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NORTH FLORIDA SOUTHEAST GEORGIA GROUNDWATER MODEL (NFSEG v1.1)

by

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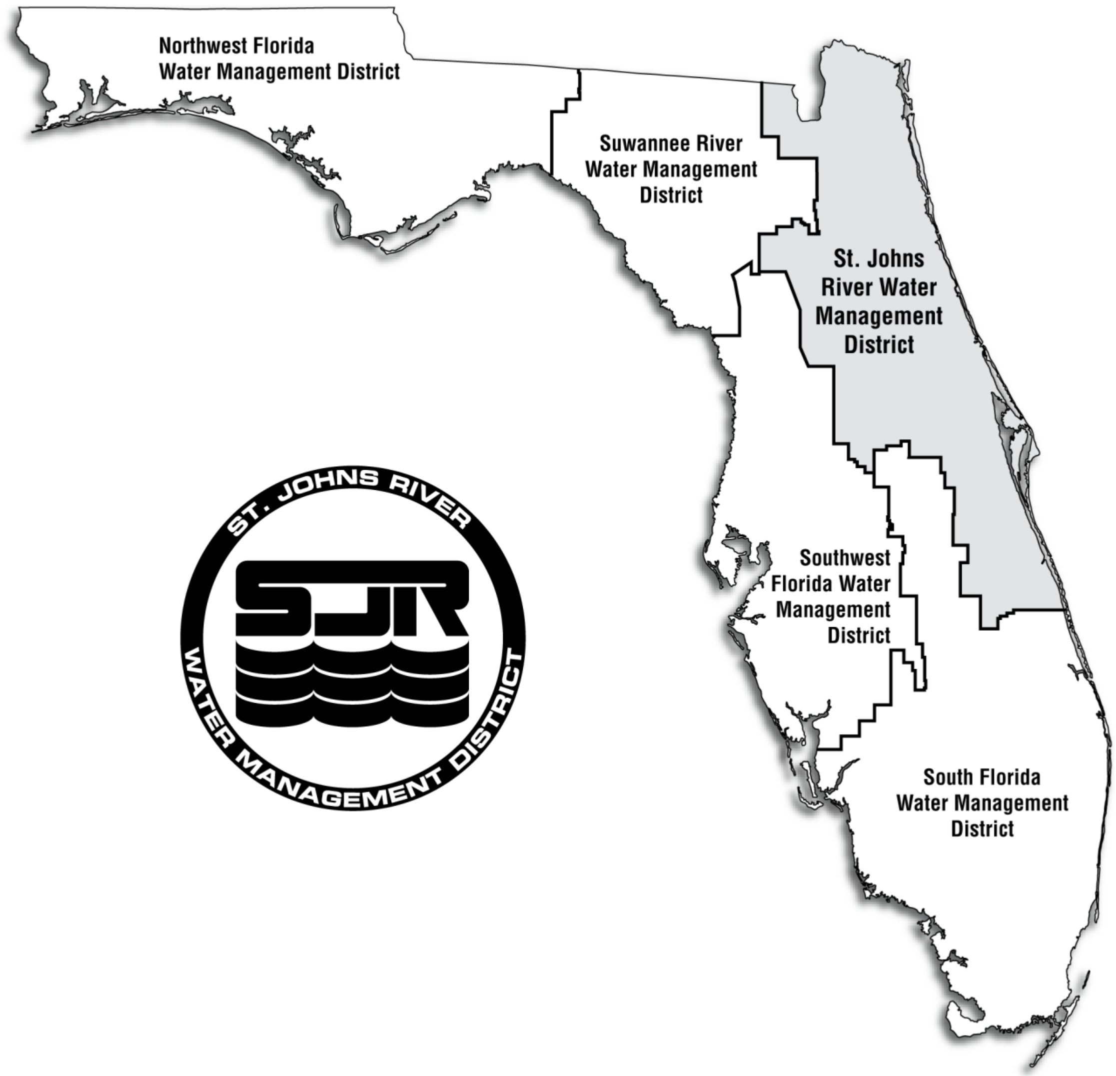

The St. Johns River Water Management District was created in 1972 by passage of the Florida Water Resources Act, which created five regional water management districts. The St. Johns District includes all or part of 18 counties in northeast and east-central Florida. Its mission is to preserve and manage the region's water resources, focusing on core missions of water supply, flood protection, water quality and natural systems protection and improvement. In its daily operations, the district conducts research, collects data, manages land, restores and protects water above and below the ground, and preserves natural areas.

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EXECUTIVE SUMMARY

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1. INTRODUCTION

The St. Johns River Water Management District (SJRWMD) develops and applies groundwater models to facilitate decision making regarding water resources and groundwater uses. An application of the SJRWMD's Northeast Florida Groundwater Flow Model (NEF) indicated the potential for significant water resource related impacts in areas of both the Suwannee River Water Management District (SRWMD) and SJRWMD due to projected groundwater withdrawals within the NEF model domain. In 2009, a groundwater modeling group was assembled to discuss issues regarding the NEF model. The meetings of the groundwater modeling group, which were facilitated by the University of Florida Water Institute (UFWI), occurred between August 2009 and February 2010 and enabled all stakeholders to come together for a series of meetings in which issues regarding the SJRWMD NEF model development and application were investigated. The stakeholders included a variety of groups, including water utilities, private industry, governmental organizations, and environmental groups.

As a result of the facilitation process, a summary report on groundwater modeling was prepared by Dr. Wendy Graham and Lisette Staal of the UFWI (Graham and Staal, 2010). Several recommendations for further groundwater model development were included as part of the report. One of the recommendations stated that: "More time should be spent 'up-front' with stakeholders providing input on methods and model evaluation criteria than on defending and/or critiquing the end-product. Given the sensitive hydrologic and ecological conditions at the boundary between the SJRWMD and SRWMD, the two Districts should work toward developing a common North Florida model." Because of these recommendations, the SJRWMD and SRMWD undertook the joint creation of the North Florida Southeast Georgia regional groundwater flow model (NFSEG). The Districts agreed that the use of one model would enhance efficiency and effectiveness and provide consistency in planning and permitting decisions.

PURPOSE AND SCOPE

A technical team of experts from SJRWMD, SRWMD, and stakeholders from water utilities, private industry, governmental organizations, and environmental groups initiated development of the NFSEG model in 2012. The technical team's directive was to ensure appropriate science is applied to the modeling and data analysis to support decision making, and that the work completed is defensible, understood by the team, and collaboratively developed, as described in the Partnership's charter, which is available at northfloridawater.com. The primary purpose of the NFSEG model is to enable improved evaluations of inter-district (e.g., SJRWMD/SRWMD) and inter-state (e.g., Florida/Georgia) water level changes in the surficial and Floridan aquifer systems resulting from groundwater use over the model domain.

The technical team completed an interim version of NFSEG (NFSEGv1.0) in 2016. NFSEG v1.0 was utilized to support the North Florida Regional Water Supply Plan (2015-2035). Several documents resulted from the development of version 1.0 and include:

1. Data Availability for Development of the North Florida Southeast Georgia (NFSEG) Regional Groundwater Flow Model in the Area of its Potential Domain (Durden 2012);
2. North Florida Southeast Georgia (NFSEG) Groundwater Flow Model Conceptualization (Durden, Cera, and Johnson 2013); and
3. Development and Calibration of the North Florida Southeast Georgia Groundwater Model V1.0 - Draft (Gordu, Durden, and Grubbs 2016).

The Data Availability report (item 1 above) includes a brief description of the study area, a general description of the groundwater flow system of the area, the types and expected availability of data required for construction of the NFSEG groundwater model, and potential boundaries of the model domain. The Conceptualization report (item 2), details the plan for construction of the NFSEG groundwater flow model, including: model extent, configuration, and lateral and internal boundary conditions; an analysis and interpretation of data needed for determination of the model calibration years; a plan for determination of groundwater recharge and maximum saturated evapotranspiration rates; and proposed NFSEG model calibration objectives. The third report describes the construction and calibration of version 1.0 of the NFSEG groundwater model.

The NFSEG v1.0 has been updated since 2016. The purpose of this report is to describe the development of the next version of the groundwater flow model, NFSEGv1.1.

DESCRIPTION OF MODEL AREA

The approximately 60,000 square miles model domain encompasses a large area of the Floridan aquifer system in north Florida, Georgia, and South Carolina (Figure 1-1). Land surface elevations range from sea level to more than 450 feet, NAVD88 in northern Georgia.

Physiography

The model area lies within the Coastal Plain physiographic province of Florida, Georgia, and South Carolina. This area has been subdivided into the Sea Island, East Gulf Coastal Plain, and Floridian Sections (Fenneman and Johnson 1946; Figure 1-2). The Coastal Plain extends from the Fall Line, the line of outcrop of the igneous and metamorphic rocks of the Piedmont region, southward towards the Atlantic and Gulf coasts. The topography of the Coastal Plain varies from low-lying flat plains to rounded foothills of the Piedmont region. Karstic landscapes prevail in areas where limestone is near land surface. Low-lying coastal terraces occupy much of the area and reflect changes in Pleistocene sea-level stands (Renken 1996).

Land Use

According to the National Land Cover Database (NLCD) land use coverage, in 2001, excluding the ocean, forested areas covered a significant portion of the model area (36.5%; Figure 1-3). Wetlands, agricultural lands, and urban areas constituted 23%, 16.5%, and 9% of land uses, respectively.

Major Surface Water and Groundwater Basins

Major surface water basins that are partially or fully encompassed by the study area include the St. Johns, Suwannee, Altamaha, Satilla, and Savannah River basins. Smaller basins include those of the Flint, Ochlocknee, Aucilla, Steinhatchee, Wacissa, St. Marks, St. Marys, and Ocklawaha Rivers.

For this study, seven major groundwater basins were delineated based on the UFA potentiometric surface (Figure 1.4). The potentiometric surface highs in southeast Clay County, Florida, the Keystone Heights area of north-central Florida, and Valdosta, Georgia are the major features that divide major groundwater basins in north Florida. These groundwater basins are similar to those mapped by Bush and Johnston (1988).

Municipalities and Other Major Pumping Centers

Major pumping centers are located generally in large cities, where municipal, commercial, and industrial water requirements are concentrated. These cities include Jacksonville, Gainesville, Fernandina Beach, and Tallahassee in Florida, and Savannah, Brunswick, and Albany in Georgia. Areas of notable agricultural withdrawals include southwest Georgia, eastern Putnam, southern St. Johns and Flagler counties, Florida, and the Suwannee River basin in Florida.

Climate

The climate of the area is characterized as subtropical, with hot, humid summers and mild winters. Temperatures in the summer range typically from the low 70's to the low 90's degrees Fahrenheit. Temperatures in the winter typically range from the low 30's to the low 70's degrees Fahrenheit on average ('Climate of Florida', 2012, 'Climate of Georgia', 2012). Winter rainfall patterns tend towards widespread frontal activity, while summer rainfall patterns tend towards afternoon thundershowers ('Climate of Florida', 2012, 'Climate of Georgia', 2012)**.** Long-term average rainfall within the model domain is approximately 50 inches. Figure 1-5 provides long-term averages as well as 2001 and 2009 annual rainfall totals for several locations with the model area.

2. HYDROLOGY OF THE AREA

The hydrology within the NFSEG model domain is comprised of surface water and groundwater systems. The groundwater system is comprised of the Floridan aquifer system and, where present, the overlying intermediate confining unit and surficial aquifer system. The surface water systems are of concern because of the interactions with the groundwater flow system. A brief description of surface water systems within the NFSEG domain is provided, followed by a detailed description of the groundwater flow system.

SURFACE WATER SYSTEMS

Surface water systems of the area include streams, lakes, wetlands, estuaries, the Atlantic Ocean, and the Gulf of Mexico. Hundreds of streams and rivers and more than 300 lakes are represented in the NFSEG model. Hydraulically, surface water bodies are of interest because of their potential for water exchange and for influencing water levels of adjacent groundwater systems. The rate of exchange between a surface water body and surrounding groundwater system depends on the level of resistance to flow of the materials connecting the two systems and the head gradient between them. The head gradient is the difference in water level between the surface water body and the aquifer with which it is in hydraulic contact divided by the distance over which the decline in water level occurs. Where resistance to flow is greater, a larger head gradient between a given surface water body and surrounding aquifer is required to realize the same rate of exchange. Less resistance to flow requires a smaller head gradient to drive flows, so water levels of surface water bodies and groundwater systems to which they are connected hydraulically tend towards similarity under conditions of low flow resistance. The manner of representing surface water bodies in the NFSEG model is discussed in detail in later sections of the report that describe the model lateral and internal boundary conditions, including the descriptions of implementation of the MODFLOW River, Drain, General Head Boundary, and Basic Packages.

The following discussion includes brief descriptions of selected rivers, lakes, wetlands, and the Atlantic Ocean and Gulf of Mexico, focusing primarily on the interaction of these bodies with the groundwater system. The types of interactions that occur between surface water bodies and groundwater flow system within the NFSEG model depend on various conditions, including the degree of confinement of the Floridan aquifer system and relative water levels of a given surface water body and aquifer(s) with which it interacts hydraulically. In addition to the two ocean bodies, the selected surface water bodies include rivers, lakes, and wetlands, thus encompassing the range of types of surface water bodies that occur within the NFSEG model domain, given that estuaries are treated as extension of oceans.

Rivers

Major rivers in the NFSEG model domain include the Suwannee River and Santa Fe River, a tributary to the Suwannee River. The Suwannee and Santa Fe rivers, in their respective upper reaches, correspond to areas in which the Floridan aquifer system is confined or semiconfined.

Hence, in their respective upper reaches, these rivers are in hydraulic contact with the surficial aquifer system. However, these rivers down cut progressively through underlying sediments in their respective down gradient courses. Each river first down cuts into the intermediate confining unit and eventually into the Floridan aquifer system. Hence, baseflow in these rivers is ultimately derived from all three aquifer systems, although the Floridan aquifer system becomes the dominant source of baseflow once they are incised into it, as evidenced by numerous, large springs that contribute to the flows of the two rivers along those respective portions of their courses.

Two other important tributaries to the Suwannee River are the Alapaha and Withlacoochee rivers. Most of the respective basins of these two rivers are in Georgia. Their respective confluences with the Suwannee River occur just south of the Florida-Georgia state line. Baseflows in these rivers are derived from the surficial aquifer system, intermediate confining unit, and Floridan aquifer system, as contact with all three aquifer/confining unit systems occurs along their respective courses, depending on location.

Under low flow conditions, all flow in the lower reaches of the Alapaha River is captured by the Floridan aquifer system by a series of sinks just upstream of and at the end of a small distributary known as the Dead River. The flow reemerges from the Floridan aquifer system at the Alapaha Rise, from which the reemergent Alapaha River flows another mile or so to its confluence with the Suwannee River. The intermediate confining unit is absent in the general areas of the Dead River and Alapaha Rise, so the Floridan aquifer system in this area is unconfined.

The Withlacoochee River also loses water to the Floridan aquifer system in areas in which the intermediate confining unit is absent or has been breached by karst features. North of Valdosta, Georgia, a portion of the river flow is diverted to sink during high flows, and all of it is during low flows. Direct recharge to the Floridan aquifer system contributes greatly to the formation of the Valdosta potentiometric high, a regionally important feature of the potentiometric surface of the Floridan aquifer system. Discharge to the river via springs emanating from the Floridan aquifer system occurs near the Florida-Georgia state line (Krause 1979).

Located east of the Suwannee River near the Atlantic coast, the St. Johns River flows northwardly from its headwaters, which are south of the southern extent of the model domain. The St. Johns River is in close hydraulic contact with the Floridan aquifer system in the southern area of its occurrence within the model domain. Discharge from the Floridan aquifer system to the St. Johns River at Lake George, a large lake that occurs along the course of the St. Johns River in northwestern Volusia, eastern Marion, and southeastern Putnam counties, contributes to a noticeable low in the potentiometric surface of the Floridan aquifer system in the area. Discharge to several springs in this area, including Silver Glen and Salt springs, also contribute. The runs of these springs form tributaries to the St. Johns River, as they discharge to Lake George. North of Lake George, the thickness of the intermediate confining unit increases along the course of the St. Johns River. At the town of Green Cove Springs, Florida, Green Cove Springs emanates from the Floridan aquifer system, and the discharge travels via a short run to the St. Johns River. This occurs despite significant confinement of the Floridan aquifer system by the intermediate confining unit, which is approximately 250 thick at this location. Further to the north, in Jacksonville, Florida, significant hydraulic contact with the St. Johns River is limited to the surficial aquifer system, as the Floridan aquifer system in this area is heavily confined, the intermediate confining unit being on the order of 400 feet thick.

In Georgia, a major river system that is in close hydraulic contact with the Floridan aquifer system near the northern extent of the model domain is the Ocmulgee River, the principal tributary to the Altamaha River, which is formed by the confluence of the Ocmulgee and Oconee rivers. The Oconee River is also in close hydraulic contact with the Floridan aquifer system near its intersection with the northern boundary of the model domain. These rivers derive baseflow from the surficial aquifer system, the intermediate confining unit, and the Floridan aquifer system.

The rivers mentioned in the preceding discussion are a small, albeit important, sampling of rivers within the vast model domain. Other rivers are present, many of which are in close contact with the Floridan aquifer system over significant portions of their runs due to prevailing unconfined conditions in the Floridan aquifer system. Such rivers include the Flint River in southwestern Georgia and the Steinhatchee River of Lafayette, Dixie, and Taylor counties, Florida. Others lack close contact with the Floridan aquifer system due to confinement. Those rivers are in contact with the surficial aquifer system and/or intermediate confining unit.

Lakes

Many naturally formed lakes in the model domain are sinkhole lakes, which are formed in depressions that occur due to the collapse of cavities in the limestone of the underlying Floridan aquifer system. Resistance to downward vertical leakage due to the presence of the intermediate aquifer system aids in the retention of water in the resulting depressions, thus helping to form lakes. Large numbers of sinkhole lakes are found in Keystone Heights, Florida, and surrounding areas. Lakes Brooklyn and Geneva are examples of such lakes. These lakes are part of the Upper Etonia Creek basin chain of lakes, which has been the subject numerous hydrological assessments. A similar group of lakes occurs in Lowndes and Lake Park counties of Georgia and surrounding areas.

Sinkhole lakes can act as sources of relatively concentrated recharge to the underlying Floridan aquifer system in recharge areas. Leakage rates beneath them to the Floridan aquifer system is often enhanced by disturbances that occurred in the intermediate confining unit during the collapse(s) within the Floridan aquifer system that resulted in their formation. In and surrounding the town of Keystone Heights, Florida, rates of recharge, which are enhanced by downward leakage from numerous sinkhole lakes, are large enough to result in the formation of the Keystone Heights potentiometric high, a prominent, hydrologically important feature of the potentiometric surface of the Floridan aquifer system. The Keystone Heights potentiometric high is centered approximately on the Upper Etonia Creek basin chain of lakes, which includes Lake Brooklyn, as mentioned previously. A strong correlation exists between the water levels of Lake Brooklyn and the Floridan aquifer system (Motz et al. 1991).

Other lakes occur in areas in which the Floridan aquifer system is unconfined. The water levels of such lakes usually are close to the level of the potentiometric surface of the Floridan aquifer system. An example of such a lake is Lake Grandin in Putnam County, Florida.

Swamps/Wetlands

Wetlands within the NFSEG model domain are related to the hydrogeology of the system in several ways. Of course, in recharge areas, confinement of the Floridan aquifer system in flat terrain can impede leakage to the Floridan aquifer system, while the flatness of the terrain impedes runoff. The Okefenokee Swamp in southeast Georgia is an example of such a swamp. Other swamps occur in recharge areas in which the Floridan aquifer system is generally unconfined due to the absence or thinness of the intermediate confining unit, but, due to lower horizontal and vertical hydraulic conductivity within the Floridan aquifer system, potential recharge to the Floridan aquifer system spills over to land surface, thus forming wetland areas. Mallory Swamp, which is centered on the boundary between Lafayette and Dixie counties, Florida, is an example of this type of swamp. A third type of wetland occurs in coastal discharge zones in which the Floridan aquifer system is unconfined and in which its potentiometric surface is above land surface, thus enabling artesian discharge to relatively flat land. This results in pooling of the discharged water on the land surface, i.e., swamp formation. Wetlands resulting from this type of exchange occur extensively along the coast of the Gulf of Mexico.

Atlantic Ocean and Gulf of Mexico

The Atlantic Ocean and Gulf of Mexico are the ultimate catchments of whatever water remains within the Floridan aquifer system seaward of their respective coasts. Horizontal gradients in the surficial aquifer system and Floridan aquifer system at either coast are generally towards the coast. Water levels in the Floridan aquifer system along the coasts of both the Atlantic Ocean and Gulf of Mexico generally exceed sea level, except locally along the Atlantic coast where intense pumping occurs, so vertical gradients are generally directed upwardly. Remaining fresh groundwater within the surficial aquifer discharges at the coast. Along the Gulf coast, the Floridan aquifer system is generally unconfined, so the water remaining within it likely discharges within a very short distance of the coast, probably within 5 miles in most areas. Heavy confinement exists along the Atlantic coast of southeast Georgia and northeast Florida, between Savannah, Georgia, south to the Duval/St. Johns county line. The heavy confinement enables freshwater within the Floridan aquifer system to extend offshore for many miles, perhaps up to 50 miles along parts of this coast. South of the general area of St. Augustine, Florida, however, confinement lessens. This enables increasing discharge to nearby offshore areas, and water levels within the Floridan aquifer system decline markedly from St. Augustine, Florida, to areas south of it within the model domain. Crescent Beach Springs is located about 2.5 miles offshore of Crescent Beach, Florida. The rate of discharge of this spring is unknown, but it creates a noticeable “boil” at the water surface. The decline in the water levels of the Floridan aquifer system from St. Augustine south parallels increasing concentrations of relict seawater in the same direction. Municipal water supplies obtained from the Floridan aquifer system in this area are mixed with freshwater obtained from the surficial aquifer system and/or subjected to treatment processes to reduce total dissolved concentrations to levels prescribed by drinking water standards.

GROUNDWATER SYSTEM

The domain of the NFSEG model includes large areas of both Florida and Georgia and a portion of South Carolina (Figure 2-1). Major aquifer systems in this area include the Floridan aquifer system and, where present, the intermediate confining unit and surficial aquifer system. The Southeastern Coastal Plain aquifer system underlies the entire area (Miller 1990; Figure 2-1), but its influence on flow in the Floridan aquifer system is only in the northern extent of the model domain, primarily north of the Gulf Trough. The following sections provide more detailed descriptions of these aquifer systems.

Surficial Aquifer System

The surficial aquifer system is the uppermost aquifer system within the domain of the NFSEG model. The surficial aquifer system occupies a large portion of the model domain (Miller 1990; Davis and Boniol, digital communication). The surficial aquifer system is unconfined generally and is comprised primarily of unconsolidated beds of sand, shelly sand, shell, and clay of post-Miocene age (Miller 1986; Table 2-1).

In some areas, the surficial aquifer system is divided between an upper unconfined and lower semiconfined zone by beds of relatively low permeability. An example is the surficial aquifer system of Volusia County, Florida, where the surficial aquifer system is comprised of an upper unconfined zone consisting primarily of sand separated by clay or silt layers from a lower semiconfined zone consisting primarily of sand and shell (Phelps 1990).

Hydraulic Properties

Generalized regional maps of the hydraulic properties of the surficial aquifer system are not available, as the surficial aquifer system has been characterized in most cases on a localized basis or, in more recent modeling studies, on a subregional basis. The surficial aquifer system has been the subject of aquifer performance tests (e.g., Hayes 1981 and Annable et al. 1996). The transmissivity of the surficial aquifer system has been estimated as ranging from 1,000 to 10,000 feet squared per day (ft^2/d) with a maximum range of 25,000 to 50,000 ft^2/d (Miller 1990).

In St. Johns County, Florida, estimates of the transmissivity of the lower permeable zone of the surficial aquifer system ranged from 6,500 to 7,000 ft^2/d (Hayes 1981). Other investigations resulted in values ranging from 1,300 ft^2/d to as high as 25,500 ft^2/d, the upper end value representing a shell bed of 60 feet or more in thickness (Spechler and Hampson 1983). In Volusia County, Florida, the transmissivity of the surficial aquifer system was determined to range from 100 to 9,300 ft^2/d (Phelps 1990).

An aquifer performance test at Halfmoon Lake in Putnam County, Florida, resulted in estimates of horizontal hydraulic conductivity that range as high as 62 feet/day (ft/d; Annable et al. 1996).

Table 2-1. Summary of Groundwater Hydrology System.

Downdip of Gulf Trough			Updip of Gulf Trough		
Series	Hydrogeologic Unit		Series	Hydrogeologic Unit	
Post-Miocene	Surficial Aquifer System		Post-Miocene	Surficial Aquifer System[1]	
Miocene	Intermediate Aquifer System/Intermediate Confining Unit		Miocene	Intermediate Aquifer System/Intermediate Confining Unit[1]	
Oligocene	Upper Floridan Aquifer*	Floridan Aquifer System	Oligocene	Upper Floridan Aquifer	
Upper Eocene			Upper Eocene	Pearl River Aquifer Confining Unit	Southeastern Coastal Plain Aquifer System
Middle Eocene	Middle Confining Unit*; East: Lower Permeability; West: Higher Permeability or part of the transmissive system		Middle Eocene	Pearl River Aquifer	
	Lower Floridan Aquifer* (Upper Zone)				
Lower Eocene	Lower Semiconfining Unit		Lower Eocene		
Paleocene	Lower Floridan Aquifer (Fernandina Permeable Zone)		Paleocene	Chattahoochee River Aquifer Confining Unit	
Upper Cretaceous	Sub-Floridan Confining Unit		Upper Cretaceous	Chattahoochee River Aquifer	

*Where the middle confining unit is absent, the entire Floridan aquifer system is comprised of the Upper Floridan aquifer

Structure

The top of the surficial aquifer system coincides with land surface (Figure 2-2). The bottom of the surficial aquifer system coincides with the top of the intermediate confining unit, where it is present (Miller 1990; Davis and Boniol, digital communication 2013; Figure 2-3). The thickness of the surficial aquifer system is generally less than 100 feet (ft; Miller 1990), but ranges upwardly to nearly 300 feet (e.g., areas near Brunswick, Georgia; Figure 2-4).

Water Levels

Generally, the water table of the surficial aquifer system is a subdued reflection of land surface (Miller 1986). Currently, a domain-wide map of the water table is not available, due to a lack of available water level data in many areas. Nevertheless, the water level of the surficial aquifer system is known at the locations of numerous monitoring wells within the model domain (Appendix A).

The water levels of the surficial aquifer system relative to those of the underlying Floridan aquifer system determine the direction of leakage to or from the Floridan aquifer system in semiconfined to confined regions of the Floridan aquifer system. Interactions of the surficial aquifer system with surface water bodies that are in hydraulic contact with it can influence the water levels of the surficial aquifer system to a large degree locally. Partly for this reason, the surficial aquifer system is generally not viewed as a regional flow system, despite its large extent within the model domain. Another factor in this is the potential for strong localized influences of the Floridan aquifer system in semiconfined regions of the Floridan aquifer system.

Intermediate Confining Unit

Throughout most of its extent, the Floridan aquifer system is overlain by middle Miocene age (i.e., Hawthorn Group) to post-Miocene age, clay rich units, which function as the intermediate confining unit (Miller 1986; Bush and Johnston 1988; Table 2-1). Depending on location, the clays of the intermediate confining unit are interbedded with sand, shell, and or carbonate lenses that are adequately extensive and permeable as to constitute aquifers of limited lateral and vertical extent (Miller 1986). Perhaps the most notable and well known of such aquifers is the Brunswick aquifer system in the Brunswick area of southeast Georgia (Steele and McDowell 1998). Because of the presence of internal aquifers, the intermediate confining unit is often referred to alternatively as the intermediate aquifer system (Florida Geological Survey 1986). The intermediate confining unit separates the underlying Floridan aquifer system from the overlying surficial aquifer system throughout a large portion of the NFSEG model domain. In some areas, the Floridan aquifer system is unconfined due to the absence of the intermediate confining unit. Examples are the area of the lower Suwannee River basin in the SRWMD and the Flint River basin of southwest Georgia (Bush and Johnston 1988). In other areas within the model domain, the intermediate confining unit is quite thick. In Duval and Nassau counties, Florida, and Camden and Glynn counties, Georgia, for instance, its thickness is in the hundreds of feet.

A primary controlling factor on flow within the Floridan aquifer system is the degree to which it is confined by the intermediate confining unit. Conditions in this regard range from unconfined to heavily confined within the model domain, as mentioned previously. In confined areas, the leakance of the intermediate confining unit in conjunction with the water level difference between the underlying Floridan aquifer system and overlying surficial aquifer system determine the rate and direction of leakage to or from the Floridan aquifer system.

Diffuse recharge to the Floridan aquifer system in confined areas must first pass through the surficial aquifer system and intermediate confining unit. Of the amount that makes its way to the surficial aquifer system in confined areas, a smaller amount generally ends up in the Floridan aquifer system due to diversions incurred in the surficial aquifer system and intermediate confining unit. Additionally, surface water runoff is generally higher in confined areas, making less recharge available to the surficial aquifer system at the start. In unconfined areas, net recharge to the Floridan aquifer system is generally higher because diversions of potential recharge to the Floridan aquifer system are typically less. Surface water runoff, for instance, is often relatively small to nonexistent in unconfined areas. Potential diversions that occur in the surficial aquifer system and intermediate confining unit are not a factor, as recharge occurs directly to the Floridan aquifer system. In many unconfined areas with thick overburden above the Floridan aquifer system, rates of evapotranspiration are often relatively low because depth to water table (i.e., depth to the potentiometric surface of the Floridan aquifer system) is often relatively large.

Structure

The top of the intermediate confining unit (Davis and Boniol, digital communication 2013) coincides with the bottom of the surficial aquifer system, where the surficial aquifer system is present (Figure 2-5). The bottom of the intermediate confining unit coincides with the top of the Floridan aquifer system (Figure 2-6). Within the NFSEG model, the thickness of the intermediate confining unit ranges from 0 ft in areas in which the Floridan aquifer system is unconfined to more than 600 ft in parts of Georgia (Davis and Boniol, digital communication 2013; Figures 2-7).

In unconfined areas, discontinuous outliers of the intermediate confining unit are numerous and scattered throughout (Davis and Boniol, digital communication 2013; Figure 2-6), as are outliers of the surficial aquifer system (Davis and Boniol, digital communication 2013; Figure 2-4). The complexity of occurrence of the surficial aquifer system and intermediate confining unit in unconfined regions of the model domain led to simplification of their respective representations in the NFSEG model, as will be discussed in a later section of this report.

In past studies (e.g., Miller 1990), the areal extent of the surficial aquifer system was represented as somewhat smaller than that of the intermediate confining unit, but much additional data have been collected and analyzed since then. Currently, a distinct line of pinch-out of the surficial aquifer system is difficult to specify. For the intermediate confining unit, this somewhat easier but still difficult. Current results (i.e., those of Davis and Boniol, digital communication 2013) indicate a much more complex distribution of the surficial aquifer system and intermediate confining unit sediments than representations of past studies (Figures 2-4 and 2-7).

Hydraulic Properties

The leakance of the intermediate confining unit has been estimated based on aquifer performance tests and the results of previous modeling studies (e.g., Bush and Johnston 1988). Estimates vary widely depending on location. However, leakance estimates are generally lower in areas of greater intermediate confining unit thickness. In areas in which the intermediate confining unit is thick, intermediate confining unit leakance may be on the order of 10^{-6} per day or lower (Bush and Johnston 1988; Figure 2-8). In areas in which the intermediate confining unit is thin, intermediate confining unit leakance may be on the order of 10^{-4} per day or higher (Bush and Johnston 1988; Figure 2-8). The clay content of the intermediate confining unit affects leakance also, with greater clay content tending towards lower leakance. In some areas, relatively thin but continuous clay layers can effectively confine the Floridan aquifer system (Bush and Johnston 1988).

The horizontal hydraulic conductivity of the intermediate confining unit is generally low, ranging between 10^{-6} to 10^{-2} ft/d in most areas, except in areas in which aquifers of significant size and permeability are present, such as the Brunswick aquifer system. Aquifer performance tests of the Lower Brunswick aquifer at Colonel's Island in Glynn County, Georgia, indicate transmissivities of 2,000 to 4,700 ft^2/d with corresponding hydraulic conductivities of 20 to 57 ft/d (Clarke et al. 1990).

Vertical Hydraulic Gradient

The water level difference across the intermediate confining unit, estimated as the difference in water level between the overlying surficial aquifer system and underlying Floridan aquifer system, is referred to herein as the intermediate confining unit vertical head difference. The ratio of the intermediate confining unit vertical head difference to the thickness of the intermediate confining unit approximates the vertical hydraulic gradient across the intermediate confining unit. The vertical hydraulic gradient can be indicative of the degree of confinement provided by the intermediate confining unit (Figures 2-9 and 2-10).

Observations of the intermediate confining unit water level are sensitive to the position of the open interval of intermediate confining unit monitoring wells. For this reason, these observations were not utilized to the same degree as estimates of vertical head difference in the present study.

Floridan Aquifer System

The Floridan aquifer system within the NFSEG model domain is comprised primarily of carbonate rocks of Upper Cretaceous to Early Miocene age (Table 2-1). The Floridan aquifer system underlies the entire state of Florida, southeastern Georgia, and parts of Alabama and South Carolina (Miller 1990). In many areas, water within the Floridan aquifer system is brackish or saline (Miller 1990). However, the Floridan aquifer system is highly productive and has become an essential source of water wherever water quality permits (Miller 1990). In much of its extent, the Floridan aquifer system is comprised of an upper aquifer, the Upper Floridan aquifer, and lower aquifer, the Lower Floridan aquifer (Miller 1986). The two aquifers are separated by a semiconfining unit referred to herein as the middle confining unit. Regionally, the middle confining unit varies in lithologic composition and hydraulic characteristics, and the degree of confinement of the middle confining unit can vary significantly (Miller 1986). Where the middle confining unit is not present, the Floridan aquifer system is a single aquifer, referred to as the Upper Floridan aquifer (Miller 1986). In northeast Florida and southeast Georgia, the Lower Floridan aquifer is further subdivided into an upper zone, referred to as the upper zone of the Lower Floridan aquifer herein, and a lower zone, the Fernandina permeable zone (Miller 1986; Falls et al. 2005). The upper zone of the Lower Floridan aquifer is separated from the

Fernandina permeable zone by a confining unit, referred to herein as the lower semiconfining unit (Miller 1986; Falls et al. 2005; Table 2-1).

Gulf Trough

A geological feature that causes notable resistance to lateral flow within the Floridan aquifer system is the Gulf Trough in Georgia (Kellam and Gorday 1990; Figure 2-1), also known as the Suwannee Straits. The Gulf Trough is hypothesized as a system of fault-induced grabens into which lower permeability Miocene sediments have down-dropped (Miller 1986). This feature is linear in shape and is oriented generally along a southwesterly-northeasterly alignment (Figure 2-1). The increased resistance to lateral flow within the Gulf Trough manifests in the form of bunched potentiometric contours along its length on maps of the potentiometric surface of the Floridan aquifer system (i.e., a linear feature characterized by high horizontal hydraulic gradients).

Southeastern Coastal Plain Aquifer System

The Southeastern Coastal Plain aquifer system within the NFSEG model domain is comprised of several regionally mapped aquifers, including from top to bottom, the Pearl River aquifer, the Chattahoochee River aquifer, and the Black Warrior River aquifer, separated by regionally extensive confining units (Barker and Pernik 1994; Renken 1996; Figure 2-11; Table 2-1). The thickness of the Southeastern Coastal Plain aquifer system increases from its line of pinch-out, the Fall Line, towards the Gulf of Mexico and the Atlantic Ocean. The clastic rocks of the Southeastern Coastal Plain aquifer system grade by facies change both laterally and vertically into the carbonate rocks of the Floridan aquifer system in western South Carolina, southern Georgia, and southeastern Alabama, resulting in a direct hydraulic connection between the two aquifer systems at such boundaries (Barker and Pernik 1994). Downgradient of such boundaries, the hydraulic connection between the Southeastern Coastal Plain aquifer system and the Floridan aquifer system manifests in the form of diffuse leakage across the semiconfining units that separate the Southeastern Coastal Plain aquifer system from the overlying Floridan aquifer system (McFadden and Perriello 1983). Although leakage between the Floridan aquifer system and Southeastern Coastal Plain aquifer system occurs, the amounts represent a relatively small proportion of the total flux of the Floridan aquifer system (Barker and Pernik 1994).

The Pearl River aquifer is the Southeastern Coastal Plain aquifer system equivalent of the Lower Floridan aquifer, and the two aquifers are in direct hydraulic connection at their boundaries (Barker and Pernik 1994). In Georgia, the Pearl River aquifer is known subregionally as the Claiborne aquifer in its western area of occurrence and as the Gordon aquifer in its eastern area of occurrence (McFadden and Perriello 1983; Brooks et al. 1985; Long 1989; Lee et al. 1997). The Pearl River aquifer and Lower Floridan aquifer are treated as a single aquifer in the present study, consistent with previous groundwater modeling studies of the Floridan aquifer system that encompass parts of Georgia and Florida (e.g., Krause and Randolph 1989 and Payne et al. 2005).

Structure

A complicating factor related to the stratigraphy of the Floridan aquifer system involves the presence of saline water within the Floridan aquifer system. The onset of saline water is determined herein by comparison to a surface that represents the approximate onset of groundwater within the Floridan aquifer system of total dissolved solids (TDS) concentration greater than 10,000 milligrams per liter (mg/l; Williams, digital communication 2013; Figure 2-12). Groundwater below this surface is treated as being outside the zone of freshwater flow. The presence of saline water limits the lateral and vertical extents of the model representations of all aquifers and semiconfining units comprising the Floridan aquifer system within the NFSEG model domain, as the model is limited in representation to the freshwater flow system.

The maps shown herein are limited to the respective estimated lateral and vertical extents of freshwater flow within the various subject hydrogeologic units. This means that where the estimated onset of saline water is above the bottom of a unit, the "bottom" of the unit as shown is the estimated elevation of the onset of saline water. Where the estimated onset of saline water is below the bottom, then the bottom as shown is an estimate of the elevation of the actual bottom. A sparsity of data regarding the hydrostratigraphic extents of the Fernandina permeable zone and its overlying semiconfining unit does not enable an alternative representation regarding these two units. More details regarding the process of mapping these two units is provided below.

The accuracy of the maps lessens with increasing distance from the Atlantic coast, due to sparsity of data. The representation of the surficial aquifer and intermediate confining unit indicate a high level of complexity in their respective sediment distribution, contiguity, and thickness, more so than can be represented in the NFSEG model. Comparisons of the maps of the surficial aquifer system and intermediate confining unit to maps of corresponding model layers indicates the degree of generalization that was implemented in the respective model representations. The maps of the hydrogeologic units of the Floridan aquifer system are nearly identical to those of the corresponding model layers.

Another complication is related to the discontinuous nature of the middle confining unit. Miller (1986) mapped four different middle confining units in the model domain (numbers 1, 2, 3, and 7). In more recent studies, the tops and bottoms of these units were found to coincide with the corresponding top and bottom of a marker unit, which is generally present throughout the model domain (Jeff Davis, personal communication), although data needed to characterize the hydraulic properties of this unit are not. Within the lateral extents of the middle confining units mapped by Miller (1986), this marker unit was interpreted, based on current geophysical and stratigraphic information, to represent the top and bottom elevations of the middle confining units.

In the regions that lie beyond the middle confining units of Miller (1986), the marker unit was used to vertically divide the Upper Floridan aquifer (i.e., the Floridan aquifer system in areas in which Miller (1986) did not map middle confining units) into three separate (upper, middle, and lower) layers. This vertical discretization of the Upper Floridan aquifer was facilitated by use of the marker unit to represent the middle confining units of Miller (1986) within their respective extents. It also allowed for continuity of model layering with areas where Miller (1986) had not mapped the presence of a middle confining unit, thus resulting in the definition of three continuous layers representing the Floridan aquifer system throughout the model domain, referred to hereafter as zones 1, 2, and 3 in the present report (Table 2-2). Zone 1 is comprised only of the upper layer of the Upper Floridan aquifer in areas in which Miller (1986) did not map a middle confining unit and of the entire Upper Floridan aquifer elsewhere. Zone 2 is comprised only of the middle layer of the Upper Floridan aquifer in areas in which Miller (1986) did not map a middle confining unit and of the middle confining unit elsewhere. Zone 3 is comprised only of the lower layer of the Upper Floridan aquifer in areas in which Miller (1986) did not map a middle confining unit and of the Lower Floridan aquifer elsewhere. Within the extent of the Fernandina permeable zone, it includes only the upper zone of the Lower Floridan aquifer (i.e., the portion of the Lower Floridan aquifer that is above the lower semiconfining unit of the Fernandina permeable zone). The definition of zones 1, 2, and 3 facilitated subsequent model development in a way that recognized more recent stratigraphic analyses, as well as uncertainties arising from a lack of hydraulic data to correlate with these analyses.

Table 2-2. Summary of Zones Used to Define the Floridan Aquifer System

Areas Outside Limits of Miller (1986) Middle Confining Units	Areas Within Limits of Miller (1986) Middle Confining Units	Present Study
Upper Floridan Aquifer – Upper Layer	Upper Floridan Aquifer	Zone 1
Upper Floridan Aquifer – Middle Layer	Middle Confining Unit	Zone 2
Upper Floridan Aquifer – Lower Layer	Lower Floridan Aquifer	Zone 3

Upper Floridan Aquifer

The top of the Upper Floridan aquifer ranges in elevation from less than -750 feet, North American Datum 1988 (ft NAVD88), in southeast Georgia to nearly 375 ft NAVD88 near the northern extent of the model domain (Davis and Boniol, digital communication 2013; Figure 2-6).

The bottom of zone 1 ranges in elevation from approximately -1,000 ft NAVD88 in southeast Georgia to approximately 225 ft NAVD88 near the northern extent of model domain (Davis and Boniol, digital communication 2013; Figure 2-13). The thickness of the Upper Floridan aquifer ranges from near 0 ft along the Gulf Trough in Georgia to nearly 1,000 ft in the northwest region of the model domain (Figure 2-14).

The top of zone 2 coincides with the bottom of zone 1 (Figure 2-13). The bottom of zone 2 coincides with the top of zone 3 (Figure 2-15). Onshore, it ranges in elevation from approximately -1,000 ft NAVD88 in southeast Georgia to approximately 500 ft NAVD88 near the northern extent of the model domain (Davis and Boniol, digital communication 2013). The thickness of zone 2 ranges from less than 75 ft throughout numerous large areas of the NFSEG model domain to more than 700 ft in Marion County, Florida (Figure 2-16).

The bottom of zone 3 ranges from -2,100 ft NAVD88 in Glynn County, Georgia, to more than 160 ft NAVD88 near the northern extent of the model domain (2-17). Where the lower semiconfining unit that lies atop the Fernandina permeable zone is present, the bottom of zone 3 coincides with the estimated top of the lower semiconfining unit. The thickness of zone 3 ranges from 0 to more than 1,500 ft within its freshwater extent (Figure 2-18).

The bottom of the Floridan aquifer system within the model domain ranges from approximately -2,300 ft NAVD88 in Glynn County, Georgia, to around 165 ft NAVD88 near the northern extent of the model domain (Figure 2-19). As with all other reported bottom elevations herein, these elevations refer to the elevation of the onset of saline water where the onset is above the estimated actual bottom of the Floridan aquifer system. This surface was based on data obtained from Williams, digital communication 2012, and partly on Miller (1986).

Lower Semiconfining Unit

The lateral extent of the lower semiconfining unit was not available to the present study via a previous study. Its western boundary was assumed to coincide with the western boundary of the Fernandina permeable zone as shown in Miller (1986). Its *freshwater* extent to the north and south and to the east beneath the Atlantic Ocean was determined by intersecting its estimated top and bottom surfaces with the estimated 10,000 milligrams per liter (mg/l) total dissolved solids (TDS) concentration iso-surface of Williams, digital communication (2013; Figure 212). The discussion below regards the freshwater extent of the lower semiconfining unit.

The top of the lower semiconfining unit is based partly on thickness data of the lower semiconfining unit obtained from Miller (written communication 1991). A thickness layer was created in ArcGIS based on these data. The thickness layer incorporated the western extent of the Fernandina permeable zone as depicted by Miller (1986), along which the lower semiconfining unit thickness was assumed to be zero. The resulting thickness layer was intersected with the 10,000 mg/l TDS concentration iso-surface (Williams, digital communication 2013; Figure 2-12) to determine the freshwater extent of the lower semiconfining unit. The resulting freshwater thickness distribution of the lower semiconfining unit was then added to the top surface of the Fernandina permeable zone, described below, to obtain the top surface of the lower semiconfining unit (Figure 2-20). It is constrained to intersect with the bottom of the Floridan aquifer system along its western boundary, as is the bottom of the lower semiconfining unit and the top and bottom of the Fernandina permeable zone, which implies a coincident line of pinch-out of the lower semiconfining unit and Fernandina permeable zone along the western boundary. This treatment is consistent with the representation of the Fernandina permeable zone in Miller (1986). The top of the lower semiconfining unit, which coincides with the bottom of the upper zone of the Lower Floridan aquifer within its extent, ranges from about -1,300 ft NAVD88 in northeast Alachua County, Florida, to about -2,100 ft NAVD88 in Glynn County, Georgia to (Figure 2-20).

The bottom of the lower semiconfining unit coincides with the top of the Fernandina permeable zone within its area of extent. The top of the Fernandina permeable zone is described below. However, the extent of the lower semiconfining unit is different from that of the Fernandina permeable zone, so it is shown here as a separate map. Its elevations range from -2,200 ft NAVD88 to -1,400 ft NAVD88 (Figure 2-21).

The freshwater thickness of the lower semiconfining unit was estimated primarily on data obtained from Miller (written communication 1991) but also on other sources of information and assumptions, as noted above in the description of the lower semiconfining unit top. The freshwater thickness of the lower semiconfining unit ranges from 0 to approximately 325 feet (Figure 2-22).

Fernandina Permeable Zone

The top of the Fernandina permeable zone was based primarily on Miller (1986) and Miller (written communication 1991; Figure 2-23). The surface is assumed to coincide with the bottom of the Floridan aquifer system along the western extent of the Fernandina permeable zone, where Miller (1986) indicated that the Fernandina permeable zone pinches out. Elsewhere, the freshwater extent of the top of the Fernandina permeable zone was determined by intersecting the top surface with the 10,000 mg/l TDS iso-surface of Williams, digital communication 2013; Figure 2-12). The resulting surface ranges in elevation from more than -2,000 ft NAVD88 in Glynn County, Georgia, to approximately -1,200 ft NAVD88 in northeastern Alachua County, Florida, (Figure 2-23).

The bottom of the Fernandina permeable zone coincides with the bottom of the Floridan aquifer system, described below. It ranges in elevation from approximately -2,300 ft NAVD88 in Glynn County, Georgia, to approximately -1,450 ft NAVD88 in northeastern Alachua County, Florida (Figure 2-24).

The freshwater thickness of the Fernandina permeable zone ranges from 0 along its western boundary, a line of pinch-out, to approximately 450 ft in southeast Duval County, Florida (Figure 2-25).

Hydraulic Properties

Transmissivity of Zone 1

Estimates of the transmissivity of zone 1 within the NFSEG model domain are based largely on aquifer performance tests (Figure 2-26) and the results of previous groundwater modeling studies (for example Johnston and others, 1988). Bush and Johnston (1988) mapped the transmissivity of the Upper Floridan aquifer. Their map shows low to moderate transmissivity along the corridor of and west of the Ochlockonee river in the Florida panhandle and into Georgia along the general path of the Gulf Trough (10,000 to 100,000 ft^2/d). Between the Aucilla and Ochlockonee rivers, the transmissivity is generally high (>1,000,000 ft^2/d). In the Suwannee River Basin, extending northeast into Georgia, transmissivity is moderately high (250,000 to 1,000,000 ft^2/d). In coastal areas of Georgia and northeast Florida, transmissivity is low to moderate (10,000 to 100,000 ft^2/d; Figure 2-27).

Using flow-net analysis, Faulkner (1973) determined the transmissivity of the Upper Floridan aquifer near Silver Springs to be greater than 1,000,000 ft^2/d in areas surrounding Silver Springs. The maximum transmissivity estimate resulting from the analysis was 25,500,000 ft^2/d. The average transmissivity over the entire flow net was 2,090,000 ft^2/d.

Kuniansky and others, (2012) mapped the results of numerous aquifer performance tests of the Upper Floridan aquifer. Based on their map, the transmissivity of the Upper Floridan aquifer tends to be lower in east-central and northeast Florida and north and west of the Gulf Trough (< 50,000 ft^2/d generally) and higher in the unconfined areas of the Suwannee River basin and Gulf Coast (>50,000 ft^2/d). The areas of highest transmissivity are in southeast Georgia, parts of the Suwannee River basin, and Silver and Rainbow springs basins (>100,000 ft^2/d; Kuniansky, and others, 2012).

Leakance of the Middle Confining Unit

Other than results of modeling studies, the leakance of the middle confining unit is not known well in Florida. A recent aquifer performance test of the middle confining unit near Ocala, Florida, resulted in a leakance estimate of 1.05X10^{-2} per day (CDM Smith 2017). In Georgia, the vertical hydraulic conductivity of the middle confining unit in Brunswick is reported to be 4X10^{-6} ft/d (Clarke and others, 2004). At Savannah, Georgia, the vertical hydraulic conductivity is reported to be 6.7X10^{-4} ft/d (Clarke and others, 2004).

Transmissivity of the Lower Floridan Aquifer

The transmissivity of the Lower Floridan aquifer is not as well-known as that of the Upper Floridan aquifer. Only three aquifer performance tests of the Lower Floridan aquifer in the Florida portion of the NFSEG model domain are known to have been performed. These tests were performed near Keystone Heights (Connect Consulting, Inc. 2009), Grandin (Kleinfelder 2017), and Ocala (CDM Smith 2017), Florida, and resulted in estimated Lower Floridan aquifer transmissivity values of 60,000; 57,000; and 3,500,000 ft^2/d, respectively.
In Georgia, transmissivity values of the Lower Floridan aquifer range from 170 to 15,000 ft^2/d with a median of 3,500 ft^2/d in areas in which the Lower Floridan aquifer is primarily clastic and from 500 to 43,000 ft^2/d with a median of 2,900 ft^2/d in areas in which it is primarily carbonate (Clarke and others, 2004).

In Duval County, Florida, tests performed using multi-aquifer wells (wells open to the Upper Floridan aquifer and an upper portion of the Lower Floridan aquifer) have resulted in transmissivity values of 2,100 ft^2/d at well D-168 and 200,000 ft^2/d at well M503 (Clarke and others, 2004).

Water Levels

The water level of the Upper Floridan aquifer is known at numerous monitoring wells that are cased to and penetrate the Upper Floridan aquifer (Appendix A). In the present study, medians of these water levels were determined for the years 2001 and 2009, and, along with estimated river stages in unconfined areas, contoured to create maps of the median potentiometric surface of the Upper Floridan aquifer in the years 2001 and 2009 (Figures 2-28 and 2-29). In some cases, statistical methods were used to augment the number and quality of water-level observations in areas of limited water-level data availability (Appendix B).

As with the intermediate confining unit, the middle confining unit vertical-head difference can be indicative of the degree of confinement of the middle confining unit. The absolute value of the middle confining unit vertical head difference is typically less than 10 ft (Figures 2-30 and 2-31).

The water levels of the Lower Floridan aquifer are known at many monitoring wells (Appendix A). Fresh water levels in the Fernandina Permeable zone are known at two monitoring wells in the years of interest (Appendix A).

Recharge and Evapotranspiration Rates

Bush and Johnston (1988) estimated net recharge to the predevelopment Upper Floridan aquifer throughout the extent of the Upper Floridan aquifer. Estimates in the unconfined regions of the NFSEG model domain range from 5 to 20 inches/year (in/yr) over a large proportion of the area. Bush and Johnston (1988) did not indicate any significant change in recharge rates in these areas since predevelopment.

Using a water budget analysis, Knowles (1996) estimated total annual net recharge to the springshed areas of Rainbow and Silver springs as 15.2 in/yr and 11.6 in/yr, respectively, for the period of 1965 through 1994. These basins are unconfined, so net recharge to these springs was assumed to be equivalent to discharge from the springs.

Bush and Johnston (1988) estimated total rates of ET (sum of saturated and unsaturated ET rates) as ranging from 31 in/yr in the northern extent of the model domain in Georgia to 41 in/yr parts in parts of the Steinhatchee and lower Suwannee river basins. An average value appears to be on the order of 35 in/yr for the NFSEG model domain-wide. Based on water budget analyses of the period of 1965 through 1994, Knowles (1996) estimated total average annual evapotranspiration from the combined springshed areas of Rainbow and Silver springs to be 38 in/yr.

Spring Flows

Spring flows are a major mode of discharge from the groundwater system in the model domain. More than 300 springs are represented in the NFSEG model, most of which are in areas in which the ICU is thin or absent. Spring discharge totaled approximately 6,029 cubic feet per second (cfs) in 2001 and 7,911 cfs in 2009. All but five springs within the NFSEG model domain emanate from the Upper Floridan aquifer, with the remaining five emanating from the ICU (Figures 2-32 and 2-33).

A unique type of spring that occurs in karstic terrains, which are found within NFSEG model domain, is the river rise. River rises are upwellings that occur downgradient of sinks into which part or all the flow in a river or stream is captured. Upon entering the sink, the river flow may mix with groundwater flow before emerging at the rise location. The exact proportion of surface water versus groundwater at river rises is not well defined. Major river rises in the model domain include the Alapaha River Rise, St. Marks River Rise, Santa Fe River Rise, Steinhatchee River Rise, and Holton Creek Rise.

Springs with discharge rates that are greater than or equal to 100 cfs on average are classified as first magnitude springs. There are 18 first magnitude springs in the NFSEG model, not counting major river rises. The estimated total discharge of first magnitude springs was 2,932 cfs in 2001 and 5,234 cfs in 2009 (Figure 2-34).

Baseflows

Baseflows were determined by averaging the results of four different hydrograph separation techniques and a fifth approach that utilizes flow duration curves. Three of the four hydrograph separation techniques were implemented using the United States Geological Survey (USGS) computer program *Groundwater Toolbox* (Barlow et al. 2015; https://water.usgs.gov/ogw/gwtoolbox/#over). These three methods are the BFI standard and modified technique (Institute of Hydrology 1980a, b) and the HYSEP local minimum technique (Sloto and Crouse 1996). The fourth hydrograph separation technique is that of Perry (1995; aka, "the USF method"), a low pass filter method that utilizes a moving window of 121 days. The fifth method utilizes flow duration curves and is based partly on empirical results of previous investigations (e.g., Stricker 1983). In the implementation of the current study, baseflow discharges of the years 2001 and 2009 were estimated as corresponding to a probability of exceedance of 70 percent on annualized flow duration curves of the years 2001 and 2009, respectively.

Estimates derived from the HYSEP fixed interval and sliding interval methods and the PART method (Rutledge 1998) were considered also, as these approaches are also implemented in *Groundwater Toolbox* (Barlow et al. 2015). However, these methods resulted in baseflow hydrographs that mimic too closely the respective total flow hydrographs from which they are derived, resulting in overestimated baseflows. This conclusion was based on inspection of the results of analyses of the total flow hydrographs of 14 USGS streamflow gages within the NFSEG model domain (Figure 2-35).

The baseflow estimates derived from the BFI standard and modified methods and HYSEP Local Minimum method tend to cluster at the high end of a range, while the estimates resulting from the USF Method (Perry 1995) and exceedance plot-based approach tend to cluster at the low end. Using this approach, average annual baseflow rates were determined at 92 USGS gages for 2001 and 77 USGS gages for 2009. Estimates were not determined for tidally affected sites, sites located immediately downstream of dams, or sites missing more than a few average daily flows in 2001 or 2009. Determining baseflow rates based on the averages of five widely accepted methods presumably moderates potential eccentricities of any one of the approaches and thus helps attain better all-around estimates.

Cumulative Baseflow Estimates

Cumulative baseflows are defined herein as the total of all baseflows above a given USGS gage location in a stream. Cumulative baseflows determined using the averaging techniques discussed above are shown in Figures 2-36 and 2-37 for the years 2001 and 2009, respectively. They were determined primarily for gages located in the middle to lower reaches of major systems, including the Suwannee, Alapaha, Withlacoochee, Santa Fe, St. Marys, Ochlocknee, and Satilla rivers and Orange Creek. These cumulative baseflows represent averages over relatively large proportions of the respective stream basins, and are therefore applicable to evaluation of large areas of the NFSEG model domain. The cumulative baseflow rates for 2001 range from 5.7 cfs at Orange Creek at Orange Springs to approximately 3,000 cfs at Suwannee River at Branford. For 2009, estimates range from approximately 8.4 cfs at Orange Creek at Orange Springs to 3,320 cfs at Suwannee River at Branford (Figures 2-36 and 2-37).

Baseflow Pickup Estimates

A baseflow pickup is a measure of the contribution of the groundwater system to the flow of a stream between a downstream point and one or more upstream points. In the current study, baseflow pickups were determined generally as differences in baseflow between a downstream gage (i.e., a "to" gage) and the sum of baseflows of one or more upstream gages (i.e., the "from" gages). In some cases, however, a "from" gage is not available. In these cases, the "to" gage baseflow pickup estimate is, strictly speaking, a cumulative baseflow. The "to" gage in these cases is generally located in the upper reaches of the stream basin in which it is located, however, so these baseflows are comparable to other baseflow pickups.

The baseflows used in the baseflow pickup determinations were derived mostly using the averaging technique discussed above. An alternative approach was utilized for determining baseflow pickups between adjacent gages that bound river reaches with contributing basin areas in which the ICU is absent completely, and which lack a well-developed, channelized, surface drainage network. In this approach, baseflow pickup was determined by taking the difference in the total observed flows of the upstream and downstream bounding gages, based on the assumption that overland runoff is negligible in areas in which the Upper Floridan aquifer is unconfined. The resulting baseflow pickup estimates range from less than 5 cfs to more than 500 cfs for 2001 and from less than 5 cfs to more than 1,000 cfs for 2009 (Figures 2-38 through 2-43).

<u>Concentrated Groundwater Inflows</u>

Concentrated groundwater inflows represent a significant form of recharge to the groundwater flow system within the NFSEG model domain. They are both human induced and naturally occurring. Human induced inflows occur via rapid infiltration basins (RIBs), drainage wells, and injection wells. Naturally occurring inflows occur via sinks. In RIBs water is applied to land surface so inflow due to them is usually directed to the surficial aquifer system. Drainage wells are constructed into the Upper Floridan aquifer, and the injection wells located in the NFSEG model domain are constructed into the Lower Floridan aquifer. Inflow via sinks is to the Upper Floridan aquifer. Rates of inflow to drainage wells and sinks have been approximated in the present study as runoff to closed basins in HSPF. For sinks, measured flows are available in some cases.

<u>Groundwater Withdrawals</u>

Groundwater withdrawals in the NFSEG model domain include withdrawals for purposes of public/commercial/industrial/institutional supply; agricultural irrigation supply; recreational irrigation supply (e.g., golf courses); and domestic self supply. Most large withdrawals take place from the Upper Floridan aquifer, but significant amounts of water are also withdrawn from the Lower Floridan aquifer using wells that are open to both the Upper and Lower Floridan aquifers. In areas in which the Floridan aquifer system water quality requires extensive treatment; the surficial aquifer system is utilized as an alternative source for enhancement of supplies obtained from the Floridan aquifer system (Figures 2-44 through 2-47).

Single aquifer wells cased to and open to the Upper Floridan aquifer are primary mode of major withdrawals within the model domain. Multi-aquifer wells are wells that are open to more than one aquifer. In the case of the NFSEG model domain, the open interval of these wells extends from the Upper Floridan aquifer into the Lower Floridan aquifer. These wells are used extensively in Duval and Clay counties, Florida, for major withdrawals and can be found less extensively in other parts of the model domain. The actual distribution of withdrawals between the Upper and Lower Floridan aquifers in these wells is not well defined.

3. MODEL CONFIGURATION

At its maximum extent, the active domain of the NFSEG model corresponds to portions of three states—Florida, Georgia, and South Carolina, and portions of the Atlantic Ocean and the Gulf of Mexico, an area of approximately 60,000 square miles (Figure 3-1). In its present form, the model is fully three dimensional and steady state and has been calibrated to hydrologic conditions of years 2001 and 2009. The model consists of seven active layers that represent, from top to bottom, the surficial aquifer (where present, or the unconsolidated sediments overlying the Upper Floridan aquifer otherwise), the intermediate aquifer or intermediate confining unit (where present, Upper Floridan aquifer otherwise), the Upper Floridan aquifer, the middle confining unit (MCU) or the Upper Floridan aquifer where the MCU is absent, the Lower Floridan aquifer (or the Upper Floridan aquifer where the MCU is absent or the upper zone of the Lower Floridan aquifer within the extent of the Fernandina Permeable zone), the lower semiconfining unit, and the Fernandina Permeable zone of the Lower Floridan aquifer, where these hydrogeologic units are present (Table 3-1).

MODEL CODE SELECTION

The NFSEG model is an application of the MODFLOW-NWT (Niswonger et al. 2011) formulation of the MODFLOW 2005 (Harbaugh 2005) groundwater flow simulation software. MODFLOW-NWT was developed to provide an improved method for addressing numerical difficulties that result from the nonlinearity of the unconfined groundwater flow equation. More specifically, as compared to other versions of MODFLOW, MODFLOW-NWT provides enhanced rewetting capabilities in simulations of the water table of unconfined aquifers. Unconfined conditions occur throughout the area corresponding to the NFSEG model domain in the surficial aquifer or in outcrops of the intermediate confining unit or the Upper Floridan aquifer.

The ability of MODFLOW-NWT to represent drying and rewetting processes effectively was the primary consideration in its selection for use in the NFSEG model development. Other important considerations were the ability of MODFLOW-NWT to represent aquifer systems in a fully three-dimensional manner under both steady state and transient conditions. In addition, as a product of the U.S. Geological Survey, MODFLOW-NWT is recognized worldwide, resides in the public domain, and is available for download as executable and source code at no cost to the user.

The geometries and locations of conduits providing preferential flow to springs within the Floridan aquifer are unknown or poorly known in most cases. An exception to this within the NFSEG model domain is Wakulla Springs, a first order magnitude spring with a mean flow rate exceeding 400 cubic feet per second (cfs). An extensive network of conduits supplying preferential flow to Wakulla Springs has been mapped through underwater cave exploration (Rupert 1988; Lane 2001; http://www.usdct.org/wakulla2.php; http://www.gue.com; http://www.wkpp.org). An additional network of conduits has been inferred through knowledge of the hydrological system, evaluation of solute travel times, and calibration of existing groundwater models (Davis 1996; Davis and Katz 2007; and Davis and others 2010). The simulation of groundwater flow within the Floridan aquifer in the surrounding and including Wakulla Springs and its network of mapped and inferred conduits using the standard MODFLOW approach (i.e., with simulated groundwater flow represented as Darcian flow) was shown by Kuniansky (2016) to compare well to that of an alternative MODFLOW model in which conduit flow to Wakulla Springs was represented more rigorously using the MODFLOW Conduit Flow Package (Shoemaker et al. 2008). The results of the study indicated that the presence of conduits, even an extensive network of relatively large conduits such as that of Wakulla Springs, should not necessarily preclude application of the standard Darcian flow approach, as implemented in standard applications of MODFLOW-NWT, for simulation of flows averaged over a month or longer (Kuniansky 2016). Based on these results and given the large extent of the Wakulla Springs conduit system and the relatively large sizes of its mapped and inferred conduits, the standard MODFLOW approach is assumed to be applicable throughout the NFSEG model domain.

Table 3-1. Primarily Represented Hydrogeologic Units of NFSEG Model Layers

Downdip of Gulf Trough				Updip of Gulf Trough			
Series	Hydrogeologic Unit		Model Layer	Series	Hydrogeologic Unit		Model Layer
Post-Miocene	Surficial Aquifer System		Layer 1	Post-Miocene	Surficial Aquifer System[1]		Layer 1
Miocene	Intermediate Aquifer System/Intermediate Confining Unit		Layer 2	Miocene	Intermediate Aquifer System/Intermediate Confining Unit[1]		Layer 2
Oligocene	Upper Floridan Aquifer	Floridan Aquifer System	Layer 3	Oligocene	Upper Floridan Aquifer		Layer 3
Upper Eocene				Upper Eocene	Pearl River Aquifer Confining Unit	Southeastern Coastal Plain Aquifer System	Layer 4
Middle Eocene	Middle Semiconfining Unit; East: Lower Permeability; West: Higher Permeability or part of the transmissive system		Layer 4	Middle Eocene	Pearl River Aquifer		Layer 5
	Lower Floridan Aquifer (Upper Zone)		Layer 5				
Lower Eocene	Lower Semiconfining Unit		Layer 6	Lower Eocene			
Paleocene	Lower Floridan Aquifer (Fernandina Permeable Zone)		Layer 7	Paleocene	Chattahoochee River Aquifer Confining Unit		Layer 6[1]
Upper Cretaceous	Sub-Floridan Confining Unit		Inactive	Upper Cretaceous	Chattahoochee River Aquifer		Layer 7[1]
							Inactive

[1] This unit not represented.

NFSEG GRID

The NFSEG model grid consists of 752 rows and 704 columns. The grid cells are uniformly 2,500 feet (ft) by 2,500 ft in dimension horizontally (Figure 3-1). The NFSEG model grid is nested within that of an early version of the grid of the U.S. Geological Survey system-wide groundwater flow model (http://fl.water.usgs.gov/floridan/numerical-model.html), which has since been revised. The size of the grid cells relative to the extent of the active model domain provides a high degree of resolution in the representation of the regional groundwater system without overburdening the NWT solver routine. Grid uniformity lends towards simplicity of design and supports the potential for equally good representation of all major regions within the area corresponding to the model domain.

The NFSEG model was constructed using an Albers Equal Area Map Projection, with the following specifications:

Projection: Albers
False_Easting: 0.0
False_Northing: 0.0
Central_Meridian: -84.0
Standard_Parallel_1: 29.5
Standard_Parallel_2: 45.5
Latitude_Of_Origin: 23.0
Linear Unit: Meter (1.0)

Geographic Coordinate System: GCS_North_American_1983
Angular Unit: Degree (0.0174532925199433)
Prime Meridian: Greenwich (0.0)
Datum: D_North_American_1983
Spheroid: GRS_1980
Semimajor Axis: 6378137.0
Semiminor Axis: 6356752.314140356
Inverse Flattening: 298.257222101

The above specifications are referred to as NAD83 Albers, meters, horizontal coordinate system. This custom projection was provided early in the model development by the USGS (Jason Bellino, personal communication 2011). The vertical datum used for all elevation data in this study is feet above the North American Vertical Datum of 1988 (NAVD 1988).

MODEL LAYERS

Each of the seven NFSEG model layers generally represents a single hydrogeologic unit, although there are some important exceptions (Table 3-1). In areas in which the estimated thickness of a given hydrogeologic unit is less than a layer specified minimum, the corresponding grid cells of the layer are assigned the minimum thickness of that layer in place of the estimated thickness (Tables 3-1 and Table 3-2; Figures 3-2 through 3-7). The hydraulic properties assigned to these grid cells, which are calibration derived, represent vertically averaged composite values of the primarily represented hydrogeologic unit, assuming it is present, and the included portions of the hydrogeologic units that bound it above and/or below. This approach is implemented in the representations of all primarily represented hydrogeologic units (Tables 3-1 and 3-2). It is referred to hereafter as the "minimum thickness approach."

Table 3-2. Minimum Layer Thicknesses

NFSEG Model Layer	MODFLOW-NWT UPW Layer-Type Designation	Applied Minimum Thickness (Feet)
1	Unconfined	30
2	Confined	30
3	Confined	50
4	Confined	30
5	Confined	50
6	Confined	10
7	Confined	10

Although the minimum thickness approach is used in the representations of all hydrogeologic units represented in NFSEG, it is used most widely in respect to the surficial aquifer system and intermediate confining unit, which are represented primarily by model layers 1 and 2, respectively (Tables 3-1 and 3-2; Figures 3-2 through 3-7). Relatively small and isolated (laterally discontinuous) areas of both hydrogeologic units can occur within portions of the unconfined region of the model domain (Figures 2-4 and 2-7), and their geographic distributions can be quite complex. They range in area from less than that of a single grid cell (0.22 square miles) to collective areas of many grid cells (Figures 2-4 and 2-7). For either unit, where the estimated thickness is less than 30 feet (ft), a minimum thickness of 30 ft is assigned, and the top and bottom elevations of underlying model layers are adjusted as needed to also maintain their respective minimum thicknesses. This means that no grid cells are designated as inactive within the active extents of layers 1 and 2, regardless of whether the surficial aquifer system or intermediate confining unit is present. The same also applies to the representations of all primarily represented hydrogeologic units in the other respective model layers. Unconsolidated sediments make up layers 1 and 2 as well as in the regionally unconfined area. They are typically unsaturated, seasonally saturated, or saturated but without a discernible vertical head difference between them and the Floridan aquifer system.

It is presumed in the calibration process that in the unconfined zones of the Floridan aquifer system, the uppermost 30 feet of hydrogeologic material resembles the surficial aquifer system more closely than the Floridan aquifer system in its hydraulic properties. Therefore, layer 1 horizontal hydraulic conductivities in the unconfined zones of the Floridan aquifer system are limited to 50 ft/d, as they are in the remaining part of the model domain (as a maximum hydraulic conductivity value for sand, silts, and clayey sand). In layer 2, the value of vertical hydraulic conductivity assigned to a given layer 2 grid cell in an unconfined zone (where the intermediate confining unit was mapped as having a thickness of less than 30 feet), the hydraulic properties are assumed to be equal to the value assigned to the layer 3 grid cell of the same vertical column of grid cells. This is because layer 2 is presumed to correspond more closely to the Floridan aquifer system than to the surficial aquifer system or the intermediate confining unit because of its depth, keeping in mind that depth to the top of the Floridan aquifer system in unconfined regions is usually small (less than 30 ft). The decrease in layer thickness of model layer 3 required to implement minimum layer thicknesses for layers 1 and 2 is relatively small in most instances, so effects on transmissivity calculations are small.

Nevertheless, separate maps of the transmissivity of layer 3 versus estimates for the entire thickness of upper Floridan aquifer, both resulting from model calibration, are provided in section 4, which contains the description of the model calibration process.

Limiting correspondence of layer grid cells to the representation of only one hydrogeologic unit is feasible in a large portion of the NFSEG active model domain, and where this is the case, model grid cells of a given layer correspond entirely to one hydrogeologic unit only. Restricting grid cell representation of large regions within a layer is often desirable, because it can facilitate aspects of the model development, such as simplifying the pre- and postprocessing necessary to implement model calibration. However, in the unconfined zones of the Floridan aquifer system, this approach is impractical because of system complexity and, furthermore, would likely contribute to numerical instability.

An additional advantage of the minimum thickness approach lies in the relative simplicity afforded by it in implementing internal boundary conditions, such as the MODFLOW River and Drain Packages. In all but a few cases, river boundaries are assigned to layer 1 or 2, and in all cases, drain boundaries are assigned to layer 1. In all cases, maximum saturated evapotranspiration is assigned to layer 1, as all extinction depths are contained within layer 1. This is all possible because of the minimum thickness of 30 ft assigned to layers 1 and 2. The minimum thickness approach also allows for refining the assignment of hydraulic properties described above through the calibration process. Thus, unnecessarily detailed representations of complex distributions of surficial aquifer system and intermediate confining unit outliers (whose locations and properties may not be well defined) are avoided, and whose portrayal as scattered “islands” of active grid cells would likely undermine model stability.

Layer 1

Layer 1 is used primarily to represent the surficial aquifer system, as discussed above (Tables 3-1 and 3-2). Outside the contiguous extent of the surficial aquifer system, individual grid cells of layer 1 represent a composite of the surficial aquifer system, the intermediate confining unit, and/or the Upper Floridan aquifer. The active areal extent of layer 1 was made equivalent to that of layer 3. The top, bottom, and thickness of layer 1 are depicted on Figures 3-8, 3-9, and 3-10, respectively. Details regarding the determination of the active areal extent of layer 3 are provided in the discussion of layer 3 below.

Layer 2

Layer 2 is used primarily to represent the intermediate confining unit (Tables 3-1 and 3-2). Outside the contiguous extent of the intermediate confining unit, individual grid cells of layer 2 are assumed to represent the intermediate confining unit or the Upper Floridan aquifer. Although layer 2 represents the intermediate confining unit, or the Upper Floridan aquifer in the noncontiguous extent of the intermediate confining unit, it is assumed in the model calibration process, described in detail in section 4, that the hydraulic properties of layer 2 resemble those of the Floridan aquifer system more closely than those of the intermediate confining unit in these areas. For this reason, calibration determined vertical hydraulic conductivity values assigned to grid cells in the noncontiguous areas of the intermediate confining unit are biased towards the values assigned to corresponding layer 3 grid cells. The areal extent of layer 2 was made equivalent to that of layer 3. The top, bottom, and thickness of layer 2 are depicted on Figures 3-9, 3-11, and 3-12, respectively. Details regarding the determination of the areal extent of layer 3 are provided in the discussion of layer 3 below.

Layer 3

Layer 3 is used primarily to represent the Upper Floridan aquifer. Where the Upper Floridan aquifer is not present as a separate hydrogeologic unit (i.e., where the middle confining unit is effectively absent), layer 3 represents a shallower section of the Floridan aquifer system (Zone 1 of the present study, as noted in Table 2.2). The assigned minimum layer thickness of model layer 3 is 60 ft (Tables 3-1 and 3-2; Figures 3-11, 3-13, and 3-14).

The primary consideration in specifying the locations of the lateral boundaries of layer 3 was to eliminate or at least minimize their influences on critical portions of the active model domain. The approach for achieving this was to place the lateral boundaries, as much as feasible, at locations that correspond approximately to the physical boundaries of the Floridan aquifer system or the boundaries of freshwater flow therein. Where placement at physical boundaries was infeasible, placement was made at locations that are as far as feasible from areas of critical concern.

The domain of the NFSEG model is oriented along southwest-northeast and northwest-southeast alignments (Figure 3-1). Hence, the lateral limits of the model are defined by a northwest facing lateral boundary, a northeast facing lateral boundary, a southeast facing lateral boundary, and a southwest facing lateral boundary. For simplicity, these are referred to hereafter as the northern, eastern, southern, and western lateral boundaries, respectively. As stated previously, the general approach in specifying the locations of the lateral boundaries was to place them at the physical boundaries of the Upper Floridan aquifer or the limits of the freshwater flow system therein to the extent that such placement was feasible.

As model development proceeded, however, additional criteria were applied to enhance numerical stability. The implementation of these criteria resulted in changes in the northern, eastern, and western lateral boundaries and a corresponding reduction in the active areal extent of layer 3 due to removal from the active model domain of grid cells that failed to meet the additional criteria. The additional criteria are as follows: (1) the freshwater thickness of the Upper Floridan aquifer was required to be at least 50 feet (prior to introduction of the minimum thickness); and (2) the height of the 2010 potentiometric surface as depicted by Kinnaman and Dixon (2011) was required to be at least 100 feet above the tops of the grid cells of layer 4. The purpose of these criteria was to reduce or eliminate the tendency of grid cells located near the original northern and eastern lateral boundaries of layers 3, 4, and 5 to desaturate due to numerical instability.

The physical boundary of the Upper Floridan aquifer north of the Gulf Trough in Georgia is its line of pinch-out, approximated by Williams and Kuniansky 2015 (Figure 2-1). Accordingly, prior to implementation of the additional criteria described above, the northern boundary of layer 3 was set to coincide with this line. The active domain of layer 3 in areas representative of portions of the Floridan aquifer system that lie beneath the Gulf of Mexico and the Atlantic Ocean extends to the approximate limits of freshwater flow within the Floridan aquifer system. In the case of the Atlantic Ocean, the seaward limit of freshwater flow in the Floridan aquifer system was assumed initially to be coincident with the onset of the Florida-Hatteras slope, a transition in depth that connects the relatively shallow waters of the continental shelf to the deeper waters of the Blake Plateau off the southeast coast of the United States (Milliman 1972). Accordingly, prior to implementation of the first of the two additional criteria listed above, the eastern seaward limit of model layer 3 was set to correspond with the onset of the Florida-Hatteras slope.

Along the portions of the Gulf Coast that correspond in location to portions of the active model domain, the Floridan aquifer system is unconfined, and with aquifer hydraulic heads exceeding sea level by only a few feet. Therefore, it was assumed that the limit of freshwater flow in the Upper Floridan aquifer is within a relatively short distance seaward of the coast. Accordingly, the lateral boundary of layer 3 was made to correspond to locations that are within approximately five to 10 miles of the Gulf Coast, a distance that should be sufficient to include the limits of fresh groundwater flow in an unconfined, highly transmissive system.

Placement of the southern lateral boundary was designed to be of sufficient distance from critical areas to the north, such as the Keystone Heights potentiometric high and the Lower Suwannee River basin, so that influences of the southern lateral boundary would be negligible. The Silver and Rainbow springs complexes are highly influential features of the Floridan aquifer system within their respective springsheds. These springsheds, as delineated by Faulkner 1973 and Knowles 1996, are encompassed fully within the area corresponding to the NFSEG active model domain. The southern lateral boundary is delineated based on persistent features of the Upper Floridan aquifer potentiometric surface (e.g., Kinnaman and Dixon 2011), as discussed in greater detail below.

The implementation of the additional criteria stated above, resulted in a decrease in the size of the active model domain of layer 3. The intersection of the estimated 10,000 mg/l TDS concentration iso-surface with the top of layer 3 along the seaward most portion of the eastern lateral boundary, which is the result of implementing additional criterion 1 above, represents in an improvement over the initial assumption for the location of this boundary, i.e., coincidence with the Florida-Hatteras slope. The southern lateral boundary was unaffected, and the western lateral boundary was minimally affected. The northern lateral boundary was affected the most. It now falls roughly along a line referred to by the U.S. Geological Survey as the "approximate up-dip limit of (the) productive part of Upper Floridan aquifer" (Williams and Kuniansky 2015). This change is due to the implementation of criterion 1, stated above.

Layer 4

The specified minimum thickness for layer 4 is 30 feet (Tables 3-1 and 3-2; Figures 3-13, 3-15, and 3-16). The western and eastern lateral boundaries of layer 4 were determined primarily by intersecting the estimated 10,000 mg/l TDS concentration iso-surface with the estimated top of layer 4. The northern boundary and the portions of the western and southern lateral boundaries within the freshwater flow system coincide with the respective corresponding lateral boundaries of layer 3. Where the middle confining unit is assumed to be absent, due to relatively high vertical conductivity, layer 4 represents a subdivision (discretization) within the Floridan aquifer system (Zone 2 of the present study).

Layer 5

The specified minimum thickness of model layer 5 is 50 feet (Tables 3-1 and 3-2; Figures 3-15, 3-17, and 3-18). The western and eastern lateral boundaries of layer 5 were determined primarily by intersecting the estimated 10,000 mg/l TDS concentration iso-surface with the estimated top of model layer 5. The northern boundary and portions of the western and southern lateral boundaries within the freshwater flow system coincide with the respective corresponding lateral boundaries of model layer 3. Where the middle confining unit is assumed to be absent, due to relatively high vertical conductivity, layer 5 represents a deeper segment of the Floridan aquifer system (Zone 3 of the present study).

Layer 6

The specified minimum thickness of model layer 6 is 10 feet (Tables 3-1 and 3-2; Figures 3-19 through 3-21). The areal extent of model layer 6 was determined primarily by intersecting the estimated 10,000 mg/l TDS concentration iso-surface with the estimated top and bottom of layer 6 (Figures 2-12, 3-19, and 3-20). The top of layer 6 is based on data obtained from Miller (written communication, 1991). The bottom of layer 6 (and top of layer 7) is based on data provided in Miller (1986) and other data obtained from Miller (written communication, 1991). A portion of the western lateral boundary coincides with the approximate pinch-out of the lower semiconfining unit, as detailed below in the description of the model lateral boundaries.

Layer 7

The specified minimum thickness of model layer 7 is 10 feet (Tables 3-1 and 3-2; Figures 3-22 through 3-24). The areal extent of model layer 7 was determined primarily by intersecting the estimated 10,000 mg/l TDS concentration iso-surface with the estimated top of model layer 7 (Figures 2-12 and 3-22). The top of model layer 7 was based on Miller (1986) and Miller (written communication, 1991). A portion of the western lateral boundary coincides with the approximate pinch-out of the Fernandina permeable zone, as detailed below in the description of the lateral boundaries.

Lateral Boundary Conditions

The model lateral boundary conditions represent prevailing flow conditions at locations corresponding to the edges of the active domains of the model layers. In some cases, lateral boundaries coincide approximately with the pinch-out of a hydrogeologic unit or the freshwater flow system. In other cases, lateral boundaries are oriented parallel to the direction of groundwater flow, as inferred from the configuration of the potentiometric surface of the Floridan aquifer system. Conditions at lateral boundaries in these cases are specified as no-flow because no flow is assumed to occur across the model lateral boundaries. Where flux across lateral boundaries is inferred based on the configuration of the potentiometric surface of the Upper Floridan aquifer, general head boundary (GHB) conditions are specified. To facilitate the following discussion of the model lateral boundary conditions, the lateral boundaries of model layers 3 through 5 are subdivided into northern, eastern, southern, and western segments and subsegments. The lateral boundaries of model layers 6 and 7 are subdivided into two subsegments, respectively, also for this purpose.

Layers 1 and 2

Layers 1 and 2 represent primarily the surficial aquifer system or the intermediate confining unit, respectively, although the hydraulic properties of layer 2 are assumed to represent those of Zone

1 of the Floridan aquifer system (present study nomenclature) in areas where the intermediate confining unit doesn't exist or is less than a minimum thickness. Flow in the surficial aquifer system and intermediate confining unit is typically local in nature in the case of the surficial aquifer system or dominated by vertical gradients in the case of the intermediate confining unit, and therefore generally isn't driven by regionally significant lateral gradients. Therefore, the lateral boundaries of model layers 1 and 2 are specified as no-flow boundaries.

Layer 3

Northern (N3)

Although the northern lateral boundary of layer 3, referred to hereafter as "N3," was relocated somewhat to the south of the estimated line of pinch-out of the Floridan aquifer system as delineated by Williams and Kuniansky 2015 (Figure 2-1), it is still assumed to approximate conditions of zero lateral flux. Hence, no-flow lateral boundary conditions are specified for the entire length of N3 (Figure 3-25).

Eastern, Upper (EU3)

The eastern lateral boundary of layer 3 is subdivided into three subsegments, to facilitate the present discussion. The northernmost subsegment is labeled "eastern, upper" and is referred to hereafter as "EU3" (Figure 3-25). This subsegment is oriented parallel to the direction of groundwater flow, as inferred from the configuration of the 2010 potentiometric surface of the Upper Floridan aquifer (Kinnaman and Dixon 2011). Conditions along EU3 are accordingly represented as no-flow.

Eastern, Central (EC3)

The middle eastern lateral boundary subsegment is labeled "eastern, central" and referred to hereafter as "EC3." EC3 passes through an area of induced lateral influx to layer 3. The lateral influx is induced by a large cone of depression in the potentiometric surface of the Floridan aquifer system that results from groundwater withdrawals near Savannah, Georgia. EC3 is accordingly represented with GHB lateral boundary conditions along its length (Figure 3-25). The source heads of the GHB conditions were interpolated from the May-June 2010 map of the potentiometric surface of the Floridan aquifer system (Kinnaman and Dixon 2011).

Eastern, Lower (EL3)

Moving clockwise, generally, the southernmost lateral boundary subsegment of the first three eastern lateral boundary subsegments is labeled "eastern, lower" and is referred to hereafter as "EL3" (Figure 3-25). EL3 corresponds in location to areas of the Floridan aquifer system that lie beneath the Atlantic Ocean. Groundwater flow in this area is assumed to be unaffected by onshore pumping and therefore in the same general direction as groundwater flow along EU3. Conditions along EL3 are designated accordingly as no-flow.

Eastern, Seaward (ES3)

The "eastern, seaward" (Figure 3-25) lateral boundary subsegment is the most seaward of the eastern lateral boundary subsegments. It is referred to hereafter as "ES3." ES3 represents the approximate line of pinch-out of freshwater flow in the Floridan aquifer system beneath the Atlantic Ocean. Conditions along ES3 are therefore designated as no-flow.

Southern, East (SE3)
The southern lateral boundary of layer 3 is subdivided into three subsegments, the easternmost of which is labeled "southern, east" and referred to hereafter as "SE3" (Figure 3-25). SE3 is oriented parallel to the general direction of groundwater flow. Conditions along SE3 are designated therefore as no-flow.

Southern, Central (SC3)
The Polk City (Green Swamp) potentiometric high, which occurs mainly to the south of the NFSEG model domain, intersects the NFSEG model domain along the "southern, central" subsegment of the southern lateral boundary, referred to hereafter as "SC3" (Figure 3-25). SC3 is represented accordingly with GHB conditions. The source heads of the GHB conditions were interpolated from maps of the potentiometric surface of the Floridan aquifer system. For 2001, a map representing the average of water levels observed in May and September of 2001 was derived from the maps of Knowles (2001) and Knowles and Kinnaman (2001) and was utilized for this purpose. A similar map of 2009 average water levels, based on the maps of Kinnaman and Dixon (2009) and Boniol (digital communication 2013), was utilized for interpolation of 2009 source heads.

Southern, West (SW3)
The westernmost subsegment of the southern lateral boundary of layer 3 is labeled "southern, west" and referred to hereafter as "SW3" (Figure 3-25). SW3 is oriented parallel to the general direction of groundwater flow. Conditions along SW3 are designated therefore as no-flow.

Western, Seaward (WS3)
The western lateral boundary of layer 3 is subdivided into two subsegments. The more southerly is the "western, seaward," referred to hereafter as "WS3" (Figure 3-25). WS3 represents an approximation of the maximum seaward limit of freshwater flow in the Upper Floridan aquifer beneath the Gulf of Mexico. GHB conditions were specified along WS3 to allow for the possibility that freshwater flow in the Floridan aquifer system might, in places, extend farther seaward than the position of WS3. The source heads of all GHB conditions used for WS3 are equivalent freshwater heads of the Gulf of Mexico.

Western, North (WN3)
The more northerly subsegment of the western lateral boundary is the "western, north," referred to hereafter as "WN3" (Figure 3-25). In Florida, WN3 is oriented parallel to the general direction of groundwater flow and is therefore designated as a no-flow condition. In Georgia, WN3 is coincident with the path of Spring Creek, the smallest of three tributaries whose confluence forms the Apalachicola River. Spring Creek is in close hydraulic connection with the Floridan aquifer system, as evidenced by the configuration of the 2010 potentiometric surface of the Floridan aquifer system along its path (Kinnaman and Dixon 2011), so groundwater flow is assumed to be converging on it from opposing directions. Spring Creek therefore approximates

a line of stagnation within the Floridan aquifer system, a no-flow condition for lateral flux within layer 3. Accordingly, conditions along the entire length of WN3 are designated as no-flow.

Layer 4

As compared to layer 3 lateral boundaries, the corresponding lateral boundary subsegments in model layer 4 are referred to as “N4,” “EU4,” “EC4,” “ES4”, “SE4,” “SC4,” “SW4,” “WS4,” and “WN4” (Figure 3-26). Because of the way the 10,000 mg/l TDS concentration iso-surface intersects the top of layer 4, these subsegments differ in exact shape and/or length as compared to the respective, corresponding layer 3 subsegments. Also for this reason, a layer 4 subsegment corresponding to EL3 does not exist.

Conditions at WS4, which corresponds to the Gulf coastal region, are designated as no-flow, in contrast with those of WS3, which were designated as GHB. The intersection of the 10,000 mg/l TDS concentration iso-surface with the top of layer 4 occurs more to landward because layer 4 represents a deeper section of the Floridan aquifer system in an area in which the onset of saline water is relatively shallow. Hence, WS4 is considered a reasonable approximation of the maximum seaward limit of freshwater flow in layer 4 in the region of the Gulf Coast and is designated accordingly as a no-flow boundary.

Conditions at EU4, EC4, ES4, SE4, SC4, SW4, and WN4 are assumed to be similar in nature to those of corresponding subsegments of layer 3. The source heads of GHB conditions assigned to EC4 are identical to those of the corresponding GHB conditions of EC3. The source heads of GHB conditions assigned to SC4 are identical to those of the corresponding GHB conditions of SC3.

Conditions along N4 are designated as GHB, in contrast with the no-flow designation of N3. No-flow conditions are specified along N3 because the northern lateral boundary approximates the line of pinch-out of the Floridan aquifer system. The lines of pinch-out of hydrogeologic units beneath the Floridan aquifer system are farther to the north, however. Use of GHB conditions to represent conditions along N4 enables simulation of lateral fluxes via N4 without having to extend the active model domain of layer 4 northward beyond that of layer 3. The source heads of GHB conditions specified along N4 are interpolated from the May-June 2010 map of the potentiometric surface of the Floridan aquifer system (Kinnaman and Dixon 2011).

Layer 5

The corresponding lateral boundary subsegments in layer 5 are “N5,” “EU5,” “EC5,” “ES5,” “SE5,” “SC5,” “SW5,” “WS5,” and “WN5” (Figure 3-27). Because of the way the 10,000 mg/l TDS concentration iso-surface (Figure 2-12) intersects the top of layer 5, layer 5 subsegments differ in exact shape and/or length with respect to corresponding layer3 and layer 4 subsegments.

Conditions along WS5, which corresponds to the Gulf coastal region, are designated as no-flow, in contrast with those of WS3, which were designated as GHB. The intersection of the 10,000 mg/l TDS concentration iso-surface with the top of layer 5 occurs more to landward because layer 5 represents a deeper section of the Floridan aquifer system in an area in which the onset of saline water is relatively shallow. Therefore, it is considered a reasonable approximation of the seaward boundary of freshwater flow in model layer 5 along the Gulf Coast and is designated accordingly as a no-flow boundary.

Conditions at EU5, EC5, ES5, SE5, SC5, SW5, WS5, and WN5 are assumed to be similar in nature to those of corresponding subsegments of layer 3. The source heads of GHB conditions assigned to EC5 are identical to those of the corresponding GHB conditions of EC3. The source heads of GHB conditions assigned to SC5 are identical to those of the corresponding GHB conditions of subsegment SC3.

Conditions along N5 are designated as GHB, in contrast with the no-flow designation of N3. No-flow conditions are specified along N3 because the northern lateral boundary approximates the line of pinch-out of the Floridan aquifer system. The lines of pinch-out of the middle semiconfining unit and the Lower Floridan aquifer (or equivalent hydrogeologic units in this area) are farther north, however. Use of GHB conditions to represent conditions along N5 enables simulation of lateral fluxes across N5 without having to extend the active domain of model layer 5 northward beyond that of layer 3. The source heads of GHB conditions specified along N5 are interpolated from the map of the May-June 2010 potentiometric surface of the Floridan aquifer system (Kinnaman and Dixon 2011).

Layer 6

The lateral boundary of model layer 6 is comprised of two subsegments, one that is the result of the intersection of the 10,000 mg/l TDS concentration iso-surface (Figure 2-12) with the top of model layer 6, referred to as "FWSW6" (Figure 3-28) and another that approximates the line of pinch-out of the lower semiconfining unit, referred to as "HGL6" (Figure 3-28). Conditions along FWSW6 and HGL6 are designated accordingly as no-flow.

Layer 7

The lateral boundary of model layer 7 is comprised of two subsegments, one that is the result of the intersection of the 10,000 mg/l TDS concentration iso-surface (Figure 2-12) with the top of model layer 7, referred to as "FWSW7" (Figure 3-29), and another that approximates the line of pinch-out of the lower semiconfining unit, referred to as "HGL7" (Figure 3-29). Conditions along FWSW7 and HGL7 are designated accordingly as no-flow.

INTERNAL BOUNDARY CONDITIONS

Internal boundary conditions enable the representation of interaction with features, such as streams, lakes, springs, and the ocean, that are hydraulically connected to the groundwater flow system. In the NFSEG model, internal boundary conditions are utilized to represent the following flow phenomena: groundwater flux to and from perennial streams and lakes; groundwater discharge to ephemeral streams; discharge to springs; artesian discharge to land surface; discharge to single zone wells; discharge to multi-zone wells; recharge to the groundwater system; discharge to the atmosphere via evapotranspiration, and discharge to oceans. These processes are represented through implementation of various MODFLOW packages, described as follows.

River Package

Discharge between the groundwater flow system and perennial streams and lakes are represented in the NFSEG model by implementation of the MODFLOW River Package. An estimate of stage, conductance, and bottom elevation is required for each River Package boundary condition.

<u>River Stage and Bottom Elevation</u>

The paths of streams were represented using flowlines of the National Hydrography Dataset Plus, Version 2 (NHDPlusV2; McKay et al. 2013; http://www.horizon-systems.com/NHDPlus/NHDPlusV2_documentation.php). This data set includes Strahler order classifications for stream and river reaches. Stream reaches classified as Strahler order 2 and above were included in the NFSEG model implementation of the MODFLOW River Package as perennial streams. Stream reaches classified as Strahler order 1 were included in the implementation of the MODFLOW Drain Package as ephemeral streams (Figure 3-30), described in greater detail below in the section on the Drain Package implementation.

The estimation of stream stages involved first intersecting NHDPlusV2 flowlines with the NFSEG model grid in ArcGIS, thereby breaking the NHDPlusV2 flowlines into flowline subsegments (Figure 2-25, Appendix B). Within each grid cell, a bank elevation for each of the resulting subsegments was computed by averaging the United States Geological Survey 3DEP 10-meter digital elevation model (USGS 3DEP 10m DEM; http://nationalmap.gov/3DEP/index.html) elevation values over the length of each sub-segment.

The mean depth of the stream was calculated according to the following formula, obtained from Moore (2007):

$$Ym = 0.28Q^{0.22}, \text{ where}$$

Ym = mean channel depth (meter [m]), and
Q = mean channel discharge (m3/second [s]).

The value of Q was approximated as the flow parameter Q0001E (m3/s) of the NHDPlusV2 dataset (McKay et al. 2013).

The “incised” depth of the stream, i.e., the distance from bank to stream bottom, was assumed to be 1.25 times the mean depth, as suggested by Moore (2007). The incised depth was then subtracted from the USGS 3DEP 10m DEM derived bank elevation to yield an estimate of the stream bottom elevation. The mean depth of the stream was then added to the bottom elevation to obtain an estimate of the stream stage. Stages so derived were implemented throughout the model domain initially except in the cases of portions of the St. Johns and Suwannee Rivers (and selected reaches of their major tributaries) for which stages were derived using existing surface water models and river stages measured at gaging stations.

Later, many of the USGS 3DEP 10m DEM derived stages and corresponding bottom elevations were altered to address a tendency in the derived elevations to increase in the downstream direction along portions of some NHDPlusV2 flowlines, rather than decline consistently. These alterations were affected through use of an interpolation process carried out in ArcGIS. The interpolation process resulted in smooth, steady declines in stage from the uppermost flowline subsegments to as far downstream as necessary. Stages for “flow-through” lakes, which were estimated through a process described below, were honored in this process. Additional details concerning these processes are described by Desmarais (written communication, 2016; Appendix H).

Stages and river bottom elevations for portions of the Suwannee River and its tributaries that are incised into the Floridan aquifer system, and portions of the St. Johns River and its tributaries were not estimated using the approach outlined by Desmarais (written communication 2016; Figure 3-31). In the case of the Suwannee River and selected reaches of the contributing Withlacoochee, Santa Fe, and Ichetucknee Rivers, River Package stages were estimated by using simulated water surface profiles from HEC-RAS surface water models of these rivers to interpolate stage data from stream gages. Channel thalweg data from these models were also used to estimate river bottom elevations that are specified in the River Package (Environmental Consulting and Technology 2014). In the case of the St. Johns River, stages and bottom elevations were obtained from a hydrodynamic model of the St. Johns River created by the St. Johns River Water Management District (SJRWMD; Suscy et al. 2012).

Lake Stage and Bottom Elevation

Representations of lake areas were obtained from the National Land Cover Database (NLCD; http://www.mrlc.gov). The lake areas were converted to lake polygons in ArcGIS and then intersected with the NFSEG model grid, resulting in the formation of lake sub-polygons. Elevations were extracted from the 10-meter DEM at the centroid location of each sub-polygon for use as an approximate lake stage, unless actual stage data were available. Sources of actual lake stage data included the SJRWMD, the Northwest Florida Water Management District, and the U.S. Geological Survey. Lake bottom elevations were based on an assumed average depth, usually eight feet. Where lake sub-polygons coincided with river boundary subsegments, river boundary subsegments were removed. Likewise, river boundary subsegments were also removed wherever specified head boundary conditions were assigned to represent the Atlantic Ocean or Gulf of Mexico. Only lakes covering more than 50% of the grid cell area were modeled using the River Package.

Initial Conductance Estimates

Initial River Package conductance values were estimated based on assumed horizontal and vertical hydraulic conductivities, corresponding total hydraulic areas, and assumed flow-path lengths. The bottom areas of stream subsegments were determined as the products of subsegment lengths and mean widths, with the length determined by ArcGIS and the mean width determined according to the following formula, obtained from Moore (2007), as follows

$$W = 11.95Q^{0.47}, \text{ where}$$

W = mean width (m), and
Q = mean channel discharge (m3/s).

The value of Q was approximated as the flow parameter Q0001E (m3/s) of the NHDPlusV2 dataset (McKay et al. 2013). The total hydraulic area is determined as the sum of the bottom area and the side area of a given stream subsegment. The side area is determined as the subsegment length multiplied by the estimated depth times 2.

General Head Boundary Conditions
In addition to representing fluxes via lateral boundaries, GHB conditions were used also to represent springs in the NFSEG model. In this application, the value of the GHB condition source head represents the elevation of the surface of the receiving body of water into which a spring discharges (i.e., the “spring pool elevation”). Use of the GHB package as opposed to the drain package to represent springs enables the simulation of reverse spring flow. This occurs when the spring pool elevation exceeds the aquifer head at a spring and is typically the result of seasonally high surface water.

Most springs within the NFSEG model domain emanate from the Floridan aquifer system. A smaller number emanate from the intermediate aquifer system. Accordingly, most GHB conditions used to represent springs are assigned to layer 3, with the remaining ones being assigned to aquifer layer 2 (Appendix E). Spring pool elevations were obtained from observation data, River Package stage estimates, estimated from topographic maps, or the USGS 3DEP 10m DEM representation.

Drain Package
<u>Artesian Derived Wetlands</u>
The MODFLOW Drain Package is used in the NFSEG model to represent discharge from the Floridan aquifer system to land surface in relatively flat, low-lying, unconfined areas along the coast of the Gulf of Mexico and other areas in which the Floridan aquifer system water level exceeds the land surface elevation. Under such conditions, discharge from the Floridan aquifer system tends to pool on the ground, forming artesian derived wetlands. To represent the discharge from the Floridan aquifer system that results from this process, drain boundaries were assigned to grid cells in parts of the model domain that correspond to such areas (Figure 3-32). The grid cells were selected based on the following criteria:

1. Wetland areas as shown on the U.S. Fish and Wildlife Service Wetlands Inventory map (https://www.fws.gov/wetlands/data/NSDI-Wetlands-Layer.html) are present;
2. Upper Floridan aquifer water levels as shown on the map of the Upper Floridan aquifer potentiometric of 2010 (Kinnaman and Dixon 2011) exceed average land surface elevation as derived from the USGS 3DEP 10m DEM; and
3. Unconfined conditions prevail, based on mapping of the ICU thickness (Figure 2-10).

The conductance of the assigned drain boundaries was initially estimated based on the estimated vertical hydraulic conductivity of layer 1 and the area of the wetlands contained within the affected grid cells. The assigned drain elevation was the average land surface elevation of the affected grid cells.

Ephemeral Stream Reaches

The Drain Package was used also to represent ephemeral portions of streams. The portion of a stream represented by a given drain boundary condition flows only when the elevation of the simulated water table of the grid cell to which it is assigned exceeds the elevation of the drain boundary. Ephemeral portions of streams were identified in this process as the portions of the NHDPlusV2 flowlines with a Strahler order designation of 1. The portions of streams with Strahler order greater than 1 are represented using the NFSEG model river package implementation (Figure 3-30). Additional drain features were later added to areas where excessive flooding occurred in the model. These additional drain features represented surface water canals and sloughs determined to be present based on a review of available information including aerial photographs, USGS topographic maps, etc.

Recharge and Evapotranspiration

As stated above, recharge rates were obtained from 55 different HSPF models developed specifically for supplying surface water related data to the NFSEG model (Figure 3-33). Implementation of these data in the Recharge Package requires determining weighted averages of the sums of the "AGWI" (i.e., active groundwater inflow) and "IGWI" (i.e., inactive groundwater inflow) parameters of the HSPF models (Figure 3-34). Separate recharge arrays were developed using this approach for the years 2001 and 2009 (Figures 3-35 and 3-36).

During model simulations, a specified recharge rate is applied to the uppermost active grid cell of each vertical column of grid cells. In the usual situation, all NFSEG model layers are active. However, in some cases, the grid cells of layer 1 or layers 1 and 2 are simulated as being dry. Such grid cells are treated as inactive by the model in the application of recharge rates. Dry cells occur in areas of the model domain in which the water table is simulated as lying beneath the bottom of layer 1 or bottoms of layers 1 and 2. Areas in which layer 1 or layers 1 and 2 are dry correspond generally to those in which the surficial aquifer system and/or intermediate confining unit are thin to nonexistent. In cases in which layer 1 is active, recharge is applied to layer 1. For cases in which layer 1 is dry but layer 2 is not, recharge is applied to layer 2. For cases in which layers 1 and 2 are both dry, recharge is applied to layer 3.

The Evapotranspiration (ET) Package simulates evapotranspiration from the saturated groundwater flow system. This package requires arrays of the maximum rate of saturated evapotranspiration (MSET), the ET surface elevation (the water table elevation at which the maximum rate of ET is realized—specified as land surface elevation in the NFSEG model), and the ET extinction depth (the depth at which the ET rate declines to zero). As stated above, arrays of MSET for the years 2001, 2009, and 2010 were estimated using HSPF models (Figure 3-37 and 3-38). The approach used for estimating ET extinction depths (Figure 3-39) was based on an adaptation of the approach of Shah et al. (2007). The adaptation was developed by Freese (written communication 2014; Appendix C) and implemented in ArcGIS by Stokes and Finer (digital communication 2014).

Well Packages

The MODFLOW Well Package was used to represent single aquifer withdrawal wells. Single aquifer withdrawals are from wells that are open to only one aquifer or model layer. The MNW2 Package was used to represent “dual-zone” withdrawal wells. Dual-zone wells have open intervals that intersect the Upper Floridan aquifer, the middle confining unit, and the Lower Floridan aquifer and thus potentially extract water from both the Upper and Lower Floridan aquifers.

The MNW2 package calculates the contributions to the total well withdrawal of the various aquifers intersected by the open interval of a multi-aquifer well. In the implementation of MNW2, the distribution of the total discharge from a represented multi-aquifer well is based on the respective aquifer water levels and assigned horizontal hydraulic conductivities of the Upper Floridan aquifer, the middle confining unit, and upper zone of the Lower Floridan aquifer at the location of the well. Because NFSEG is a regional model with a relatively large grid size, friction loss in the well bore was not simulated.

Most wells represented in the NFSEG model are single aquifer wells and are thus represented in the Well Package. Multi-aquifer wells, however, tend to be larger and deeper and therefore extract a disproportionate share of total groundwater withdrawals. Figures 3-40 through 3-44 depict locations of fluxes into and out of the model domain that were simulated with the Well and MNW2 packages.

Time Variant Specified Head Package

The Time Variant Specified Head Package was used to implement the assignment of specified head boundaries. Specified head boundaries were used in the model primarily to represent water levels of the Atlantic Ocean and the Gulf of Mexico. These levels were represented as equivalent freshwater heads (Figure 3-45). They are assigned to grid cells of layer 1 that correspond to offshore locations and nearshore locations.

As applied in the current study, equivalent freshwater head is determined based on the following formula and was determined at the centroid of each grid cell that corresponds in location to the offshore region:

$$Hef = d(\Upsilon s/\Upsilon f-1), \text{ where}$$

Hef = equivalent freshwater head (feet NAVD88);
d = depth of ocean (feet);
ϒs = the specific weight of seawater (pounds per cubic foot)
ϒf = specific weight of fresh water (pounds per cubic foot).
ϒs/ϒf = specific gravity of seawater (1.025 in the NFSEG application).

The depth d above was based on land surface and bottom elevation data provided in the USGS 3DEP 10m DEM.

4. MODEL CALIBRATION

APPROACH

The NFSEG model calibration process included the selection of two calibration years. The primary considerations in the selection of the years were steadiness of groundwater levels and the degree to which rainfall could be characterized as average with respect to annual totals and monthly distributions. An additional requirement was that the years should be recent to increase the likelihood that needed data, such as water use, water level, and flow data, would be accessible and available. Due to this requirement, the selection period was limited to the years 2000 through 2010. As part of the resulting selection process, groundwater hydrographs and rainfall records were obtained and analyzed (Durden et 2013). The analyses included principal component analyses of groundwater hydrographs and analyses of departures from long-term monthly averages of rainfall amounts at various stations (Durden et al. 2013). Based on the results of the analyses, the NFSEG Technical Team concluded that 2001 and 2009 exhibited adequately constant groundwater levels and rainfall amounts that are acceptably close to long-term averages. An additional consideration was that 2001 was relatively dry while 2009 was relatively wet, thus providing the calibration process with a challenging range of climatic conditions.

The model was calibrated through implementation of the model-independent parameter estimation code (PEST; Doherty 2015; Doherty 2016a; and Doherty 2016b). Prior to the PEST facilitated calibration, an initial calibration process was undertaken with the following objectives:

- To develop an improved understanding of the hydrological system;
- To develop improved understanding of model sensitivity to changes in hydraulic conductivity and other parameters;
- To develop improved understanding of potential ranges of horizontal and vertical hydraulic conductivity within model layers;
- To develop improved understanding of model numerical requirements, resulting in improved numerical stability and performance through implementation of MODFLOW-NWT; and
- To identify and implement needed improvements and/or corrections in model features.

The initial calibration process involved matching model simulated water levels and spring discharges to corresponding observed or estimated values throughout the model domain. The groundwater flow system was approximated as steady state in this analysis, and matching was carried out to 2001 and 2009 median observed conditions, as with the PEST calibration. The initial calibration culminated in a high level of consistency between simulated and observed water levels and spring discharges throughout the model domain for both 2001 and 2009. Insights and results obtained from the initial calibration process were used to guide the PEST facilitated calibration process.

PEST Facilitated Calibration

The following description provides a general outline of the process used to calibrate the NFSEG model through implementation of PEST. PEST calibration is organized around two primary groups of data, observation groups and calibration parameter groups. Observation groups are comprised of water level and flow rate observations. Enablement of adequate simulation of the observations that comprise the observation groups is the primary objective of the calibration process. PEST facilitates calibration through a process of systematic adjustment of the various model parameters that constitute the calibration parameter groups. In the context of the NFSEG model, parameters are model representations of physical aspects of the hydrological system that control groundwater levels and flow rates.

PEST runs a model many times through numerous optimization iterations. For each of these iterations, and prior to estimating a set of parameter values, PEST constructs a Jacobian matrix, which contains the derivative of each observation with respect to each model parameter. PEST uses the resulting Jacobian matrix to arrive at an improved parameter data set by adjusting parameter values at the beginning of an iteration within ranges established by the PEST user. The quality of a parameter set is encapsulated in the PEST objective function, a measure of the goodness of fit between the observations that comprise the observation groups and model simulated counterparts. In its simplest form, the PEST objective function is defined as follows:

$$\Phi = \sum_{i=1}^{n} (w_i r_i)^2$$

where

Φ is the value of the PEST objective function resulting from a given PEST iteration, equal to the summation of the squares of the products of w_i and corresponding value of r_i, summed over *n* observations;

w_i is the weight assigned to the residual of observation *i*;

r_i is the difference between the value of observation *i* and its model simulated counterpart (i.e., the residual of observation *i*); and

n is the number of all observations comprising the various observation groups.

Through multiple iterations, PEST determines numerous parameter data sets, resulting in numerous objective function values. The objective of the process is to minimize the value of the objective function while maintaining the values of the various calibration parameters within user specified ranges.

PEST calibration requires detailed design, oversight, and analysis of the results of the calibration process and thus is not an automated process. The process can be influenced using pre- and postprocessing programs that control the interpretation of PEST determined parameters, an approach that was utilized extensively in the NFSEG calibration. PEST users influence the calibration process through specification of initial, maximum, and minimum values of calibration parameters (i.e., starting values and acceptable ranges of parameters). PEST users also influence the calibration process through specification of weights assigned to residuals of observations (i.e., the relative influence of a residual).

An additional component of the PEST objective function is often utilized, in addition to the one discussed above. That component is based on the difference between the initial value of a given calibration parameter and the corresponding PEST determined value. The process of implementation of the additional objective function component is called regularization. In the application of PEST, however, this component was deemphasized due to time constraints and difficulties in implementation. Therefore, in the NFSEG model application, the PEST objective function is represented nearly entirely by the value of Φ as stated above.

OBSERVATION DATA GROUPS

Through implementation of PEST, the NFSEG model was calibrated simultaneously to median observed water levels and flow rates for the years 2001 and 2009, with conditions for both years represented as steady state. Table 4-1 provides a detailed listing of the observation groups utilized in the PEST calibration process. The observation groups listed there may be categorized generally as follows:

- Groundwater levels;
- Spring discharge rates;
- Baseflow rates (as total baseflow accumulation for specific gages, i.e., “cumulative baseflows,” and as the difference in baseflow between gages, i.e., “pickups”);
- Vertical head differences, i.e., between corresponding observed groundwater levels in the surficial aquifer system and Upper Floridan aquifer (model layers 1 and 3) or between the Upper Floridan aquifer and Lower Floridan aquifer (model layers 3 and 5);
- Horizontal head differences within the Upper Floridan aquifer (i.e., layer 3); and
- Estimated lake leakage rates.

In the earlier stages of the calibration process, a wetting penalty function that incorporated observations of maximum water table elevations was also implemented in limited areas to help prevent excessive simulated flooding in layer 1. This function was based on assumed maximum heights of the water table above land surface in wetlands and uplands.

Groundwater Levels

The groundwater level observation groups contain data obtained from various sources, including the U.S. Geological Survey, the SJRWMD, the SRWMD, the Southwest Florida Water Management District, and the Northwest Florida Water Management District. Statistical methods were used to augment the number and quality of water level observations in areas of limited water level data availability, as detailed in Appendix A.

Table 4-1. NFSEG PEST Observation Groups

Observation group name	Description
h2001_lay1	Heads in layer 1: 2001
h2001_lay2	Heads in layer 2: 2001
h2001_lay3	Heads in layer 3: 2001
h2001_lay4	Heads in layer 4: 2001
h2001_lay5	Heads in layer 5: 2001
h2001_lay7	Heads in layer 7: 2001
h2009_lay1	Heads in layer 1: 2009
h2009_lay2	Heads in layer 2: 2009
h2009_lay3	Heads in layer 3: 2009
h2009_lay4	Heads in layer 4: 2009
h2009_lay5	Heads in layer 5: 2009
h2009_lay7	Heads in layer 7: 2009
hd2001_lay3	Lateral head differences in layer 3: 2001
hd2009_lay3	Lateral head differences in layer 3: 2009
td_lay1	Temporal head differences: layer 1
td_lay2	Temporal head differences: layer 2
td_lay3	Temporal head differences: layer 3
td_lay4	Temporal head differences: layer 4
td_lay5	Temporal head differences: layer 5
td_lay7	Temporal head differences: layer 7
wp_dry_2001	'penalty function' for minimizing the occurrence of dry cells areas in wetland areas: 2001
wp_dry_2009	'penalty function' for minimizing the occurrence of dry cells areas in wetland areas: 2009
wp_wet_2001	'penalty function' for minimizing the occurrence of 'flooded cells': 2001
wp_wet_2009	'penalty function' for minimizing the occurrence of 'flooded cells': 2009
vd_1to3_01	Vertical head differences: layer 1 to 3 in 2001
vd_1to3_09	Vertical head differences: layer 1 to 3 in 2009
vd_3to5_01	Vertical head differences: layer 3 to 5 in 2001
vd_3to5_09	Vertical head differences: layer 3 to 5 in 2009
qr01	Inflow to river reaches bounded by one or more gages: 2001
qr09	Inflow to river reaches bounded by one or more gages: 2009
qspring01	Inflow to springs: 2001
qspring09	Inflow to springs: 2009
qs_spring01	Inflow to spring groups: 2001
qs_spring09	Inflow to spring groups: 2009
qs01	Cumulative inflow to collections of river reaches: 2001
qs09	Cumulative inflow to collections of river reaches: 2009
qlake01	Flow to/from lakes: 2001
qlake09	Flow to/from lakes: 2009

Spring Flow Rates

Spring flow rates for the years 2001 and 2009 were estimated from available field measurements (Figures 2-33 through 2-35; Appendix E). Generally, for springs with field measurements specific to 2001 and/or 2009, the medians of the available field measurements were utilized. For cases in which data specific to 2001 and/or 2009 were not available, period of record (POR) estimates were used. Outside of the SRWMD, POR estimates were utilized directly. Within the SRWMD, POR estimates were reduced by approximately 25 percent and 5 percent in the years 2001 and 2009, respectively, to reflect more closely the hydrologic conditions of the two calibration years. For some cases in which regression relations between spring flows and concurrent groundwater levels or other data were available, improved estimates of the 2001 and 2009 spring flow targets were computed based on the regression relations. In addition, differences between upstream and downstream flow estimates or geochemical data were used to estimate flows from selected river rises. Sources of data include the U.S. Geological Survey, the SJRWMD, the SRWMD, the Southwest Floridan Water Management District (SWFWMD), and the Northwest Florida Water Management District (NWFWMD).

Baseflow Rates

Baseflow estimates to reaches bounded by one or more gages and baseflow estimates from collections of these reaches were used as calibration targets, as discussed in section 2 (Figures 2-36 through 2-44; Appendix F). Baseflow rates are generally estimated through baseflow separation analysis, as detailed in section 2.

Vertical Head Differences

Vertical head differences were computed from observations obtained in the same year from two wells that are open to different aquifers at or near the same geographical location. Vertical head differences between the surficial aquifer system and zone 1 (between model layers 1 and 3; see section 2 for definitions of zones 1, 2, and 3) and between zones 1 and 3 (between model layers 3 and 5) were so computed (Figures 2-9 and 2-10; Figures 2-31 and 2-32; Appendix B). The main purpose of this group is to provide information for calibration of the vertical hydraulic conductivity of model layers 2 and 4.

Horizontal Head Differences

Horizontal head differences are based on observations obtained in the same year from two wells that are open to the same aquifer at different geographical locations and that are typically aligned along the path of a groundwater streamline as inferred from a map of the potentiometric surface of the Upper Floridan aquifer. This observation group is based solely on lateral water level differences in zone 1 (Figures 4-1 and 4-2; Appendix H; see section 2 for definitions of zones 1, 2, and 3). The purpose of this group was to improve estimation of horizontal hydraulic conductivity of layer 3 through improved simulation of horizontal head gradients in layer 3.

Lake Leakage Rates

The purpose of the lake leakage observation groups is to prevent the simulation of unrealistically high lake leakage rates. During calibration, unrealistically high simulated lake leakage rates can compensate for other processes or parameters that are poorly represented in the model and thus mask underlying calibration issues with respect to those processes or parameters as well as lake leakage rates. Including limits on lake leakage rates helped to constrain leakage rates to reasonable values and prevent masking of other calibration issues as well.

Except for some lakes in the Keystone Heights region in southeast Clay County and lakes in the Orange Creek Basin in Alachua County, Florida, lake leakage rates were estimated as the difference between rainfall and potential evapotranspiration. The leakage rates of lakes Brooklyn and Geneva of the Upper Etonia Creek basin chain of lakes as well as lakes Orange and Lochloosa in the Orange Creek Basin were estimated based on values cited in previous studies (Clark et al. 1963; Deevey 1988; Dykehouse 1998; Hirsch and Randazzo 2000; Annable et al. 1996; Merritt 2001; Motz et al. 1994; and Lin 2011).

Wetting Penalty

The wetting penalty is a special observation data group created for purposes of reducing the occurrence of excessive simulated flooding. In the wetting penalty implementation, the NFSEG model grid is subdivided into grid cell blocks of 10 rows by 10 columns. Each active grid cell of each grid cell block is designated as wetland or upland, depending on prevailing conditions within the grid cell. A wetting penalty is then determined for each active grid cell, depending on its designation. The wetting penalty is a contribution to the PEST objective function that depends on the grid cell designation and the height of the simulated water table above land surface within the grid cell.

For each wetland designated grid cell given grid cell block *p*, the wetting penalty is determined according to the following formula:

л = $w_p(m-1)$ for $m \geq 1$ foot and
л = 0 for $m < 1$ foot

where

л = wetting penalty contribution to the PEST objective function of the grid cell in question,
w_p = the weight assigned to all grid cells contained within grid cell block *p*; and
m = height of the simulated water table above the average land surface elevation of the grid cell (feet).

For each upland designated grid cell of grid cell block *p*, the wetting penalty is

л = $w_p(m)$ for $m \geq 0$ foot and
л = 0 for $m < 1$ foot

The wetting penalty can be emphasized to a lesser or greater degree over an entire grid cell block through adjustment of the assigned wetting penalty weight, as the same weight is used for all grid cells within a grid cell block. By setting the weight to zero, the contribution to the value of the objective function of a cumulative wetting penalty of an entire grid cell block can be eliminated.

As the calibration phase of the NFSEG model development progressed, flooding issues were determined to be due to the lack of representation of surface water drainage features in most cases. In most of such instances, the omitted surface water feature was in the form of sloughs, which are indicated on U.S. Geological Survey 1: 24,000 scale quadrangle maps, aerial photography, and/or the USGS 3DEP 10m DEM. These data were used to determine the appropriate flow paths of the omitted streams or sloughs and to implement their representation in the NFSEG model Drain Package as ephemeral reaches within larger stream networks, the simulated flows of which are constrained in the calibration process through comparisons to estimated baseflows. Implementation of the wetting penalty was not required in such cases.

Calibration Data Groups

Table 4-2 provides a detailed listing of the calibration parameter groups utilized in the NFSEG PEST calibration process. The calibration parameter groups listed there may be categorized generally as follows:

1. Hydraulic conductivity (horizontal and vertical), horizontal and vertical hydraulic conductivity multipliers, and anisotropy ratio;
2. GHB conductance for spring representation;
3. River Package conductance multipliers for determination of river package conductance in representation of perennial stream reaches;
4. Drain Package conductance multipliers for determination of drain package conductance in representation of ephemeral stream reaches and selected wetlands;
5. River Package conductance multipliers for lake representation;
6. Lake zone multipliers for adjustment of model layer 2 vertical hydraulic conductivity beneath lakes to constrain lake leakage rates;
7. Recharge multipliers; and
8. Maximum saturated ET multipliers.

PEST calibration requires specification of an initial value and an upper and lower bound for each parameter member of the calibration parameter groups. Additional information concerning the calibration parameter groups follows.

Horizontal and Vertical Hydraulic Conductivity

<u>Horizontal Hydraulic Conductivity Determination for Layers 1, 3, and 7 and Vertical Hydraulic Conductivity Determination for Layer 6</u>

Horizontal hydraulic conductivity is determined in the NFSEG PEST calibration process directly for layers 1, 3, and 7 at the locations of “pilot points.” Vertical hydraulic conductivity is likewise determined directly for layer 6 at pilot points. Pilot points are points at which the values of calibration parameters are determined in the PEST calibration process. After the determination of hydraulic conductivity at pilot points, PEST is used to determine values of hydraulic conductivity at individual grid cells by interpolating between pilot points using kriging.

Table 4-2. NFSEG PEST Calibration-Parameter Groups

Parameter Group Name	Parameterization Device	Description
k1x	pilot points	horizontal hydraulic conductivity – layer 1
k3x	pilot points	horizontal hydraulic conductivity – layer 3
k5xk3x	pilot points	horizontal hydraulic conductivity multiplier outside MCU – layer 5
k5x	pilot points	horizontal hydraulic conductivity – layer 5
k7x	pilot points	horizontal hydraulic conductivity – layer 7
k2z	pilot points	vertical hydraulic conductivity – layer 2
k2zk3z	pilot points	vertical hydraulic conductivity multiplier outside ICU – layer 2
k4zk3z	pilot points	vertical hydraulic conductivity multiplier outside MCU – layer 4
k4z	pilot points	vertical hydraulic conductivity – layer 4
k6z	pilot points	vertical hydraulic conductivity – layer 6
vanis1	entire layer	vertical anisotropy – layer 1
vanis2	zoned according to presence/absence of ICU	vertical anisotropy – layer 2
vanis3	pilot points	vertical anisotropy – layer 3
vanis4	zoned according to presence/absence of MCU	vertical anisotropy – layer 4
vanis5	zoned according to presence/absence of MCU	vertical anisotropy – layer 5
vanis6	entire layer	vertical anisotropy – layer 6
vanis7	entire layer	vertical anisotropy – layer 7
lcm	zoned according to lakes	multiplier applied to lakebed conductance
rcm	zoned according based on HUC10 hydrologic basin boundaries	multiplier applied to river reach conductance
sc	1 parameter per spring	GHB conductance at springs
rechmul	zoned according based on HUC10 hydrologic basin boundaries	multiplier applied to recharge rates
evtrmul	zoned according based on HUC10 hydrologic basin boundaries	multiplier applied to maximum EVT rates
lkzmul	zoned according to lakes	vertical conductivity multiplier under lakes

Pilot points are user specified. In the calibration process, the determination of pilot point locations was initialized through application of *Groundwater Vistas*, a program that facilitates the processing of input and output data for MODFLOW and for MODFLOW related applications of PEST. Implementation of this feature of *Groundwater Vistas* resulted in the creation of pilot point meshes comprised of triangular patterns formed around observation wells. Gaps in a mesh, which can occur due to localized sparseness in the observation well network, were filled with pilot points spaced at regular intervals of 25,000 to 125,000 feet (varies by layer). Thus, localized, rectilinear patterns of pilot points were interspersed within the triangular mesh that was generated initially by *Groundwater Vistas*. As a final step, individual or small groups of pilot points were added at specific locations as deemed necessary or desirable. Such points corresponded usually to places within the model domain for which additional information was needed from the calibration process or at which additional information was available for application to it. Examples of such places include areas of steep gradients in the potentiometric surface of the Upper Floridan aquifer and near springs (Figures 4-3 through 4-6).

<u>Vertical Hydraulic Conductivity of Model Layers 2 and 4, Horizontal Hydraulic Conductivity of Model Layer 5, and Vertical and Horizontal Hydraulic Conductivity Multipliers</u>

For layer 2, vertical hydraulic conductivity is determined directly in the NFSEG PEST calibration process at pilot points in the parts of the model domain that correspond to areas in which the intermediate confining unit is contiguous (Figure 4-7). This is the same approach as described above regarding the determinations of horizontal hydraulic conductivity in layers 1, 3, and 7 and vertical hydraulic conductivity in layer 6. Likewise, after the determination of the vertical hydraulic conductivity of layer 2 at pilot points, PEST is used to determine vertical hydraulic conductivity at individual grid cells by interpolating between the pilot points using kriging.

For portions of the model domain that correspond to areas in which the intermediate confining unit is thin or absent, i.e., unconfined regions, a slightly more complicated approach, referred to hereafter as “the multi-step approach,” is used for determining the vertical hydraulic conductivity of model layer 2. The multi-step approach is designed to address the possibility that areas of local confinement may exist within areas that are broadly classified as unconfined. In this approach, the hydraulic properties of layer 2 are assumed to be the same as the Upper Floridan aquifer unless calibration data indicate that a degree of local confinement exists.
In the implementation of this approach to the determination of layer 2 vertical hydraulic conductivity in areas in which the intermediate confining unit is generally absent, layer 2 vertical hydraulic conductivity at a particular cell is equated to the product of the vertical hydraulic conductivity of the underlying layer 3 grid cell and a multiplier assigned by PEST. Prior to assigning multipliers to individual grid cells, PEST is first used to determine multipliers at pilot points located in parts of the model domain that correspond to noncontiguous areas of the intermediate confining unit. The values assigned to individual grid cells are determined by interpolating between pilot points (Figure 4-7).

This approach tends towards similarity between the distributions of layer 2 and layer 3 vertical hydraulic conductivity in parts of the model domain that correspond to areas in which the intermediate confining unit is generally absent. Layer 2 is thus assumed as being generally more representative of the hydraulic characteristics of the Floridan aquifer system than the intermediate confining unit in such areas, due to the general absence of the intermediate confining unit and thinness of the overburden above the Floridan aquifer system. Nevertheless, the approach provides for the possibility of deviation of the vertical hydraulic conductivity of layer 2 from that of layer 3, to a significant degree if needed, to match observed data.

A similar approach is used for layers 4 and 5 due to the discontinuous nature of the middle confining unit. Vertical hydraulic conductivity values of layer 4 and horizontal hydraulic conductivity values of layer 5 are determined directly using PEST in portions of the model domain that correspond to areas in which the middle semiconfining unit is present according to Miller (1986). These values are determined for respective arrays of pilot points in layers 4 and 5. Values of vertical hydraulic conductivity of layer 4 and horizontal hydraulic conductivity of layer 5 are determined at grid cells of layers 4 and 5, respectively, by interpolating between the respective arrays of pilot points (Figures 4-8 and 4-9).

In the parts of the model domain that correspond to areas in which the middle semiconfining unit is not present according to Miller (1986) (noted shaded region on Figures 4-8 and 4-9), PEST is used to determine the vertical hydraulic conductivity of layer 4 and horizontal hydraulic conductivity of layer 5 using a multi-step approach similar to the one described above regarding the vertical hydraulic conductivity of layer 2. As in that case, the multi-step approach was implemented to address the possibility that areas of local confinement may exist within areas that are broadly classified as unconfined. In this approach, the hydraulic properties of layers 4 and 5 are assumed to be the same as those of layer 3 unless calibration data indicate that a degree of local confinement exists.

In the portions of layer 4 that correspond to areas in which the middle semiconfining unit is not present according to Miller (1986), the vertical hydraulic conductivity of a given grid cell is equated to the product of the vertical hydraulic conductivity multiplier as interpolated by PEST for the grid cell in question and the vertical hydraulic conductivity of the overlying grid cell of layer 3. With respect to portions of layer 5 that correspond to this area, the horizontal hydraulic conductivity of a given grid cell of layer 5 is equated to the product of the horizontal hydraulic conductivity multiplier as interpolated by PEST at the grid cell in question and the horizontal hydraulic conductivity of the overlying grid cell of layer 3. For both layers, PEST bases its respective interpolations on values assigned to the respective distributions of pilot points of layers 4 and 5 (Figures 4-8 and 4-9).

Vertical Anisotropy Ratio

The ratio of vertical anisotropy as applied in the calibration process is defined as the ratio of horizontal hydraulic conductivity to vertical hydraulic conductivity. PEST was used to determine values of the vertical anisotropy ratio through the calibration process. For layer 3, values of vertical anisotropy are determined by PEST at pilot points and then determined for individual grid cells through kriging (Figure 4-10). Thus, each active grid cell of layer 3 is assigned a separate value of vertical anisotropy.

Layer 2 has two anisotropy values, one for the area in which the intermediate confining unit is present and another for areas in which the intermediate confining unit is thin or absent (Table 4-3). Layers 4 and 5, similarly, have two values each, one for areas in which the middle confining unit is present according to Miller (1986) and another for areas in which it is not. Layers 6 and 7 each have only one value of anisotropy ratio.

Table 4-3. PEST-Generated Anisotropy for Layers other than Layer 3

Area of Application	PEST-Generated Anisotropy
Model Layer 1	7.0
Model Layer 2, ICU Present	8.2
Model Layer 2, ICU Not Present	26.0
Model Layer 4, MSCU Present	9.5
Model Layer 4, MSCU Not Present	10.3
Model Layer 5, MSCU Present	10.0
Model Layer 5, MSCU Not Present	9.2
Model Layer 6	10.0
Model Layer 7	10.0

As described above, horizontal hydraulic conductivity was determined for layers 1, 3, 5, and 7, either directly or through a multi-step approach that utilized multipliers. For layers 2, 4, and 6, vertical hydraulic conductivity was determined likewise. To obtain corresponding values of vertical hydraulic conductivity for layers 1, 3, 5, and 7, the already determined horizontal hydraulic conductivity values were divided by the applicable anisotropy ratio (Figure 4-8 and Table 4-3). Similarly, to obtain corresponding horizontal hydraulic conductivity values for layers 2, 4, and 6, the already determined vertical hydraulic conductivity values were multiplied by the applicable anisotropy ratio (Figure 4-8 and Table 4-3).

GHB Conductance for Representation of Spring Discharge

As stated previously, GHB conditions were used in the representation of springs (Figures 2-33 through 2-35; Appendix E). GHB conductance is an important factor in the simulation of spring flows. GHB conductance is scale dependent and is not readily observable. Therefore, it must be determined through the calibration process. The set of GHB conductance values used in the representation of springs is therefore included in the calibration process as a calibration parameter group.

The primary objective of the calibration process with respect to the determination of spring conductance is to enable the model to simulate spring flow rates adequately. In general, a greater emphasis is placed on matching the flows of larger springs and the total flows of spring groups, as the estimates of such flows are generally more reliable due to greater data availability. They are more significant in terms of their effects on the flow system as well and therefore more critical to the overall representation of the groundwater system.

River Package Conductance Multipliers for Representation of Stream Baseflow

As stated previously, the River Package was used in the representation of perennial stream reaches. The primary objective of the calibration process in this regard is adequate simulation of stream baseflow rates. As detailed in section 2, baseflow rates were estimated at stream gages within the model domain (Figure 2-36 through 2-44). River package conductance is an important factor in the simulation of stream baseflow rates.

The conductance of River Package boundaries is determined in the calibration process as the product of a multiplier determined by PEST for the HSPF sub-watershed to which the boundary corresponds in location and the area of the stream segment that it represents. The same multiplier is assigned to all River Package boundaries that correspond to a given HSPF sub-watershed.

Drain Package Conductance Multipliers for Representation of Stream Baseflow

As stated previously, the Drain Package was used in the representation of ephemeral stream reaches. As with the River Package implementation, the conductance of a given Drain Package boundary is determined in the calibration process as the product of a multiplier of the HSPF sub-watershed to which the Drain Package boundary corresponds in location and the area of the stream segment that it represents. The same multiplier is assigned to all Drain Package boundaries that correspond to a given HSPF sub-watershed.

Lake Related Multipliers: River Package Conductance and Lake Zone Multipliers

Two sets of multipliers are associated with lakes represented in the NFSEG model. The first of these is used in the calculation of the conductance values of the River Package boundaries used to represent a given lake. For lake representation, this value is a primary controlling factor in the determination of rates of exchange between the lake and the aquifer that bounds it, usually the surficial aquifer system. The conductance of River Package boundaries used to represent lakes are determined in the same manner as for any other river Package boundary, as the product of a multiplier determined by PEST for the HSPF sub-watershed to which the boundary corresponds in location and the area of the stream segment that it represents.

The second type of multiplier is used to help constrain the rate of leakage between a given lake and the underlying Floridan aquifer system. This is accomplished with lake “zones” for which “lake zone” multipliers are estimated for application to the vertical hydraulic conductivity of layer 2. A lake zone is defined in this process as a specified group of layer 2 grid cells that underlie a given lake, with a single lake zone multiplier for each lake.

Recharge and Maximum Saturated ET Multipliers

Multipliers for recharge and maximum saturated ET were also included in the set of parameters available for calibration to adjust the HSPF derived recharge and maximum saturated ET by sub-watershed. The purpose of these multipliers was to allow for the adjustment of the HSPF derived recharge and maximum saturated ET rates during the calibration, if needed. To date, however, this feature of the calibration process has not been activated, except as part of the parameter and prediction analysis, which is discussed in a separate section and appendix of the report.

WEIGHTING SCHEME

As previously described, weights are multiplied by residuals (observed minus simulated values) to estimate the contribution of each observation to the objective function, which is the sum of the squared weighted residuals. Weights therefore help to determine the relative influence of each observation on the value of the objective function. The objective function is minimized by PEST during model calibration for determination of optimal parameter estimates to enable adequate simulation of groundwater flows and levels. Ideally, weights should account for measurement errors of observation data used in model calibration and structural errors that result from the inevitable differences between a model and the groundwater flow system that it represents. Structural errors are typically the dominant source of error in models, but, unfortunately, they are difficult or impossible to quantify (Doherty J., et al, 2010). Weights also help to equalize differences in the relative influences of observation groups that result merely from differences in their general range of magnitude as expressed in their units of measure (groundwater flows vs. levels, for instance). In the calibration process, weights were initially assigned uniform values or were based on an assumed constant ratio of the standard deviation of the observation error and the value of an observation. As the calibration process proceeded, the initial values of the weights were modified in some cases based on information gained from simulation results. The final weighting scheme used to calibrate the NFSEGv1.1 model is summarized below.

Groundwater Levels

<u>Layer 1 (2001 and 2009)</u>

A uniform weight of 1 was assigned to all observations except for selected observations for which weights were reduced for one of the following reasons, as described below:

- Observed water levels of some of the monitoring wells were higher than layer 1 top elevations. This occurs because layer 1 top elevations represent land surface elevation averaged over the area of model grid cells (2,500 feet by 2,500 feet).
- The surveyed top elevations of some of the monitoring wells were more than 10 feet above the model layer 1 top elevations.
- Some of the water levels were estimated from USGS topographic quadrangle maps, rather than from groundwater level measurements. This was done, for example, in some areas where wetlands occurred, based on the assumption that the groundwater level in layer 1 should be at or near land surface.

<u>Layer 2 (2001 and 2009)</u>

A uniform weight of 0.1 was assigned to all observations. Observed water level elevations in the intermediate confining unit, which is represented by layer 2, can be strongly dependent on casing depths and positions of open intervals of monitoring wells in many locations because of large vertical hydraulic gradients across the intermediate confining unit. Since the NFSEG model was not designed to simulate vertical heterogeneity of the intermediate confining unit, layer 2 observations were not considered important targets for the model calibration. Instead, estimated groundwater level differences between the surficial aquifer system and Upper Floridan aquifer (i.e., vertical head differences between layers 1 and 3) were the primary targets utilized for estimating the degree of confinement of layer 2 in the calibration. However, because the number of these targets was limited, observations of water levels within the intermediate confining unit were included in the model calibration process also, although their importance was deemphasized by assignment of the relatively low weight of 0.1.

Layers 3 through 7 (2001 and 2009)
A uniform weight of 1 was initially assigned to all groundwater level observations in layers 3 through 7. During model calibration, weights of some observations in layer 3 were increased to improve calibration in certain critical areas in north Florida. In some instances, zero-valued weights were also assigned to some targets because it was discovered that the groundwater levels were not representative. Examples include wells in layer 2 that were dry or wells in layer 7 that were affected by saline water.

Groundwater Level Differences
Vertical groundwater level differences between layers 1 and 3 (2001 and 2009)
A weight of 2 was assigned to the observations of vertical head differences between layers 1 and 3 (observation groups vd_1to3_01 and vd_1to3_09) if a vertical groundwater level difference was calculated using a layer 1 observation having a weight of 1. Otherwise, a weight of 0.1 was assigned. The higher weight of 2 was applied to increase the visibility of these observations since their magnitudes were relatively smaller than the water level observations.

Horizontal groundwater level differences (2001 and 2009)
A uniform weight of 1 was assigned to all observations (observation groups hd2001_lay3 and hd2009_lay3).

Vertical groundwater level differences between layers 3 and 5 (2001 and 2009)
A uniform weight of 10 was assigned to observations of vertical groundwater level differences between layers 3 and 5. The larger weight utilized for these observation groups was intended to make them relatively more visible to PEST since they are generally small as compared to other water level difference observations.

Flows
Baseflows and changes in baseflows (2001 and 2009)
For observations of baseflows or changes in baseflows along river reaches (observation groups qr01, qr09, qs01, and qs09), weights were calculated as the inverse of ten percent of the estimated flows, thus resulting in weighted flows of 10 cfs. For example, for a baseflow estimate of 50 cfs, a weight of 0.2 was used. Weights of zero were applied in instances of unreliable baseflow estimates, which can result from missing hydrograph data, tidal effects, proximity to

reservoirs, or generally poor data quality. Assignment of zero weights effectively eliminated these baseflow estimates from the calibration process.

Individual spring flows (2001 and 2009)

For observations of flows at individual springs (observation groups qspring01 and qspring09), the general approach was to apply larger weights to springs of greater magnitudes, in accordance with the following:

- If the spring flow is 10 cfs or less, the weight was calculated as the inverse of 10 percent of the observed flow, thus resulting in a weighted spring discharge of 10 cfs;
- If the spring flow is greater than 10 or less than 100 cfs, a weight was applied so that the weighted spring flow would be 50 cfs;
- If the spring flow is greater than 100 or less than 500 cfs, a weight was applied so that weighted spring flow would be 250 cfs; and
- If the spring flow is greater than 500 cfs, a weight was applied so that weighted spring flow would be 500 cfs.

Flows for spring groups (2001 and 2009)

For observations of flows of collection of springs (observation groups qs_spring01 and qs_spring09), a uniform weight of 1 was assigned to all observations except for the 2001 flows of Wakulla Springs, to which zero weight was assigned due to lack of confidence in the data.

Other Observations

Flooding and drying penalties for model cells (2001 and 2009)

Nonzero weights were also assigned to the flooded and dry cell observation groups, as well as the lake leakage observation groups. Only twelve observations in the flooded and dry cell observation groups (wp_wet_2001, wp_wet_2009, wp_wet_2001, and wp_wet_2009) received nonzero weights, and all were assigned a weight of 2. These penalties were developed to prevent excessive flooding and drying and were used for only a few areas, which were decided upon during the calibration process.

The areas to which flooding penalties were applied were small, generally corresponding in extent to only one or two grid cells. These areas are generally subject to significant inflow but lack nearby surficial aquifer system water level observations that could be used to guide the calibration process. The number of these observations with nonzero weights was limited to mitigate against potential numerical instabilities that might arise due to the nonlinear nature of this observation class.

Lake leakage rates (2001 and 2009)

The lake leakage observation groups (qlake01 and qlake09) were implemented to minimize the likelihood of individual lakes becoming infinite sources or sinks for water. A uniform weight of 1 was assigned to all observations except for a few critical lakes for which estimates of leakage were available in the literature. The weights for these lakes were adjusted as needed during calibration process to improve calibration.

Calibration Results

As described previously, a primary objective of the calibration process was to minimize differences between various observations and their model simulated counterparts. Accordingly, the following description of the calibration results is presented largely in terms of comparisons of simulated groundwater levels, groundwater level differences, and groundwater flows to corresponding observations. The differences between observed values of groundwater levels and their model simulated counterparts (groundwater level residuals) are summarized statistically. In addition, an extensive set of maps and graphs of groundwater level and flow residuals, calibration determined parameters, and simulated water level and flow related data are presented. Collectively, the statistical summaries, maps, and graphs are intended to facilitate assessment of the quality of the calibration. In the following discussion, the maps and graphs are categorized further as follows: calibration results heads (CRH), calibration results flows (CRF), and calibration results parameters (CRP).

Summary Statistics

Statistical summaries of the groundwater level residuals are presented in Table 4-4. Table 4-4 summarizes statistical goals for the NFSEG model calibration and various statistics of groundwater level residuals, aggregated across the model domain. Statistical summaries were determined for the overall model and layer 3 only for both calibration years, 2001 and 2009. The statistical goals were specified prior to construction and calibration of the NFSEG model in the conceptualization report (Durden et al. 2013). As indicated in the model conceptualization report, the calibration goals shown in Table 4-4 are ambitious targets and are not intended as hard and fast requirements.

For the overall model, the mean groundwater level residuals for 2001 and 2009 are somewhat greater than zero but less than one, indicating a slight bias towards under simulation of groundwater levels in both calibration years. The means of the absolute values of the residuals indicate a generally good match between observed and simulated groundwater levels for both years. For layer 3 alone, a slight bias towards over simulation of groundwater levels occurred. The standard deviations of the groundwater level residuals of layer 3 alone as compared to the respective standard deviations of the overall model indicate generally much less scatter about the respective means of layer 3 alone. This indicates that groundwater level residuals of layer 3 alone are generally smaller than those of the overall model. This likely is because the groundwater level residuals of the overall model include values that are based on observations of surficial aquifer system groundwater levels, which can be more difficult to match due to the relatively high level of variation that can occur in the elevation of the water table over the extent of single grid cell. The mean absolute values of the groundwater level residuals of layer 3 alone indicate a good match between simulated and observed groundwater levels, especially considering the large range in groundwater levels and the large degree of variation in flow conditions across the domain of layer 3. Whereas the ambitious goals of the NFSEG model conceptualization report were not attained fully, the percentages of the groundwater level residuals within 2.5 and 5 feet, respectively, generally indicate a very good match between observed and corresponding simulated values.

Table 4-4. Summary Residual Statistics

Statistical Criterion	Proposed Target	All Target Wells		Layer 3 Only	
		2001	2009	2001	2009
-5 feet < Residual < 5 feet	80%	72%	74%	76%	76%
-2.5 feet < Residual < 2.5 feet	50%	42%	48%	43%	49%
Mean of Residuals		0.1	0.3	-0.4	-0.9
Standard Deviation of Residuals		6.6	8.4	4.8	4.6
Mean of Absolute Residuals		4.4	4.4	3.6	3.4
Number of Targets		1355	1738	977	993

Heads

The CRH group is a set of maps and graphs that provide comparisons of observed versus corresponding simulated groundwater levels (i.e., hydraulic heads). These include maps of groundwater level residuals of layers 1, 3, and 5; graphs of observed versus simulated hydraulic head; and maps of the simulated water table of layer 1 and simulated potentiometric surfaces of layers 3 and 5 (Figures 4-11 through 4-40).

<u>Groundwater Level Residuals of Layer 1</u>

Maps of residuals of the groundwater levels of layer 1 show the difference between observed groundwater levels of layer 1 at various observation wells in 2001 and 2009 and their model simulated counterparts (Figures 4-11 and 4-12; Appendix A). The water levels of layer 1 represent the water table of the surficial aquifer system (where present).

The 2009 data set includes estimates (as opposed to observations) of the water table elevation, primarily in wetland areas, that were based on USGS 1: 24,000 scale topographic maps and elevations extracted from the USGS 3DEP DEM. In upland areas, the stages of nearby lakes were used to estimate the water table elevation at some locations. These estimates were obtained at locations for which water table estimates were needed to provide additional constraint to the calibration but for which observations were not available. These estimates were assigned a lower weight in the calibration process, so differences between them and corresponding simulated values tend to be larger than average for layer 1. A large proportion of these points are positioned in the general region of pinch-out of the intermediate confining unit (the Cody Escarpment), and this is the reason for the relatively large number of residual values of layer 1 in 2009 that exceed 15 feet in that area (Figure 4-12). This may point to the need for additional surficial aquifer system monitoring wells in these areas.

The maps of hydraulic head residuals of layer 1 show a reasonably good comparison between the simulated and observed water levels. One should bear in mind that water levels of the surficial aquifer system are sensitive to local conditions and are therefore more difficult to match at the regional scale, as variation of actual water levels across the area corresponding to a model grid cell, which can be considerable in the case of the water table, is reduced to a single average value in simulation results.

Observed versus Simulated Groundwater Levels of Layer 1

Scatter plots of observed versus simulated hydraulic head provide a graphical comparison of observed and simulated hydraulic heads of layer 1 in 2001 and 2009 (Figures 4-13 and 4-14). Generally, these graphs indicate a good match between observed and simulated values of hydraulic head of layer 1. The comparison for 2009 shows noticeably greater scatter than that of 2001. This is because of the numerous estimated water levels, as opposed to observed water levels, included in the 2009 comparison. As stated above, estimated water levels of the surficial aquifer system were assigned significantly lower weights in the calibration process.

Simulated Water Table of the Surficial Aquifer System

The 2001 and 2009 simulated water levels of layer 1 represent the water table of the surficial aquifer system in 2001 and 2009, respectively, where the surficial aquifer system is present (Figures 4-15 and 4-16). The simulated water table is similar in appearance and general configuration for both years. In confined regions, it is reflective of the topography of the land surface but also reflects the influence of various rivers and streams in the form of v-shaped distortions in the contours of the water table that point upstream. In unconfined regions, the simulated water table resembles more closely the Upper Floridan aquifer potentiometric surface, with differences likely being because of the overburden above the Floridan aquifer system. As expected, the simulated water table approaches sea level with increasing proximity to the Atlantic Ocean and the Gulf of Mexico.

Residuals of Vertical Head Differences between Layers 1 and 3

In the most cases, the match between estimated and corresponding simulated vertical head differences between layers 1 and 3 is within 5 feet (Figures 4-17 and 4-18; Appendix B). This comparison can be indicative of the degree to which the confining properties of the intermediate confining unit are represented in the model, although numerous other factors can also influence the value of a vertical head residual at any given location.

Observed versus Simulated Vertical Head Differences between Layers 1 and 3

Scatter plots of observed versus simulated vertical head differences between layers 1 and 3 show generally good agreement between corresponding observed and simulated values (Figures 4-19 and 4-20; Appendix B). Scatter in these plots may be indicative of a lack of precision in knowledge of the confining properties of the intermediate confining unit at specific locations.

Groundwater Level Residuals of Layer 3

Maps of residuals of the groundwater levels of layer 3 for 2001 and 2009 indicate a good match between observed and corresponding simulated water levels of the Upper Floridan aquifer

(Figures 4-21 and 4-22; Appendix A). The absolute value of groundwater level residuals were generally less than 5 feet within the model domain, with larger residuals occurring in some areas. The residual map of 2001 shows a relatively high concentration of underestimated water levels along the coast of northeast Florida and southeast Georgia. For both calibration periods, clusters of relatively large residuals occur in Leon, Wakulla, and Citrus Counties, Florida.

Observed versus Simulated Hydraulic Head of Layer 3

The scatter plots of observed versus simulated hydraulic head of layer 3 for 2001 and 2009 provide a generally good match (Figures 4-23 and 4-24). The scatter that is present is to be expected for such a varied and complex range of conditions.

Residuals of Horizontal Head Difference of Layer 3

The maps of horizontal head difference of layer 3 indicate a generally good match overall between simulated and observed horizontal head differences (Figures 4-25 and 4-26; Appendix H). For example, the steep horizontal head differences just west of the Suwannee River in Lafayette County were generally well simulated, as were the steep gradients near the potentiometric high associated with the Waccasassa Flats region in Gilchrist County, Florida. In addition, the flatter gradients east of the Suwannee River in Suwannee County, Florida, and near the Ichetucknee and Lower Santa Fe rivers in southern Columbia and northwestern Alachua Counties, Florida, and eastern Gilchrist County, Florida, were generally well simulated. Note that the horizontal distance between the well pairs associated with each difference is implicitly represented when the simulated values of these horizontal differences are calculated during model calibration. Therefore, simulated values of layer 3 horizontal head *differences* that are similar to their observed counterparts also indicate a good correspondence between simulated and observed horizontal *gradients* in the Upper Floridan aquifer.

Observed versus Simulated Horizontal Hydraulic Head Differences of Layer 3

Plots of observed versus simulated horizontal head differences of layer 3 in 2001 and 2009 show very good to excellent matches, with somewhat more scatter in 2009 than 2001 (Figures 4-27 and 4-28; Appendix H). This indicates that the model is representing lateral gradients in hydraulic head well within the Upper Floridan aquifer.

Simulated Potentiometric Surface of Layer 3

The model generated water levels of layer 3 represent the simulated potentiometric surface of the Upper Floridan aquifer (Figures 4-29 and 4-30). These surfaces represent a good to excellent match to the respective observed potentiometric surfaces of 2001 and 2009 (Figures 2-29 and 2-30). Most major features of these maps are well represented in the respective simulated potentiometric surfaces of 2001 and 2009, including the Keystone Heights potentiometric high, the Waccasassa Flats potentiometric high, the Mallory Swamp potentiometric high, the Valdosta potentiometric high, the zone of high horizontal gradient across the Gulf Trough, the area of low horizontal gradient within the Silver and Rainbow springsheds, and pumping induced cones of depression at Fernandina Beach, Florida, and Brunswick and Savannah, Georgia.

Residuals of Vertical Head Differences between Layers 3 and 5

The maps of the residuals of vertical head differences between layers 3 and 5 can be indicative to an extent of the ability of the model to represent the degree of confinement provided by the middle confining unit. The observed values of vertical head differences between layers 3 and 5 are generally small (less than a few feet), and simulated values were also small in magnitude. Thus, both the observed and simulated values are consistent with a generally leaky middle confining unit (Figures 4-31 and 4-32; Appendix B).

Observed versus Simulated Vertical Head Differences between Layers 3 and 5

The scatter plots of observed versus simulated vertical head differences between layers 3 and 5 indicate a relatively good match between observed and simulated values (Figures 4-33 and 4-34; Appendix B).

Groundwater Level Residuals of Layer 5

The residuals of groundwater levels of layer 5 are concentrated along the Atlantic coastal region, as this area is where most Lower Floridan aquifer monitoring wells are located. In Duval and St. Johns counties, the 2001 residual map indicates concentrations of, in some cases, significant (greater than 10 feet) underestimation of water levels in the Lower Floridan aquifer. The same area in the 2009 map, however, indicates moderate underestimation. Good matches between observed and simulated values are seen in most of the other locations in 2001 and 2009 (Figures 4-35 and 4-36; Appendix A).

Observed versus Simulated Groundwater Levels of Layer 5

The scatter plots of observed versus simulated groundwater levels of layer 5 indicate generally good comparisons between observed and simulated water levels of the Lower Floridan aquifer for both 2001 and 2009 (Figures 4-37 and 4-38). More scatter is seen in these plots than in the corresponding plots of layer 3, but this is to be expected because there are fewer observations for the Lower Floridan aquifer.

Simulated Potentiometric Surface of Layer 5

The model generated water levels of layer 5 represent the simulated potentiometric surface of zone 3 (see section 2 for definitions of zones 1, 2, and 3). As might be expected, this surface resembles closely that of layer 3 (Figures 4-39 and 4-40).

Flows

The CRF group is a set of maps and graphs that provide comparisons of observed versus corresponding simulated flows. These include graphs of observed versus simulated spring discharge and estimated versus simulated baseflow rates. The CRF group also includes maps of simulated net recharge rates and simulated downward leakage rates to layer 3 and upward leakage rates from layer 3.

First Magnitude Springs and Spring Groups

Maps of observed spring flows for first magnitude springs and spring groups with corresponding flow residuals (differences between observed and simulated flow rates) were created for the 2001 and 2009 simulations (Figures 4-41 and 4-42). These are major springs and spring groups within the model domain (average flows generally greater than 100 cfs). The maps indicate generally good to excellent agreement between observed and corresponding simulated values.

Observed versus Simulated Spring Flows

Plots of observed versus simulated spring flows for 2001 and 2009 show generally good agreement between observed and simulated spring flows throughout the model domain (Figures 4-43 and 4-44). An exception to this is St. Marks Rise in the Florida Panhandle, which is the observation point in both plots that is farthest removed from the line of equality of observed and simulated values.

Observed versus Simulated Spring Group Flows

Spring groups are collections of springs associated with a given river reach, and a spring group flow is the combined flow of all the springs that constitute a given spring group. Spring groups in the NFSEG model include the Crystal River, Silver River, Wacissa River, Ichetucknee River, and the Lower Santa Fe River spring groups. Spring groups represent relatively large spring flow and are therefore particularly important to the calibration process. Plots of observed versus simulated spring group flows for 2001 and 2009 show excellent agreement between observed and corresponding simulated spring group flows (Figures 4-45 and 4-46).

Baseflows

As detailed in section 2, the baseflow estimates were derived from applications of baseflow separation techniques, with a few important exceptions for reaches along the Suwannee River. Therefore, more uncertainty exists regarding these estimates than for the other members of the flow observation groups. Potential errors in baseflow estimates may be an important contributing factor in poor comparisons between estimated and simulated values.

Maps of estimated baseflow pickup rates and corresponding residuals for 2001 and 2009 indicate a generally poor to fair comparison between estimated and simulated baseflow pickup rates, with some good to excellent matches shown as well (Figures 4-47 through 4-52; Appendix F).

Plots of estimated versus simulated baseflow pickup rates for 2001 and 2009 indicate a generally poor comparison between estimated and simulated baseflow pickup rates, though good to excellent matches do occur in numerous cases, more so for 2001 than 2009. Baseflow pickup rates are difficult to estimate and simulate in many cases, especially in cases of relatively short stream reaches (Figures 4-53 and 4-54).

Maps of cumulative baseflow rates and corresponding residuals for 2001 and 2009 indicate generally poor to fair comparisons in most cases, with some good to excellent matches, more so in 2001 than 2009 (Figures 4-55 and 4-56).

Plots of estimated versus simulated cumulative baseflow rates for 2001 and 2009 indicate generally poor to fair comparison between estimated and simulated cumulative baseflow rates also (Figures 4-57 and 4-58). Some good to excellent matches do occur, in the 2001 simulation.

Simulated Net Recharge Rates

Maps of net recharge rates (differences between inflow rates specified in the MODFLOW recharge package and simulated rates of evapotranspiration) are shown in figures 4-59 and 4-60. Simulated net recharge rates are generally higher in areas in which the depth to water table is greater, where runoff is less and are more internally drained, and lower in areas of shallow depth to water table, in wetlands for instance (Figures 4-59 and 4-60), where evapotranspiration rates are typically relatively high due to the presence of a shallow water table. The range of simulated net recharge rates is similar to that of Bush and Johnston (1988).

Simulated Downward Leakage Rates of Layer 2 to 3

Maps of simulated downward leakage rates from layer 2 to 3 for 2001 and 2009 show wide expanses within the model domain of downwardly directed leakage into the Upper Floridan aquifer (Figures 4-61 and 4-62). In most of the model domain, the rates are less than 5 inches/year (in/yr). In the unconfined regions of the model domain, rates are generally much higher, ranging in many areas from 10 to 50 in/yr. Not surprisingly, these are also some of the areas with the highest rates of net recharge.

Simulated Upward Leakage Rates of Layer 3 to 2

Maps of simulated upward leakage rates from layer 3 to 2 for 2001 and 2009 show significant areas of discharge from the Upper Floridan aquifer (Figures 4-63 and 4-64). Discharge areas are concentrated along the coasts of the Gulf of Mexico and the Atlantic Ocean within the model domain, except in areas in and around Savannah, Georgia, where intense pumping has reversed the vertical hydraulic gradient between the surficial aquifer system and the Floridan aquifer system. These also include areas along some of the river corridors, in areas of concentrated flow to springs, and in some areas where the intermediate confining unit pinches out.

Simulated Downward Leakage Rates of Layer 4 to 5

Maps of simulated downward leakage rates from layer 4 to 5 for 2001 and 2009 show a large overall area of downwardly directed leakage into layer 5 (Figure 4-65 and 4-66). The patterns of downward leakage are much more complex than corresponding 2001 and 2009 patterns from layer 2 to layer 3. The highest rates of downward leakage generally occur in the unconfined zones of the Upper Floridan aquifer.

Simulated Upward Leakage Rates of Layer 5 to 4

Maps of simulated upward leakage rates from layer 5 to 4 for 2001 and 2009 show large areas of upwardly directed leakage from layer 5 to 4 (Figures 4-67 and 4-68). Leakage rates are highest along the Suwannee River, the coastal regions of the Gulf of Mexico, west-central Marion County, Florida, and the southern extent of the St. Johns River.

Parameters

The CRP group is a set of maps and graphs of calibration derived hydraulic parameters, including horizontal and vertical hydraulic conductivity, aquifer transmissivity, and semiconfining unit leakance. Included in this collection is a graphical comparison of calibrated versus APT derived aquifer transmissivity values, and a calibration derived map of the transmissivity of layer 3. Also, a calibration derived map of the sum of the transmissivities of layers 1 through 3 in unconfined zones of the Floridan aquifer system and layer 3 in confined zones of the Floridan aquifer system. The purpose of the latter map is to show the effects of the model layering scheme on transmissivity values in unconfined zones of the Florida aquifer system.

Horizontal Hydraulic Conductivity of Layer 1

The horizontal hydraulic conductivity of layer 1 represents horizontal hydraulic conductivity of the surficial aquifer system, where the surficial aquifer system is present, as derived in the calibration process (Figure 4-69). This map shows values of horizontal hydraulic conductivity that are generally low, less than 20 feet/day (ft/day), which is as expected for the surficial aquifer system in most places.

Horizontal Hydraulic Conductivity of Layer 3

Layer 3 horizontal hydraulic conductivity values also exhibit expected geographic patterns of high and low values (Figure 4-70). Examples of areas with low horizontal hydraulic conductivity are the general area of the Gulf Trough in Georgia, Mallory Swamp in Lafayette County, Florida, and Waccasassa Flats in Lafayette and Gilchrist counties, Florida. Areas of high horizontal hydraulic conductivity include regions with high concentrations of springs, including the Rainbow and Silver springs basins, the Suwannee River corridor, the Santa Fe River Basin, including areas near the Ichetucknee River and High Springs Gap physiographic region, and the Woodville Karst Plain.

Horizontal Hydraulic Conductivity of Layer 5

The horizontal conductivity of zone 3 (see section 2 for definitions of zones) is generally not well known. The calibration results show high horizontal hydraulic conductivity in the Silver and Rainbow springs basins, as expected (Figure 4-71). It also shows regions of high horizontal hydraulic conductivity that generally correspond geospatially to areas of high hydraulic conductivity in Layer 3. These areas include the Silver and Rainbow springs basins. Also included is an area that extends roughly from Valdosta, Georgia, eastward towards the Atlantic Coast and then southward from the Florida-Georgia state line between Camden County, Georgia, and Nassau County, Florida, into St. Johns County, Florida. A branch of this zone extends from northeastern Baker County, Florida, and southern Charlton County, Georgia, and intersects with main portion of the zone in south-central Nassau and northern Duval counties, Florida. This zone of high hydraulic conductivity connects inland recharge areas to coastal discharge areas.

Another zone of high horizontal hydraulic conductivity extends from the Florida-Georgia state line southwest of Valdosta, Georgia, to the general area of southeast Leon and west-central Jefferson counties, Florida. This is an area of numerous karstic features, including numerous sinkholes, lying just north of the Woodville Karst Plain.

Areas of relatively low horizontal hydraulic conductivity within layer 5 include the general area of Mallory Swamp in Lafayette County, Florida, and Waccasassa Flats in Lafayette and Gilchrist counties, Florida. Generally low horizontal hydraulic conductivity is consistent with the lower values of overlying, shallower parts of the Floridan aquifer system in these areas.

Horizontal Hydraulic Conductivity, Layer 7

The horizontal hydraulic conductivity of layer 7 represents that of the Fernandina permeable zone, which is the lower zone of the Lower Floridan aquifer in northeast Florida and southeast Georgia. The horizontal hydraulic conductivity of this part of the Lower Floridan aquifer is not well defined. Layer 7 horizontal hydraulic conductivities resulting from the calibration range from less than 50 ft/day to more than 100 ft/day (Figure 4-72). Only two groundwater level observation points were available to the calibration process for this layer for 2001 and 2009.

Transmissivity of Layer 3

The calibration derived transmissivity distribution of layer 3, consistent with the distribution of horizontal hydraulic conductivity, is generally high and low where expected (Figure 4-73).

Transmissivity of Layer 3 in Confined Areas and the Sum of Transmissivities of Layers 1 through 3 in Unconfined Areas

The map of transmissivity of layer 3 in confined areas and the sum of transmissivities of layers 1 through 3 in unconfined areas, referred to hereafter as the “composite transmissivity map,” shows the effective transmissivity of layer 1 through 3 in unconfined areas rather than the transmissivity of layer 3 only (Figure 4-74). The effective transmissivity in unconfined areas is calculated as the sum of the transmissivities of layer 1, 2, and 3. The map shows layer 3 transmissivity only in confined areas. The purpose of the map is to show the effects on transmissivity estimates of the model layering scheme in unconfined areas. This map and that of layer 3 transmissivity are similar in configuration and general ranges, but significant differences occur in highly karstic areas, such as parts of the Silver and Rainbow springs basins (Figure 4-75).

Observed versus Calibration Derived Transmissivity of the Upper Floridan Aquifer

The comparison of calibration derived transmissivity of the Upper Floridan aquifer to corresponding values derived from aquifer performance test (APT) is shown in Figure 4-76. APT derived transmissivity values are presented using the untransformed values from reports documenting the APTs and as “normalized values,” which are reported values divided by depth of penetration of the pumped well and multiplied by the thickness of the aquifer. The APT results and comparison to model calibrated values should be interpreted with a degree of caution. APTs are limited in ability to stress highly transmissive systems, such as the Upper Floridan aquifer. This limits the spatial extent of the stresses, and therefore the extent to which APT derived transmissivities can represent the system. APT results are therefore more localized, and differences should be expected between those results and the calibration results of models such as the NFSEG model with grid cell dimensions that represent larger “samples” of the aquifer.

Transmissivity, Layer 5

The calibration derived transmissivity distribution of layer 5 is consistent generally with the horizontal hydraulic conductivity distribution of layer 5 insofar as the relative distribution of high and low values of transmissivity (Figure 4-77). The transmissivity values of layer 5 also exhibit similar spatial patterns to those of layer 3, such as higher values in areas with greater spring flows and lower values in areas such as Mallory Swamp and Waccasassa Flats.

Vertical Hydraulic Conductivity of Layer 2

Calibration derived values of vertical hydraulic conductivity of layer 2 were associated with confinement. For layer 2, values of moderately high to high vertical hydraulic conductivity in areas in which the intermediate confining unit is thin or absent and higher values in which the intermediate confining unit has been mapped (Figure 4-78).

Vertical Hydraulic Conductivity of Layer 4

The calibration derived values of vertical hydraulic conductivity of layer 4 shows moderate to low values of vertical hydraulic conductivity in areas in which Miller (1986) mapped various middle confining units within the NFSEG model. Values are moderately high to very high outside of those areas (Figure 4-79).

Vertical Hydraulic Conductivity, Layer 6

Calibration derived vertical hydraulic conductivity of layer 6 shows generally low values of vertical hydraulic conductivity (Figure 4-80).

Leakance of Layer 2

Geographic patterns of model calibrated leakance of layer 2 resemble those shown in the calibration derived map of vertical hydraulic conductivity of layer 2 in terms of the distributions of high versus low values. Values ranged from less than 10^{-7} to greater than 1 day^{-1}. Higher values were associated with areas in which the intermediate confining unit is thin or absent, and lower values generally occurred in areas in which it is relatively thick (Figure 4-81).

Leakance, Layer 4

Similarly, leakance distribution of layer 4 corresponds, in a relative sense, to the calibration derived map of vertical hydraulic conductivity of layer 4 (Figure 4-82).

5. Model Simulations

As part of NFSEGv1.1 model development, a verification simulation and a no-pumping simulation were conducted to assess the performance of the NFSEG model for predicting groundwater levels and flows.

Verification Simulation

For the NFSEG model verification, the year 2010 was selected at an early stage of model development by the NFSEG technical team, composed of the modeling team as well as technical experts assigned by stakeholders. Based on annual average rainfall distribution from NLDAS used in NFSEG model development, the year 2010 does not resemble either of the calibration years (2001 and 2009) which makes it suitable for a verification simulation (Figure 5-1). The year 2009 was generally considered a wet year and the year 2001 was generally considered a dry year throughout most of the model domain. The year 2010, however, was drier than 2001 in some parts of model domain, such as areas along the eastern model boundary covering much of the St. Johns River watershed and eastern parts of Georgia and South Carolina, whereas it could be considered an average rainfall year along the western model boundary in Florida (Figure 5-2). Relative to the year 2009, the year 2010 was drier throughout most of the model domain, except for areas along the southwestern model boundary which includes Marion and Levy counties (Figure 5-2).

To setup the 2010 verification simulation, model input files were developed for the year 2010 based on methods established in the calibration simulations, which are described in detail in the following section. The prediction performance of the NFSEG model was assessed using the 2010 verification results by reviewing the difference between simulated and observed values of groundwater levels, spring flows and baseflows, simulated 2010 potentiometric surface of the UFA and simulated 2010 mass balance for reasonableness.

Model Input Files

The following section includes brief descriptions of the MODFLOW-NWT packages that were updated with 2010 input data for the verification simulation. To maintain consistency and enable comparison with the NFSEGv1.1 calibration simulations, model input files were developed for the year 2010 using the same methods established for the years 2001 and 2009 during model calibration. Section 3 of this report includes more detailed information regarding the NFSEGv1.1 model calibration input files and implementation.

<u>Recharge and Maximum Saturated Evapotranspiration</u>

In the NFSEG model verification simulation, separate external arrays of recharge and maximum saturated evapotranspiration (MSET) rates were developed for 2010 using HSPF models developed for the NFSEG model (see Appendix # for more information). Figure 5-3 shows the distribution of the 2010 MSET as well as average annual MSET in 2001, 2009 and 2010 within delineated groundwater basins (GWBs). Figure 5-4 shows the difference between MSET in 2010 relative to the years 2001 and 2009 within delineated groundwater basins (GWBs). Despite similarity in average annual MSET within each GWB among all three years, there is evident spatial variation in MSET in 2010 relative to each calibration year. In the year 2010, MSET was generally lower than 2001 and 2009 along the western model boundary and higher along the eastern model boundary (Figure 5-4).

The applied recharge rate in 2010 and average annual recharge rate for 2001, 2009 and 2010 within each GWB are shown in Figure 5-5. There appears to be greater variation in the average annual recharge rate within each GWB relative to MSET. The spatial variations in the recharge rate in the year 2010 relative to 2001 and 2009 are shown in Figure 5-6. In the year 2010, the recharge rate was higher than in 2001 and 2009 in the southwest portion of the model and generally lower along the eastern model boundary. In parts of southern Georgia, the recharge rate in the year 2010 was generally higher than in the year 2001 but lower than in the year 2009 (Figure 5-6). Like rainfall distribution, geographic variations in MSET and applied recharge rates in 2010 are distinct from those in 2001 and 2009.

Drain and River Package

Stage and bottom elevation estimation for development of the 2010 Drain and River Packages followed the same methodology used for 2001 and 2009. Sources of actual stream and lake stage data for 2010 include the USGS and various water management districts, which provided median water levels for 2010. Where stage data were unavailable, land surface elevation was used to represent stage. In the Suwannee River and some of its tributaries, stages for 2010 were obtained from the SRWMD HEC-RAS surface water models. A hydrodynamic model developed by SJRWMD was the source of stages for the St. Johns River for 2010.

Well and Multi-Node Well Packages

The Well Package was used to represent single aquifer withdrawal wells, while the Multi-Node Well Package was used to represent withdrawal wells open to both the Upper and Lower Floridan aquifers in 2010. All water uses represented in the 2001 and 2009 groundwater withdrawal dataset are included in 2010. Figure 5-7 through Figure 5-8 show the distribution of groundwater withdrawals by water use type and counties in 2010. Influxes due to rapid infiltration basins (RIBS), natural sinks, drainage wells and injection wells were also simulated with the Well Package (see section 3 for more information). Figure 5-9 includes the multi-aquifer withdrawal wells included in the 2010 simulation. Table 5-1 includes the total groundwater withdrawals and influxes (in mgd) in 2010 compared to those in 2001 and 2009.

General Head Boundary Package

Lateral Boundaries

For the 2010 verification simulation, lateral boundary conditions types were identical to those used in the 2001 and 2009 calibration, with most of the NFSEG model lateral boundaries assigned no-flow boundaries (See section 3 for more information). For the small portion of the lateral boundaries that were represented with the General Head Boundary (GHB) Package, source heads for model layer 3 (UFA) were generated using the May-June 2010 potentiometric surface (Kinnaman and Dixon, 2011) and average observed water levels in 2010. Where GHB source heads were assigned for other layers, the values were the same as for the UFA.

Table 5 1. Summary of Groundwater Withdrawals and Influxes

Groundwater Withdrawals and Influxes	Q 2001 million gallons per day	Q 2009 million gallons per day	Q 2010 million gallons per day
Single aquifer well withdrawals	1,568	1,557	1,487
Multi-aquifer well withdrawals	125	119	120
Influxes (RIBS, injection wells, swallets, drainage wells)	315	392	457

Spring Pool Elevations

The GHB package was also used to simulate spring discharges by specifying spring pool elevations for the springs in the NFSEG model domain (Figure 2-1). Spring pool elevations were assigned based on observed median water levels for 2010. In the case where no observed data was available for 2010, if a spring is adjacent to a river, the nearby 2010 river stage was assumed to be the pool elevation. In cases where no observed data were available, or were based on limited observations, and no adjacent river cell was available, the USGS 3DEP 10m DEM elevation was used to set the pool elevations. The assigned spring pool elevations were later compared with the observed 2010 potentiometric surface of the UFA to ensure that the pool elevations were lower than the UFA water levels for a flowing spring.

Observation Datasets

To assess model performance for the year 2010, residual statistics were evaluated for the three types of observation groups: Groundwater levels; Spring discharge rates; and Baseflow rates.

Groundwater levels

The groundwater level observation data were compiled from a variety of sources, including the USGS and water management districts. Observed UFA water levels for 2010 were compared with the May-June 2010 UFA potentiometric surface developed by the USGS to check for significant discrepancies that could be due to measurement error. The May-June 2010 potentiometric surface was selected for comparison because this was the only data available from USGS in the year 2010 in which the UFA potentiometric surface extended into Georgia. As a result, a total of 1329 observation wells with a 2010 median observed water level were used to assess model performance using the results of the 2010 simulation (Figure 5-10). Appendix I includes the observation well water level data for 2010.

Springflows

Spring discharge rates for the year 2010 were developed based on direct observations if available for 2010 or estimates using direct observations from other years if sufficient data was not available. Sources of actual spring discharge included the USGS and water management districts. If sufficient data were not available for a spring, a literature value from the Florida Geological Survey (FGS) Bulletin 66 (Scott and others, 2004) was used as an initial estimate of spring flow. Appendix J includes the 2010 observed/estimated spring discharge rates in the model domain.

Baseflows

As discussed in detail in section 2, baseflows were estimated for the year 2010 by averaging the results of five baseflow estimation approaches. Although the average of all approaches was used as the initial baseflow estimation for a given gage, the minimum and maximum estimated baseflow of all techniques was considered for evaluation of simulated baseflows. For gages within unconfined areas, in which total streamflow is dominated by groundwater discharge, total streamflow was used to estimate changes in baseflow at a given gage. Two baseflow observation data groups were developed for the year 2010 – the baseflow pickup group, representing the change in baseflow between a downstream and zero or one upstream gage, and the cumulative group, representing the total baseflow contributions from collections of baseflow pickup reaches to a given gage. Based on available data, baseflow pickup estimates were developed for 41 USGS gages and cumulative baseflow estimates were developed for ten USGS gages in 2010. Appendix K includes the 2010 estimated baseflow pickups and cumulative baseflows as well as the range of flows estimated from the five baseflow separation techniques described in section 2.

Assessment of 2010 Simulation Results

The results of the 2010 verification simulation (modeled minus observed) are included in Appendices I through K. Appendix I includes the 2010 simulated groundwater levels and residuals. Appendix J includes the 2010 simulated spring discharge rates and residuals. Appendix K includes the 2010 simulated baseflow pickups and cumulative baseflows and residuals.

The performance of the NFSEG model was assessed using the 2010 verification results as follows:

- Groundwater level, spring flow and baseflow residual statistics from the 2010 simulation were compared with the 2001 and 2009 calibration statistics;
- The spatial distribution of the 2010 UFA level residuals was compared with that of 2001 and 2009 UFA level residuals;
- The simulated 2010 potentiometric surface of the UFA was compared with the observed 2010 potentiometric surface of the UFA; and
- The simulated 2010 mass balance was reviewed for reasonableness.

Residual Statistics

Residual statistics were computed for simulated 2010 groundwater levels, spring discharge rates and baseflow rates and compared with 2001 and 2009 calibration statistics.

Groundwater Levels

The overall distribution of simulated and observed groundwater levels for Layers 1, 3 and 5 are shown in Figures 5-11 through 5-13. The groundwater level residual statistics of the 2010 simulation were compared with the groundwater level residual statistics of the 2001 and 2009 calibration simulations (Figure 5-14). Overall, groundwater level residual statistics in 2010 were similar to those in 2001 and 2009. The 2010 simulation performed slightly better in predicting Layer 1 groundwater levels than in 2009, whereas the 2010 residuals were slightly higher than the 2001 and 2009 residuals in Layers 3 and 5. Appendix X includes the 2010 simulated groundwater levels and residuals for the 1329 observation wells included in the 2010 simulation.

Spring Flows

Figure 5-15 shows the distribution of simulated and observed spring flows in 2010. Spring flow residual statistics in 2010 were compared to those in 2001 and 2009 for individual springs in the NFSEG model (Figure 5-16). Overall, spring flow residual statistics in 2010 were similar to residual statistics in 2001 and 2009. Relative to 2001 and 2009, the 2010 simulation resulted in a higher absolute mean spring flow residual. The 2010 residual mean is lower than 2001 and 2009, but still negative, which suggests an overall slight underestimation of spring flow. The residual standard deviation of 2010 spring flow is higher than the residual standard deviation in 2001, but lower than the residual standard deviation in 2009 (Figure 5-16).

Table 5-2 includes simulated and observed spring flows in 2010 for important first magnitude springs and spring groups. As shown in Table 5-2, the model performed well in matching important spring flows except for Silver Springs group, Rainbow Springs, St. Marks River Rise and Spring Creek Springs Group. This could be due to uncertainties in some of the parameters such as spring pool elevation, flow estimates, recharge and maximum saturated ET (MSET). St. Marks River Rise and Spring Creek are both located in Northwest Florida, which was an area of less focus for the NFSEG model. The model calibration of this area was relatively poor in 2001 and 2009 simulations, which may be improved in later versions of the model.

Rainbow Springs and Silver Springs are within a groundwater basin with higher annually averaged precipitation and estimated recharge in 2010 than either 2001 or 2009 (GWB-6 in Figures 5-2 and 5-6). Spring flows are highly sensitive to recharge and MSET values which were estimated through surface water models. For example, the estimated recharge in GWB-6 is between 15 and 30 inches per year (Figure 5-5). A potential error of 10 to 15% (which is acceptable in recharge estimates) could easily make up the difference between the simulated and observed flows of Silver and Rainbow springs in 2010.

Examination of available data indicated that flows at Silver and Rainbow Springs are highly sensitive to pool elevation, an estimated input parameter in the model. The observed data show that increases in pool elevations by 0.2 feet at Silver Springs and 0.4 feet at Rainbow Springs correspond to a flow increase of approximately 100 cfs, which is close to what the model is overestimating by in 2010. In addition, according to recently completed minimum flows and levels reports for both springs, there has been significant change in the relationship between pool elevation and spring flows mainly due to increased aquatic vegetation in the river runs since

2000, which would also reduce the model's ability to predict flows for these springs in recent periods. It should also be noted that no pool elevation measurements at Rainbow Springs were available for the simulation year, 2010. Thus, the pool elevation at Rainbow Springs in 2010 had to be estimated based on limited pool elevation measurements at the spring from 2014 through 2017 and downstream stage recorded at USGS gage 02313100. Appendix J includes the simulated spring flows and residuals for all springs included in the 2010 simulation.

Table 5-2. Observed and simulated spring flows

Important first magnitude springs and spring groups	Water Management District	Estimated Discharge, (cfs)	Simulated Discharge, (cfs)	Residual Discharge, (cfs)	Percent Error
Wacissa Springs Group	SR	440	411	29	7%
Ichetucknee Springs Group	SR	287	264	23	8%
Crystal River Springs Group	SWF	473	490	-17	4%
Rainbow Springs	SWF	618	757	-139	22%
Springs on the Santa Fe River between the gages near Worthington Springs and Fort White	SR	687	721	-34	5%
Silver Springs Group	SJR	588	693	-105	18%
Lower Santa Fe Springs Group	SR	881	916	-35	4%
Wakulla Spring Main Vent	NWF	728	717	11	2%
Wacissa Head Spring	SR	159	155	4	3%
Madison Blue Spring	SR	129	122	7	5%
Alexander Spring	SJR	102	104	-2	2%
Silver Glen Spring	SJR	100	101	-1	1%
St. Marks River Rise	NWF	452	226	226	50%
Spring Creek Springs Group	NWF	307	452	-145	47%

Estimated Baseflows

Figure 5-17 shows the distribution of simulated and estimated baseflow pickups in 2010. The 2010 estimated baseflow pickup residual statistics were compared with the 2001 and 2009 calibration statistics (Figure 5-18). Overall, baseflow pickup residual statistics in 2010 were similar to those in 2001 and 2009. The residual absolute mean and residual standard deviation in the year 2010 were larger than 2001, but smaller than 2009. The residual mean in the year 2010 was negative, which indicates an overall underestimation of baseflow pickups, compared to an

overall overestimation of baseflow pickups in 2001 and 2009 (Figure 5-18). Appendix Z includes the range of estimated baseflow pickups along with simulated residuals in 2010.
Cumulative baseflow estimates were developed for 10 USGS gages based on available data. Table 5-3 includes the range of cumulative baseflow estimates, based on five baseflow estimation techniques, along with simulated cumulative baseflows in 2010. These results are also displayed graphically in Figure 5-19. Figure 5-20 includes the cumulative baseflow residual statistics for 2010, compared to 2001 and 2009. The mean residual in 2010 is negative, which suggests an overall underestimation of cumulative baseflow, while 2001 and 2009 both simulated an overall overestimation of cumulative baseflow. The residual standard deviation and residual absolute mean are larger in 2010 relative to 2001 and 2009. It should be noted, however, that these statistics are highly dependent on the estimated baseflow target, which represents the average of five baseflow estimation techniques. When comparing to the range (minimum and maximum) of estimated cumulative baseflows, the 2010 simulation predicted a cumulative baseflow within the estimated range for 8 of the 10 USGS gages in which a cumulative baseflow was estimated with available data. (Table 5-3). Simulated cumulative baseflow at USGS gages 02315500 and 02320500 were outside of the estimated cumulative baseflow range, which could be attributed to uncertainty associated with each baseflow estimation technique.

Spatial Distribution of UFA Level Residuals

The spatial distribution of groundwater level residuals in 2010 for Model Layer 1 and Model Layer 3 within delineated GWBs is shown in Figure 5-21 and Figure 5-22, respectively. Of the 1329 total observation wells used as simulation targets in 2010, 238 are in Model Layer 1 and 829 are in Model Layer 3. The predicted water level was within 5 feet of the observed water level for most of the wells located in Model Layer 1 and Model Layer 3. Overall, the 2010 spatial distribution of residuals in Model Layer 1 and Model Layer 3 are similar to the 2001 and 2009 calibration results, suggesting a reasonable prediction of water level in the year 2010.

Groundwater level residuals in 2010 were compared to those in 2001 and 2009 at each 2010 overlapping observation well. With this method, only observations common in all three years were directly compared. Using this approach, 165 wells were directly compared in Model Layer 1 and 829 wells were directly compared in Model Layer 3 for all years. The percentage of wells meeting a statistical criterion of residuals within +/- 5 feet and +/- 2.5 feet were compared for each year within delineated GWBs and model-wide in Model Layer 1 (Table 5-4) and Model Layer 3 (Table 5-5). Model-wide, the percentage of wells in Model Layer 1 with a residual within ±5 feet (70 percent) was slightly lower, but comparable to those of 2001 (72 percent) and 2009 (79 percent). Similarly, the percentage of wells in Model Layer 3 with a residual within ±5 feet (73 percent) was slightly lower, but comparable to those of 2001 (77 percent) and 2009 (78 percent). The percentage of wells in Model Layer 1 with a residual within ±2.5 feet (41 percent) was slightly lower, but comparable to those of 2001 (48 percent) and 2009 (55 percent). The percentage of wells in Model Layer 3 with a residual within ±2.5 feet (43 percent) was also slightly lower, but comparable to those of 2001 (44 percent) and 2009 (50 percent).

Table 5 3. Range of estimated cumulative baseflow and simulated baseflow

USGS Gage	Gage Name	Estimated Average Baseflow (cfs)	Estimated Minimum Baseflow (cfs)	Estimated Maximum Baseflow (cfs)	Simulated Baseflow (cfs)
02228000	Satilla River at Atkinson, Ga	-653	-220	-974	-656
02231000	St. Marys River Near Macclenny, Fl	-106	-35	-152	-41
02243000	Orange Creek at Orange Springs, Fl	-7	-3	-10	-10
02315500	Suwannee River at White Springs, Fla.	-542	-106	-863	26
02317620	Alapaha River Near Jennings Fla	-607	-145	-915	-447
02319000	Withlacoochee River Near Pinetta, Fla.	-607	-151	-892	-365
02319500	Suwannee River at Ellaville, Fla	-3253	-1656	-4332	-1864
02320500	Suwannee River at Branford, Fla.	-4376	-2873	-5708	-2695
02321500	Santa Fe River at Worthington Springs, Fla.	-74	-17	-123	-33
02322500	Santa Fe River Near Fort White, Fla.	-790	-697	-851	-803

***Note: A negative sign indicates flow from the surficial aquifer system to a stream reach. A positive sign indicates reverse flow, from the stream into the surficial aquifer system.**

Simulated UFA Potentiometric Surface

The simulated 2010 UFA potentiometric surface (Figure 5-23) was compared with the observed 2010 UFA potentiometric surface (Figure 5-24). The observed 2010 UFA potentiometric surface was developed using medians of observed water level data and, in unconfined areas, estimated river stages, which were interpolated and contoured to create a median potentiometric surface map. The comparison between the simulated and observed UFA potentiometric surface suggested that the 2010 simulation closely captured the general shape of the observed 2010 potentiometric contours including the major features in the potentiometric map, such as the Valdosta potentiometric high, the Keystone Heights potentiometric high, and wellfield drawdown in the Gainesville area.

Simulated Model Fluxes

Section 6 presents a detailed model mass balance summary using simulated flows into and out of each model layer for 2001, 2009 and 2010. Figure 5-25 includes the model-wide mass balance for the year 2010. Table 5-5 presents a summary of simulated net fluxes into the model in 2010, compared to 2001 and 2009. Drain and river flows in 2010 are slightly higher than in 2001, but lower than in 2009 throughout the model. GHB flows out of Layer 3 in 2010 are higher than in 2001 and 2009. However, the portion of GHB flows in Layer 3 represented by spring flows in the year 2010 is higher than in the year 2001, but less than spring flows in 2009. Applied recharge in 2010 is within the range of applied recharge in 2001 and 2009. Similarly, simulated evapotranspiration from groundwater in 2010 is higher than that simulated in 2001, but lower than 2009. Model fluxes into and out of Model Layer 3 in 2010 are comparable to corresponding simulated fluxes in 2001 and 2009.

Table 5 4. Distribution of Water Level Residuals in Model Layer 1 by GWB

Groundwater Basin	-5 feet < Residual < 5 feet % of wells			-2.5 feet < Residual < 2.5 feet % of wells		
	2001	2009	2010	2001	2009	2010
GWB-1 (9 wells)	78	89	89	56	44	44
GWB-2 (6 wells)	33	67	50	0	17	0
GWB-3 (20 wells)	70	90	70	65	50	45
GWB-4 (45 wells)	76	69	58	47	51	38
GWB-5 (3 wells)	67	100	100	0	67	33
GWB-6 (14 wells)	71	71	71	43	64	50
GWB-7 (68 wells)	72	82	76	51	60	44
Model-wide (165 wells)	72	79	70	48	55	41

***Note: Only observations common in all years (2001, 2009 and 2010) were used in this analysis.**

Table 5 5. Comparison of Simulated Net Fluxes to Model for 2001, 2009 and 2010

Groundwater Basin	-5 feet < Residual < 5 feet % of wells			-2.5 feet < Residual < 2.5 feet % of wells		
	2001	2009	2010	2001	2009	2010
GWB-1 (144 wells)	79	81	83	43	45	52
GWB-2 (94 wells)	70	76	65	32	40	30
GWB-3 (179 wells)	79	74	69	51	41	40
GWB-4 (131 wells)	73	81	70	44	60	34
GWB-5 (39 wells)	46	41	44	23	31	18
GWB-6 (126 wells)	83	83	75	50	63	55
GWB-7 (116 wells)	85	84	85	47	58	53
Model-wide (829 wells)	77	78	73	44	50	43

***Note: Only observations common in all years (2001, 2009 and 2010) were used in this analysis.**

NO-PUMPING SIMULATION

Predictions of groundwater levels and spring flows under a no-pumping condition are needed to support a variety of water resource decisions. These types of predictions are used to help assess whether minimum flow and level standards (and proxies for these standards) are being met at water bodies of interest. The NFSEGv1.1 model was developed in large part so that no-pumping simulations would not be limited by issues such as lateral boundary proximity that have affected other models.

Staff conducted a historical review of previous regional modeling efforts where groundwater withdrawals were completely removed for a model simulation. There has generally been an evolution through time of approaches with the most early regional groundwater flow models using a specified head surficial aquifer that served as a boundary condition for the simulation. As model complexity, data collection, and computing power increased, the surficial aquifer has been more routinely actively simulated and earlier steady-state approaches have been increasingly replaced by transient simulations. The testing or demonstration of the reasonableness of no-pumping scenarios is also becoming more common.

The most recent example of evaluating a no-pumping condition was for the Integrated Northern Tampa Bay (INTB) model by the University of South Florida (Ross and Trout, 2017). The INTB model is a transient integrated surface and groundwater model encompassing a domain of 4,000 square miles in west-central Florida (Geurink and Basso, 2013). From the USF report:

> *Comparisons between heads and fluxes were made for pumping and no-pumping scenarios to determine if the differences were reasonable… Because limited data exist to validate how well the model can predict the effects of the elimination of groundwater pumping across the domain, the approach taken here is mostly to examine the change in various groundwater flow-system components and determine if the overall weight of evidence is consistent with expected results.*

Selected elements from the USF review of the INTB model were applied to the NFSEGv1.1 model review to test the reasonableness of the model predictions of simulated withdrawal impacts using the difference between the steady-state no-pumping condition and the 2009 condition. Components examined for this review included groundwater levels, spring discharges, groundwater above land surface and a comparison of the simulated no-pumping UFA potentiometric surface to the USGS predevelopment potentiometric surface.

Groundwater Levels

The USGS compiled a map of the potentiometric surface of the Floridan aquifer system (Figure 5-26), which represents and estimate that surface prior to significant withdrawals/development (Johnston et al, 1980: Figure 5-26). The map was based on a composite of previously developed maps with modifications where necessary, and potentiometric surface maps where pumping was relatively low. According to Johnson et al. (1980), the purpose of the map was not to show precise water level data at specific sites; rather, to show the best estimate of the configuration of the predevelopment potentiometric surface using the best available data at that time. This data was used to evaluate the reasonableness of simulated groundwater levels when all pumping is removed from the NFSEG v1.1 model.

A comparison of no-pumping simulated groundwater levels for layer 3 was made to the USGS predevelopment groundwater levels within a sub-region of the NFSEG model domain (Figure 5-27) that includes areas of the upper basin of the Santa Fe River, that are likely to be the focus of future applications of the NFSEG model. It excludes areas that correspond to northern portions of the NFSEG domain that may be unduly influenced by the specified source heads of the GHB conditions used to simulate flux across the northern lateral boundary, as well as other areas where changes in the regional potentiometric surface have been less pronounced.

Several factors may contribute to the differences between the estimated potentiometric surface and the surface from the no-pumping simulation. Some inaccuracies in the USGS map may be present because of limited observations and some approximations, as detailed by Johnston et al (1980). Differences in rainfall amounts between 2009 and the general period that the observations on which the USGS map is based, may explain some differences within the sub-region. The effects of changes to the predevelopment hydrological system other than pumping also play a role. Simulation error is a contributing factor; the no-pumping simulation represents a major departure from the general conditions to which the NFSEG model was calibrated.

In general, the simulated no-pumping surface is about 0 to 15 feet lower than the estimated predevelopment potentiometric surface (Figure 5-28). In most of the areas of the Keystone Heights potentiometric high and of the upper Santa Fe basin (Figures 5-27 and 5-28) simulated no-pumping heads are within 0 to 10 feet of the estimated potentiometric surface. In the central portion of the sub-region, simulated water levels are generally 10 to 15 feet lower than corresponding estimated predevelopment potentiometric surface. This includes areas of intense groundwater withdrawals along the coasts of northeast Florida and southeast Georgia. In a few areas, differences in water levels exceed 15 feet, but these are relatively small in extent.

The comparison shows a reasonable agreement in the configuration of the two surfaces (Figure 5-28), and changes in the configuration from pumps-on to no-pumping conditions are consistent with expected changes associated with removal of pumping stresses. For example, the surface from the no-pumping simulation reproduced the coastwise parallel contour configuration along the Atlantic coastline in southern Georgia and northeastern Florida. In addition, the higher contours near the Keystone Heights potentiometric high in the modern surfaces exhibited an expected migration toward coastal areas to the east and towards the upper Suwannee River to the west.

Spring Discharges

A comparison of simulated no-pumping spring discharges for selected springs to observed values reported by Stringfield (1936) shows simulated no-pumping spring discharges that are generally within the provided range of corresponding observed discharges (Table 5-6). These observations are used for the comparison because they were made in a period in which large-scale pumping impacts had generally not occurred yet and, thus, are the best available data representative of a no-pumping condition.

Given these considerations, along with the fact that the NFSEG v1.1 was not calibrated to the no-pumping condition, the model performance is generally good in matching the spring discharges, apart from White Springs and Juniper Springs, both of which have been affected by anthropogenic changes since the Stringfield measurements were made. In general, the model is matching minimums of Stringfield's (1936) observations well. The range of Stringfield's (1936) observations shows the potential for temporal variation in the discharges of many springs. These variations would presumably have been due largely to variations in rainfall amounts.

Table 5-6. Simulated 2009 and No-pumping Spring Discharges and Corresponding Observations of Stringfield (1936) for Selected Springs.

Spring	2009 Simulated Discharge (cfs)	No-pumping Simulated Discharge (cfs)	Stringfield (1936) Observed Discharges				
			Minimum Discharge (cfs)	Date	Maximum Discharge (cfs)	Date	Mean Discharge (cfs)
Silver	509	555	526	6/6/1933	1240	9/9/1933	808
Rainbow	570	593	487	10/3/1932	910	10/4/1933	652
Itchetucknee	264	270	260	6/4/1932	467	6/30/1930	340
Homosassa	124	127	141	2/14/1933	177	3/15/1932	159
Manatee	129	131	149	3/14/1932	n/a	n/a	149
Silver Glen	101	103	90	2/7/1933	125	3/17/1931	104
Alexander	102	103	112	2/12/1931	124	2/7/1933	68
Juniper	15	15	106	2/7/1933	117	3/3/1932	112
Fanning	68	70	79	3/14/1932	109	10/25/1930	94
Salt	92	93	62	2/7/1933	105	5/5/1931	85
Poe	43	44	31	3/14/1932	87	2/19/1917	59
Madison Blue	104	120	75	3/15/1932	n/a	n/a	75
White	6	1	36	11/4/1931	67	5/8/1927	48
Suwanacoochee	29	32	18	3/16/1932	41	11/6/1931	30
Ponce de Leon	21	23	20	3/7/1932	22	2/11/1929	21

Simulated Flooding in Layer 1

An important indication of the ability of the model to simulate the no-pumping condition is the degree to which simulated flooding in layer 1 increases due to the elimination of simulated groundwater pumping. Limited flooding in layer 1 occurs in both the 2001 and 2009 version of the model. When simulated groundwater pumping, which is mostly concentrated in layers 3 and 5, is removed, the resulting increases in groundwater levels of layer 3 propagate into layer 1 and cause additional flooding in some areas. Figure 5-25 shows the change in simulated flooding depths between the 2009 and no-pumping simulations. The maximum increase in flooding depth is between 7 and 10 feet, and this occurs over relatively small areas. In most areas, the simulated increase in flooding depth is less than a foot. This result is another indication of the ability of the model to respond reasonably to the removal of pumping stresses.

6. WATER BUDGET ANALYSIS

To gain insight into the behavior of the groundwater flow system and the NFSEGv1.1 model simulations, water budgets were developed for the overall model domain and for individual groundwater basins. In each of these areas, separate water budgets were developed for the 2001, 2009, 2010 verification, and 2009 no-pumping simulations. These water budgets provide information about the relative magnitudes of the various sources, sinks, and interlayer exchanges of groundwater in the model.

The model domain was delineated into seven groundwater basins (GWB) based primarily on maps of the estimated and simulated 2009 potentiometric surfaces of the UFA (Figure 6-1). The configuration of groundwater sub-basins by Bush and Johnston (1988) and the 2010 potentiometric surface of Kinnaman and Dixon (2010) also guided the GWB delineation.

Fluxes accounted for in this analysis include simulated discharges to or from the MODFLOW boundary condition packages that were implemented in NFSEGv1.1 model (GHB, River, Drain, ET, Recharge, Well, and Specified Head boundary conditions), as well as vertical transfers between model layers. Each boundary condition type is used to represent one or more aspects of the groundwater flow system. Simulated fluxes across lateral boundaries between groundwater basins occurs in some cases in the GWB analyses. The GWB boundaries were drawn to approximate groundwater streamlines (effectively a type of no-flow boundary). However, some inaccuracy in delineating these boundaries is inevitable and shifts of simulated flux is indicative of a degree of inaccuracy associated with delineation of GWB boundaries, as flux across streamlines does not occur in actual flow systems. This type of flux is denoted below as QLat.

The simulated water budgets for the individual basins highlight the differences within the overall groundwater flow system from region to region. Ranges of values or percentages discussed below represent the results from the 2001, 2009, and 2010 stress periods unless otherwise stated.

MODEL-WIDE SUMMARY

Model-wide simulated flows are generally greater in 2009 than 2001, reflecting the generally drier conditions observed in 2001 and wetter conditions observed in 2009. Simulated 2010 flows corresponded more closely to 2009 than 2001 simulated values. Flows for the 2009 no-pumping simulation are generally similar to the 2009 simulation results. Well package flows are used to represent natural influxes to the Floridan aquifer system via sinks in all simulations. Individual basin flows for 2010 are closer to 2009 individual basin flows in the western GWBs (GWBs 2, 3, 5, 6) and closer to 2001 basin flows in the eastern GWBs (GWBs 1, 4, 7). These results reflect the drier prevailing conditions that occurred in 2010 in the eastern area of the model domain and the wetter conditions that occurred in the western area.

Net recharge into layer 1 (RCH – GW ET) ranges from 4.93 to 7.06 in/yr for 2001, 2009, and 2010 (Figures 6-2 to 6-4). Twenty-nine to thirty seven percent of the net recharge to layer 1 is transferred to layer 2, with nearly all the remainder flowing to drains and rivers. Of the vertical flow from layer 1 to layer 2, 86-88% is transferred from layer 2 to layer 3, and the remainder flows out of layer 2 to rivers. Flow from layer 2 comprises 80-85% of flows into layer 3, and the remaining 15-20% flows upwardly from layer 4. Discharge to GHBs that represent springs and lateral flux boundaries remove the most water from layer 3 model wide. Nearly all of this GHB discharge is to features representing springs. Simulated layer 3 GHB flows representing spring discharge are 1.36, 1.63, and 1.48 in/yr for 2001, 2009, and 2010, respectively. Simulated layer 3 GHB flows representing net lateral boundary flux are much smaller: 0.08, 0.08, and 0.37 in/yr, respectively (out of the model domain). Simulated well withdrawals make up 18-23% of discharge from layer 3. Most of the water transferred from layer 4 to layer 3 originates as influx to layer 5 via GHBs that simulate lateral boundary flux. Influx via these GHBs accounts for 100% of inflow to layer 5 model wide. Of the total influx to layer 5, 85-86% is transferred vertically to layer 4, and the remainder discharges to wells.

For layer 1, the no-pumping simulation increased constant head outflows by 19%, drainage outflows by 1.9%, river outflows by 7.8%, GW ET by 1.2%, and decreased vertical flow from layer 1 to 2 by 16.9%. River outflow from layer 2 increased by 13.7%, and vertical flow from layer 2 to layer 3 decreased by 20.4%. Spring boundary outflows from layer 3 increased by 6.7%, and the vertical flow of water from layer 4 to layer 3 increased by 3%. General head boundary flows into and out of layer 5 did not significantly change, nor did the vertical flow of water from layer 5 to layer 4. The positive inflows to layer 3 from wells represent the natural influx to the Floridan aquifer system via sinks. Downward leakage rates from layers 1 and 2 in the 2009 no-pumping water budget (Figure 6-5) are smaller than corresponding rates for the 2009 (pumps on) water budget. This reduction in leakage is consistent with expected reductions of pumping induced recharge to underlying layers.

Groundwater Basins Summary

Mass balance calculations for individual basins highlight the differences in groundwater flow within the groundwater basins. Flows in GWB 1 are largely affected by UFA pumping, with almost all water contributed to layer 3 removed via well withdrawal. GWB 2 is a river dominated groundwater basin with most surface recharge contributed to river boundary flows, resulting in less vertical flow to layer 3. As such, well withdrawal from layer 3 results in relatively large vertical flows from layer 4 in GWB 2. GWB 3 is dominated by spring flows, as most water contributed to layer 3 is discharged by springs. Highly confined layers in GWB 4 result in relatively low vertical flows to the Floridan, which results in high lateral boundary flows that balance layer 3 and layer 5 well withdrawals. GWB 5 is spring dominated, similar to GWB 3, with contributions from the surface flowing to layer 3 spring discharge and 100% of all vertical flow to layer 5 withdrawn from wells. GWB 6 is also spring dominated and less confined than GWB 5, which results in the vertical flows of water from the surface and from layer 5 to make up spring discharge in layer 3. GWB 7 is dominated by surface flows, as water from layer 5 boundary heads flows upward to layer 3 spring discharges and layer 1 river and drainage boundaries. Details for each GWB are provided below.

GWB 1

Net recharge into layer 1 is 3.84, 5.98, and 3.81 in/yr for 2001, 2009, and 2010 respectively (Figures 6-6 to 6-8). Seven to ten percent of the Layer 1 net recharge is transferred to layer 2, and the remainder discharges from layer 1 to river and drain boundaries in near equal proportions. Of the water transferred from layer 1 to layer 2, 75-82% flows vertically downward to layer 3, with the remainder flowing out of layer 2 to river boundaries. Eighty-four to ninety two percent of the inflows to layer 3 are derived from downward leakage from layer 2, with other contributions occurring from layer 4 (5-13%) and from general head boundary flows (2-3%). Well withdrawals from layer 3 make up 87-90% of all flows out of layer 3, with flows to river boundaries making up about 8% and lateral boundary flows making up 2-5% of all layer 3 outward flows. General head boundary flows make up all water flows into layer 4. In 2001, 62% of layer 4 outflows were to layer 3, whereas in 2009 and 2010, 50-71% of layer 4 outflows were to layer 5. Of the water transferred to layer 5 from layer 4, 8-9% was discharged to wells, and the remainder flowed laterally out of the layer.

For the 2009 no-pumping simulation, the flows into and out of layer 1 show an increase in constant head outflows from 0.03 to 0.08 in/yr, 1.4% greater drainage outflows, 3.5% increase in river outflows, 0.65% increase in GW ET, and a 52.3% decrease in vertical flow from layer 1 to layer 2 (Figure 6-9). River outflow from layer 2 increased by 11.1%, and vertical flow from layer 2 to layer 3 decreased by 64.7%. The direction of vertical flow of water between layers 3 and layer 4 reversed, and increased in magnitude from 0.02 to 0.06 in/yr in the no-pumping scenario. The rate of vertical flow from layer 5 to layer 4 increased from 0.05 to 0.14 in/yr. The reduction in downward leakage from layer 2, reversal in flow direction between layers 3 and 5, and increase in downward leakage to layer 5 are also consistent with an expected reduction in pumping induced leakage to layer 3 and corresponding increase in groundwater flow to downgradient sinks, such as rivers and springs that are sustained by flows from the Upper Floridan aquifer. General head boundary flows into and out of layer 5 did not significantly change.

GWB 2

Net recharge into layer 1 is 11.96, 15.78, and 11.67 in/yr for 2001, 2009, and 2010 respectively (Figures 6-10 to 6-12). Forty-six to fifty three percent of the layer 1 net recharge flows to river boundaries, 41-49% flows vertically to layer 2, and 5-6% is discharged to drainage boundaries. Lateral flows make up less than 1% of all water flows into layer 2. Rivers make up 64-79% of layer 2 water outflows, consistent with low confinement in the region, and the remainder is transferred vertically to layer 3. Of the total water entering layer 3, 52-73% of water flows vertically from layer 2, 17-31% flows vertically upward from layer 4, and 6-17% flows laterally from the basin boundary. Almost 100% of all water entering layer 3 is removed via well withdrawals, with a small amount contributed to river boundary flows. Vertical flow from layer 5 to layer 4 makes up 87-92% of all water flow into layer 4, with the remainder contributed from general and lateral boundary heads. Of all water transferred into layer 5 via general and lateral heads, 4-7% is withdrawn via wells, and the remainder is transferred to layer 4.

Compared to the 2009 simulation, the 2009 no-pumping simulation flows into and out of layer 1 show 17.9% greater drainage outflows, 27.6% increase in river outflows, 6.7% increase in GW ET, and a 42.7% decrease in vertical flow from layer 1 to layer 2 (Figure 6-13). River outflow from layer 2 increased by 14.2%, and vertical flow from layer 2 to layer 3 decreases by 42.1%. The vertical flow of water from layer 4 to layer 3 decreased by 2% and general head boundary flows into layer 4 decreased by 66.7%. General head boundary flows into and out of layer 5 decreased by 66.7% and lateral influxes to layer 5 decreased by 66%.

GWB 3

Net recharge into layer 1 is 7.02, 9.87, and 10.56 in/yr for 2001, 2009, and 2010 respectively (Figures 6-14 to 6-16). There is 0.06 in/yr of water flows into layer 1 at river boundaries for 2001, and 1.04 and 1.10 in/yr of water flows out of layer 1 at river boundaries for 2009 and 2010 respectively. These river outflows represent about 9 to 11 percent of the net recharge to layer 1. An additional twelve to eighteen percent of the net recharge to layer 1 is discharged to drain boundaries, but the bulk of the net recharge to layer 1 (68-84%) is transferred vertically to layer 2. Most of GWB 3 is unconfined, and the simulation results reflect this with downward flow from layer 1 representing the only water budget component with a net inflow to layer 2, and approximately 88-90% of the water entering layer 2 then flowing downward to layer 3. The remainder of the layer 2 inflows are transferred to rivers. Vertical flow from layer 2 to layer 3 makes up 92-96% of all water entering layer 3 with the remainder consisting of vertically upward flow from layer 4 and lateral boundary head flows. Of the total water entering layer 3, 8% was removed through well withdrawals for 2001, and about 4% was removed for well withdrawals in 2009 and 2010, which is consistent with 2001 being a dry year. The simulated layer 3 GHB flows consist of 5.17, 6.10, and 4.75 in/yr spring boundary discharge rates and 0.01, 0.21, and 1.65 in/yr rates of lateral outflow rates for 2001, 2009, and 2010 respectively. Vertical flow from layer 4 to layer 3 was 84%, 80%, and 56% of the vertical flow from layer 5 into layer 4 for 2001, 2009, and 2010, respectively. Flow of water into layer 5 included lateral boundary flows from adjacent GWBs, making up 91-97% of all flows into the layer, with injection well contributions (Q_WEL) making up the remaining flow into the layer.

For the flows into and out of layer 1, the cessation of well withdrawals results in no change in constant head outflows, 2.5% greater drainage outflows, 13.5% increase in river outflows, 1.3% increase in GW ET, and a 3.9% decrease in vertical flow from layer 1 to layer 2 (Figure 6-17). River outflow from layer 2 increased by 13.6%, and vertical flow from layer 2 to layer 3 decreases by 5.9%. Spring boundary outflows from layer 3 increased by 13.9%, and the vertical flow of water from layer 4 to layer 3 increased from 0.33 to 0.73 in/yr. General head boundary flows into and out of layer 5 did not significantly change. The vertical flow of water from layer 5 to layer 4 increased from 0.41 to 0.81 in/yr. Lateral boundary flows into layer 5 increased from 0.39 to 0.80 in/yr. The positive inflows to layer 3 from wells represent the natural influx to the Floridan aquifer system via sinks. Downward leakage rates from layers 1 and 2 in the 2009 no-pumping water budget are smaller than corresponding rates for the 2009 (pumps on) water budget. As described previously, this reduction is consistent with expected reductions in pumping induced leakage to layer 3.

GWB 4

Net recharge into layer 1 is 1.81, 2.68, and 1.08 in/yr for 2001, 2009, and 2010 respectively (Figures 6-18 to 6-20). Of the total net recharge, 13-30% flows vertically to layer 2, and the remainder flows outward to river boundaries, drain boundaries, constant heads, and, to a lesser extent, well withdrawals. All leakage from layer 1 into layer 2 flows vertically downward to layer 3. Of that vertical flow into layer 3, 94-103% of that is removed from layer 3 via well withdrawals. Lateral flows into layer 3 make up any potential deficits in the mass balance due to well withdrawal. Flows from layer 3 to layer 4 ranged from 0.06 to 0.08 in/yr, and 100% of that water continues to flow downward to layer 5. Well withdrawals are up to 4 times greater than the vertical flow of water into layer 5. Lateral boundary flows make up any deficits in the mass balance of layer 5.

For the 2009 no-pumping simulation, the removal of well withdrawals results in 32% greater constant head outflows, 5.8% greater drainage outflows, 7.4% increase in river outflows, 1.9% increase in GW ET, and an 86% decrease in vertical flow from layer 1 to layer 2 (Figure 6-21). Vertical flow from layer 2 to layer 3 similarly decreases by 86%. Reduced well withdrawals from layer 3 results in a decrease in vertical flow from layer 3 to layer 4 from 0.08 to 0.03 in/yr. Vertical flow from layer 4 to layer 5 also decreased from 0.08 to 0.03 in/yr. General head boundary flows into and out of layer 5 did not significantly change. Lateral boundary flows into layer 5 decreased from 0.18 to 0.03 in/yr.

GWB 5

In GWB5, net recharge into layer 1 is 10.00, 15.42, and 13.77 in/yr for 2001, 2009, and 2010 respectively (Figures 6-22 to 6-24). Of the net recharge into layer 1, 44-47% is discharged at drain boundaries, 32-36% flows vertically down to layer 2, and the remainder flows out via constant heads, river boundaries, and lateral head boundary flows. Flows from layer 1 to layer 2 make up 97-98% of all water flow into layer 2, with the remainder made up of net inflows from River Package features. Vertical flow from layer 2 to layer 3 makes up all of layer 2 outflows. Of the total water flows into layer 3, 7-8% comes from well contributions (representing surface to sinkhole flows), and the remainder flows vertically from layer 2. GHB spring flows make up 83-88% of all water outflow from layer 3, with the remainder consisting of vertical flow to layer 4 and, to a lesser extent, lateral boundary flow. The simulated layer 3 GHB flows consist of 3.88, 4.19, and 5.19 in/yr spring discharge and 0.54, -0.60 (outflow), and 0.57 in/yr inflows across lateral flux boundaries for 2001, 2009, and 2010 respectively. All water flowing from layer 3 to layer 4 continues to flow vertically downward to layer 5. Moreover, downward vertical flow from layer 4 makes up 100% of the total water inflow to layer 5. Well withdrawals from layer 5 are less than 1 mgd for each study period. As such, essentially of all water outflow from layer 5 consists of lateral boundary flows.

Comparing the water budget for the no-pumping simulation with the corresponding 2009 simulation, indicated that, for layer 1, the changes in well withdrawals result in less than 1 percent increases in constant head, drainage, and change in GW ET flows; a 7 percent change in river outflows, and a 6 percent reduction in vertical flow from layer 1 to layer 2 (Figure 6-25). Simulated vertical flow from layer 2 to layer 3 also fell by 6 percent. Simulated spring outflows from layer 3 increased by about 2 percent, and the vertical flow of water from layer 3 to layer 4 decreased by 13 percent. Corresponding reductions in the flows from layer 4 to 5 and across lateral boundaries of layer 5 were also simulated. The positive inflows to layer 3 from wells represent the natural influx to the Floridan aquifer system via sinks.

GWB 6

In GWB 6, simulated net recharge into layer 1 is from 7.80, 8.13, and 13.90 in/yr for 2001, 2009, and 2010 respectively (Figures 6-26 to 6-28). Three to nine percent of the simulated layer 1 net recharge flows to river boundaries, 67-77% flows vertically to layer 2, 12-18% discharges at drain boundaries, and the nearly all of the remainder flows out to constant heads. Lateral flows make up less than 1% of all water flows into layer 2. River boundary flows make up about 1% of layer 2 water outflows, and most of the remainder is transferred vertically to layer 3. Of the total water entering layer 3, 62-73% of water flows vertically from layer 2, 26-37% flows vertically upward from layer 4, and less than 1% flows laterally from the basin boundary. Approximately 91-93% of all water entering layer 3 is removed as GHB springflows, and the remainder is removed from layer 3 through well withdrawals. The simulated layer 3 GHB flows consist of 6.00, 6.12, and 7.60 in/yr spring discharges and 2.57, 2.72, and 4.19 in/yr lateral boundary outflows for 2001, 2009, and 2010 respectively. Vertical flow from layer 5 to layer 4 makes up 92-96% of all water flow into layer 4, with the remainder contributed from lateral boundary flows. General head boundary flows into layer 5 make up 85% of all water flows for 2001 and 57-58% for 2009 and 2010, with the remainder consisting of lateral boundary flows. Of all water transferred into layer 5 via lateral boundary flows, less than 1 percent is withdrawn via wells, and the remainder is transferred to layer 4.

For the 2009 no-pumping simulation, the removal of well withdrawals resulted in 3.6% greater simulated constant head outflows, 5.7% greater drainage outflows, 51.7% increase in river outflows, 2.7% increase in GW ET, and a 5.3% decrease in vertical flow from layer 1 to layer 2 (Figure 6-29). River outflow from layer 2 increases by 11%, and vertical flow from layer 2 to layer 3 decreases by 5.5%. Spring boundary outflows from layer 3 increased by 6.9%, and the upward vertical flow of water from layer 4 to layer 3 decreased by 0.87%. General head boundary flows into and out of layer 5 decreased by 1.6%, and the vertical flow of water from layer 5 to layer 4 decreased by 0.92%

GWB 7

In GWB 7, simulated net recharge into layer 1 is 4.73, 4.49, and 3.82 in/yr for 2001, 2009, and 2010 respectively (Figures 6-30 to 6-32). Net recharge makes up 80-88% of water flow into layer 1, with vertical upward flow from layer 2 and, to a lesser extent, well contributions making up the remainder. Flows to river boundaries make up 54-57% of all flows out of layer 1, discharge at drain boundaries makes up 40-43%, and constant heads make up about 3%. Vertical flow from layer 3 makes up all water inflows to layer 2, and about 99% of that inflow is transferred vertically upward to layer 1, with the remainder flowing out at river boundaries. Vertical flow from layer 4 makes up 98-99% of all water inflow to layer 3, and the remainder consists of lateral boundary flows. Of the total layer 3 inflow, 58-60% is transferred out through GHB springflows, 19-23% is withdrawn through wells, and the remainder is transferred vertically to layer 2. The simulated layer 3 GHB flows consist of 2.27, 2.31, and 2.00 in/yr spring discharge and 0.04, 0.01, and 0.33 in/yr general boundary outflows for 2001, 2009, and 2010 respectively. One hundred percent of inflow to layer 4 is vertically transferred from layer 5, and 100% of that continues to flow upward to layer 3. Approximately 0.01 in/yr flows from layer 5 to layer 6 and then to layer 7. Most water inflow into layer 5 is from general head boundary flows, with a lesser amount contributed from lateral boundary flows. Of the total outflows of water from layer 5, 1-2% consists of well withdrawals.

For the flows into and out of layer 1, the changes in well withdrawals for the 2009 no-pumping simulation result in 29% greater simulated constant head outflows, 4.5% greater drainage outflows, 6.5% increase in river outflows, 4.3% increase in GW ET, and a 90.6% increase in upward vertical flow from layer 2 to layer 1 (Figure 6-33). Upward vertical flow from layer 3 to layer 2 increases similarly by 89.5%. Spring outflows from layer 3 increased by 2.2 percent, and total general head boundary flows changed from a 0.17 in/yr inflow to a 1.36 in/yr outflow from layer 3. The vertical flow of water from layer 4 to layer 3 decreased by 2.6%, and the vertical flow of water from layer 5 to layer 4 decreased by the same percentage. General head boundary flows into layer 5 decreased by 4%, and lateral boundary flows into layer 5 decreased by 40%. The small (0.01 in/yr) positive inflows to layer 3 from wells represent the natural influx to the Floridan aquifer system via sinks.

7. SENSITIVITY AND UNCERTAINTY ANALYSIS

The NFSEGv1.1 model was designed to be a tool that can be used to evaluate inter-district and inter-state groundwater pumping impacts, in addition to within-district impacts. A primary function of the model is to simulate regional effects of pumping on groundwater levels, stream and river base flows, and spring flows. To further support use of this tool, a parameter sensitivity and uncertainty assessment was conducted to help estimate the uncertainty associated with the model estimated parameters and predictions of future system scenarios. The objectives of these analyses were to: 1) Evaluate the sensitivity of model parameters used to calibrate the NFSEG version 1.1; 2) Provide a quantitative assessment of the overall NFSEG version 1.1 calibration performance; and 3) Provide quantitative estimates of the uncertainty of key model predictions.

The PEST software (Doherty, 2010a) used in the model calibration, was also used to facilitate aspects of the sensitivity and uncertainty analyses. A PEST defined parameter is any variable used to determine the value of a model input variable. For example, values of horizontal hydraulic conductivity parameters are estimated by PEST at specified points called pilot points. Therefore, horizontal hydraulic conductivity values determined by PEST at two different pilot points are two different parameters, even if the two pilot points are assigned to the same model layer. The actual model input values assigned to model grid cells are determined by interpolating between the pilot points. PEST also estimates parameter values without the use of pilot points. For example, there is a unique PEST conductance parameter associated with each spring which is used to directly estimate the corresponding conductance value for that spring in the MODFLOW GHB Package input file.

PEST organizes related sets of parameters into parameter groups. The NFSEG model has nearly 9,000 parameters, most of which are adjustable parameters that are estimated through model calibration. Each of these parameters are assigned to one of 23 PEST parameter groups. For example, the horizontal hydraulic conductivity pilot points in layer 1 are assigned to the PEST parameter group, ‘k1x’. Similarly, PEST organizes related sets of observations (‘calibration targets’) into observation groups. For example, 2001 groundwater level observations for model layer 3 are assigned to the PEST observation group, ‘h2001-lay3’. This grouping of parameters and observations provided a useful framework for organizing the sensitivity analyses described below.

PARAMETER SENSITIVITY ANALYSIS

The sensitivity of model outputs to individual parameters was evaluated to better understand the importance of various model input parameters to the behavior of simulated flows and levels. The sensitivity analysis included calculation of “traditional” parameter sensitivities as well as calculation of composite-scaled sensitivities (Hill and Tiedeman, 2007). Each of these analyses is discussed below. It should also be noted that parameter sensitivities are a key component of parameter and prediction uncertainty analysis.

Traditional Sensitivity Analysis

The traditional sensitivity analysis evaluated changes in the average and standard deviation of groundwater level, baseflow, and spring flow residuals in response to changes to the parameter groups or sets of parameter groups. These changes were quantified by increasing and decreasing the calibrated parameter values for a given parameter group or set of parameter groups, running the model, and calculating new statistics for the groundwater level, baseflow, and spring-flow residuals. Changes in parameter values were limited to their respective upper or lower bounds as specified in the model calibration. To implement the traditional sensitivity analysis, parameters were organized into 'traditional sensitivity analysis parameter sets' (parameter sets). In some cases, these parameter sets represented collections of PEST parameter groups, while in other cases they only contained one PEST parameter group (Table 7-1).

Table 7-1. Traditional Sensitivity Analysis Parameter Sets.

Parameter Set ID	Description
kx	Horizontal hydraulic conductivity pilot points in layers 1, 3, 5, and 7. Includes PEST parameter groups k1x, k3x, k5x, k7x.
kz	Vertical hydraulic conductivity pilot points in layers 2, 4, and 6. Includes PEST parameter groups k2z, k4z, k6z.
k3xz	Vertical hydraulic conductivity multipliers in layers 2, 4, and 5 where the middle confining unit of the Floridan aquifer system is assumed to be absent. Includes PEST parameter groups k2zk3z, k4zk3z, k5xk3x.
vanis	Vertical anisotropy for each layer 1 through 7. Includes PEST parameter groups vanis1 through vanis7.
lcm	Lakebed conductance multipliers.
rcm	Riverbed conductance multipliers.
sc	Spring conductance multipliers for each spring.
rechmul	Recharge multipliers.
evtrmul	Maximum saturated evapotranspiration rate multipliers.
lkzmul	Vertical hydraulic conductivity conductance multipliers beneath lakes.
ghb	GHB source heads.

Parameter sensitivity was evaluated by plotting the standard deviation of residuals for all observation wells and total simulated baseflows and spring flows against the multiplier used for each parameter group. The multiplier range for all parameter sets except maximum saturated evapotranspiration rate multiplier (evtrmul) varied from 0.2 to 5. Evtrmul varied over a narrower range of 0.2 to 2 to minimize issues associated with model convergence. The sensitivity of groundwater levels, baseflows, and spring flows to lateral boundary (GHB) water levels was also evaluated by adding 'offset values' to GHB lateral water levels over an interval of ±5 feet. In some instances, the large changes in parameter values prevented the NWT solver from achieving convergence (for example for model runs where the recharge parameter set, rechmul, was scaled with multiplier values of 0.2 and 0.5).

Results from the sensitivity analysis (Figure 7-1 to 7-6) indicated that simulated water levels were most sensitive to recharge, horizontal hydraulic conductivity, vertical hydraulic conductivity, and evapotranspiration multipliers that were less than 1 (Figure 7-1). Simulated water levels were moderately sensitive to vertical hydraulic conductivity multipliers in layers 2, 4, and 5 where the middle confining unit of the Floridan aquifer system was assumed to be absent, and to the anisotropy of layers 1 through 7. Simulated water levels were relatively insensitive to lakebed conductance, riverbed conductance, spring conductance, lake conductance multipliers, evapotranspiration multiplier values greater than 1 (Figure 7-1), and to changes in GHB lateral boundary heads (Figure 7-4).

Simulated baseflows were highly sensitive to changes in recharge, horizontal hydraulic conductivity, evapotranspiration, vertical hydraulic conductivity, and conductance multipliers beneath lakes when those multipliers were greater than 1.25 (Figure 7-2). Simulated baseflows were moderately sensitive to changes in vertical anisotropy, spring conductance, river conductance, and conductance multipliers beneath lakes for multiplier values less than 1. Baseflows were insensitive to changes in lake conductance (Figure 7-2), and GHB lateral boundary heads (Figure 7-5).

Simulated spring flow was highly sensitive to changes in recharge, horizontal hydraulic conductivity, vertical hydraulic conductivity, and spring conductance. Note that the change in the slope of sensitivity versus multiplier curve for recharge at multiplier values between 0.2 and 0.5 is most likely caused by solver convergence issues. Simulated spring flow was moderately sensitive to changes in evapotranspiration, and vertical anisotropy. Total spring flow was insensitive to changes in lakebed conductance, vertical hydraulic conductivity conductance multipliers beneath lakes (Figure 7-3), and GHB lateral boundary heads (Figure 7-6).

Composite-scaled Sensitivity Analysis

Composite-scaled sensitivities (css; Hill and Tiedeman, 2007) were calculated for each PEST parameter by summing the product of the sensitivity of each observation to a given parameter, the observation weight, and the parameter value:

$$css_i = \sum_{j=1}^{N} \left| \frac{\partial y_j}{\partial k_i} \right| k_i w_j$$

where:

css_i : composite-scaled sensitivity for PEST parameter, k_i
N : total number of observations,
$\frac{\partial y_j}{\partial k_i}$: sensitivity of observation, y_j, with respect to parameter, k_i, and
w_j : weight assigned to observation, y_j.

Composite-scaled sensitivities may be further aggregated by summing the *css* values of all members in a PEST parameter group (Sepúlveda and others, 2012). This approach is useful when large numbers of parameters are used during model calibration, and was therefore adopted for the analysis of the NFSEGv1.1 model. Thus, the composite-scaled sensitivities in this report represent an aggregate measure of the sensitivities of observations to PEST parameter groups. Parameter groups with large *css* values relative to the other parameters indicate that model simulated equivalents of observations are more sensitive to those parameters.

Parameter group *css* values are presented for four sets of observations:

- Composite scaled sensitivities for all observations combined,
- Composite scaled sensitivities for all groundwater level observations,
- Composite scaled sensitivities for spring flow observations, and
- Composite scaled sensitivities for all river baseflow observations.

The horizontal hydraulic conductivity parameter group k3x was associated with consistently high *css* values across all of sets of observations, which indicates the high sensitivity of both water level and flow observation types to layer 3 horizontal hydraulic conductivity pilot point values (Figures 7-7 through 7-10). This sensitivity is reasonable, given the importance of the hydraulic conductivity of the Upper Floridan aquifer in establishing horizontal-head gradients and spatial patterns of groundwater flow within the aquifer and to river reaches, including those sustained by spring discharge. Higher *css* values for the k3x parameter group are expected because of the large number of groundwater level, baseflow, and spring flow observations in layer 3. When groundwater level, baseflow, and spring flow observations are considered together, the k3x and spring-conductance (sc) parameter groups have the highest *css* values (Figure 7-7).

When the analysis of *css* values is limited to groundwater level observations, the k3x parameter group had the largest values (Figure 7-8). The k2z parameter group was also associated with large *css* values. Larger k2z css values for this set of observations is consistent with the fact that vertical hydraulic conductivity of the intermediate confining unit affects groundwater levels in the surficial as well as Floridan aquifer system through its role in mediating recharge rates to the Floridan aquifer in confined areas.

The k3x parameter group was also associated with the largest *css* values when the analysis was restricted to baseflow observations (Figure 7-9). This association is consistent with the fact that spatial variability in the horizontal hydraulic conductivity of the Upper Floridan aquifer is one of the most critical factors affecting patterns of groundwater flow within the aquifer, including the disposition of recharge entering the aquifer. The k2z parameter group *css* values were the second largest among the various parameter groups, a result that is expected given the importance of the intermediate confining unit vertical hydraulic conductivity in determining recharge rates to the Upper Floridan aquifer in confined areas.

The sc parameter group was associated with the largest *css* values when the analysis was restricted to spring flow observations (Figure 7-10). Simulated spring discharge is directly proportional to spring conductance, and differences in spring conductance values among springs in a given area can also influence discharge rates to the springs relative to one another. Larger *css* values are consistent with an expectedly influential role of this parameter group. The *css* value of the k3x parameter group was nearly as large as that of the sc group, which again illustrates the importance of this parameter group in determining spatial patterns of groundwater flow within the Floridan aquifer system.

Uncertainty Analysis

A parameter and predictive uncertainty analysis was conducted to quantify the uncertainty of calibrated model parameters and simulated key model predictions. Although the sensitivity analysis was useful to assess the influence of observations and parameters on each other, additional analyses are required to estimate the uncertainties of the parameter estimates obtained from the model calibration and the model predictions made from model simulations

The overall approach for the uncertainty analysis included a nonlinear uncertainty analysis, like that described in Sepulveda and Doherty (2015), in which a set of random, calibration-constrained parameter datasets (called realizations) were generated and used to estimate uncertainty of parameters and predictions of interest. The analysis consisted of two main components; (1) an initial linear analysis; and (2) a nonlinear analysis for estimating the uncertainty of parameters and model predictions.

The initial linear analysis was performed to generate estimates of pre-calibration parameter and prediction uncertainty and initial estimates of post-calibration parameter and prediction uncertainty. This helped assess the improvement in the predictive capabilities and original parameter estimates. The objective of the nonlinear analysis was to estimate the uncertainty of model parameters and a set of key model predictions by generating many different calibration-constrained model parameter datasets.

The analysis used an approach that does not depend exclusively on an assumption of model linearity. The analysis employed a process to generate calibration-constrained parameter sets and included: (1) random generation of parameter datasets by sampling the post-calibration parameter distribution estimated from the initial linear analysis; and (2) retaining parameter datasets that produced calibration statistics like those from calibrated parameters. The results of the uncertainty analyses subtasks are described below with additional details presented in Appendix L.

Parameter Uncertainty Analysis Results

A total of 522 reasonable sets of parameters were generated as part of the NFSEG uncertainty analysis, each of which fit the observation dataset used in the calibration almost as well as the calibrated model did. Therefore, they represent other possible versions of the NFSEG model which could be developed through model calibration. The uncertainties of model parameters were estimated by calculating the standard deviation of the parameter values from these 522 parameter sets. Parameter uncertainties can also be expressed using histograms and estimated probability distributions, and with maps of standard deviations or related variables. Examples of these are presented in Appendix L, which provides a detailed description of the methods and results of the uncertainty analysis.

To facilitate comparison of parameter uncertainty across model layers and among different parameter types, coefficients of variation were used to illustrate the range of parameter uncertainty within and between parameter groups (Figure 7-11). Among the vertical anisotropy parameters (vanis), only the layer 3 vertical anisotropy parameter was included because that is the only vertical anisotropy parameter spatially varying within the model domain. Coefficient of variation is a measure of uncertainty and is calculated here by dividing the parameter standard deviation by the estimated mean parameter value Model parameters with high coefficients of variation relative to the other parameters indicate the uncertainty (as a fraction of the estimated mean parameter value) is higher for that parameter. The range of coefficient of variation values for each parameter group is shown using boxplots, which summarize the 25th percentile, medium, 75th percentile, as well as values occurring beyond the 25th and 75th percentiles.

When compared across model layers, as shown in Figure 7-11, the coefficient of variation boxplots indicated that uncertainty is generally similar for hydraulic conductivity values of layers 1 through 3. The uncertainty is highest for hydraulic conductivity values for layers 6 and 7. This is not unexpected because there were not many observations available for calibration of model parameters in these layers. The median coefficient of variation for layer 5 hydraulic conductivity is larger than values for layers 1 through 4, but smaller than layers 6 and 7. The number of observations in layer 5 available for model calibration was more than those in layers 6 and 7 but less than those in layers 1 and 3. The lake conductance parameter group had the highest uncertainty. Recharge and maximum saturated ET multipliers appear to be the parameters with the lowest uncertainty.

The length of the boxplot is equal to the interquartile range, and longer boxplots indicates more variability in the uncertainty within the parameter group. Thus, the lkzmul parameters that were used to adjust the vertical hydraulic conductivity of layer 2 underneath the lakes appear to have the largest variability in uncertainty.

Predictive Uncertainty Analysis Results

The objective of the nonlinear uncertainty analysis was to assess the uncertainty of predicted values of groundwater levels and flows for a hypothetical 2035 pumping scenario, as well as the predicted change in groundwater flows and levels (differences) from 2009 to 2035 at a representative set of locations (Figure 7-12). At each location, a predicted value was generated for each of the 522 sets of parameters described previously. The uncertainty of each prediction was summarized by plotting histograms and computing standard deviations from the set of predictive values generated by simulating 2035 withdrawal conditions with the 522 sets of parameters.

Figure 7-13 shows the range of predicted drawdown in the Upper Floridan aquifer level near Lake Brooklyn resulting from the simulations performed using 522 different sets of parameters. As shown in the figure, when the same 2009 and 2035 pumping conditions were simulated using 522 different sets of parameters, the predicted UFA drawdown near Lake Brooklyn due to change in pumping from 2009 to 2035 was generally between 1.7 and 1.95 feet. The uncertainty (expressed as standard deviation) for this prediction was estimated at 0.05 feet.

Figure 7-14 shows the range of predicted flow reductions from 2009 to 2035 in the Santa Fe River near Fort White resulting from the simulations performed using 522 different sets of parameters. As shown in the figure, when the same 2009 and 2035 pumping conditions were simulated using 522 different sets of parameters, the predicted flow reduction in the Santa Fe River near Forth White due to change in pumping from 2009 to 2035 was generally between 14.5 and 17 cfs. The uncertainty (expressed as standard deviation) for this prediction was estimated at 0.77 cfs.

Appendix L includes the uncertainty estimates at all 48 selected prediction locations. The uncertainty estimates of the predicted differences (drawdown and flow reduction) are much smaller than the uncertainty estimate of absolute values of predicted groundwater levels and spring and river flows. This is consistent with the expectation that the model performs better at predicting the differences than absolute values of groundwater levels and flows. As discussed in Appendix L in detail, predictive errors potentially resulting from model approximation of the real system will tend to cancel when predictive differences are computed. It should also be noted that NFSEG v1.1 will mostly be used to predict differences rather than absolute values.

8. MODEL LIMITATIONS

The NFSEG model was designed to evaluate inter- and intra-district and interstate changes in groundwater levels, spring flows, and river baseflows in the surficial and Floridan aquifer systems resulting from groundwater use within the model domain. Towards that goal, the model development included a wide variety of observation types, including groundwater levels, differences in groundwater levels between adjacent points within zone 1 (i.e., horizontal-head differences within layer 3), differences in groundwater levels across the intermediate confining unit and zone 2 (i.e., vertical-head differences across layers 2 and 4), spring flows, and river baseflows. The results of the model development indicate that the model can be used for sub-regional and local-scale evaluations with the same level of accuracy as existing regional-scale models, including assessment of changes in groundwater levels and flows in the surficial and Floridan aquifer systems.

Limitations of the NFSEGv1.1 model are like those of other regional groundwater flow models and are typically related to approximations or simplifications that are necessary for development of large regional groundwater models. Generalizations of the groundwater hydrology system and approximations due to data availability or quality are examples of simplifications. These approximations or simplifications do not prevent the application of the NFSEGv1.1 model for its intended uses. A description of limitations that should be considered during application of the model are described below.

One limitation that is inherent to all regional groundwater models is grid-cell size. Grid-cell size limits the degree of resolution in the representation of simulated groundwater-level and drawdown distributions, as only one value is determined per grid cell. This type of limitation should be considered when simulating groundwater levels in areas with significant variability in the water table of the surficial aquifer system or potentiometric surface of the Floridan aquifer system over distances smaller than those of individual grid cells. Grid-cell size also limits the degree of resolution of input parameters such as horizontal hydraulic conductivity, as only one value can be assigned per grid cell. However, NFSEG individual grid cells are relatively small (0.224 square miles) given the 60,000 square miles model domain; and their size is comparable to or better than other existing groundwater models.

The NFSEG model simulates a single groundwater level representing a vertical average of the units that constitute the surficial aquifer system, rather than a vertical distribution of groundwater levels. Representation of the surficial aquifer system as a single layer may be an additional model limitation because this assumes that groundwater levels within the surficial aquifer system do not vary vertically. It is not common to represent the surficial aquifer system with this level of detail in regional models and the hydrogeologic information necessary for delineation of vertical differences is typically not available except at local scales. This should be considered when applying the model to evaluate more local surficial aquifer level changes.

A similar generalization is utilized in the simulation of the intermediate confining unit, which is represented in the NFSEG model as a single layer (layer 2). A single groundwater level that represents a vertical average across the vertical extent of the intermediate confining unit is simulated rather than a vertical distribution of groundwater levels, which means local aquifers that may exist within the intermediate confining unit/aquifer system are not represented explicitly in the NFSEG groundwater model. Therefore, the NFSEG model is not intended to evaluate the effects of pumping from intermediate aquifers.

The NFSEG model represents the groundwater system as steady state, whereas in the actual groundwater system, levels and flows fluctuate continuously with time. The assumption of steady state conditions may affect the calibration, as changes in storage are assumed to be negligible. For this reason, the calibration years, 2001 and 2009, were selected with consideration of groundwater level stability. As a result. no storage parameters were estimated through calibration. Therefore, NFSEG model is intended to be used primarily for steady state evaluation of changes in groundwater levels, spring flows, and river baseflows in the surficial and Floridan aquifer systems. The model should not be used for transient phenomenon, such as short-term climatic events, replication of aquifer performance tests, etc.

The representation of the groundwater flow system is limited to that of the freshwater groundwater flow system in the NFSEG model. The model assumes the location of freshwater boundaries are fixed, and it is not intended to simulate variable density flow.

As noted in Kuniansky, 2016, properly conceptualized single-continuum porous-equivalent (SCPE) models are adequate for simulation of the Floridan aquifer system to address water-supply problems involving monthly or annual conditions, even in regions with well-defined conduit networks, such as in the Woodville Karst Plain/Wakulla Springs region. More complex models incorporating conduit systems are required for shorter term simulations, such as replicating spring discharge from a single storm event. Being an SCPE model, solution features such as conduits that occur near springs that discharge from the Floridan aquifer system are not explicitly represented in the NFSEG model. This may limit the use of the NFSEG model in determining travel times of solutes in karstic areas of the Floridan aquifer system. This limitation may not be as influential in confined areas of the Floridan aquifer system, where solution features may be less prevalent.

The effects of lateral boundaries may limit the accuracy of model results near lateral boundaries. In the case of no-flow lateral boundaries that do not represent physical boundaries, simulated changes in groundwater levels in response to increases in groundwater withdrawals may be overestimated near these boundaries. In the case of GHB lateral boundaries, simulated changes in groundwater levels in response to increases in groundwater withdrawals may be underestimated near these boundaries.

9. Summary and Conclusions

The NFSEG model was developed through a collaborative effort over several years among a technical team of experts from SJRWMD, SRWMD, SWFWMD, and stakeholders from water utilities, private industry, governmental organizations, and environmental groups. The technical team's directive was to ensure appropriate science is applied to the modeling and data analysis to support decision making, and that the work completed is defensible, understood by the team, and collaboratively developed, as described in the Partnership's charter, which is available at northfloridawater.com. The model was designed to be a tool that can be used to evaluate inter-district and inter-state groundwater pumping impacts, as well as within district impacts. A primary function of the NFSEG model is to simulate the regional effects of pumping on groundwater levels, stream base flows, and spring flows. Intended applications of the model include evaluations of proposed consumptive use permits, support of analyses of minimum flows and levels, and water supply planning.

The NFSEG model covers about 60,000 square miles, encompassing a large area of the Floridan aquifer system in north Florida, Georgia, and South Carolina (Figure 1-1). Land surface elevations range from sea level to more than 450 feet, NAVD88 in northern Georgia. The area includes hundreds of streams, rivers, lakes and more than 300 springs. The model is fully three-dimensional and steady-state and has been calibrated to hydrologic conditions of 2001 and 2009. The model consists of seven aquifer layers that represent, from top to bottom, the surficial aquifer system, the intermediate confining unit, the Upper Floridan aquifer, the middle semiconfining unit, the upper zone of the Lower Floridan aquifer, the lower semiconfining unit, and the Fernandina Permeable zone of the Lower Floridan aquifer, where these hydrogeologic units are present.

The model development process included delineation of the model domain, a listing of necessary data and a plan for attainment of the data, a plan for the model configuration, including an approach to model layering, lateral boundary conditions, internal boundary conditions, selection of calibration periods, and the calibration process. Two of the more important water budget components are recharge and maximum saturated evapotranspiration (MSET). To improve estimates of recharge and MSET for groundwater model input, surface water hydrology for all the surface water basins within the groundwater model boundary were simulated using the Hydrological Simulation Program—FORTRAN (HSPF) software (Bicknell et al. 2001). HSPF is a comprehensive, rainfall-runoff-water-quality model. Calibration of HPSF models to observed surface water flows represents a significant improvement in estimation of recharge and MSET over the previous Soil Conservation Service (SCS) curve number model and approach. The SCS model does not track evaporation and infiltration which are important components of the surface water balance. Based on the nonlinear uncertainty analysis, recharge and maximum saturated ET multipliers appear to be the parameters with the lowest uncertainty. This could be because both recharge and maximum saturated ET values were obtained from HSPF models which were also calibrated using many observations.

The NFSEG model encompasses all or parts of seven large and diverse groundwater basins. The hydrogeology of much of the area is extremely complex because of its karstic nature. For example, the area contains numerous closed basins, direct stream to sink discharges, as well as more than 300 springs, which are a major source of groundwater discharge in key areas of the model domain. Observed groundwater levels in the surficial and Floridan aquifer system range from -50 ft to more than 350 ft NAVD88 in 2009. Areas of groundwater levels that are below sea level occur on the Atlantic coast (near Fernandina Beach, Florida, and Brunswick and Savannah, Georgia) due to intense groundwater withdrawals from the Floridan aquifer system. These areas are characterized by unusually large horizontal gradients of the potentiometric surface of the Upper Floridan aquifer.

The model was calibrated using PEST, a program widely used to facilitate model calibration. The PEST calibration process involved minimizing differences between various types of observations and their model simulated equivalents through adjustment of specified model parameters within defined ranges. Observation types included groundwater levels, differences in vertical and horizontal groundwater levels, spring flows and baseflows. Formal consultation and interactions with the NFSEG technical team, stakeholders, and peer-review panel were conducted throughout the model-development process to avoid potential oversights and inappropriate approaches.

Emphasis of numerous types of calibration targets in addition to groundwater levels supported a more realistic simulation of many different aspects of the groundwater flow system, as over-reliance on groundwater level targets can result in unrealistic estimates of model hydraulic parameters. Inclusion of many observation types serve to lower the uncertainty of parameters to which they are sensitive. Because predictions of interest are also sensitive to these parameters whose uncertainties were reduced by these observations, their uncertainties would have been correspondingly reduced. This was likely partially responsible for the relatively low uncertainties that were associated with most of the predictions (particularly those associated with predictive differences) made by the NFSEG model, as quantified by the nonlinear uncertainty analysis.

The 2001 and 2009 steady state simulations yielded reasonable head and springflow residuals. Although the calibration goals were not fully met, the percentages of the groundwater level residuals within 2.5 and 5 feet, generally indicate a good match between observed and corresponding simulated values. It is important to note that the calibration goals were not intended as absolute requirements but as ambitious goals, as stated in the model-conceptualization report.

Geographic patterns in the transmissivity of layer 3, which represents the Upper Floridan aquifer in areas in which the middle confining unit is present, and upper zone of the Upper Floridan Aquifer elsewhere, are consistent with expected patterns based on the hydrology and hydrogeology of the model domain. For example, model calibrated values of transmissivity are low in the areas with expected low transmissivity in the general area of the Gulf Trough in

Georgia, Mallory Swamp in Lafayette County, Florida, and Waccasassa Flats in Gilchrist and Levy counties, Florida. Similarly, model calibrated values of transmissivity are high in the areas where high transmissivity values are expected, including the Rainbow and Silver springs basins, the Suwannee River corridor, the Santa Fe River Basin, including areas near the Ichetucknee River and High Springs Gap physiographic region, and the Woodville Karst Plain. Comparisons to the results of APTs are generally within an order of magnitude in confined areas of the Floridan aquifer system. In unconfined areas of the Floridan aquifer system, the comparison is somewhat less favorable, but this may be due at least partially to complications associated with the karstic nature of the flow system in these areas (e.g., APTs may considerably underestimate hydraulic conductivity values if the pumping well does not penetrate a conduit system). The leakance of layer 2, which represents the intermediate confining unit where it is present, is generally high in areas in which the intermediate confining unit is thin or absent and relatively low where it is present, as expected. Therefore, the results of the calibration with respect to the transmissivity distribution of the Upper Floridan aquifer and leakance of the intermediate confining unit appear to be generally reasonable.

The simulation of groundwater flow for the year 2010 was conducted as a verification run, as the model was not calibrated to 2010 conditions. Comparisons of simulated and observed groundwater levels and flows indicated a reasonable correspondence between observed groundwater levels and spring flows. Also, the general configuration of the 2010 simulated potentiometric surface of the Upper Floridan aquifer compared well to that of the observed 2010 potentiometric surface. As stated in section 5 of this report, the results of the 2010 verification simulation are an additional indication of the adequacy of the model calibration.

The pumps off simulation, described in section 5 also, represents another test of the ability of the model to simulate a condition to which it was not calibrated, to a much greater extent than the 2010 result. The results indicate a reasonable comparison to the configuration of the USGS estimated predevelopment potentiometric surface of the Upper Floridan aquifer and to the flows of major springs observed in the early 1930s, a period that preceded widespread development of the Floridan aquifer system in the area. The simulated groundwater levels of the Upper Floridan aquifer were generally lower than the corresponding groundwater levels as shown on the USGS predevelopment potentiometric surface, within about 10 feet in many areas but up to 15 feet in some. According to Johnson et al. (1980), the purpose of the USGS map was not to show precise water level data at specific sites; rather, to show the best estimate of the configuration of the predevelopment potentiometric surface using the best available data at that time. Thus, the results of the pumps-off simulation indicate a reasonable simulation of the change in the configuration of the potentiometric surface in response to the removal of pumping stresses, a condition that represents a major departure from the general conditions to which the NFSEG model was calibrated.

The NFSEG model was calibrated and configured in a manner that is consistent with generally accepted standards to enable reliable fulfillment of its intended uses. In particular, a wide variety of observation types were employed in the development of the model, including observations that are directly and indirectly related to the head and flow predictions of interest. The differences between groundwater levels and their model-simulated equivalents were consistent with the goals specified at the outset of the project. In addition, predictive uncertainty analyses indicate that model may be capable of simulating changes in flows and groundwater levels with an accuracy that is comparable to or better than models currently used for planning or regulatory purposes. The uncertainty analyses also indicate that the model performs better at predicting the differences than absolute values of groundwater levels and flows, which could be mainly because predictive errors potentially resulting from model approximation of real system will tend to cancel when predictive differences are computed. It should also be noted that NFSEG v1.1 will mostly be used to predict differences rather than absolute values.

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Appendix A - Groundwater Levels 2001 and 2009

APPENDIX B - VERTICAL HEAD DIFFERENCES 2001 AND 2009

APPENDIX C - COMPILATION OF PRIMARY GROUNDWATER LEVEL DATA SET

APPENDIX D - EXTINCTION DEPTH DETERMINATION

APPENDIX E - SPRINGS DATA 2001 AND 2009

APPENDIX F – BASEFLOW PICK-UP ESTIMATES 2001 AND 2009

APPENDIX G - UPDATES TO RIVERS AND SPRING STAGES

APPENDIX H – HORIZONTAL HEAD DIFFERENCES 2001 AND 2009

APPENDIX I – OBSERVED GROUNDWATER LEVELS 2010

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APPENDIX J – SPRINGS DATA 2010

APPENDIX K – BASEFLOW PICK-UP ESTIMATES 2010

APPENDIX L – UNCERTAINTY ANALYSIS