Water Management District, 2012, October 2012 Hydrologic Conditions for the District, p. 17.

U.S. Environmental Protection Agency, 2009, National primary drinking water regulations, EPA 816-F-09-004: http://water.epa.gov/drink/contaminants/upload/mcl-2.pdf (accessed December 2014).

Vernon, R.O., 1951, Geology of Citrus and Levy Counties, Florida: Florida Geological Society Bulletin No 33. p. 256.

Williams, L.J., 2013. Personal communication. U.S. Geological Survey.

Zheng, C., and Bennett G.D., 1995, Applied Contaminant Transport and Modeling, Theory and Practice Van Nostrand Reinhold. p. 440

APPENDIX A

WITHDRAWAL RATES FOR SPRINGS AND IRRIGATION WELLS SIMULATED IN THE GROUNDWATER MODEL

Fanning Springs			Manatee Springs		
Initial Time Step	Final Time Step	Amount m^3/d	Initial Time Step	Final Time Step	Amount m^3/d
0	61	165,206	0	61	259,319
61	123	153,805	61	123	229,962
123	184	224,678	123	184	318,033
184	245	175,309	184	245	225,681
245	305	131,861	245	305	305,801
305	366	14,140	305	366	332,711
366	427	100,352	366	427	259,319
427	489	160,827	427	489	254,426
489	550	194,636	489	550	371,854
550	611	162,099	550	611	259,319
611	670	174,600	611	670	305,801
670	730	98,174	670	730	242,194
0	61	241,754	0	61	259,319
61	123	232,360	61	123	320,479
123	184	224,947	123	184	371,854
184	245	211,467	184	245	259,319
245	305	56,316	245	305	305,801
305	366	57,539	305	366	332,711
366	427	174,942	366	427	259,319
427	489	232,360	427	489	320,479
489	550	131,739	489	550	371,854
550	611	139,641	550	611	259,319
611	670	190,599	611	670	305,801
670	730	171,933	670	730	332,711
730	792	105,244	730	792	259,319
792	854	167,065	792	854	320,479
854	914	172,349	854	914	318,033
914	976	192,459	914	976	225,681
976	1035	130,565	976	1035	251,980
1035	1095	119,385	1035	1095	242,194

Ginnie Springs			Gilchrist Blue Springs		
Initial Time Step	Final Time Step	Amount m^3/d	Initial Time Step	Final Time Step	Amount m^3/d
0	61	86,847	0	61	85,747
61	123	90,395	61	123	93,991
123	184	91,006	123	184	83,471
184	245	97,122	184	245	59,986
245	305	91,006	245	305	49,662
305	366	97,807	305	366	89,392
366	427	96,144	366	427	85,747
427	489	90,395	427	489	62,139
489	550	97,807	489	550	117,305
550	611	97,122	550	611	74,615
611	670	91,006	611	670	49,662
670	730	97,807	670	730	81,734
0	61	86,847	0	61	62,139
61	123	90,395	61	123	76,206
123	184	97,807	123	184	83,471
184	245	97,122	184	245	59,986
245	305	97,807	245	305	89,049
305	366	97,807	305	366	89,392
366	427	86,847	366	427	85,747
427	489	90,395	427	489	76,206
489	550	97,807	489	550	83,471
550	611	97,122	550	611	59,986
611	670	97,807	611	670	49,662
670	730	97,807	670	730	81,734
730	792	96,144	730	792	62,139
792	854	90,395	792	854	76,206
854	914	97,807	854	914	83,471
914	976	99,936	914	976	59,986
976	1035	91,006	976	1035	49,662
1035	1095	101,893	1035	1095	81,734

Ichetucknee Springs			Poe Springs		
Initial Time Step	Final Time Step	Amount m^3/d	Initial Time Step	Final Time Step	Amount m^3/d
0	61	127,213	0	61	79,875
61	123	107,642	61	123	81,270
123	184	110,088	123	184	109,403
184	245	97,856	184	245	73,025
245	305	105,195	245	305	62,212
305	366	112,535	305	366	103,972
366	427	127,213	366	427	79,875
427	489	107,642	427	489	81,270
489	550	110,088	489	550	127,947
550	611	97,856	550	611	101,061
611	670	105,195	611	670	62,212
670	730	112,535	670	730	84,548
0	61	127,213	0	61	79,875
61	123	107,642	61	123	117,379
123	184	110,088	123	184	127,947
184	245	108,865	184	245	101,061
245	305	100,303	245	305	62,212
305	366	97,856	305	366	84,548
366	427	100,303	366	427	56,708
427	489	95,410	427	489	56,708
489	550	100,303	489	550	109,403
550	611	97,856	550	611	73,025
611	670	105,195	611	670	62,212
670	730	112,535	670	730	84,548
730	792	127,213	730	792	56,708
792	854	107,642	792	854	81,270
854	914	110,088	854	914	109,403
914	976	108,865	914	976	73,025
976	1035	100,303	976	1035	62,212
1035	1095	97,856	1035	1095	84,548

Rock Bluff
Springs

Initial Time Step	Final Time Step	Amount m^3/d
0	61	61,331
61	123	41,173
123	184	57,564
184	245	44,500
245	305	38,727
305	366	51,130
366	427	40,806
427	489	41,173
489	550	63,607
550	611	44,500
611	670	38,727
670	730	51,130
0	61	76,866
61	123	51,252
123	184	63,607
184	245	44,500
245	305	46,115
305	366	51,130
366	427	76,866
427	489	51,252
489	550	63,607
550	611	90,126
611	670	46,115
670	730	51,130
730	792	76,866
792	854	51,252
854	914	57,564
914	976	90,126
976	1035	38,727
1035	1095	40,806

Alachua County	Irrigation	Withdrawals	Columbia County	Irrigation	Withdrawals
Initial Time Step	Final Time Step	Amount m^3/d	Initial Time Step	Final Time Step	Amount m^3/d per well
0	61	208	0	61	63
61	123	104	61	123	31
123	184	78	123	184	23
184	245	26	184	245	8
245	305	26	245	305	8
305	366	78	305	366	23
366	427	208	366	427	63
427	489	104	427	489	31
489	550	78	489	550	23
550	611	26	550	611	8
611	670	26	611	670	23
670	730	78	670	730	8
0	61	208	0	61	63
61	123	104	61	123	31
123	184	78	123	184	23
184	245	26	184	245	8
245	305	26	245	305	8
305	366	78	305	366	23
366	427	208	366	427	63
427	489	104	427	489	31
489	550	78	489	550	23
550	611	26	550	611	8
611	670	26	611	670	8
670	730	78	670	730	23
730	792	208	730	792	63
792	854	104	792	854	31
854	914	78	854	914	23
914	976	26	914	976	8
976	1035	26	976	1035	23
1035	1095	78	1035	1095	8

Dixie County	Irrigation	Withdrawals	Gilchrist County	Irrigation	Withdrawals
Initial Time Step	Final Time Step	Amount m^3/d Per Well	Initial Time Step	Final Time Step	Amount m^3/d Per Well
0	61	197	0	61	1,475
61	123	98	61	123	738
123	184	74	123	184	553
184	245	25	184	245	184
245	305	25	245	305	184
305	366	74	305	366	553
366	427	197	366	427	1,475
427	489	98	427	489	738
489	550	74	489	550	553
550	611	25	550	611	184
611	670	74	611	670	184
670	730	25	670	730	553
0	61	197	0	61	1,475
61	123	98	61	123	738
123	184	74	123	184	553
184	245	25	184	245	184
245	305	25	245	305	184
305	366	74	305	366	553
366	427	197	366	427	1,475
427	489	98	427	489	738
489	550	74	489	550	553
550	611	25	550	611	184
611	670	25	611	670	184
670	730	74	670	730	553
730	792	197	730	792	1,475
792	854	98	792	854	738
854	914	74	854	914	553
914	976	25	914	976	184
976	1035	74	976	1035	184
1035	1095	25	1035	1095	553

Levy County	Irrigation	Withdrawals	Suwannee County	Irrigation	Withdrawals
Initial Time Step	Final Time Step	Amount m^3/d Per Well	Initial Time Step	Final Time Step	Amount m^3/d Per Well
0	61	1,529	0	61	106
61	123	765	61	123	53
123	184	573	123	184	40
184	245	191	184	245	13
245	305	191	245	305	13
305	366	573	305	366	40
366	427	1,529	366	427	106
427	489	765	427	489	53
489	550	573	489	550	40
550	611	191	550	611	13
611	670	191	611	670	13
670	730	573	670	730	40
0	61	1,529	0	61	106
61	123	765	61	123	53
123	184	573	123	184	40
184	245	191	184	245	13
245	305	191	245	305	13
305	366	573	305	366	40
366	427	1,529	366	427	106
427	489	765	427	489	53
489	550	573	489	550	40
550	611	191	550	611	13
611	670	191	611	670	13
670	730	573	670	730	40
730	792	1,529	730	792	106
792	854	765	792	854	53
854	914	573	854	914	40
914	976	191	914	976	13
976	1035	191	976	1035	13
1035	1095	573	1035	1095	40

Lafayette County Initial Time Step	Irrigation Final Time Step	Withdrawals Amount m^3/d Per Well
0	61	74
61	123	37
123	184	28
184	245	9
245	305	9
305	366	28
366	427	74
427	489	37
489	550	28
550	611	9
611	670	9
670	730	28
0	61	74
61	123	37
123	184	28
184	245	9
245	305	9
305	366	28
366	427	74
427	489	37
489	550	28
550	611	9
611	670	9
670	730	28
730	792	74
792	854	37
854	914	28
914	976	9
976	1035	9
1035	1095	28

APPENDIX B

OUTPUT OF TOTAL DISSOLVED SOLIDS FOR SIMULATED WELLS AND SPRINGS

Cross City
2010
4,368 kL/d TDS (g/L)

Depth (m)	Time Step (d)	1056	1279	1431	1614	1797
Surface		0.47	0.46	0.46	0.46	0.46
WellScreen		0.47	0.47	0.47	0.47	0.47
-100		0.47	0.47	0.47	0.47	0.47
-150		0.60	0.60	0.60	0.60	0.60
-200		3.00	3.00	3.00	3.00	3.00
-250		3.00	3.00	3.00	3.00	3.00
-300		5.00	5.00	5.00	5.00	5.00
-400		5.00	5.00	5.00	5.00	5.00

Cross City
2030
5,731 kL/d TDS (g/L)

Depth (m)	Time Step (d)	1056	1279	1431	1614	1797
Surface		0.47	0.46	0.46	0.46	0.46
WellScreen		0.47	0.47	0.47	0.47	0.47
-100		0.47	0.47	0.47	0.47	0.47
-150		0.60	0.61	0.61	0.61	0.61
-200		3.00	3.00	3.00	3.00	3.00
-250		3.00	3.00	3.00	3.00	3.00
-300		5.00	5.00	5.00	5.00	5.00
-400		5.00	5.00	5.00	5.00	5.00

HighSprings
2010
1,768 kL/d TDS (g/L)

Depth (m)	Time Step (d)	1056	1279	1431	1614	1797
Surface		0.22	0.22	0.22	0.22	0.22
WellScreen		0.23	0.24	0.24	0.24	0.24
-100		0.23	0.24	0.24	0.24	0.24
-150		0.59	0.59	0.59	0.59	0.59
-200		0.80	0.80	0.80	0.80	0.80
-250		1.00	1.00	1.00	1.00	1.00
-300		1.00	1.00	1.00	1.00	1.00
-400		1.00	1.00	1.00	1.00	1.00

High Springs
2030
2,169 kL/d

TDS (g/L)

Depth (m)	Time Step (d)	1056	1279	1431	1614	1797
Surface		0.23	0.23	0.23	0.23	0.23
WellScreen		0.23	0.23	0.23	0.23	0.23
-100		0.23	0.23	0.23	0.23	0.23
-150		0.50	0.50	0.50	0.50	0.50
-200		1.00	1.00	1.00	1.00	1.00
-250		1.00	1.00	1.00	1.00	1.00
-300		1.00	1.00	1.00	1.00	1.00
-400		1.50	1.50	1.50	1.50	1.50

Newberry
2010
2,347 kL/d

TDS (g/L)

Depth (m)	Time Step (d)	1056	1279	1431	1614	1797
Surface		0.20	0.20	0.20	0.20	0.20
WellScreen		0.23	0.23	0.23	0.23	0.23
-100		0.23	0.23	0.23	0.23	0.23
-150		0.61	0.61	0.61	0.61	0.61
-200		0.81	0.81	0.81	0.81	0.81
-250		1.00	1.00	1.00	1.00	1.00
-300		1.00	1.00	1.00	1.00	1.00
-400		1.03	1.03	1.03	1.03	1.03

Newberry
2030
3,074 kL/d

TDS (g/L)

Depth (m)	Time Step (d)	1056	1279	1431	1614	1797
Surface		0.20	0.20	0.20	0.20	0.20
WellScreen		0.23	0.23	0.23	0.23	0.23
-100		0.23	0.23	0.23	0.23	0.23
-150		0.61	0.61	0.61	0.61	0.61
-200		0.81	0.81	0.81	0.81	0.81
-250		1.00	1.00	1.00	1.00	1.00
-300		1.00	1.00	1.00	1.00	1.00
-400		1.03	1.03	1.03	1.03	1.03

Manatee Springs kL/d

TDS (g/L)

Depth (m)	Time Step (d)	1056	1279	1431	1614	1797
Surface		0.52	0.58	0.56	0.54	0.51
WellScreen		0.52	0.58	0.56	0.54	0.51
-100		0.55	0.59	0.59	0.58	0.57
-150		0.97	1.06	1.06	1.03	1.00
-200		0.97	1.06	1.06	1.32	1.27
-250		1.31	1.39	1.37	1.32	1.27
-300		1.74	1.78	1.74	1.66	1.59
-400		2.93	2.77	2.65	2.51	2.40

Fanning Springs

TDS (g/L)

Depth (m)	Time Step (d)	1056	1279	1431	1614	1797
Surface		0.35	0.35	0.35	0.35	0.35
WellScreen		0.35	0.35	0.35	0.35	0.35
-100		0.35	0.36	0.36	0.36	0.36
-150		0.60	0.59	0.59	0.59	0.59
-200		0.80	0.80	0.80	0.80	0.80
-250		1.00	1.00	1.00	1.00	1.00
-300		1.00	1.00	1.00	1.00	1.00
-400		3.00	3.00	3.00	3.00	3.00

Gilchrist Blue Springs

TDS (g/L)

Depth (m)	Time Step (d)	1056	1279	1431	1614	1797
Surface		0.24	0.23	0.24	0.24	0.24
WellScreen		0.24	0.23	0.24	0.24	0.24
-100		0.25	0.25	0.58	0.26	0.26
-150		0.58	0.58	0.58	0.57	0.57
-200		0.80	0.80	0.80	0.80	0.80
-250		1.00	1.00	1.00	1.00	1.00
-300		1.00	1.00	1.00	1.00	1.00
-400		0.24	0.23	0.24	0.24	0.24

Ginnie Springs

TDS (g/L)

Depth (m)	Time Step (d)	1056	1279	1431	1614	1797
Surface		0.24	0.24	0.24	0.24	0.24
WellScreen		0.24	0.24	0.24	0.24	0.24
-100		0.25	0.25	0.25	0.25	0.25
-150		0.60	0.60	0.60	0.60	0.60
-200		0.80	0.80	0.80	0.80	0.80
-250		1.00	1.00	1.00	1.00	1.00
-300		1.00	1.00	1.00	1.00	1.00
-400		1.00	1.00	1.00	1.00	1.00

Hart Springs

TDS (g/L)

Depth (m)	Time Step (d)	1056	1279	1431	1614	1797
Surface		0.24	0.23	0.23	0.23	0.22
WellScreen		0.24	0.24	0.23	0.23	0.22
-100		0.24	0.24	0.24	0.23	0.23
-150		0.60	0.60	0.60	0.60	0.60
-200		0.80	0.80	0.80	0.80	0.80
-250		1.00	1.01	1.01	1.01	1.02
-300		3.00	3.00	3.00	3.00	3.00
-400		0.24	0.23	0.23	0.23	0.22

Poe Springs

TDS (g/L)

Depth (m)	Time Step (d)	1056	1279	1431	1614	1797
Surface		0.23	0.23	0.23	0.23	0.23
WellScreen		0.23	0.23	0.23	0.23	0.23
-100		0.24	0.24	0.24	0.25	0.25
-150		0.57	0.56	0.56	0.56	0.56
-200		0.80	0.80	0.80	0.80	0.80
-250		1.00	1.00	1.00	1.00	1.00
-300		1.00	1.00	1.00	1.00	1.00
-400		0.23	0.23	0.23	0.23	0.23

Rock Bluff
Springs

TDS (g/L)

Depth (m)	Time Step (d)	1056	1279	1431	1614	1797
Surface		0.24	0.23	0.23	0.23	0.22
WellScreen		0.24	0.24	0.23	0.23	0.22
-100		0.24	0.24	0.24	0.23	0.23
-150		0.60	0.60	0.60	0.60	0.60
-200		0.80	0.80	0.80	0.80	0.80
-250		1.00	1.01	1.01	1.01	1.02
-300		3.00	3.00	3.00	3.00	3.00
-400		0.24	0.23	0.23	0.23	0.22