MODELING REGIONAL SURFACE AND GROUNDWATER HYDROLOGY NEAR THE OKEFENOKEE NATIONAL WILDLIFE REFUGE

by

BRIAN S. LANDERS

(Under the Direction of C. Brock Woodson)

ABSTRACT

The Southeastern Coastal Plain in Georgia has a unique hydrologic system that sustains ecosystems, contributes to water security, and provides recreational opportunities. Important hydrologic features in the study region include the Okefenokee National Wildlife Refuge (ONWR), the Satilla, St. Marys, and Suwannee Rivers, and the underlying surficial and Floridan aquifers. This region is also known for its heavy minerals, which have been sought by the mining industry for decades. As mining in Northeastern Florida progressed into Georgia, concerns were raised regarding large-scale mining adjacent to the federally protected ONWR, suggesting the need to conduct environmental assessments to ensure preservation of Southeast Georgia's water resources and ecosystems. This study serves to contribute to a better understanding of the hydrologic connectivity of surface and groundwater in Southeast Georgia and Northeast Florida by developing a regional groundwater flow model using Visual MODFLOW Flex. The steady-state model developed for this study provides insight into regional hydrology and serves as a basis for assessing hydrologic effects from mining in Southeast Georgia.

INDEX WORDS: Okefenokee Swamp; hydrology; hydrogeology; groundwater; MODFLOW; hydrologic modeling; Floridan aquifer system; surface water groundwater interactions; Southeast Georgia; surficial aquifer; stream-aquifer interactions; wetland-aquifer interactions; finite difference analysis; hydraulic conductivity, groundwater modeling

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ABBREVIATIONS

BAS	Brunswick Aquifer System
BCCU	Bucatunna Clay Confining Unit
DEM	Digital Elevation Model
FAS	Floridan Aquifer System
GIS	Geographic Information System
HMS	Heavy Mineral Sands
LCU	Lower Confining Unit
LFA	Lower Floridan Aquifer
LISAPCU	Lisbon-Avon Park Composite Unit
MAPCU	Middle Avon Park Composite Unit
MCU	Middle Confining and Composite Unit
ONWR	Okefenokee National Wildlife Refuge
SWAT	Soil and Water Assessment Tool
UCU	Upper Confining Unit
UFA	Upper Floridan Aquifer
USDA	United States Department of Agriculture
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
VMF	Visual MODFLOW Flex

CHAPTER 1

INTRODUCTION

The Southeastern Coastal Plain physiographic region of Georgia has a unique hydrologic system that provides vital water resources. With the region's subtle topography and gentle coastward slope, many rivers reach their lower course as they approach Georgia's Atlantic shoreline. This topography promotes the formation of dispersed geographically isolated wetlands and large riparian zones. Several of these surface water features, including the Okefenokee Swamp, Satilla River, Altamaha River, and others, are cherished by Georgia's residents for their unique ecosystems, recreational opportunities, and resources.

Beneath the Southeastern Coastal Plain of Georgia, the shallow surficial aquifer is underlain by the Floridan aquifer system (FAS), which extends into Georgia, South Carolina, Alabama, and Florida (Williams & Kuniansky, 2015). The FAS is one of the most productive aquifers in the world and a vital water supply for nearly ten million people in cities across the Southeastern United States, fulfilling water resource needs for agriculture, recreation, and industrial purposes (Marella & Berndt, 2005). Furthermore, the surficial aquifer, which has a general thickness of less than fifteen meters (fifty feet), also acts as an essential water supply for public and domestic use (Miller, 1990).

In addition to Southeast Georgia's hydrologic resources, the region is rich in mineral resources, specifically heavy mineral sands (HMS), that are sought for their economic value and ability to be processed into zircon and titanium-based products including titanium-dioxide pigments, ceramics, and refractories (Pirkle et al., 2013). The presence of economic deposits of

HMS in the region has drawn the attention of the mining industry, seeking raw minerals for sale and processing into other marketable products. Since the discovery of HMS in Southeast Georgia and Northeast Florida in the early twentieth century, mining companies have been targeting areas of high mineral concentration (>2-3% heavy minerals) for open-pit strip mining operations intent on extracting, refining, and processing raw minerals (Van Gosen & Ellefsen, 2018).

With advancements in modern technology regarding mining efficiency and environmental impact assessment, there has been a push to investigate and ensure environmentally-conscious mining practices so that the ecological integrity and hydrologic systems of Southeast Georgia are preserved. This study focuses on developing a better understanding of the hydrologic connectivity of surface and groundwater systems in parts of Southeast Georgia and Northeast Florida to contribute to a long-term, multi-phase research objective of assessing potential hydrologic impacts of mining operations associated with previous, current, and proposed mine sites.

Outlined herein is the first phase of an ongoing investigation of regional hydrology, with a focus on groundwater flow processes pertaining to the surficial and Upper Floridan aquifer systems and their connectivity to surface water features including the Okefenokee Swamp, Satilla, St. Marys, and Suwannee Rivers, and other regional wetlands and streams. Phase one of this research involves the acquisition of data and resources pertaining to the study region, and the development of a baseline pre-development, steady-state groundwater flow model that serves as a starting point for continued modeling and investigation of select areas of Southeast Georgia and Northeast Florida to further the understanding of regional hydrology and provide a basis for simulating local and regional effects of mining on surface and groundwater systems in the area of interest.

This study employs the use of Waterloo Hydrogeologic's Visual MODFLOW Flex (VMF) groundwater modeling software and ArcGIS for development of a 3D regional groundwater flow model that simulates hydrologic relationships between surface water features, the surficial aquifer system, and the Upper Floridan aquifer (UFA). Ultimately, this research builds upon previous studies of the region while providing new opportunities for investigating specific hydrologic relationships and features of interest. This will contribute to the ability to conduct a risk-informed, performance-based analysis that provides insight into the consequences associated with hydrologic effects of mining operations to identify areas of higher risk and inform future management scenarios.

For this study, a three-layer conceptual framework of regional geologic units is developed, distinguishing the aquifers and confining layers included in the model, where the uppermost layer represents the surficial aquifer, the middle layer represents the regional confining unit, and the bottom layer represents the UFA. The conceptual model is then populated with material properties for each model layer and boundary conditions that dictate flow on the model surface, along model borders, and through model layers. The conceptualized system is then assigned a structured finite-difference grid and converted to a numerical model for steady-state groundwater flow simulations.

The remainder of this report contains an in-depth literature review pertaining to previous investigations of heavy mineral sands and mining operations, the surficial and Floridan aquifer systems, the Okefenokee Swamp hydrologic system, and methods for modeling groundwater and wetland systems; a detailed description of methods used for development of the regional groundwater model; presentation and discussion of model simulation results; primary conclusions drawn from this study; and suggestions for future work in subsequent phases of this research. This report also includes an appendix with an overview on the function and uses of MODFLOW and VMF and supplemental information pertaining to the study area.

CHAPTER 2

LITERATURE REVIEW

2.1 Atlantic Coastal Plain Region

The Atlantic Coastal Plain physiographic province of the United States extends along the Eastern seaboard from New York to Florida below the Piedmont province. The separation of the Coastal Plain and Piedmont regions is indicated by the “Fall Line” which represents the paleoshoreline of the Atlantic Ocean (Shah et al., 2017). The Coastal Plain region is the land between the Fall Line and the current Atlantic shoreline. This region was exposed during ocean level decline in the Pleistocene epoch. Paleo sea-level regression occurred in phases, where variations in global temperature influenced sea levels. Intermittent periods of warming and glaciation throughout the mid-Pliocene and Pleistocene epochs prompted eras of stagnant ocean levels, during which geomorphic processes, including tidal, wind, wave, and fluvial influences, prompted the formation of a series of paleo shorelines and resulting lagoons along the Atlantic Coastal Plain (Rovere et al., 2015; Kellam et al., 1991).

Through erosive processes, disaggregated minerals from inland sources were transported coastward by rivers and streams. Upon deposition into the coastal ocean, tidal, wave, and wind forces sort the sediments by density, where the denser particles settle into areas influenced by the foreshore, including the beach face, sand dunes, tidal lagoons, and barrier islands. Lower-density particles remain suspended and are carried back into the wave zone. This process results in a layering of sands, silts, humates, heavy minerals, and clays in paleo shorelines (Van Gosen & Ellefsen, 2018).

In Southeast Georgia, the remaining paleoshorelines are characterized by a sequence of North-South trending terraces consisting of Pliocene to Pleistocene-aged deposits. Notable paleoshoreline complexes in Southeast Georgia include the Silver Bluff, Princess Anne, Pamlico, Talbot, Penholoway, Wicomico, Okefenokee, Waycross, Argyle, Oaxton, Pearson and Hazlehurst terraces (Figure 2.1) (Kellam et al., 1991). These features exhibit promising mineral concentrations for profitable mining operations.

2.2 Heavy Mineral Mining in Northeast Florida and Southeast Georgia

Heavy mineral mining began in Northeast Florida in 1916 and has persisted since. In 1947, geologists with the DuPont mining company (now Chemours Company) discovered economic deposits of HMS along Trail Ridge, which has been identified as one of the largest HMS deposits in the Southeastern United States (Van Gosen & Ellefsen, 2018). Open-pit mining along the southern portion of Trail Ridge in Northern Florida began in 1949, and has been proceeding northward along the ridge to date (Van Gosen et al., 2014). Trail Ridge is part of the Wicomico paleo barrier island complex and contains an average heavy mineral concentration of four percent (Pirkle et al., 2013; Van Gosen & Ellefsen, 2018). Early geologic exploration of Trail Ridge identified notable concentrations of heavy minerals including ilmenite, zircon, rutile, staurolite, tourmaline, sillimanite, kyanite, corundum, and monazite (Force & Rich, 1989).

Transgression of the paleo Okefenokee Shoreline created a tidal lagoon on the western side of the Trail Ridge complex. The once intercoastal lagoon, referred to as the “Okefenokee lagoon,” gave way to the present-day Okefenokee Swamp basin, where Trail Ridge forms the eastern boundary of the swamp (MacNeil, 1949). Extending over 200 km from near Starke, Florida to near Jesup, Georgia, the Trail Ridge complex is characterized by an average thickness of 11 m, with widths ranging from 1-2 km (Van Gosen & Ellefsen, 2018). Global HMS deposits are typically less than 50 m thick but can exhibit substantial horizontal extents, with footprints achieving areas greater than 10 km^2. Furthermore, HMS deposits are generally overlain by up to 20 m or more of overburden material. With an estimated area of 12.4 km×2.3 km, mining operations on Trail Ridge in Northern Florida have been substantially larger than reported average HMS mine operation extents, which have a median size of roughly 4.2 km×1.8 km (Van Gosen et al., 2014).

As mining operations on Trail Ridge in Northeastern Florida progressed northward, approaching the Georgia-Florida state line, environmental concerns were raised regarding the idea of large-scale mining operations occurring directly adjacent to the federally protected Okefenokee National Wildlife Refuge (ONWR). Trail Ridge serves as the eastern boundary of the Okefenokee Swamp complex and acts as an impoundment, prompting the formation and continued existence of the feature (Force & Rich, 1989). Therefore, environmental specialists, representatives from government agencies, and Okefenokee Swamp enthusiasts fear the potential consequences associated with mine activity along the ONWR border. Specifically, the proposed Twin Pines Minerals, LLC Saunders Demonstration Mine, which would sit approximately 1.6 km (1 mi) from the nearest point of the ONWR, involves groundwater pumping and pit dredging with consequences that are difficult to predict.

The proposed Twin Pines Trail Ridge operation in Charlton County would involve a four-year period of Floridan aquifer withdrawal at rates of 5.45 ML/d (1.44 mgd). Furthermore, the proposed mining plan involves excavating pits at depths up to 15 m (Holt & Tanner, 2020; White & Reeves, 2020). With open pits at depths of 15 m below land surface, there is concern that local water table elevation would exceed the elevation of the pit bottom, creating a hydraulic gradient that lowers the local groundwater elevation when pits are dewatered.

Because of the mine location, this concern extends to the Okefenokee Swamp, raising questions on the hydrologic connectivity of the Okefenokee Swamp and surficial aquifer system, with special consideration regarding the potential for dewatering of wetlands as a result of reduction in water table elevation. Similarly, there is concern that the resulting cone of depression from Floridan aquifer pumping would promote downward leakage from the surficial aquifer and connected surface water features, further contributing to the potential for water level reduction in the Okefenokee Swamp and St. Marys River. A lack of agreed-upon literature that analyzes groundwater contributions to Okefenokee Swamp water balance and its deep aquifer connectivity contributes to the cautious proceedings associated with the permitting of mine activity near the swamp. Alterations to these hydrologic systems could affect wetlands, disrupt ecosystem services, and threaten wildlife both near the site and down river (Southern Environmental Law Center, 2019).

2.3 Surficial Aquifer

The hydrogeologic properties of the surficial aquifer are important for assessing mining impacts on local surface-water features. More specifically, mining effects on nearby wetlands, rivers and watersheds, lakes, and water-table elevations are generally key factors for environmental and hydrologic analysis in strip-mine impact assessment.

It is often assumed that there is little connectivity between the surficial aquifer system and the underlying FAS within the region of interest in Southeast Georgia and Northeast Florida. This is a result of the presence of a thick, lower-permeability confining layer that separates the surficial and Floridan aquifer systems and is considered consistent across Southeast Georgia. Typically, groundwater from the surficial aquifer is thought to recharge the Floridan aquifer in areas where the confining layer is thin or absent. For example, the Gulf Trough is a geologic feature northwest of the study area caused by regional plate tectonics where the clastic sediments of the confining layer were eroded away, leading to greater recharge (Torak et al., 2010).

The surficial aquifer system includes any groundwater flow that occurs between the land surface and the underlying confining unit that restricts vertical flow to deeper, confined aquifers. Surficial aquifers are typically unconfined, where the water table acts as a free water surface of variable elevation, influenceable by climate driven and atmospheric conditions such as pressure, evapotranspiration, and recharge from infiltrated precipitation. The ability of the water table elevation to fluctuate creates a variable vadose zone in which evapotranspiration rates may be higher with increased water table elevation.

Groundwater typically moves quickly downgradient through the surficial aquifer system and is discharged into streams or wetlands. Three subsystems exist within the surficial aquifer system, characterizing different flow processes based on depth and length of flow paths (Figure 2.2). These subsystems include local flow, intermediate flow, and regional flow. Local flow accounts for rapid groundwater movement from a topographic high point or recharge zone to an adjacent low point or discharge zone. Intermediate flow paths are longer and deeper, containing one or more local flow systems between points of recharge and discharge. Regional groundwater flow systems are the deepest of the three subsystems, accounting for subsurface flow from a regional groundwater divide to a regional discharge zone such as a wetland at a topographic minimum (Priest, 2004). With heterogeneous geologic structure and hydraulic properties within the surficial aquifer and confining unit, groundwater may enter or leave the surficial aquifer system as vertical leakage to or from deeper aquifers (Miller, 1990).

In Southeast Georgia, groundwater in the surficial aquifer generally moves coastward or toward the nearest surface water body (Miller 1990). Acting as the surface of the surficial aquifer system, the water table approximates the overlying topography and typically sits less than three meters (ten feet) below the land surface (Torak et al., 2010). The surficial aquifer is characterized by layers of Pliocene to Holocene aged deposits consisting of sand, gravel, clay, and sandy or shelly limestone. The older, deeper layers developed as a result of marine deposits, while the newer, shallow layers come from inland-sourced fluvial deposits (Williams & Kuniansky, 2015).

Surficial deposits in Southeast Georgia have an average thickness of 18 m (60 ft) but tend to thicken coastward (Miller, 1990). Reported transmissivity of the surficial aquifer ranges from 1.51E-05 to 7.2E-03 m^2/s (14 to 6,700 ft^2/d) (Cherry, 2015). Near the city of Brunswick, Georgia, the presence of a syncline, known as the Southeast Georgia Embayment, resulted in the accumulation of a thicker layer of surficial deposits, leading to higher reported transmissivity values for that region (Cherry, 2019). Here, surficial deposits achieve depths of over 61 m (200 ft) (Williams & Dixon, 2015).

In previous groundwater flow models developed by the United States Geological Survey (USGS) for the Brunswick area of Southeast Georgia, the surficial aquifer was assigned an isotropic hydraulic conductivity value of 3.7E-04 m/s (105 ft/d) (Cherry, 2015; Cherry, 2019). With higher hydraulic conductivity, the surficial aquifer is seen as a productive system that serves as an alternative water supply for the FAS. This has led to surficial aquifer withdrawals from agricultural and industrial pumping (Clarke, 2003; Miller, 1990).

The higher hydraulic conductivity of the surficial aquifer system also contributes to the exchange of water from the groundwater system to surface water features. Thus, any concern regarding mine-induced effects to the surficial aquifer system extends to the nearby surface water features that serve as groundwater discharge zones. Water levels in the unconfined surficial aquifer and the surface water bodies to which it discharges, such as streambeds, floodplains, wetlands, and lake beds, are dependent upon recharge from precipitation (Torak et al., 2010; Miller 1990). An estimated twelve percent of annual precipitation infiltrates as recharge into the groundwater system (Joiner & Cressler, 1993).

Infiltrated precipitation either recharges the deeper aquifers through vertical leakage where confining unit thickness and hydraulic properties permit, or it flows through the surficial aquifer system to a discharge zone (Torak et al., 2010). Along with the Okefenokee Swamp and other surrounding wetlands, the study region contains river basins that serve as local, intermediate, or regional discharge zones for the surficial aquifer system. Included in these basins are the Satilla, St. Marys, and Suwannee Rivers, and their floodplains. Smaller tributaries associated with the contributing watersheds for these river systems also occur within the study domain (Williams & Dixon, 2015; Priest & Clarke, 2003).

Along with the aforementioned concerns associated with the mining process, including aquifer pumping and water table reduction from deep open pit dewatering, there is concern that surficial aquifer flow could be disrupted as a result of altered hydraulic properties from mine spoil backfill (Southern Environmental Law Center, 2019). After excavated materials are processed to extract heavy minerals, the remaining sand is returned to the pit from which it was removed. An estimated 98% of excavated materials are returned to the pit (Holt et al., 2020). This process poses concerns that the spoil material may possess a larger hydraulic conductivity than the undisturbed material, altering the flow rate at which groundwater infiltrates and moves laterally through the system. Increased hydraulic conductivity could create an inability for wetlands to form, or an increased discharge rate to nearby discharge zones.

2.4 Confining Unit and Intermediate Aquifers

In Southeast Georgia and Northeast Florida, the surficial aquifer is separated from the deeper, FAS by a low-permeability confining unit consisting of Miocene-aged deposits. In the area of interest for this study, the confining unit is known as the Hawthorn Group, which is the thickest and most extensive unit of Miocene deposits of those sitting above the FAS. The Hawthorn Group is composed of variable clastic, low-permeability rock, serving as the Upper Confining Unit (UCU) of the Floridan aquifer where present (Williams & Dixon, 2015).

The reported vertical hydraulic conductivity of the Hawthorn Group ranges from 1.87E-10 to 1.06E-05 m/s (5.3E-05 to 3 ft/d) (Cherry, 2015). The thickness and extent of the UCU across the entirety of the FAS was characterized by the USGS using information from 4,610 wells. Within the region of interest for this study, the UCU is estimated to be around 122 m (400 ft) thick, but ranges from absent to 305 m (1,000 ft) thick across the extent of the FAS (Williams & Kuniansky, 2015). Within the UCU, the presence of local sand or sandy limestone beds create zones of higher permeability. These tend to exist in areas where the UCU is thicker (Williams & Kuniansky, 2015).

Permeable zones of significant size within the confining layer are generally considered intermediate aquifer systems, sitting between the surficial aquifer and FAS. Within the extent of the FAS, intermediate aquifers exist in Southwestern Florida and coastal Georgia. The intermediate aquifer in coastal Georgia is a productive system known as the Brunswick Aquifer System (BAS), which extends into the northeastern corner of the study domain used for this research (Williams & Dixon, 2015).

The BAS consists of two water bearing zones, referred to as the Upper and Lower Brunswick aquifers, where the Upper Brunswick aquifer is thinner than the Lower, giving the

Lower a greater transmissivity. The Upper and Lower Brunswick aquifers have reported transmissivities of 2.15E-05 to 3.76E-03 m^2/s (20 to 3,500 ft^2/d) and 2.15E-03 to 5.05E-03 m^2/s (2,000 to 4,700 ft^2/d), respectively. The highest values within these ranges for both the Upper and Lower Brunswick aquifers occur as a result of the increased thickness associated with the Southeast Georgia Embayment.

Layers of Oligocene-aged dense phosphatic dolomite and silty clay separate the Brunswick aquifer from the underlying Floridan. This portion of the confining unit has a reported vertical hydraulic conductivity ranging between 8.11E-10 and 1.06E-05 m/s (2.3E-04 and 3 ft/d) (Cherry, 2015). With restrictions on withdrawal from the FAS, the BAS is a major source of water for the Brunswick and Glynn County area. Models developed by the USGS suggest a simulated withdrawal rate of 171 ML/d (45.2 mgd) from the BAS as of 2015 (Cherry, 2019).

2.5 Floridan Aquifer System

The FAS, being one of the most productive aquifer systems in the world and extending over 258,999 km^2 (100,000 mi^2), has been extensively studied, modeled, and characterized by state and federal agencies including the USGS, Environmental Protection Division (EPD), Florida Department of Environmental Protection (FDEP) and others (Bellino et al., 2018). As of the Year 2000, groundwater withdrawal quantities from the FAS ranked fifth largest of the United States' 66 principal aquifers (Bellino et al., 2018). Efforts to better understand the Floridan aquifer hydrologic system, preserve its water supply, and assess impacts from groundwater pumping have led to an extensive collection of literature and datasets pertaining to the system.

To contribute to the understanding and preservation of the Floridan aquifer's groundwater supply, the USGS has assembled numerous reports, datasets, and models that assist in characterizing the system at both the regional and local scales. Included in these resources are digital surfaces and thicknesses of hydrogeologic units, borehole geophysical logs, tabulated Floridan aquifer transmissivity and storage properties, simulated effects of groundwater withdrawal for areas with high pumping rates, notable structural or hydrologic features within the system, land surface hydrologic features overlaying the system, climate conditions above the system, and detailed descriptions characterizing the current state of knowledge of both the system's hydrogeologic setting and its processes regarding groundwater movement, quality, and quantity (Williams & Dixon, 2015; Williams & Kuniansky, 2015; Kuniansky & Bellino, 2012; Williams et al., 2016; Bellino et al., 2018; Cherry, 2019; Torak et al., 2010; Peck & Painter, 2016). The data used by the USGS to produce Floridan aquifer datasets and develop a conceptualization of the system were acquired from over 5,000 wells across Florida and parts of Georgia, South Carolina, and Alabama (Williams & Dixon, 2015).

Like the BAS, the Floridan consists of two distinguished water-bearing zones known as the Upper Floridan and Lower Floridan aquifers. The two zones are separated by a series of discontinuous, subregional confining units that are grouped into a single lithostratigraphic layer referred to as the Middle Confining and Composite Unit (MCU) in USGS Data Series 926 for simplicity in regional representation of the FAS (Williams & Dixon, 2015). The MCU is composed of three specific sub regional units: the Bucatunna Clay Confining Unit (BCCU), the Lisbon-Avon Park Composite Unit (LISAPCU), and the Middle Avon Park Composite Unit (MAPCU), which may be overlapping or discontinuous in parts of the aquifer system.

Each of these units has an associated coverage region, where the BCCU occupies Florida's western panhandle, the LISAPCU occupies the northernmost region of the FAS, and the MAPCU occupies peninsular Florida. Furthermore, variable lithology, degree of confinement, and leakage potential across their respective extents provides a means for further subdivisions within the MCU's composite units. In Georgia's coastal region, the LISAPCU is reported to be a semi-confining unit with high leakage potential, minimizing hydraulic head differences between the Upper and Lower Floridan aquifers (Williams & Kuniansky, 2015).

The UFA is bounded above by the UCU and below by the MCU, and in coastal Georgia, the upper and lower confining entities are the Hawthorn Group and LISAPCU. Consisting of Tertiary carbonate rock, including limestone and dolomite from the Eocene and Oligocene epochs, the UFA is a highly permeable and productive system, supplying an estimated 90% of groundwater withdrawals from the FAS as of the Year 2000 (Bellino et al., 2018; Clarke et al., 2004). In 2005, groundwater withdrawal rates from the UFA in coastal Georgia reached about 1,166 ML/d (308 mgd) (Peck et al., 2011).

Across the extent of the FAS, the UFA ranges in thickness, with a minimum of just a few meters near inland outcrop areas and a maximum of over 518 m (1,700 ft) in Southwest Florida (Williams & Kuniansky, 2015). As a result of UFA zones of varying permeability and thickness, reported UFA transmissivities range from 8.6E-06 to 10 m^2/s (8 to 9,300,000 ft^2/d) across the extent of the FAS (Bellino et al., 2018). In coastal Georgia and adjacent parts of Florida and South Carolina, reported transmissivities measured from 239 wells range from 5.7E-04 to 0.65 m^2/s (530 to 600,000 ft^2/d) (Clarke et al., 2004). Here, the UFA reaches an estimated maximum thickness of 518 m (1,700 ft) (Leeth et al., 2007). Previous USGS groundwater models assessing Floridan aquifer flow conditions assigned an isotropic hydraulic conductivity ranging between

2.65E-03 and 1.20E-02 m/s (750 and 3,415 ft/d) for the region of UFA within the area of study for this research (Cherry, 2019).

The Lower Floridan Aquifer (LFA) is confined above by the MCU where present and below by the Lower Confining Unit (LCU) which serves as the base of the FAS and is composed of lower permeability rock of the late Eocene to late Paleocene epochs (Willaims & Dixon, 2015). The LCU separates the Floridan aquifer from the underlying, predominantly clastic aquifers of Cretaceous to late Tertiary period associated with the Southeastern Coastal Plain aquifer system (Miller, 1992). Using data from geophysical logs and log information from deep oil testing and injection wells, a raster surface file of the LCU was constructed by the USGS and released with Data Series 926. The data used to construct the LCU surface was collected from 488 wells across the FAS (Williams & Dixon).

Like the UFA, the LFA is composed of highly permeable dolomitic limestones of the early and middle Eocene. The LFA also exhibits a range of thickness and permeability across its extent, creating zones with varying degrees of productivity (Cherry, 2019). Across the extent of the FAS, the LFA ranges in thickness from just a few feet near the extreme margins of the inland updip limit to over 671 m (2,200 ft) in coastal areas (Williams & Kuniansky, 2015). In coastal Georgia near the city of Brunswick, the LFA reaches thicknesses of more than 610 m (2,000 ft) as it thickens towards the Southeast Georgia Embayment (Cherry, 2015).

Though generally less transmissive than the UFA, the LFA still exhibits high transmissivity with a reported range of 1.40E-04 to 0.54 m^2/s (130 to 500,000 ft^2/d) based on 64 aquifer tests (Williams & Kuniansky, 2015; Kuniansky & Bellino, 2012). The LFA has historically been pumped less than the UFA because of well depth requirements and risk of saltwater intrusion. Because the LFA is deeper and sits at or below sea level, pumping from the

LFA can cause increased concentrations of saline water contamination. This also poses risks to the UFA and intermediate aquifers in areas where the MCU is leaky or discontinuous (Cherry, 2019).

In many areas across the FAS, discontinuous or leaky sections of the MCU enable the UFA and LFA to effectively act as one unit (Williams & Kuniansky, 2015). Storage properties for the FAS were reported in USGS Data Series 669 based on degree of confinement, where unconfined areas had a storage coefficient ranging from 2.6E-05 to 0.05, thinly confined areas had a storage coefficient ranging from 1.3E-05 to 0.39, and confined areas had a storage coefficient ranging from 3.0E-09 to 0.41 (Kuniansky & Bellino, 2012).

Furthermore, the FAS consists of eight major groundwater basins distinguished by groundwater divides (Figure 3.3) that are consistent with reported potentiometric surface contours of the UFA (Williams & Kuniansky, 2015). Each basin has a unique conceptual groundwater flow system depending on its degree of confinement, pumping rates, hydraulic gradient, geologic structural features, heterogeneity in properties, presence of saline water, and other factors (Bellino et al., 2018). The eight subregional groundwater basins of the FAS are the Panhandle, Dougherty Plain-Apalachicola, Thomasville-Tallahassee, Southeast Georgia-Northeast Florida-South South Carolina, Suwannee, West-central Florida, East-central Florida, and South Florida basins.

The area of interest for this research falls within the Southeast Georgia-Northeast Florida-South South Carolina basin, where groundwater moves in a general coastward direction or toward major pumping centers (Bellino et al., 2018). This groundwater basin is confined over the majority of its extent, and it extends a minimum of 89 km (55 mi) offshore between Brunswick and Savannah. Unconfined areas of this basin occur mostly at inland updip limits allowing direct recharge from the surficial aquifer. Recharge also occurs from the surficial aquifer as leakage through the UCU. Additionally, pumping wells and coastal lowland areas promote diffuse upward leakage, discharging groundwater from the system (Bellino et al., 2018).

2.6 Wetlands and the Okefenokee Swamp

2.6.1 Background and Relevance

With wetlands occupying almost 50% of the land cover within the region of interest for this research, understanding wetland contributions to surface and subsurface hydrologic processes is essential for analyzing and modeling the regional hydrologic system and assessing potential impacts of open-pit mining operations (USGS & MRLC, 2019). The wetland land cover types within the study region are a combination of woody wetlands (approximately 91% of total wetland coverage) and emergent herbaceous wetlands (approximately 9% of total wetland coverage). Woody wetlands include inland geographically isolated wetland systems and riparian wetlands associated with river floodplains. Woody wetlands are the dominant wetland type in this study that are close to mining operations and have strong linkages to the water table, making them at higher risk of short-term hydrologic impacts.

Included in the woody wetlands land cover classification is the majority of the Okefenokee Swamp, which accounts for over 41% of all wetlands within the study region. Most emergent herbaceous wetlands in the study region occur near the coast as tidal marshes or estuaries, owing their hydrologic influence largely to climatic factors, tidal effects, and incoming streamflow (FGDC, 2013), making them less susceptible to immediate hydrologic impacts from mining operations. By evaluating the interconnectivity of the region's wetlands, inflowing and outflowing streams, the surficial aquifer, and the deeper aquifer system, a better understanding of potential mine activity impact propagation can be reached.

2.6.2 Introduction

Wetlands are unique environments that not only provide sanctuary for a diverse collection of life but are essential for the regulation of both water quality and quantity in surface and subsurface flows at the watershed scale (FGDC, 2013). However, wetland loss and degradation as a result of natural and anthropogenic influence is a significant issue across the globe (Restrepo et al., 2005). As of 2009, up to 33% of global wetlands have been lost (Hu et al., 2017). Therefore, wetland protection and restoration has been of high importance as researchers seek to better understand, model, and predict wetland behavior in response to altered land use in and adjacent to wetland environments.

In order to successfully generate a model capable of both accurately simulating wetland hydrologic characteristics and assessing the risks associated with wetland loss, it is essential to first understand the role of wetlands in a watershed and its subsurface. The purpose of this section is to develop a better understanding of wetland connectivity to rivers, shallow groundwater, and deeper aquifer systems to better incorporate these processes into a regional model of the integrated surface and subsurface hydrologic systems in the area of interest in Southeast Georgia and Northeast Florida. Doing so will promote a greater ability to predict environmental impacts, preserve wetland resources, and influence land development decisions.

2.6.3 Wetlands and Their Classifications

The term "wetland" is broadly used to define land cover that represents the convergence of terrestrial and aquatic environments. Wetlands typically involve a surface or near-surface water table that permits seasonal or permanent coverage of a shallow layer of surface water above a saturated soil media, and they are identified by distinguishing characteristics related to hydrology, vegetation, and soils (U.S. EPA, 2002). With variable characteristics, wetlands can be further classified into several subcategories depending on their hydrology, geographic location, vegetation, and substrate, lending to a higher level of complexity in generalizing wetland characteristics for hydrologic analysis. Wetlands are commonly classified as one or a combination of, Palustrine, Lacustrine, Riverine, Estuarine, or Marine systems (USGS, 1996). Each of which provides essential ecosystem services pertaining to flood control, pollution control, and ecological stability (FGDC, 2013). The Okefenokee Swamp system is generally categorized as a Palustrine wetland, or depressional, geographically isolated wetlands that are sustained in large by precipitation, with relatively minor contributions from upland streams (USGS, 1996).

2.6.4 Water Balance

Although it is useful to group geographically isolated wetlands into a subcategory of Palustrine wetlands, depressional wetland systems still demonstrate a high level of variability. Further classifications are distinguished based on characteristics including topography, vegetation, inlet and outlet streamflow, groundwater connectivity, physiochemical soil properties, physiochemical water properties, geology, and climate (Brinson, 2016). While topography and streamflow are important factors in understanding the movement of surface water into and out of a geographically isolated wetland, the other aforementioned characteristics define the storage and subsurface exchange capabilities between a wetland system and its watershed. Cumulatively, these factors can be assessed and used to define the overall water balance of a wetland system, which can be described by the relation:

$$\Delta V = P - ET + Q_{surf} - Q_{spill} \pm Q_{local} \qquad \textbf{(Equation 2.1)}$$

where ΔV is the change in water volume of the wetland, P is precipitation, ET is evapotranspiration, Q_{surf} is surface runoff from upland areas, Q_{spill} is surface outflow from the wetland, and Q_{local} is groundwater flow into or out of the system. All terms are in units of m^3/day (Evenson et al., 2018).

For wetland water balance analysis, certain storage volume contributions can be more easily quantified than others. Both global and national datasets provide widely available weather, streamflow, soil, land elevation, and land use data that can greatly help with accuracy in assessing wetland storage contributions. While observed data from these sources provides insight into direct contribution from precipitation and surface flows, evapotranspiration and groundwater exchange require further analysis for accurate representation in wetland hydrologic models. Evapotranspiration and seepage are dominant factors in wetland storage losses but are often difficult to quantify because of the complexity of their governing processes and variability in wetland structure (Hill & Neary, 2008).

2.6.5 Evapotranspiration

Evapotranspiration encapsulates climate driven losses from the system to the atmosphere from both evaporation and transpiration. Climatic factors that influence evapotranspiration rates include temperature, solar radiation, humidity, wind, atmospheric pressure, and precipitation (Hill & Neary, 2008). Other factors that further influence evapotranspiration losses within a watershed include land use, vegetation, and soil moisture (Hill & Neary, 2008). Therefore, a given watershed will have a large amount of variability in evapotranspiration losses with climatic fluctuations at the daily, diurnal, and seasonal time scales (USGS, 1996). Because of this variability, evapotranspiration losses must be considered over a multiyear period, when using the water balance method for transient conditions, to identify trends and limit uncertainty (Yin & Brook, 1992).

While evaporation can be physically observed and measured, transpiration rates are much more difficult to estimate (USGS, 1996). With advancements in satellite imagery and remotely sensed data availability, hydrologic modeling is widely accepted as the leading approach for estimating evapotranspiration (Abiodun et al., 2018). Observations of evapotranspiration trends in hydrologic modeling have shown correlations between evapotranspiration, groundwater recharge, and water table elevation in wetlands, where areas with high evapotranspiration have less groundwater recharge and a lower water table compared to areas with low evapotranspiration and more groundwater recharge (Neff et al., 2019).

2.6.6 Groundwater Exchange

The relationship between evapotranspiration and water table elevation is largely a factor of subsurface soil properties and geologic structure (Neff et al., 2019). Groundwater flow contributions are essential for wetland water balance analysis, especially in the case of Palustrine wetlands with small contributions from inflowing streams. For wetland systems primarily sustained by precipitation, understanding the geophysical properties of the underlying strata can provide insight into the movement of groundwater through the system in response to surface water infiltration (Rahman et al., 2016).

Directly beneath the ground surface is the unsaturated zone, where surface water drains after a rainfall event. The water table occurs at the interface between the unsaturated and the underlying saturated zones. The unconfined surficial aquifer system begins in the saturated zone. Here, groundwater is able to move laterally through permeable media in the direction of down sloping hydraulic gradient. Water in the shallow aquifer can also be drawn upward through root uptake and evaporation or leak downward through the underlying confining unit.

Wetland systems are unique in that they have little or no unsaturated zone, with water tables above or near the soil surface, providing more opportunity for seepage, lateral flow, and evapotranspiration. Beneath the shallow aquifer, the lower permeability confining layer separates the surficial aquifer from the deep, or confined, aquifer system (USGS, 1996). Groundwater exchange between the shallow and deep aquifers is dependent on the permeability, consistency, and extent of the confining layer, making it an important consideration for wetland storage and drainage.

Like evapotranspiration, groundwater flow can be difficult to quantify as it is characterized by hydrogeologic properties that may vary substantially at small spatial scales (Stolt et al., 2001). While groundwater flow is heavily dictated by climate, hydraulic gradient, and wetland stage, knowledge of the underlying material and its properties is essential for understanding and modeling groundwater interactions between a wetland system and its watershed. Specifically, the vertical and horizontal hydraulic conductivity (the ease at which water passes through the pore spaces in soil and rock) of the subsurface media must be known or estimated with high accuracy to properly determine groundwater flow contributions into or out of a wetland (Restrepo et al., 1998).

However, wetland soil samples suggest that particle size distribution can vary drastically both across a wetland and within the soil column (Stolt et al., 2001). Therefore, hydraulic conductivity must be parameterized at a high resolution to accurately simulate groundwater flow in wetland modeling. Furthermore, wetland systems can serve as both groundwater discharge and groundwater recharge areas depending on watershed topography, wetland condition, climate, aquifer pumping, and local hydrogeology (USGS, 1996). Depressional wetlands often act as a groundwater sink, as groundwater flows down-gradient from the surrounding uplands when wetland stage is low. Alternatively, vertical leakage from wetland storage can recharge the underlying shallow or deep aquifer, especially in circumstances when aquifer head is low from seasonal fluctuation or aquifer pumping (Golden et al., 2014; USGS, 1996). Conversely, wetlands can be formed by upward leakage of groundwater from underlying aquifer systems in cases when hydraulic pressure and permeability allow for artesian conditions.

2.6.7 Modeling Wetlands

With subsurface flows being an important aspect of wetland water balance analysis and wetland function at the watershed scale, developing a hydrologic model that accurately represents surface flows, subsurface flows, and their interactions is key in fully understanding the system behavior and response to changes in land cover (Wilsnack et al., 2001; Kazezyılmaz-Alhan et al., 2007). However, groundwater and surface flow models have generally been developed independently (Restrepo et al., 1998). Several studies have used modified surface or groundwater flow models to represent wetland structure and surface-subsurface interactions within a watershed.

The Soil and Water Assessment Tool (SWAT) is a semi-distributed watershed-scale modeling software that has been widely adopted for analyzing wetland function at the watershed scale (Lee et al., 2018). The extensive literature on SWAT applications, including studies that analyze wetland loss impacts on downstream flows, nutrient loading, and sediment transport, make SWAT an appealing approach for further investigation of wetland hydrology (Lee et al., 2018). Though such studies have successfully used the SWAT model to incorporate wetlands in watershed modeling, the default SWAT modules for wetland processes tend to oversimplify wetland geospatial representation and hydrologic interactions between a wetland and its surroundings (Lee et al., 2018). Therefore, the application of the SWAT model for wetland-rich landscapes requires modifications to the default SWAT wetland modules to better incorporate wetland structure and distribution, inter-wetland hydrologic processes, and hydrologic interactions between wetlands and their corresponding watershed (Lee et al., 2018; Evenson et al., 2018; Rahman et al., 2016).

Another common approach for simulating wetland hydrologic processes that better incorporate subsurface exchange is the use of groundwater modeling software. MODFLOW is a "quasi-industry standard" distributed, finite-difference model created by the USGS for simulating three-dimensional groundwater flow (Golden et al., 2014). For modeling groundwater flow in wetland-rich landscapes, researchers have successfully developed a modified wetlands package for MODFLOW (Restrepo et al., 1998; Wilsnack et al., 2001). However, applications for the MODFLOW model are limited because like other groundwater models, MODFLOW tends to oversimplify surface processes including infiltration, surface runoff, and land-atmosphere interactions (Bailey et al., 2016; Wilsnack et al., 2001; Kazezyılmaz-Alhan et al., 2007).

With the subsurface flow limitations of semi-distributed surface-based watershed models such as SWAT, and the oversimplified surface processes of groundwater flow models such as MODFLOW, a coupled surface-subsurface modeling approach is identified as a promising method for simulating wetland hydrology (Golden et al., 2014). The implementation of coupled model components has become a common practice for modeling scenarios in which a single model cannot fully simulate surface-subsurface interactions (Getahun & Demissie, 2018). The need for a coupled modeling approach for accurately simulating surface-groundwater interactions led to the increased development of such models, including the SWAT-MODFLOW coupled model.

The integrated SWAT-MODFLOW model mitigates the individual limitations of each of the two models, better representing actual hydrogeological processes (Chunn et al., 2019). The SWAT model uses a semi-distributed modeling approach for delineating hydrologic response units (HRUs) based on areas of similar topography, soil types, and land use, which can inaccurately lump subsurface properties such as hydraulic conductivity. By coupling SWAT and MODFLOW models, heterogeneity in hydrogeologic properties can be better distributed into grid cells of higher resolution (Kim et al., 2008; Golden et al., 2014). The SWAT-MODFLOW model is publicly available, making it an appealing tool for modeling surface-groundwater interactions (Chunn et al., 2019). While there is a wealth of literature discussing SWAT-MODFLOW applications, few studies have looked at its use for wetlands specifically. Therefore, further study of its use for wetland specific cases may require the additional, previously discussed modifications to the default SWAT and MODFLOW models.

2.6.8 Okefenokee Swamp Case Study

For the case of the Okefenokee Watershed and surrounding areas of interest, both surface-based and groundwater-based modeling approaches would greatly contribute to the overall understanding of the hydrologic system. A coupled SWAT-MODFLOW modeling approach could be a viable option for simulating surface-subsurface interactions and predicting the effects of land use change on hydrologic processes. To accurately build a model for the Okefenokee Swamp Watershed, the physical characteristics of the area must be identified and incorporated into the model boundary conditions.

The Okefenokee Watershed is a 3702 km^2 area in which 51% is occupied by the Okefenokee Swamp and 49% is occupied by forested uplands that drain into the swamp through surface and subsurface flows based on precipitation (Mao et al., 2013; Patten & Matis, 1982).

The Okefenokee Swamp is bounded on the east by Trail Ridge (USGS, 1996; The Geological Society of America, 1986). Beneath the Okefenokee is the shallow surficial aquifer which is separated from the underlying FAS by the confining layer, regionally known as the Hawthorn Group. Furthermore, the Okefenokee Swamp serves as the headwaters for the St. Marys and Suwannee rivers. In the early 1960s, a dam, known as the Suwannee River Sill, was constructed at the Swamp's outlet to the Suwannee River to prevent fires and retain the swamp's water during seasonal lows (Loftin, 1997). These components of the Okefenokee Swamp system are important for assessing the area's water balance.

Previous studies have been conducted to assess the Swamp's hydrology, with primary emphasis on surface-based processes and the effects of the Suwannee River Sill. These studies have concluded that precipitation and evapotranspiration largely dictate water balance inputs and outputs, respectively. An estimated 72-78% of swamp input comes directly from precipitation, with the remainder coming mostly from streamflow from uplands (Brook & Sun, 1987). Furthermore, evapotranspiration accounts for an estimated 80% of total losses from the swamp, with the remainder owing largely to outflow from rivers (Loftin, 1997).

However, when it comes to groundwater flow into and out of the system, there seems to be discrepancy in the overall significance of groundwater on the system's water balance. Several studies state that groundwater flow is insignificant for water balance analysis, with an estimated 1-8% of total swamp input coming from groundwater (Brook & Hyatt, 2013; Brook & Sun, 1987; Loftin, 1997). Other studies suggest that there is a strong relationship between surface and subsurface flows in the area, making them an important component of the system's water balance (Patten & Matis, 1982; Mao et al., 2013), with Trail Ridge being a significant source of groundwater flow into the swamp (Geological Society of America, 1986). Additionally, fluxes in the Okefenokee's water storage correspond to fluxes in the underlying Floridan Aquifer with an approximate lag of one month, suggesting that vertical leakage from the swamp to the deep aquifer is a relevant loss consideration for water balance analysis (Kitchens & Rasmussen, 1995). Conversely, some argue that with a thickness of greater than 91 m (300 ft), the Hawthorn Group underlying the Okefenokee basin completely isolates the Floridan aquifer, allowing extremely low to no potential for vertical exchange between groundwater in the surficial aquifer and the UFA (Torak et al., 2010).

While these studies provide useful information on the hydrologic interactions in the Okefenokee watershed, further analysis with modern modeling techniques and data sources could supplement their findings to better quantify the role of groundwater in the Okefenokee Swamp system and its surroundings. The majority of the previous studies on the Okefenokee Swamp and its corresponding watershed discussed herein were conducted in the 1980s and 1990s. With most of the previous studies for this area being focused on surface-based processes, the development of a groundwater flow model with higher data resolution and modern modeling software could provide new insight and expand upon previously established conclusions regarding surface water and groundwater exchange within the hydrologic system.

Furthermore, a regional groundwater-focused model would better capture the potential effects of mining operations on the Okefenokee Swamp and other nearby wetlands. With the current and proposed mining operations being a distance away from the Okefenokee Swamp, any changes to the swamp's hydrologic system would likely be groundwater-induced through aquifer pumping and water table alteration. Therefore, a groundwater modeling approach using MODFLOW has been selected for initial model development and hydrologic simulations for this study, providing a basis for a coupled surface-subsurface flow model and opportunities for future expansion on the scope of this research.

2.7 Groundwater Modeling Overview

Process-based numerical groundwater modeling is a powerful tool that allows researchers to develop a quantitative framework of a groundwater system to draw conclusions and answer questions pertaining to hydrologic systems and their responses to stresses. Furthermore, it provides the opportunity to evaluate measured field data within the broader context of the system as a whole (Beddows, 2016).

Applications for mathematical groundwater modeling have evolved substantially since its earliest uses in the late 1800s. Since the development and widespread availability of high-speed digital computers in the 1960s, numerical modeling of groundwater flow has been the primary approach for studying groundwater systems (Wang & Anderson, 1982). With modern modeling software and data collection techniques, groundwater modeling applications have expanded from basic flow characterization and water resource assessment to a wide variety of environmental and industrial scenarios pertaining to water quality and quantity.

Modern groundwater modeling applications include characterization of aquifer systems, aquifer development impact assessment, water resource availability investigation, production well yield and sustainability assessment, solute transport simulation, groundwater quality remediation design, saltwater intrusion risk assessment and mitigation, delineation of well capture zones and wellhead protection areas, optimization of construction dewatering plans, groundwater response to land development, and more (Jakab & Doerken, 2021). Each of which is dependent on the availability or collection of field data pertaining to the site and system of interest.

While field data is useful in itself, applying scattered field data to a numerical model allows for a deeper understanding of the relationships between data sites and their context within the bigger picture. Like any numerical model based on real-world conditions, development of a groundwater model's conceptual framework and simulation reliability depends on the quantity and quality of the input data, which dictates the capacity at which a model resembles its representative system (Wang & Anderson, 1982). However, numerical groundwater modeling comes with a unique set of challenges because of its dependency on data that is expensive to collect and difficult to observe at high resolution.

The bulk of groundwater system analysis requires knowledge of the hydrogeologic processes occurring beneath land surface, limiting observation-based conceptualization of the system to point-specific field measurements. While spatial distribution of field data is continuously improving with advancements in data collection techniques such as remote sensing, many groundwater study sites are limited to data collected from point-specific sources such as groundwater observation wells, geophysical logs, and lithologic borehole samples, making it difficult to capture hydrogeologic heterogeneities within the system, especially depending on the scale of the model domain (Brandenburg, 2020).

Depending on the scope of the project, these data types can be expensive to collect, requiring expertise in well drilling, geologic characterization from borehole cuttings, and geophysical borehole logging where data is not already available. The point-based nature of typical groundwater model input data leads to a dependency on assumptions for characterization of much of the hydrologic and geologic properties of the system, which are often derived through interpolation techniques between measured values (Brandenburg, 2020).

The overall function of mathematical groundwater modeling is to use model inputs to obtain analytical or numerical solutions to the governing partial differential groundwater flow equation across the flow domain. The fundamental groundwater flow equation embedded in numerical groundwater modeling software code is based on a combination of the continuity principle (conservation of mass) and Darcy’s Law. For fluids, the conservation of mass principle states that the change in mass storage of an elemental control volume is equal to the difference of incoming and outgoing fluxes as shown in Figure 2.4 (Jakab & Doerken, 2021).

For density-dependent transient groundwater flow, the continuity equation is:

$$-\frac{\partial(\rho q_x)}{\partial x}-\frac{\partial(\rho q_y)}{\partial y}-\frac{\partial(\rho q_z)}{\partial z}=\rho S_S\frac{\partial h}{\partial t} \qquad \textbf{(Equation 2.2)}$$

Where: ρ = fluid density [mass/volume]
q = specific discharge [volume/time/area]
S_S = specific storage [1/length]
h = hydraulic head [length]

For water, which is essentially incompressible, the fluid density is constant and can be removed from the equation, yielding:

$$-\frac{\partial(q_x)}{\partial x}-\frac{\partial(q_y)}{\partial y}-\frac{\partial(q_z)}{\partial z}=S_S\frac{\partial h}{\partial t} \qquad \textbf{(Equation 2.3)}$$

Darcy’s Law is an empirical equation developed by Henry Darcy (1856) for characterizing fluid flow through porous media. Through lab experiments that analyzed the relationship between fluid flow rate and head difference across sand filters, Darcy concluded that volumetric flow rate per unit area in any direction is directly proportional to change in head, inversely proportional to change in length, and dependent on a constant of proportionality (hydraulic conductivity) (Jakab & Doerken, 2021).

The resulting equation is:

$$\boldsymbol{q = -K\frac{\Delta h}{\Delta l}} \qquad \textbf{(Equation 2.4)}$$

Where: q = specific discharge [volume/time/area]

K = hydraulic conductivity [length/time]

Δh = change in head [length]

Δl = change in length [length]

Substituting Darcy's Law into the continuity equation yields the governing partial differential groundwater flow equation that is solved numerically in groundwater modeling software:

$$\boldsymbol{\frac{\partial(K_{xx}\frac{\partial h}{\partial x})}{\partial x} + \frac{\partial(K_{yy}\frac{\partial h}{\partial y})}{\partial y} + \frac{\partial(K_{zz}\frac{\partial h}{\partial z})}{\partial z} + W = S_S\frac{\partial h}{\partial t}} \qquad \textbf{(Equation 2.5)}$$

Where: K = hydraulic conductivity [length/time]

h = hydraulic head [length]

W = contributions from sources and sinks [1/time]

S_S = specific storage [1/length]

For steady-state analysis, all unsteady (time-variable) terms can be removed from the equation, yielding:

$$\boldsymbol{\frac{\partial(K_{xx}\frac{\partial h}{\partial x})}{\partial x} + \frac{\partial(K_{yy}\frac{\partial h}{\partial y})}{\partial y} + \frac{\partial(K_{zz}\frac{\partial h}{\partial z})}{\partial z} = 0} \qquad \textbf{(Equation 2.6)}$$

While there are several other equations embedded in the boundary condition subroutines of groundwater modeling code, as well as different governing equations for modeling contaminant transport, the equations listed above are the backbone of all numerical groundwater flow models. The numerical solutions calculated by groundwater modeling software depend upon the user-inputs that define the structure and properties of the system under investigation.

2.7.1 Defining Model Domain

The first step in groundwater model development is establishing the horizontal and vertical extents of the model domain boundary. Model boundaries can be developed for both local or regional simulations depending on the underlying research questions. In both cases, the model boundary should encompass all surface and subsurface features that have influence on the system or process under investigation. The model boundary should be developed to approximate natural hydrologic boundaries that constrain the groundwater system on the top, bottom, and sides of the study domain.

Natural hydrologic boundaries that are often used for model boundary delineation are geologic divides, surface water divides, and groundwater divides. By selecting a model boundary that approximates these features, the model is given a set of known conditions at the model edges that provide the basis for numerical simulations within the model interior. Careful consideration in selecting a model boundary improves the accuracy of model results, reduces complexity at model boundaries, and makes subsequent steps in model development less challenging (Jakab & Doerken, 2021).

2.7.2 Define Geologic Structure

After data is acquired and a model boundary has been identified, the next step in developing a groundwater flow model involves delineating a conceptual framework of the system's geologic structure. This includes characterization of the structural surfaces of each geologic horizon to be included in the vertical extent of the model domain in a 3D modeling environment. Typically, this is done by interpreting point-specific lithological and geophysical logs from boreholes, developing cross sections between data points, and extending cross-section lithology across the model domain through interpolation techniques.

Accurate characterization of the geologic horizons of a groundwater system is essential for successful model development, as the zones between the horizons become the water-bearing or confining units that dictate groundwater movement through the system. Ideally, structural surfaces are developed from datasets consisting of evenly spaced data points, where a larger number of data points increases the accuracy of the interpolated surface contours. In this case, it is less likely that a structural discrepancy, such as a fault or lineament, will go unnoticed (Brandenburg, 2020). After developing the horizon surfaces and assigning them a reference elevation, the thickness of water bearing zones and confining units within the system can be calculated by subtracting layer elevations. The procedure discussed herein was employed by the USGS in development of the structural surfaces associated with the FAS in USGS Data Series 926 (Williams & Dixon, 2015).

2.7.3 Define Hydrogeologic Properties

The next step in developing a groundwater flow model is parameterizing the zones between geologic surfaces by identifying and assigning hydrogeologic properties to the layers. By assigning layer material properties, the modeler provides the model with parameters necessary for solving the governing partial differential groundwater flow equation that serves as the basis for numerical model simulations. Properties of aquifers and aquitards are measured, estimated, or calculated for model input through lab experiments and empirical methods (Woessner & Poeter, 2020).

Again, many field measurements used to estimate hydrogeologic properties can only assess properties at a single point within the system. Such methods include aquifer pump tests, permeameters, and analysis of groundwater level response to natural perturbations. Properties measured at individual sites are extended across the model domain through interpolation techniques (Brandenburg, 2020). Aquifer properties are often heterogeneous both horizontally and vertically within model layers, making them difficult to quantify at high resolutions across a model domain. Property distribution is often simplified to a higher level of homogeneity for model input, with the ability to be refined during model calibration. A list of aquifer properties for groundwater system conceptualization and model development is provided in Table 2.1.

Material property inputs for groundwater flow modeling depend on the type of model under development. Specifically, different parameter sets are required for steady state model simulations (time-independent) and transient model simulations (time-dependent) (Jakab & Doerken, 2021). Steady state analysis provides insight into long-term average conditions of the system, with results that represent the system's average state at a single point in time. Transient analysis adds complexity, requiring time-series data that provides insight into system dynamics, encompassing variable conditions such as seasonal fluctuations, Earth tides, climate driven factors, and variation in aquifer pumping rates. While transient simulations provide a better understanding of a system's response to stresses, they induce challenges with model convergence and stability, emphasizing the importance of model calibration and uncertainty analysis (Moore & Doherty, 2021).

2.7.4 Define Boundary Conditions

After material properties are identified and applied to their respective model zones, the next step in groundwater model development is establishing the initial and boundary conditions for the simulation domain. Proper selection of initial and boundary conditions is considered the most important aspect of groundwater modeling (Franke et al., 1987). Identifying and characterizing model boundary conditions is made easier when a model boundary is developed to approximate natural hydrologic or geologic features. Numerical groundwater models take user-defined property inputs to calculate the partial differential groundwater flow equation. By establishing model boundary conditions, the groundwater flow equation becomes a boundary-value problem, where specified boundary and initial conditions must be satisfied within the model's solution to the governing partial differential groundwater flow equation at all points within the simulation domain (Franke et al., 1987). Essentially, boundary and initial conditions provide the model with a starting point and constraints for solving the governing equations. This is what gives groundwater models for different systems unique solutions. Initial conditions are those, such as initial heads and storage, that dictate the baseline scenario of a model during the first time step (for transient models). Boundary conditions are those that provide the model with known hydrologic information at certain locations in or around the model domain. A list of common groundwater modeling boundary conditions is provided in Table 2.2.

2.7.5 Simulate Numerically

Once the structural framework, material properties, and boundary conditions have been established for a groundwater model, the conceptual model framework is complete and ready for numerical simulations. Different numerical groundwater modeling software provide a variety of options for solution techniques and solver packages. Numerical solutions to the groundwater flow equation require a gridded model domain, where the equation can be solved to identify fluid flow and hydraulic heads through each grid cell within the domain. By creating a model grid, known distances or volumes between cells are substituted into the groundwater flow equation to replace the infinitesimal differences associated with conductivity and head partials, reducing the unknowns and providing a solution basis for the selected solver.

Common groundwater model grid types and solution techniques include the finite difference, finite element, and finite volume methods. Each of these methods have certain advantages and disadvantages associated with them. For example, finite element and finite volume models provide better grid cell discretization for refining grid size around areas of interest. However, they typically involve complex solutions and higher computational cost, whereas finite difference models provide simple solutions and are relatively computationally inexpensive, but have inefficient discretization capabilities (Jakab & Doerken, 2021). Ultimately, the type of model grid and solver technique is left up to the modeler and will depend on the overall goals and scale of the model.

2.7.6 Evaluate Simulation Results

The final step in groundwater model development takes place after the model has successfully converged and provided simulated results for the study system. Because models are designed to approximate natural systems, model results must be analyzed and compared to real-world observed measurements to assess the accuracy and reliability of the model. This process is known as model calibration and validation, which essentially quantifies the level of trust that can be assigned to model results. Model calibration can be done through computer-assisted software packages, or manually by the modeler. This process involves inputting observed data collected from field measurements, including hydraulic heads in observation wells or gaged streamflow, into the model domain to provide a basis for comparing simulated values to observed values and evaluating model uncertainty and error. The goal of model calibration is to iteratively adjust model parameters until a certain objective function criterion is achieved, indicating a satisfactory comparison between observed and simulated values (Jakab & Doerken, 2021).

In many cases, model calibration is supplemented by sensitivity analysis, which provides the modeler or computer-assisted calibration software with a basis for adjusting parameters for model calibration. Sensitivity analysis is most effective when assisted by computer software, in which iterations of model simulations are run and compared to observed values to develop an understanding of model output sensitivity and uncertainty with respect to adjustments in certain parameters. This process gives the modeler an idea of which parameters should receive more weight and the range at which specific parameters should be adjusted for improving calibration results (Jakab & Doerken, 2021). After model results are calibrated such that an objective function is satisfied, the model can be validated by comparing simulated model results to observed conditions for a time period that has not yet been simulated. This proves that the calibrated model has acceptable performance for scenarios and stresses that have not yet been modeled and were not included in calibration.

Figures

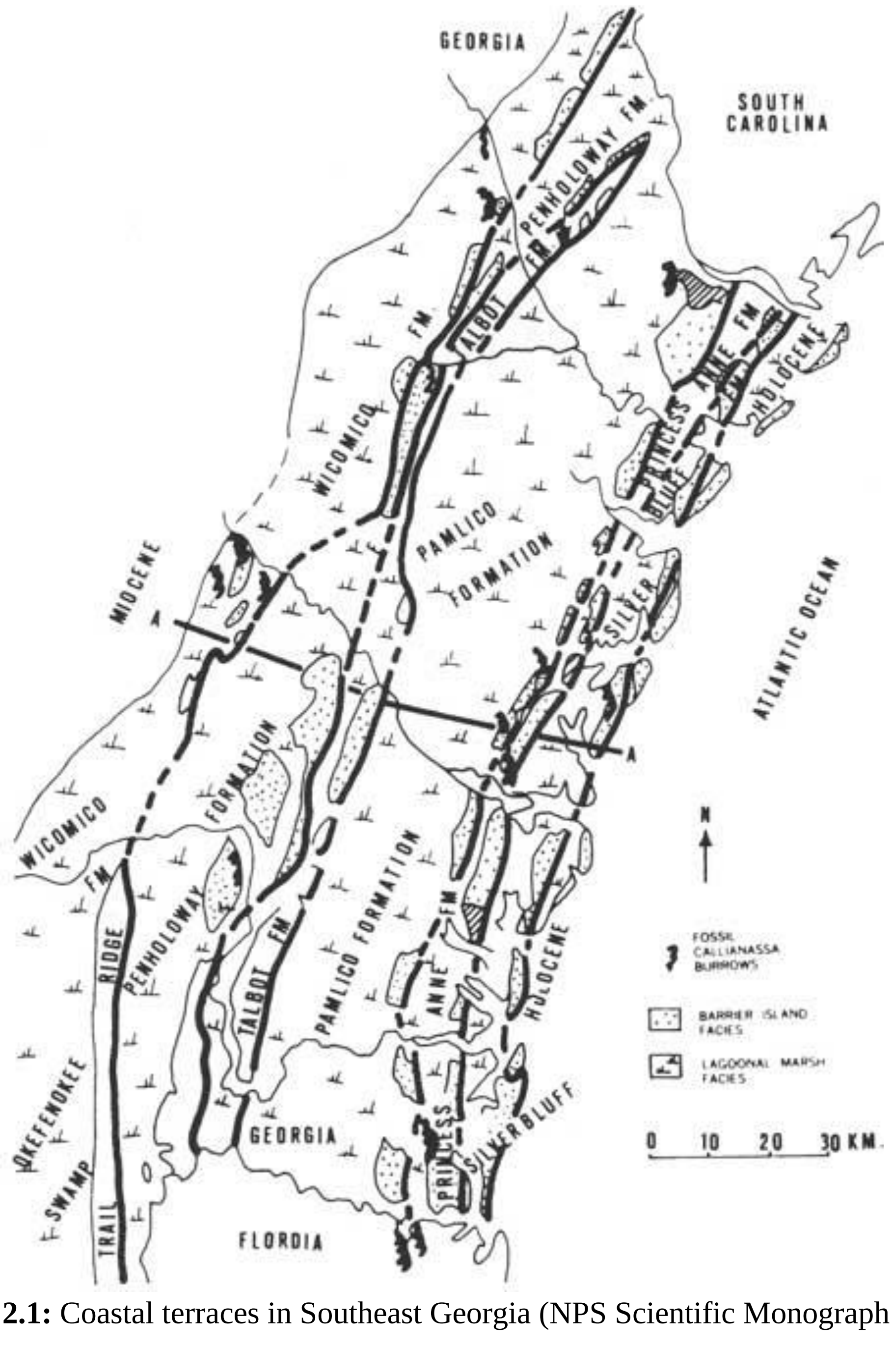

Figure 2.1: Coastal terraces in Southeast Georgia (NPS Scientific Monograph No. 3)

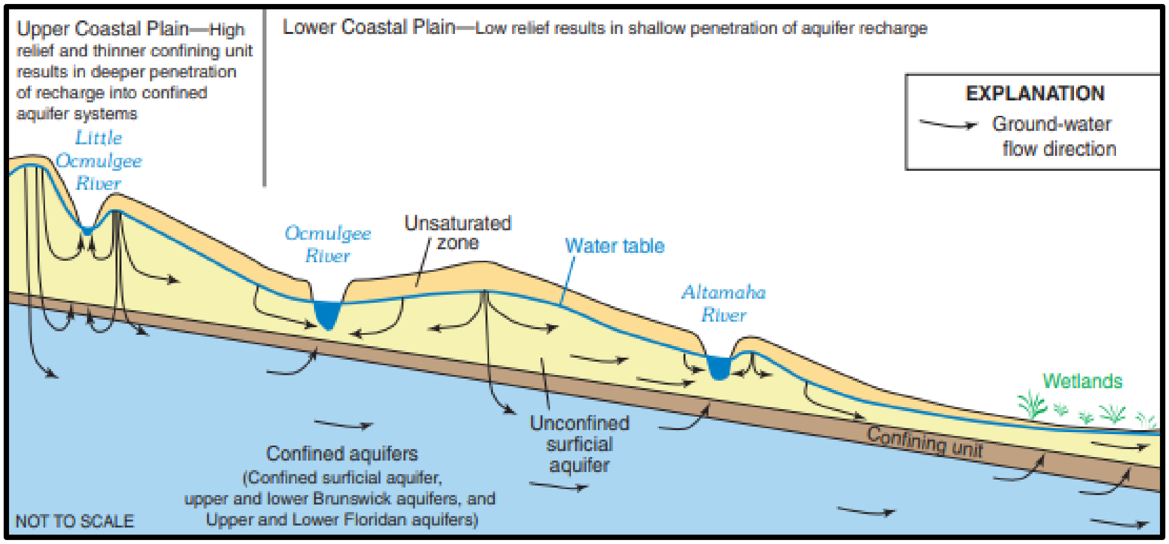

Figure 2.2: Surficial aquifer subsystem schematic (Priest, 2004)

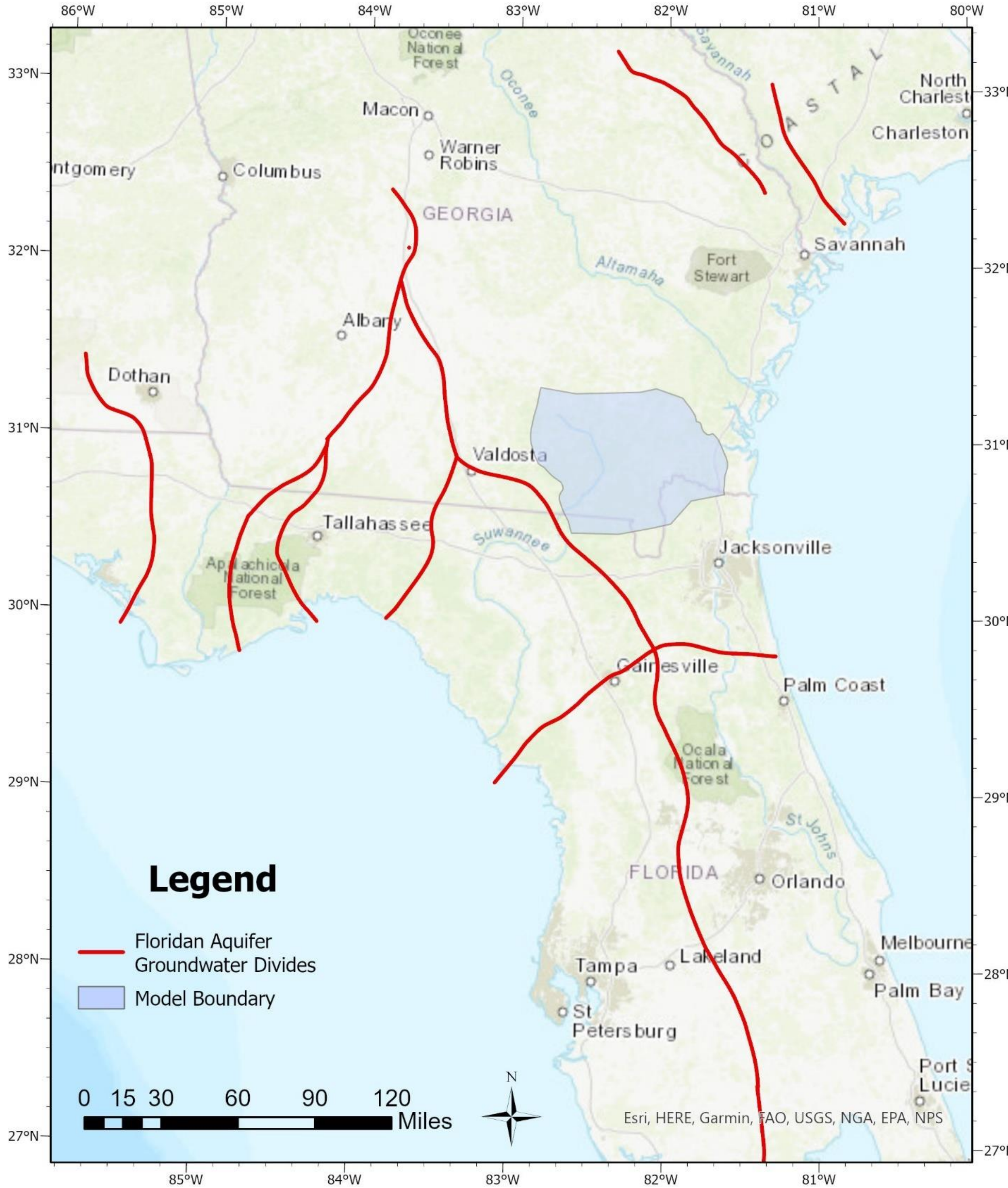

Figure 2.3: Groundwater basins of the Floridan aquifer system

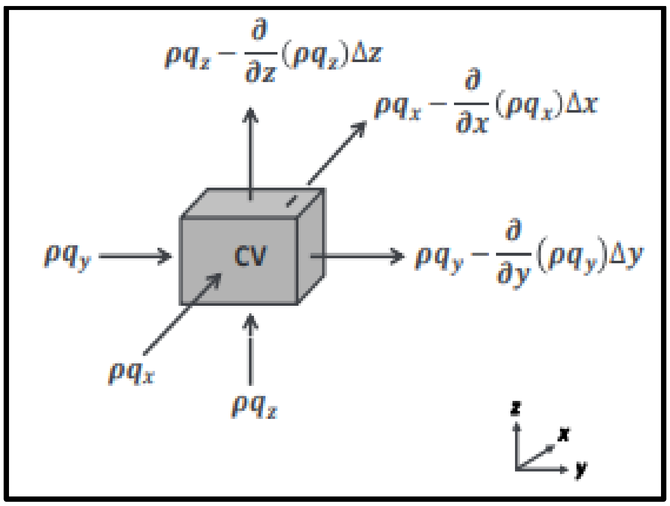

Figure 2.4: Conservation of fluid mass through a control volume (Jakab & Doerken, 2021)

Tables

Table 2.1: Aquifer Properties used for system conceptualization and model development. (Jakab & Doerken, 2021; Woessner & Poeter, 2020)

Property	Definition	Equation & Units	Simulation Type
Hydraulic Conductivity (K_x, K_y, K_z)	Measure of a geologic unit's ability to transmit groundwater	$K = \frac{-Q}{A(dh/dL)}$ [L/T]	Steady State & Transient
Porosity (η)	Ratio of volume of voids to the total volume of soil or rock	$\eta = \frac{V_V}{V_T}$ [Dimensionless]	Steady State & Transient
Effective Porosity (η_e)	Interconnected porosity though which flow occurs (excludes volume stored in dead end pores)	Total Porosity-Specific Retention [Dimensionless]	Steady State & Transient
Transmissivity (T)	The product of hydraulic conductivity and saturated aquifer thickness	T= Kb $[L^2/T]$ b = aquifer thickness	Steady State & Transient
Specific Yield (S_y) (Unconfined)	Ratio of the volume of water that drains from saturated rock (from gravity) to the total volume of the rock	$S_y = \frac{V_D}{V_T}$ [Dimensionless]	Transient
Specific Storage (S_S) (Confined)	Volume of water produced by a unit volume of confined aquifer from storage, per unit decline in the hydraulic head	$S_s = \rho g(\alpha + \eta_e \beta)$ [1/L] α = aquifer compressibility β = water compressibility	Transient
Storativity (S) (Confined) (A.K.A. Storage Coefficient)	Volume of water removed or stored in an aquifer per unit change in head	$S=S_S b$ [Dimensionless] b = aquifer thickness	Transient

Table 2.2: Common groundwater modeling boundary conditions
(Jakab & Doerken, 2021)

Boundary Condition Type	**Description**
Recharge	Water entering the groundwater system as infiltration through the ground surface
Evapotranspiration	Loss of water from the water table from combined evaporation and transpiration
Constant Head Boundary	Assigns a known hydraulic head elevation to a location where head is constant such as groundwater equipotentials or large surface water bodies, creating an infinite supply of water to the system.
River Boundary	Applied to the top layer of a model to indicate river stage elevation and conductance for potential groundwater-surface water exchange zones
Drain Boundary	Specifies drain elevation and conductance to determine flow out of a drain cell. Used for features such as tile drains, drainage ditches, seepage faces, etc.
General Head Boundary	Used to simulate effects of a hydraulic boundary outside of the model domain (often for local scale models)
Specified Flux Boundary	Assigns a known groundwater flux value to areas such as groundwater divides, streamlines, or aquifer pinch-outs. Commonly used for No-Flow boundaries where flux across a model boundary is zero.
Pumping Wells	A version of specified flux that is applied to pumping wells which can influence groundwater levels and flow direction

CHAPTER 3

METHODS

3.1 Model Overview

The initial approach for modeling groundwater interactions and hydrologic connectivity between Mission Mine, the Okefenokee Swamp, local rivers, and the underlying aquifer system involves the development of a regional, steady-state, three-dimensional groundwater flow model that encompasses each of these features of interest. For the purposes of this study, Waterloo Hydrogeologic's VMF software was selected for model development and groundwater flow simulations. Additionally, ArcGIS applications were used for geospatial data management. All geospatial data used for this study reference the North American Datum of 1983 (NAD 83)-Universal Transverse Mercator (UTM) Zone 17N Projection and the North American Vertical Datum of 1988 (NAVD88).

VMF supports two methods for constructing a groundwater model structure. The user has the option to begin model development in either a conceptual modeling workflow or a numerical modeling workflow. The conceptual modeling workflow is best applied for model development involving raw geospatial data input for creating model data objects. With sufficient data, the conceptual modeling approach provides the opportunity to develop a robust 3D representation of the hydrogeologic system of interest. After developing a conceptual model, the model structure and associated properties are then tessellated by constructing a grid for numeric calculation. After the grid is established, the conceptual model can then be converted to a numerical model. The conceptual model can serve as the basis for multiple versions of a numerical model, making it advantageous for testing different scenarios. In the numerical modeling workflow, data objects are assigned to a pre-established grid structure. Here, data objects are assigned to individual grid cells or sets of cells defined by the user or an imported shapefile. The numerical workflow provides the opportunity for the user to select the desired solver engine, run the model, and view results. For this study, the model structure is first developed using the conceptual modeling workflow, then converted to a numerical model for simulations.

3.2 Site Description

The Mission Mine site is located in Charlton and Brantley counties between the cities of Nahunta and Folkston in Southeast Georgia. The area of interest for this study is a large region in Southeast Georgia and Northeast Florida (Figure 3.1) with notable features including the ONWR, sections of the Satilla, Suwannee, and St. Marys rivers, several smaller streams (Figure 3.2), Trail Ridge, and the Penholoway Terrace, selected to incorporate the most important regions of hydraulic influence with the Mission Mine site. The study region is dominated by wetland land cover with about 49.5% of the total study area occupied by riparian or isolated wetlands (Figure 3.3). Of the wetland cover, the Okefenokee Swamp contributes about 41.5% of total wetland area (Table 3.1).

Furthermore, the study site is underlain by a shallow surficial aquifer and the deeper FAS, which are separated by a low-permeability upper confining layer known in the region of interest as the Hawthorn formation. The FAS consists of an upper and lower permeable zone differentiated by a middle composite confining unit that is reported to be consistent within the study area (Williams & Dixon, 2015). The upper and lower permeable zones are known as the “Upper Floridan aquifer” and “Lower Floridan aquifer,” respectively. The Floridan aquifer sits above the Southeastern Coastal Plain aquifer system and is separated by a lower confining unit

(Williams & Kuniansky, 2015). The northeast corner of the study site contains an intermediate aquifer, known as the BAS, that is positioned within the Hawthorn Formation between the surficial and Upper Floridan aquifer systems. The northeast corner of the model also has a structural syncline known as the Southeast Georgia Embayment over which the surficial deposits are deeper.

3.3 Data Acquisition

For the purposes of this study, field data collection was not a viable means for gathering information for model input. Therefore, existing models, datasets, and publications were used for model development. The necessary data for development of the conceptual framework of the regional groundwater flow model were extracted from the USGS Data Series 926, "Digital Surfaces and Thicknesses of Selected Hydrogeologic Units of the FAS in Florida and Parts of Georgia, Alabama, and South Carolina" (Williams & Dixon, 2015). Relevant GIS files included in this dataset are 1000 m x 1000 m digital surfaces of geologic layers, thicknesses of geologic layers, top of Floridan aquifer potentiometric surface contours (20 m), stream locations, lake locations, geophysical and lithologic well locations, major groundwater divides, intermediate aquifer extent polygons, and UFA transmissivities.

The digital surfaces and thicknesses for the geologic layers generated by the USGS were created by interpolating data from approximately 900 key geophysical and lithologic wells. In total, the USGS used over 5,000 wells to collect data detailing hydrogeologic properties of the aquifer system. Layer thicknesses were determined using GIS applications for raster surface subtraction. Land use distribution data (Figure 3.3), soil distribution data, and ten-meter, ground-surface Digital Elevation Models (DEMs) for the model domain (Figure 3.4) were acquired from the United States Department of Agriculture (USDA) Natural Resource Conservation Service

(NRCS) Geospatial Data Gateway. These datasets were used accordingly for conceptual modeling, parameterization, and calibration of regional and local groundwater flow models.

Additional USGS resources, including scientific investigations reports, previous Floridan aquifer model data releases, stream gage measurements, and groundwater monitoring well measurements were used to estimate aquifer properties, delineate boundary conditions, estimate boundary condition properties, and calibrate the groundwater model. These data sources will be further discussed in subsequent sections. Further data specific to the ONWR were acquired through representatives from the ONWR and United States Fish and Wildlife Service (USFWS). This data includes the ONWR boundary, significant surface water features, and monitoring stations. Mission Mine site specific data was also acquired from the Chemours team. This data includes site permit boundaries, well locations, and local wetland locations. Further information for estimating properties in the area of interest was acquired from scientific research publications conducted within the study region or similar sites.

3.4 Model Boundary

The boundary for the regional groundwater model was delineated to encompass Mission Mine, the ONWR, the Satilla River, and other notable features to assess groundwater flow and connectivity between these areas of interest (Figure 3.5). 20 m equipotential contours acquired from the USGS Data Series 926 were used to construct a model domain with constant head and no-flow boundary conditions in the UFA (Figure 3.6). More specifically, the eastern and western borders of the model domain are constant head boundaries, whereas the northern and southern borders are no-flow boundaries (perpendicular to equipotentials).

The regional model domain has an area of approximately 8630 km^2 (3,332 mi^2) and extends into parts of Ware, Charlton, Clinch, Brantley, Atkinson, Echols, Pierce, and Camden counties of Georgia, and Baker, Columbia, and Nassau counties of Florida. The entirety of the model area falls between FAS groundwater divides, suggesting that groundwater flow within the model domain trends the same general coastward direction. This is also confirmed with the equipotential lines used to delineate the model boundary, with the Westernmost contour at a higher elevation than the Easternmost contour. The model is bounded on the bottom by the middle confining unit which separates the Upper and Lower Floridan aquifers. For initial model simulations, the lowermost layer is the UFA. However, the LFA may be integrated in subsequent regional simulations.

3.5 Model Layers

The schematic shown in Figure 3.7 was provided in the accompanying report for the USGS Data Series 926 (Williams & Dixon, 2015) and was used to determine the necessary layers for conceptual modeling of the UFA. The schematic depicts the cross-sections of the FAS by region. The area of interest for this study is within region 4, "Southeast Georgia and Northeast Florida." Region 4 is characterized by a continuous surficial aquifer system, a continuous upper confining unit, an area of higher permeability representing the UFA, and a middle composite confining unit. Layers beneath the MCU were not included in the initial modeling of the study area.

The USGS Data Series 926 provides geological layer surfaces for the vertical and horizontal extents of the FAS. For the purposes of this study, all layers from the ground surface to the interface of the Upper and Lower Floridan aquifer were extracted and clipped to the model boundary for model development in VMF (Figure 3.8). Layers that were extracted from the USGS Data Series 926 for inclusion in the groundwater flow model of the surficial and Upper Floridan aquifers are included in Table 3.2.

From these files, the surface for the upper confining unit was generated in ArcGIS using raster subtraction. The thickness of the surficial aquifer was subtracted from the ground surface DEM from the USDA Data Gateway, resulting in a raster surface for the interface between the surficial aquifer and upper confining unit. To perform this raster subtraction, the ground surface DEM was resampled from 10 m resolution to 1000 m resolution to match the surficial aquifer thickness raster resolution. However, the initial 10 m resolution ground surface DEM was used in the VMF model. The surface representing the top of the FAS is also the base of the upper confining unit. This was validated by subtracting the thickness raster for the upper confining unit from the surface raster for the upper confining unit. After input into VMF, the resulting model structure consisted of three vertical zones, representing the surficial aquifer, UCU, and UFA, respectively.

Though the intermediate Brunswick aquifer only extends into a small portion of the model domain, a separate property zone was assigned to the associated area within the Hawthorn Group to capture higher permeability through the system. To delineate the Brunswick aquifer property zone, the upper confining unit was divided into three layers of equal thickness, such that a unique property zone could be assigned to the middle layer of the confining unit independently. A polygon from the USGS Data Series 926 representing the approximate extent of the BAS was then used to define the horizontal extents of the property zone. The remainder of the confining unit was assigned properties such that it would be treated as one composite layer. The final model structure consists of five layers, where Layer One is the surficial aquifer system, Layers Two through Four are the confining unit with the Brunswick aquifer present in the eastern edge of Layer Three, and Layer Five is the UFA.

3.6 Model Properties

VMF accepts inputs for initial heads, storage, and hydraulic conductivity (K) for each model layer. For initial groundwater simulations, model properties were assigned to model layers assuming high homogeneity within geologic zones. For steady-state simulations, aquifer hydraulic conductivity (K_x, K_y, K_z) is the most significant parameter for model performance, while initial heads and storage properties play a larger role in transient simulations. Hydraulic conductivity values for each model layer were estimated based on simulated and measured properties reported in several USGS scientific investigations reports (Table 3.3), where horizontal hydraulic conductivity (K_h) includes K_x and K_y and vertical hydraulic conductivity (K_v) refers to K_z. Reported and simulated values from these reports were compared for parameter estimation and model input.

For each layer, an assumed anisotropy of 1:100 K_h: K_v was used to differentiate horizontal and vertical permeability, where $K_x = K_y = 100K_z$. Based on the values presented in Table 3.3, the surficial aquifer was assigned a uniform K_h and K_v of 3.70E-04 and 3.70E-06 m/s, respectively. With the exception of the Brunswick aquifer property zone, the UCU, Layers Two through Four, was assigned a K_h and K_v of 3.53E-11 and 3.53E-13 m/s, respectively. The Brunswick aquifer, though naturally occurring as two permeable zones, the Upper and Lower Brunswick aquifer, separated by a confining layer (Cherry, 2019), was modeled as one composite unit following the approach of USGS Scientific Investigations Report 2005-5089 (Payne et al., 2005). This property zone was assigned a K_h of 5.30E-05 m/s and a K_v of 5.30E-07 m/s. Furthermore, the UFA, model Layer Five, was assigned a K_h of 1.06E-02 m/s and a K_v of 1.06E-04 m/s. After initial simulations, these property values are subject to change as the model is calibrated to observed well data.

3.7 Boundary Conditions

3.7.1 Constant Head & No-Flow

The model domain was bounded on the edges by a combination of constant head and no-flow boundary conditions, where the eastern and western borders were assigned constant heads based on Upper Floridan potentiometric surface contours as reported in USGS Data Series 926. The northern and southern model boundaries were delineated perpendicular to the Upper Floridan equipotentials and assigned no-flow conditions by default VMF settings. Upper Floridan equipotential contour polylines were imported from ArcGIS into VMF for boundary condition delineation. The original Upper Floridan equipotential polyline GIS files extracted from USGS Data Series 926 were labeled with an attribute detailing their elevation relative to the National Geodetic Vertical datum of 1929 (NGVD 29). Before import into Visual MODFLOW Flex, the equipotentials were assigned z-values based on their elevation attribute, then were re-referenced from NGVD 29 to NAVD 88 to ensure alignment with the existing model inputs. This provided the necessary information to assign the constant head boundary conditions at reported head elevations.

The constant head values extracted from USGS Data Series 926 are not representative of surficial aquifer water levels, and therefore were only assigned to Layers Two through Five of the conceptual model, excluding the surficial aquifer. Extending constant head boundaries into the surficial aquifer may contribute to better steady-state model results, but would require known water table elevations which are not available along the model boundary. Though the constant head boundary conditions themselves were not delineated for the surficial aquifer layer, the UFA constant head elevations assigned to the eastern and western model boundaries extend into the surficial aquifer per reported potentiometric surface contours of the UFA. Although data was not acquired for constant head delineation in the confining unit, the constant head boundaries were assigned to the UCU layer under the assumption that the confining unit exhibits similar heads to the UFA. While the confining unit likely has less hydraulic pressure, it sits at a higher elevation than the UFA, providing the basis for this assumption. This condition provides further constraints for establishing the boundary-value problem solved in model simulations.

Constant head elevations along the Eastern and Western model boundaries were extracted from a USGS Data Series 926 file called "plate4_Top_FAS_countours_20," which is described as "potentiometric surface contours for the top of the Floridan aquifer system-20 foot interval" (Williams & Dixon, 2015). The head elevation values reported in this file for the eastern and western model boundaries were -480 ft and -100 ft, respectively, which were converted to values of -146.6 m and -30.7 m after translating the vertical datum from NGVD29 to NAVD88. However, these values do not make physical sense for UFA piezometric potential, as they would indicate potentiometric surface elevations below sea level, allowing salt water to enter the aquifer system from the coast. It is possible that the description of the "plate4_Top_FAS_countours_20" file misrepresents the actual feature associated with the contours. While the term “potentiometric surface” generally refers to the elevation at which groundwater would rise under unconfined conditions or in a well, the elevations associated with the "plate4_Top_FAS_countours_20" file seem to represent structural elevations at the interface between the UCU and UFA.

Therefore, another USGS Data Series 926 file "fig53_May2010_potentiometric_contour" which is described as "Potentiometric surface contours of the Upper Floridan aquifer in May 2010" (Williams & Dixon, 2015) was used to obtain constant head boundary values. The head values associated with the contours of "fig53_May2010_potentiometric_contour" are much more probable than those identified in "plate4_Top_FAS_countours_20," and reflect realistic, above sea-level groundwater heads across the model domain. Contours from this additional file that approximate those of "plate4_Top_FAS_countours_20" were used to assign values to the model's constant head boundaries. Based on reported head elevations from the May 2010 UFA potentiometric surface contours, constant head elevations of approximately 20 m and 5 m were identified as reasonable boundary condition inputs for the western and eastern model borders, respectively.

3.7.2 Recharge

A static recharge value was assigned to the top layer of the model to simulate hydrologic inputs into the groundwater system from annual rainfall events. This value was estimated based on average annual rainfall within the study area. The average annual rainfall in the study region, at a value of 1,397 mm/year, was extracted from a USGS Data Series 584 annual precipitation shapefile that detailed average annual rainfall by region above the FAS (Bellino, 2011). With approximately 12 percent of annual rainfall entering the surficial aquifer as groundwater recharge (Joiner & Cressler, 1993), an initial recharge value of 167.6 mm/year (1,367 mm/yr * 0.12) was applied to the top layer of the model. Because this recharge value accounts for evapotranspiration pertaining to rainfall events, an evapotranspiration boundary condition was not included on the top layer of the model for initial simulations.

3.7.3 Wetlands

The region of interest for this study consists of about 49.5% wetland land cover relative to other land use classifications. While some of the smaller wetlands in the study area are assumed to have negligible effects on the regional groundwater system, larger wetland areas and those closest to the active mine site were included in the model to assess potential mine induced hydrologic impacts on these features. For initial model simulations, the wetlands associated with the Okefenokee Swamp and those directly adjacent to the Mission Mine site were included as boundary conditions on the top layer of the model.

These features were parameterized using the Lake (LAK3) package in VMF, with property estimations based on previous studies conducted in the region of interest or similar sites. Though the Okefenokee Swamp is known to consist of a hydrologic system of higher complexity than that of a homogeneous lake, initial steady-state model efforts aim to provide a general understanding of the swamp's influence on water table elevation and interactions between significant surface water features and groundwater in the area. The VMF LAK3 package requires inputs for stage elevation, bottom elevation (beneath bed material), bed material thickness, bed hydraulic conductivity, annual precipitation, annual evapotranspiration, annual input from overland runoff, and annual artificial withdrawal. These inputs are then used by VMF to calculate the lake bed conductance as (Waterloo Hydrogeologic, 2021):

$$C = \frac{L \times K_v \times W \times \alpha}{M} \qquad \textbf{(Equation 3.1)}$$

Where:

C = Conductance
K_v = Vertical hydraulic conductivity of the lakebed
α = Conversion factor for converting K to [L] and [T] units used by C
M = Lakebed thickness
L = Length of grid cell
W = Width of grid cell

For the Okefenokee Swamp lake boundary condition, the stage elevation was set equivalent to the ground surface DEM. For the bottom elevation, a new raster surface was created in ArcGIS using raster subtraction. With an average stage of 1.0 m (Loftin & Kitchens, 2001) and an average peat layer and bed thickness of 1.5 m (Bellino, 2011; Smedley, 1968), the raster used to assign the swamp bottom elevation was created by subtracting a total of 2.5 m from the ground surface DEM. The bed thickness field was assigned an initial value of 1.5 m based on average thickness of peat layers from GIS shapefiles provided by representatives from the USFWS. A similar value was reported in the USGS "Summary Report on the Geology and Mineral Resources of the Okefenokee National Wildlife Refuge, Georgia" (Smedley, 1968).

With an estimated range of Okefenokee peat soil hydraulic conductivity between 1.6E-01 and 1.7E-03 m/s (Rizzuti, Cohen, & Stack, 2004), an initial bed conductivity of 1.6E-03 m/s was assigned to the Okefenokee lake boundary condition. Annual precipitation and evapotranspiration rates were assigned values of 1298 and 1032 mm/yr, respectively (Yin & Brook, 1991). Because an estimated 72-78% of Okefenokee Swamp water input comes from precipitation falling directly on the swamp surface, overland flow contributions were assumed negligible for initial simulations. Furthermore, data limitations for quantifying overland flow into the Okefenokee Swamp contributed to this assumption. Artificial withdrawals from the Okefenokee Swamp were also assigned a zero value for initial simulations.

Although the wetlands bordering the Mission Mine site are small relative to the model domain and Okefenokee Swamp, they were included in initial modeling because of their proximity to the mining operation, making them more likely to be affected by hydrologic perturbations. For the Mission Mine wetlands, the stage elevation was also set to the ground surface DEM, while the bottom elevation was set to an elevation 1.25 m below that of the ground surface. With the exception of bed thickness, the remainder of the inputs for the Mission Mine wetlands were assigned the same values as the Okefenokee Swamp boundary condition. The bed thickness field for the Mission Mine wetlands was assigned a value of 1.0 m. A lack of field measurements contributed to assumption-based parameterization for these properties, though they are subject to change during model calibration.

3.7.4 Rivers and Streams

Within the study region, several rivers and streams contribute to surface and groundwater interactions, making them important for quantifying hydrologic connectivity between surface water bodies and the surficial aquifer. Major rivers in the model domain include the Satilla, St. Marys, North Prong St. Marys, Suwannee, Alabaha, and Crooked Rivers, while smaller streams include the Little St. Marys River, Red Bluff Creek, Suwannoochee Creek, Suwannee Creek, Middle Fork Suwannee River, and Gum Swamp. GIS shapefiles representing the location and extent of these waterways were acquired from USGS Data Series 926.

Using ArcGIS, the stream file was clipped to the model domain and separated into individual polylines according to their associated name attribute. This allowed each river section to be input and assigned parameters individually in VMF. Each river and stream were input into VMF using the River (RIV) package approach. The VMF RIV package uses a rather simplified conceptualization of river systems, with a primary objective of distinguishing an exchange zone between surface water and groundwater. This contributes to the model's ability to predict water table elevations. In the RIV package, rivers are assumed to have a rectangular cross-section with a seepage layer along a flat channel bed and impermeable channel walls. Use of the RIV package involves a few drawbacks including the oversimplification of channel geometry, lack of ability to simulate the system's mass balance, and lack of ability to simulate effects of variations in flow rate.

However, for systems with unavailable or sparse data, the RIV package provides the model with an assumption basis for estimating surficial aquifer exchange and water table elevations. When applying the "Use Default Leakance" option for the MODFLOW RIV package, each river requires input data for river stage elevation, riverbed bottom elevation, riverbed thickness, leakance, riverbed Kz, and river width. For the "Use Default Leakance" method, leakance is a read only field, calculated by VMF as riverbed vertical hydraulic conductivity divided by riverbed thickness. These inputs are then read by VMF to calculate riverbed conductance by cell. Riverbed conductance is calculated by the RIV package using (Waterloo Hydrogeologic, 2021):

$$C = \frac{L_R \times K_v \times W_R \times \alpha}{B} \qquad \textbf{(Equation 3.2)}$$

Where:

C = Conductance
K_v = Vertical hydraulic conductivity of the riverbed
α = Conversion factor for converting K to [L] and [T] units used by C
B = Riverbed thickness
L_R = Length of river reach in each grid cell
W_R= width of river in each grid cell

Here, cell conductance is also equal to the product of the streambed leakance and cell area.

Within the study site, nine USGS stream gages were used to estimate input parameters for the larger rivers in the system (Table 3.4). With limited data pertaining to spatial river geometry variations and riverbed properties, river input parameters were assumed to be similar across all river sections of comparable size. Using this approach, the larger, gaged rivers were assigned similar properties regarding riverbed thickness and vertical hydraulic conductivity, while the smaller regional streams were given a different set of homogenized properties. Because the study region in Southeast Georgia is characterized by sandy surficial deposits, sandbed rivers are the dominant streambed type. Therefore, a vertical hydraulic conductivity value of 1.04E-08 m/s was assigned for each river and stream section in the model to simulate exchange between riverbeds and the surficial aquifer system (Wojnar et al., 2013).

With stage elevation measurements available only at stream gage locations, a uniform river stage was set for each stream section based on annual stage averages. For the larger, gaged rivers in the domain, an average of yearly average stages was determined for each gage location using data representing the complete period of record for each gage site. Based on these averages, the larger rivers in the region were assigned a stage of 2 m (6.56 ft), a value that reflects average river depths over time over the entire domain. With limited availability of riverbed thickness data, the riverbed thickness of all larger rivers was assumed to be 0.5 m.

To ensure that the river depths stayed consistent over topographical variation and coastward elevation decline, river stage elevations were input with the “use surface” option in VMF. By assigning a river stage elevation equal to the ground surface DEM file, the river surfaces follow the regional topography and fit into their associated channel locations. For the river bottom elevation, a new surface raster was created by subtracting 2.5 m from the original ground surface DEM to account for a 2 m stage and a 0.5 m riverbed thickness across each river section in the model domain. By assigning this new DEM surface to the river bottom elevation field, each of the larger rivers exhibits a uniform depth and bed thickness that changes accordingly with topographic elevation changes.

For the larger rivers in the study region, river widths were determined using averages taken from all reported width measurements at each USGS streamgage individually. Based on these measurements, channel widths were assigned to the river reach best corresponding to the associated stream gage location. Typically, river width increases coastward as the bed slope and flow velocity decrease. River width estimates used as input parameters are shown in Table 3.5. Note, the shapefile acquired from USGS Data Series 926 that was used to delineate stream locations contained a short, unnamed stream section close to the coast, on the easternmost edge of the model domain. Because VMF requires input parameters for all present polylines, the unnamed section was treated as a large river because of its proximity to the coast. Therefore, it was assigned an assumed width based on widths of river sections sharing a comparable proximity to the GA coast.

With no available gage data for the smaller, less hydrologically important streams in the system, input parameters were assumed homogeneous across all sections. The streams were also assigned a vertical hydraulic conductivity of 1.04E-08 m/s and a stage elevation equal to that of the ground surface DEM. All streams were assumed to have a depth of 1 m (3.3 ft) with a bed thickness of 0.25 m. Therefore, an additional DEM raster was created by subtracting 1.25 m from the ground surface DEM and assigned to the “riverbed bottom” elevation field to create a uniform 1.25 m thickness for all stream layers across the model domain. Furthermore, an assumed channel width of 10 m was assigned to all small streams in the study region.

3.8 Model Grid

When approaching model development through the conceptual modeling workflow in VMF, the model structure, properties, and boundary conditions are first specified using geospatial data objects in a grid-independent work environment. Upon completion, the conceptual model is then assigned a grid before being converted to a numerical model. VMF supports multiple options for grid delineation, selected to best facilitate numerical simulations of the study site based on model structure, key data object features, and target resolution for specified areas of interest. The available grid types include options for a user-defined Finite Difference Grid, Unstructured Voronoi Grid, Unstructured QuadTree Grid, and Finite Element Mesh. Each of which provide unique benefits and drawbacks regarding solver compatibility, boundary condition package compatibility, computational cost, and grid cell refinement.

When it comes to selecting a grid type, the conceptual modeling workflow is advantageous in that the user can convert the conceptual model structure into multiple numerical model variations, each with an independent grid style and structure. In the case of regional-scale modeling objectives, computational cost and targeted grid refinement become increasingly important with model size. For example, it is much less computationally expensive to run a model with fewer, larger grid cells, but doing so can cause resolution discrepancies for smaller features such as rivers, wells, point-source contamination, and the like. In these situations, a grid cell intersecting one of these features would then be treated as having the properties of that feature throughout the extent of the cell. This can cause unrealistic scenarios such as an observation well occupying the entirety of a 1000 m x 1000 m grid cell, which would result in inaccurate, mis-scaled simulation results. Therefore, an iterative approach in which successful low-resolution numerical simulations are gradually refined after first validating model convergence provides the opportunity to assess model performance before increasing computational cost and simulation time.

For this reason, initial simulations were run using a simple, low-resolution structured finite difference grid. The initial numerical model was constructed using a square grid with 50 rows and 50 horizontal columns, where the polygon representing the model domain was used to differentiate active cells from inactive cells. Grid cells outside the model boundary were assigned an inactive designation such that they were excluded from model simulations. For the initial grid, each cell had a length (east-west) of 2475.33 m and a width (north-south) of 1843.65 m. Initial simulations excluded grid refinement around areas of interest to encourage a high rate of convergence for quickly assessing model performance, identifying problematic model results, and troubleshooting parameter discrepancies and sensitivities for preliminary heuristic calibration.

For the vertical component of the initial model grid, each of the five model layers were discretized into an additional three sublayers, creating a total of fifteen layers for simulation. With a structured finite-difference grid type, each cell is treated as an elemental control volume, where the governing partial differential groundwater flow equation (Equation 2.5) is solved by MODFLOW using the Finite Difference Method. Here, a known distance between the central nodes of each grid cell is substituted for the differential element in each direction of the groundwater flow equation. Thus, the solution to the groundwater flow equation in each cell is dependent on the flow between the six neighboring cells. Because of this solution method, a minimum of three vertical cells per layer provides better resolution by allowing a transition cell between geological zones of variable vertical hydraulic conductivity. For example, if there were only one vertical grid cell in the confining layer, the solution to that cell would be dependent on the vertical hydraulic conductivity of the surficial aquifer above and that of the UFA below, making the solution to that cell less accurate than it would be given a transitional cell above and below.

3.9 Solver and Settings

After the model was assigned a grid type and converted to a numerical model, model run settings were specified before running model simulations. Settings that must be specified before running the model include the flow engine, property package, run type, solver type. At this stage, the user also has the option to specify convergence criteria, set max iteration numbers, modify initial head options, deactivate boundary conditions, and several other options that apply to specific flow engines or modeling objectives. The settings specified in this step of the modeling process are then translated from VMF file formats to data files required for the selected numeric engines.

Because a finite-difference grid type was selected for initial simulations, the MODFLOW-2005 flow engine was selected to run the model. Next, the Layer-Property Flow (LPF) package was selected to specify properties controlling flow between cells. Other property packages available for MODFLOW-2005 include the Block Centered Flow package (BCF) and the Hydrogeologic-Unit Flow package (HUF2). These also specify properties that control flow between cells, but are typically used for specific modeling goals or boundary condition types that were not included in this study. After selecting the property package, a steady-state run type was selected for time-independent model simulation.

Several solver options are available through MODFLOW-2005. For this study, the default Conjugate Gradient Solver (PCG) was selected for model simulations. Within the PCG solver settings, the max outer iteration (MXITER), max inner iteration (ITER1), head change criterion (HCLOSE), residual criterion (RCLOSE), and relaxation parameter (RELAX), were modified from the default settings to establish model convergence tolerance. For initial simulations, MXITER and ITER1 were set to 500 iterations, HCLOSE and RCLOSE were set to 0.1, and RELAX was set to 0.8. Model convergence was also tested with an HCLOSE setting of 0.01. The model converged under both HCLOSE criterion.

The initial head settings were also modified during this modeling stage. VMF provides the user with the option to use specified heads, ground elevation, or previous MODFLOW runs for initial heads. Without reliable head data for the extent of the model domain, the “use ground elevation” option was selected for initial simulations. This contributed to model convergence for early simulations. However, refined water table results from manual calibration could provide a good estimate of starting heads, making the “previous MODFLOW run” a good alternative for initial heads in future model iterations. Before translating the model settings and running simulations, the boundary condition settings were checked to ensure all boundary condition packages used for model development were activated for file translation and model simulations. For early simulations that experienced convergence failure, all boundary condition packages were deactivated and reactivated one at a time to determine the source of convergence error and resolve the underlying issues.

3.10 Preliminary Model Calibration

Preliminary model calibration was done manually using a heuristic approach. While VMF provides computer-assisted calibration methods, such as the Parameter Estimation (PEST) tool, it is beneficial to first adjust model inputs based on simulated model results and their correlation to known physical characteristics of the system. This allows the modeler to make intuitive adjustments to model parameters through an iterative process that promotes incremental improvements toward feasible simulation results while also providing insight into sensitive model parameters. Best calibration results are achieved when manual calibration is used to develop feasible model results, followed by an in-depth computer-assisted calibration that compares simulated results to field-derived observation data. This provides the opportunity to assess model uncertainty and align feasible results from manual calibration with the true values that exist in the system.

Computer-assisted calibration enables a higher level of predictive analysis by varying model parameters in a series of simulation iterations to identify parameter values that best match simulated results with observed data. The ability of computer-assisted calibration to vary model parameters in a series of simulations also provides opportunity for in-depth sensitivity analysis which offers insight into parameters that should be given more focus in subsequent simulations. Though this is a powerful tool, the results of these calibration techniques are limited by the availability of observational data. In scenarios where little or no observational data exists for a model region, the model has no basis for calibrating parameters and assessing model uncertainty, therefore making intuitive-based manual calibration a better approach.

Available groundwater level observation data for the model domain is limited to a single UFA USGS monitoring well centrally located within the model region. This renders computer-assisted calibration unreliable for current model simulations, making manual calibration the best approach for refining initial model results. Therefore, model calibration thus far has consisted of manual parameter adjustments with a primary focus on achieving realistic results for simulated water table elevations. Boundary conditions and layer properties were adjusted iteratively, where new simulations were run to assess the effects of changes to individual parameters.

In general, discrepancies in water table results are easier to identify than those of other model outputs. The water table should generally approximate surface topography, discharge toward surface water basins, represent standing water in wetlands and rivers, and appear just below land surface in the uppermost model layers, whereas groundwater heads and flow velocities in deeper layers are less observable, making it more difficult to assess the feasibility of model results without spatially distributed observational data. Therefore, initial manual calibration focused on improving simulated water table elevations and included adjustments to the Western constant head boundary condition, recharge boundary condition, Okefenokee Swamp boundary condition, and vertical and horizontal hydraulic conductivity of the surficial aquifer and confining unit. Individual simulations were run for each adjustment to improve overall water table results, observe the effects of changing each parameter, and assess the model's sensitivity to boundary conditions and layer properties.

Figures

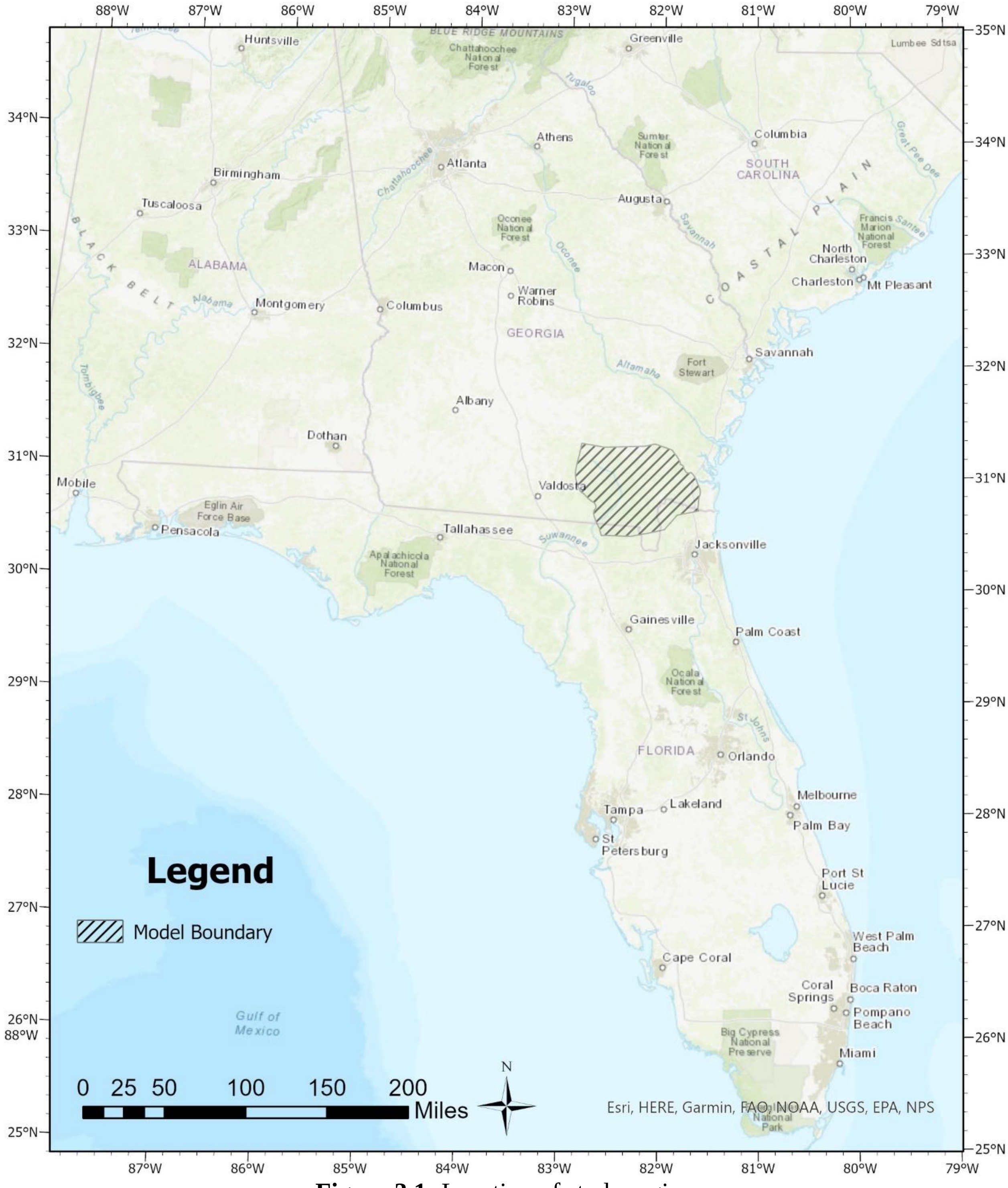

Figure 3.1: Location of study region

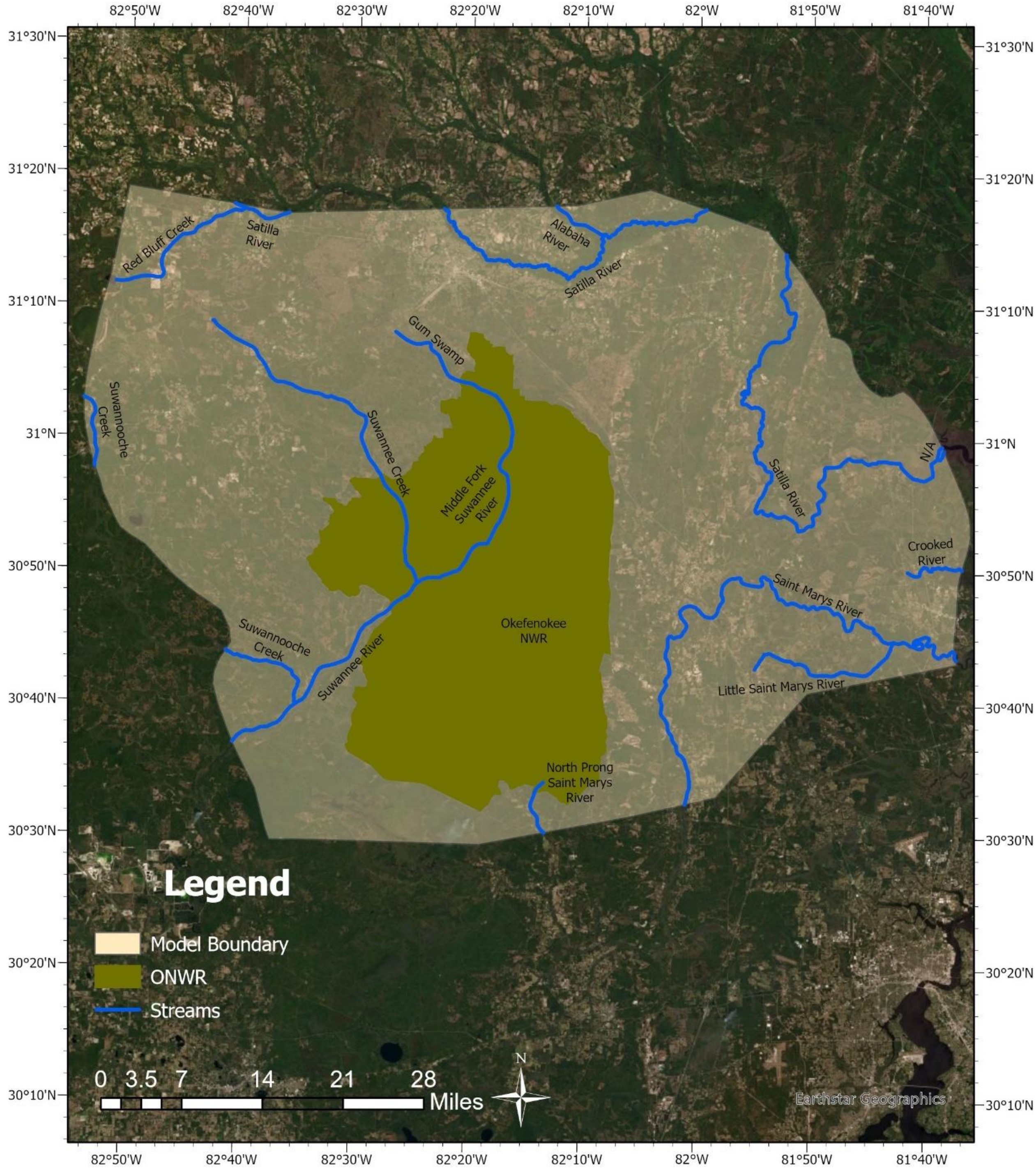

Figure 3.2: Major rivers and streams within model domain

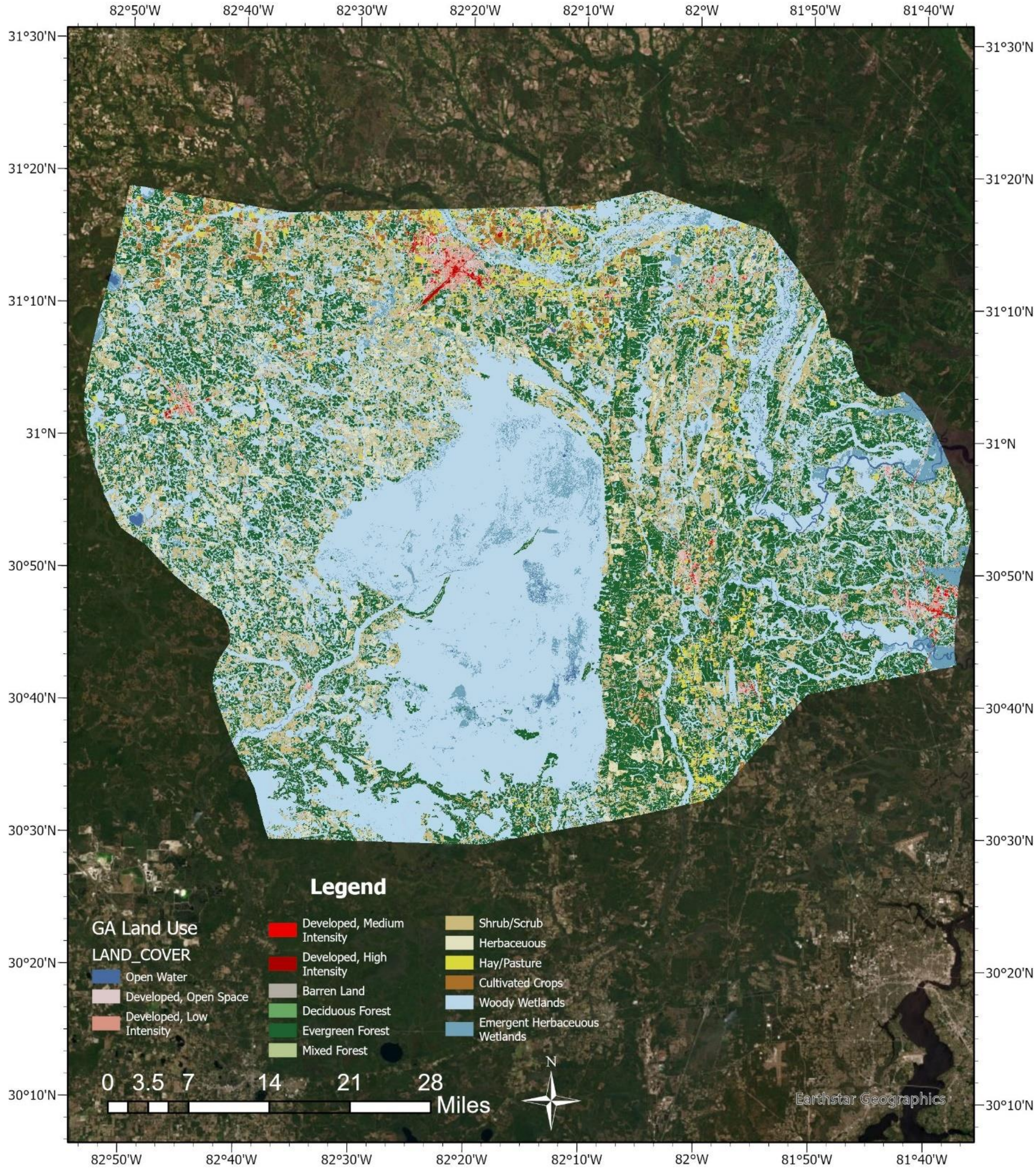

Figure 3.3: Land use distribution in study region (USDA NRCS Data Gateway)

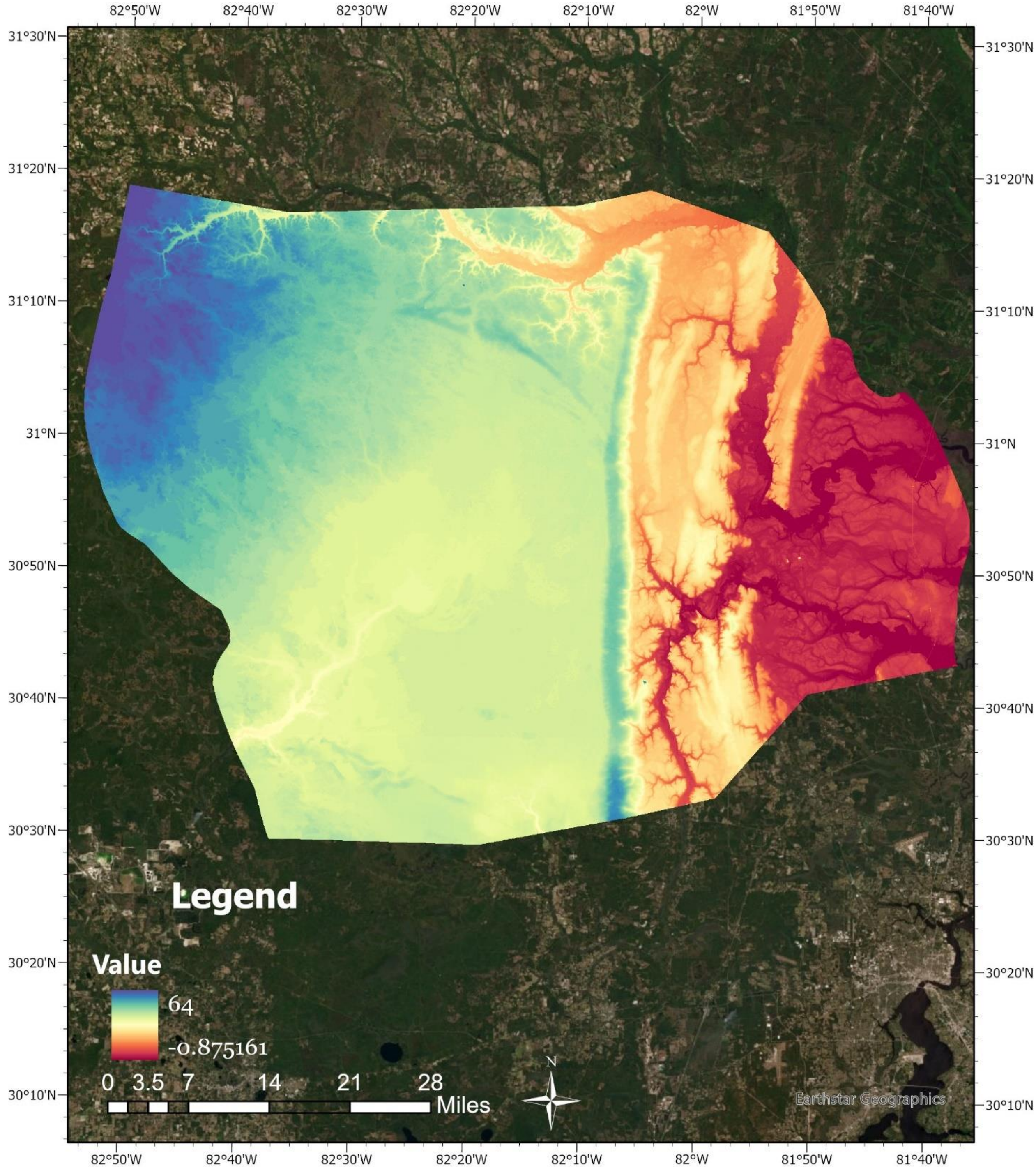

Figure 3.4: 10 m surface topography DEM for study region (USDA NRCS Data Gateway)

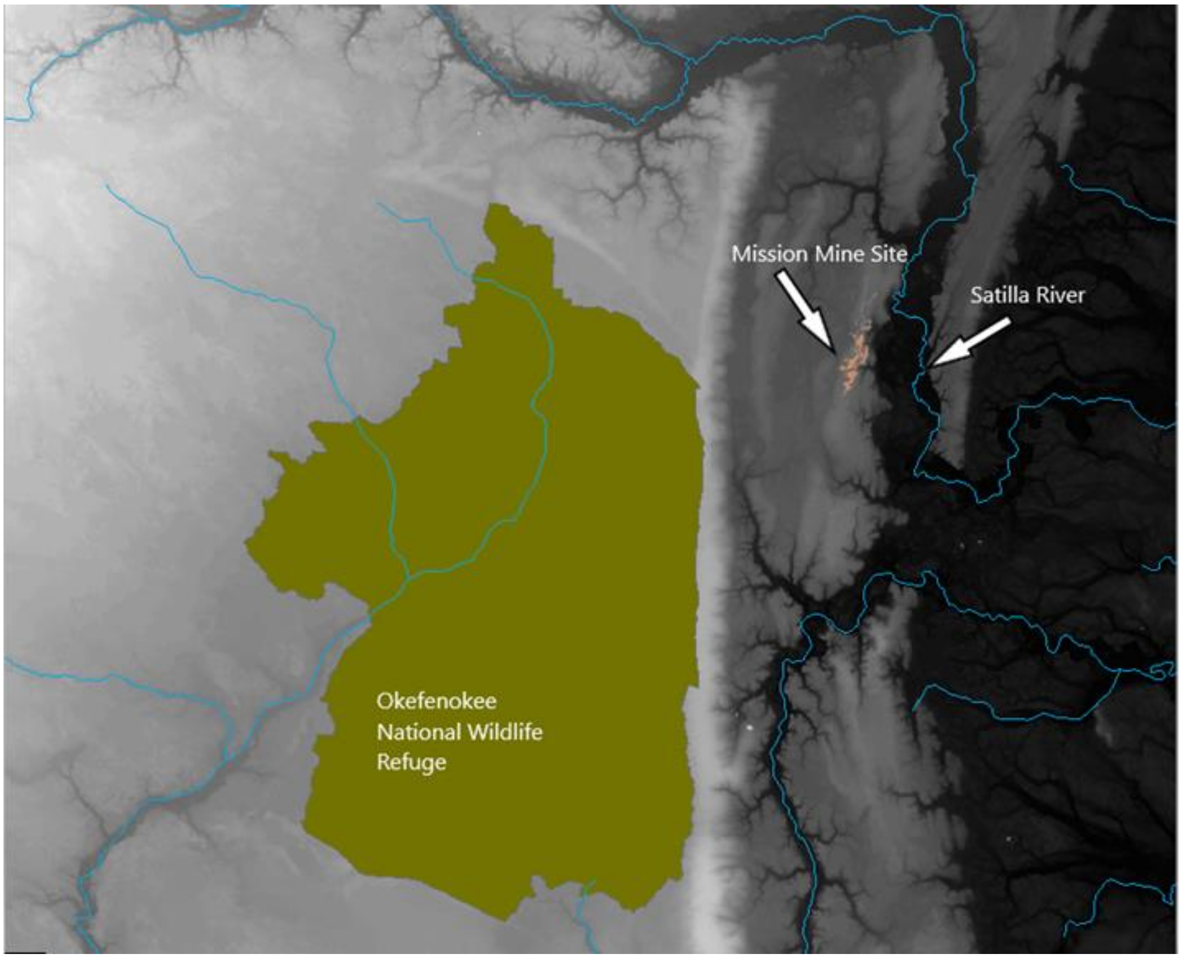

Figure 3.5: Locations of ONWR, Satilla River, and Mission Mine site

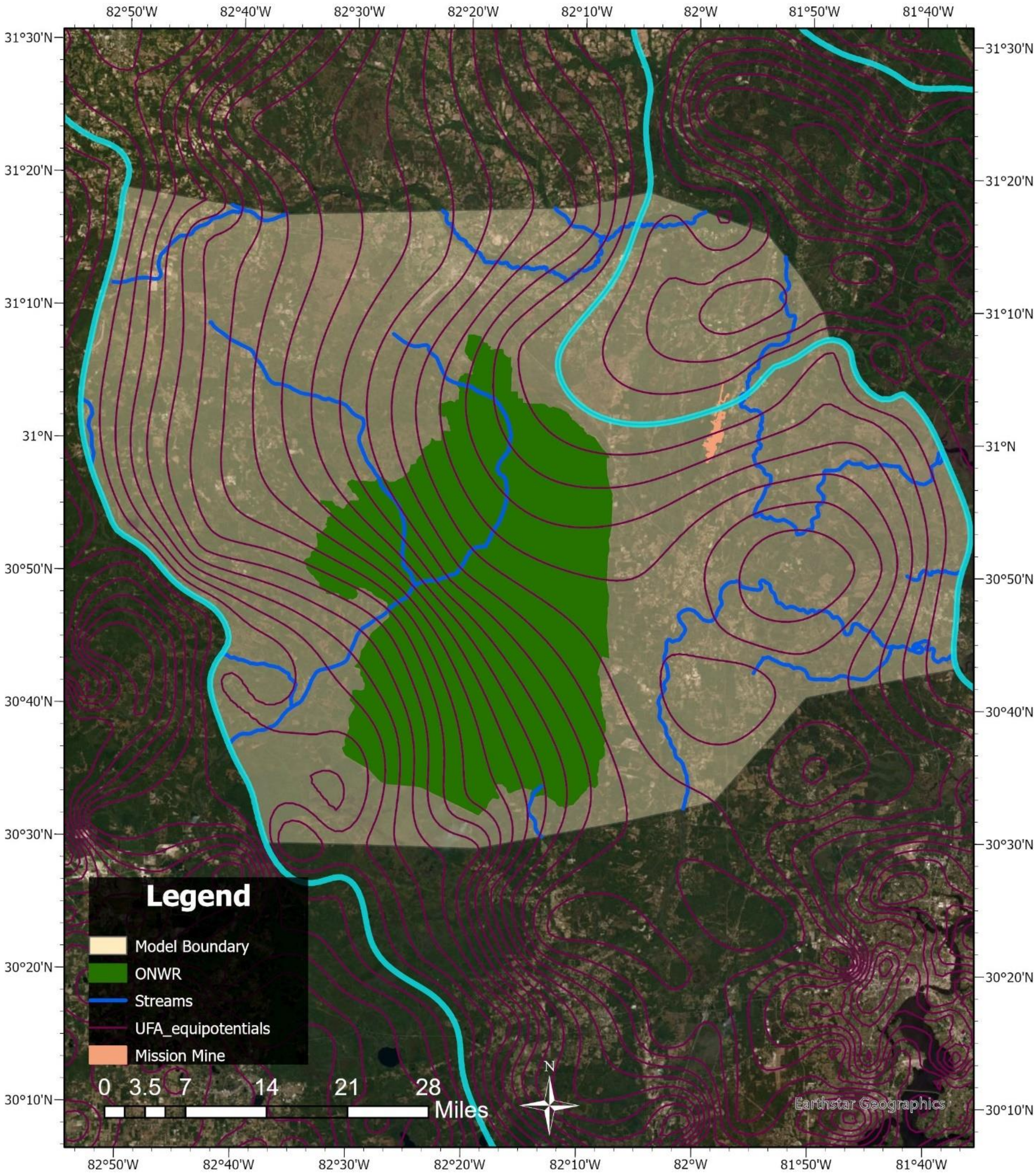

Figure 3.6: Regional model boundary (equipotential lines used for constant head boundaries highlighted in light blue)

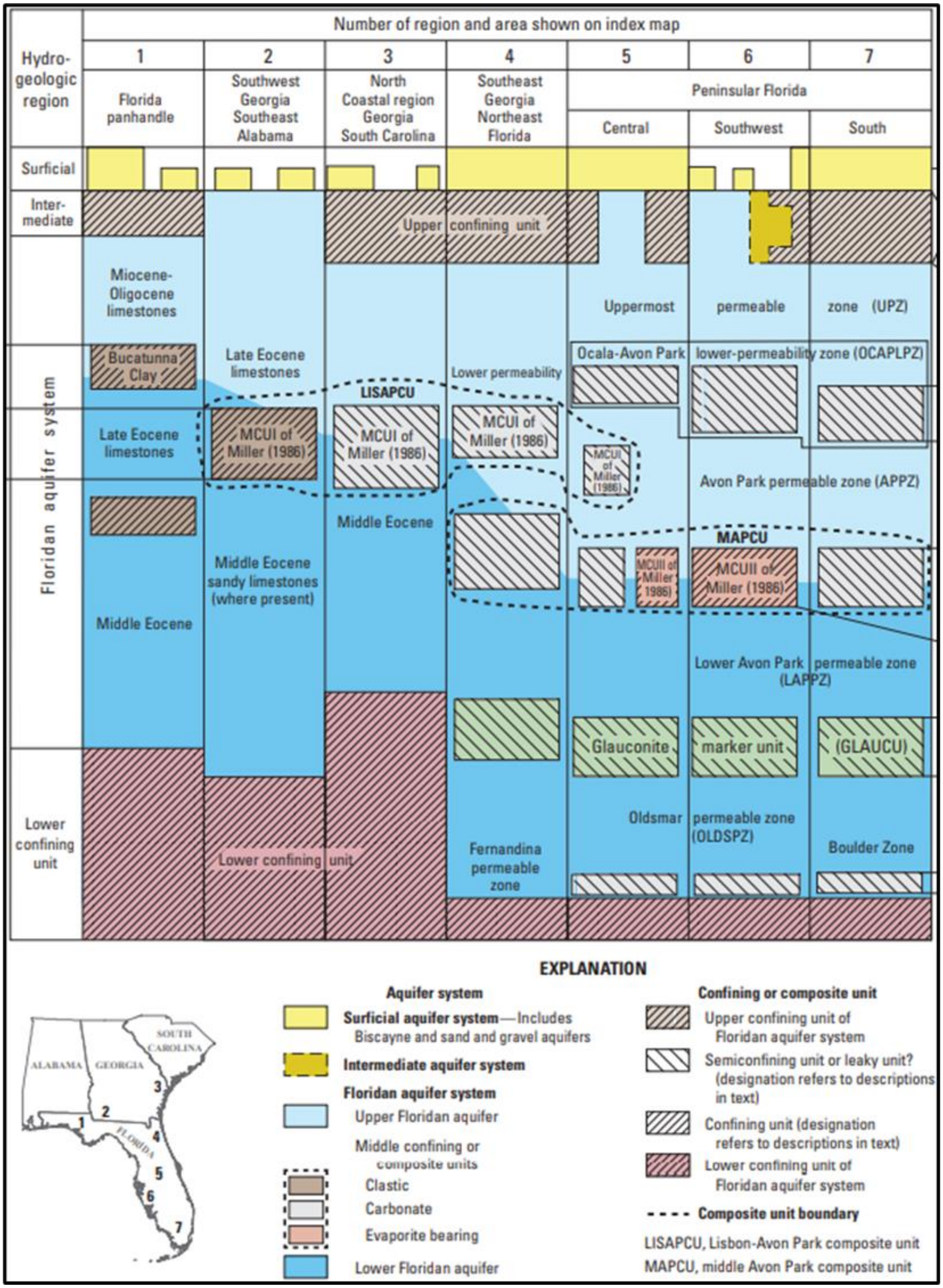

Figure 3.7: Floridan aquifer system cross-sections by region (Williams & Kuniansky, 2015)

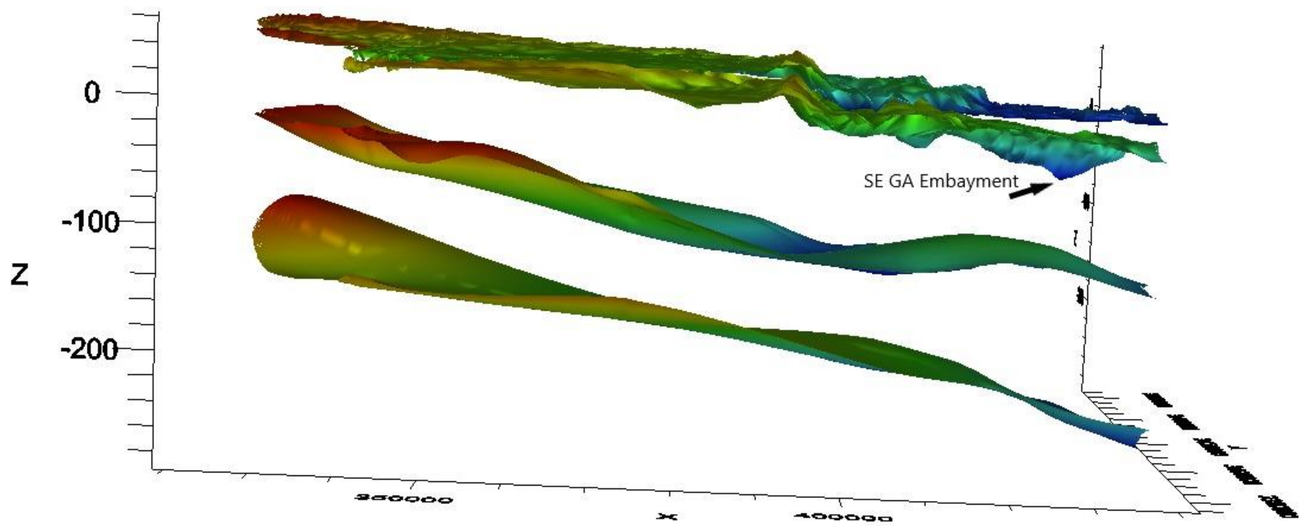

Figure 3.8: DEM surface files for land surface and geological horizon characterization

Tables

Table 3.1: Calculations for wetland coverage in model domain

Total % Wetlands =	49.47
Model Area (sq mi) =	3331.36
Total Wetland Area (sq mi) =	1647.94
Okefenokee Area (sq mi) =	684.38
Okefenokee % of wetlands =	41.53

Table 3.2: Names and descriptions of GIS files extracted from USGS Data Series 926

File Name	Description
fig_20_thickness_surficial_raster	Thickness of undifferentiated material above upper confining unit
Plate3_thickness_UCU_raster	Thickness of upper confining unit (Hawthorn Group)
Plate4__Top_FAS_raster	Top of Floridan aquifer system
mcu_regional_raster	Base of Upper Floridan aquifer

Table 3.3: Data sources for model property inputs

Layer	Source	Transmissivity (ft^2/day)	T (m^2/s)	Kh (ft/day)	Kh (m/s)	Kv (ft/day)	Kv (m/s)	Type
Layer 1- Surficial Aquifer	USGS Scientific Investigations Report 2019-5035	14 - 6,000	1.51E-05 - 6.45E-03	105	3.70E-04	105	3.70E-04	Model Input
	USGS Scientific Investigations Report 2005-5065	500	5.38E-04	6	2.12E-05	6	2.12E-05	Reported
	Ground-Water Conditions and Studies in Georgia, 2004-2005	6,000	6.45E-03	70	2.47E-04	70	2.47E-04	Reported
	USGS Scientific Investigations Report 2005-5089	14 - 6,700	1.51E-05 - 7.2E-03	70	2.47E-04	70	2.47E-04	Reported
	USGS Scientific Investigations Report 2010-5072	1,000 - 10,000	1.08E-03 - 1.08E-02					Reported
Layer 2-4 -Upper Confining Unit	USGS Professional Paper 1807			1.00E-03	3.53E-09	1.00E-03	3.53E-09	Reported
	USGS Scientific Investigations Report 2015-5061			5.30E-05 - 3	1.87E-10 - 1.06E-05	5.30E-05 - 3	1.87E-10 - 1.06E-05	Reported
	USGS Scientific Investigations Report 2005-5089			5.30E-05 - 3	1.87E-10 - 1.06E-05	5.30E-05 - 3	1.87E-10 - 1.06E-05	Reported
				1.70E-04 - 0.2	5.99E-10 - 7.06E-07	1.70E-04 - 0.2	5.99E-10 - 7.06E-07	Simulated
	USGS Scientific Investigations Report 2019-5035			1.00E-05	3.53E-11	1.00E-05	3.53E-11	Model Input
Layer 3- Brunswick Aquifer Zone	USGS Professional Paper 1807	15 - 4,700	1.61E-05 - 5.05E-03					Reported
	USGS Scientific Investigations Report 2015-5061	20 - 4,700	2.15E-05 - 5.05E-03	10 - 20	3.53E-05 - 7.06E-05	10 - 20	3.53E-05 - 7.06E-05	Model Input
	USGS Scientific Investigations Report 2005-5089	15 - 4,700	1.61E-05 - 5.05E-03	50	1.76E-04	50	1.76E-04	Model Input
	USGS Scientific Investigations Report 2019-5035			10 - 20	3.53E-05 - 7.06E-05	10 - 20	3.53E-05 - 7.06E-05	Model Input
	Ground-Water Conditions and Studies in Georgia, 2004-2005			20	7.06E-05	20	7.06E-05	Reported
	Ground-Water Conditions and Studies in Georgia, 2002-2003			2	7.06E-06	2	7.06E-06	Reported
Layer 5-Upper Floridan Aquifer	USGS Data Series 669	98,000 (AVG from Aquifer Pump Test) 40,000 (AVG from Specific Capacity Data)	1.05E-01 4.30E-02					
	USGS Scientific Investigations Report 2019-5035			750 - 3,415	2.65E-03 - 1.20E-02	750 - 3,415	2.65E-03 - 1.20E-02	Model Input
	USGS Scientific Investigations Report 2005-5089	530 - 600,000	5.70E-04 - 6.45E-01	150 - 2,819	5.29E-04 - 9.94E-03	150 - 2,819	5.29E-04 - 9.94E-03	Model Input
	USGS Scientific Investigations Report 2010-5072			0.7 - 58,000	2.47E-06 - 2.05E-01	0.7 - 58,000	2.47E-06 - 2.05E-01	Reported
	USGS Scientific Investigations Report 2004-5264	530 - 600,000	5.70E-04 - 6.45E-01	1.34E-03 - 160.4	4.73E-09 - 5.66E-04	1.34E-03 - 160.4	4.73E-09 - 5.66E-04	Reported

Table 3.4: USGS stream gages used for model parameter estimates

Gage Name	Gage Number
Satilla River near Waycross, GA	02226500
Satilla River at Atkinson, GA	02228000
Satilla River at US 17, at Woodbine, GA	02228070
North Prong St. Marys River at Moniac, GA	02228500
St Marys River at Ferry Landing near Folkston, GA	02231175
St Marys River at I-95, near Kingsland, GA	02231254
Alabaha River at GA 203, near Blackshear, GA	02227270
Suwannee River above Fargo, GA	02314495
Suwannee River at US 441, at Fargo, GA	02314500

Table 3.5: Stream gages used to determine river width parameter for model input

River Section	Reference Gage(s)	Polyline Identifier	River Width Input (m)
Satilla 1	02226500	Polyline 9 Zone 1	50
Satilla 2	02226500	Polyline 9 Zone 2	60
Satilla 3	02228000	Polyline 9 Zone 0	107
North Prong St. Marys	02225800	Polyline 6	15.25
St. Marys	02231175/02231254	Polyline 8	180
Suwannee	02314500	Polyline 11	70
Crooked	N/A	Polyline 1	80
Unlabeled	N/A	Polyline 5	100

CHAPTER 4

RESULTS AND DISCUSSION

The results of this study include a baseline 3D conceptual groundwater flow model for pre-development conditions within the study region, a simulated theoretical framework of water table elevations, groundwater heads, and Darcy groundwater velocities (fluxes), a better understanding of data needs within the region of interest, and an accumulation of datasets and resources pertaining to the modeled system. Each of which contribute to an overall understanding of the region's surface water and groundwater systems and their interactions. Furthermore, the results of this study provide a basis for continued research and modeling of local and regional hydrologic systems in Southeast Georgia and Northeast Florida to contribute to a long-term goal of assessing potential hydrologic impacts associated with heavy mineral mining in the region.

4.1 Conceptual Model

The resulting conceptual model structure (Figure 4.1) includes three layers, where the topmost layer represents the surficial aquifer system, the middle layer represents the regional confining unit and intermediate Brunswick aquifer (Figure 4.2), and the bottom layer represents the UFA. The conceptual model also includes boundary conditions used to delineate regional streams and the Okefenokee Swamp on the surface of the model.

Model Layer 1, the surficial aquifer, has a volume of 1.72E+11 m^3 and a maximum thickness of 83.21 m. Layers 2 through 4, the confining unit layers, each have a volume of 3.28E+11 m^3 and a maximum thickness of 58.78 m, for a combined volume of 9.84E+11 m^3 and maximum thickness of 176.34 m. The Brunswick aquifer property zone occupies an area of 1.13E+9 m^2 with a volume of 4.92E+10 m^3 in Layer 3. Layer 5, the UFA, has a volume of 8063E+11 m^3 with a maximum thickness of 150.63 m. Additional layer geometries are presented in Figure 4.3.

4.2 Numerical Model

The numerical model used for initial simulations consists of a horizontal 50x50 finite difference grid where each layer was discretized into three vertical cells, making a total of fifteen numerical model layers across the model domain (Figures 4.4 and 4.5). Cells in the numerical grid that exist outside of the model boundary are assigned an inactive designation. Each boundary condition applies to its associated layers such that cells containing wetland and stream boundary conditions exist in the layers that correspond to their depths. Therefore, cells containing streams are present in Layers 1 and 2, and the Okefenokee Swamp and additional wetlands are present in Layer 1. Similarly, cells containing UFA constant head boundaries are present in their associated layers, extending from Layers 4 through 15.

4.3 Steady-State Simulation Statistics

Initial steady-state model simulations involved convergence issues which required iterative troubleshooting to identify and rectify sources of error in boundary condition inputs. After simulation errors were resolved, the model consistently converges with all boundary conditions applied. The uncalibrated model typically converges between 200 and 300 iterations, with a convergence residual of 9.796E-02 and a maximum change of 2.227E-04. Simulated theoretical mass balance for the groundwater system as modeled is displayed after every model run (Figure 4.6). Because the model is run under steady-state conditions during one time step, cumulative volumes are equal to rates in the mass balance output.

The mass balance results for the most up-to-date simulation indicate that the system is accumulating more water than it is losing. However, this could change with future model iterations that include groundwater withdrawal from aquifer pumping. Furthermore, the system is constrained by no-flow boundaries along the Northern and Southern borders of the model domain. Because these boundaries were designed to constrain flow in the UFA, groundwater that would likely leave the system along stream channels that pass through the Northern and Southern borders in the surficial aquifer is kept in the system by the no-flow boundaries. To mitigate this occurrence, an additional specified-flux boundary condition will need to be applied at the locations where streams enter and exit the model domain. This will be discussed in greater detail later in this section.

4.4 Simulated Water Table Elevation

The simulated water table elevation results (Figure 4.7) indicate a general coastward trend in groundwater flow, following the surface topography. Furthermore, water table elevations accurately indicate topographic lows where groundwater would discharge, such as the Okefenokee Swamp basin and large river sections. However, the water table results contain a few discrepancies that do not represent natural conditions. For example, water table elevations in land areas upgradient of surface water features are simulated above the ground surface. Though it is promising that groundwater elevations are approximating land surface topography, it seems that the groundwater table needs to be slightly lowered uniformly across the model area.

Northwest of the Okefenokee Swamp basin, the simulated water table exhibits the highest elevation of anywhere in the model and is mounding above the land surface. The land surface west and northwest of the mounding location is at a slightly higher elevation and should therefore have a higher water table elevation. This occurrence is likely a result of the existing boundary conditions on the western and northern model borders. The constant head boundary on the western model border may need to be adjusted to better approximate the down-sloping gradient from north to south along the model edge, such that near-surface groundwater elevations are higher in the northwest corner of the model than those of the southwest corner. Along the northern boundary, the Satilla River exits the model domain and re-enters farther east (indicated by blue arrows in Figure 4.7). The northern model border serves as a no-flow boundary, restricting groundwater flow into and out of the system along that section. The no-flow boundary was delineated according to UFA potentiometric surface contours as provided in USGS Data Series 926, making this a reasonable boundary for the UFA.

However, the surficial aquifer is separated from the UFA by the Hawthorn Group such that the two systems behave independently, where groundwater flow in the surficial aquifer has more correlation with surface water and topographic features. Therefore, it is predicted that surficial aquifer groundwater that would typically flow in the direction of stream channels is being restricted from leaving the model domain along the Satilla River because of the no-flow condition. This issue could be mitigated by applying a specified flux condition that approximates streamflow to the cells in which the Satilla River meets the model boundary.

Another discrepancy in simulated water table elevations exists where the Suwannee River exits the Okefenokee Swamp Basin (indicated by a red arrow in Figure 4.7). Water table elevations should be lower along the Suwannee River channel than the Okefenokee Swamp Basin, but initial simulations did not provide the expected result. This is also a result of boundary condition influence where the Suwannee River exits the western model border. The western model boundary was assigned a constant head condition per UFA equipotentials as reported in USGS Data Series 926. This pre-establishes groundwater elevations at the location where the Suwannee River exits the domain, likely causing a backwater effect since the constant head elevation is higher than Okefenokee Swamp levels. Water table elevations displayed in Figure 4.7 show the result of replacing constant head values with specified flux values for Suwannee River Cells that border the model domain. While this improved the issue, further boundary condition testing would provide better results for lowering the water table along the Suwannee River basin.

A second approach that may improve water table results for the Suwannee River would be applying the VMF streamflow routing (SFR2) boundary condition package for river systems. This package allows the user to delineate stream networks with options for defining junctions, diversions, and flow directions for intersecting stream segments. Furthermore, it provides the opportunity to include streamflow into or out of lakes or wetlands. The SFR2 uses model inputs to calculate mass balance between stream reaches, which contributes to a better representation of flow through surface water features and quantification of hyporheic zone interactions. The Okefenokee Swamp Basin receives inflow from Gum Swamp and Suwannee Creek and serves as the headwaters for the Suwannee and St. Marys Rivers which have tributaries of their own within the model domain. Therefore, use of the SFR2 boundary condition package for delineating surface water networks could improve simulated water table elevations for the model's wetland and river basins.

4.5 Simulated Heads

The simulated head results from the latest model iteration provide a theoretical basis for understanding groundwater head distribution across the model domain (Figures 4.8-4.16).

Additionally, simulated head results will enable the model to be calibrated to observed groundwater levels when additional field data has been obtained for the study region. Simulated head results indicate a general coastward decline in groundwater levels from west to east across the model domain. Based upon UFA equipotentials reported by the USGS, this is a reasonable theoretical result, as groundwater levels correspond to topographic gradients. Within the study region, the ground surface elevation declines approaching sea level, and the underlying geological layers follow this trend. The structural zones of the system get thicker as they approach the coast, but relative to the model datum, groundwater levels are lower in the eastern portion of the model when compared to their upgradient counterparts further inland. Simulated heads are typically lower within wetland and river basins across the model domain. Furthermore, there is a notable reduction in groundwater levels east of Trail Ridge, where the land surface elevation rapidly declines from Trail Ridge into the St. Marys and Satilla River floodplains.

Simulated heads are typically higher in the western portion of the model domain in every vertical layer. While hydraulic gradients contribute to groundwater elevations, the primary influence on simulated heads are the constant head boundaries on the eastern and western borders of the model. These boundary conditions provide the model with a basis for simulating heads in the model interior. Per reported USGS equipotentials, the constant head boundary on the western model edge is higher than that of the eastern edge, such that model solutions satisfy both conditions while providing interior simulated head results that transition between the two constant head boundaries, relate to topographic gradients, and factor in surface water conditions. In addition to influence from constant head boundaries, thinner sections of aquifer layers on the western half of the model domain may experience increased hydraulic pressure, contributing to higher potentiometric surfaces for that model region.

The simulated head results indicate a strong influence of low-elevation surface water features on groundwater levels in underlying layers. When analyzing head results in individual layers, it is evident that simulated heads are lower in cells that are below sizable wetland and river systems with free water surfaces (Figures 4.9-4.11). Specifically, the presence of the Okefenokee Swamp, Satilla River, and St. Marys River is observable in all model layers besides those associated with the UFA. Although the presence of these features is less obvious in deeper model layers, the reflection of surface water features on UCU heads was not an anticipated model result. Whether these results are feasible is still under speculation and will require further investigation through continued refinement and calibration of model results. Hydraulic head elevation is governed by the combined influence of elevation head and pressure head. Therefore, the lower elevations and free water surfaces of the features that are influencing heads in underlying layers may contribute to this result.

These results may also be influenced by the properties and boundary conditions used to define the model's boundary-value problem. For example, the UCU hydraulic conductivities that provided the best water table elevation results during manual calibration are at the higher end of estimated ranges reported in previous investigations of the system. The assumed homogeneity of model layer properties may be contributing to this result, where a simulation with a higher level of heterogeneity and spatial distribution of properties could reduce the propagation of surface-derived head influence on deeper layers. In the real system, there may be cases where UCU K_v is much lower under portions of the Okefenokee Swamp or river systems than was modeled in this study, limiting the influence on head elevations in underlying layers by reducing vertical leakage, limiting connectivity, and increasing pressure head. The feasibility of this result will be difficult to quantify without additional groundwater level observation data for the Upper Floridan and surficial aquifers.

The simulated head results also contain some discrepancies that indicate potential sources of error in model inputs. As seen in Figure 4.8, a few of the cells on the model surface have simulated head results that are displayed as a dark green/brown color that is not part of the color palette used to depict head elevations. These results are not well documented in VMF supporting materials, but it is assumed that they represent “dry” cells for which maximum groundwater elevations are below the cell bottom. These cells are only present in the topmost model layer and typically seem to appear in areas of higher land surface elevation, such as Trail Ridge and the northwest corner of the model domain, where regional topographic elevations are at a maximum. For the cells in the northwest corner, adjusting the constant head boundary at the top of the western edge may resolve the problem cells. If the constant head boundary value was increased, the cells in the vicinity of the adjustment would have an elevated supply of incoming groundwater.

The problem cells on Trail Ridge require a different approach, as Trail Ridge is an isolated sand terrace, where groundwater may drain west into the Okefenokee Swamp and east into the St. Marys River. It is also possible that groundwater moves west to east across the entire width of the terrace, with the land surface elevation on the eastern side being lower than that of the western. To remedy dry cells along Trail Ridge, the hydraulic conductivity of the feature could be lowered to reduce the flow of water out of cells and increase groundwater elevation. Acquisition of additional field data pertaining to Trail Ridge hydraulic conductivity could provide a better basis for model property input along the feature or in certain problem cells. By lowering K_h or K_v in the problem cells and neighboring cells, inputs from recharge could be retained, mitigating the drying problem. One model iteration was run to evaluate this assumption. Surficial aquifer K_h and K_v were lowered by three orders of magnitude in a cell that displayed head issues, and the results indicated that the problem was resolved, with no notable effect on water table elevation results. This approach could also be used on the problem zone in the northwest corner of the model if constant head adjustments are not sufficient.

Simulated heads along the western model boundary (Figure 4.16) also indicate potential issues in model results. One of which is the stark contrast in simulated heads between the first and second conceptual model layers of the UCU (numerical model layers 6 and 7). Here, simulated heads increase substantially from one layer to the next. This is a direct result of the assumptions made for assigning values to the western constant head boundary, where the simulated head differences closely reflect the head elevations assigned to the boundary condition. While these values were assigned to improve water table results, achieve model convergence, and encourage groundwater flow into the system, the boundary condition inputs need to be refined to better reflect realistic conditions.

In the actual system, there is likely a smoother transition in head elevations across model layers, and it is unlikely that the UCU would have high piezometric heads. It also may be the case that UFA heads are higher than those of lower UCU layers because of greater hydraulic pressures in confined aquifers. However, accurate representation of head elevations on the western model border will be difficult without additional groundwater level observation data. Without additional data, initial attempts for resolving this issue will require further manual calibration.

Another anomaly exists on the western model border where the Suwannee River exits the model domain. Here, simulated heads deviate from surrounding cells in every model layer, where heads below the constant head transition line are higher than surrounding cells, and those above the transition line are lower than surrounding cells. This is a direct result of deactivating the western constant head boundary in cells underlying the Suwannee River. Though this improved simulated head results in Suwannee River cells in the surficial aquifer layers, it did not fully achieve the desired water table results. Therefore, it may be useful to reactivate the constant head boundary in deeper model layers to reduce the downward propagation of head reduction from the Suwannee River. Further boundary condition modifications pertaining to the Suwannee River will need to be made to manage head discrepancies and achieve the desired water table results.

Further anomalies in simulated head results along the western model boundary occur at grid corners. This issue is mostly present in the surficial aquifer and UCU layers. Above the constant head transition line, grid corners simulate lower heads than surrounding cells, and below the transition line, grid corners simulate higher heads. The most notable of grid corner anomalies occurs just left of the center of the western model border (Figure 4.8). Here, simulated heads of approximately 55 m extend down into deeper UCU grid layers. This issue occurs at lower intensities on other sides of the model domain and is a result of how corner cells handle boundary conditions along the model edge. Refinement of the finite-difference grid or use of a different grid type could help resolve these discrepancies.

4.6 Simulated Velocities

VMF model outputs provide Darcy groundwater flow velocity, or flux, results through the model domain in the X, Y, and Z-directions (V_x, V_y, V_z), giving insight into how the model properties and boundary conditions affect flow in each direction. Furthermore, flow direction can be analyzed in individual layers, rows, or columns. Simulated flow velocities and velocity vector directions reflect many of the same results and discrepancies associated with simulated heads and water table elevations, while also providing some new considerations.

Because of the general coastward sloping topography and positioning of constant head and no-flow boundaries, most of the variations in simulated flow velocities are observable in the V_x results (Figure 4.17). Simulated V_x results show higher flow velocities in the UFA, especially in the eastern portion of the model, and in surficial aquifer layers that are influenced by surface water bodies. The V_x results on the model surface show increased flow velocity as groundwater moves down topographic gradients toward the Okefenokee Swamp Basin and stream channels. While the rate at which groundwater flows into surface water basins cannot be confirmed until compared with well-recovery or streamflow data, the general increase in velocity as groundwater discharges towards features of lower elevation is a feasible result.

Furthermore, higher flow velocities in the UFA is also reasonable because of the coastward gradient and high permeability. However, it was expected that flow velocity through the UFA would be more equally distributed across the UFA. The sudden increase in V_x near the eastern model border may indicate that the head elevation assigned to the constant head boundary condition on the eastern model edge is lower than it should be. In addition, simulated velocity results do not indicate much of a difference between groundwater flow in the UCU, surficial aquifer, and Brunswick aquifer along model borders. With the permeability of the UCU being much lower than that of other layers, it was expected that groundwater would move slower through the confining unit. These results could be tested and refined through model calibration and a decrease in UCU conductivity values.

Model outputs for V_z (Figure 4.19) also provided unexpected results for the vertical movement of groundwater through the system. For most areas on the model surface, V_z results indicate downward leakage from the model surface to underlying layers. However, the V_z results for the Okefenokee Swamp have a positive value, indicating upward leakage into the basin. Upward leakage is also simulated for river systems on the eastern side of the model domain. While it was expected that groundwater would flow into these basins from surrounding uplands, upward leakage through the bottom of these features was not anticipated per literature pertaining to Okefenokee Swamp water balance analysis. These results require further investigation by comparison to existing studies and additional model testing. Subsequent model iterations could benefit from assessing the effects of changing the bed thickness and conductance inputs for these features. Furthermore, transient model solutions may provide better estimates of flow direction, allowing water levels to fluctuate in model layers which would correlate vertical flow with hydraulic pressure and head differences.

Similar to the V_x results, V_z results do not indicate slower movement of groundwater through the UCU. With the input value for UCU K_v being lower than K_h, it was expected that groundwater was less likely to permeate vertically through the UCU. The V_z model results show little difference between values for the UCU and water bearing zones. Additionally, areas around the model border also show zones with positive simulated V_z values, indicating upward leakage through model layers. However, in the case of positive V_z values for the model surface and layers along the model border, the V_z component of the velocity vectors are very small compared to the V_x and V_y components, indicating that the flow in these locations may have a slight upward trend, but overall, travels in a relatively horizontal direction.

Where present, the small positive vertical components of flow velocities may be a result of the flow restrictions along the bottom and sides of the model domain. The current model is steady-state with minimal losses from the flow system. It is possible that the system is being supplied with too much water from recharge, the constant head boundary on the western model border, and initial head elevations. In this case, the hydraulic pressure of the system may be outweighing the force of gravity, causing groundwater to push toward the free surface of the model.

Further conclusions can be drawn on the feasibility of model results from analysis of directional velocity vectors in model layers, rows, or columns. Flow directions in model Layer 1 (Figure 4.20) show a strong correlation between horizontal flow paths and surface water features, where groundwater discharges to wetlands and rivers and generally trends coastward. However, flow direction where rivers exit the Okefenokee Swamp coincide with the water table elevation issues previously discussed.

Additionally, Layer 1 results show groundwater flowing from just east of the Okefenokee Swamp toward Trail Ridge. This either suggests that water from the swamp seeps under Trail Ridge toward the St. Marys River basin, which contradicts the common belief that Trail Ridge impounds the swamp, or that all recharge into Trail Ridge drains east toward the St. Marys River. Of these, the latter is more plausible for a couple of reasons. First, it is more likely that groundwater movement under the swamp would trend south toward the outflowing St. Marys River. Also, with the elevation east of Trail Ridge being lower than that on the west, it is possible that the majority of groundwater flow from Trail Ridge travels toward the lower gradient.

However, it has been reported that Trail Ridge is thought to contribute groundwater inputs into the swamp (Geological Society of America, 1986). This result can be evaluated in subsequent model iterations with varied hydraulic conductivity along Trail Ridge. Additionally, it is possible that the current resolution of the model grid contributes to the general eastward groundwater flow results across Trail Ridge. The current grid has Trail Ridge defined by three cells in the east-west direction. At this resolution, average flow direction may trend eastward, with a larger quantity of groundwater from trail ridge moving toward the St. Marys River. However, a higher east-west resolution along Trail Ridge could better capture the direction and quantity of groundwater flow, where a groundwater divide may exist along Trail Ridge such that groundwater flows both toward the Okefenokee Swamp and the St. Marys River.

Flow directions in model Layer 4 (Figure 4.21) indicate the propagated influence of streams and topographic features on the top of the confining unit. Similar results exist in model layers throughout the UCU. Layer 4 flow directions also show that groundwater beneath the Okefenokee Swamp travels west to east toward Trail Ridge. This result is feasible based on the modeled surface of the UCU unit which has an eastward down-sloping gradient under the Swamp Basin.

Model Layer 13 shows groundwater flow paths at the top of the UFA (Figure 4.22). Underlying UFA layers show very similar results. For the most part, flow through the UFA moves as expected with a uniform trend from west to east, adhering to model border boundary conditions. However, there is a substantial anomaly on the western side of the model domain in all UFA layers. Simulated flow directions in these layers show a groundwater divide that extends from north to south across the entire model domain. Here, groundwater west of the divide travels toward the western model edge, and groundwater east of the divide moves in the opposite direction. It was not expected for any UFA groundwater to travel toward the western model edge.

Under the assumption that this was a result of head elevations being too low in the UFA aquifer portion of the western constant head boundary, an additional model iteration was run to assess the effects of adjusting the boundary condition. For this simulation, the constant head boundary elevation of 55 m was deactivated from UCU model Layers Four and Five, and the value of 20 m was replaced by 40 m in all lower layers. This resolved the groundwater divide problem in the UFA, while also smoothing head results along the western model edge, resolving dry cells across the model surface, and improving stream drainage from the Okefenokee Swamp. However, it also raised simulated water table elevations across the model domain, worsening groundwater mounding in upland areas. With high potential for overall better model results, this approach for assigning the western constant head boundary should be further investigated in future model iterations.

Analysis of flow direction results in individual rows and columns provides insight into vertical flows through model layers in certain areas of interest. Near surface flows in model Row 35 (Figure 4.23) show that groundwater under Trail Ridge primarily moves east, toward the St. Marys River, with little indication of flow toward the Okefenokee Swamp. This result is consistent in most model rows along Trail Ridge. Furthermore, model Row 19 (Figure 4.24) shows that groundwater moves from West to East along the Penholoway Terrace and beneath the Mission Mine site. However, these results cannot be assumed true until the model has been adequately calibrated and validated.

The cross-sectional views of flow directions through individual rows and columns also indicate downward leakage of surficial aquifer groundwater through the UCU and horizontal flow through the UFA within the model interior. Supplementing flow direction results with simulated velocity magnitudes in individual rows and columns (Figure 4.26) indicates that groundwater movement through the UCU is four orders of magnitude slower than flows through the surficial and Upper Floridan aquifers. This is a feasible result because of the lower permeability of the UCU. Also shown in Figure 4.26, simulated velocity magnitude results indicate low flow velocities through the Okefenokee Swamp Basin, while also showing faster horizontal groundwater transmission in the Brunswick aquifer. Simulated velocity magnitudes in layer views also indicate that these results apply to vertical flow speeds for the Okefenokee Swamp Basin and Satilla and St. Marys riverbeds. Future efforts in model calibration will improve these results and assess their associated uncertainty.

4.7 Manual Calibration and Sensitive Parameters

Initial manual calibration efforts provide insight into sensitive parameters and their effects on model results. Results from initial calibration serve to narrow the focus on key parameters and their sensitive ranges for future manual calibration iterations and provide a basis for calibrating the steady-state model to observed values when sufficient field data are acquired.

Initial model simulations produce water table results with unrealistic elevations for topographic features in the domain. Discrepancies in water table elevations primarily occurred where wetland and river boundary conditions were applied on the model surface. Baseline simulations produced water table elevations that were higher in the Okefenokee Swamp Basin than the surrounding areas, which is opposite of natural conditions. To address this issue, incremental adjustments were made to model boundary conditions and layer properties that were assumed to influence Okefenokee Swamp levels and overall model performance for simulated water table elevations.

The constant head values used for initial model development were 20 m on the western boundary in all layers below the surficial aquifer and 5 m on the eastern boundary in all layers below the surficial aquifer. However, the 20 m constant head on the western boundary caused simulation errors and convergence failure because head elevations were lower than layer elevations for layers above the UFA. Therefore, western boundary constant heads were adjusted iteratively until model convergence was achieved and incremental improvements were made on simulated water table elevations, specifically. The best water table results to date were achieved by assigning a constant head value of 55 m to Layers Four through Six (top-most layer of the UCU) of the numerical model, while keeping all subsequent layers at a constant head of 20 m. This enabled model convergence and lowered simulated water table elevations west of the Okefenokee swamp, but did not resolve the elevated water table within the basin and caused discrepancies in other model outputs. These results may be further improved in later model iterations by incorporating a smoother transition from 20 m to 55 m within model layers assigned the western constant head boundary condition or by assigning a higher head value in lower model layers while removing or lowering the condition from all or specified layers of the UCU.

This parameter has a significant influence on results for every model simulation output type. At the current stage of this research, the best input value for western constant head boundary elevation has not yet been identified, but the effects of varying the boundary condition have been observed as a major factor for model convergence and quality of simulated heads, water table elevations, and flow velocities.

If the head elevation for this boundary condition is too low, results for water table elevations, groundwater head elevations, and groundwater flow direction suffer. A constant head elevation that is too low causes upgradient groundwater flow toward the western boundary, dry cells on the model surface, low water table elevations, and errors in model convergence. Furthermore, a constant head value that is too high causes mounded water table results, problems with stream drainage, inaccurate head elevations in the UCU, and a general oversupply of water to the system. The best cumulative results from editing this boundary condition were achieved with a constant head value of 40 m in model Layers 6 through 15 and no constant head boundary in higher model layers. A narrowed range for this input has not yet been identified, but it is somewhere between 20 and 55 m. Further calibration of this parameter should involve varying the head elevation between the recommended values and varying the depth at which the boundary is applied to the model edge for best results in each model output type.

Because the Okefenokee Swamp boundary condition already incorporates input from precipitation, it was assumed that adjusting the recharge boundary condition on the model surface could contribute to lowering water table elevations in the Okefenokee Swamp. Recharge was varied incrementally from 100 mm/yr to the original 167 mm/yr, with new simulations run for each adjustment. By reducing recharge, water table elevations were slightly reduced uniformly across the domain, but the Okefenokee Swamp discrepancy was not resolved relative to its surroundings. Because simulated water table elevations across the model domain generally approximated land surface elevation before reducing the value, the original 167 mm/yr was kept for subsequent model runs.

The next approach for resolving the Okefenokee Swamp water table discrepancy was editing the bed hydraulic conductivity assigned to the LAK boundary condition used to delineate the Okefenokee Swamp Basin. The initial bed hydraulic conductivity of 1.6E-03 m/s was incrementally increased by three orders of magnitude with negligible effects on the water table elevation over the Swamp. This indicated that the bed hydraulic conductivity for the Okefenokee LAK boundary condition is not a sensitive parameter for the model. The original 1.6E-03 m/s conductivity value was used for subsequent simulations.

To promote flow out of the Okefenokee basin into its surroundings, the vertical and horizontal hydraulic conductivity of the surficial aquifer was adjusted. It was assumed that by increasing the initial K_h and K_v of the surficial aquifer, the mounded water in the swamp would be able to drain into the surficial aquifer and move laterally through the system. While increasing the surficial aquifer K_h did not provide the desired results, overall improvements were made to simulated water table elevations across the model domain when K_v was increased. An increased K_h resulted in a general flattening of the water table. However, an increase in surficial aquifer K_v served to lower water levels in the Okefenokee Swamp Basin and reduce mounded groundwater elevations in other areas of the model. This likely improved the balance between recharge and vertical leakage through the system. Though this improved the issue with Okefenokee Swamp water levels, further adjustments were required to achieve realistic water table results such that groundwater would drain from uplands into the Swamp Basin.

The final and most effective approach for improving water table elevations in the Okefenokee Basin was adjusting the K_h and K_v of the UCU. For this method, it was predicted that higher UCU hydraulic conductivities would allow more water to drain from the surficial aquifer, further contributing to the balance between recharge and vertical leakage. If surficial aquifer water trapped under the Okefenokee Swamp by the UCU could drain, this would encourage a reduction in water table elevation at the swamp surface. The initial UCU K_h and K_v inputs were 3.53E-11 and 3.53E-13 m/s, respectively. These hydraulic conductivities are very low, essentially restricting any downward leakage from the surficial aquifer into the UCU. Heterogeneous K_h and K_v were assigned to the Hawthorn Group because of a lack of spatially distributed data, but it is likely that the UCU has zones of higher permeability or discontinuities such as faults or fractures that would have a higher capacity to transmit water.

UCU K_h and K_v values were both increased incrementally over several orders of magnitude. To date, the best simulated water table elevations were obtained through manual calibration of UCU conductivities and have reasonable results for groundwater levels in the Okefenokee Swamp Basin, the majority of large river basins, and general topographic gradients. Continued iterations for manual calibration of UCU hydraulic conductivities and better spatially distributed material property data would further improve these results.

After resolving the Okefenokee Swamp water table discrepancy, water table elevations along the Suwannee and St. Marys Rivers, which drain from the Okefenokee Swamp, were not simulated at lower elevations than the Swamp Basin, misrepresenting the natural movement of groundwater through the surficial aquifer. This is likely caused by the boundary conditions along the western and southern model edges. Efforts to remedy these issues involved modifying the boundary conditions at the locations where the rivers meet the model borders.

For the St. Marys River, the no-flow boundary on the southern edge of the model prevents flow leaving the Okefenokee Swamp from exiting the model domain, raising the water table where the St. Marys channel should be. To fix this issue, a constant head boundary was added to the cell along the southern model border where the river leaves the model domain. The head elevation was assigned a value of 35 m based on the land surface elevation and river stage measurements from USGS Stream Gage 02228500, which is downstream of the river section within the model domain. The new constant head boundary lowered the water table elevation at the desired location, providing an outlet from the Okefenokee Swamp.

For the Suwannee River, the constant head boundary on the western model border was removed from all model layers at the location where the river intersects the model border. This slightly lowered the water table along the stream channel, but it was still higher than that of the Okefenokee Swamp. The cell at the interface of the stream channel and model boundary was then assigned a specified flux boundary condition using the VMF FHB package in the three surficial aquifer layers of the numerical model grid to promote flow out of the model domain and further lower the water table.

Initial considerations for specified flux input values were based on discharge measurements from USGS Stream Gage 02314500 which is downstream of the location where the stream exits the model domain. Annual statistics from the gage's full period of record suggests an average discharge value of 82,323,884 m^3/d (953 ft^3/s (or cfs)) for model input. However, a discrepancy regarding required FHB input units was discovered between the VMF user manual, and the FHB input prompt within the VMF software interface.

The user manual suggests required units of L^3/T, while the VMF boundary condition input prompt displays units of m/day. It is likely that the FHB package calculates and applies specified flux in units of L^3/T based on user input in L/T and the area of the associated cell face [L^2] when using a finite-difference model grid and solver type. Therefore, a reserved specified flux value of -1000 "m/d" was assigned to the FHB boundary condition for simulation to see how results would be affected. With a cell size of 1,843.65 m x 1.92 m on the applied cell face (east-west), this yields a flux rate of -3,539,808 m^3/d.

The specified flux lowered the water table elevation where the Suwannee River exits the Okefenokee Swamp, but the lowered elevation did not extend to the model boundary as desired. Furthermore, the water table region influenced by the FHB input was wider than desired because of the grid resolution. Subsequent iterations were run with different input values, but essentially produced the same result, lowering water table elevations close to the Swamp, but not at the model border. Values of greater magnitude than -1000 m/d further widened the area of influence from the specified flux condition. This issue will require further attention and possibly a different approach as model development progresses. One possible solution that has not yet been tested is the replacement of the specified flux condition with a new constant head or general head boundary in the upper model layers that approximates river stage and land surface elevation.

In varying material properties for improving water table results, it was determined that surficial aquifer and UCU hydraulic conductivities have substantial effects on simulated water table elevations, where the UCU has an overall greater influence on model performance. For the surficial aquifer, the K_h was more sensitive than the K_v. A decrease in surficial aquifer K_v causes elevated water table results, reducing the ability of surface recharge to infiltrate into the system, whereas K_v could be increased by several orders of magnitude with negligible effects on water table results. Even with a higher K_v value, water from the surficial aquifer is unable to drain because of the underlying confining unit.

Varying surficial aquifer K_h values yields different results than varying the K_v values. Reducing surficial aquifer K_h by one order of magnitude causes a significant increase in water table elevations and worsens water table mounding in upland areas. Unlike surficial aquifer K_v values, increasing the K_h by one order of magnitude flattens the water table across the domain reducing the influence of topographic features on water table elevations. Increasing K_h by two orders of magnitude causes convergence failure. Therefore, surficial aquifer K_h is more sensitive than K_v. The best water table results to date were achieved with surficial aquifer $K_h = K_v = 3.7E\text{-}04$ m/s.

UCU hydraulic conductivities also proved to have notable effects on model performance and water table elevation results. Both UCU K_h and K_v were increased by several orders of magnitude from their original values before improvements were made on water table results. However, UCU K_v proved to be much more sensitive than K_h because it dictates the ability of water to drain from the surficial aquifer. From the original value of 3.53E-13 m/s, UCU K_v was increased by five orders of magnitude before improvements were made on water table results. From here, any additional increase in UCU K_v serves to drain the surficial aquifer and flatten the water table across the model domain. Within the UCU K_v order of magnitude that provides reasonable water table results, it was determined that a range of 1.0E-08 to 2.0E-08 m/s provides decent water table results, while any value below that range causes overflow in the surficial aquifer, and any value above that range drains the surficial aquifer. To date, the best water table results were achieved with a K_h of 1.0E-07 m/s in all UCU layers of the numerical model and a K_v of 1.4E-08 m/s for numerical model Layers 4 through 9 and 1.6E-08 m/s for numerical model Layers 10 through 12.

While constant head elevations for the western model boundary, UCU K_v, and surficial aquifer K_h proved to be sensitive parameters through manual calibration, the other parameters that were varied for assessment of their influence on model results seem to have little impact on model performance. These parameters included recharge, Okefenokee Swamp bed conductance, and evapotranspiration. Of these, recharge and Okefenokee Swamp conductance seem to have little effect on model results unless they are changed drastically to values that are not realistic. However, recharge does have importance in establishing a balance between precipitation inputs and UCU Kv. Additionally, it is possible that sensitive ranges for these parameters have not yet been identified. Evapotranspiration inputs typically led to model convergence failure in early model iterations. Because this model currently simulates steady state conditions, losses from evapotranspiration were assumed to be included in recharge, and it was excluded from further simulations. There are still some model parameters, such as riverbed conductance, that have not yet been adjusted, so future manual calibration could benefit from analyzing the effects of varying these parameters as well.

As further adjustments are made to model parameters and conclusions are drawn on model sensitivity and uncertainty, it will be important to consider the feasibility of parameter ranges that provide the best results. Equifinality refers to the ability of a model to produce similar results with different sets of parameters. Thus, it is possible to achieve model results that satisfy objective function criterion but do not accurately represent real-world properties. This is especially important to consider when conducting computer-assisted calibration and sensitivity analysis, where calibrated parameters are identified without consideration of realistic characteristics of the system. Here, the modeler must use intuition and knowledge of the modeled system to compare parameter sets that provide similar results regarding model performance and uncertainty. This will allow the modeler to identify parameter combinations that accurately reflect measured properties, minimize model uncertainty, and indicate satisfactory model performance.

Figures

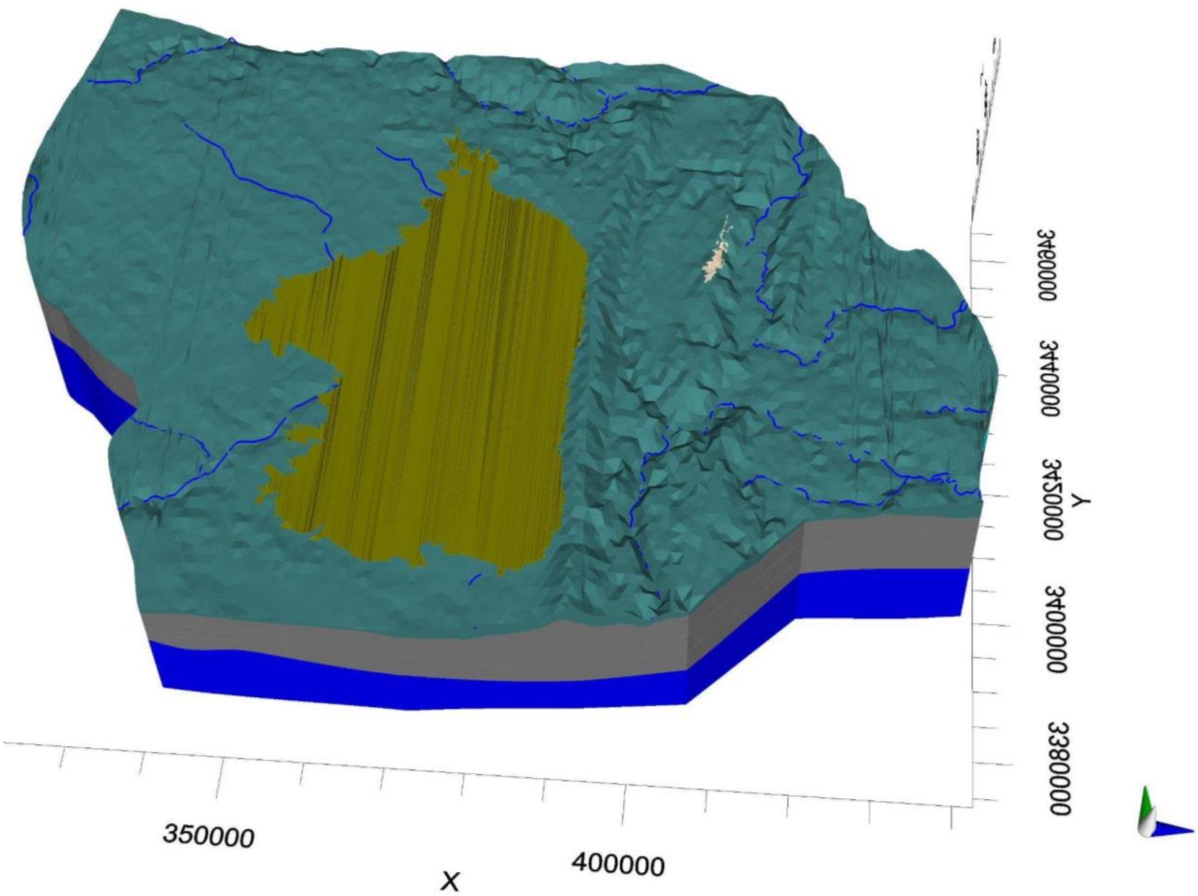

Figure 4.1: Conceptual groundwater flow model

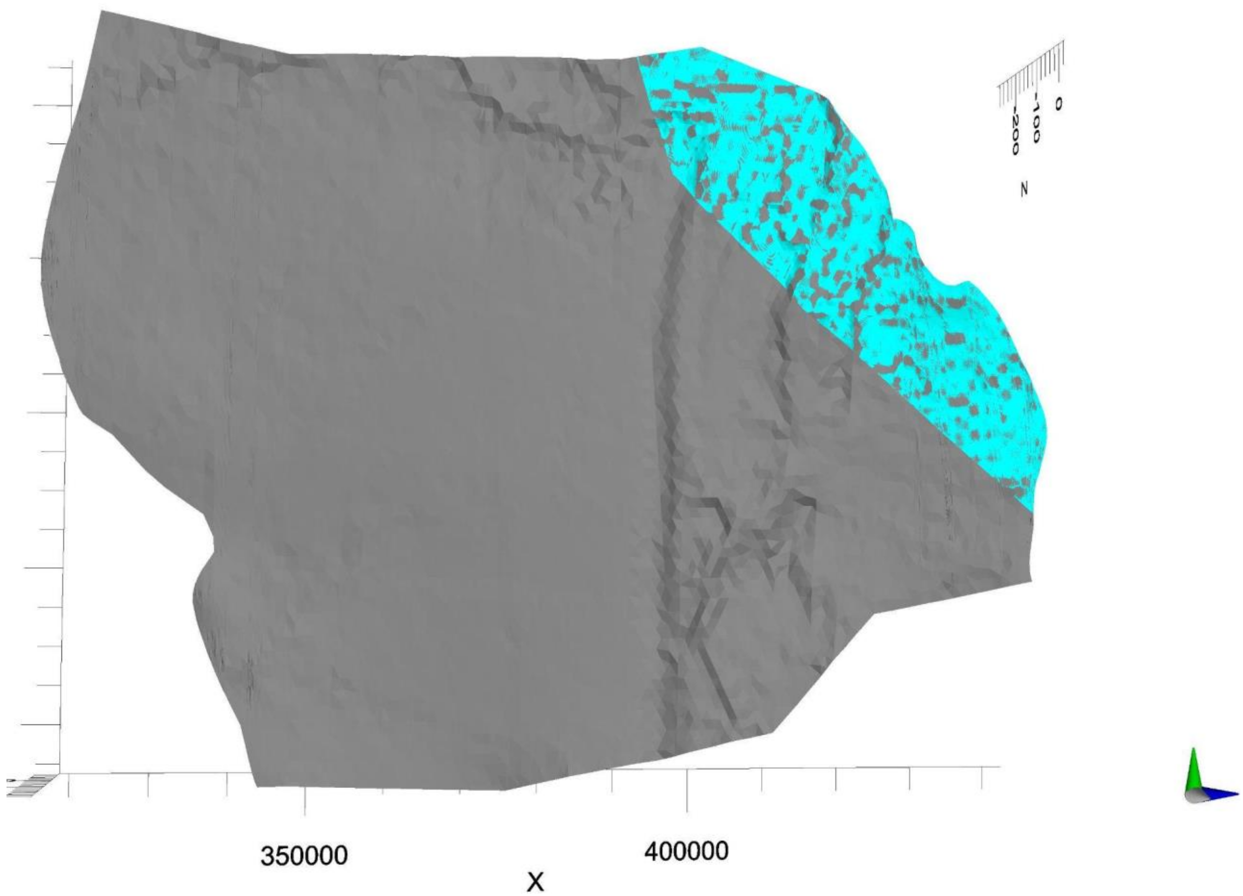

Figure 4.2: Brunswick aquifer property zone (blue) within confining unit

Layer 1

Parameter	Value	Unit
X Max	442561.07	m
X Min	318794.52	m
Y Max	3465949.91	m
Y Min	3373767.38	m
Z Max	67	m
Z Min	-79.08	m
Volume	1.72E+11	m^3
Area	8.63E+9	m^2

Layer 2

Parameter	Value	Unit
X Max	442561.07	m
X Min	318794.52	m
Y Max	3465949.91	m
Y Min	3373767.38	m
Z Max	52.48	m
Z Min	-107.34	m
Volume	3.28E+11	m^3
Area	8.63E+9	m^2

Layer 3

Parameter	Value	Unit
X Max	442561.07	m
X Min	318794.52	m
Y Max	3465949.91	m
Y Min	3373767.38	m
Z Max	33.69	m
Z Min	-149.21	m
Volume	3.28E+11	m^3
Area	8.63E+9	m^2

Layer 4

Parameter	Value	Unit
X Max	442561.07	m
X Min	318794.52	m
Y Max	3465949.91	m
Y Min	3373767.38	m
Z Max	22.65	m
Z Min	-196.4	m
Volume	3.28E+11	m^3
Area	8.63E+9	m^2

Layer 5

Parameter	Value	Unit
X Max	442561.07	m
X Min	318794.52	m
Y Max	3465949.91	m
Y Min	3373767.38	m
Z Max	11.97	m
Z Min	-297.38	m
Volume	8.63E+11	m^3
Area	8.63E+9	m^2

Brunswick Aquifer Property Zone

Parameter	Value	Unit
X Max	442561.07	m
X Min	389674.82	m
Y Max	3465138.72	m
Y Min	3407259.2	m
Z Max	33.69	m
Z Min	-149.21	m
Volume	4.92E+10	m^3
Area	1.13E+9	m^2

Figure 4.3: Model layer geometry

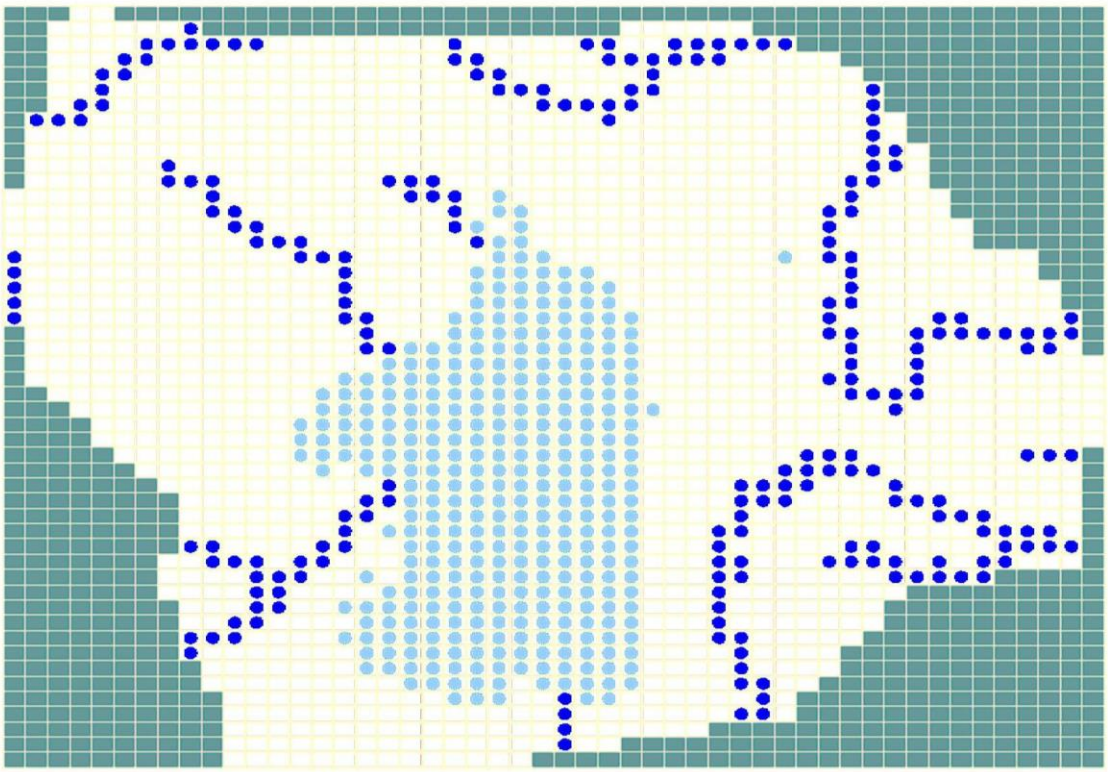

Figure 4.4: Numerical model Layer 1

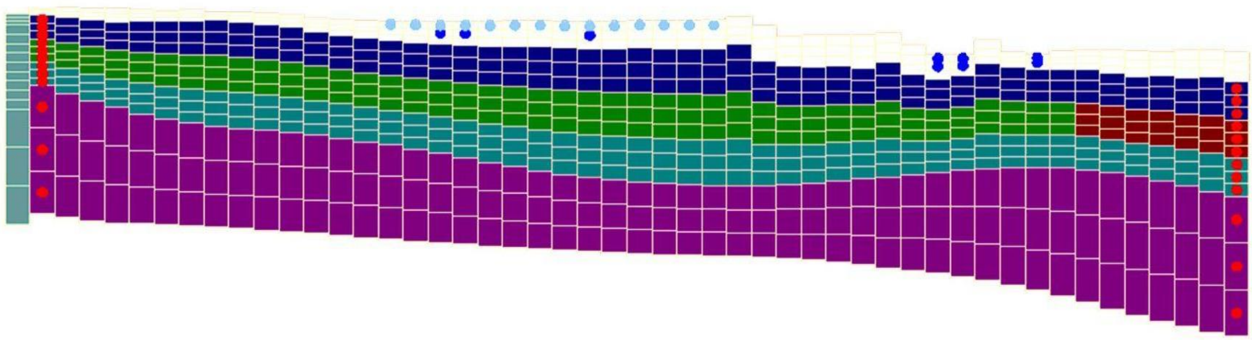

Figure 4.5: Numerical model Row 25 cross section (looking north)

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 VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    1, STRESS PERIOD   1
 ------------------------------------------------------------------------------

    CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
    ------------------                 ------------------------

          IN:                                      IN:
          ---                                      ---
            STORAGE =           0.0000              STORAGE =           0.0000
      CONSTANT HEAD =     1141376.6250        CONSTANT HEAD =     1141376.6250
      RIVER LEAKAGE =        1839.9891        RIVER LEAKAGE =        1839.9891
           RECHARGE =     3194577.0000             RECHARGE =     3194577.0000
    SPECIFIED FLOWS =           0.0000      SPECIFIED FLOWS =           0.0000
      LAKE  SEEPAGE =      274266.5000        LAKE  SEEPAGE =      274266.5000

           TOTAL IN =     4612060.0000             TOTAL IN =     4612060.0000

         OUT:                                     OUT:
         ----                                     ----
            STORAGE =           0.0000              STORAGE =           0.0000
      CONSTANT HEAD =     3543026.2500        CONSTANT HEAD =     3543026.2500
      RIVER LEAKAGE =      939665.7500        RIVER LEAKAGE =      939665.7500
           RECHARGE =           0.0000             RECHARGE =           0.0000
    SPECIFIED FLOWS =           0.0000      SPECIFIED FLOWS =           0.0000
      LAKE  SEEPAGE =      129250.3438        LAKE  SEEPAGE =      129250.3438

          TOTAL OUT =     4611942.5000            TOTAL OUT =     4611942.5000

           IN - OUT =         117.5000             IN - OUT =         117.5000

 PERCENT DISCREPANCY =           0.00     PERCENT DISCREPANCY =           0.00
```

Figure 4.6: Simulated mass balance information

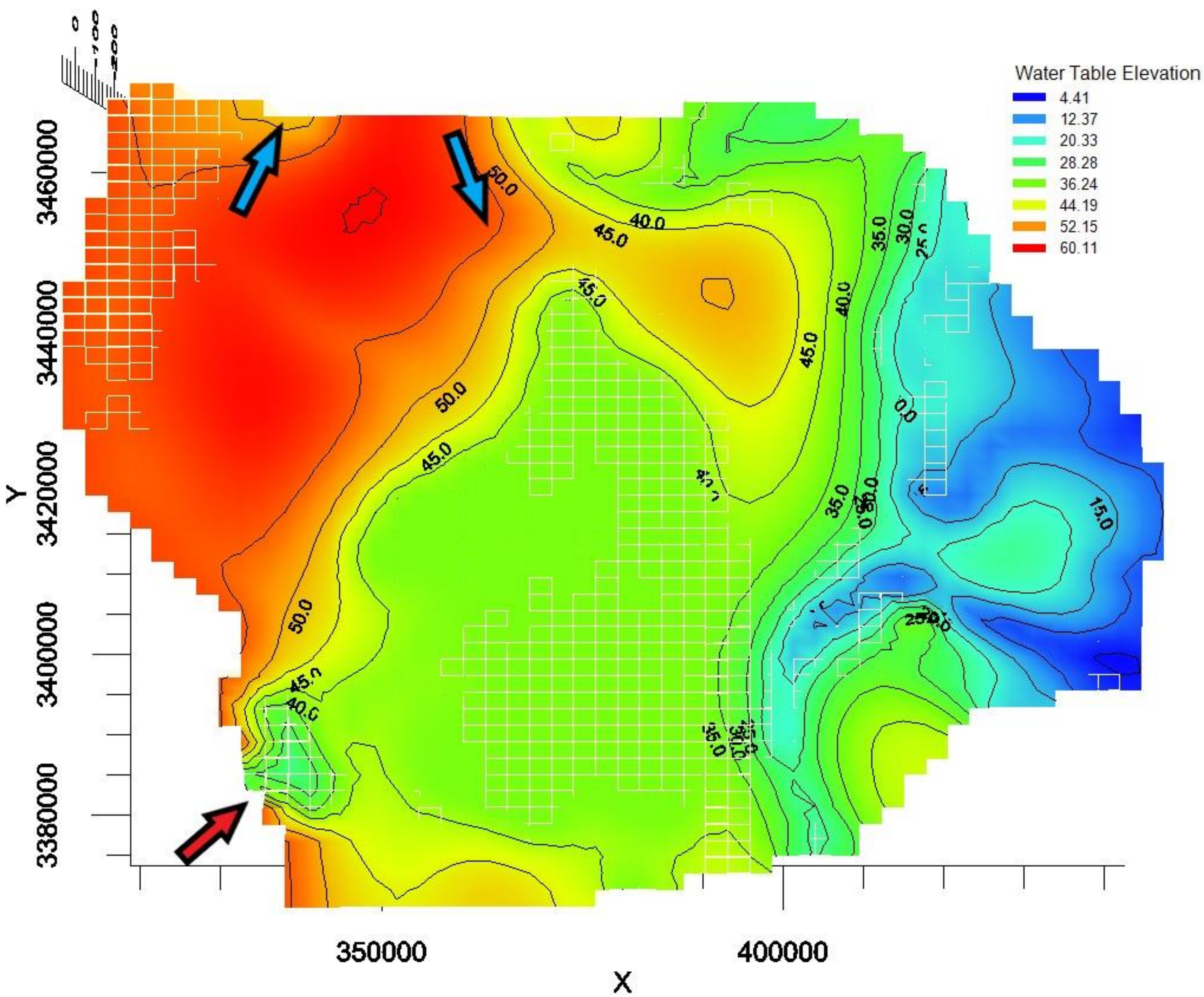

Figure 4.7: Simulated water table elevations (blue arrows indicate Satilla River flow and red arrow indicates Suwannee River problem zone)

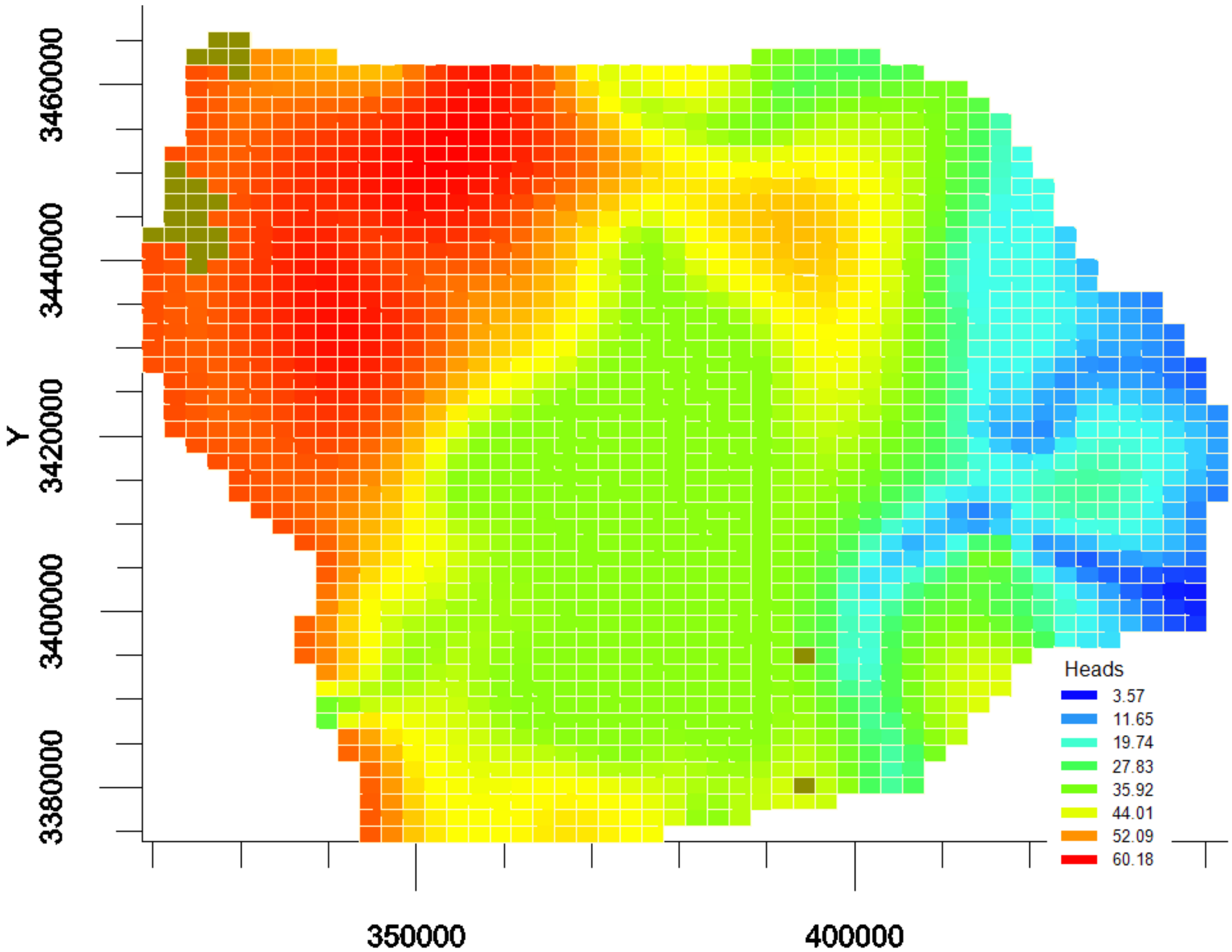

Figure 4.8: Simulated head results for model surface (Layer 1)

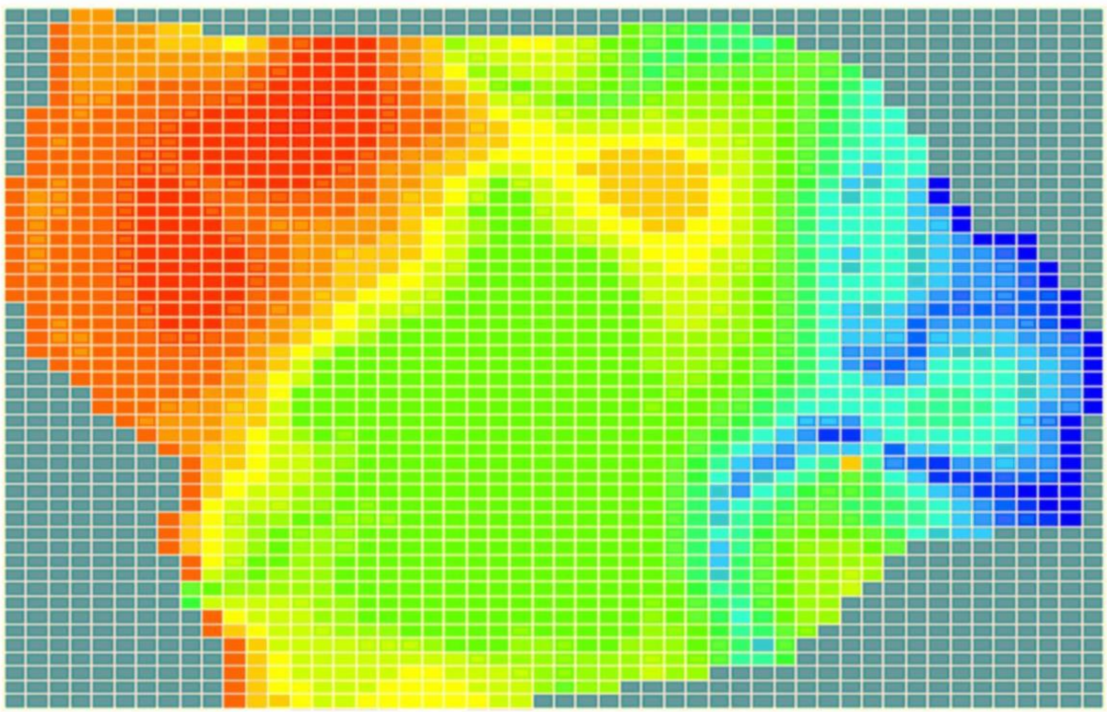

Figure 4.9: Simulated head results for top UCU layer (Layer 4)

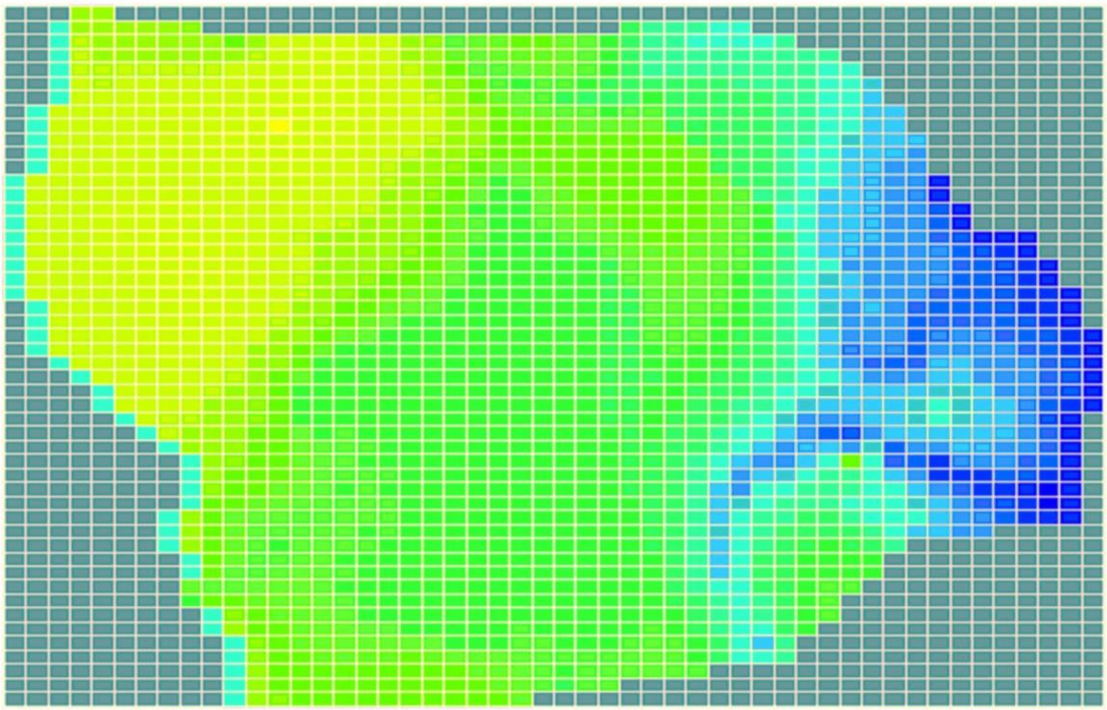

Figure 4.10: Simulated head results for middle UCU layer where BAS is present (Layer 7)

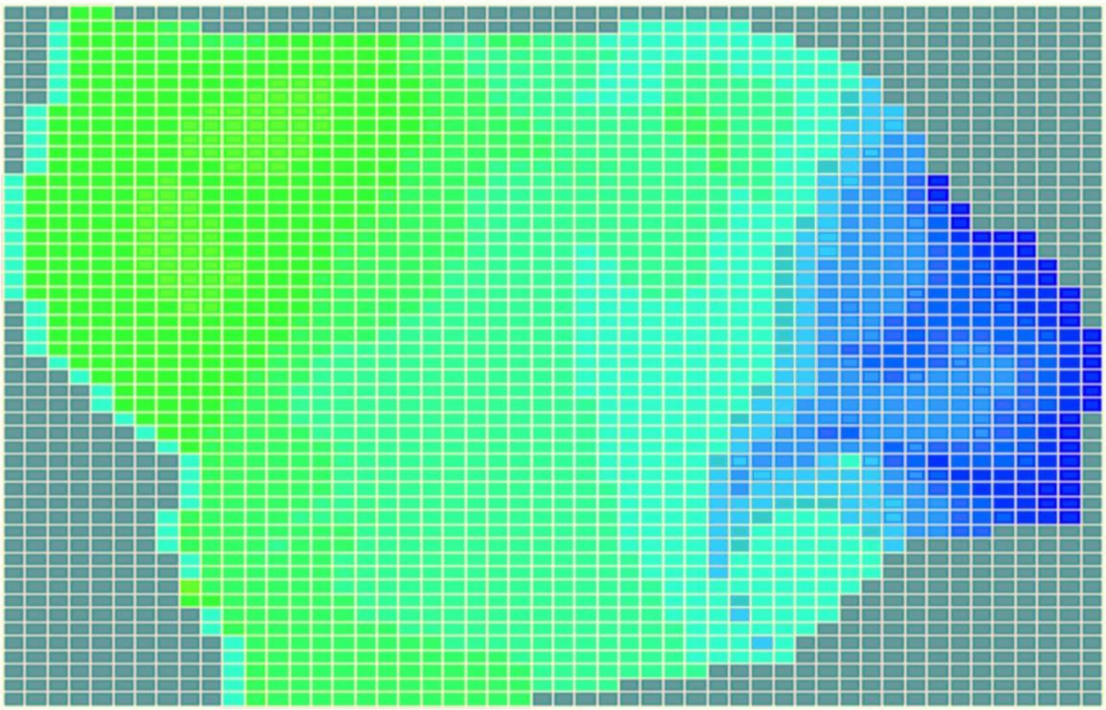

Figure 4.11: Simulated head results for bottom UCU layer (Layer 10)

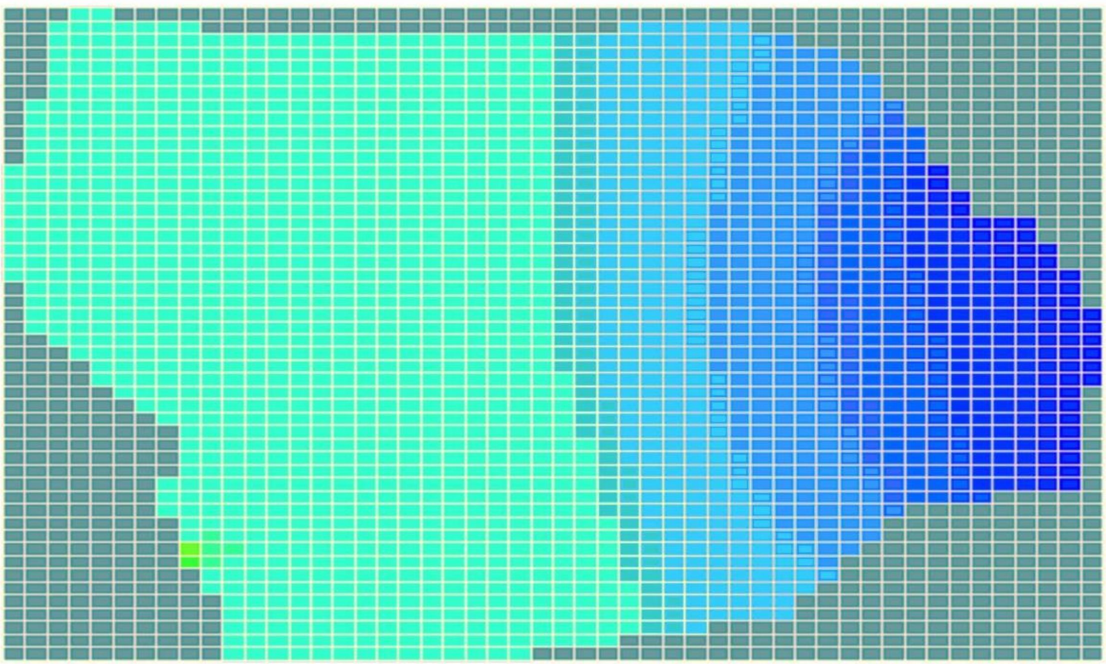

Figure 4.12: Simulated head results for top of UFA (Layer 13)

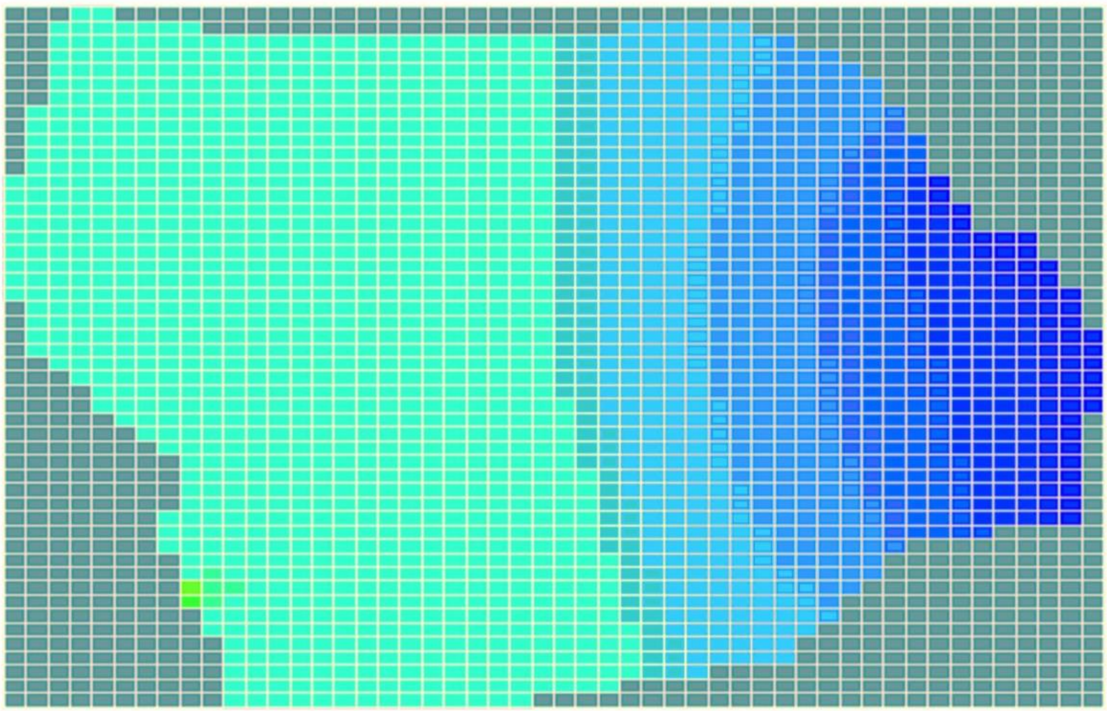

Figure 4.13: Simulated head results for base of UFA (Layer 15)

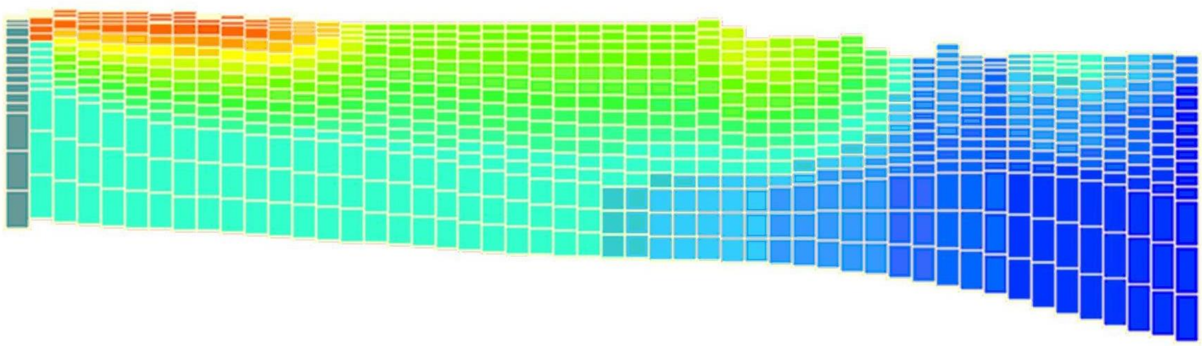

Figure 4.14: Simulated head results model Row 25 (looking north)

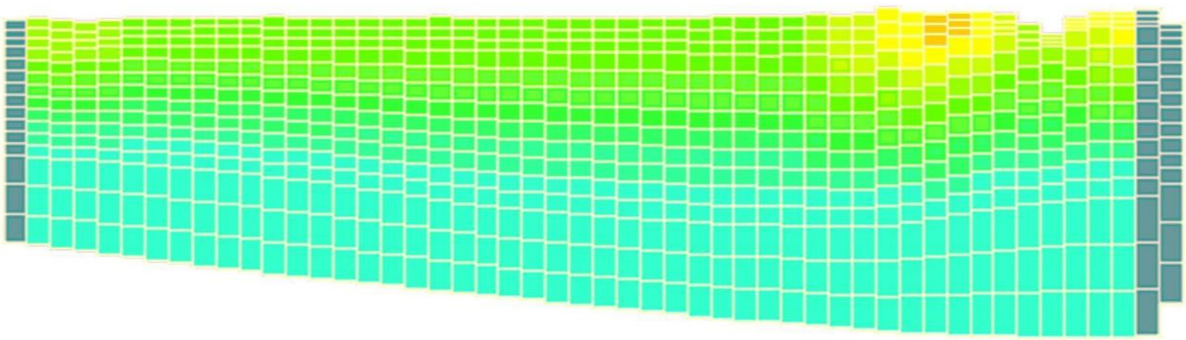

Figure 4.15: Simulated head results model Column 25 (looking east)

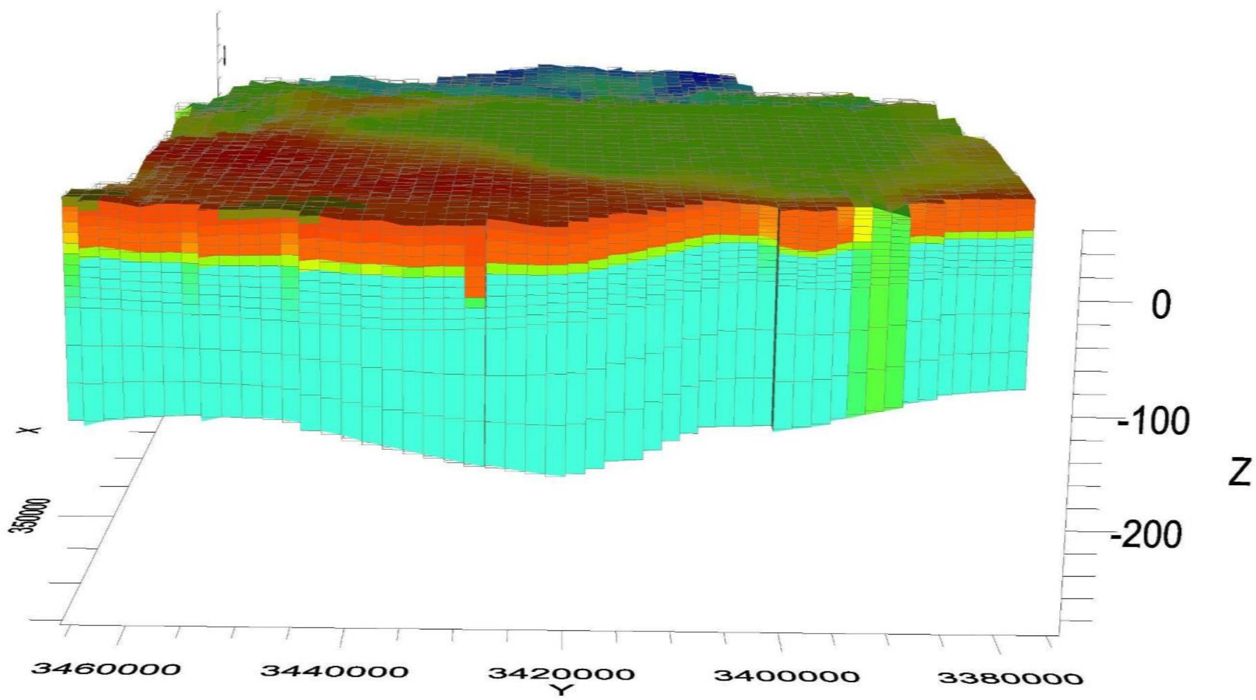

Figure 4.16: Simulated head results on western model boundary

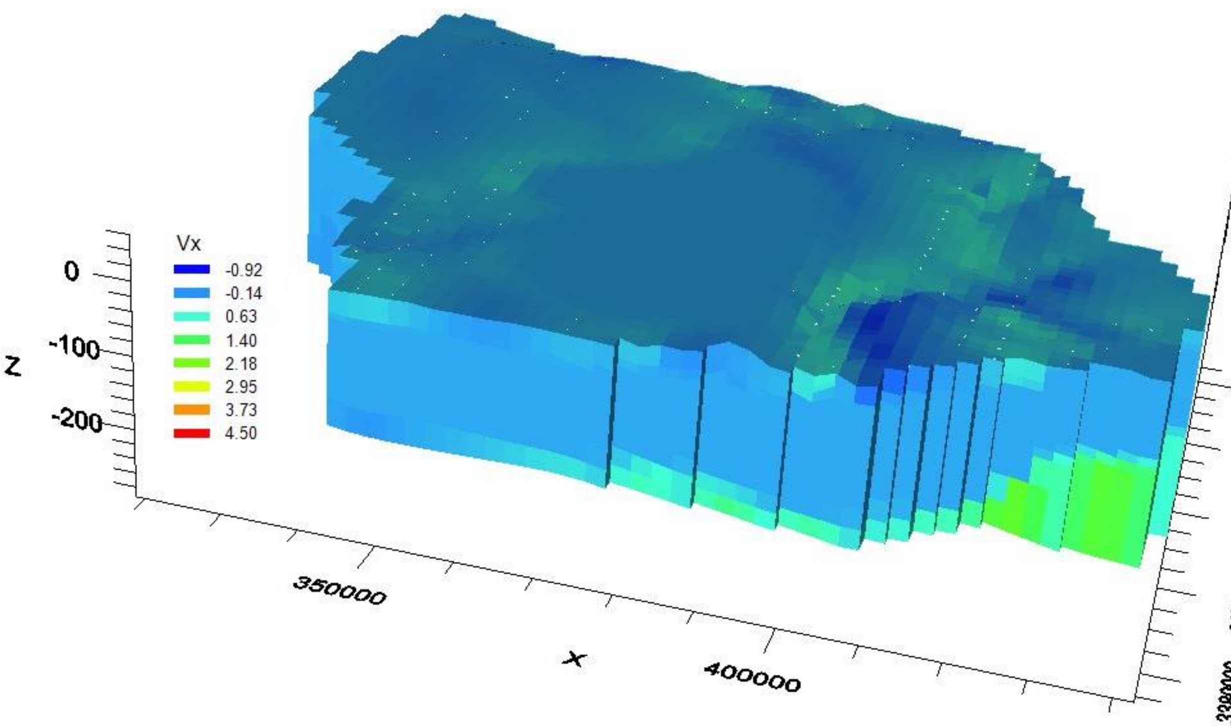

Figure 4.17: Simulated velocity results in the X-direction (V_x)

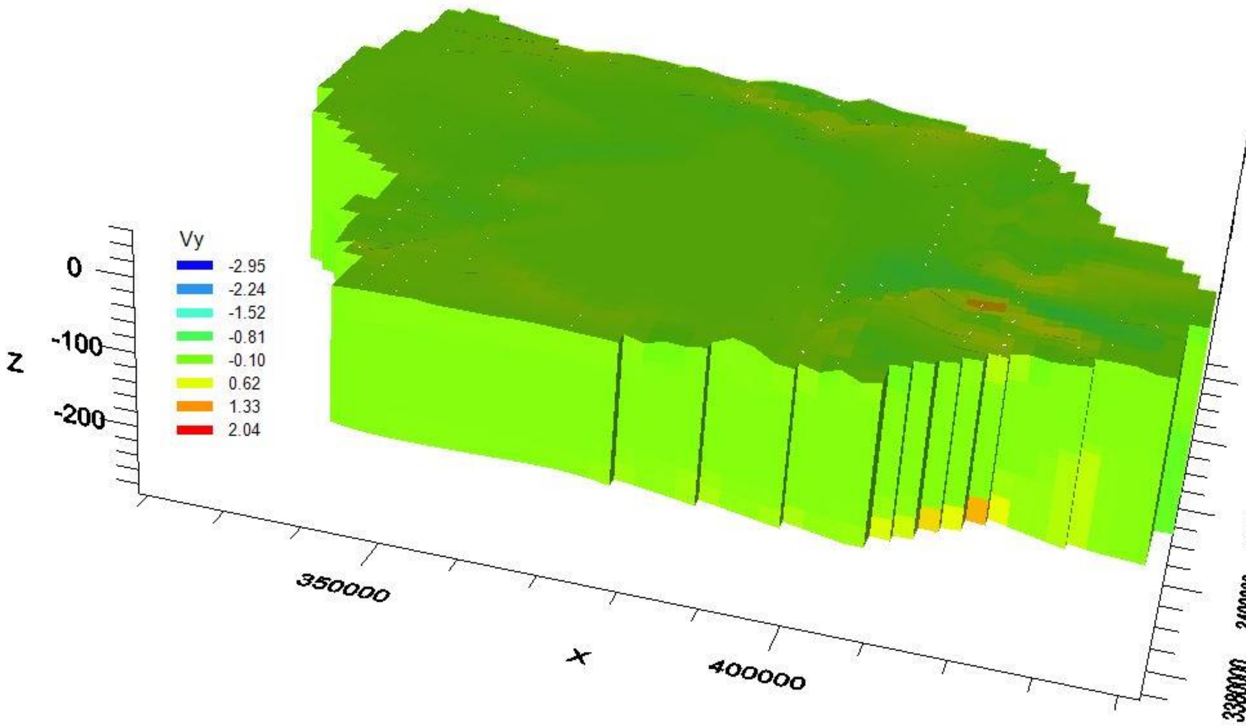

Figure 4.18: Simulated velocity results in the Y-direction (V_y)

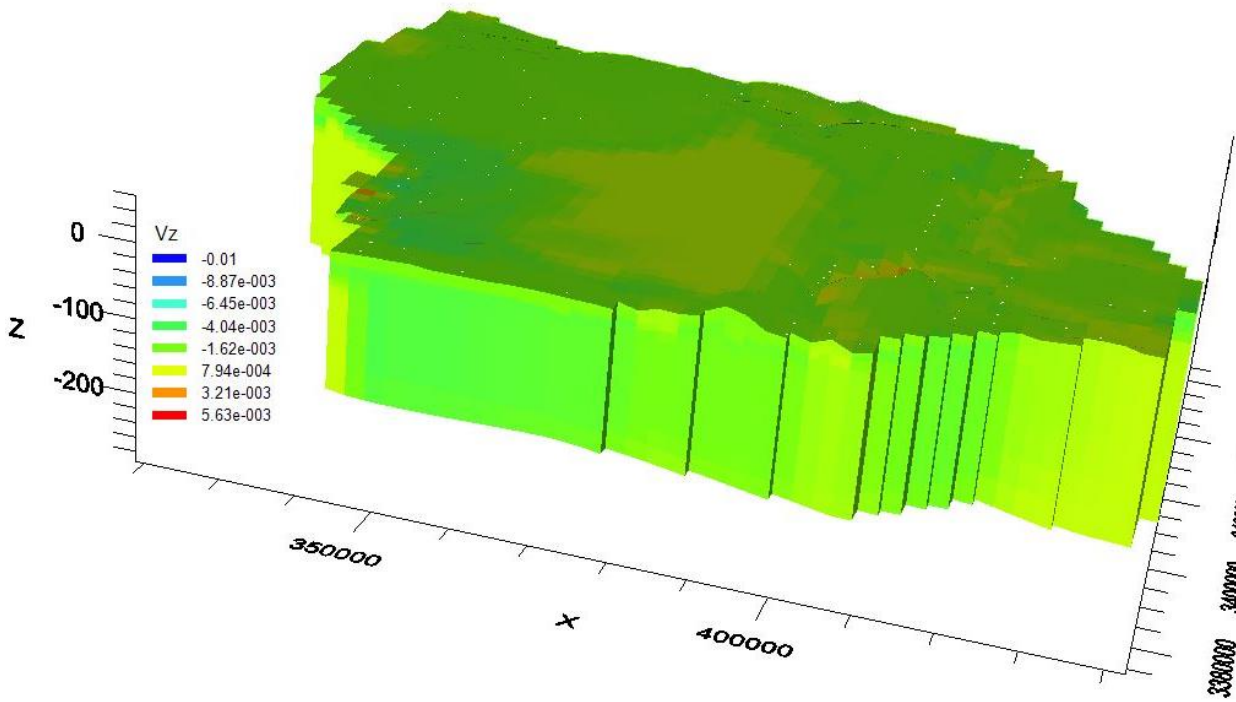

Figure 4.19: Simulated velocity results in the Z-direction (V_z)

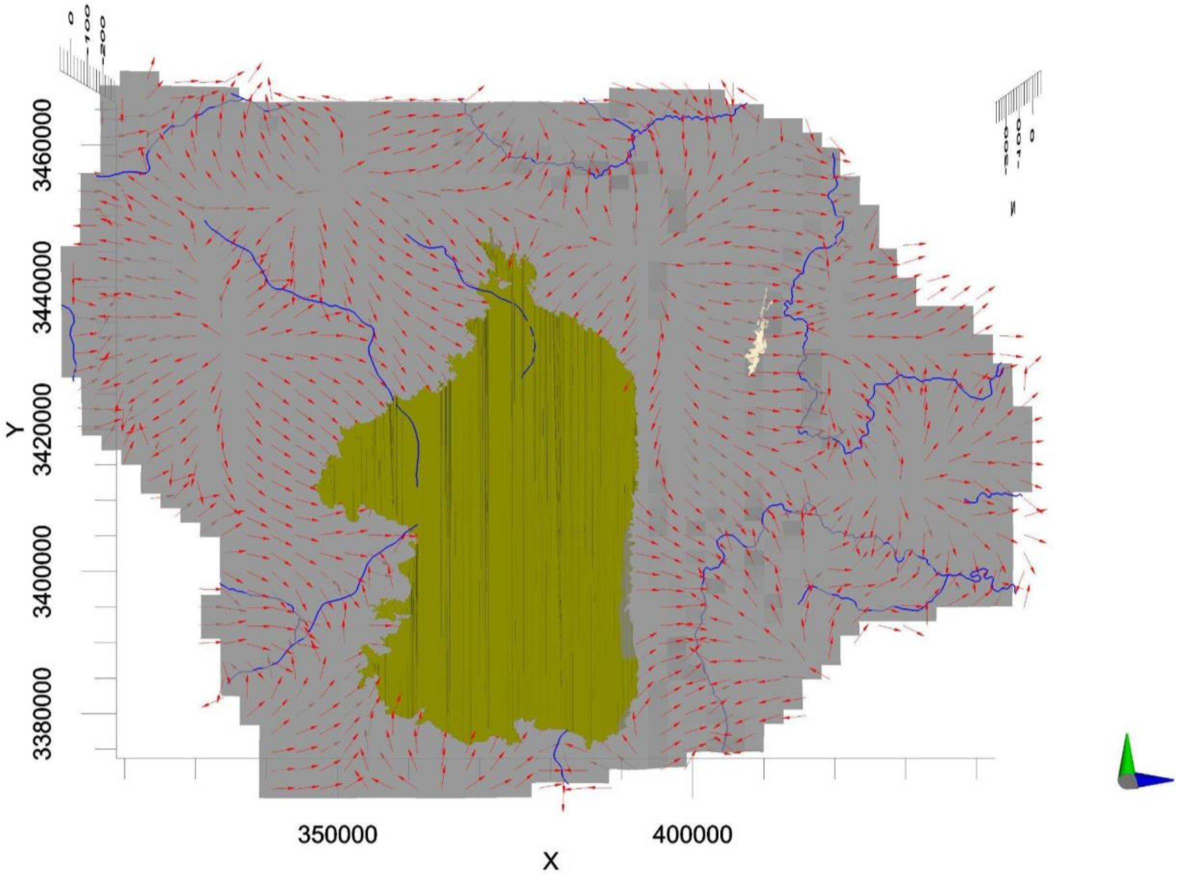

Figure 4.20: Simulated velocity vector directions for model Layer 1

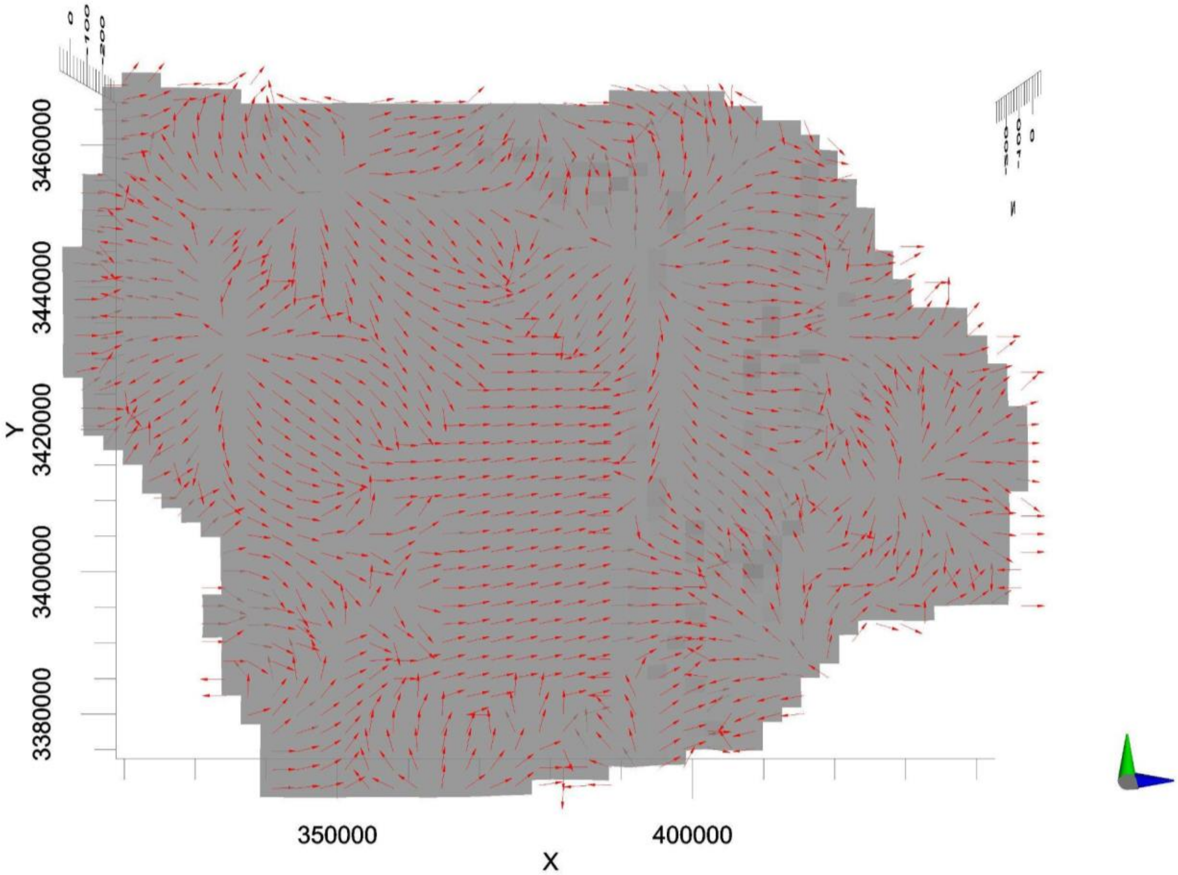

Figure 4.21: Simulated velocity vector directions for model Layer 4

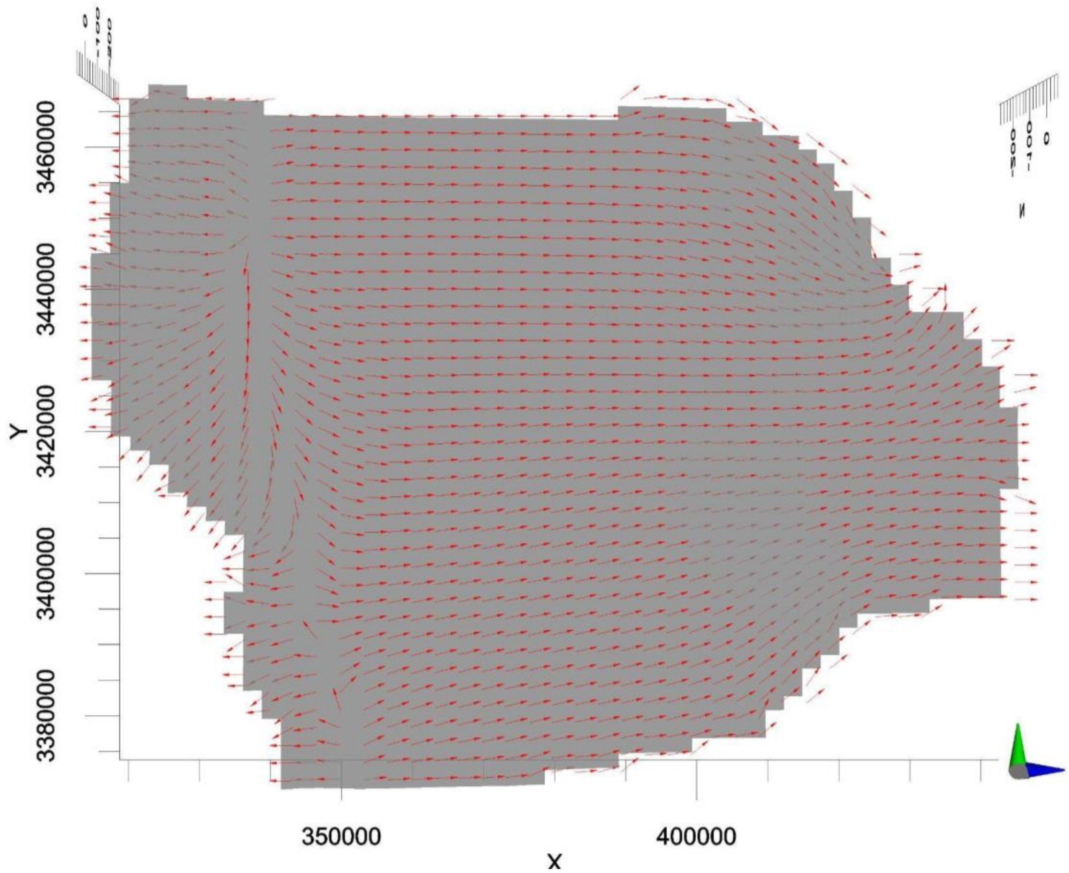

Figure 4.22: Simulated velocity vector directions for model Layer 13

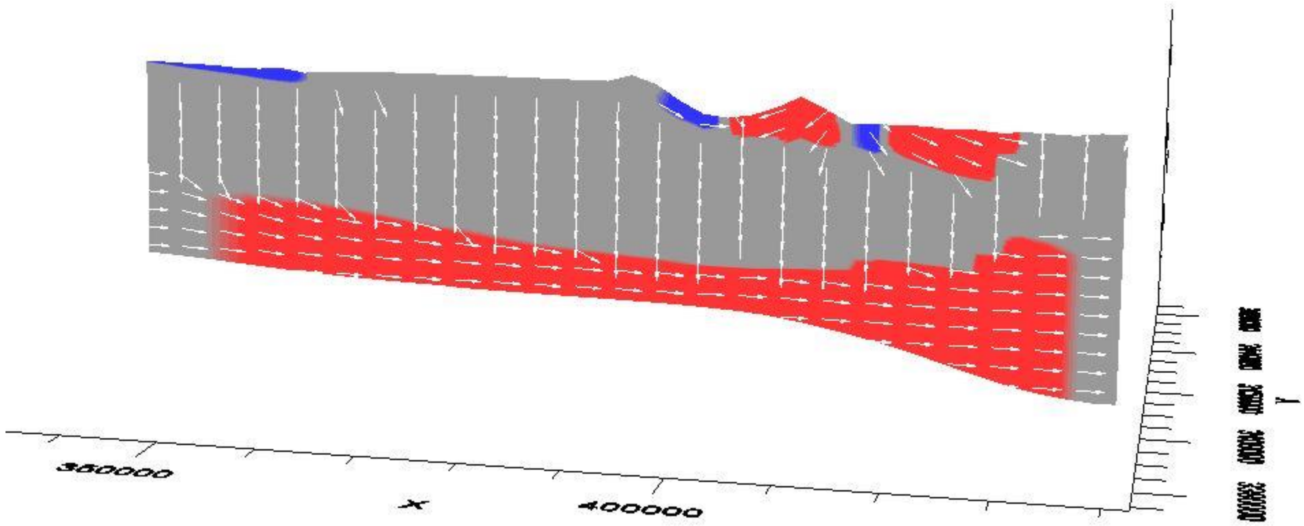

Figure 4.23: Simulated velocity vector directions for model Row 35 (looking north)

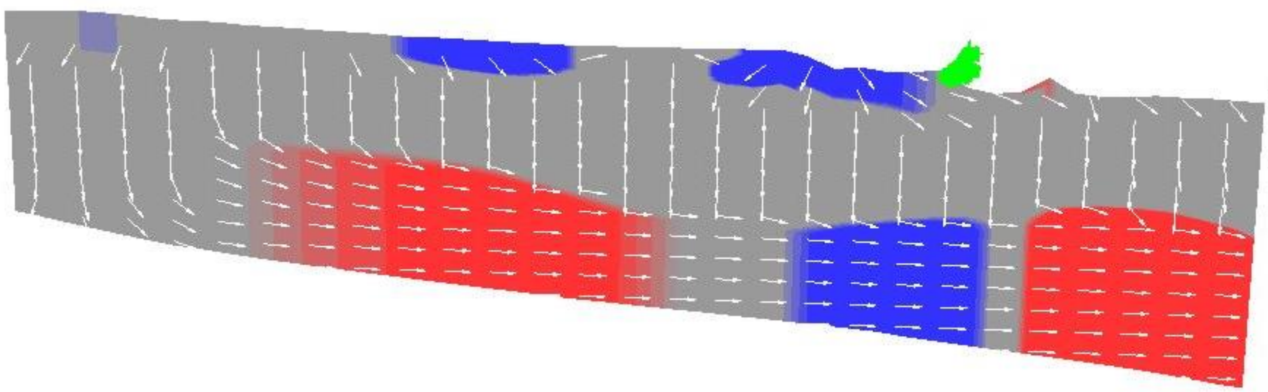

Figure 4.24: Simulated velocity vector directions for model Row 19 (Mission Mine location in green)

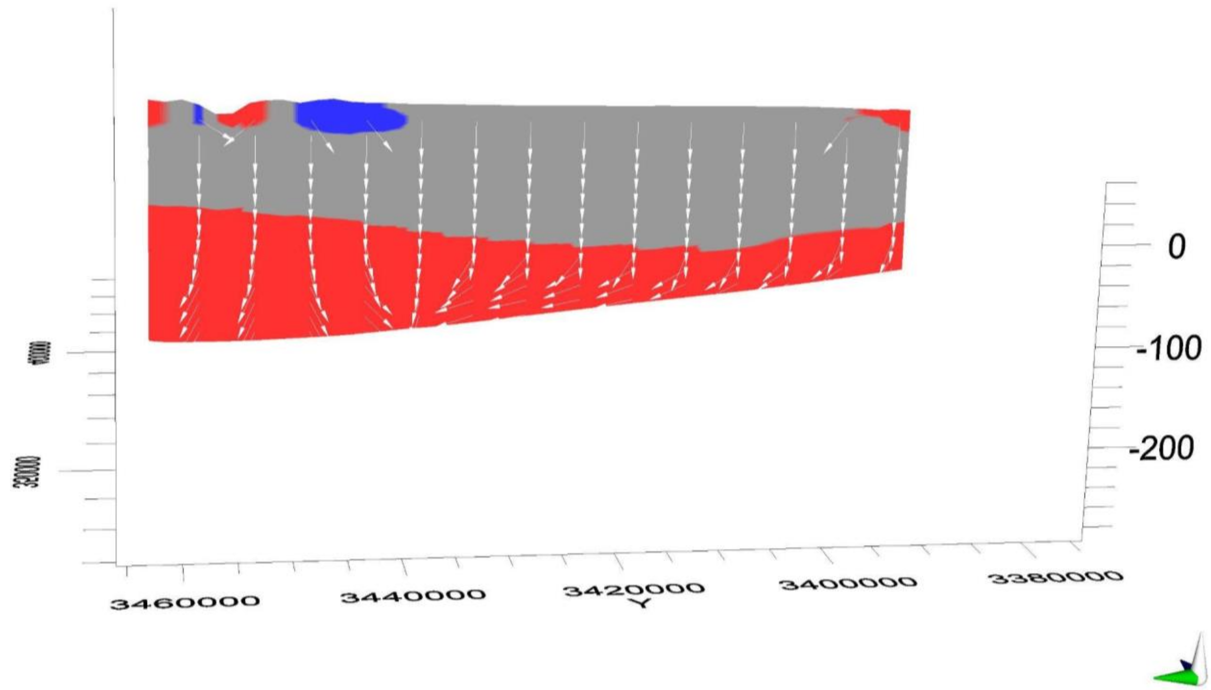

Figure 4.25: Simulated velocity vector directions for model Column 25 (looking east)

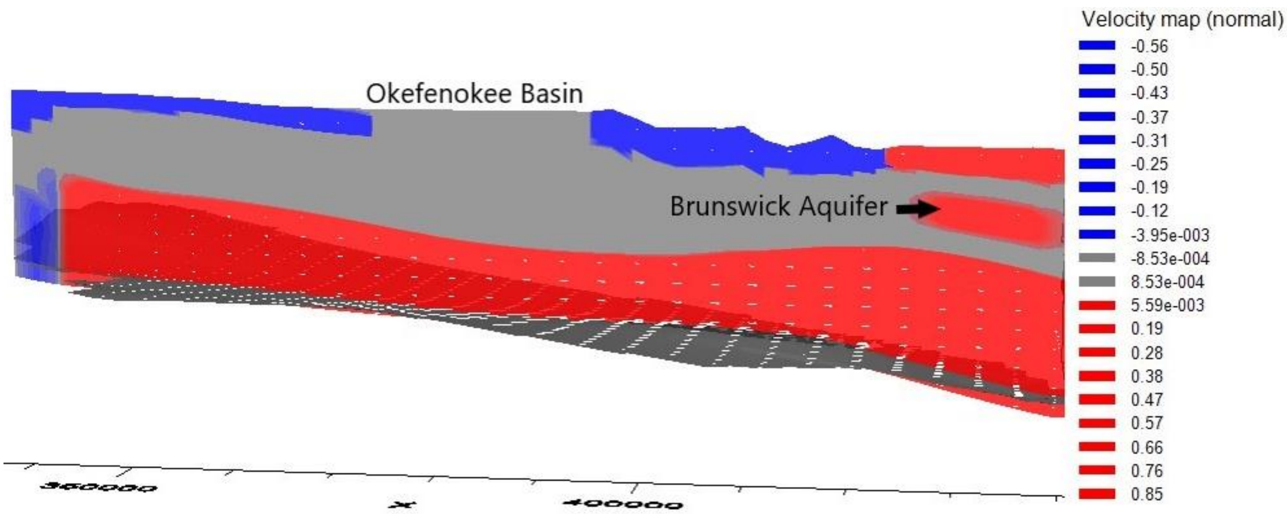

Figure 4.26: Simulated velocity vector magnitudes for model Row 25 (looking north)

CHAPTER 5

CONCLUSION AND FUTURE WORK

This research focuses on acquiring, managing, and analyzing data for the study area and modeling groundwater hydrology for select regions of Southeast Georgia and Northeast Florida. The research presented herein contains an in-depth literature review on previous investigations in Southeast Georgia and Northeast Florida pertaining to the Okefenokee Swamp hydrological system, heavy mineral mining, the Floridan and surficial aquifer systems, and approaches for modeling groundwater and wetland systems; methods used for developing a regional groundwater flow model using VMF; the current status of an ongoing study to understand and model regional hydrology; and results produced from initial steady-state model simulations.

Overall, this research contributes to a general understanding of surface and groundwater hydrology as it pertains to the Okefenokee Swamp system, regional river systems, and the underlying aquifer systems. It also provides a baseline for continued investigations of these systems and their hydrologic relationships, with long term implications for assessing potential effects of mining on local and regional hydrology. Throughout this research process, it has become evident that there is a general lack of data pertaining to hydrologic systems within the study region, which has limited the ability to develop conclusive results in both this study and those previous, leading to ambiguity on certain hydrologic relationships within the region of interest.

For example, literature suggests a lack of agreement regarding hydrologic connectivity between the surficial aquifer, surface water features, and the Floridan aquifer within the study region. While some research claims that the UCU of the Floridan aquifer in the study region provides little to no opportunity for leakage from the surficial aquifer to the FAS (Torak et al., 2010), others claim that there is an observable relationship between water levels in the Okefenokee Swamp and FAS (Kitchens & Rasmussen, 1995). Though the results of this study are theoretical and require further development, preliminary model results indicate that the UCU allows low rates of vertical leakage from the surficial aquifer system to the FAS, while also identifying the UCU as a major influence on the feasibility of simulated water table elevations, where the UCU causes exaggerated groundwater elevations in the surficial aquifer when assigned low conductivities. Future refinement of this model and calibration of its results could lend to agreement on previously disputed hydrologic relationships in the region.

The model developed for this research serves as a baseline, unstressed steady-state representation of the system under investigation and will be passed on to subsequent researchers for further development and investigation. The research discussed herein outlines the first studies and model iterations for an ongoing investigation of the area of interest, providing insight into the unknowns associated with expanding the scope of this study. With an inability to collect new field data for this research, finding available data for this data-sparse region has been a major hurdle, leading to assumptions in material property homogeneity, an overall low-resolution representation of the regional hydrologic system, and inability to perform high-level calibration for assessing model results and uncertainty. However, this study has been beneficial in compiling existing datasets and identifying data needs for the area of interest.

5.1 Data Needs

As this project proceeds, there is significant potential for improving the quantity and quality of current data acquired for the system. An increase in field data would contribute to the overall characterization and resolution of the system under investigation, providing a better representation of natural conditions and heterogeneities, with less assumption-based model inputs. Additional data pertaining to groundwater levels, hydrogeologic properties of aquifers and aquitards, river geometry and bed material properties, Okefenokee Swamp water levels and leakage potential, and regional climate conditions would greatly improve model resolution and accuracy of future results. This data could come from existing site-specific data sources that have not yet been found or newly collected field data as part of future research efforts for this study. A higher-resolution model framework will be especially important for local-scale analysis of specific mine sites. While field data would help to characterize the model in better detail, additional observation data would also be useful for model calibration and uncertainty analysis.

Within the current model domain, there is only one available groundwater observation well that can be used to calibrate simulated model results and assess model sensitivity. This greatly restricts the ability to assess model performance and evaluate steady-state model results. Furthermore, as model development continues, data pertaining to system stresses, such as climate data, pumping schedules, and recovered mine site properties, will need to be acquired and incorporated into future model scenarios. Additionally, time-series data for water level observations and boundary condition delineation will need to be implemented into the model as simulations move from steady-state to transient conditions.

5.2 Options for Model Calibration and Validation

To date, model calibration efforts for this study have been limited to manual calibration based on knowledge of groundwater flow concepts and expected system behavior as reported in previous studies of the area. This was a result of the general lack of field data within the model domain. The one existing UFA groundwater level monitoring well (USGS well 27E004) does not provide sufficient spatial coverage for calibrating model simulations across the domain. As shown in Figure 5.1, there is a second USGS monitoring well (27G003) within the model domain, but it extends into the LFA, below the model domain. However, some USGS literature used for initial conceptualization of the study area suggest that regional discontinuities of the MCU allow a high level of groundwater exchange between the UFA and LFA (Williams & Kuniansky, 2015). This provides a potential option for adding the LFA well into the model for calibration. If measured heads in the LFA reflect UFA levels, the well could be assigned a false bottom elevation, perhaps near the model base, for input into the model. However, this would require further investigation and comparison between UFA and LFA head observations in other wells in coastal Georgia.

The model developed for this research was done using VMF version 7.0. Waterloo Hydrogeologic has recently released a new version, VMF 8.0. The updated version of VMF provides new features that could remedy the current calibration limitations, allowing user input for different types of field observations. In addition to head observations at well locations, VMF 8.0 accepts observation data for streams (SFR), lakes (LAK), zone budget zone flow, and boundary condition flow. The user can specify observation data for stream stage, depth, streambed seepage, outflow, head difference between stream midpoint and associated groundwater cell centroid, groundwater head, or diverted flow.

Several USGS stream gages exist within the model domain, making this a promising addition for calibration distribution across the model area. Lake observation data, including lake stage, volume, inflow, and outflow can also be used for model calibration. This could be a useful tool for applying available measured data for Okefenokee Swamp levels. The boundary condition flow observations allow the user to input measured net volumetric flow exchange between groundwater and a specified boundary condition if observation data is available (Waterloo Hydrogeologic, 2022). As work progresses with this research, adding observation data and improving model calibration should be the initial focus.

5.3 Model Grid Considerations

As well-data are added to the model domain for observation points or pumping scenarios and streams are characterized using higher resolution and calibration potential, it will be important to refine the model grid around these locations for better representation in the model. Grid refinements should be done to accurately represent the extent and geometry of wells and streams. The existing 50 x 50 grid will require substantial refinement around wells and streams as the model is further developed. Furthermore, as the model is populated with better data, simulated results improve, and advancements are made with model calibration, the whole model domain would benefit from a grid refinement. A 50 x 50 grid for a large model domain is good for initial simulations because it reduces complexity and computation time, making it easier to analyze model results and make the necessary changes to promote model convergence.

However, when the model is functional, a refined grid with smaller grid cells provides better spatial representation of features of interest, boundary conditions, and model results. This is especially important for assessing localized zone results from regional simulations. In addition to grid refinement, it may also be useful to explore various grid types. Different grid types provide different options for grid refinement. While finite difference grids only allow grid refinement across an entire row, column, or layer, unstructured grids and finite element meshes allow for localized grid refinement. This reduces computational time and provides better refinement options for complex geometries such as stream planform.

5.4 Regional Model Expansion and Localized Models

Furthermore, this research would benefit from both an expansion of the current model domain and a downscaled localized model for assessing mine site-specific results. By expanding the model domain, the model boundary would include entire watersheds instead of specific stream segments. Additionally, other nearby existing and proposed mine sites could be included in the model domain for impact assessment.

The original model boundary was created to approximate reported potentiometric surfaces and no-flow boundaries of the UFA. While this provides exterior boundary conditions for steady-state simulations, transient simulations will require different boundary conditions along the model border. For transient simulations, model boundaries that approximate near-surface hydrologic features such as watershed boundaries or streams provide better opportunity to bound the model by observable time-dependent flow conditions, whereas constant head boundaries at the model borders only reflect average groundwater conditions at a single point in time unless site-specific time series data is available.

After model results are calibrated to an acceptable criterion, downscaling model results to a local scale would provide the opportunity to analyze groundwater conditions and potential hydrologic impacts at specific sites of interest including mine sites, the Okefenokee Swamp, and associated streams. The baseline pre-development regional model provides a basis for downscaling to localized models for in-depth analysis. A localized model will require higher resolution regarding grid cell spacing and parameterization, but would provide a better means of running simulations for analyzing scenarios related to mine operations such as pumping conditions and post-mine site reclamation.

5.5 Transient Models

While a steady-state model is useful for initial simulations to confirm model convergence, calibrate average conditions, and develop a general understanding of the hydrologic system, a transient model is essential for analyzing system responses to hydrodynamic stresses. A transient model allows an understanding of system responses to variable flow conditions from both climate-driven and anthropogenic influence. For assessing potential effects of mine site recovery, such as altered hydraulic conductivity from mine spoil backfill, a second steady-state simulation could be developed to represent the new conditions for comparison with the original baseline model.

However, a transient solution is necessary for evaluating the effects on the surficial and Upper Floridan aquifers from time-dependent pumping scenarios within mine sites. It also provides a better representation of cumulative effects on surface water features from seasonal water level fluctuations and mining operations. For example, a steady-state model may indicate that mine-site groundwater pumping has little effect on nearby streamflow under average conditions, but a transient model could show that pumping rates have more effect on streamflow or wetland stage during periods of low-flow.

Although a transient model provides a better overall characterization of the system, it requires new boundary conditions, new time-series data for lake stages, stream stages, and observed groundwater levels, and a higher level of model complexity with potential complications in model convergence. For example, transient simulations require constant head boundaries to be converted to boundary conditions that capture time-dependent fluctuations in water levels; transient calibration not only assesses general model performance pertaining to water table elevations and groundwater heads, but also considers a model’s ability to simulate real-time variability in water levels. A calibrated transient model greatly enhances a model's predictive power by enabling the ability to extrapolate past groundwater responses into future scenarios.

A transient model also provides the ability to analyze a system and its response to perturbations over several time scales. This allows for a better understanding of both short term and long-term responses to a variety of system stresses. For example, short-term responses in groundwater levels can be analyzed for individual pumping events to better understand aquifer properties and well recovery. Additionally, the cumulative effects of long-term pumping (5-10 years) from past scenarios can be analyzed to better predict aquifer response and recovery from current pumping conditions. Furthermore, assessing transient model behavior over large time scales (50+ years) can provide insight into general changes and trends in a system due to the effects of climate change. This can assist in predicting future conditions of a system as climate-driven inputs continue to change.

5.6 Groundwater Pumping Boundary Conditions

Moving forward, the existing regional, pre-development groundwater flow model will need to be updated with boundary conditions that capture the effects of pumping wells. While a pre-development model indicates natural hydrologic conditions, industrial, municipal, residential, and agricultural groundwater pumping also have a role in defining the current state of a groundwater system. Depending on pumping rates and well concentrations, groundwater pumping can have significant influence on the direction, velocity, and quantity at which groundwater moves through the aquifer system. A pre-development model may misrepresent groundwater flow in the presence of significant pumping centers.

The inclusion of pumping data is of great importance with an expansion of the model area, with notable pumping centers existing in Jesup and Brunswick, Georgia, which are just outside of the existing model domain. Furthermore, mine site-specific pumping data needs to be analyzed and incorporated into a transient model simulation to accurately quantify potential effects of mine operations on nearby surface and groundwater systems.

5.7 Particle Tracking

A transient model also provides the opportunity to run particle tracking simulations to observe the fate of chemical leaching from mine tailings. Mine tailings are byproducts from the processing of raw mined material and are typically used as backfill for open-pit operations in the context of heavy mineral mining. While tailings from heavy mineral mines consist of materials that naturally exist in the environment, their disturbance and homogenized redistribution may induce changes to localized hydrogeologic properties of the groundwater system, resulting in ambiguity on the transport and dispersion of tailings through the system.

With the particle tracking and solute transport packages available in VMF, transient particle tracking simulations would provide insight into the dispersion rate of leaching from mine tailings through the groundwater system. This would be useful for assessing previous mine-site recovery efforts with implications for predicting future conditions of existing and proposed mining operations, which could influence post-mine site management decisions in the future.

5.8 Coupled Surface and Groundwater Models

After groundwater model results are ground-truthed and able to make reliable predictions for various scenarios, model development could proceed to incorporate better characterization of surface-based hydrologic processes through a coupled groundwater-surface water modeling approach. With the high concentration of wetlands and stream networks in the model area, the addition of refined modeling for surface water systems would mitigate limitations in MODFLOW's ability to accurately represent the complexities of surface water processes in water balance analysis.

A coupled surface-groundwater modeling approach has been identified as a promising technique for evaluating wetland water balance and connectivity to groundwater systems (Golden et al., 2014). Applying these modeling techniques would contribute to a better understanding of the hydrologic processes associated with the Okefenokee Swamp Basin. Additionally, this would contribute to investigations for mine operation influence on proximal wetlands and river systems. Furthermore, this approach would open opportunities to evaluate the potential propagation of mining impacts through watersheds.

The capabilities associated with coupled models has led to development of modeling software that directly targets systems with complex surface and groundwater interactions. SWAT is a publicly available watershed modeling software that also uses a geospatial modeling environment for analyzing surface water systems. Furthermore, a coupled SWAT-MODFLOW modeling software is an available tool that integrates the capabilities of both programs. Development of a coupled SWAT-MODFLOW model is worth consideration for later stages of this investigation. SWAT-MODFLOW is discussed in greater detail in the "Modeling Wetlands" section of the Literature Review written for this study.

Figures

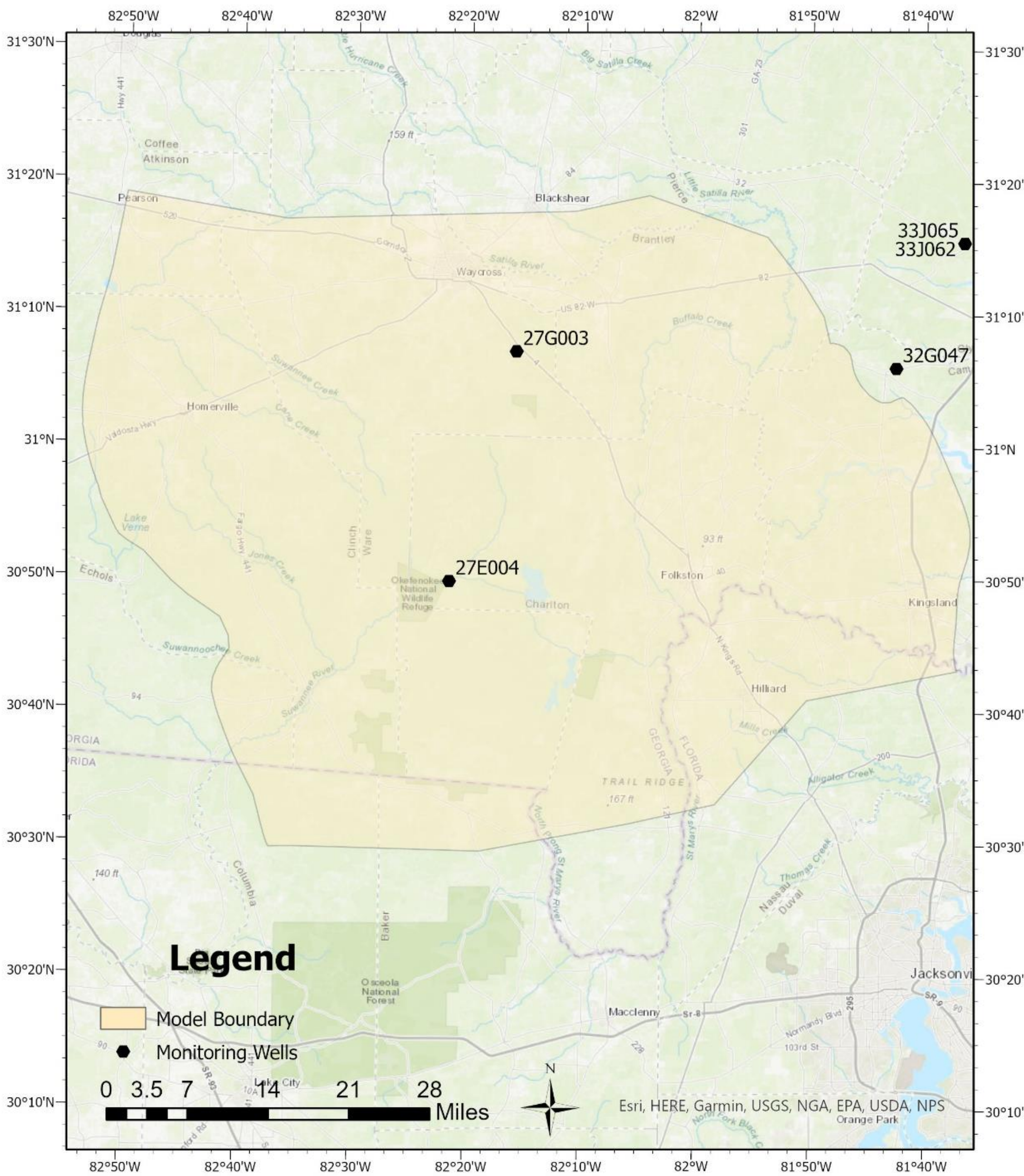

Figure 5.1: USGS monitoring well locations in model domain

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APPENDICES

Appendix A: Additional Site Information

This section provides additional information pertaining to the study region, including graphs comparing water level fluctuations in the Suwannee River, Okefenokee Swamp, and UFA, climate information, regional geology, watersheds, hydrography, water bodies, and monitoring locations. Most of the figures presented in this section were acquired from a water resources inventory assessment conducted by Geospatial & Hydrologic Services LLC for the study region. This information could serve to provide a basis for locating and acquiring supplemental data sets to contribute to the overall characterization of the study region. Data from the surface and groundwater monitoring locations and climatology networks could enable better delineation of model boundary conditions and provide better distribution of observational data for model calibration. Furthermore, the information pertaining to regional hydrography and water bodies would allow a higher resolution for surface water features within the model domain.

Furthermore, an in-depth comparative analysis of water table fluctuations in surface and groundwater features (Figures A1 and A2) can provide insight into aquifer properties and potential connectivity between surface water bodies and underlying aquifers. For example, notable responses in surface water fluctuations from system stresses, such as precipitation or drought, can be related to fluctuations in groundwater levels, providing insight on surface and groundwater connectivity. Furthermore, analysis of groundwater level response to stresses, such as aquifer pumping, can provide insight into both aquifer properties and effects of groundwater drawdown on surface water levels.

Figure A1 shows UFA groundwater levels in USGS monitoring well 27E004 compared with Suwannee River stage from USGS stream gage 02314500. Though it is difficult to draw conclusions on the relationships in water levels from the graph alone, an analysis that removes groundwater level response from stresses such as Earth tides and barometric pressure and incorporates techniques such as regression deconvolution of time-series data can highlight the effects of precipitation on water levels in both systems, providing insight on their connectivity and lag time associated with vertical leakage through the surficial aquifer and UCU.

Figure A2 compares water level fluctuations in the Suwannee River at USGS stream gage 02314500 and water levels in the Chase Prairie of the Okefenokee Swamp provided by the USFWS. From this graph, it is easier to observe correlation between water levels in the Okefenokee Swamp and Suwannee River, where peaks in river stage are reflected swamp levels. This data would benefit from a comparison with precipitation data over the same time period. Note, the gages in the Okefenokee Swamp and Suwannee River reference different vertical datums, so a value of 80 feet was subtracted from all water level measurements in the Okefenokee Swamp to allow better comparison between the two datasets. This was done because the fluctuations in the systems are of higher importance than the elevations themselves when comparing the data on a plot.

Figures

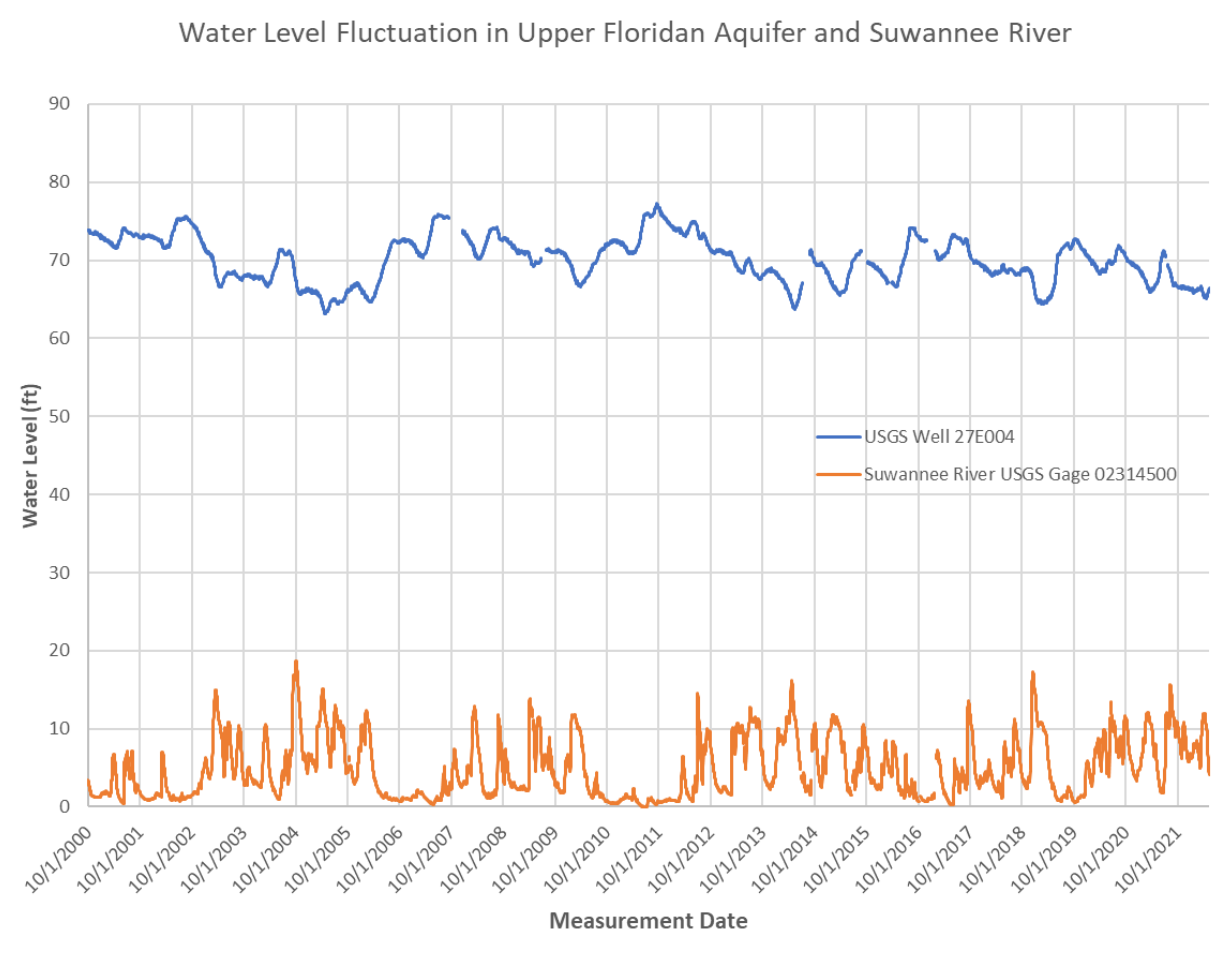

Figure A1: Comparison of water levels in the UFA and Suwannee River

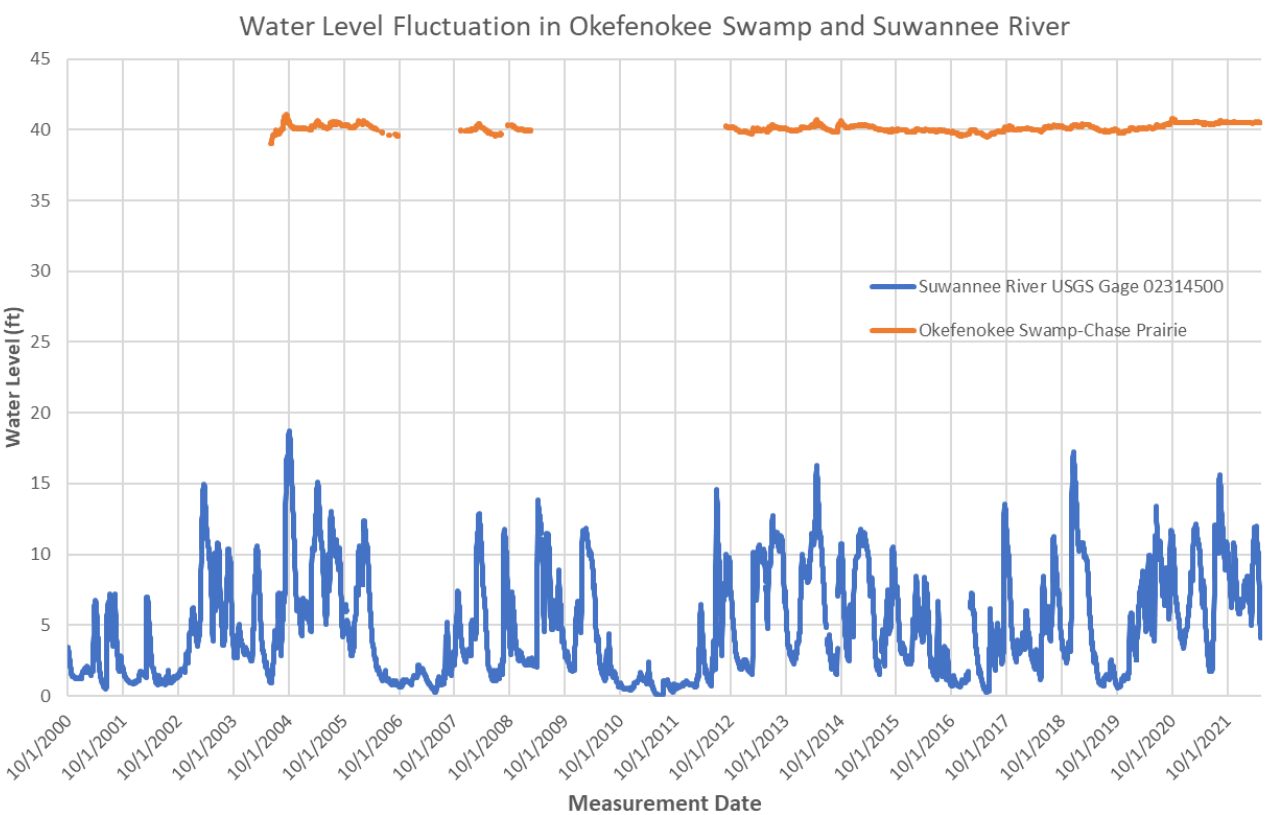

Figure A2: Comparison of water levels in the Okefenokee Swamp and Suwannee River

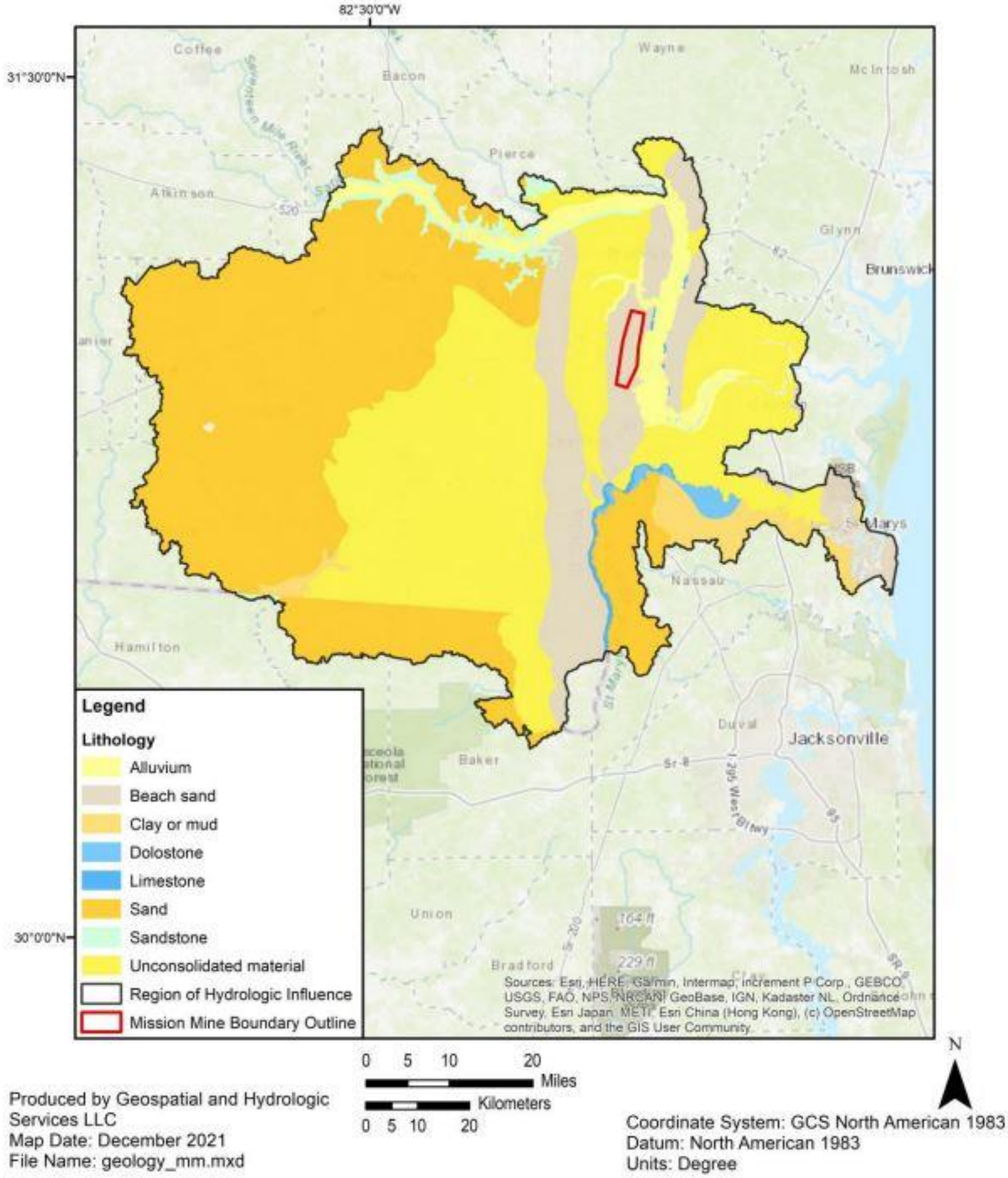

Figure A3: Map of regional geology

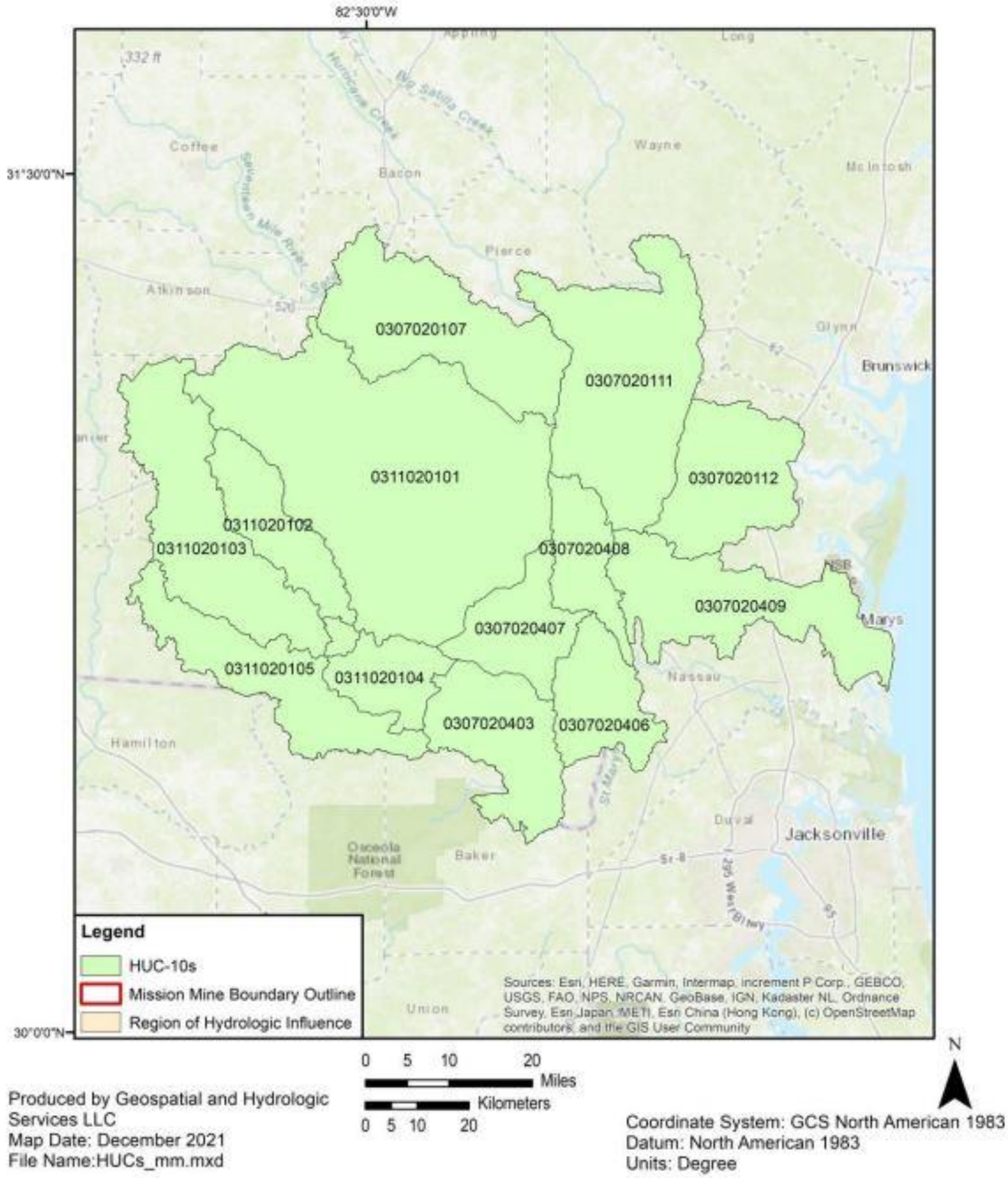

Figure A4: Watersheds in region of study

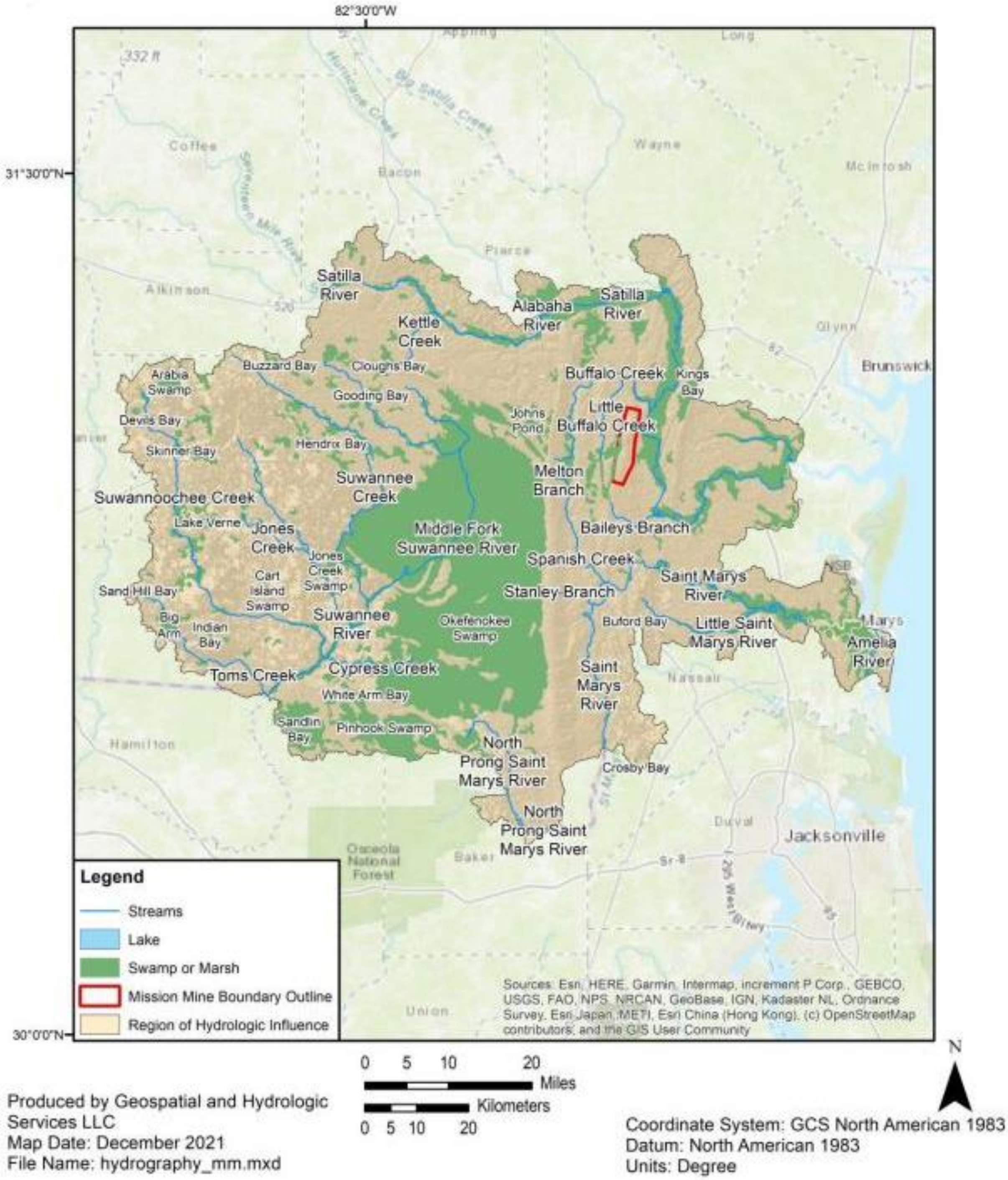

Figure A5: Map of regional hydrography

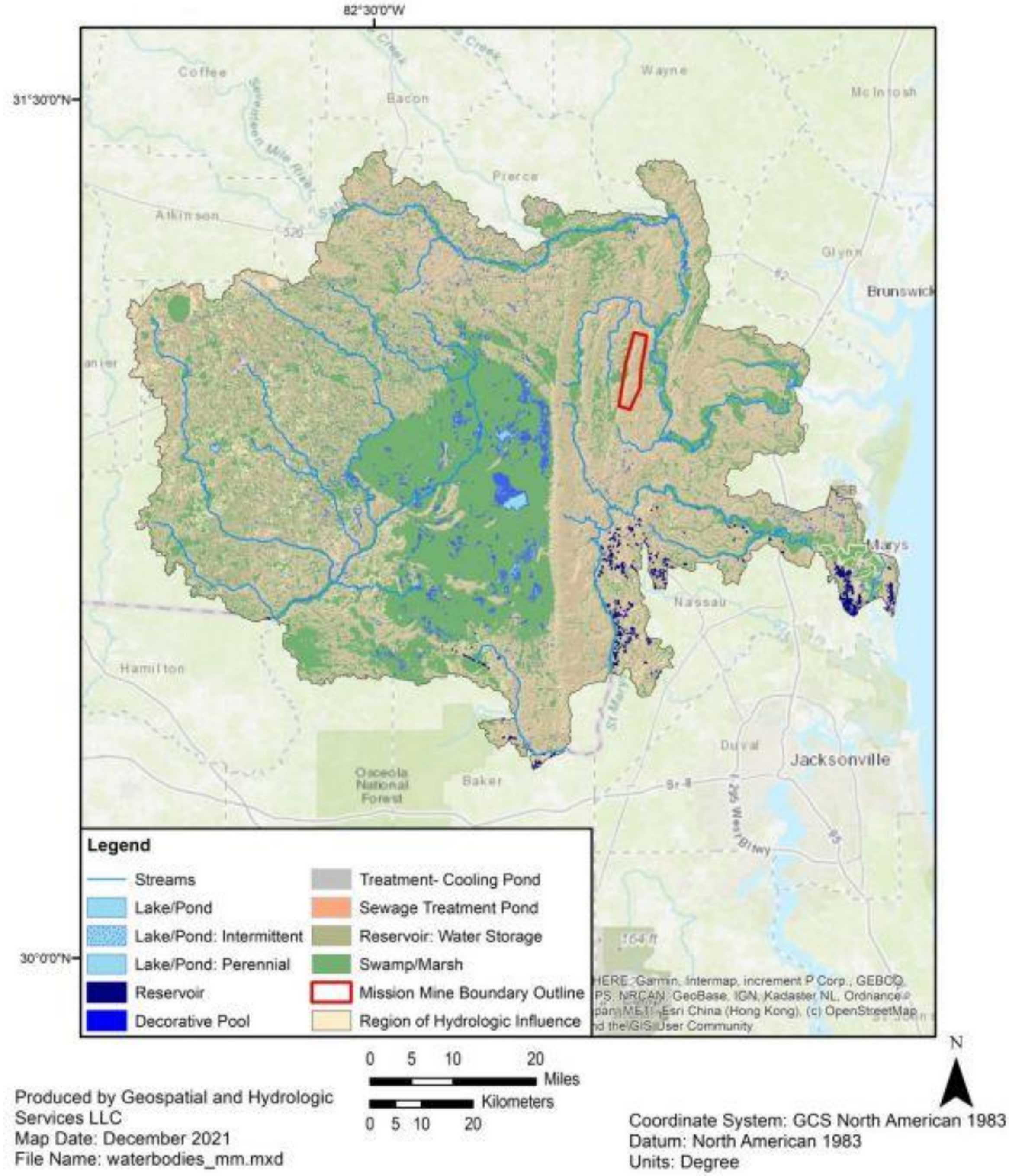

Figure A6: Water bodies in region of study

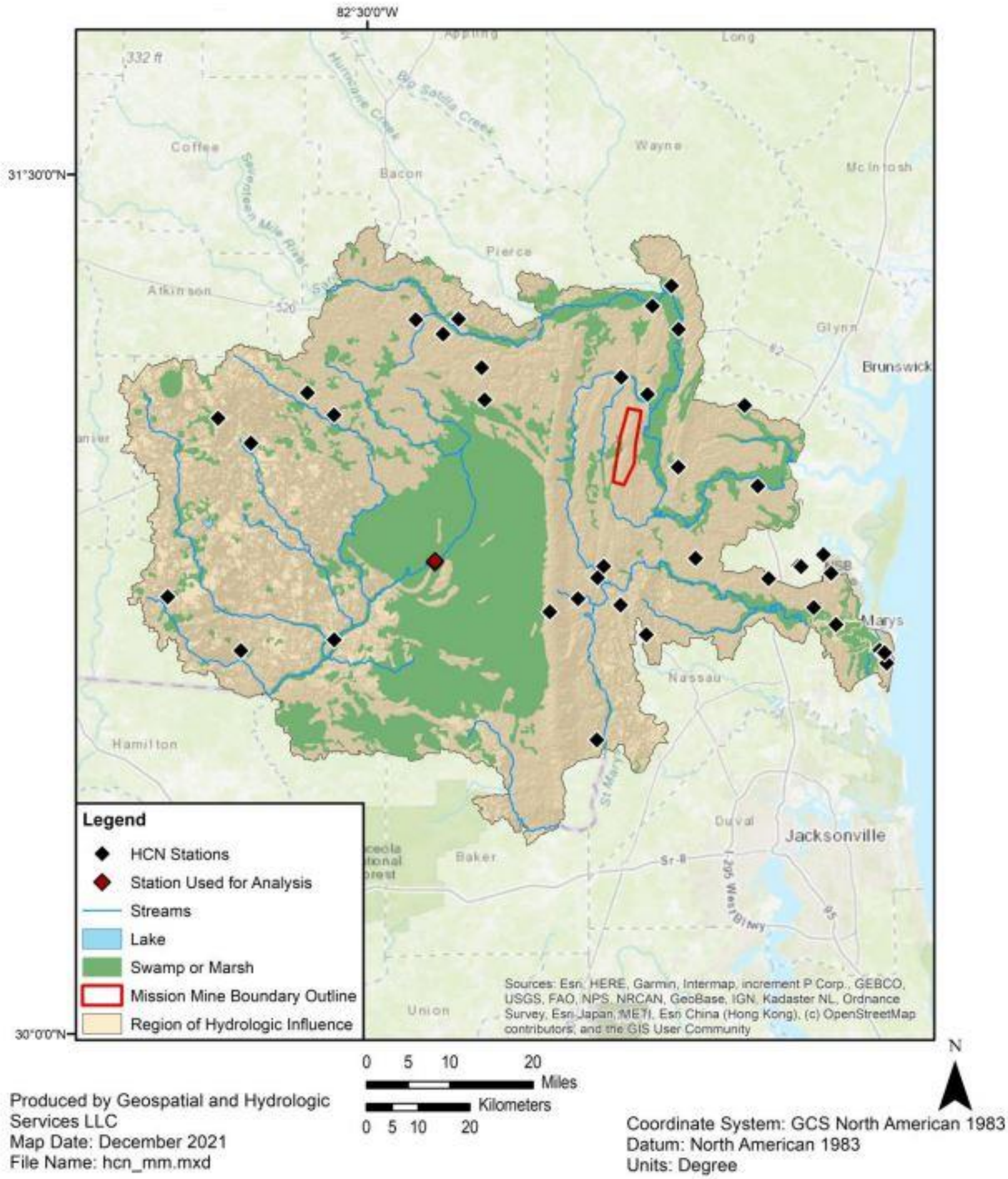

Figure A7: Historical Climatology Network (HCN) stations in region of study

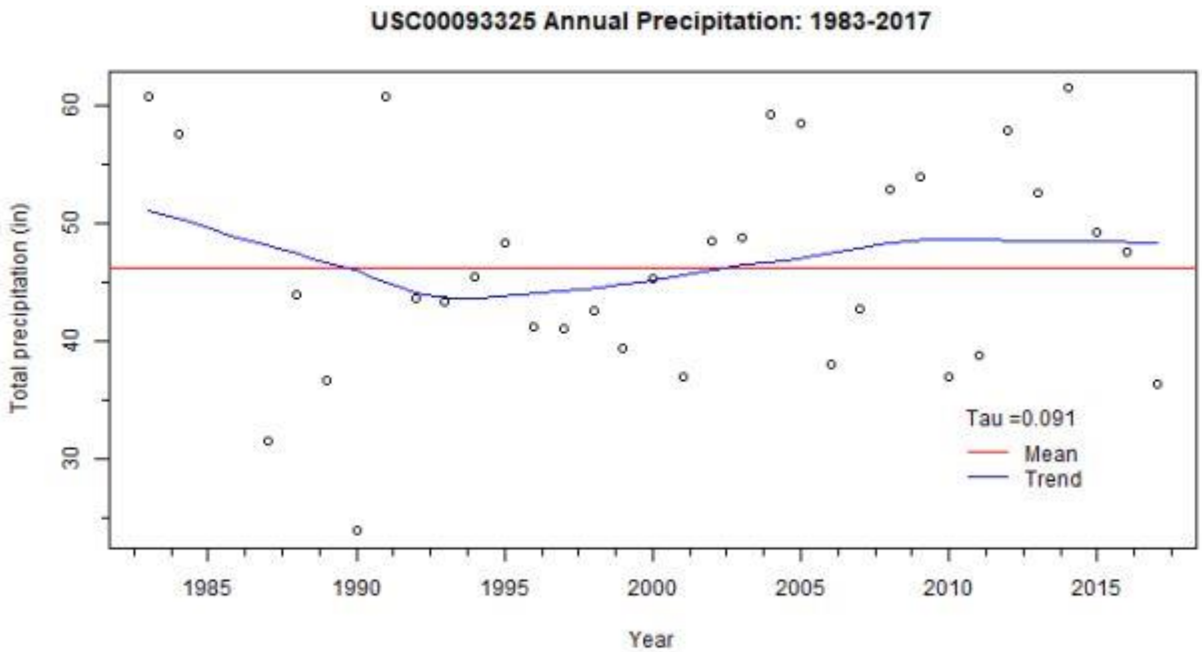

Figure A8: Average yearly precipitation from USC00093325 (station marked in red in Figure A7)

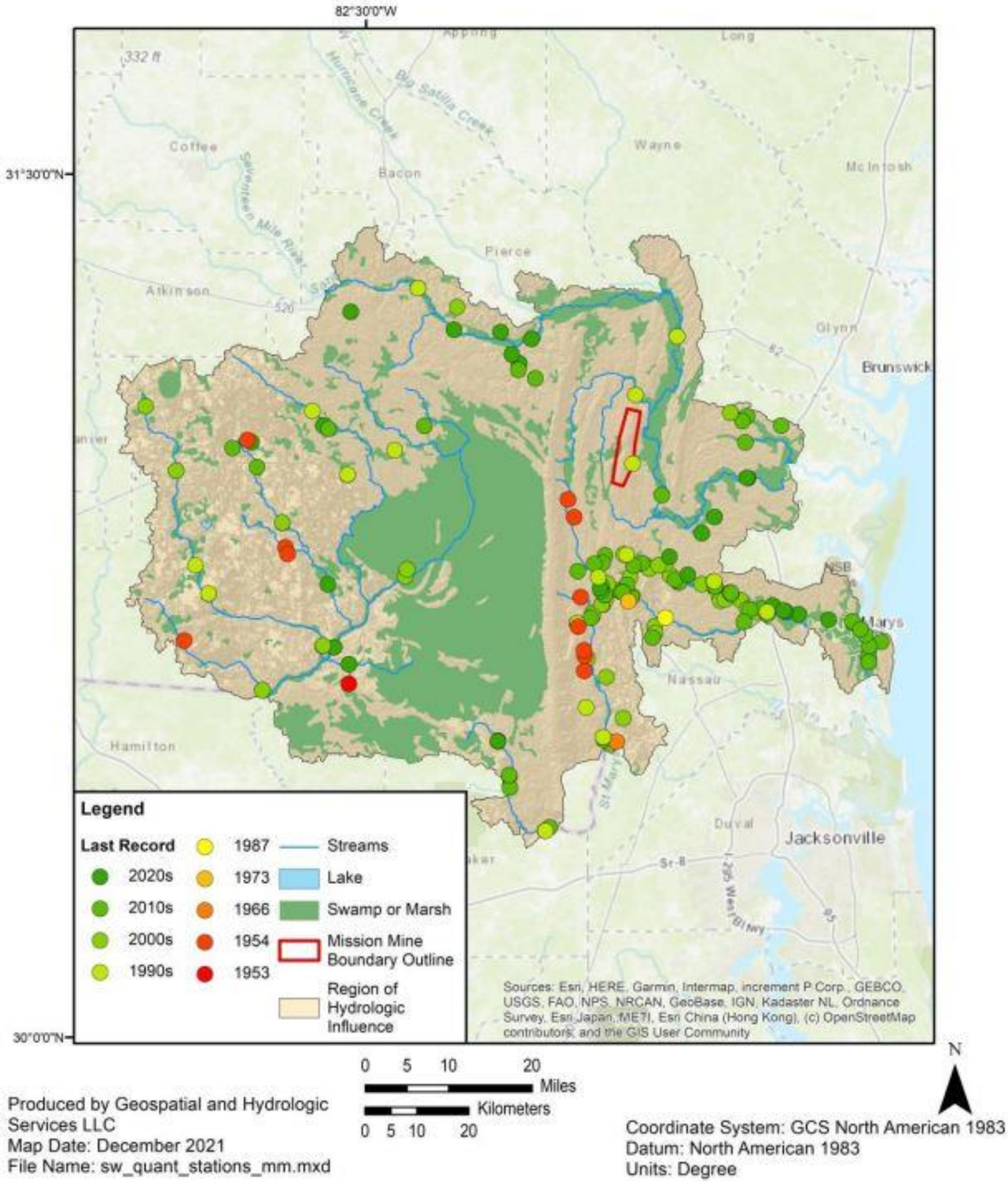

Figure A9: Surface water level monitoring stations in region of study

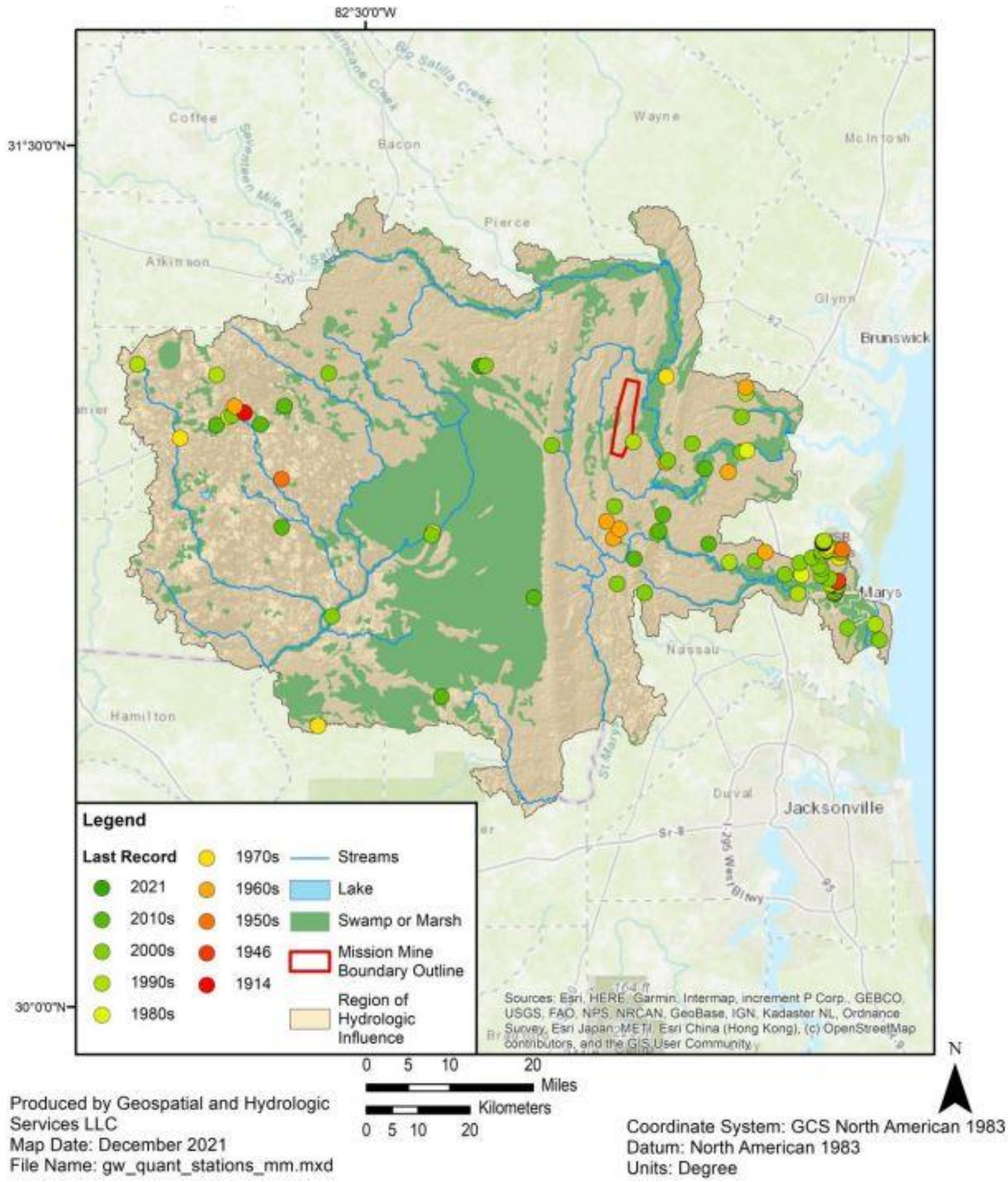

Figure A10: Groundwater level monitoring stations in region of study

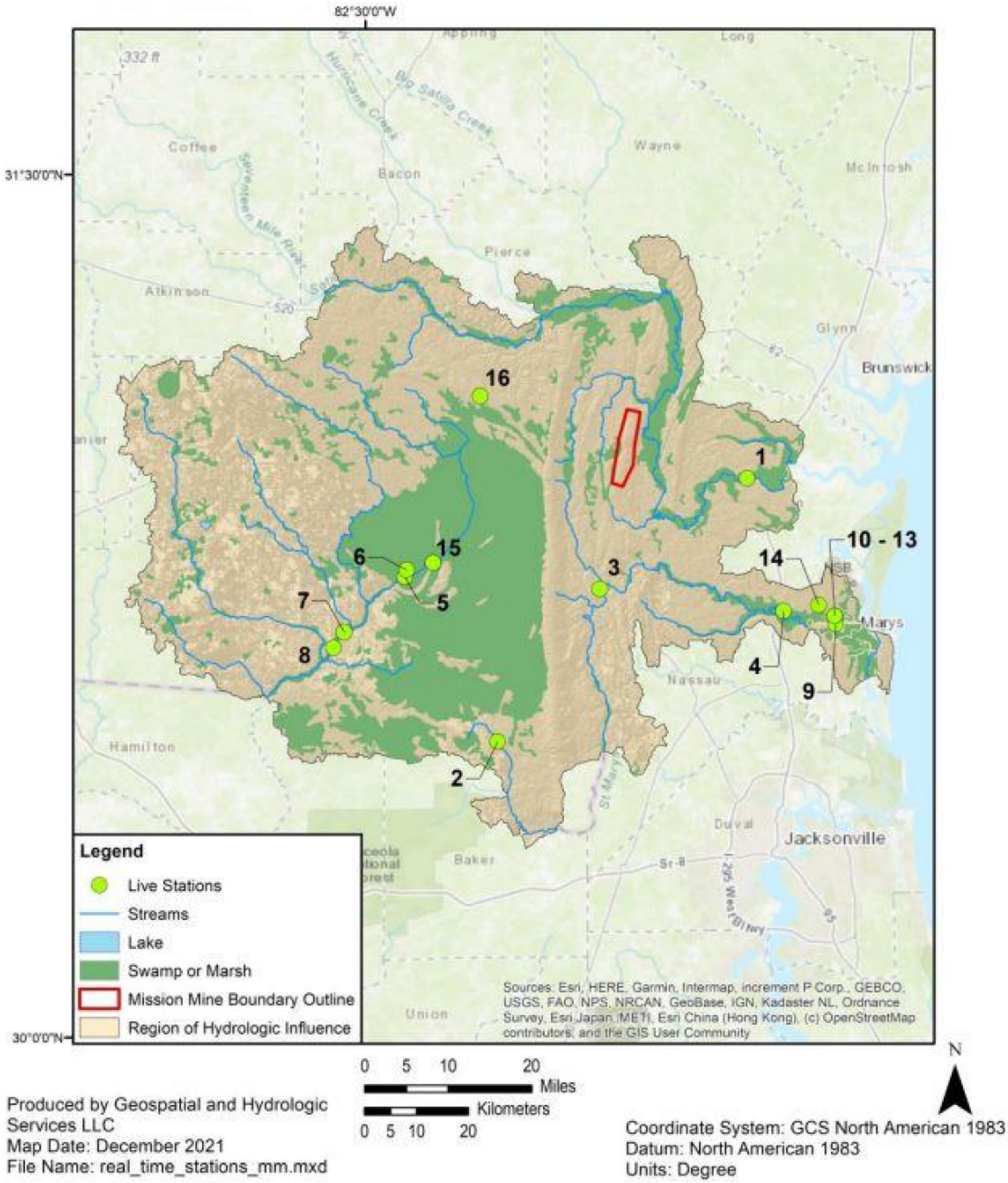

Figure A11: Real-time surface or groundwater level monitoring stations in region of study

Appendix B: MODFLOW and VISUAL MODFLOW Flex Overview

A leading groundwater modeling code that calculates the groundwater flow equation and simulates groundwater flow through a user-defined system is the USGS's MODFLOW program, which is considered an international standard for groundwater modeling (Harbaugh, 2005). MODFLOW is a modular, three-dimensional, finite-difference, distributed groundwater modeling program that was originally developed by the USGS in the early 1980s to consolidate available groundwater simulation programs into a single code that was easy to understand and work with (Harbaugh, 2005). Since its development, MODFLOW has gone through a series of updates and versions that have expanded its capabilities and uses. While MODFLOW itself only solves for groundwater heads, several expansions have been developed to incorporate additional groundwater flow processes such as solute transport, providing a variety of solution techniques (Jakab & Doerken, 2021).

Available MODFLOW packages include the core version, which is currently MODFLOW 6, updated from the previous core version, MODFLOW-2005, as well as specialized packages including MODFLOW-NWT, MODFLOW-USG, MODPATH, MT3D-USGS, SEAWAT, PEST and several others, each providing unique solving techniques for specialized groundwater problems. However, MODFLOW requires data input in the form of text files, making model development more complex and time-consuming, limiting the amount of able users (Hariharan & Uma Shankar, 2017).

VMF is a fully-integrated graphical user interface (GUI) for MODFLOW and related programs, first developed by Waterloo Hydrogeologic in 1994 (Hariharan & Uma Shankar, 2017; Jakab & Doerken, 2021). VMF is a powerful groundwater modeling tool that provides a user-friendly 3D modeling environment and enables high-quality visualization of groundwater systems from initial conceptualization to simulated results. With VMF, data entry is made easier, accepting data inputs from Excel spreadsheets, Surfer grids, and ESRI files (Waterloo Hydrogeologic, 2022; Hariharan & Uma Shankar, 2017).

In VMF, Waterloo Hydrogeologic has provided a single program that incorporates industry-standard codes for simulating groundwater flow and contaminant transport while also providing unique options for solving specialized or complex groundwater problems through variable user-defined solver techniques and grid type options (Waterloo Hydrogeologic, 2021). Furthermore, VMF provides a geospatially aware interface that pairs well with any Geographic Information System (GIS), allowing smooth development and management of conceptual groundwater systems through use of georeferenced raster and shape files, which contributes to the visualization and spatial integrity of a model. To supplement the ease at which a user can navigate the modeling process from start to finish, VMF provides specified conceptual and numerical modeling workflows that guide the user through model development in a sequential order through which each step in the modeling process is prompted for completion before model development can proceed (Jakab & Doerken, 2021).

The VMF conceptual modeling workflow allows the user to build a grid-independent framework of the groundwater system under investigation using raw GIS files. Within the conceptual modeling workflow, the user is able to import geospatial data to define geologic horizons, delineate property zones, assign properties and boundary conditions, and visualize the hydrogeologic system under development. The result of a finalized conceptual model is a data-dependent representation of the modeler's interpretation of the groundwater system, where the model's resolution can be as high as the data used to define it (Jakab & Doerken, 2021).

VMF also includes several boundary condition packages that prompt required data input, simplifying boundary condition delineation. Available VMF boundary condition packages include options for well (WEL), constant head (CHD), river (RIV), general head (GHD), drain (DRN), streamflow-routing (SFR2), recharge (RCH), evaporation (EVT), lake (LAK), specified flux (FHB), time-varying material properties (TMP), and unsaturated zone flow (UZF) inputs. Some of which are only compatible with certain solver engines (Waterloo Hydrogeologic, 2022). Because a conceptual model is grid and simulator-independent, it must be converted into a numerical model before running simulations. This makes conceptual modeling a powerful tool in that it can serve as the foundation for several numerical models, giving the modeler the opportunity to test different grid types, solvers, or scenarios from a single model framework (Waterloo Hydrogeologic, 2022). Furthermore, a well thought out and carefully constructed conceptual model can reduce the effort needed to calibrate the numerical model (Jakab & Doerken, 2021).

In VMF, the numerical modeling workflow provides the option for establishing a grid for a previously defined conceptual model framework or building a framework from scratch in a grid-based modeling environment. Development of a grid-based model structure in the numerical modeling workflow would typically be better suited for local models with relatively heterogeneous geologic structure or scenarios where geologic surface data is not available. When converting a conceptual model into a numerical model, the user has the option of selecting a Finite-Difference Grid, Finite Element Mesh, Unstructured Voronoi Grid, or Unstructured

Quadtree Grid and specifying the associated solver, such as MODFLOW-2005, MODFLOW-USG, MODFLOW-NWT, etc. (Waterloo Hydrogeologic, 2022).

Within the numerical modeling workflow, the user has the opportunity to modify the model grid to refine grid cells around areas of interest and improve model resolution. The numerical modeling workflow then provides the user the opportunity to use a grid-based approach for adding or editing properties and boundary conditions. Additionally, the numerical modeling workflow allows the user to define observation data for model calibration, define zone budget zones for subregional analysis, and define particles for particle tracking. The numerical modeling workflow then allows the user to establish simulation settings, run the model, analyze model results, and perform model calibration and sensitivity analysis through built-in parameter estimation software packages (PEST) (Waterloo Hydrogeologic, 2022). After a model is run, the modeler has the option to return to the numerical modeling workflow to adjust parameters, refine the grid, and further calibrate the model as needed based on simulated results. The modeler can also return to the conceptual modeling workflow to develop an additional numerical model if necessary.

Since its early development, VMF has been continuously updated and improved by Waterloo Hydrogeologic to expand the software's capabilities and offer its users a seamless modeling experience. With the user-friendly interface and workflow, VMF has been applied to a variety of groundwater problems. Table B1 provides a few examples of Visual MODFLOW applications for various groundwater problems.

Tables

Table B1: Examples of Visual MODFLOW applications (Hariharan & Uma Shankar, 2017)

Publication	Application
Rao, 2001	Assessed groundwater contaminant dispersion from an industrial site with results indicating increased dispersion rates due to stream-aquifer interactions
Vandecasteele, 2010	Developed a groundwater flow model for a catchment in Northern Ethiopia to calculate the soil-water budget for a perched water table
Varalakshmi, 2011	Modeled an aquifer system to determine average input, output, and withdrawals from the system
Wang, 2013	Conducted an environmental impact assessment to better understand surface and groundwater flow impacts from soil and water conservation efforts
Zhai, 2014	Assessed drainage of a predominantly limestone aquifer to identify remedial measures for poor-draining areas underlying a mining operation
Parameswari, 2015	Analyzed leachate migration through groundwater from a dump yard in India under transient conditions to assess contaminant influence on nearby supply wells
Guan, 2015	Predicted groundwater level decline near a river basin as a result of excessive groundwater withdrawal
Qadir, 2016	Studied groundwater sustainability for agricultural activities near the Indus River in Pakistan, predicting drawdowns for a forecasted simulation period of 35 years
Lee, 2016	Simulated stream-aquifer interactions to assess the impacts of seasonal pumping on streamflow
Vijay, 2016	Assessed safe groundwater withdrawal rates and quantified future water supply demands for Puri, India, where groundwater is subject to saltwater contamination