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Construction and Calibration of the Eastern District Regional Groundwater Flow Model

Version 1.0

Northwest Florida Water Management District
81 Water Management Drive
Havana, Florida 32333
(850) 539-5999
www.nwfwater.com

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NORTHWEST FLORIDA WATER MANAGEMENT DISTRICT

DISTRICT OFFICES

Havana (Headquarters)
DeFuniak Springs
Youngstown
Milton

For additional information, write or call:

Northwest Florida Water Management District
81 Water Management Drive
Havana, Florida 32333-4712
(850) 539-5999
www.nwfwater.com

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Primary Authors:

Kathleen Coates, P.E., Tony Countryman, P.G., and James Sutton

External Contractors:

Tetra Tech, Inc., INTERA, and Taylor Engineer (formerly Interflow Engineering, LLC)

Editorial and Supporting Contributions:

Carlos Herd, P.G., Ken Friedman, Katie Price, Beth Hollister, Shawn Halphen, and Karen Kebart

Supporting contributions from current and prior staff of the St. Johns River Water Management District and Suwannee River Water Management Districts:

Douglas Durden, P.E., Tim Cera, P.E., Fatih Gordu, P.E., Trey Grubbs, Douglas Hearn, P.G.,
Tammy Bader, Jacy Crosby, Yassert Gonzalez, and Jill Stokes

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Abbreviations and Acronyms

DEM	Digital Elevation Model
DRN	Drain Boundary (MODFLOW-NWT Package)
EDM	Eastern District Model
ET	Evapotranspiration
Ft/d	Feet Per Day
Ft^2/d	Feet Squared Per Day
Ft^3/d	Feet Cubed Per Day
FGS	Florida Geological Survey
GHB	General Head boundary (MODFLOW-NWT Package)
HSPF	Hydrologic Simulation Program-Fortran
MAE	Mean Absolute Error
ME	Mean Error
MGD	Million Gallons Per Day
Mg/L	Milligrams Per Liter
MODFLOW	Modular Three-dimensional Finite-difference Groundwater Flow Model
NAVD 88	North American Vertical Datum of 1988
NFSEG	North Florida-Southeast Georgia model
NWFWMD	Northwest Florida Water Management District
RMSE	Root Mean Squared Error
RIV	River Boundary (MODFLOW-NWT Package)
SJRWMD	St. Johns River Water Management District
SRWMD	Suwannee River Water Management District
USGS	U.S. Geological Survey
WELL	Well (MODFLOW-NWT Package)

Executive Summary

A steady-state groundwater flow model was developed to support regional water supply planning, minimum flows and minimum water levels, and water use permitting evaluations for waterbodies in the eastern portion of the Northwest Florida Water Management District (District or NWFWMD). This report documents the work performed to date to construct and calibrate the Eastern District Model (EDM), version 1.0. The work reflects the combined effort of District staff and external contractors. Datasets developed by the St. Johns River Water Management District (SJRWMD), Suwannee River Water Management District, Florida Geological Survey, and U.S. Geological Survey were also utilized to construct the model.

The model area encompasses approximately 8,874 square miles and includes the eastern Northwest Florida Water Management District, part of the Suwannee River Water Management District (SRWMD), and all or parts of 12 counties in southwest Georgia (Figure 1). Predominant land uses in the model area are mixed forest (41.5%), row crops and pastures (22%) and forested wetlands (19.3%). Urban and developed lands comprise less than 7% of the model domain.

The EDM is fully three-dimensional and includes five layers that collectively represent the surficial aquifer system, the intermediate confining unit (or intermediate aquifer system), and the freshwater portion of the Floridan aquifer system. The Floridan aquifer is discretized into three geologic units representing permeable Miocene-age limestone formations, Oligocene-age limestone formations, and the Ocala Limestone. Only the freshwater portion of the Floridan aquifer is simulated where total dissolved solids are estimated to be less than 10,000 milligrams per liter (mg/L). The thickness of the freshwater portion of Floridan aquifer system ranges from less than 50 feet to more than 600 feet across the model area.

The groundwater flow system is modeled using the U.S. Geological Survey's (USGS) MODFLOW-NWT code, a finite-difference model that simulates laminar flow in the saturated portion of the aquifer. The EDM consists of 350 rows, 200 columns, and five layers comprising 182,499 active cells. The EDM uses a uniform grid cell size of 2,500 feet by 2,500 feet. The grid is oriented slightly northeast to southwest, parallel to the primary direction of groundwater flow in the Floridan aquifer. Lateral boundaries were selected to correspond with physical features, where possible. Model datasets were developed for three steady-state periods that represent hydrologic conditions and pumping stresses under average (2009), dry (2011), and wet (2014) conditions in the NWFWMD. The goal of simultaneously calibrating three differing steady-state models is to achieve a robust set of model parameters with the capability to simulate heads and fluxes across varying hydrologic and pumping conditions.

Model layer elevations were developed following an extensive compilation and evaluation of hydrogeologic data from multiple sources including geophysical logs, lithologic and hydrostratigraphic interpretations, drillers and geologists logs, and District databases. Data were used to develop raster surfaces of the elevations of the tops and bottoms of geologic units. Layer elevations were adjusted, where needed, to provide a minimum thickness of 10 feet. A digital elevation model (DEM) of land surface was developed to assign elevations to the uppermost active model layer. After all layer elevations were assigned, the bottom of the model was truncated to the base of the freshwater zone, based on the depth to the 10,000 mg/L total dissolved solids (TDS) surface.

The EDM simulates recharge, swallet inflows, evapotranspiration from the saturated zone, groundwater withdrawals, spring discharge, and the exchange of water between the groundwater system and lakes, perennial and intermittent streams, coastal wetlands, and the Gulf of Mexico. Recharge rates are predominantly a function of precipitation, topography, land cover, soils and geologic conditions and vary among years. Precipitation generally increases from north to south across the model domain, ranging from an average of approximately 48 inches per year in Worth County to 62 inches per year in Leon County. Recharge is applied to the uppermost active cells. Spatially distributed recharge estimates provided by SJRWMD were used as initial values. Recharge rates were subsequently modified and adjusted during the calibration process.

Total evapotranspiration (ET) ranges from approximately 36 to 42 inches per year (Bush and Johnston, 1988; Davis, 1996) and averages approximately 39 inches per year in the EDM domain (Interflow Engineering, 2015). Part of the total evapotranspiration occurs from the shallow plant root zone and the remainder occurs from the saturated (i.e. groundwater) zone. The model simulates the ET from the saturated zone. Similar to recharge, groundwater ET is a function of climate, land cover, and soil conditions and is applied to the uppermost active cells. Groundwater ET varies linearly from a maximum rate when aquifer levels are at land surface to zero when aquifer levels are at the “extinction depth.” SJRWMD provided extinction depths and estimates of maximum saturated ET rates based on output from surface water models. Maximum saturated ET rates were subsequently modified by the District and adjusted during the calibration process.

Swallets are karst features where the underlying aquifer can receive surface water inflows and act as a location for point recharge. There several streams in Leon and Wakulla counties which discharge to swallets. Swallets represented in the model include the Lost Creek swallet, Fisher Creek swallet, Ames Sink, Black Creek swallet, Patty Sink, Bird Sink, and others. Swallet inflows were estimated based on field discharge measurements and output from surface water models.

The model simulates inflows from and baseflow to perennial rivers including the Apalachicola, New, Flint, Ochlockonee, Sopchoppy, Little, Wakulla, St. Marks, Aucilla, and Okapilco Creek. Perennial river reaches are represented with a specified stage during each calibration year. Each river reach either gains water from or lose waters to the groundwater system depending on the difference between the stream stage and aquifer levels and the characteristics of the streambed materials. Intermittent stream reaches periodically go dry and are simulated as receiving baseflow when aquifer levels exceed stream elevations. Stream reach delineation and attributes were derived from The National Hydrography Dataset Plus, Version 2 (McKay et al. 2012) and District data and surface water models.

A total of 55 lakes are represented in the model. Large systems include Lake Seminole, Lake Talquin, Lake Jackson, Lake Iamonia, Lake Miccosukee, and the Lake Lafayette system. The model simulates the exchange of water between each lake and the groundwater system via leakage through the lakebed materials.

Springs are significant regional groundwater discharge features in the model. Four first-magnitude springs are included: Wakulla Spring, St. Marks River Rise, Spring Creek Spring Group, and the Wacissa Spring Group. The combined average annual discharge of these four spring systems exceeded 1.1 billion gallons per day in 2009. The model also includes four second and 13 third magnitude springs or spring groups. Modeled spring pool elevations are based on the best available data. Coastal wetlands also are represented in the model as aquifer discharge features.

Groundwater withdrawals occur throughout the model area. Pumpage data was compiled from multiple sources including District databases, the USGS, and the SJRWMD. Well construction and location information were used, where available, to assign pumpage to specific grid cells and model layers. The predominant use categories in the EDM are public supply and agriculture. Additional uses include commercial, industrial, power generation, domestic self-supply, and recreation and landscape irrigation. Groundwater withdrawals totaled 323 mgd in 2009, with 80% of the pumpage occurring in Georgia. Groundwater pumpage in the Georgia portion of the model domain totaled 260 million gallons per day (mgd) in 2009, of which 86% (223 mgd) was used for agriculture. Groundwater pumpage in the Florida portion of the model domain totaled approximately 63 mgd in 2009, with public supply being the largest use category (41 mgd).

Model datasets were calibrated for three steady-state periods: 2009, 2011, and 2014. Parameter optimization software was used to determine the set of model parameters that best matched calibration targets that included observed aquifer levels, vertical head differences, horizontal head gradients, spring flows and river baseflows for each of the three calibration years. Calibration targets were developed using data from multiple sources including District databases and the USGS. Weights assigned to targets were adjusted during the calibration process to achieve calibration metrics. A pilot point approach was used during calibration to estimate and adjust spatially varying horizontal hydraulic conductivities and anisotropy ratios. Recharge, maximum saturated ET, and streambed conductances were calibrated using 49 watershed zones. The number of adjustable model parameters totaled 1,043.

The calibrated models (i.e., 2009, 2011, and 2014) met target metrics for aquifer levels, river baseflows, and spring flow, except at Chicken Branch Spring, which had only a single discharge measurement. The resultant mass balance indicates that the largest inputs to the groundwater systems model are inflows from streams, recharge, inflows from general head boundaries, and swallet inflows (represented with the Well Package) (Table 13). The largest outflows from the model are discharge to stream features (e.g. baseflow), discharge to springs and intermittent streams, followed groundwater ET, and pumpage.

Calibrated transmissivities for the surficial aquifer range from less than 200 feet squared per day (ft^2/d) to approximately 20,000 ft^2/d. Calibrated transmissivities in the surficial aquifer are largest in northern Leon and southern Grady Counties and western Gadsden and Liberty Counties. Calibrated leakance values for the intermediate system range from $3x10^{-9}$ per day to approximately 1.0 per day. As expected, the lowest leakance values occur in the Apalachicola Embayment region. The highest leakance values occur along the Cody Scarp where the confining unit pinches out. The Miocene-age limestone formation, calibrated transmissivities range from approximately 160 ft^2/d to approximately 350,000 ft^2/d (Figure 35). The largest transmissivities are generally located in the Woodville Karst Plain, extending from southern Wakulla County through central Leon County. The lowest transmissivities for Miocene-age limestone formations are generally coincident with the Apalachicola Embayment region. Calibrated transmissivities for the Oligocene-age limestone formations (e.g. Suwannee Limestone) range from approximately 1,500 ft^2/d to approximately 2,000,000 ft^2/d. Lower transmissivities are generally located within the Embayment region. The highest transmissivities are located within or near the Woodville Karst Plain. These results are generally consistent with the conceptual model of the Floridan aquifer and prior modeling studies. Calibrated transmissivities within the Ocala Limestone range from approximately 900 ft^2/d to approximately 5,000,000 ft^2/d. The distribution of transmissivity values are general consistent with the conceptual model with the lowest calibrated transmissivities occurring in the Embayment region and largest transmissivities occurring in the Woodville Karst Plain near the Wacissa River Spring Group.

Calibrated recharge rates are spatially variable and range from 0.04 inches per year (in/yr) to approximately 42 in/yr for year 2009 (average conditions). Calibrated groundwater evapotranspiration rates for 2009 range from approximately 0.04 in/yr to approximately 30 in/yr. Parameter sensitivity analysis revealed that the vertical hydraulic conductivities of lakebed sediments are the most sensitive model parameters, with Lake Seminole, Lake Talquin, and Lake Miccosukee having the highest mean absolute sensitivities. A Monte Carlo analysis was performed to assess the impact of parameter uncertainty on simulated spring flows and river baseflows at select locations. The results indicate that lower discharge (i.e. <100 ft^3/s) springs have greater relative predictive uncertainties in the simulated spring flows than higher (>100 ft^3/s) discharge springs.

The most important calibration targets – heads, baseflows, and spring flows – generally met or exceeded the desired goals indicating that the EDM is a suitable tool to simulate the effects of average annual groundwater withdrawals on Floridan aquifer levels, spring discharge, and stream baseflow under average (2009), dry (2011), and wet (2014) hydrologic conditions. The model can also simulate the long-term average effects of groundwater withdrawals using projected pumpage for future years. However, numerical groundwater models are generally more accurate at simulating changes in heads and flows than simulating absolute values of heads or flows. Due to the limited data available for calibration, further testing is needed to determine the usefulness of the model to simulate changes in surficial aquifer levels.

Because the model is steady-state, it does not simulate changes in storage or hydrologic responses on a short time scales such as daily or weekly. The model does not simulate contaminant transport processes in karst areas, which may be influenced by local-scale aquifer heterogeneity including conduit flow processes and turbulent flow conditions. The model assumes constant water temperature and density and therefore does not simulate density-dependent flow or saltwater movement near the coast. As with any groundwater flow model, there are uncertainties in parameter estimates and simulated values. Refinement of the EDM is ongoing, with further revisions planned during 2019.

Introduction and Purpose

Regional groundwater flow models are useful tools for evaluating the effects of water withdrawals and other changing stresses on aquifer levels, spring flows, and river baseflows. The purpose of this effort was to develop a steady-state groundwater flow model to support regional water supply planning, minimum flows and minimum water levels evaluations, and water use permitting in the eastern portion of the Northwest Florida Water Management District (District). The model encompasses approximately 8,874 square miles and includes parts of the Northwest Florida Water Management District, Suwannee River Water Management District (SRWMD), and all or parts of 12 counties in southwest Georgia (Figure 1).

The spatial extent of the model domain was selected to include the estimated groundwater contribution areas for Wakulla Spring and the St. Marks River Rise, which extend into southwest Georgia. Model boundaries were extended beyond these groundwater contribution areas and are aligned with natural groundwater divides and physical features where possible. The Eastern District Model (EDM) is a fully three-dimensional model that includes five layers. These layers collectively represent the surficial aquifer system, the intermediate confining unit (or the intermediate aquifer system), and the freshwater portion of the Floridan aquifer system.

The groundwater flow system is modeled using the U.S. Geological Survey MODFLOW code, which is a finite-difference model that simulates laminar flow in the saturated portion of the aquifer. The model simulates recharge, swallet inflows, evapotranspiration from the saturated zone, groundwater withdrawals, spring discharge, and the exchange of water between the groundwater system and lakes, perennial and intermittent streams, coastal wetlands, and the Gulf of Mexico. Models and associated datasets were developed for three steady-state periods representing hydrologic conditions and pumping stresses under average (2009), dry (2011), and wet (2014) conditions.

This report documents the work performed to date to construct and calibrate version 1.0 of the Eastern District Model (EDM). The work reflects the combined effort of District staff and external contractors. Datasets developed by the St. Johns River Water Management District, Suwannee River Water Management District, Florida Geological Survey, and U.S. Geological Survey were also utilized, including datasets from the North Florida-Southeast Georgia (NFSEG) model. Work performed by contractors is summarized herein and additional documentation is provided in the appendices.

Previous Models

Prior regional scale groundwater flow modeling efforts that encompass the study area include investigations by Bush and Johnston (1988), Davis (1996), Davis and Katz (2007), and Durden et al. (2018). Smaller, sub-regional models developed in this area include work by Davis et al. (2011), Gallegos et al. (2013), and Xu et al. (2015), which were primarily focused on investigating smaller-scale flow dynamics of the Wakulla Spring system while explicitly representing flow through conduits.

Bush and Johnston (1988) developed a four layer aquifer-wide quasi-three-dimensional, steady-state, finite difference groundwater flow model to evaluate regional scale flow and the effects of groundwater withdrawals and to estimate pre-development conditions of the Floridan aquifer system. The Bush and Johnston model used a grid cell size of 8 miles by 8 miles versus the grid cell size used in the EDM which is 2,500 feet by 2,500 feet. Model calibrated transmissivities from this study in the EDM domain range from less than 10,000 feet squared per day (ft^2/d) in the Apalachicola Embayment region to greater than 1,000,000 ft^2/d in most of Wakulla, Leon and Thomas counties. The simulated hydrostratigraphic units included the upper and lower Floridan aquifers, where differentiated.

Davis (1996) developed a three layer, quasi-three-dimensional, steady-state MODFLOW model with a model domain that roughly coincides with the boundaries of the EDM. The model was developed to identify well capture zones for the City of Tallahassee and corresponding travel times estimated by subsequent particle tracking simulations. Porosity values of 5 percent and 25 percent for the Floridan aquifer were used for comparison. Capture zones delineated with the calibrated model were compared to those determined analytically. Davis simulated flow in the Floridan aquifer using two layers with the combined calibrated transmissivity ranging from less than 5,000 ft^2/d in the Apalachicola Embayment to greater than 10,000,000 ft^2/d in Leon and Wakulla counties.

Davis (2007) developed a revised four layer, fully three-dimensional, steady-state MODFLOW model based on previous work (Davis 1996). The purpose of the modeling effort was to expand on the previous effort of identifying well capture zones for City of Tallahassee production wells. The study also used water quality data collected from several of the water supply wells to estimate apparent groundwater age. Groundwater age estimates were used in combination with the flow model and particle tracking to determine an effective porosity for the upper confining unit and Floridan aquifer. The calibrated hydraulic conductivity of the Floridan aquifer ranges from less than 3 feet per day (ft/d) in the Apalachicola Embayment to greater than 15,000 ft/d in Thomas and Colquitt counties in Georgia.

The North Florida – Southeast Georgia (NFSEG) model (Durden et al. 2018) is a seven layer, fully three-dimensional, steady-state MODFLOW-NWT model that simulates groundwater flow in north Florida, southern Georgia, and western South Carolina. The model was primarily developed as a larger scale water supply planning tool, but with enough grid refinement to be used as a tool for minimum flows and minimum water level evaluations. Calibrated transmissivity values from the NFSEG study within the EDM domain range from less than 1,000 ft^2/d in the Apalachicola Embayment to greater than 10,000,000 ft^2/d in parts of Wakulla, Leon, and Jefferson counties.

Description of Model Area

A preliminary report describing the EDM area and conceptual model was prepared by Interflow Engineering, LLC (2015) (Appendix A). The Interflow report details the physiography, hydrogeology, and provides preliminary conceptual water budgets for the groundwater system within the model domain. An updated overview of topography, hydrogeology, and major inflows to and outflows from the groundwater system is provided below.

Topography, Soils, and Hydrography

Across the model area, land surface elevations range from about 425 feet NAVD 88 at the northern edge of the model domain in Worth County to sea level at the southern coastal boundary. Prominent geologic features include the Apalachicola Embayment – Gulf Trough and the Cody Escarpment (Cody Scarp) (Figure 2. Topography in the EDM Area). The Apalachicola Embayment and its northern extension, the Gulf Trough is a subsurface paleo-marine channel system that is oriented from the southwest to the northeast (Kellam and Gorday 1990). The Apalachicola Embayment extends from Gulf County, Florida through approximately Colquitt County, Georgia, and the narrower Gulf Trough extends from Colquitt County into Toombs and Tattnall counties (Kellam and Gorday 1990). As most of the study area overlaps the Apalachicola Embayment, the system is referred to collectively as the Embayment in this report.

Deposition of clastic materials within the Embayment and subsequent uplift has resulted higher land surface elevations along and southeast of the Embayment in Georgia. Stream networks are well-developed in the Embayment area and soils are well-drained, except along stream channels. Major stream features include the Apalachicola River, portions of the Ochlockonee River, and Telogia Creek. Land surface elevations in this part of the study area generally range from 175 to 340 feet NAVD 88.

The Dougherty Plain is located northwest of the Embayment. This area has rolling topography sloping to the southwest, with land surface elevations ranging from approximately 270 feet NAVD 88 in Mitchell County to 80 feet NAVD 88 near Lake Seminole. The Pelham Escarpment forms the eastern boundary This area contains numerous sinkholes including active sinks where ponds and marshes may form (Clark and Zisa, 1976). There is relatively little surface water drainage except for the Flint River system.

The area encompassed by southern Thomas and Brooks counties and northern Leon, Jefferson, and Madison counties represents a transition area. Land elevations in this area range from approximately 80 to 225 feet NAVD 88, with lower elevations present along the stream channels. Soils are generally well-drained fine sandy loams or fine sands with moderately low runoff potential. Numerous karst features characterize the landscape. Stream networks are moderately well-developed. There are several closed basins with no surface water outflow, where streams discharge directly to the underlying aquifer via swallets. There are also several large lakes in Leon County that were historically shallow prairie lakes including Lake Iamonia and the Lake Lafayette System. Many of these lakes contain sinkhole features.

The east-west trending Cody Scarp serves as a topographic divide that separates an area of greater topographic relief to the north from the flatter Woodville Karst Plain and coastal marshes to the south. Land surface elevations are approximately 100 feet NAVD 88 along the Cody Scarp and decrease to sea level at the coast. The Cody Scarp represents the erosional edge of Hawthorn Group sediments and marks a transition in thickness of overburden and the degree of confinement of the Floridan aquifer. The largest concentration of springs and sinkholes in the model area occurs south of the Cody Scarp where the Floridan aquifer is unconfined. This area includes four first-magnitude springs: Wakulla Spring, the St. Marks River Rise, the Spring Creek Spring Group, and the Wacissa Spring Group. Near Wakulla Spring the soils are well-drained, but are poorly drained in most other areas south of the Cody Scarp. Several intermittent and perennial streams in the Woodville Karst Plain discharge directly to the Floridan aquifer via swallets.

Hydrogeology

There have been several regional hydrogeologic investigations that include the model area. Key studies include work by Miller (1986), Pratt et al. (1996), Davis (1996), Torak and Painter (2006), Torak et al. (2010), Davis et al. (2011), Williams and Dixon (2015), and Williams and Kuniansky (2016). The EDM includes three hydrostratigraphic units: the surficial aquifer system, the intermediate system, and the freshwater portion of the Floridan aquifer system. For this evaluation, the Floridan aquifer is divided into three geologic units based on permeability contrasts between formations of different ages. These units represent the predominately carbonate, geologic formations of late Eocene to middle Miocene age through which the majority of active freshwater flow occurs in the EDM. Nomenclature is based on Miller (1986), Pratt et al. (1996), FGS (2009), and Torak et al. (2010).

In most areas, the surficial aquifer system comprises the uppermost hydrostratigraphic unit. It consists of Holocene to Pliocene-age materials comprising undifferentiated sediments, the Citronelle Formation and where permeable, the upper portion of the Miccosukee Formation. The surficial aquifer is generally absent in the Dougherty Plain and south of the Cody Scarp in Jefferson, Madison, Taylor, and eastern Wakulla County. The surficial aquifer is generally less than 100 feet thick and may be perched in some areas. The thickness of the surficial aquifer is greatest along the Apalachicola Embayment in western Gadsden and Liberty counties, where the thickness can exceed 125 feet. The surficial aquifer is primarily recharged by local precipitation and discharges to local streams, underlying aquifers, and the coast.

The intermediate system is defined as all sediments that collectively retard the exchange of water between the overlying surficial aquifer system and the Floridan aquifer system (Pratt, 1996). Where the intermediate system is predominately comprised of fine-grained clastic deposits, the unit is referred to as the intermediate confining unit. Where these fine-grained deposits are interlayered with carbonate beds and coarser clastic sediments, the unit may serve locally as a minor aquifer and is referred to as the intermediate aquifer system. The convention “intermediate system” is used throughout this report. The intermediate system is comprised of Pliocene-age marls, mollusk-rich sands and sandy limestones of the Jackson Bluff Formation and Intracoastal Formation and Miocene-age, sandy carbonates and clayey sediments of the Hawthorn Group (Rupert and Spencer 1988).

Within the EDM, the intermediate system predominately acts as a confining unit or semi-confining unit that impedes the vertical exchange of water with the underlying Floridan aquifer. The thickness of the intermediate system ranges from less than 20 feet to more than 600 feet. The thickness is greatest along the Embayment in southwest Georgia. Deposition within the Embayment produced a thick sequence of clastic sediments, which are overlain by younger carbonates and clastic sediments (Torak et al. 2010, Williams and Kuniansky 2016). Where the intermediate system is thick, it may include water bearing zones that are used for irrigation and domestic self-supply uses. In the Dougherty Plain and the area north of the Cody Scarp in Leon, Jefferson, and Madison counties, the intermediate system functions as a semi-confining unit and ranges in thickness from less than 20 feet up to about 125 feet. The intermediate system has been eroded away and is absent south of the Cody Scarp in the Woodville Karst Plain.

The intermediate system receives recharge from the overlying surficial aquifer or from direct precipitation where the surficial aquifer is absent. The intermediate system also receives inflow from streams and lakebed leakage. Discharge from the intermediate system aquifer occurs via minor amounts of pumpage, discharge or leakage to the underlying Floridan aquifer system, and discharge to streams, rivers, and the Gulf of Mexico.

The Floridan aquifer is the primary source of water across the model domain and is the principal aquifer of interest in this study. The Floridan aquifer is comprised of limestones and dolostones of late Eocene to middle Miocene age. In order of increasing age, geologic formations comprising the Floridan aquifer in the model area include Miocene-age limestone formations; Oligocene-age limestone formations including the Suwannee Limestone, Byram Formation, and Marianna Limestone; and the late Eocene-age Ocala Limestone.

Where permeable carbonates of Miocene age are in hydraulic connection with older carbonate formations, these formations represent the top of the Floridan aquifer. These units include the St. Marks Formation, Chattahoochee Formation, Tampa Limestone, and Bruce Creek Limestone. The water bearing characteristics of Miocene materials are highly spatially variable. Miocene-age limestone formations comprise the top of the Floridan aquifer in much of the Florida portion of the model area and parts of Brooks, Colquitt, and Cook counties, Georgia (Torak et al. 2010). In Grady and Thomas counties, water bearing zones in the Tampa Limestone supply domestic wells with yields of 1 to 10 gallons per minute (gpm) and 5 to 50 gpm, respectively, reported in these two counties (Sever 1965, Sever 1966). Permeable Miocene-age limestone formations are absent in the Dougherty Plain and southern Taylor County.

The Oligocene-age limestone formations comprise the primary water production zone and are present across most of the model area. In Florida, the Oligocene-age formations represent the Suwannee Limestone. Along the Embayment from Grady through Tift counties, the Suwannee Limestone and Ocala Limestone may be separated by Byram Formation and Marianna Limestone formations that had previously been considered part of the Suwannee Limestone (Torak et al. 2010). Oligocene-age limestone formations pinch out in the Dougherty Plain west of the Pelham Escarpment, in part of Worth County and in Madison and Taylor counties. In these areas, the Ocala Limestone is the uppermost unit in the Floridan aquifer (Kellam and Gorday 1990, Torak and Painter 2006).

The degree of confinement of the Floridan aquifer varies across the model area (Figure 3; adapted from Williams and Dixon, 2015). The Floridan aquifer is well-confined by a thick sequence of materials and is generally less productive along the Embayment. The hydraulic conductivity of the Floridan aquifer within the Embayment is relatively low with little development of secondary porosity and more mineralized groundwater. However, along the southern flanks of the Embayment in southern Colquitt and northern Thomas counties, hydraulic conductivity is higher (Kellam and Gorday 1990). The Floridan aquifer is semiconfined north of the Cody Scarp in Madison, Jefferson, and eastern Leon counties and in southern Thomas and Brooks counties. It may be confined locally in areas of higher elevation. The Floridan aquifer is most productive in karst areas such as the Dougherty Plain and the Woodville Karst Plain. Within these regions there is significant development of secondary porosity due to the dissolution of carbonates.

Only the freshwater portion of the Floridan aquifer is simulated in the model where total dissolved solids are estimated to be less than 10,000 milligrams per liter (mg/L). The thickness of the freshwater portion of Floridan aquifer system ranges from less than 50 feet to more than 600 feet across the model area. The Floridan aquifer occurs at greater depths along the axis of the Embayment and is less productive due to a thick confining unit and lower secondary porosity.

The potentiometric surface of the Floridan aquifer system ranges from more than 210 feet NGVD in the Worth County to sea level at the coast (Figure 4). Groundwater in the Floridan aquifer system generally flows south and discharges to major rivers, springs, and the Gulf of Mexico. The Dougherty Plain is part of a different regional groundwater basin where groundwater generally flows toward and discharges to the Flint River or toward Lake Seminole.

Inflows to and Outflows from the Groundwater System

Inflows to the groundwater system include recharge, groundwater flow from up-gradient areas, swallet inflows, and leakage from streambeds and lakebeds. Precipitation increases from north to south across the model area, ranging from an average of approximately 48 inches per year in Worth County to 62 inches per year in Leon County. Recharge to the groundwater system is a function of precipitation, topography, land cover, and soil conditions and is spatially variable. Recharge can also occur via point inflows at swallets. Swallets are closed depressions or sinkholes that receive water from intermittent or perennial streams and transmit it directly to the groundwater system. Swallets represented in the model include the Lost Creek swallet, Ames Sink, Black Creek swallet, Fisher Creek swallet, Patty Sink, Bird Sink, Copeland Sink, and others (Figure 5). Inflow rates for swallets represented in the model are based on stream discharge measurements taken near swallets or were estimated using surface water models.

Surface water-groundwater exchange is important to the groundwater flow system throughout the model domain. Perennial rivers include the Apalachicola, New, Flint, Ochlockonee, Sopchoppy, Little, Wakulla, St. Marks, Aucilla, and Okapilco Creek. These features either gain water from or lose water to the groundwater system depending on the characteristics of the streambed sediments and relative differences between stream stages and aquifer levels.

There are numerous lakes within the model domain that exchange water with the groundwater system. Several lakes, including Lake Jackson, Lake Iamonia, Lake Miccosukee, and Upper Lake Lafayette have sinkholes that may allow for a more direct connection and increased exchange with underlying aquifers compared to other lakes. Many lakes in the area have also been modified with water control structures that enable surface water inflows or outflows. Surface water inflows and outflows are not explicitly simulated, as lakes are represented in a simplified manner in this groundwater model. The model simulates the exchange of water between each lake and the groundwater system via leakage through the lakebed materials. The rate of lakebed leakage depends on the relative differences between lake stage and aquifer levels and the characteristics of lakebed sediments. Lakes within the District greater than 25 acres in size are included in the model. Data were unavailable regarding the distribution and acreages of lakes in Georgia and only Lake Seminole is included. However, although there are many small stream impoundments, there are few large lakes in the Georgia portion of the study area. In Grady

County, a 960-acre impoundment on Tired Creek, a tributary to the Ochlocknee River, was recently constructed and will be added during subsequent model refinements.

Outflows from the groundwater system occur via evapotranspiration, pumpage, and discharge to streams, coastal wetlands, springs, and the Gulf of Mexico. Similar to recharge, evapotranspiration (ET) is a function of climatic, land cover, and soil conditions. Predominant land uses in the model area are mixed forest (41.5%), row crops and pastures (22%) and forested wetlands (19.3%). Urban and developed lands comprise less than 7% of the model area. Total evapotranspiration is estimated to range from 36 to 42 inches per year (Bush and Johnston, 1988; Davis, 1996) and averages approximately 39 inches per year in the EDM domain (Interflow Engineering, 2015). Part of the total evapotranspiration occurs from the shallow plant root zone and the remainder occurs from the saturated (i.e. groundwater) zone. The model simulates evapotranspiration from the saturated zone (i.e. groundwater ET). The rate of evapotranspiration varies from a maximum rate when the aquifer level is at land surface and decreases to zero at the ET "extinction depth." Similar to recharge, evapotranspiration rates are spatially variable.

Springs represent significant regional groundwater discharge features. Four first-magnitude springs are included in the EDM model area: Wakulla Spring, St. Marks River Rise, Spring Creek Spring Group, and the Wacissa Spring Group. The combined average annual discharge of these four spring systems exceeded 1.1 billion gallons per day in 2009. The rate of spring discharge depends on the relative difference in elevation between the spring pool stage and the aquifer level and is simulated in this model using an equivalent porous media approach. Conduit features are not explicitly represented. Spring pool elevations were available for some first-magnitude springs but were estimated for smaller springs. The model includes four second magnitude springs and 13 third magnitude springs. Numerous smaller springs (4th magnitude and smaller or unclassified) are present in the model area but these features contribute negligible amounts of groundwater and are not explicitly represented. All springs represented in the EDM are located in Florida. There are no known first or second magnitude springs in the Georgia portion of the model area. Intermittent streams within the model domain may also discharge water from the groundwater system. Wetlands located near the coast are also represented in the model as discharge features.

Groundwater withdrawals occur throughout the model area. The predominant use categories are public supply and agriculture. Additional uses include commercial, industrial, power generation, domestic self-supply, and recreation and landscape irrigation. Groundwater withdrawals totaled 323 mgd in 2009, with 80% of the pumpage occurring in Georgia. Groundwater pumpage in the Georgia portion of the model domain totaled 260 million gallons per day (mgd) in 2009, of which 86% (223 mgd) was used for agriculture. Groundwater pumpage in the Florida portion of the model domain totaled approximately 63 mgd in 2009, with public supply being the largest use category (41 mgd).

Model Construction

Calibration Years

A multi-year steady-state model calibration approach was used in the EDM. The intent was to improve parameter estimates by simultaneously matching targets for three steady-state periods representative of average annual wet, dry, and average hydrologic conditions. Several factors were considered when selecting calibration periods. The intent was to select years with minimal changes in storage in the Floridan aquifer, but it was also desired to choose years with varying pumping and recharge stresses. Additionally, options for calibration years were constrained by data availability for features of interest.

Hydrologic conditions were reviewed as well as the availability of pumpage data, groundwater levels and spring flow targets for years from 2000 to 2016. Palmer Drought Severity indices were utilized as a measure of relative hydrologic conditions among years (NOAA 2019). Spring discharge rates and groundwater levels were also used as indicators of hydrologic conditions. Based on the data review, years 2011 and 2014 were selected as dry and wet years, respectively. Year 2009 was selected as the best year for which sufficient data were available and hydrologic conditions were near average. For each calibration period, average annual values for the calendar year were used in the EDM for recharge and ET rates, spring pool and river stages, pumpage, and calibration targets.

Model Code

MODFLOW was developed by the United States Geological Survey as an open source groundwater flow model using a finite-difference numerical approximation to solve the groundwater flow equation. The model is user-friendly in that boundary conditions and their subroutines can be added as “packages” in a modular structure.

The modeling code chosen for use in the EDM is MODFLOW-NWT (Niswonger et al., 2011), a Newton formulation of MODFLOW-2005 (Harbaugh, 2005). MODFLOW-NWT uses an improved solver to address nonlinearities encountered in unconfined groundwater flow problems when cells become dry and rewet during iterations of the finite-difference approximation of the groundwater flow equation. In practice, MODFLOW-NWT enables the EDM to be more numerically stable in areas of the model domain representing unconfined conditions.

While MODFLOW-NWT was primarily chosen for the enhanced numerical stability in unconfined conditions, a secondary consideration was the capability of converting the MODFLOW-NWT model to MODFLOW-2005 which has the flexibility of using the Conduit Flow Processes (CFP) package (Shoemaker et al., (2008)). CFP has the capability of simulating laminar and turbulent flow through a network of pipes, which may be implemented in future versions of the EDM to represent known cave passages or other karst features.

Model Domain, Grid and Units

The EDM was primarily designed to simulate flow in the freshwater portion of the Floridan aquifer and to evaluate impacts of changing stresses to waterbodies of interest. The model domain was selected based on natural no-flow or hydrologic boundaries at a regional scale observed from Floridan-wide potentiometric surface maps. The domain encompasses Leon, Jefferson, Wakulla, Liberty, Gadsden, and portions of Franklin, Taylor, and Madison counties in Florida, as well as, Decatur, Grady, Thomas, Colquitt, Mitchell, and portions of Brooks, Cook, Tift, Worth, Dougherty, Baker, and Miller counties in Georgia. All spatial and hydrologic data associated with the EDM are in units of feet and days. All elevation datasets are in or were converted to a common datum of North American Vertical Datum of 1988 (NAVD 88). The EDM consists of 350 rows, 200 columns, and five layers comprising 182,499 active cells. The EDM uses a uniform grid cell size of 2,500 feet by 2,500 feet representing a maximum extent of approximately 8,874 square miles (layer extents vary). The grid is oriented slightly northeast to southwest, parallel to the principal direction of groundwater flow in the Floridan aquifer.

Model Layers

A fully three-dimensional representation of the groundwater flow system requires the vertical discretization of the model into layers. The five layers in the EDM collectively represent the surficial aquifer, the intermediate system, and the Floridan aquifer. The Floridan aquifer was further discretized into three layers representing separate geologic ages: permeable Miocene-age limestone formations (i.e., St. Marks Formation, Chattahoochee Formation, Tampa Limestone, or Bruce Creek Limestone), Oligocene-age limestone formations (i.e., Suwannee Limestone, Byram Formation, or Marianna Limestone), and the Eocene-age Ocala Limestone (Table 1). Because all units are not spatially continuous across the model domain and MODFLOW-NWT does not allow a middle layer to be absent when there are layers above and below, model layers do not strictly coincide with geologic units. This issue is discussed further under “Use of Hydrogeologic Units to Represent Aquifer Properties.”

Table 1. Eastern District Model Generalized Layer Designations

Period	Series	Geologic Unit(s)	Hydrostratigraphic Unit	Model Layer (where all five layers present)
Quaternary	Holocene Pleistocene	Undifferentiated Sediments, Citronelle Formation, or Miccosukee Formation, where present	Surficial Aquifer System	Layer 1
Tertiary	Pliocene	Hawthorn Group sediments, Intracoastal Formation, or Jackson Bluff Formation, where present	Intermediate System	Layer 2
	Miocene	Uppermost permeable zone in Chattahoochee, St. Marks Formation, or Tampa Limestone (if present and part of Floridan aquifer)	Floridan Aquifer	Layer 3
	Oligocene	Suwannee Limestone, and where present, Marianna Limestone, and Byram Formation		Layer 4
	Eocene	Ocala Limestone		Layer 5
		Lisbon Formation, Tallahatta Formation (Claiborne Group undifferentiated), or Avon Park Formation	Middle or Lower Confining Unit	No Flow Boundary

The vertical discretization of the Floridan aquifer was largely based on a review of aquifer properties and groundwater levels measured in wells open to different geologic units. Differences in aquifer properties and groundwater levels are observed in the Apalachicola Embayment within Florida (e.g. Gadsden and Liberty Counties), where head differences between the Chattahoochee Limestone and the underlying Suwannee Limestone are as great as approximately 40 feet. Near Wakulla Spring, aquifer properties also appear to differ between the St. Marks Formation and the Suwannee Limestone. The Wakulla Spring cave system has been explored revealing extensive development of secondary porosity within the Suwannee Limestone (Rupert 1988). The additional vertical discretization of the Floridan aquifer in the EDM may facilitate future modeling efforts near Wakulla Spring as conduits could be explicitly represented in the Suwannee Limestone layer.

Below the Ocala Limestone within the EDM, the lithology of the middle Eocene-age formations generally transitions from predominately carbonates rocks in the southeast to predominately clastic rocks in the northwest. Spatially discontinuous, low-permeability units exist within these formations and have been mapped as middle and lower confining units of the Florida aquifer system. In addition, mineralized groundwater with TDS concentrations exceeding 10,000 mg/L exist at depth within these formations. Based on these conditions, the base of the active groundwater flow system within the EDM coincides with the bottom of the Ocala Limestone, with some exceptions.

Development of Raster Surfaces

A land surface DEM, raster surfaces of hydrostratigraphic and geologic units, and 10,000 TDS surface were used to discretize model layers and assign layer elevations as described below. Tetra Tech developed the digital elevation model (DEM) of land surface used in this modeling effort. District staff developed raster surfaces of the elevations of the top of the intermediate system and the top of the Floridan aquifer. INTERA developed raster surfaces of the elevations of the top of the Oligocene-age limestone formations and the top and bottom of the Ocala Limestone. The elevation of 10,000 TDS surface developed by the USGS (USGS, 2015) was revised by the District to incorporate local groundwater quality data.

Land Surface DEM

Tetra Tech created a land surface DEM that covers the entire Florida panhandle and southern portions of Alabama and Georgia. The DEM combined the following existing datasets: 1) District 2-meter DEM, 2) southwest Georgia 2-meter DEM, 3) state-wide Florida 10-meter DEM, and 4) USGS 10-meter DEMs covering Alabama and Georgia. All necessary processing, including projecting, clipping, and converting elevation values from meters to feet, was performed on individual datasets before being merged. The final land surface DEM is in NAVD 88 and has a varying spatial resolution of 2 to 10 meters.

Subsurface Rasters

The elevation of the top of intermediate system was interpolated by the District as the first vertically thick and spatially continuous sequence of fine-grained clastic sediments, generally Miocene to Pliocene in age. This typically corresponds to the base of the unconsolidated surficial aquifer system. The elevation of the top of the Floridan aquifer was interpreted by the District as the elevation of first permeable zone within the upper most limestone formation (Miocene or older) that is hydraulically part of the Floridan aquifer. As a result, the top of the Floridan aquifer was not necessarily coincident with the top of the geologic formation or represented by the same geologic unit across the model domain.

Lithologic descriptions and interpretations from the District, USGS, FGS and other WMDs were used to develop sets of control points of elevations of the top of the intermediate system and the top of the Floridan aquifer. Control points were prioritized based on one or more of the following criteria: 1) the site had an existing unit top interpretation in the District's hydrostratigraphy database, 2) deep exploratory drilling had occurred at the site through multiple geologic formations and hydrostratigraphic units, 3) multiple data types (e.g. geophysical logs, lithologic logs and water level data) existed for the site, 4) the site filled a gap in spatial coverage, and 5) the interpreted elevations generally agree with previously developed tops of unit surfaces. A total of 433 and 544 control points were used to interpolate the elevation of the tops of the intermediate system (Figure 6) and Floridan aquifer (Figure 7), respectively. The

Control points were interpolated to create continuous raster surfaces. The Natural Neighbor interpolation method was used in ArcMap 10.6 to create a 250 meter by 250 meter raster from each control point dataset. The Natural Neighbor interpolation method "finds the closest subset of input samples to a query point and applies weights to them, based on proportionate areas, to interpolate a value (Sibson 1981, ESRI 2019)." Control point elevations in vertical datum NGVD 29 were converted to vertical datum NAVD 88 before interpolation. Since each dataset was independently interpolated at a coarser resolution than the land surface DEM, quality control checks were made on the output to ensure that the elevations of the top of the intermediate system and the top of the Floridan aquifer did not exceed land surface. If exceedances were noted, land surface elevations and elevation offsets were used to create "soft control" points. The soft control points were added to the dataset and surface was re-interpolated.

Creation of each raster surface proceeded as follows: 1) control points from all data sources were combined into one dataset, 2) the dataset was interpolated using the Natural Neighbor method to create a raster surface, 3) raster math was performed to calculate the difference between the raster surface and the land surface DEM, 4) raster cells where the values of the top of unit exceeded the land surface were extracted and converted to point features, 5) the point features were intersected with the land surface DEM to extract the land surface elevation value, 6) the point features were used to provide "soft control" by subtracting a few feet from the land surface value and adding the soft control points to the dataset, and 7) the surface was re-interpolated.

Using a similar approach, INTERA compiled geologic data, developed control points and created continuous raster surfaces of the elevations of the top of Oligocene-age limestone formation and the top and bottom of the Ocala Limestone (Appendix B). Soft control points were added where data are scarce, layers pinch out, and where initial interpolated surfaces exceeded land surface.

Assignment of Layer Elevations

INTERA used the raster surfaces to assign layer top and bottom elevations. Layer elevations generally correspond to the interpolated raster surfaces. However, adjustments were made in some areas where geologic units were thin or absent. MODFLOW-NWT does not allow a middle layer to be absent where there is an active layer above and below it. To maintain vertical continuity, a minimum thickness of 10 feet was specified for each active layer below the uppermost layer. For example, Miocene-age limestone formations are absent in the Dougherty Plain but Layer 3 was assigned a minimum thickness of 10 feet to maintain vertical continuity between model layers 2 and 4. The determination of model layer elevations involved performing raster math to subtract one surface from another, check for negative layer thicknesses, and adjust elevations where thicknesses were negative or less than 10 feet. Additional details are provided in Appendix B. District staff made some minor revisions to layer elevations following work performed by INTERA. These revisions primarily involved adding an uppermost active layer or increasing the layer thicknesses in the Woodville Karst Plain where the Floridan aquifer is unconfined but a thin layer of overburden is present. In addition, the thickness of the Miocene-age limestone formations making up the top of the Floridan aquifer was increased in Georgia, along the Apalachicola Embayment.

After model layer elevations were assigned, the bottom of the model was truncated to the base of the freshwater zone based on the 10,000 mg/L TDS surface created by the USGS (Williams and Dixon, 2015). Where the 10,000 mg/L TDS surface was above the bottom of a model layer, the bottom elevation of the layer was increased to match the surface. In Franklin and Wakulla counties, water quality data from discrete interval sampling conducted during the construction of six public supply wells and two exploratory monitoring wells were used by the District to refine the depth to the 10,000 mg/L TDS surface. Following this refinement, the layer bottom elevations in this area were modified. In most areas, the bottom of the model occurs below or within Layer 5 (Ocala Limestone). However, near the coast where the freshwater zone is thinner, the bottom the model can occur in Layer 4.

Lateral Boundary Conditions

Lateral boundary assignments are shown in Figure 8 and include no-flow, constant-head, general-head and river boundary conditions. No-flow boundaries are used along the edge of the model domain where the edge follows streamlines and groundwater divides or where a hydrogeologic unit or geologic formation pinches out. A no-flow boundary is a type of specified-flux boundary in MODFLOW where the flux across the boundary is zero. The lateral boundary along the eastern edge of the model domain in all layers is a no-flow boundary that follows persistent features in the potentiometric surface of the upper Floridan aquifer. Hydrogeologic units pinch out in Layers 1 and 2 in the south, adjacent to the Woodville Karst Plain, and to the north, adjacent to the Dougherty Karst Plain. In Layer 3 the Miocene-age limestone formations of the Upper Floridan aquifer pinch out to the north in Georgia. These units are not considered to be significant aquifers along their northern extent.

The lateral boundaries along the northern edge of the model domain, in Layers 4 and 5, are represented by general head boundaries (GHB) where the edges cuts across equipotential lines of the Floridan aquifer potentiometric surface. A GHB is a type of head-dependent boundary in MODFLOW. The flux across the boundary is dependent on a fixed-head elevation, assumed to be some distance outside the model domain, and the simulated head in the boundary cell. The assignment of the lateral GHBs in Layers 4 and 5, and their attributes are described by INTERA (Appendix C). INTERA assigned heads at the GHBs based on a statistical relationship between the May 2010 potentiometric surface map (Kinnaman and Dixon, 2011) of the Floridan aquifer and USGS water level elevation data for calibration years 2009, 2011, and 2014. Conductance values were assigned based on the horizontal hydraulic conductivity specified in the NFSEG model version 1.0 (Gordu et al., 2016) for model Layer 3 which represents the Upper Floridan Aquifer; the thickness of model layers 3, 4, and 5 in the EDM; and the length of the boundary perpendicular to the flow direction (2,500 feet) in the EDM.

The lateral boundary along the western edge of the model domain in Florida is either a no-flow or river boundary depending on whether the Apalachicola River is present in the layer. A river boundary is a type of head-dependent boundary in MODFLOW. The flux across the boundary can be either into or out of the model and depends on a fixed river stage and the simulated head in the boundary cell. The Apalachicola River is a major surface water feature and represents a location of discharge for the surficial and upper Floridan aquifers where hydraulically connected. The aquifer layers below the river are a point of convergence and upward flow and are thus simulated as no-flow boundaries in the underlying layers.

Offshore, the lateral boundary along the east, west and southern edge of the model domain is either a no-flow boundary or constant-head boundary representing the Gulf of Mexico. A constant-head boundary is a type of specified head boundary in MODFLOW. The constant-head boundary is specified for cells in Layers 1, 2, and 3 where those cells are part of the upper active model layer. The specified head value is set to 0.072 feet NAVD 88; the freshwater-equivalent of mean sea level. Offshore where the southern lateral boundary is a no-flow boundary, this represents the subsurface freshwater/saltwater interface.

Depending on the location within the model domain, the base of the model coincides with either the bottom of the Ocala Limestone or the freshwater/saltwater interface as represented by the 10,000 mg/L TDS surface, as previously described. These boundaries are conceptualized as not having significant vertical flow across them within the model domain and represent the base of the fresh groundwater system. They are simulated in MODFLOW as no-flow boundaries.

Internal Boundary Conditions

Boundaries within the model domain are considered internal and are represented by all boundary types: specified head, specified flux, and head-dependent flux. Recharge and ET from the saturated zone are specified flux and head-dependent flux boundaries, respectively, which are applied to the uppermost active layer. Surface water features such as rivers, streams, springs and coastal wetlands are represented as either river or drain boundaries, which are head-dependent fluxes. A drain boundary is similar to a river boundary except the flux can only be out of the model when the simulated head in the boundary cell is above a specified drain elevation. Springs and coastal wetlands are also represented in the model as drain boundaries. Lakes are represented as general head boundaries, which are also head-dependent. Groundwater withdrawals and swallets within the model domain are represented by specified flux boundaries. These features either remove or add water to the groundwater system at a specified rate for each of the respective calibration years. Most of these boundaries are assigned to model layers based on elevation attributes and model layer top and bottom elevations while others are explicitly assigned. The development and implementation of these boundaries in the model are described in more detail below.

Recharge and Evapotranspiration

Recharge reflects the amount of precipitation that reaches the top of the uppermost saturated layer following initial abstraction, interception, runoff, ET from the unsaturated zone, and other surface losses and storages. Recharge is a function of surface topography, land cover, soil type, and other factors. Evapotranspiration from the uppermost saturated layer in the model represents the remaining potential ET after ET occurs from the surface storage and the unsaturated zone. The ET rate varies linearly from a maximum saturated ET rate when the aquifer level is at land surface to a rate of zero when the aquifer falls below the extinction depth. Extinction depths are also a function of soil type and land cover.

Initial values for recharge and maximum saturated (i.e., groundwater) evapotranspiration rates were provided for each EDM grid cell and calibration year by SJRWMD (Cera, personal communication, 2018). The values were based on output from Hydrologic Simulation Program-Fortran (HSPF) models developed for the NFSEG model. The HSPF models simulate water budget processes within surface water basins including evapotranspiration and rainfall-runoff processes. The development of the HSPF models and the recharge, maximum saturated ET, and extinction depth datasets are described in Cera et al. (2016) and Durden et al. (2018).

Initial recharge and maximum saturated ET rates provided by SJRWMD for 2009 are shown are Figure 9 and Figure 10, respectively. Extinction depths are shown on Figure 11. The SJRWMD also provided files containing daily streamflow values generated by the HSPF models from 1991 to 2014 at river reaches corresponding to USGS streamflow gauges. The HSPF-generated recharge values were larger than anticipated in some areas of the EDM domain. As a result, HSPF-generated values were reviewed and adjusted, where appropriate, prior to utilizing them in the EDM. The District contracted with INTERA, who compared estimated and simulated runoff generated by the HSPF models. INTERA applied a baseflow separation method to the HSPF simulated daily streamflow and the daily streamflow values measured by the USGS. The method utilized on a 61-day low pass filter to separate total average daily streamflow into baseflow and runoff components. ArcGIS shapefiles of the associated surface water basins provided by SJRWMD were used to calculate the area contributing to each USGS station. The runoff values derived from HSPF streamflow and USGS streamflow values were converted to inches per year across each basin. Differences in daily runoff were calculated for each basin as the runoff estimated using the HSPF streamflow minus the runoff estimated using the USGS streamflow. Positive errors indicated the HSPF-derived runoff was larger than the baseflow separation-derived runoff. Because errors in runoff could translate into errors in either recharge or groundwater ET, estimated runoff errors were divided by two and equally apportioned to make adjustments to the initial recharge and maximum saturated ET rates provided by SJRWMD.

INTERA created an ArcGIS shapefile of watershed (or basin) zones that associates each model grid cell to a surface water basin (Figure 12). Grid cells located outside a basin were assigned a zone number of zero. The differences in runoff within each watershed were then used to calculate scaling factors which were then used to adjust the recharge and maximum saturated ET rates provided by SJRWMD. Scaling factors were calculated for each basin and year combination. Cells located outside of basins with USGS gauges were adjusted using the average of the factors across all basins. INTERA performed the calculations using Excel, Microsoft Access, and ArcGIS (Appendix D).

District staff reviewed the values refined by INTERA for years 2009, 2011, and 2014, and where needed, constrained the recharge and maximum saturated ET rates to not exceed total precipitation. Total precipitation in each year was based on the maximum of the reported annual totals from among the City of Tallahassee Airport, Florida; City of Apalachicola, Florida; Camila, Georgia; and Thomasville, Georgia, rainfall stations. However, recharge applied at the City of Tallahassee sprayfield was based on actual application rates and was allowed to exceed preciptiation. Sprayfield application rates were obtained from annual reuse reports prepared by the Florida Department of Environmental Protection.

River and Drain Boundaries

Rivers and streams were simulated either as perennial or intermittent. Perennial rivers within the model domain were simulated using the MODFLOW River (RIV) Package. These features are conceptualized as always having water in them and are either gaining water from or losing water to the groundwater system. Intermittent streams within the model domain were simulated using the MODFLOW Drain (DRN) Package. First and second magnitude springs of interest within the model domain were also simulated using the MODFLOW DRN Package. Springs are conceptualized as artesian features that only discharge water from the groundwater system. River and drain boundaries are types of head-dependent boundaries in MODFLOW. The flux across the boundary is dependent on the conductance of the river or drain boundary, a fixed river stage or drain elevation and the simulated head in the boundary cell.

Tetra Tech developed a grid-independent, District-wide parent geodatabase of river and spring-related parameters for use in groundwater modeling (Appendix E). The geodatabase was built primarily around the National Hydrography Dataset Plus, Version 2 (McKay et al., 2012). The NHDPlus2 hydrography represented in the EDM is shown in Figure 5. Attributes of the NHDPlus2 dataset include river reach length, width, flow and permanence. The permanence attribute identifies a river reach as perennial or intermittent and determined whether a feature was simulated as a river or drain boundary. Additionally, most first order stream reaches, except spring runs, were simulated using drain boundaries. District stream stage, flow and depth data; spring stage and discharge; and HEC-RAS model datasets were also used to locally adjust the attributes of the NHDPlus2 data and to estimate average flow depths by Strahler number, which were used to calculate river bottom elevations (i.e., RBOT).

Tetra Tech also developed an ArcGIS modeling tool that uses the parent geodatabase to attribute river, stream and spring boundaries at the grid scale and creates formatted output files for import into GW Vistas (Appendix F). The parent geodatabase and modeling tool were used with the EDM grid to create river, stream and spring boundaries for each calibration year (2009, 2001, and 2014). River attributes and Strahler order-based criteria for width and depth, feature location, and model layer elevations were used to assign the boundaries to an active model layer. The width and length attributes, Strahler number-based criteria for riverbed vertical hydraulic conductivity, and regional multipliers were used to estimate an initial riverbed conductance value for each boundary. Conductance values were subsequently adjusted during model calibration.

Additional drain boundaries were subsequently added to the model during calibration to represent coastal wetlands that were not included in the NHDPlus2 dataset.

General Head Boundaries

A total of 55 lakes were simulated using the MODFLOW General Head Boundary (GHB) Package. The lake features are conceptualized as having both areal leakage across the lake bed and concentrated drainage through known sinkholes. The lake GHBs were developed by Tetra Tech and described in a technical memo (Appendix G). Available data provided by the District included literature documenting previous investigations of selected lakes, stage measurements at six of the 55 lakes, measured water depths, and a land surface DEM. This data was used to estimate lake stage, assign lakes to model layers, and estimate conductance for sinkhole features and initial leakance values for lakebed sediments not representing sinkholes.

For lakes with available stage data for the calibration years (i.e. 2009, 2011, or 2014), the annual average stage was used to attribute the GHB cells representing that lake (e.g Lake Seminole and Lake Talquin). For lakes with data outside the calibration years, an average stage for the entire period of record was used for all calibration years. For lakes without any stage measurements, elevations from nearby lakes with measurements were used or an average DEM elevation was used as the stage for all calibration years.

Estimates of conductance for sinkhole features within Lakes Iamonia, Jackson, and Lafayette were made using previous technical reports in which volumetric inflows were measured. For all other GHB cells representing lakes where sinkhole features were not explicitly represented, an initial vertical hydraulic conductivity of 7×10^{-5} feet per day was used. This value was based on estimates of vertical hydraulic conductivity of cores from the intermediate confining unit.

Groundwater Withdrawals

Groundwater withdrawals, or pumpage, from wells are simulated in the model as specified-flux boundaries. Best available data were utilized to develop steady-state spatially distributed pumpage estimates for calibration years 2009, 2011, and 2014 and pumpage projections for 2040. Table 2 summarizes the sources of information used to develop pumpage estimates. District staff estimated pumpage within the District for the following use categories: (1) public supply, (2) industrial, commercial and institutional uses, (3) power generation, and (4) recreation. District staff also estimated domestic self-supply withdrawals within the entire model domain. Water use estimates previously developed by the St. Johns River Water Management District (SJRWMD) for the NFSEG model were evaluated for inclusion in the EDM, including agricultural use within the District and public supply, industrial/commercial/institutional uses, and power generation within the SRWMD. USGS staff provided annual average pumpage estimates for public supply, industrial/commercial/institutional uses, and power generation within Georgia (Bellino 2017, personal communication). The specific methods used to develop pumpage estimates for each use type are described in detail by the District (NWFWMD, 2019).

Table 2. Eastern District Model Pumpage Data Sources

Water Use Categories	Region	Source
Public supply, industrial/commercial/institutional, power generation, recreation	NWFWMD	District database
Public supply, industrial/commercial/institutional, power generation	SRWMD	SJRWMD NFSEG dataset
Public supply, industrial/commercial/institutional, power generation	GA	USGS
Domestic self-supply	All	District dataset
Agriculture	All	SJRWMD

Groundwater withdrawals within the model domain vary by year and location (Table 3). The majority of the groundwater pumped (74% to 81%) occurs in the Georgia portion of the model domain. The largest use category in Georgia is agriculture. Non-agricultural uses in Georgia include public supply; industrial, commercial, and institutional use; power generation, and domestic self-supply. In the Florida portion of the model domain, agricultural pumpage is a predominant use in the SRWMD. In the District, public supply comprises the largest use category and agricultural use comprises only approximately 20% of the total groundwater pumped. Additional detail is provided in NWFWMD (2019).

Table 3. Groundwater Pumpage by Year and Region in the EDM

Region and Use Category	2009 (mgd)	2011 (mgd)	2014 (mgd)
NWFWMD, non-Agricultural	48.64	55.16	49.16
NWFWMD, Agriculture	8.00	11.76	13.57
Total NWFWMD	56.64	66.92	62.73
SRWMD, non-Agricultural	2.90	4.83	4.73
SRWMD, Agricultural Pumpage	3.45	4.74	3.21
Total SRWMD	6.35	9.57	7.94
Total Florida	62.99	76.49	70.67
Georgia, Non-Agriculture	37.06	37.53	34.26
Georgia, Agricultural Pumpage	222.85	179.59	264.26
Total Georgia	259.91	217.12	298.52
Total Whole Domain	322.90	293.61	369.19

To assign pumpage to model cells, well construction and location information were obtained from several sources including the District, SRWMD, SJRWMD, and the USGS. Wells were spatially distributed throughout the model domain by the District based on available geographic coordinates or explicitly assigned to model grid cells by the data provider, where available. Specific well locations and construction attributes were unavailable for estimated agricultural uses below permit thresholds and withdrawals for domestic self-supply in Georgia and these withdrawals were assigned to model grid cell centers.

Withdrawals were assigned to model layers based on several criteria including available well construction information, the degree to which the open interval or screened interval intercepted a model layer, or the reported aquifer to which the well is open or primarily used in an area for a particular use type. Well construction information generally was available for permitted public supply, industrial, power generation, commercial and agricultural withdrawals. Where construction data were unavailable for agricultural withdrawals, the aquifer unit utilized by the nearest agricultural well having construction data was generally used as the basis for making layer assignments. For public supply, industrial, commercial, and institutional use withdrawals in the Georgia, the District provided the EDM grid with top and bottom elevation attributes to the USGS for explicit assignment of pumpage to layers. Those withdrawals were spatially located at the associated grid cell center. Some manual revisions were made to the USGS assignments to maintain consistency between assigned layers and aquifer unit codes associated with permitted withdrawals. For all use types except domestic self-supply, pumpage was assigned to multiple layers if the open interval or screened interval was open to more than one layer. In Georgia, domestic self-supply withdrawals were assigned to a single layer based on the aquifer unit predominantly utilized for domestic self-supply. In Florida, domestic self-supply withdrawals were initially assigned based on well construction data. However, because open hole and screened intervals are relatively short for these wells, where manual adjustments were needed, they typically resulted in pumpage being assigned to a single model layer.

In areas where model layer elevations were subsequently adjusted, withdrawals were accordingly reassigned. Also, some minor quantities of withdrawals were re-assigned to lower layers during calibration in areas were the pumped layer was simulated as going dry.

Swallet Inflows

Due to the extensive karst development within the EDM domain, there are many known locations of point recharge to the Floridan aquifer from surface water streams, also known as swallets. There are 12 swallets represented in the EDM and their inflows were simulated using MODFLOW's Well Package with recharge into a model cell. Since the swallet features represented in the EDM are developed in the Floridan aquifer, their associated injection rates were assigned to either model layers 3 or 4. There are no known connections between the Ocala Limestone (model Layer 5) and swallet features within the EDM domain.

The selected swallets represented in the EDM and their associated flows have various sources of data including manual discharge measurements performed by the District, manual measurements from Kulakowski (2010), USGS gauging stations, and estimates from HSPF models (Table 4). The flow rates were assumed to be annual average daily rates and representative of steady-state conditions. The flow rates range in values from approximately 29,000 cubic feet per day at Jump Creek Swallet in 2011 to approximately 32,000,000 cubic feet per day at Lost Creek Swallet in 2014. Below is a table summarizing the swallets, estimated flows, and the data sources used in the EDM.

Table 4. Swallets and associated flow rates used in the EDM in cubic feet per day (CFD)

Name	Layer	Flow Rate 2009 (ft^3/d)	Flow Rate 2011 (ft^3/d)	Flow Rate 2014 ft^3/d)	Comments
Jump Creek Swallet	3	407,685	29,376	407,685	2009 value from Kulakowski (2010). 2014 also based on 2009 data. 2011 values represent minimum measured value.
Black Hole on Black Creek	3	365,990	70,848	1,335,744	2009 from Kulakowski (2010); 2014 is average of mean monthly USGS; 2011 is minimum USGS monthly mean discharge.
Ames Sink	4	1,318,000	1,318,000	1,318,000	Injection rate represents the average of manual discharge measurements performed by the District between 1982 - 2000; n=9
Copeland Sink	3	193,525	55,762	143,874	NFSEG/HSPF estimates
Bird Sink	3	193,525	55,762	143,874	NFSEG/HSPF estimates
Patty Sink	3	96,101	12,099	128,363	NHD intermittent stream; NFSEG/HSPF estimates
Lake Drain Sink	3	574,973	51,766	484,873	Perennial stream; NFSEG/HSPF estimates
Creek Sink	3	574,973	51,766	484,873	Perennial stream; NHD intermittent stream; NFSEG/HSPF estimates
The Cascades	3	574,973	51,766	484,873	NHD intermittent stream; NFSEG/HSPF estimates
Lake Miccosukee Sink	3	574,973	51,766	484,873	NFSEG/HSPF estimates
Fisher Creek Terminus Sink	4	3,836,160	6,392,208	9,383,040	Annual average discharge from USGS station 02326993 for years 2009. Values for 2011, and 2014 were estimated.
Lost Creek Swallet	4	11,531,016	11,934,432	31,682,880	Annual average discharge from USGS gauging station 02327033 for years 2009; values for 2011, and 2014 were

					estimated.

Model Calibration

Model datasets for the Eastern District Model were developed and calibrated for three steady-state periods: 2009, 2011, and 2014, representing average, dry, and wet conditions, respectively. The goal of simultaneously calibrating three differing steady-state models was to achieve a robust set of model parameters with the capability to simulate heads and fluxes across varying hydrologic and pumping conditions.

Hydrogeologic Units

Some geologic units are spatially discontinuous but are represented in the model with a minimum layer thickness of 10 feet to maintain vertical continuity. In fact, all geologic units are absent in some portion of the active model domain. Because model layers do not strictly coincide with geologic units, an approach was needed during model calibration to determine the geologic unit and properties associated with specific grid cells. Hydrogeologic units (HGUs) are zonation parameters that indicate which geologic unit is associated with each grid cell. The HGUs are used in the calibration process to associate pilot points and interpolated aquifer properties with specific cells in each model layer.

The designation of HGUs within this report and Appendix I is based on cells being associated with a specific hydrostratigraphic unit or geologic formation assumed to have unique hydrologic properties. Each HGU varies in spatial extent and vertical extent. Layers 1 through 4 all consist of more than one HGU (Table 5). As an example, below the Cody Scarp in the Woodville Karst Plain, the surficial aquifer and intermediate system have been eroded away. However, a thin layer of unconsolidated sediments overlies the Layer 3 Miocene-age limestone formations. Grid cells comprised of these sediments represent Layer 2 of the model and have a minimum thickness of 10 feet. Because these grid cells represent undifferentiated surficial sediments rather than low permeability materials of the Hawthorn Group, the grid cells are assigned to the Surficial Aquifer HGU.

The designation of HGUs to model grid cells was made using positive integers specified in the IBOUND arrays. Figure 13 through Figure 17 show the extent of each HGU, by layer. The IBOUND values corresponding to specific HGUs are color coded and indicate if the active cells are variable or constant. The top elevation and thickness of each HGU are shown in Figure 18 through Figure 27.

Table 5. Relationship of Hydrogeologic Units to Model Layers

Hydrogeologic Unit (HGU)	Model Layers
Surficial Aquifer System	Layer 1, 2, or 3, depending on location
Intermediate System	Layer 2 or 3, depending on location
Miocene-age limestone formations	Layer 3
Oligocene-age limestone formations	Layer 3 or 4, depending on location
Ocala Limestone	Layer 4 or 5, depending on location

Pilot Points

A pilot point approach was used to estimate spatially varying hydraulic conductivity across the model domain. Pilot points were developed for each HGU. The pilot point approach allows the flexibility in the calibration for the hydraulic conductivity of individual cells to vary. This is in contrast to a simpler approach where cells are grouped into zones, all cells within each zone are adjusted simultaneously during calibration, and hydraulic conductivities are assumed to be homogenous in each zone. With pilot points, selected cells are assigned an initial pilot point value (i.e. hydraulic conductivity) and upper and lower bounds that limit the automated calibration to assigning reasonable estimates. Once PEST has an optimal array of pilot point values, the program uses spatial interpolation to assign hydraulic conductivity values to cells in between the pilot points. Each hydraulic conductivity pilot point and each horizontal to vertical anisotropy pilot point were treated as separate calibration parameters.

The properties needed to simulate groundwater flow include layer thickness and horizontal and vertical hydraulic conductivity. Layer thicknesses are variable across the model domain and were determined previously by the vertical discretization of the hydrostratigraphic units and geologic formations into HGUs. Initial estimates of hydraulic conductivity were made based on the results of aquifer tests, previous calibrated modeling efforts and regional water resource studies. Figure 28 shows estimated transmissivity values based on reported aquifer test results. These estimates were considered, together with calibrated transmissivity values from prior modeling efforts (Davis 2007, Xu et al, 2015, Durden et al. 2018) and layer thicknesses, to establish initial upper and lower bounds on hydraulic conductivity pilot points for use during model calibration. Additional constraint on aquifer properties was obtained by grouping pilot points into zones within selected HGUs. The zones correspond to areas of similar geology, topography, depth to groundwater, thickness of overburden, and presence of karst landforms. The purpose of specifying zones with pilot points was to impart region-specific constraints on the automated calibration of model parameters.

Watershed Zones

Recharge and maximum saturated ET rates in each grid cell were adjusted during the calibration process using watershed zones. One or more HUC12 watersheds typically comprise each zone. The watershed zones delineated by INTERA were modified by the District and subsequently by Tetra Tech to provide a finer spatial resolution within the District. A total of 48 zones were used (Figure 12). Recharge and maximum saturated ET multipliers were calibrated independently, for a total of 96 parameters. Multipliers did not differ between calibration years and maintained relative differences in recharge and maximum saturated ET rates among years. To minimize the potential for calibrated rates to exceed precipitation, multipliers were generally limited to an upper limit of 1.0.

The 48 watershed zones were also used to adjust streambed conductance values. An additional 49th zone was specified to achieve a better match of simulated baseflows in the Little River basin. Lakebed sediments within each lake were assumed to have the same initial vertical hydraulic conductivity, for a total of 55 lake zones/parameters. The vertical hydraulic conductivity of cells containing identified sinkhole features were not adjusted during calibration. Conductances of each spring were calibrated separately. Summing the individual pilot points and zone parameters, the number of adjustable parameters in PEST totaled 1,043.

Detailed explanation of the EDM calibration methodology, results, and all related maps and figures can be found in Appendix I.

Calibration Targets

The calibration of the EDM included both head and flux targets that have variable distribution across the model domain. The target types included observed groundwater levels, observed spring discharge, baseflow estimated from hydrograph separation, vertical head differences, and horizontal head differences. In areas where the number of observations were sparse during the calibration years, “soft” head targets were developed to provide more constraint in those areas during calibration. The sections below describe the initial development of calibration targets and do not reflect final weighting. Weights were iteratively refined during the calibration process to meet target metric goals.

Head Targets

The aquifer head targets used in the EDM calibration dataset were compiled from observations from the District, SRWMD, and USGS databases. Due to water levels in many of the wells used as targets not being measured regularly, the number of observations and distribution of head targets varies among calibration years.

The methodology of assigning targets to model layers was based on the available well construction information and the interpolated model layer elevations at each cell. Wells that were completed in the surficial aquifer (Layer 1, where present) and the intermediate system (Layer 2, where present) all had construction information that was consistent with the interpolated model layers. That is, when the open-hole or screened intervals for each well were intersected with the interpolated model layers each of the targets intersected their discrete layer, respectively.

The assignment of head targets within model layers 3, 4, and 5 involved a slightly different approach than the assignment of head targets within model layers 1 and 2. Because of the vertical discretization of the Floridan aquifer into its three geologic formations (i.e. Miocene-age limestone formations, Oligocene-age limestone formations, and Ocala Limestone), the targets were assigned to each layer if the open-hole interval intercepted 50% or greater of the layer thickness. For example, if the open-hole interval for a well was 60% in Layer 3 and 40% in Layer 4, then that head target was assigned to Layer 3. The table below summarizes the number of head targets for each layer, by calibration year.

Table 6. Number of groundwater head targets per layer, by calibration year

Layer	2009	2011	2014
1	14	18	19
2	5	8	5
3	44	54	71
4	38	61	71
5	9	18	8

Total	**110**	**159**	**174**

"Soft" Head Targets

"Soft" head targets were developed in areas of interest (i.e. St. Marks River Rise and Wakulla Spring groundwater contribution areas) where observations were sparse or did not exist. "Soft" targets are synthetic targets based on groundwater level measurements made outside of the EDM calibration years (2009, 2011, and 2014). An initial review of groundwater level data for the EDM calibration years in Florida and Georgia was performed to create the primary water level target dataset, but data in Georgia was sparse and mostly absent in the areas of interest. The creation of soft targets provided additional control during the PEST calibration of the EDM.

The review of the data included in the creation of soft targets were historical water levels measured by the United States Geological Survey (USGS) for wells that were designated as Floridan aquifer wells and located in counties within the Wakulla Spring or St. Marks River Rise groundwater contribution areas. Some wells were removed from the dataset if there were less than four measurements or had an absence of well construction information. The final dataset included 39 individual wells.

To create soft targets within the available timeframe, priority was given to Floridan aquifer wells in Georgia within and immediately adjacent to the delineated Wakulla Spring and St. Marks River Rise groundwater contribution areas. This query included wells from Brooks, Decatur, Grady and Thomas counties. In general these wells had as few as six to as many as 244 observations ranging from the 1960's to the 2010's.

The USGS has a long-term monitor well within the search area with daily data from 1964 to present (Site ID 12F036) located in Cairo, GA, approximately in the north-central region of the Wakulla Spring groundwater contribution area. To correlate historical water levels outside of the EDM calibration years and use them as soft targets for the calibration years, the percentile rank of water levels for the period of record at 12F036 was used as a reference to identify surrogate years for which we could relate other historical water levels to our calibration years. An annual average percentile ranking was generated for each year within the period of record for 12F036 including the EDM calibrations years (i.e. 2009, 2011, and 2014). The percentile rankings for years 2009, 2011, and 2014 for 12F036 were used to identify other years with similar hydrologic conditions (based on the percentile rank of water levels at 12F036). In an effort to be inclusive enough to capture measurements from surrogate years, but exclusive enough that the surrogates still represented the hydrologic conditions of the calibrations years, a general search criteria was established as +/- 5%.

Table 7. Number of "soft" groundwater head targets per layer, by calibration year

Layer	2009	2011	2014
1	0	0	0
2	0	0	0
3	1	6	0
4	4	23	1

5	2	10	1
Total	**7**	**39**	**2**

Figures 24-38 of Appendix I show the locations of hard and soft head targets, by year and layer. The number of soft targets is summarized in Table 7. All soft targets were assigned initial weights of 0.75 for use in PEST, with the exception of wells 09G001 and 12F036 which had daily observations during 2009, 2011, and 2014. To assign these wells to EDM layers, the point shapefile containing wells with soft targets was intersected with the current model layer elevations. Wells in the soft target dataset mostly contained only casing depth information or the casing depth and total depth were identical. Well depths were converted to elevations using the land surface elevation from the USGS database. If the casing depth fell within a model layer, it was assigned to that model layer. In a few cases, the casing depth fell within Layer 2 or fell below Layer 5. If the well fell within Layer 2, it was assigned to Layer 3 as Layer 3 represents the uppermost Floridan aquifer layer. If the well fell below Layer 5, it was assigned to Layer 5. Since these wells were all identified as Floridan aquifer wells, the discrepancy in wells having casing depths above Layer 3 or below Layer 5 were assumed to be due to elevation data associated with the well not being accurate or errors in the interpolation layer elevation surfaces.

For example, the annual average percentile rank at 12F036 for 2009 was 0.556. The percentile ranks at 12F036 were reviewed in order to find other years that were similar. In this case, years 1984 (0.549), 2004 (0.531), and 2016 (0.585) were determined to have similar percentile rankings as the 2009 annual average percentile rank at 12F036. In order to find surrogate water levels (i.e. soft targets) for 2009, water level observations for the period of record were reviewed to determine if there were any measurements in 1984, 2004, and 2016. If there was an observation at another well during one of these years, it was assumed to be similar to hydrologic conditions in 2009 and was added as a soft target. The same process was performed for years 2011 and 2014.

The annual average percentile rankings at 12F036 for the EDM calibration years and entire period of record are provided in Table 8.

Table 8. Annual average percentile rankings of water levels observed at well 12F036

Year	Annual Average Percentile Ranking
2009	0.556
2011	0.375
2014	0.504

Vertical Head Difference Targets

Vertical head difference targets were developed at locations where clustered wells are located (i.e. locations with multiple wells having open-hole intervals in different aquifers). The datasets compiled to develop vertical head difference targets range in the number of observations per calibration year and the total number of targets for each calibration year. This is primarily because of the varying frequency at which the water levels are measured. Targets were generated for head differences between Layers 1 and 2, Layers 2 and 3, and between layers that comprise the Floridan aquifer (i.e. Layers 3, 4, and 5).

Vertical head difference targets added additional constraint in the model calibration which will be most advantageous in areas where head differences between layers is very small or very large. For example, in the Apalachicola Embayment where there are significant head differences between the early Miocene-age limestone formations (i.e. Layer 3) and the Oligocene-age limestone formations (i.e. Layer 4), vertical head difference targets helped to guide the optimization of model parameters during calibration. Additionally, south of the Cody Scarp, there are areas where the observed head differences are very small and similarly, this helped guide the optimization to simulate the relatively small head gradients.

The vertical head difference targets were developed only in the Florida portion of the model domain within both the District and the SRWMD. Clustered well locations were unavailable in the Georgia portion of the model domain. Vertical head difference targets are listed in Appendix I, Attachment E.

Horizontal Head Gradient Targets

Horizontal head gradient targets were developed to add constraint to the model calibration in an effort to simulate observed head gradients, particularly in areas where the observed head gradient in the Floridan aquifer can be relatively large or small over short distance. Since the generation of horizontal head gradient targets simply requires the head at two different points within the same layer and the distance between them, the development of these targets were limited to locations near the areas of interest where head gradients are steep or shallow.

The head gradient in the Floridan aquifer is very steep as it transitions from the Apalachicola Embayment to the Woodville Karst Plain, which is caused by the differences in hydraulic conductivity in the Floridan aquifer between the two regions. Horizontal head difference (or gradient) targets were developed using wells that span this transition area to add constraint in the model calibration to simulate this feature. Similarly, head difference targets were developed for Floridan aquifer wells within the Woodville Karst Plain where head gradients can be relatively shallow which is also reflective of the relatively high hydraulic conductivity in this region. The horizontal head gradient targets are shown in the table below. Figures showing the locations of these targets are provided in Appendix I.

Table 9. Horizontal head gradient targets by calibration year (from Appendix I)

NWFID Well 1	NWFID Well 2	Model Layer	2009 HHG	2011 HHG	2014 HHG
3653	3402	3	0.00035	0.00036	0.00037
3653	977	3	0.00038	0.00036	0.00041
4359	977	3	0.00037	0.00032	0.00037
392	372	3	0.00074	0.00066	0.00070
589	392	3	0.00000	-0.00001	0.00000
392	635	3	0.00016	0.00017	0.00018
3785	3342	3	0.00045	0.00047	0.00046
3342	2137	3	0.00055	0.00055	0.00053

Spring Discharge Targets

Spring discharge targets were developed for 1st magnitude (median flow > 100 ft^3/s) and 2nd magnitude springs (median flow 10-100 ft^3/s). Best available data were used to develop the spring discharge targets. Most first-magnitude springs had multiple discharge measurements. The St. Marks River Rise had estimates of daily spring discharge for all calibration years. Tetra Tech added a target to reflect the combined discharge for Wakulla Spring and the Spring Creek Spring Group, as these two systems are closely linked. Horn Spring, Crays Rise, and Chicken Branch Spring had only a single discharge measurement, which was used as the target for all three calibration years. Data were insufficient to develop targets for 3rd magnitude springs. Springs with targets are located within the District (n=7) and the SRWMD (n=5). Spring discharge targets are summarized in Table 10.

Table 10. Spring discharge targets by calibration year

Spring Name	Magnitude	2009 Average Daily Flow (ft^3/s)	2011 Average Daily Flow (ft^3/s)	2014 Average Daily Flow (ft^3/s)
St. Marks River Rise	1st	495	425	463
Wakulla Spring	1st	601	558	724
Wacissa River Spring Group	1st	102	87	90
Spring Creek Spring Group	1st (submarine)	239	NA	224
Chicken Branch Spring	2nd	23	23	23
Crays Rise	2nd (submarine)	77	77	77
Horn Spring	2nd	15	15	15
Sally Ward Spring	2nd	13	16	23
Wakulla Spring + Spring Creek Spring Group	Not Applicable	840	NA	948

Baseflow Targets

Hydrograph separation was performed by District staff to develop baseflow targets at USGS streamflow gauge locations. For each dataset, a low pass filter approach was used to derive time series of estimated daily baseflow values. The low-pass filter generally used a 60-day moving window centered on each daily value. For each site, minimum streamflow values were calculated across the time series using a 60-day moving window. A second 60-day window was then used to calculate the moving average of the minimum values. The resultant time series represents the estimated average daily baseflow. The 60-day window length was used for most streams and was selected based on an evaluation of alternate window lengths and examination of stream hydrographs and recession curves in northwest Florida. For some streams, a 15-day, 30-day or 45-day window length was used to provide a better match to observed recession curves. All calculations were performed in Microsoft Excel.

Estimated daily baseflow values were used to calculate annual average baseflow targets for each USGS streamflow station and each calibration year. Grid-to-watershed relationships were used to associate the aggregated baseflow from specific stream reaches to the baseflow values estimated at USGS streamflow gauge locations. Figure 12 shows the rivers, USGS streamflow gauges and watershed zones. For streams with multiple USGS gauges, targets also were developed for incremental baseflows, which were calculated as the difference between the baseflows estimated at an upstream and a downstream gauge. Baseflow targets for watersheds partially within the model domain were prorated by Tetra Tech using the watershed drainage area prior to model calibration. Total baseflow targets are provided in Table 11.

Table 11. Targets for total baseflow

	Total Baseflow, ft^3/s		
USGS Station	**2009**	**2011**	**2014**
Apalachicola River near Blountstown, FL*	61.94	9.89	103.06
Apalachicola River near Blountstown, FL*	253.72	147.14	393.92
Aucilla River at Lamont, FL*	63.37	4.92	181.24
Econfina River near Perry, FL*	17.92	9.65	71.82
Flint River at Bainbridge, GA*	324.72	227.18	772.10
Flint River at Newton, GA*	149.11	70.33	141.35
Flint River near Hopeful, GA*	246.39	86.64	126.01
Ichawaynochaway near Newton, GA*	2.13	0.69	2.33
Little Attapulgus Creek at Attapulgus, GA	6.93	2.75	8.63
Little River at GA 122 near Hahira, GA*	None	8.20	34.07
Little River near Adel, GA*	None	4.43	109.41
Little River near Midway, FL	84.08	34.48	110.84
Lost Creek at Arran Rd, FL	7.50	None	None
New River near Sumatra, FL	31.07	4.96	51.70
Ochlockonee near Concord, GA	298.37	72.51	502.12
Ochlockonee near Smith Creek, GA	625.37	251.69	1279.70
Ochlockonee near Thomasville, GA	125.57	25.80	207.76
Ochlockonee River at GA 188 near Coolidge, GA	44.40	5.50	86.23
Ochlockonee River near Havana, FL	291.58	63.12	None
Okapilco Creek near Quitman GA	20.85	1.36	44.53
Sopchoppy River near Sopchoppy, FL	11.93	2.62	32.62
St. Marks River near Newport, FL	618.92	525.78	510.00
St. Marks River Swallet Near Woodville	176.59	122.82	115.97
Telogia Creek near Bristol, FL	61.49	35.66	95.47
Wacissa River near Wacissa, FL	487.11	403.97	313.54
Wakulla River near Crawfordville, FL	559.38	616.54	737.34
Withlacoochee River near Quitman, GA*	6.48	1.86	18.79

* indicates baseflow was prorated to reflect partial basin Apalachicola River within the EDM domain

Calibration Setup and Processing

The three year simultaneous calibration was performed primarily using PEST, a model-independent parameter optimization program (Doherty, 2018). A suite of PEST-compatible modeling utilities were used to perform several of the calibration steps including the creation of input files, execution of MODFLOW-NWT, analysis of output files, “global search” optimization, and “local search” or gradient-based optimization, and post-processing of output files. Additional details regarding the processing scripts are provided in Appendix I. The automated calibration included a combination of global search and derivative-based methods. First, an initial global search of the parameter space was performed using the Covariance Matrix Adaptation-Evolution Strategy (CMA-ES) algorithm (Hansen, 2016) followed by the model-independent, derivative-based PEST (Doherty, 2018).

The objective function optimized by PEST represented the sum of the weighted calibration targets. Weights were scaled such that head targets and flow targets each comprised 50 percent of the objective function to avoid basis due to differences in the numbers of targets and their relative magnitudes. Penalty functions also were added to minimize heads above land surface in the uppermost active layer. Weights were iteratively adjusted during the calibration process to meet target calibration metrics. The model included more than 700 hydraulic conductivity and anisotropy pilot points, 96 recharge and ET multipliers, 49 streambed conductance multipliers, and 55 lake specific calibration parameters. Conductances for each spring were calibrated separately. The number of calibrated parameters totaled 1,043. A complete explanation of the calibration methodology can be found in Appendix I.

Types of calibration targets, calibration metrics, and metric targets for each metric are summarized in the table below. For each target type, the RMSE metric target was based on 5% of the calculated range between the lowest and highest target values observed among all target locations across the three calibration years. The RMSE metric target for heads is based on heads from all layers combined. Similarly, the RMSE for river baseflows was calculated using the range in estimated baseflows for all stream data used for calibration. In addition to RMSE metric targets, each type of calibration target has one or more additional metric targets. The metric targets are based on combined observations for all three calibration years.

Table 12. Metric and targets used in the EDM by calibration target type (from Appendix I)

Calibration Target Type	Calibration Metric[1]	Metric Target
All Targets	RMSE	5% of range in target values
Groundwater Heads	ME	Model-Wide: +/- 5 feet Woodville Karst Plain: +/- 1 foot
	MAE	10 feet
Horizontal and Vertical Head Differences	MAE ÷ Range	10%
Baseflow	MAE ÷ Target	20%
Spring Discharge	MAE ÷ Target	5-20% (variable by spring)
Year-to-Year Head Differences	MAE ÷ Target	10%

[1]RMSE = root mean square error; ME = mean error; MAE = mean absolute error

Calibration Results

The EDM was calibrated using the targets described above and using the methodology described in Appendix I. A total of 48 model runs were performed to derive the final calibrated parameters. Run logs are provided in Appendix I.

Mass Balance

The volumetric mass balance from the EDM calibration indicates that the largest inputs to the model are from rivers boundaries, followed by recharge, general head boundaries, and swallet inflows (represented with the Well Package) (Table 13). The largest outflows from the model are to river boundaries (e.g. baseflow to perennial streams), followed by drain boundaries, ET, and wells.

Table 13. Mass-balance summary from each calibration year by boundary type (from Appendix I)

		2009		2011		2014	
MODFLOW Package	**Boundary Description**	**Inflow (in/yr)**	**Outflow (in/yr)**	**Inflow (in/yr)**	**Outflow (in/yr)**	**Inflow (in/yr)**	**Outflow (in/yr)**
CHD	Gulf of Mexico	2.52E-04	3.12E-01	6.17E-04	2.77E-01	6.77E-04	2.93E-01
WEL	Groundwater Pumping	3.58E-01	7.66E-01	3.56E-01	8.97E-01	8.25E-01	6.63E-01
DRN	Springs and Intermittent Rivers	0.00E+00	7.73E+00	0.00E+00	4.95E+00	0.00E+00	7.87E+00
RIV	Perennial Rivers	1.64E+01	1.74E+01	1.70E+01	1.62E+01	1.57E+01	1.71E+01
EVT	Evapotranspiration	0.00E+00	5.73E+00	0.00E+00	5.14E+00	0.00E+00	7.13E+00
GHB	Lakes and Northern Boundary	8.62E-01	2.93E-01	7.96E-01	3.32E-01	8.81E-01	2.52E-01
RCH	Groundwater Recharge	1.46E+01	0.00E+00	9.74E+00	0.00E+00	1.60E+01	0.00E+00
Total		3.22E+01	3.22E+01	2.78E+01	2.78E+01	3.34E+01	3.34E+01
Percent Discrepancy		0.00%		0.00%		0.00%	

Groundwater Heads

Simulated versus observed heads for targets are shown in Figures 28 through 32, respectively. Groundwater head residuals met their metric targets both model-wide and in the Woodville Karst Plain with RMSE/Range, mean error (M E), and mean absolute error (MAE) values of 3.7%, 0.43 feet, and 5.88 feet, respectively. Vertical head difference target residuals met their target metric goal with a MAE/Range value of 3.6%. Horizontal head target residuals did not meet the metric target with a MAE/Range value of 15%.

Plots of simulated versus observed heads for each layer are shown on Figure 29 through Figure 33 and metrics are shown in Table 14. The mean absolute error (MAE) of all groundwater head targets combined range from approximately 5 feet in 2014 to nearly 7 feet in 2011, with the largest MAE occurring in Layer 2 for all three calibration years. The lowest MAE across calibration years was in Layers 3 and 4 (Miocene-age limestone formations and Oligocene-age limestone formations of the Floridan aquifer), ranging from approximately 4 feet to 6 feet. The mean error (ME) for all head targets combined was between 0 and 1 foot for all calibration years, indicating a slight overestimation of heads by the model. Layers 1 and 2 had negative ME values for all calibration years, with values ranging from approximately -10 feet to -0.2, indicating an underestimation of groundwater heads in the surficial aquifer/overburden and the intermediate system. It is important to note that the intermediate system had the least number of head targets compared to all other layers.

The year-to-year head difference targets had the largest residuals for any target type with a MAE/Target value of 102%.

Table 14. Groundwater head target metrics for each calibration year by layer (from Appendix I)

Layer	2009		2011		2014	
	Mean Error (Feet)	Mean Absolute Error (Feet)	Mean Error (Feet)	Mean Absolute Error (Feet)	Mean Error (Feet)	Mean Absolute Error (Feet)
1	-0.18	4.80	-3.65	5.90	-5.09	8.57
2	-6.20	8.50	-10.23	13.95	-9.49	10.37
3	-0.56	5.47	-0.76	5.90	0.10	4.05
4	1.72	5.20	3.24	6.39	1.67	4.62
5	4.70	7.22	8.01	9.84	4.48	7.51
Total	0.40	5.56	0.91	6.92	0.01	5.14

Baseflow and Spring Flow Targets

The river baseflow target residuals met their target metric goal with an MAE/Range of 17% (Table 15). All spring flow target residuals met their target metric goals except Chicken Branch Spring which had a metric goal of 50%, but has a simulated error of approximately 75% (Table 16). However, only a single discharge measurement was available for Chicken Branch Spring and was used as the target for all three years. Spring flows are generally underestimated, based on the number of negative (20) and positive (5) errors. Error statistics for the St. Marks River Rise, Wakulla Spring, and the Spring Creek Spring Group indicate that these flows are simulated very accurately.

Table 15. Final calibration target metrics summary by target type (from Appendix I)

Calibration Target Group	Units	RMSE	Range in Target Values	RMSE/ Range in Target Values	ME	MAE	Min Error	Max Error	MAE/ Range in Target Values	Model-wide MAE/ Target
Spring Discharges	(ft^3/s)	15.26	935.0	1.6%	-8.0	9.7	-40.4	7.0	1.0%	3.9%
Total Baseflows	(ft^3/s)	62.40	1,278.3	4.9%	9.8	35.9	-223.8	231.6	2.8%	17.0%
Incremental Baseflows	(ft^3/s)	28.12	422.0	6.7%	11.2	18.9	-34.0	69.4	4.5%	10.0%
Groundwater Heads	Feet	8.86	242.22	3.7%	0.43	5.88	-37.34	35.25	2.4%	12.0%
Groundwater Heads (Woodville Karst Plain)	Feet	5.36	183.55	2.9%	0.88	3.60	-37.34	11.14	2.0%	14.0%

Horizontal Head Differences	Feet	9.87	53.60	18.4%	0.85	7.79	-16.73	16.94	15.0%	31.0%
Vertical Head Differences	Feet	7.37	144.41	5.1%	0.25	5.25	-23.94	14.21	3.6%	17.0%
Year-to-Year Head Differences	Feet	4.05	48.06	8.4%	-0.83	2.55	-15.69	18.00	5.3%	102.0%

Table 16. Spring Flow target calibration statistics summary by spring name (from Appendix I)

	Relative Error (%)				
Spring	**2009**	**2011**	**2014**	**Mean Absolute Error**	**Accuracy Goal**
Spring Creek Spring Group	-5.0%	NA	-0.8%	2.9%	20%
St. Marks River Rise	-1.9%	0.0%	-0.2%	0.7%	10%
Wakulla Spring	1.2%	-1.4%	-0.2%	0.9%	10%
Wacissa River Spring Group	-5.1%	4.8%	4.5%	4.8%	50%
Chicken Branch Spring	-57.2%	-100.0%	-66.5%	74.6%	50%
Crays Rise	-47.8%	-52.5%	-48.0%	49.4%	50%
Horn Spring	-2.3%	-48.7%	-3.1%	18.0%	20%
Sally Ward Spring	42.1%	4.6%	-3.4%	16.7%	20%
Wakulla Spring + Spring Creek Spring Group	-0.6%	NA	-0.4%	0.5%	NA

Hydrologic Property Distribution

The calibrated hydrologic properties for each HGU are shown on Figures 34 through 38. For the four HGUs conceptualized as aquifer units, the property of transmissivity is shown. These include the Surficial Aquifer HGU, Miocene-age Limestone HGU, the Oligocene-age Limestone HGU, and the Ocala Limestone HGU. The Intermediate System HGU is conceptualized as a confining unit and the property of leakance is shown.

The calibrated transmissivities for the surficial aquifer range from less than 200 ft^2/d to approximately 20,000 ft^2/d (Figure 33). The greatest calibrated transmissivities in the Surficial Aquifer HGU are located in northern Leon and southern Grady Counties and western Gadsden and Liberty Counties. The calibrated Intermediate System HGU leakance values range from $3x10^{-9}$/day to approximately 1/day (Figure 35). The lowest leakance values of the confining unit are located in the Embayment region, with the low values trending from Grady County northeast to Colquitt County in Georgia. The highest leakance values are along the Cody Scarp where the confining unit pinches out. The Miocene-age Limestone HGU calibrated transmissivities range from approximately 160 ft^2/d to approximately 350,000 ft^2/d (Figure 36). The greatest transmissivities are generally located in the north-eastern Wakulla and southern Leon Counties which is approximately coincident with the Woodville Karst Plain region. The lowest transmissivities for the Miocene-age Limestone HGU are located in northern Liberty County in

Florida through the northern extent of the HGU in Colquitt County, Georgia and is generally coincident with the Embayment region.

The calibrated transmissivities within the Oligocene-age Limestone HGU (Figure 37) are generally the greatest within the EDM. Across the entire extent of this HGU, transmissivities range from approximately 1,500 ft^2/d to approximately 2,000,000 ft^2/d. The lower transmissivities within this HGU (e.g. 1,500 ft^2/d – 75,000 ft^2/d) are generally located within the Embayment region. The highest transmissivities within this HGU (e.g. 100,000 ft^2/d – 2,000,000 ft^2/d) are located within or near the Woodville Karst Plain region, with the highest transmissivities in the EDM located in southern Wakulla to central Leon Counties. These results are generally consistent with the conceptual model of the Floridan aquifer within the Woodville Karst Plain and is also consistent with calibrated transmissivities in this region in previous groundwater flow modeling studies (e.g. Bush and Johnston, 1988; Davis, 1996; Durden et al., 2018).

The calibrated transmissivities within the Ocala Limestone HGU (Figure 38) range from approximately 900 ft^2/d to approximately 5,000,000 ft^2/d. The distribution of transmissivity values are general consistent with the conceptual model with the lowest transmissivities (e.g. 900 ft^2/d – 50,000 ft^2/d being located within the Embayment region. The greatest transmissivities within the Ocala Limestone HGU are located in eastern Leon and central Jefferson Counties, which is within the Woodville Karst Plain and is proximal to the Wacissa River Spring Group.

Recharge and Maximum Saturated Evapotranspiration Distributions

The distribution of calibrated recharge and maximum saturated ET for 2009 (hydrologically average conditions) are shown in Figures 39 and 40, respectively. Calibrated recharge rates for 2009 range from approximately 0.04 in/yr to approximately 42 in/yr. Calibrated maximum saturated evapotranspiration rates for 2009 range from approximately 0.04 in/yr to approximately 30 in/yr. The recharge for a small area in southeastern Leon County ranges from approximately 78 in/yr to approximately 86 in/yr, which represented the application rates at the Tallahassee sprayfield. These application rates are metered and were fixed during model calibration. The spatial distribution in recharge is highly variable and patterns reflect the uniform adjustment of recharge within watershed zones by multipliers during the calibration process.

Parameter Sensitivity Analysis

Sensitivity analysis of the model calibration parameters was performed by Tetra Tech and a full description of the methodology can be found in the Tetra Tech EDM Calibration Final Technical Memorandum (Appendix I). The sensitivity analysis was performed using the PEST utility SENSAN. The EDM had a total of 1,043 calibration parameters and each calibration parameter was varied +/- 20% from their base values. The sensitivity analysis results showed that approximately 90% (932) of the 1,043 parameters had Mean Absolute Sensitivities (MAS) of less than 1%. The results showed that the most sensitive parameters to the model are vertical hydraulic conductivities of lakes, with Lake Seminole, Lake Talquin, and Lake Miccosukee having the highest MAS values.

Predictive Uncertainty Analysis

A Monte Carlo analysis was performed to assess the impact of parameter uncertainty on simulated spring flows and river baseflows at selected locations. The uncertainty analysis consisted of 10,000 different parameter sets and was generated such that they varied normally or log-normally with one standard deviation being equal to 10% of the calibrated parameter value. Low discharge (i.e. <100 ft^3/s) springs had greater relative predictive uncertainties in the simulated absolute values of spring flows than higher (>100 ft^3/s) discharge springs. However, groundwater models are more accurate at simulating changes in heads and flows than simulating absolute values of heads or flows. Future work may be performed to assess the uncertainty of simulated changes in heads and spring flows. A more complete explanation of the methodology and results of the EDM uncertainty analysis can be found in Appendix J.

Application of the EDM

The most important calibration targets – heads, baseflows, and spring flows – generally met or exceeded the desired metric goals indicating that the EDM is a useful tool to simulate the effects of average annual withdrawals on Floridan aquifer levels, spring discharge, and stream baseflows under average (2009), dry (2011), and wet (2014) hydrologic conditions. The model can also simulate the long-term average effects of groundwater withdrawals using projected pumpage for future years. Due to the limited data available to calibrate the surficial aquifer, further testing is needed to determine the usefulness of the model to simulate changes in surficial aquifer levels.

Because the model is steady-state, it does not simulate changes in storage. Nor does the model simulate hydrologic responses on a short time scales such as daily or weekly. The model does not simulate contaminant transport processes in karst areas, which may be influenced by conduit flow processes and turbulent flow conditions. The model assumes constant water temperature and density and therefore does not simulate density-dependent flow or saltwater movement near the coast. As with any groundwater flow model, there are uncertainties in parameter estimates and simulated values. As discussed above, Appendix I provides the results of sensitivity analysis performed for EDM, v. 1.0. Refinement of the EDM is ongoing with additional revisions planned during 2019.

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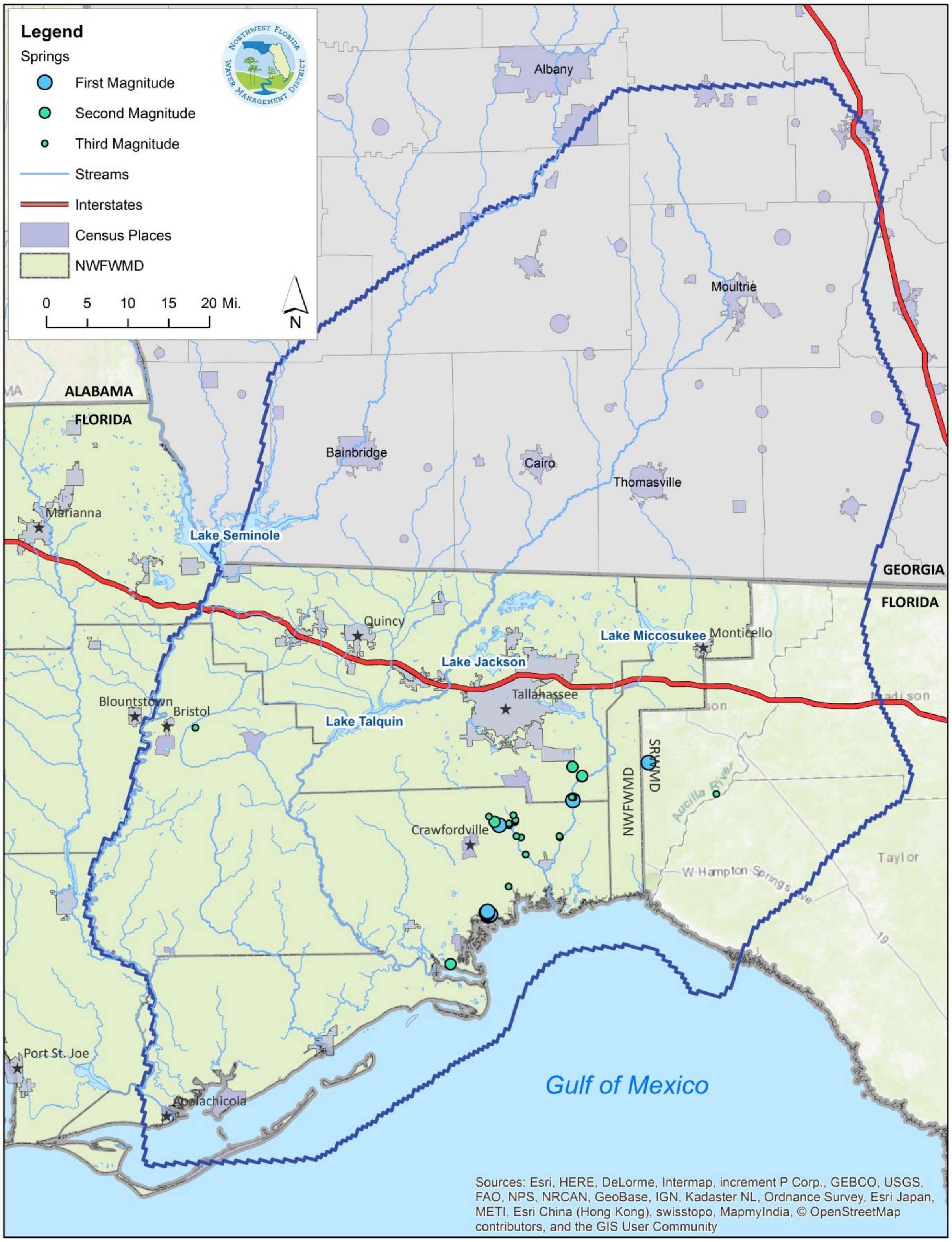

Figure 1. EDM Domain

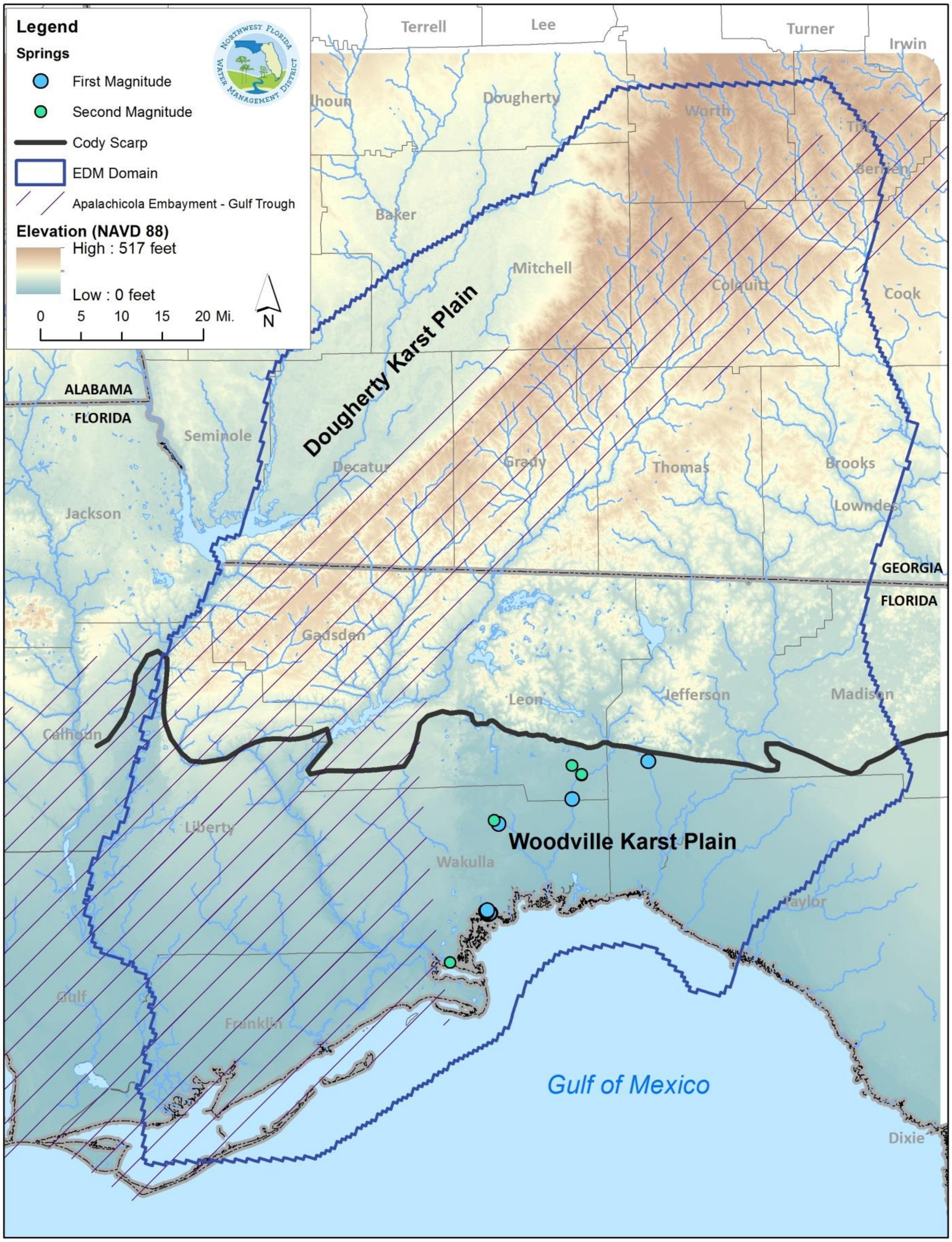

Figure 2. Topography in the EDM Area

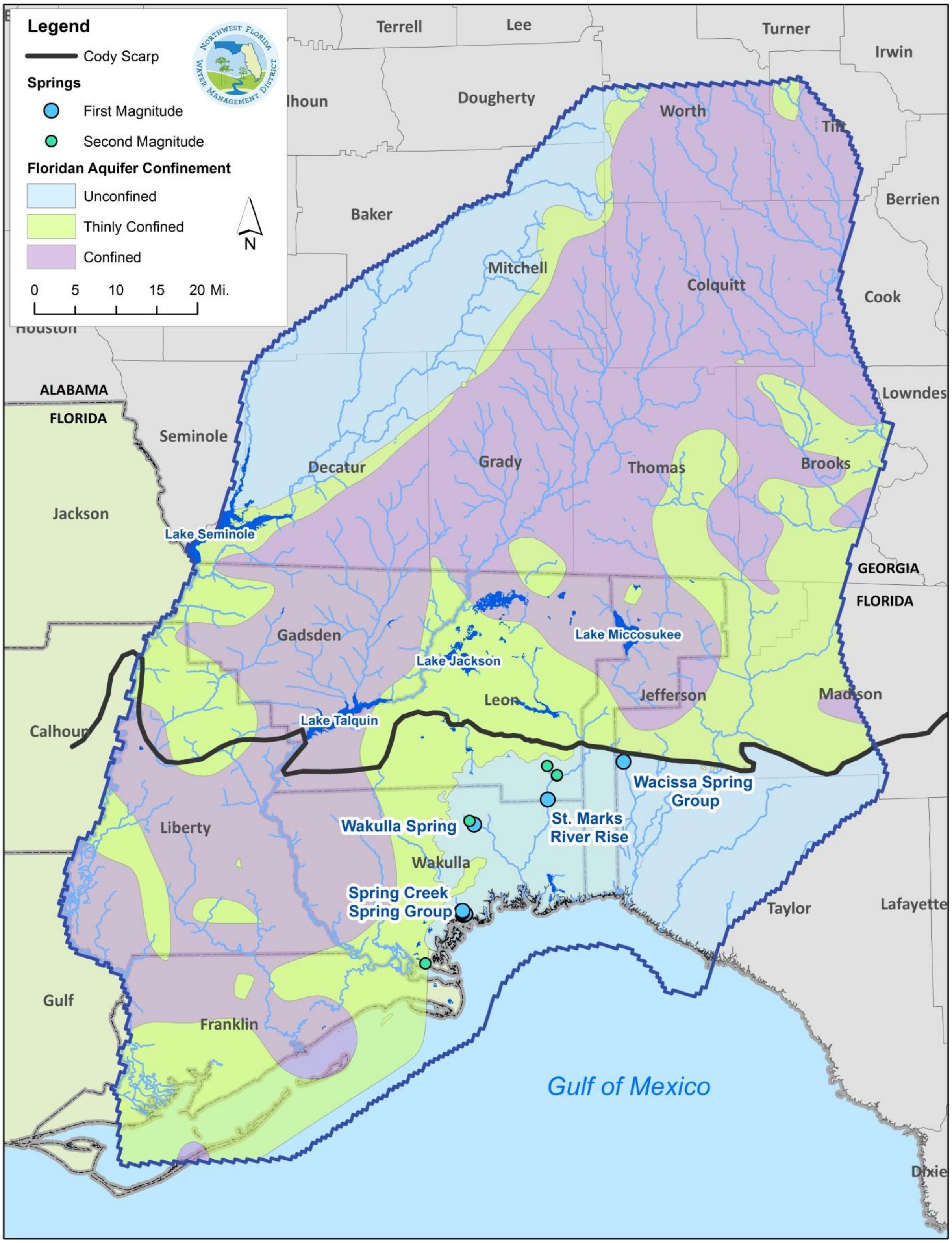

Figure 3. Generalized Degree of Confinement of the Floridan Aquifer System (Williams and Dixon 2015)

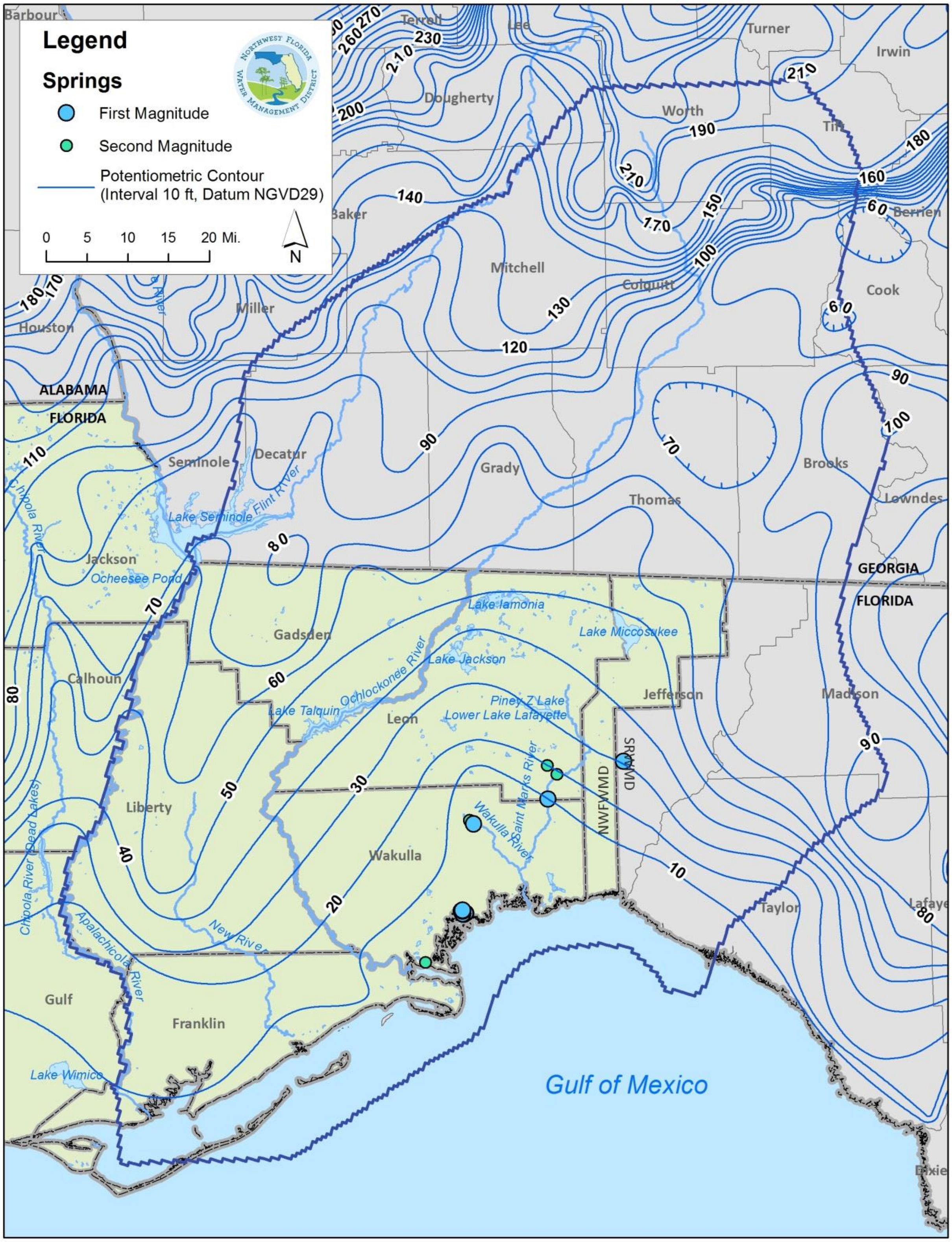

Figure 4. USGS May 2010 Floridan Aquifer Potentiometric Surface

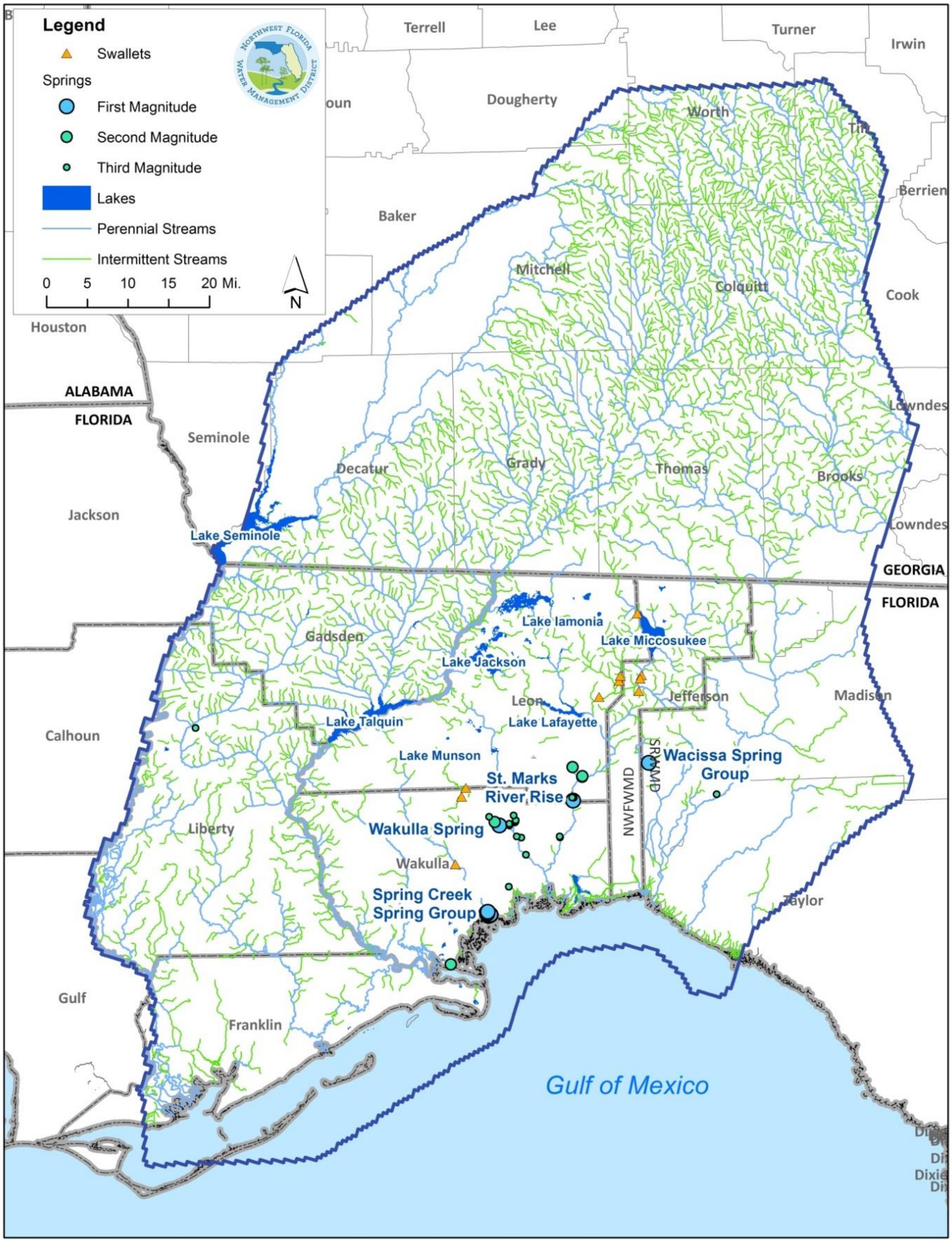

Figure 5. Hydrography Represented in the EDM

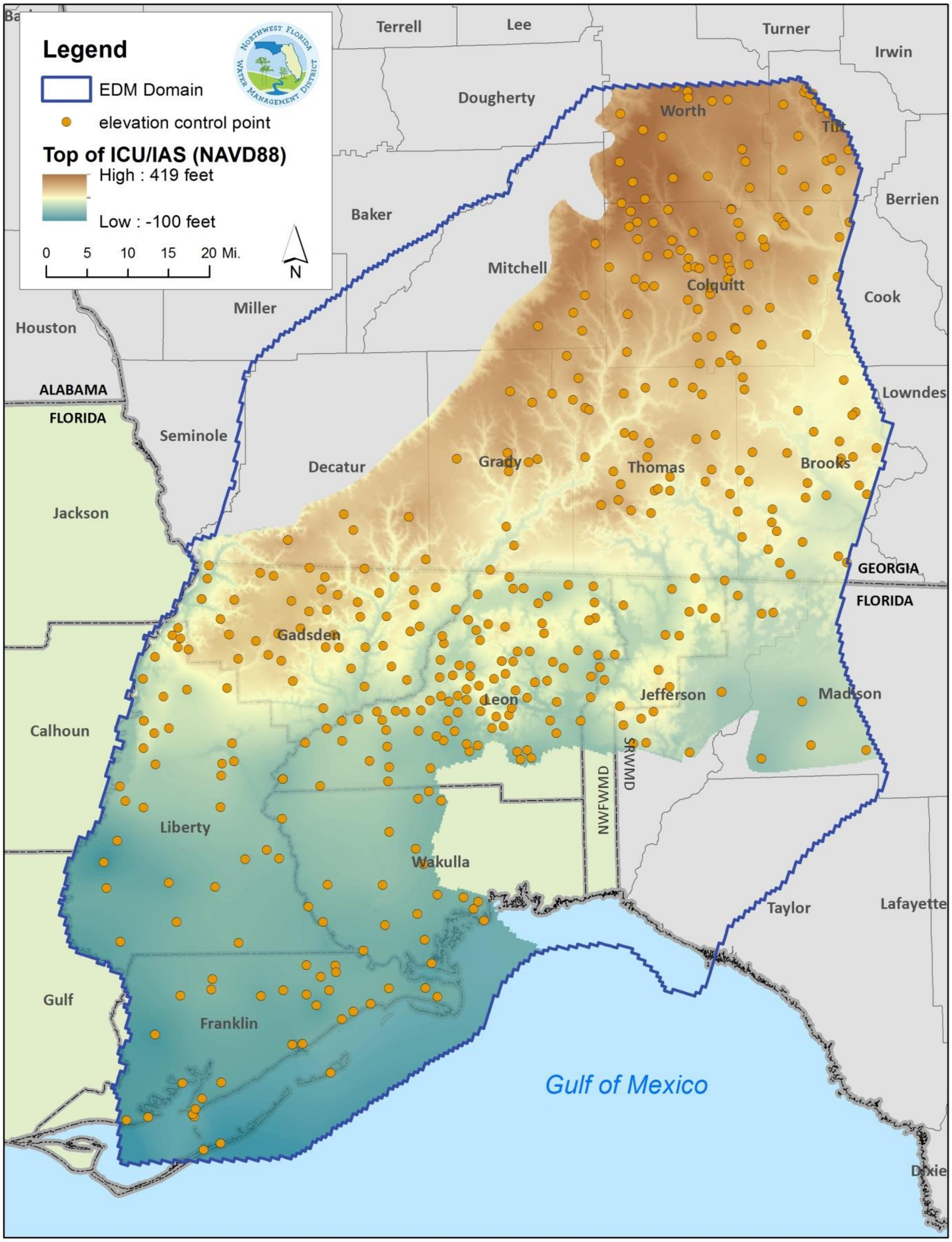

Figure 6. Elevation of the Top of the Intermediate System Within the EDM

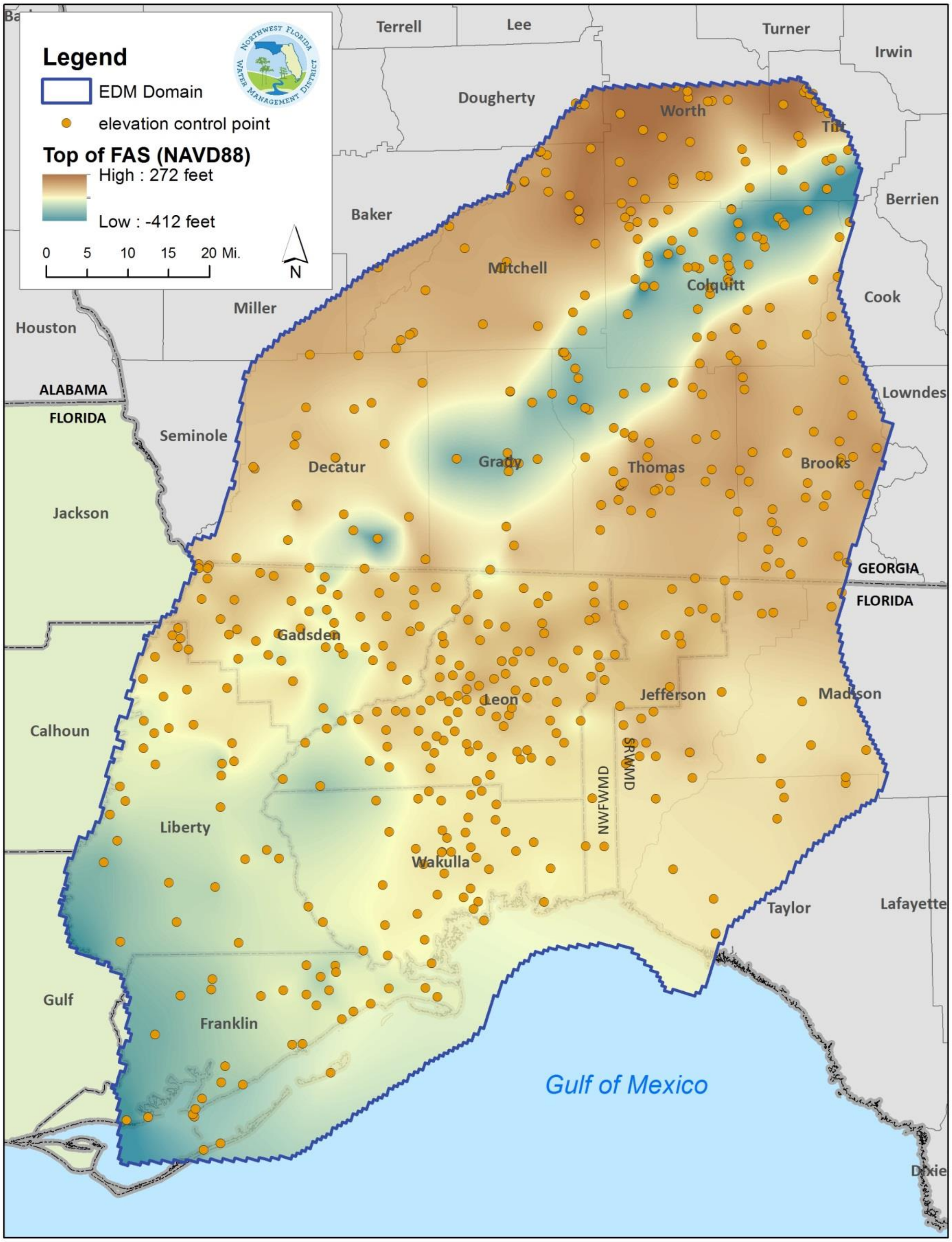

Figure 7. Elevation of the Top of the Floridan Aquifer System Within the EDM

Figure 8. Lateral Boundary Conditions in the EDM

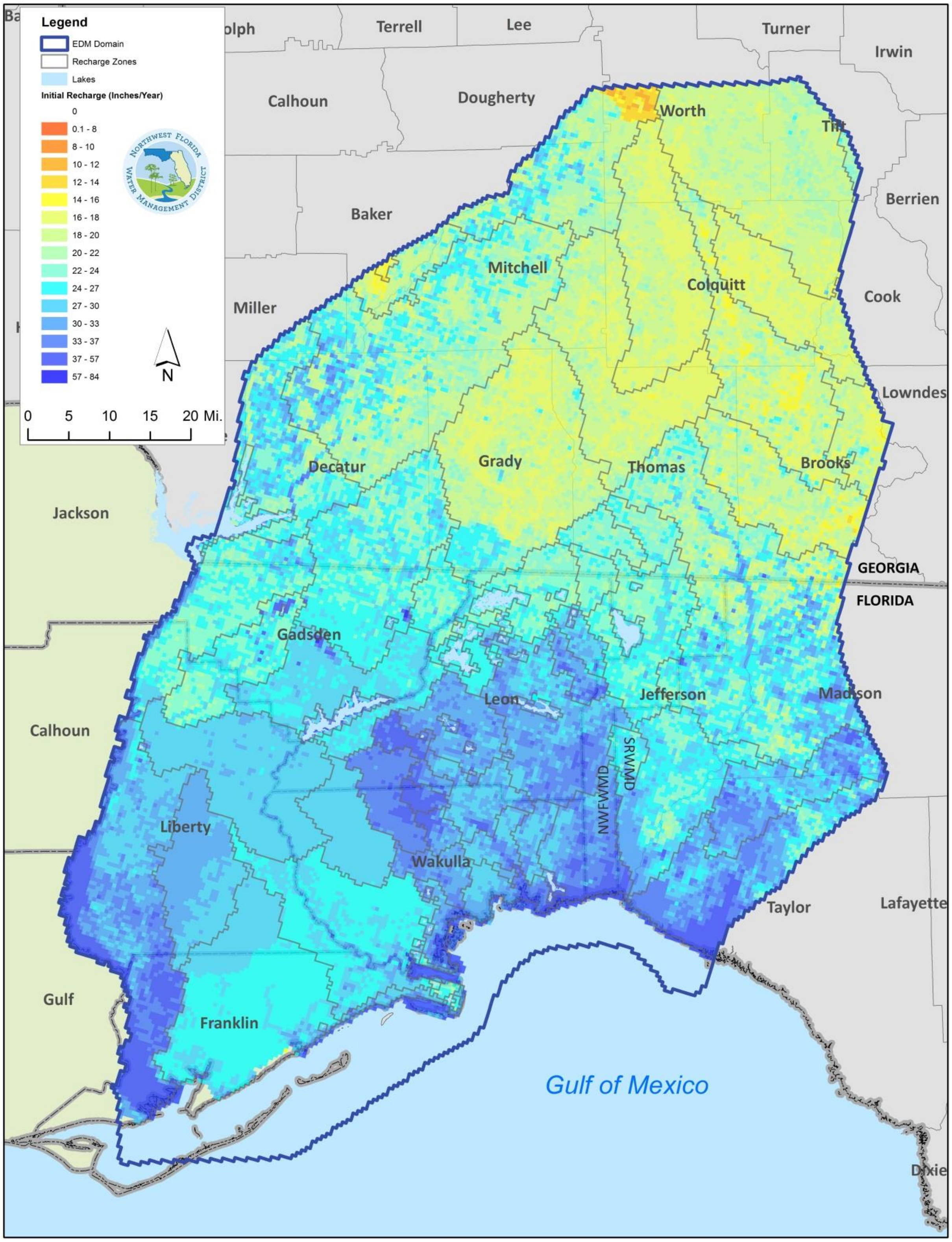

Figure 9. Initial Recharge Rates, 2009

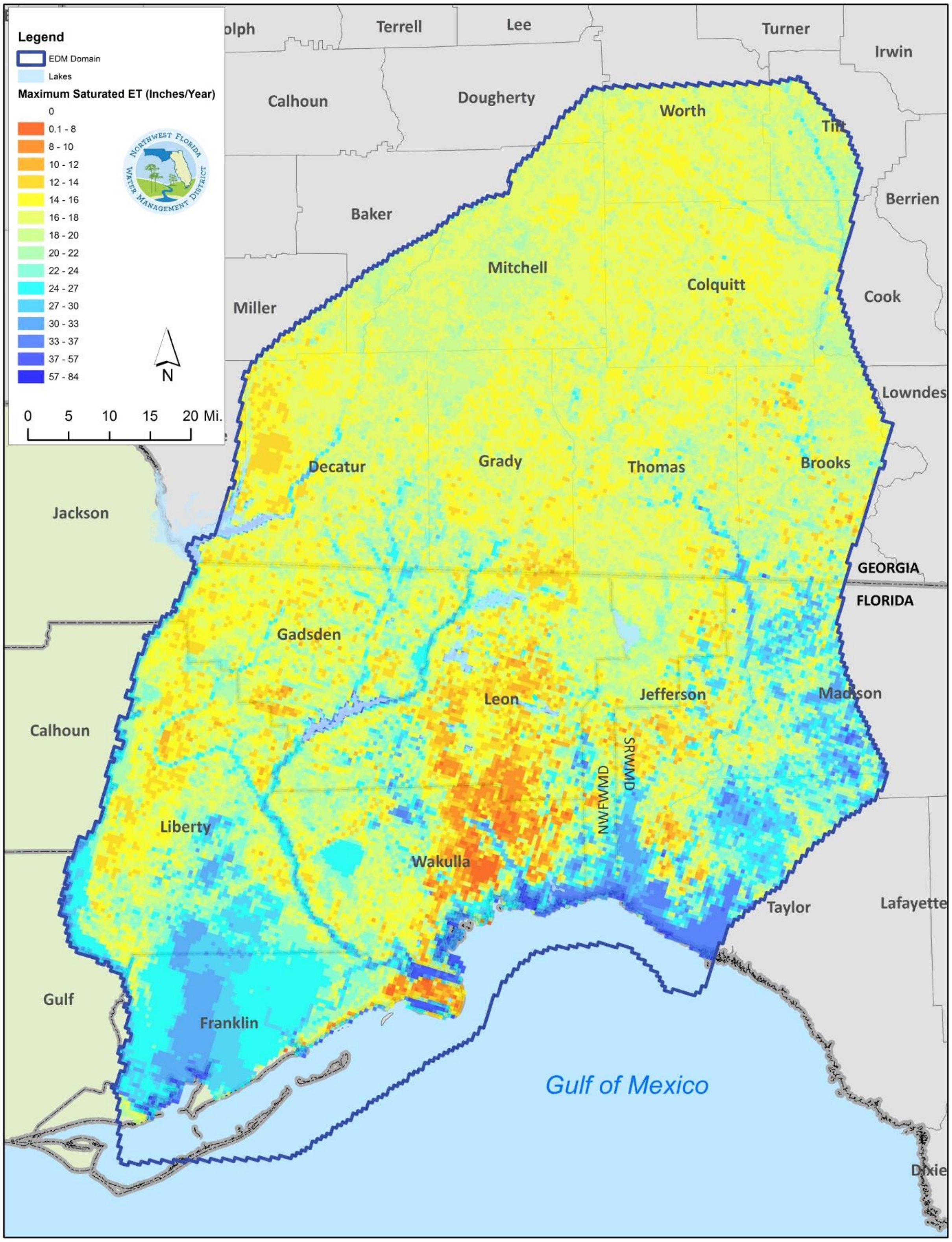

Figure 10. Initial Maximum Groundwater ET Rates, 2009

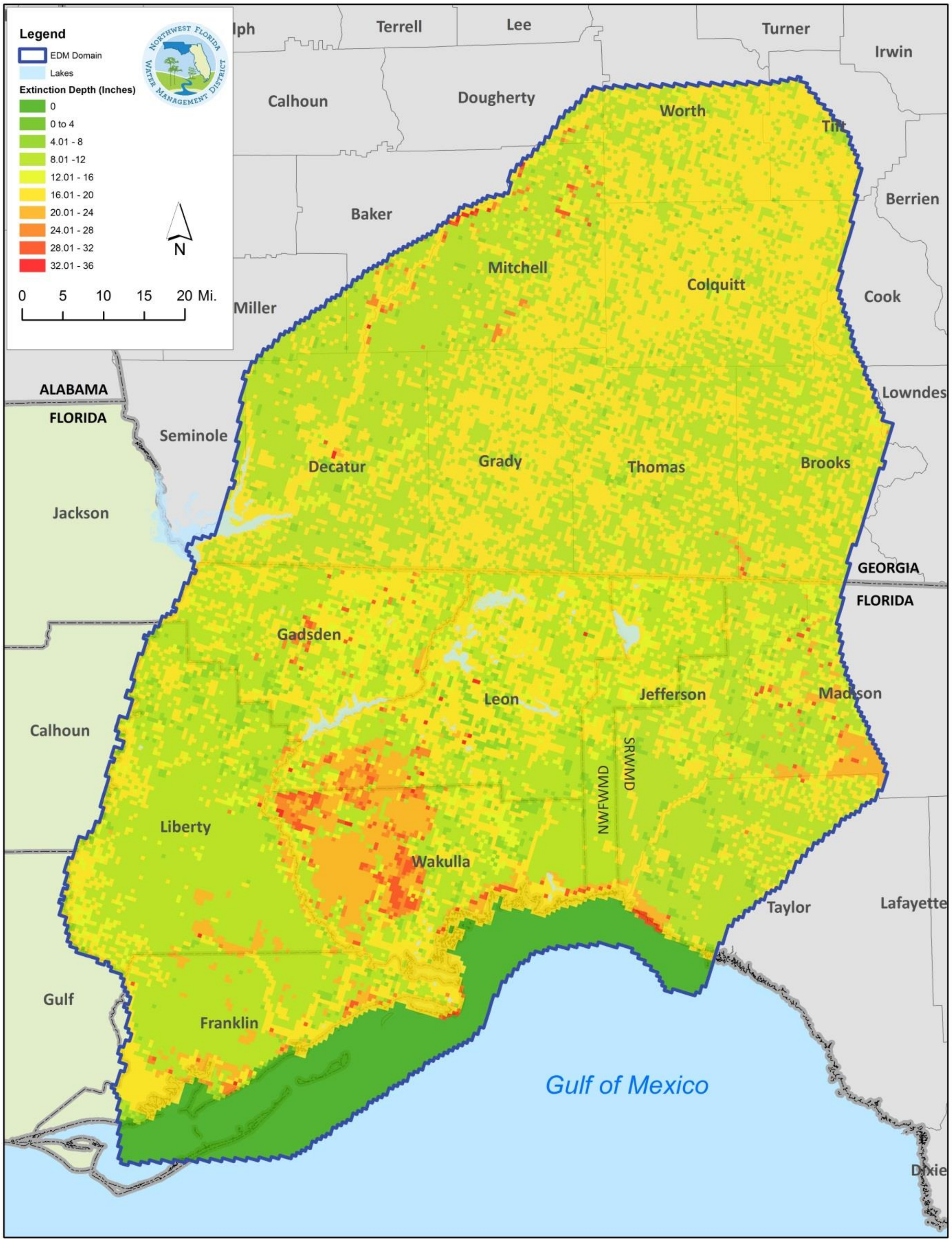

Figure 11. Extinction Depths for Groundwater ET

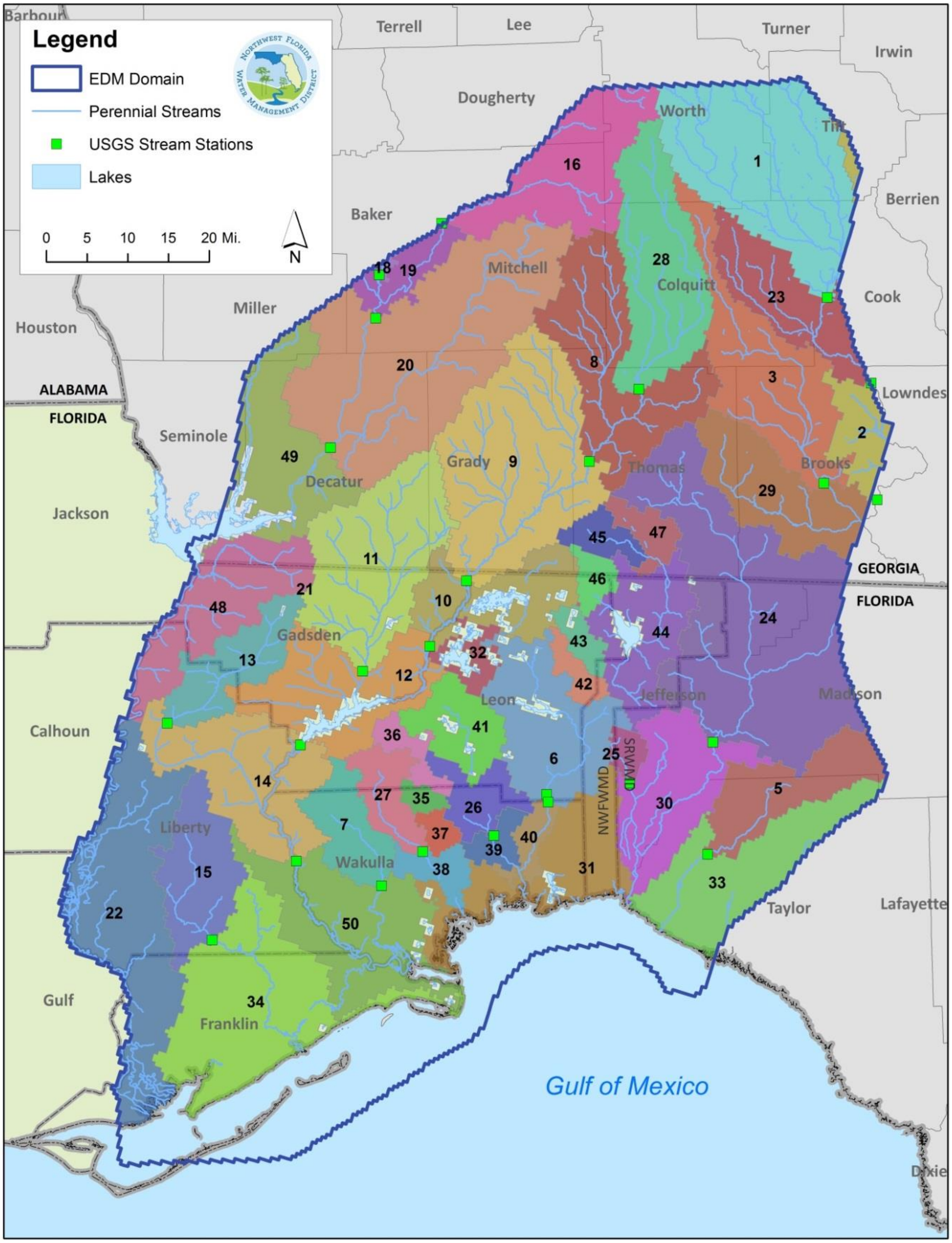

Figure 12. Watershed Zones and USGS Streamflow Stations

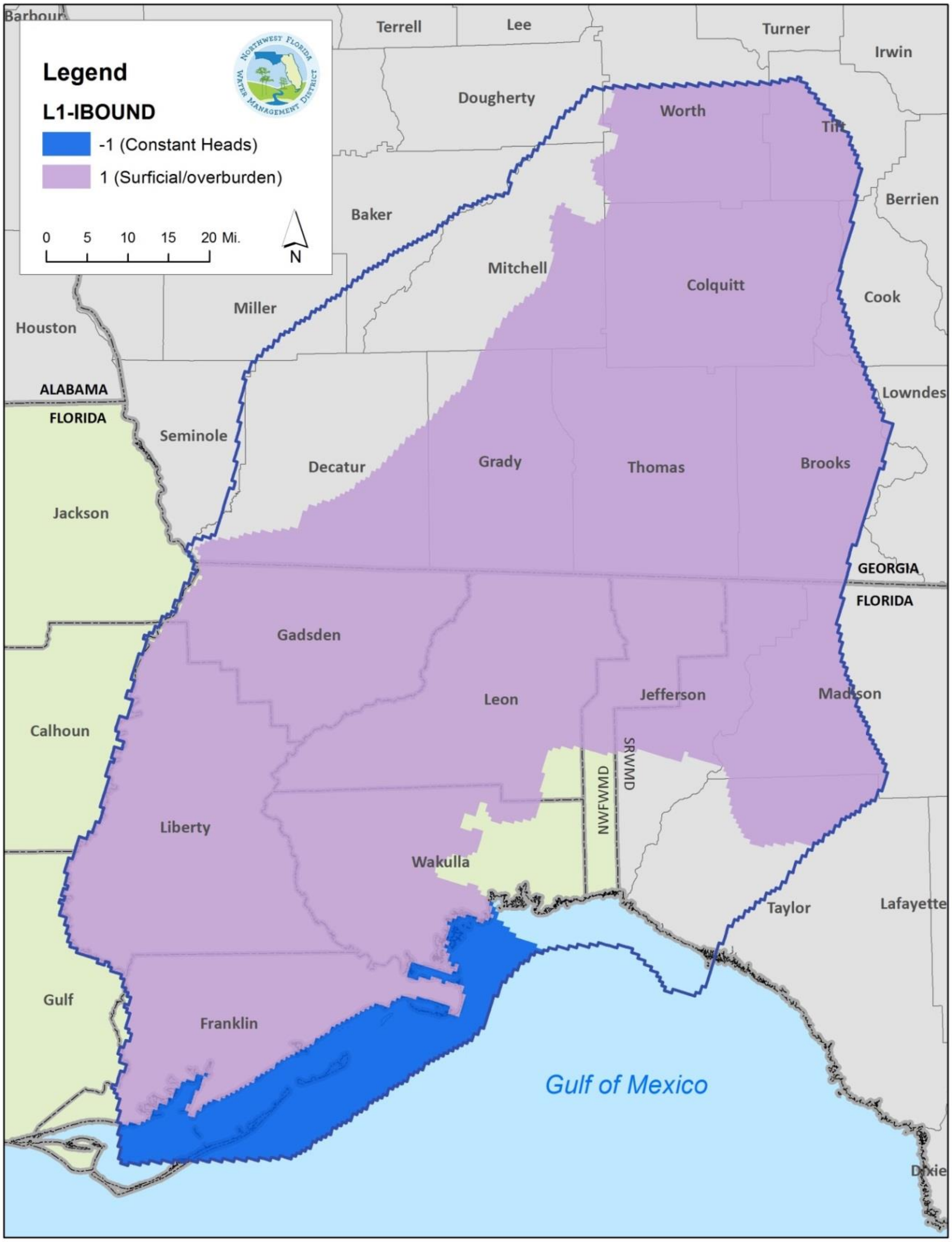

Figure 13. Layer 1 Hydrogeologic Unit IBOUND Designations

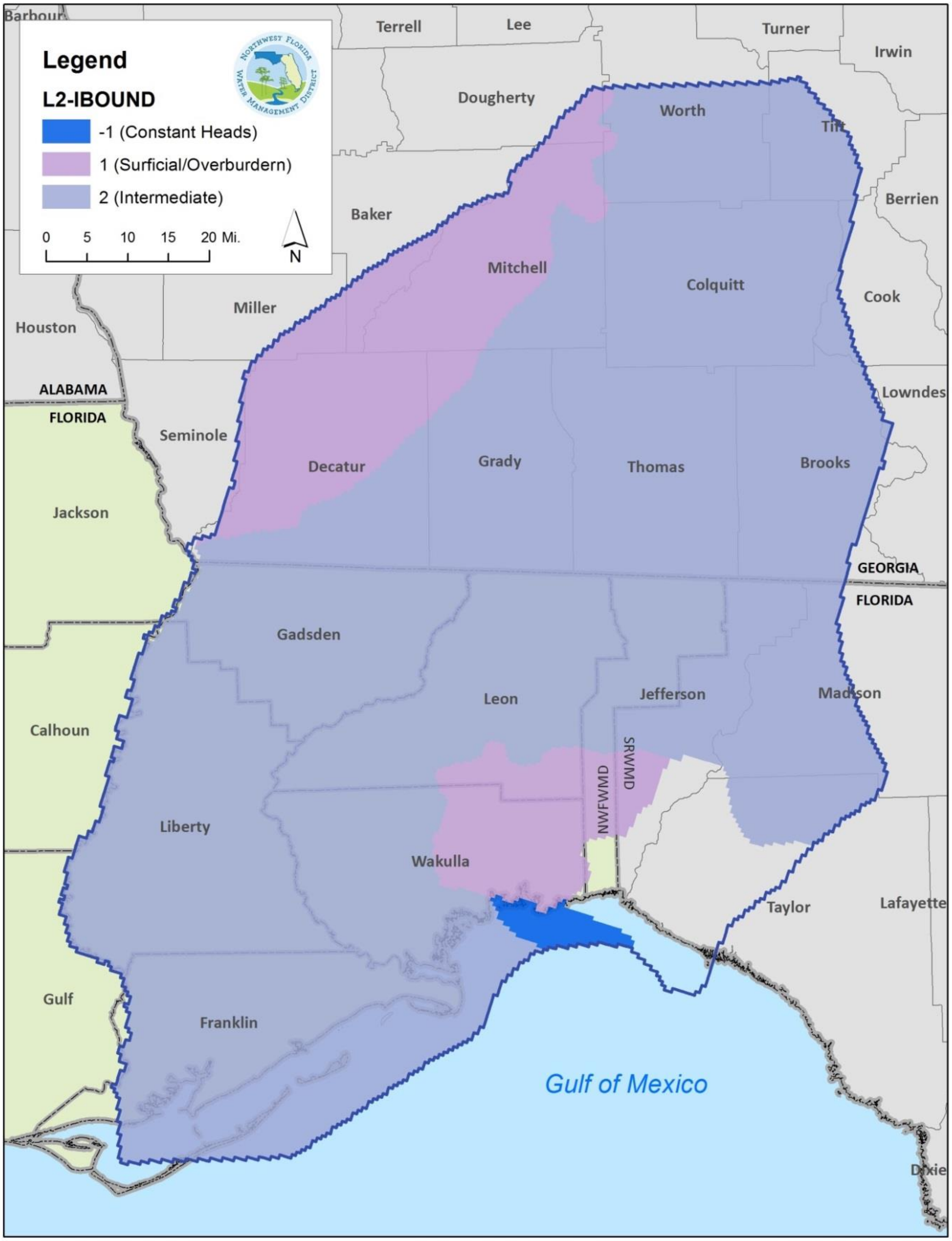

Figure 14. Layer 2 Hydrogeologic Unit IBOUND Designations

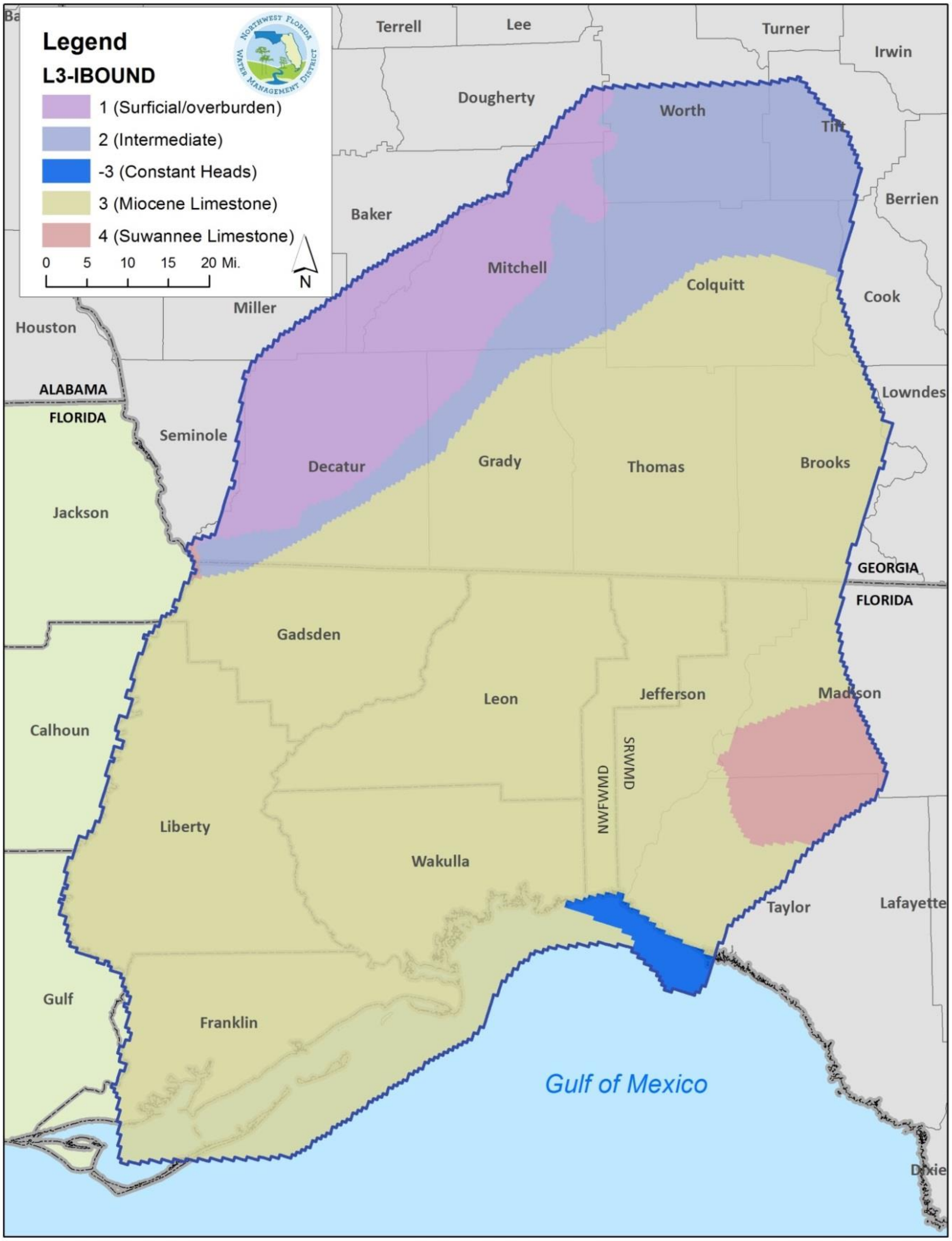

Figure 15. Layer 3 Hydrogeologic Unit IBOUND Designations

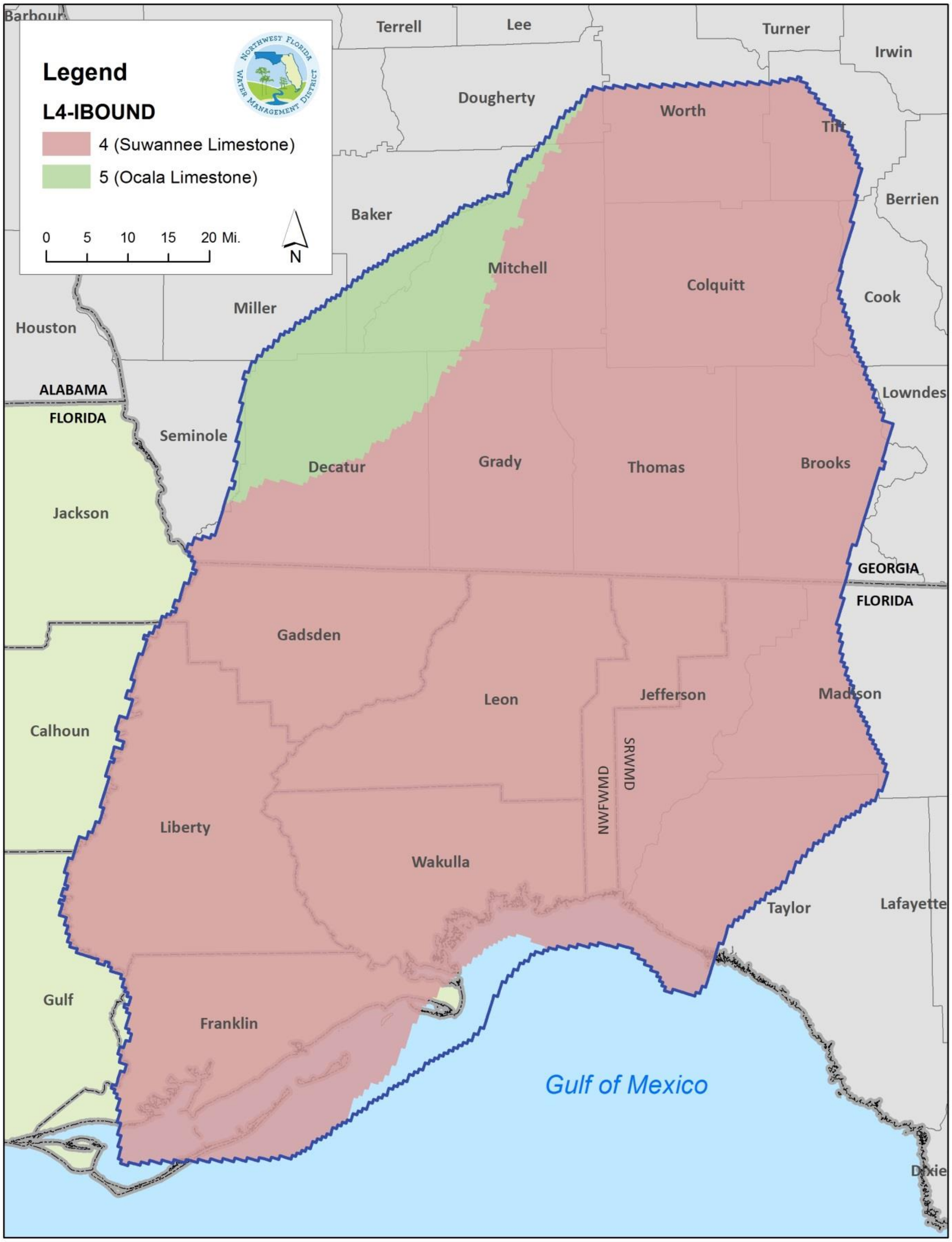

Figure 16. Layer 4 Hydrogeologic Unit IBOUND Designations

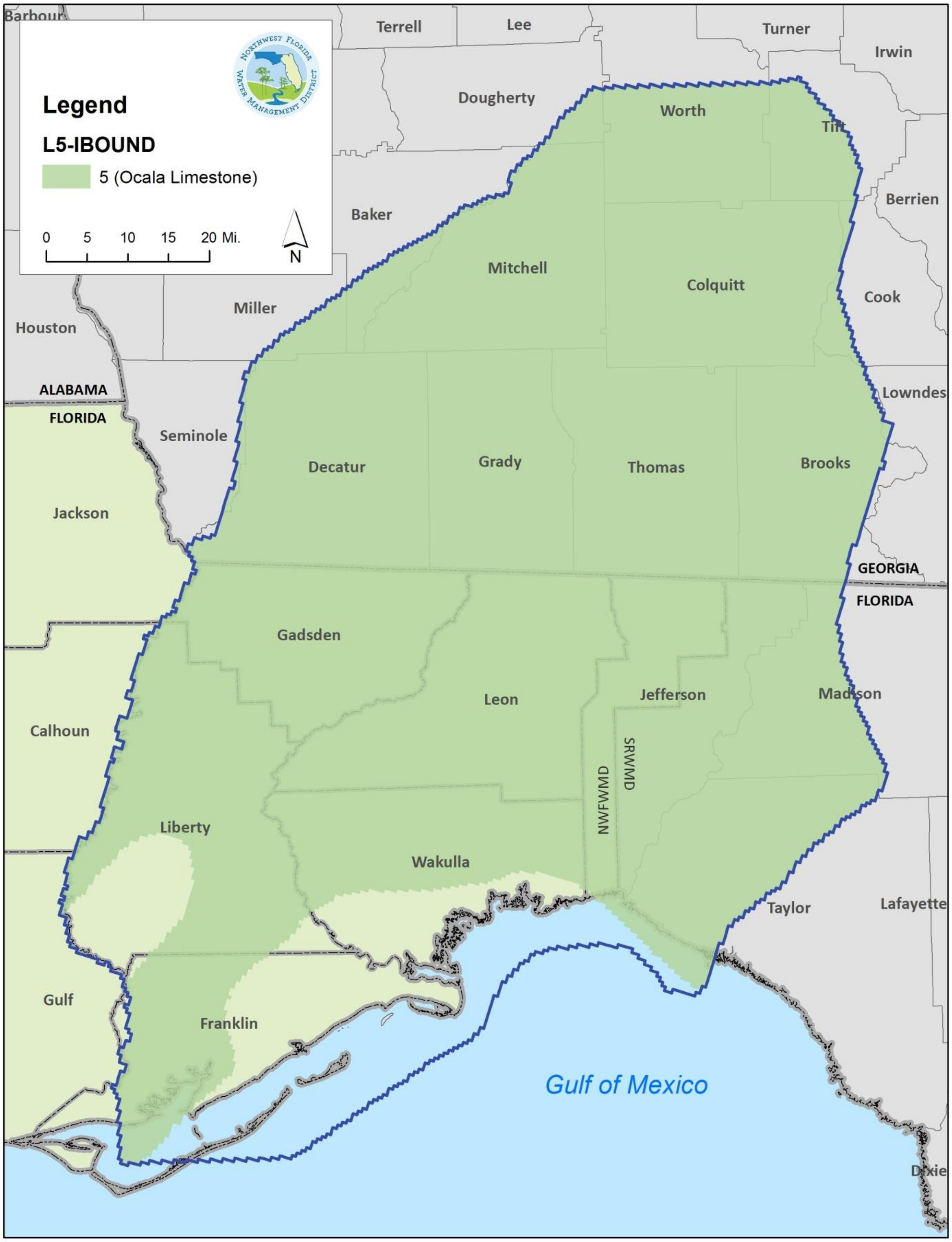

Figure 17. Layer 5 Hydrogeologic Unit IBOUND Designation

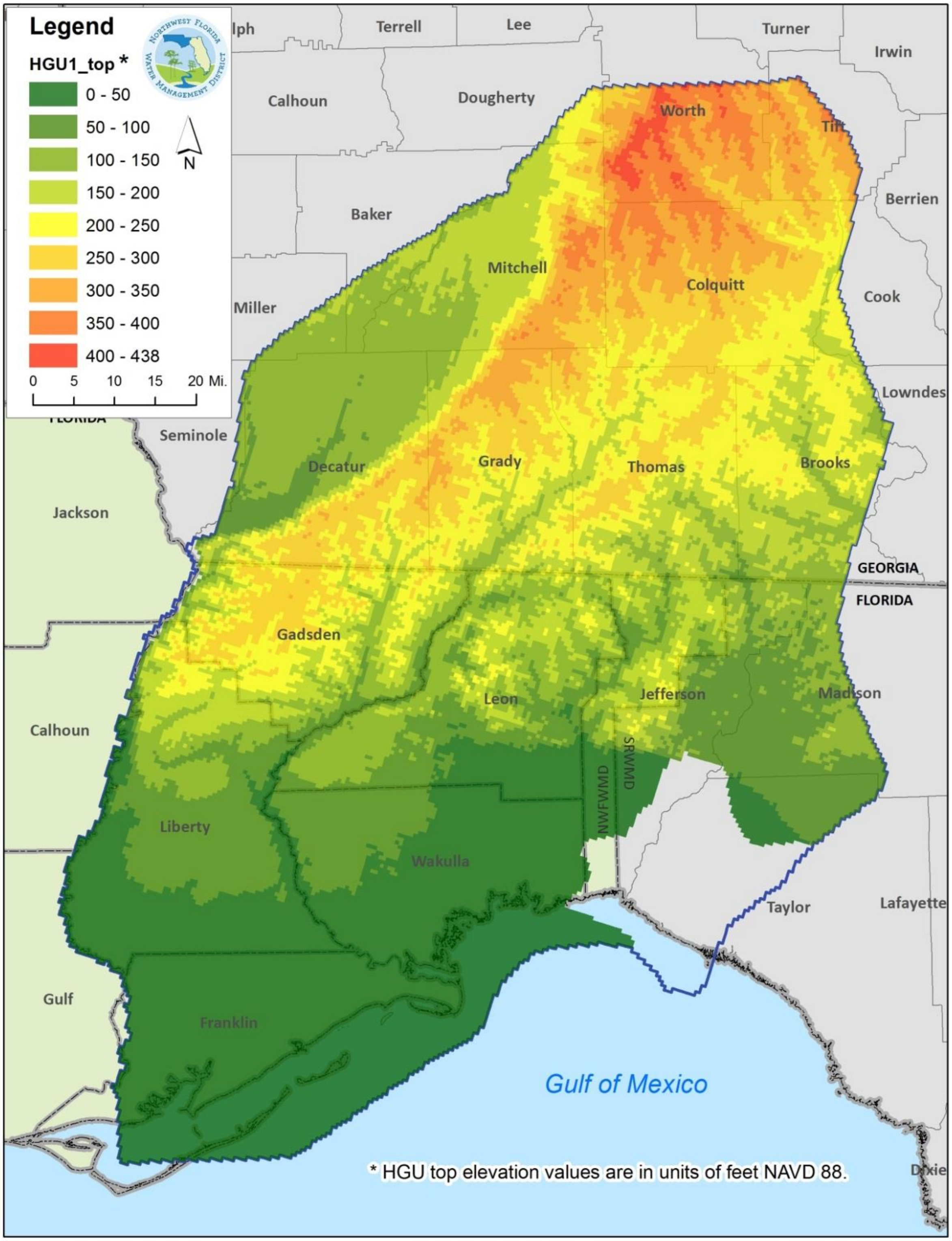

Figure 18. Altitude of the Top of HGU1 (Surficial Aquifer and Overburden) in the EDM

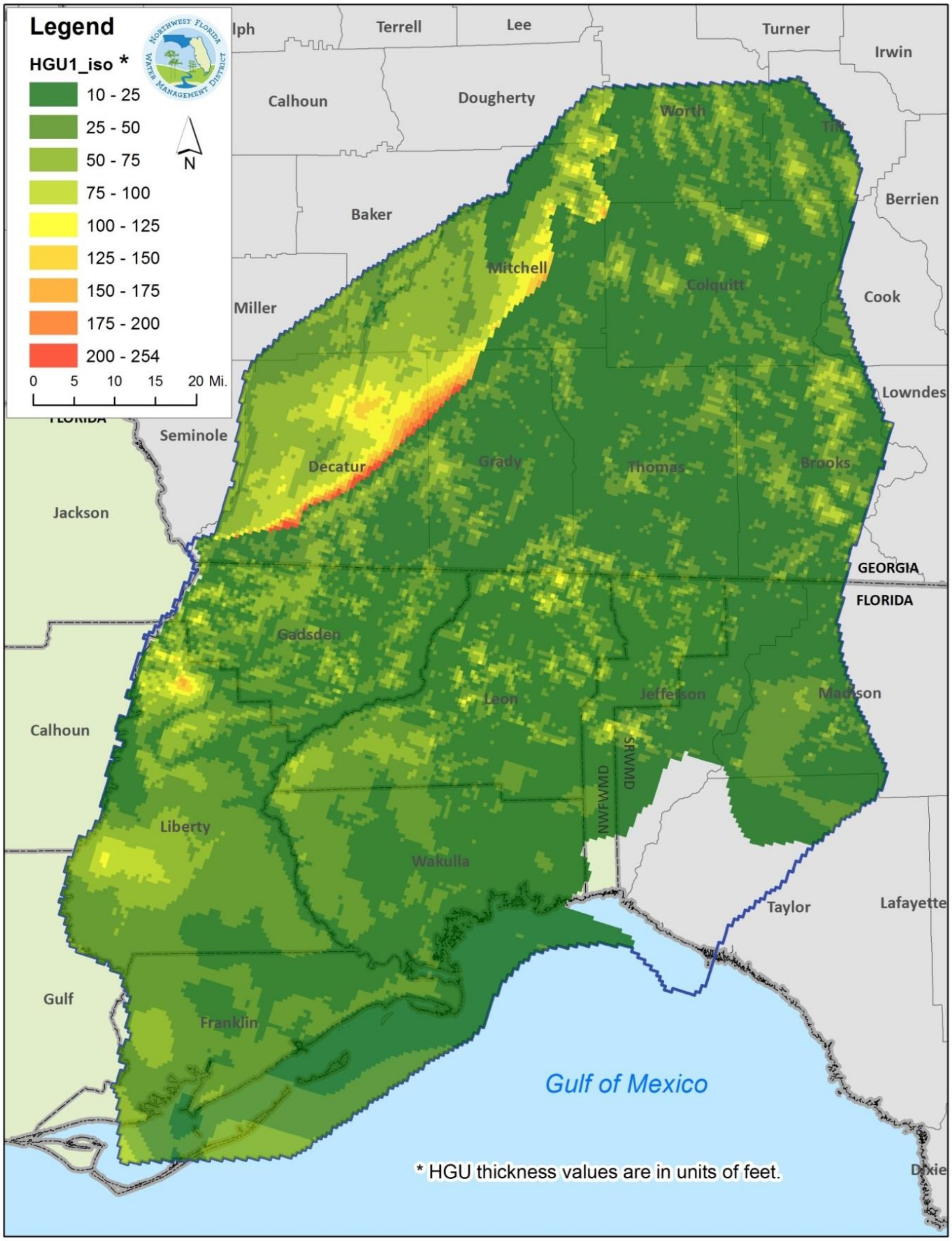

Figure 19. Thickness of HGU1 (Surficial Aquifer and Overburden) in the EDM

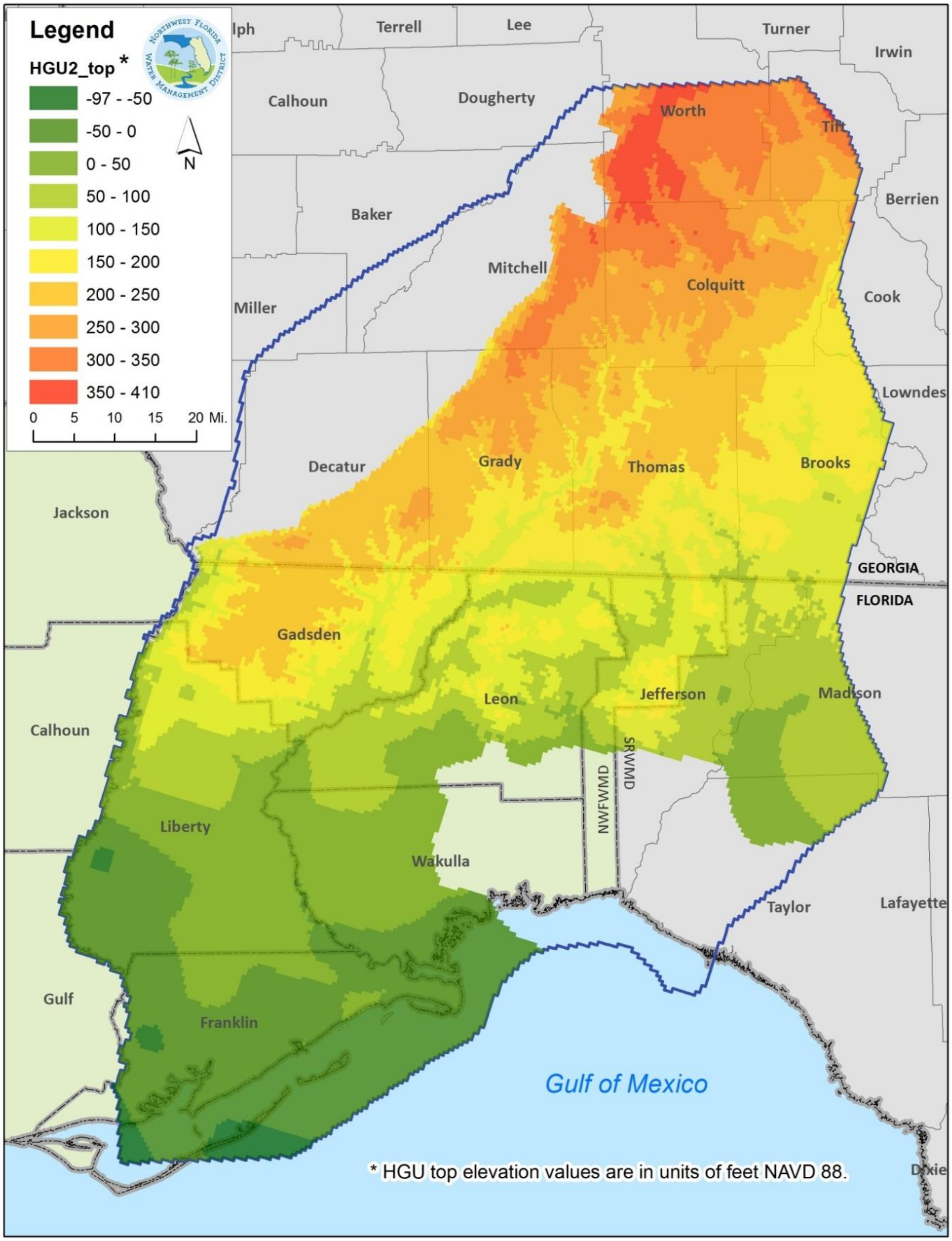

Figure 20. Altitude of the Top of HGU2 (Intermediate System) in the EDM

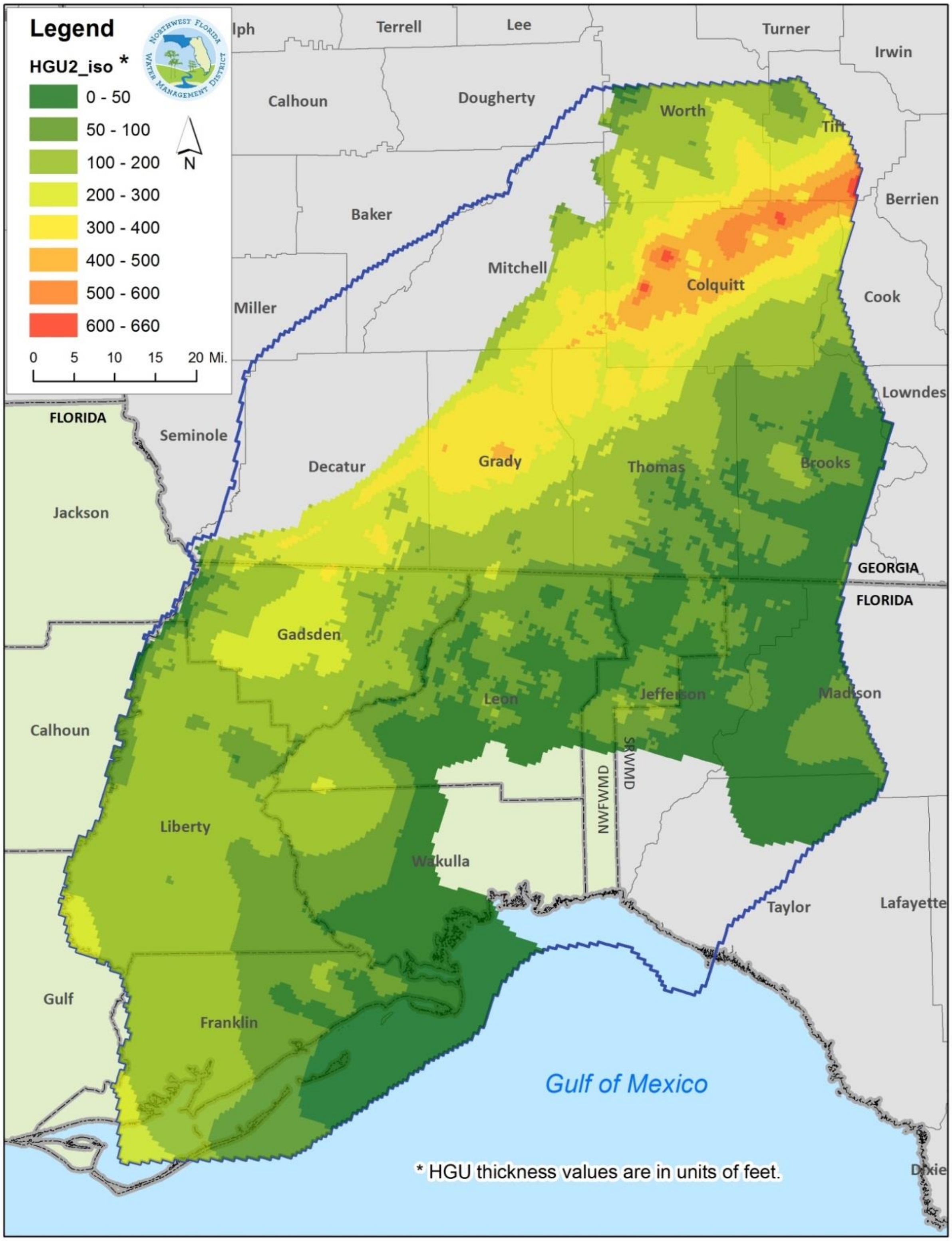

Figure 21. Thickness of HGU2 (Intermediate System) in the EDM

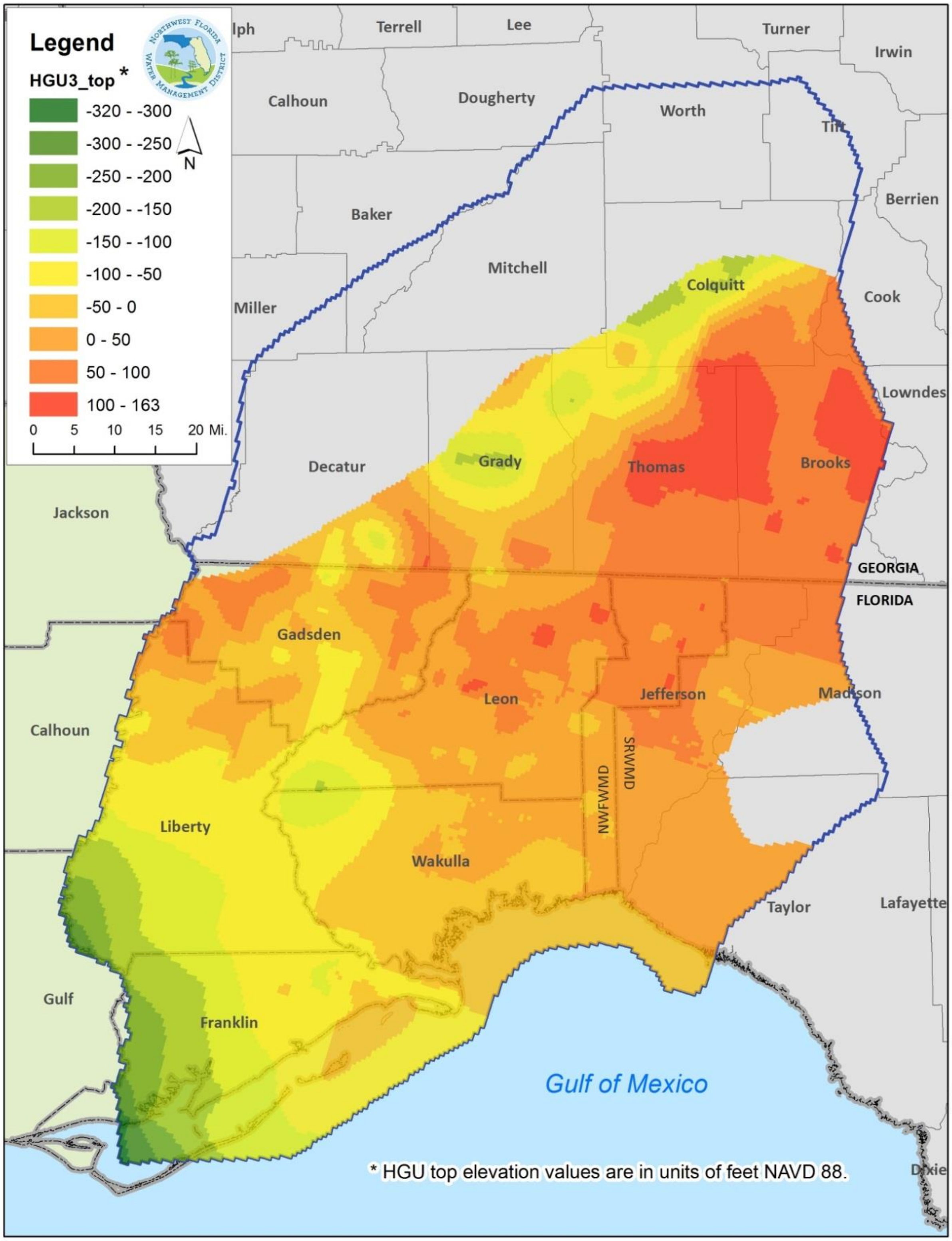

Figure 22. Altitude of the Top of HGU3 (Miocene-age Limestone Formations) in the EDM

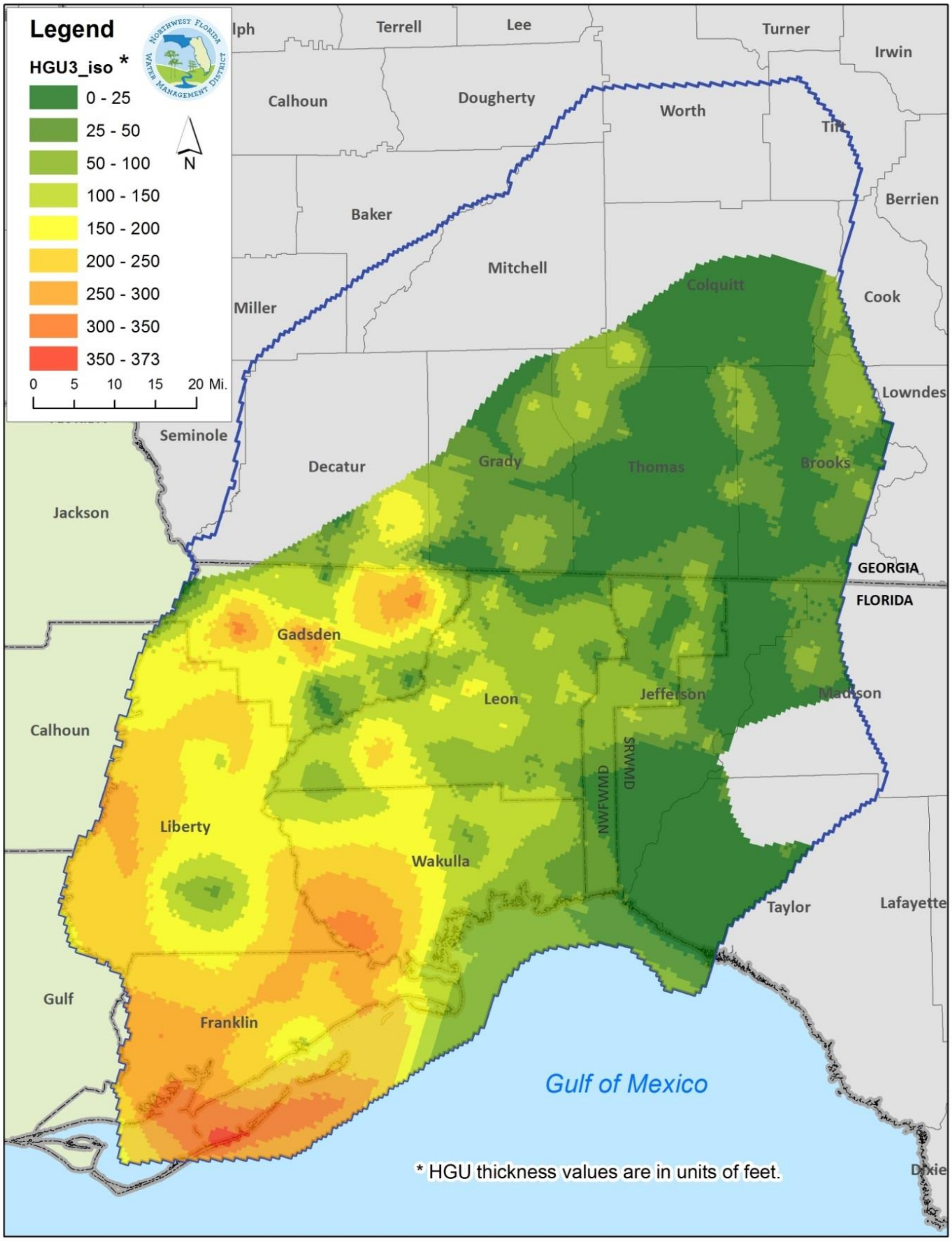

Figure 23. Thickness of HGU3 (Miocene-age Limestone Formations) in the EDM

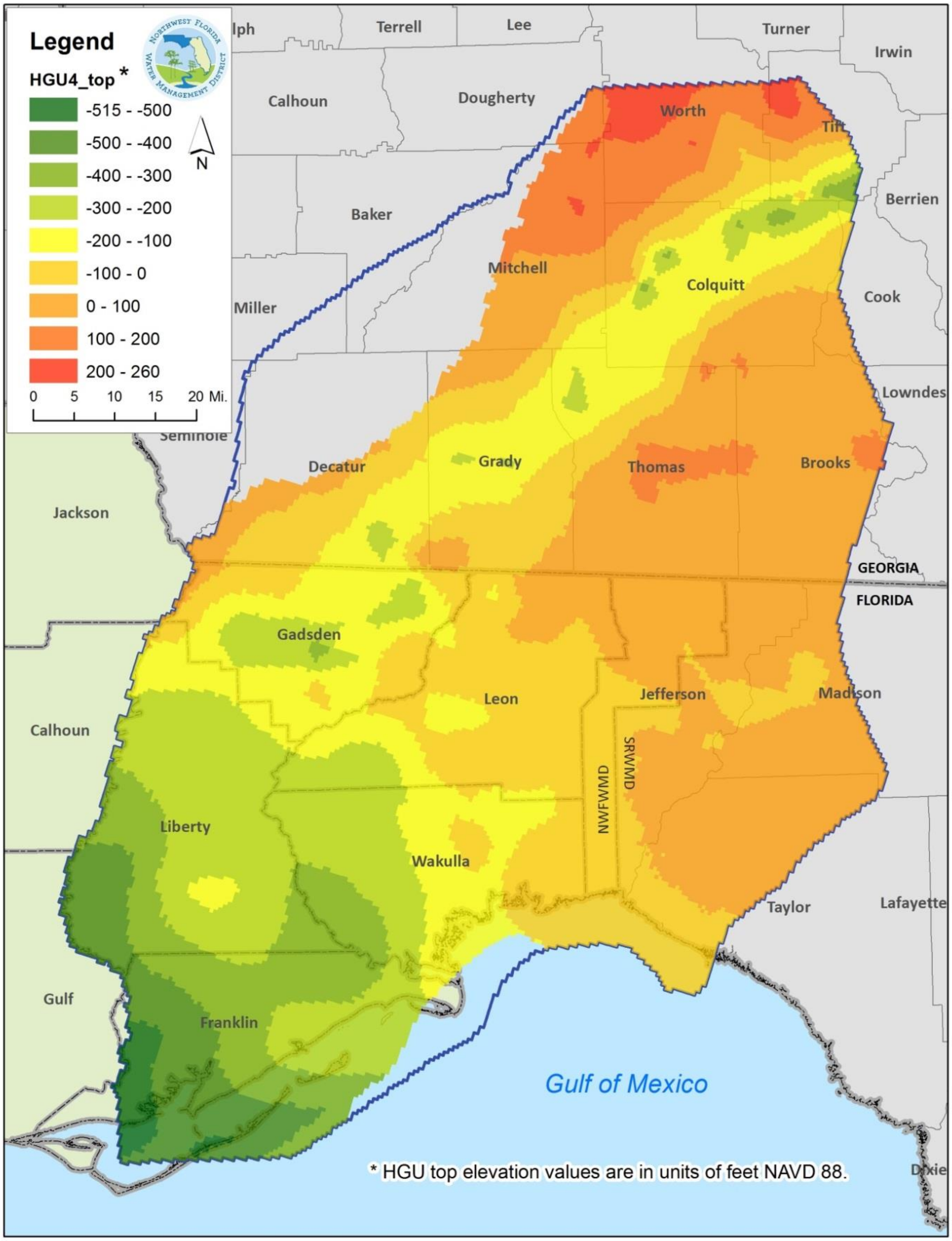

Figure 24. Altitude of the Top of HGU4 (Oligocene-age Limestone Formations) in the EDM

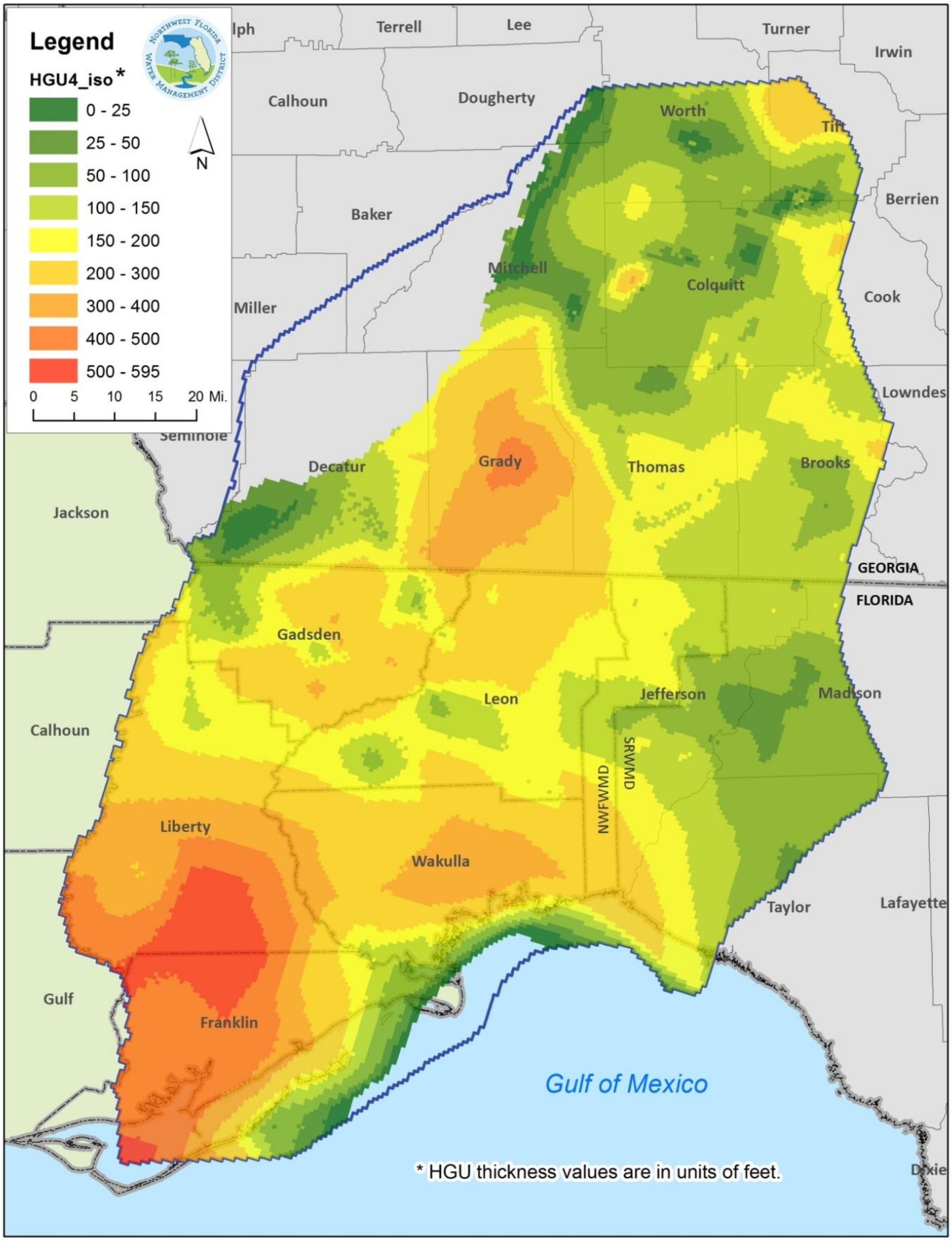

Figure 25. Thickness of HGU4 (Oligocene-age Limestone Formations) in the EDM

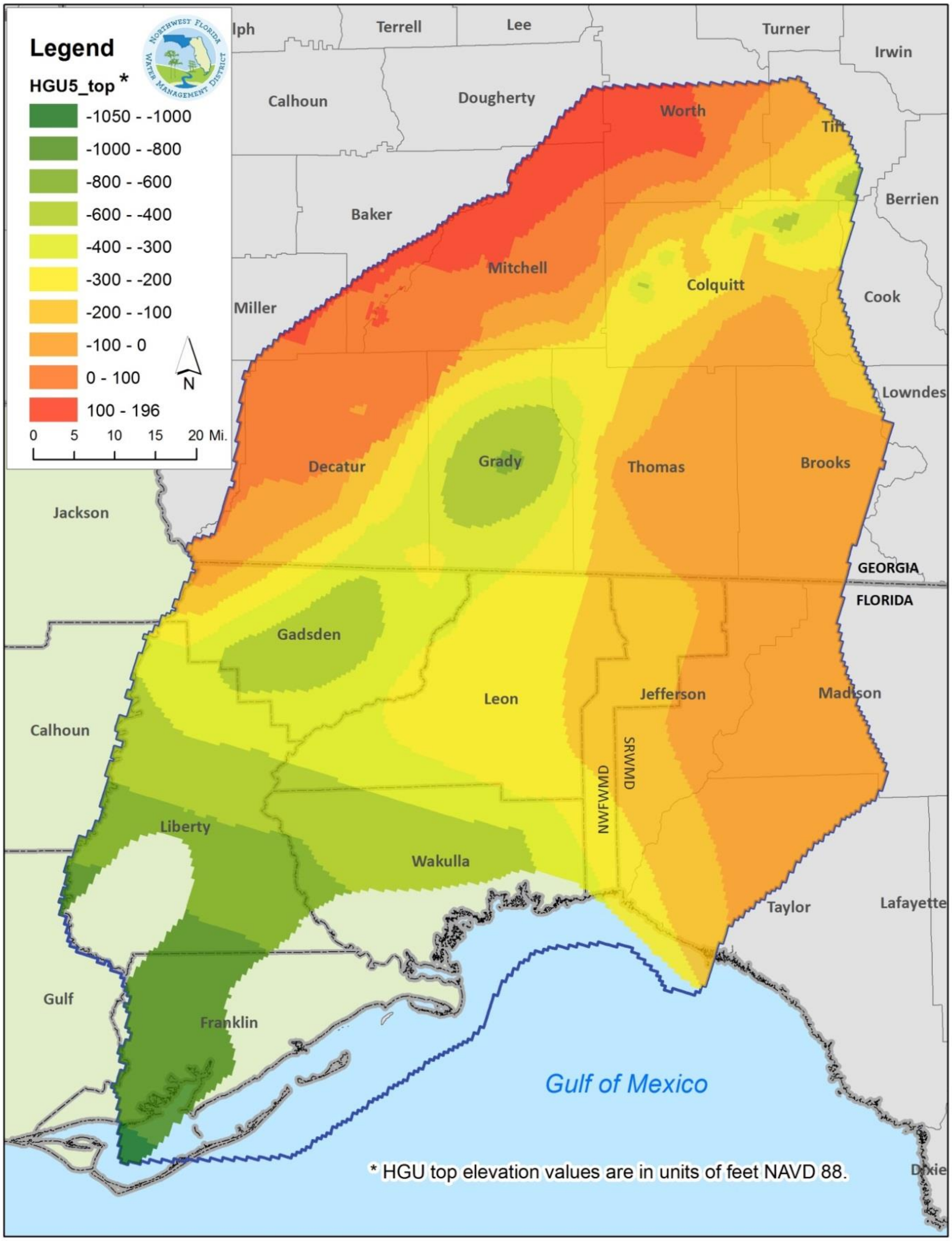

Figure 26. Altitude of the Top of HGU5 (Ocala Limestone) in the EDM

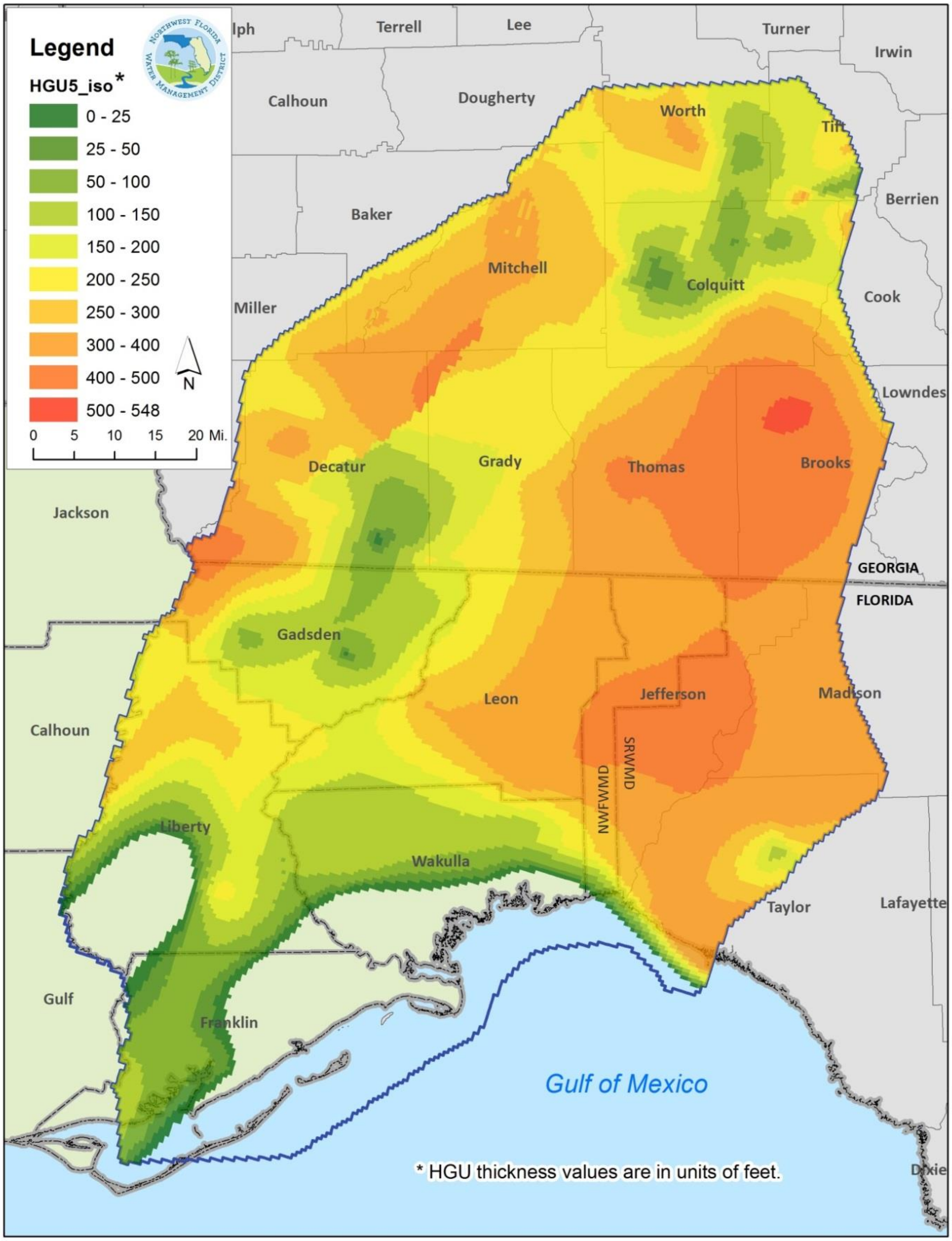

Figure 27. Thickness of HGU5 (Ocala Limestone) in the EDM

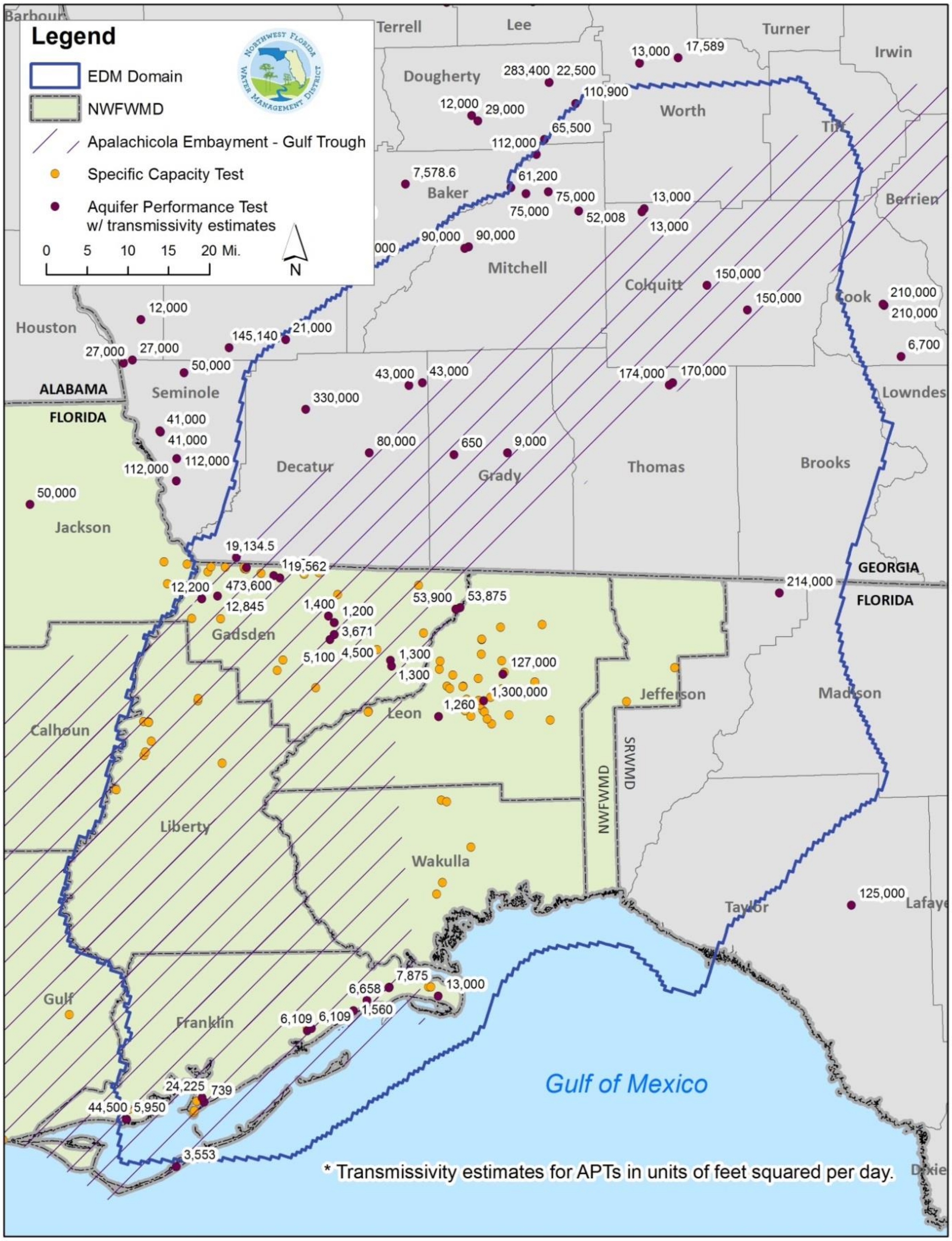

Figure 28. Location of Specific Capacity and Aquifer Performance Tests

(Transmissivity estimates shown are for aquifer performance tests only.)

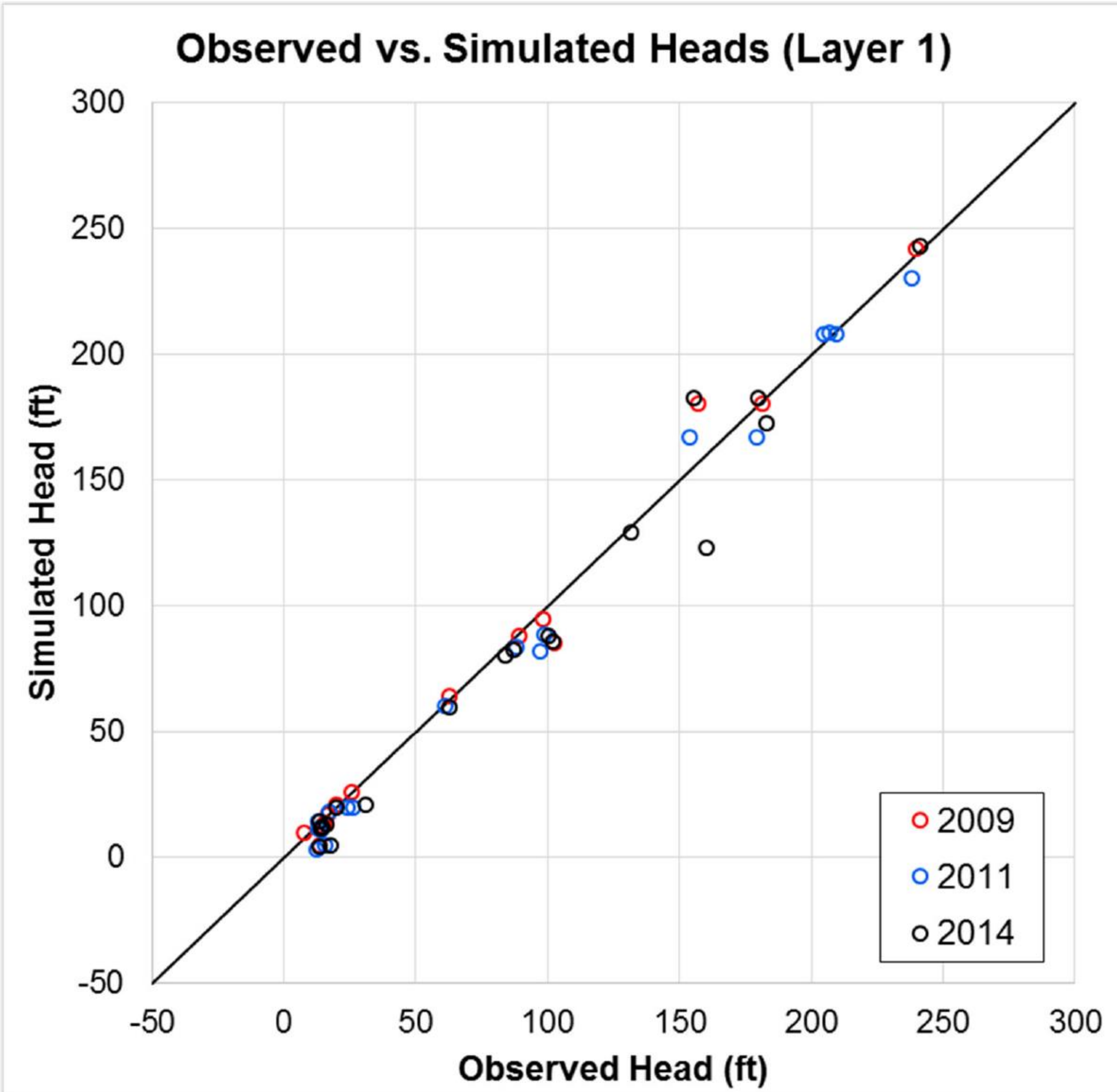

Figure 29. Observed Versus Simulated Heads in Layer 1 for All Three Calibration Years (from Appendix G)

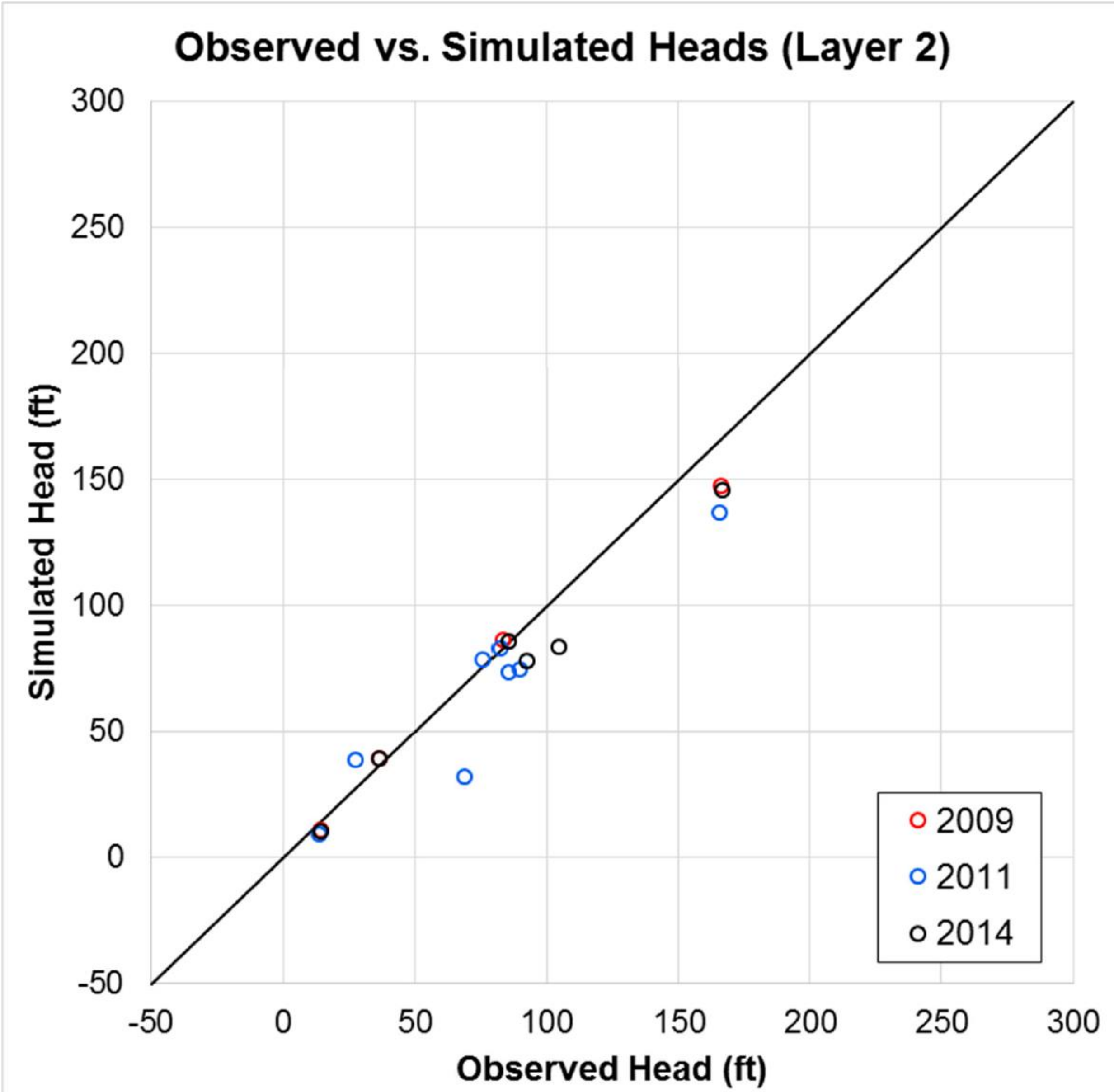

Figure 30. Observed Versus Simulated Heads in Layer 2 for All Three Calibration Years (from Appendix G)

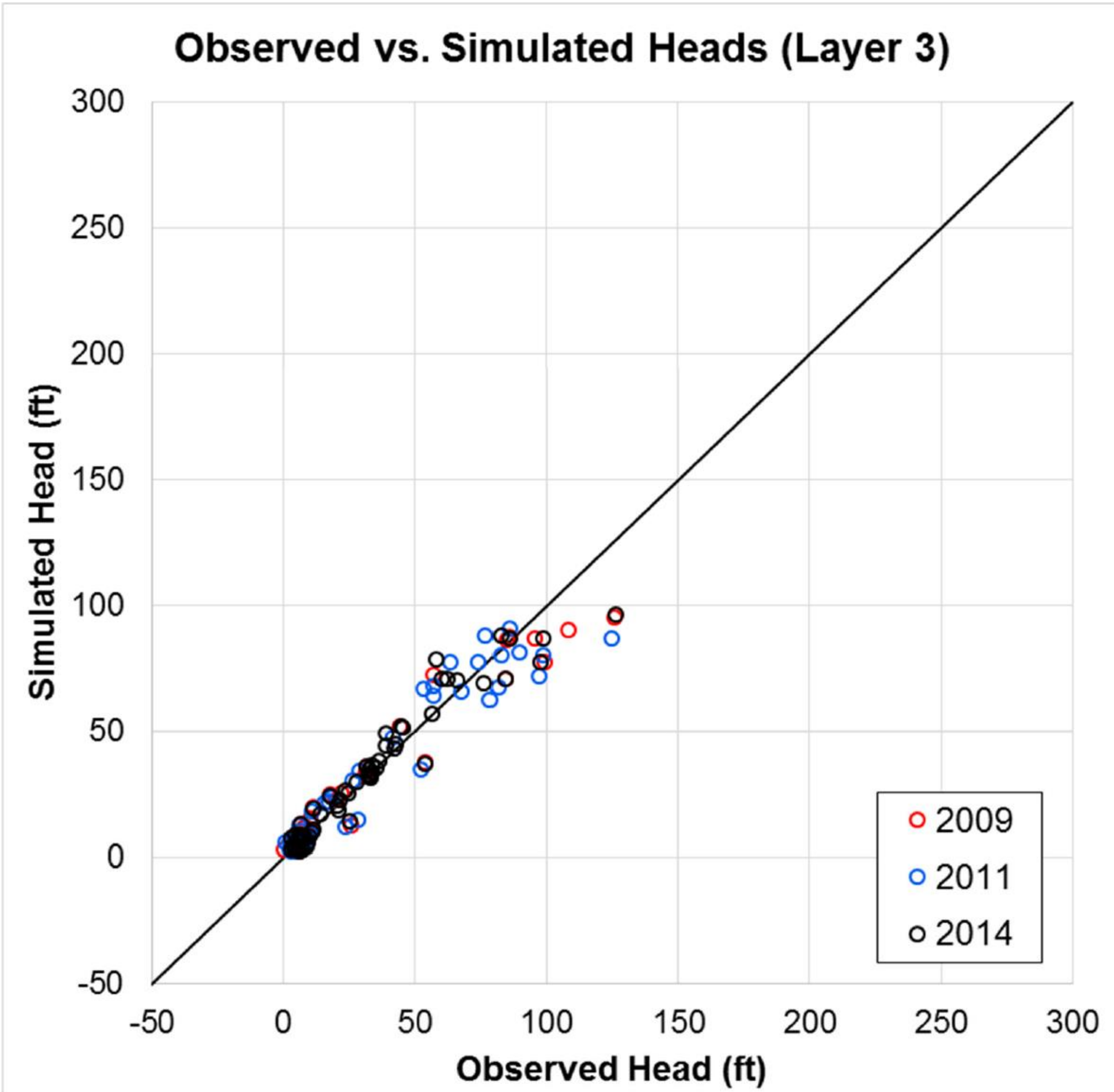

Figure 31. Observed Versus Simulated Heads in Layer 3 for All Three Calibration Years (from Appendix G)

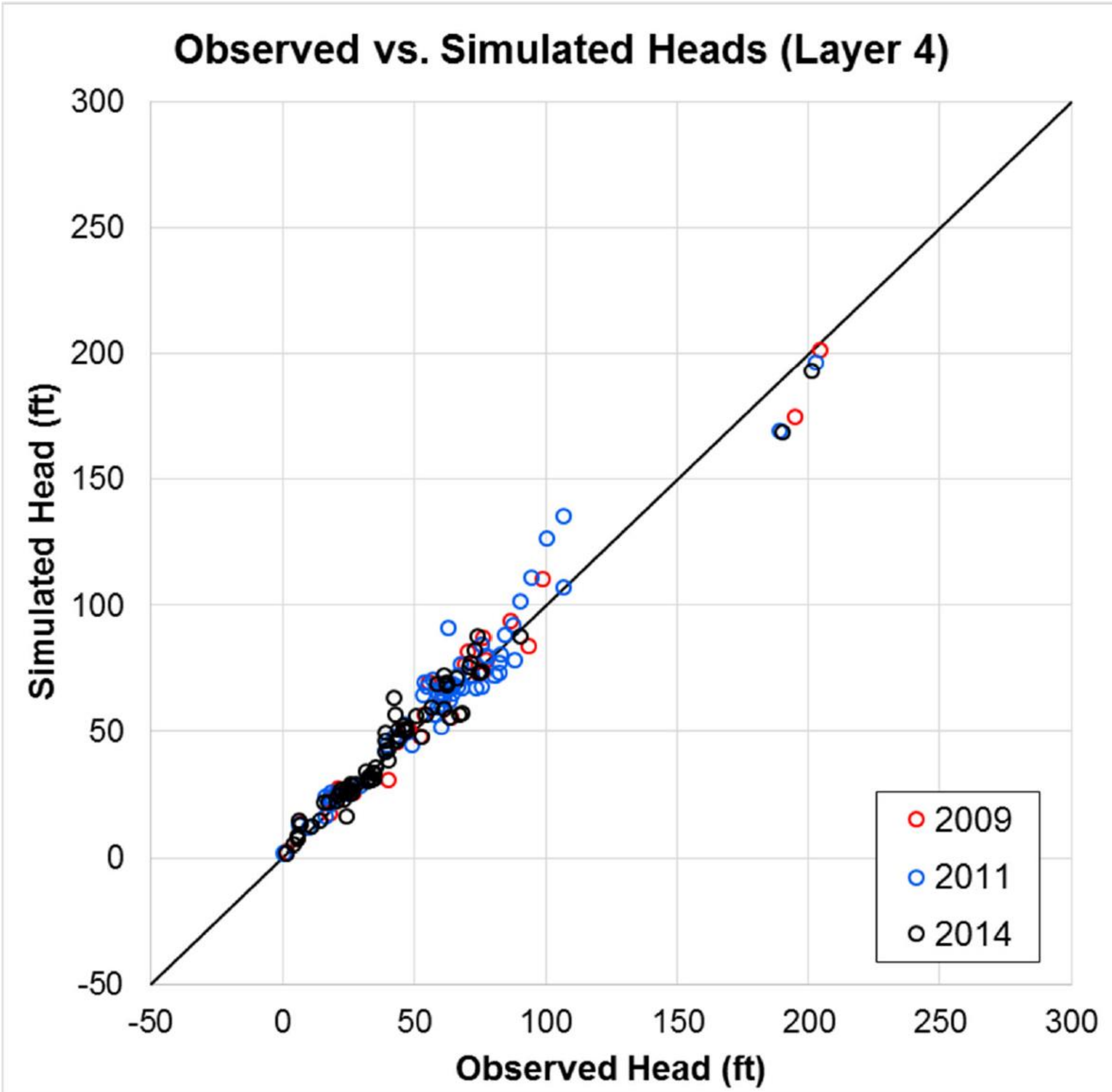

Figure 32. Observed Versus Simulated Heads in Layer 4 for All Three Calibration Years (from Appendix G)

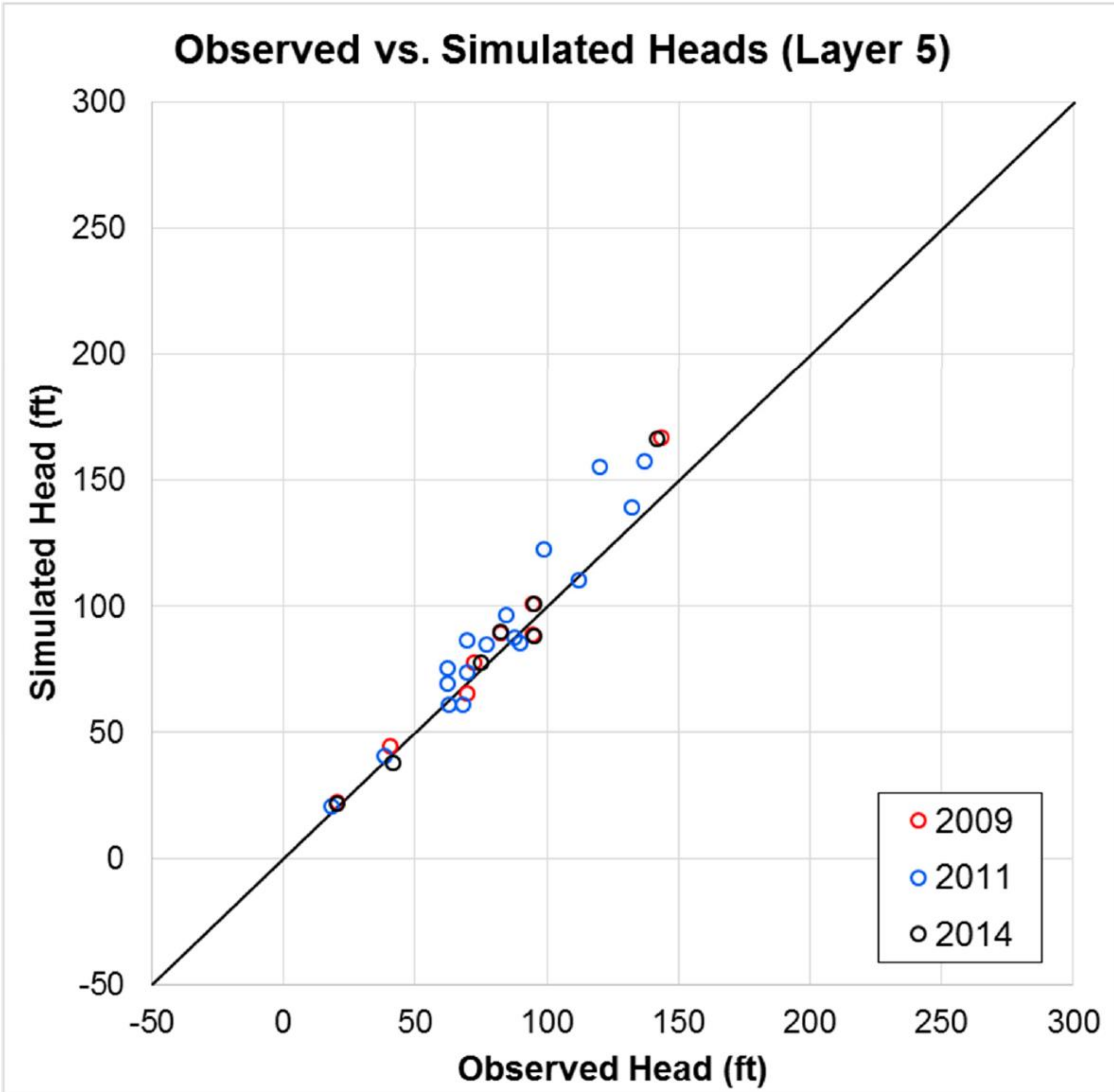

Figure 33. Observed Versus Simulated Heads in Layer 5 for All Three Calibration Years (from Appendix G)

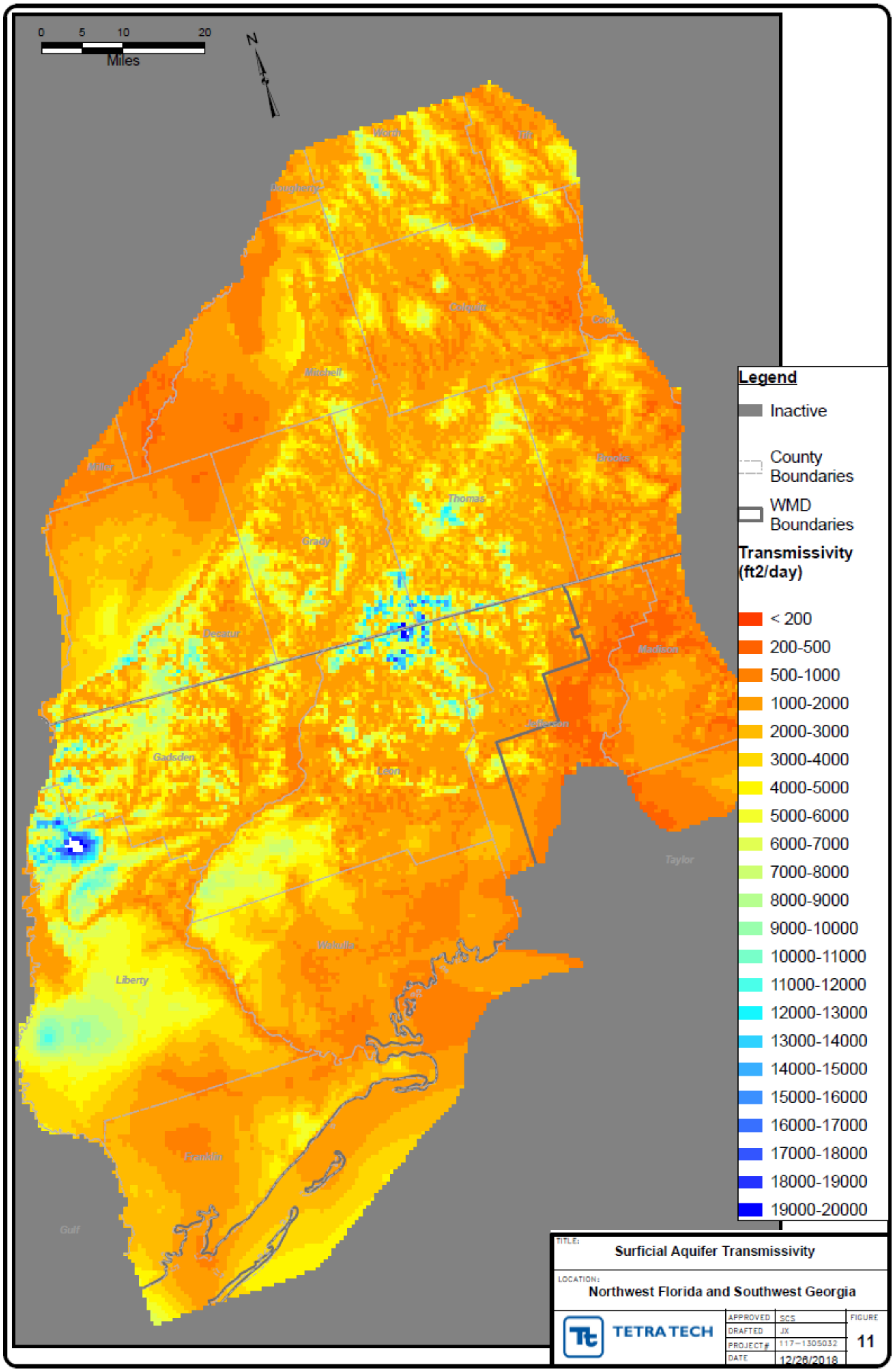

Figure 34. Calibrated Transmissivities of the Surficial Aquifer and Overburden HGU (from Appendix I)

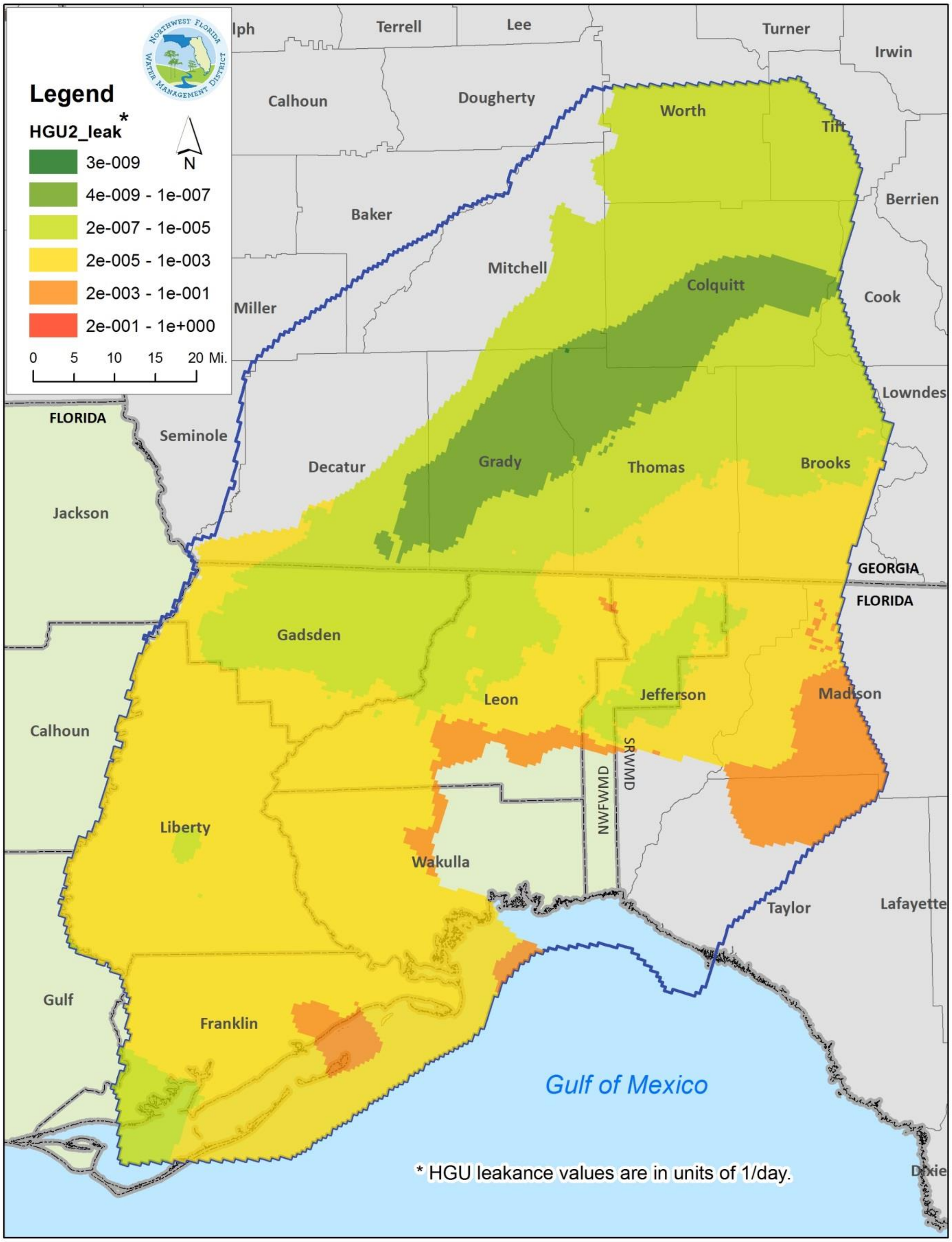

Figure 35. Calibrated Leakance of the Intermediate System HGU

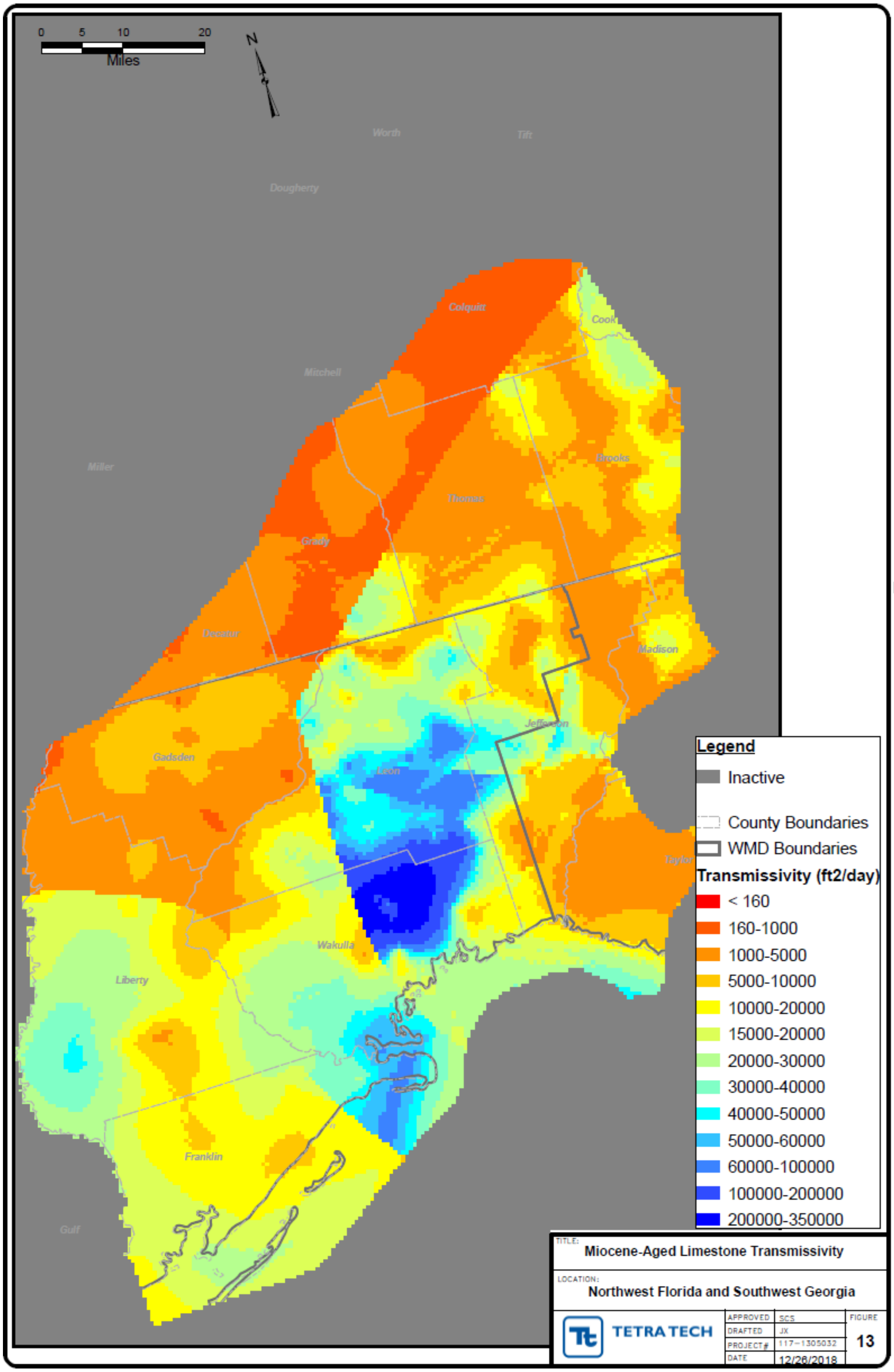

Figure 36. Calibrated Transmissivities of the Miocene-age Limestone Formations (from Appendix I)

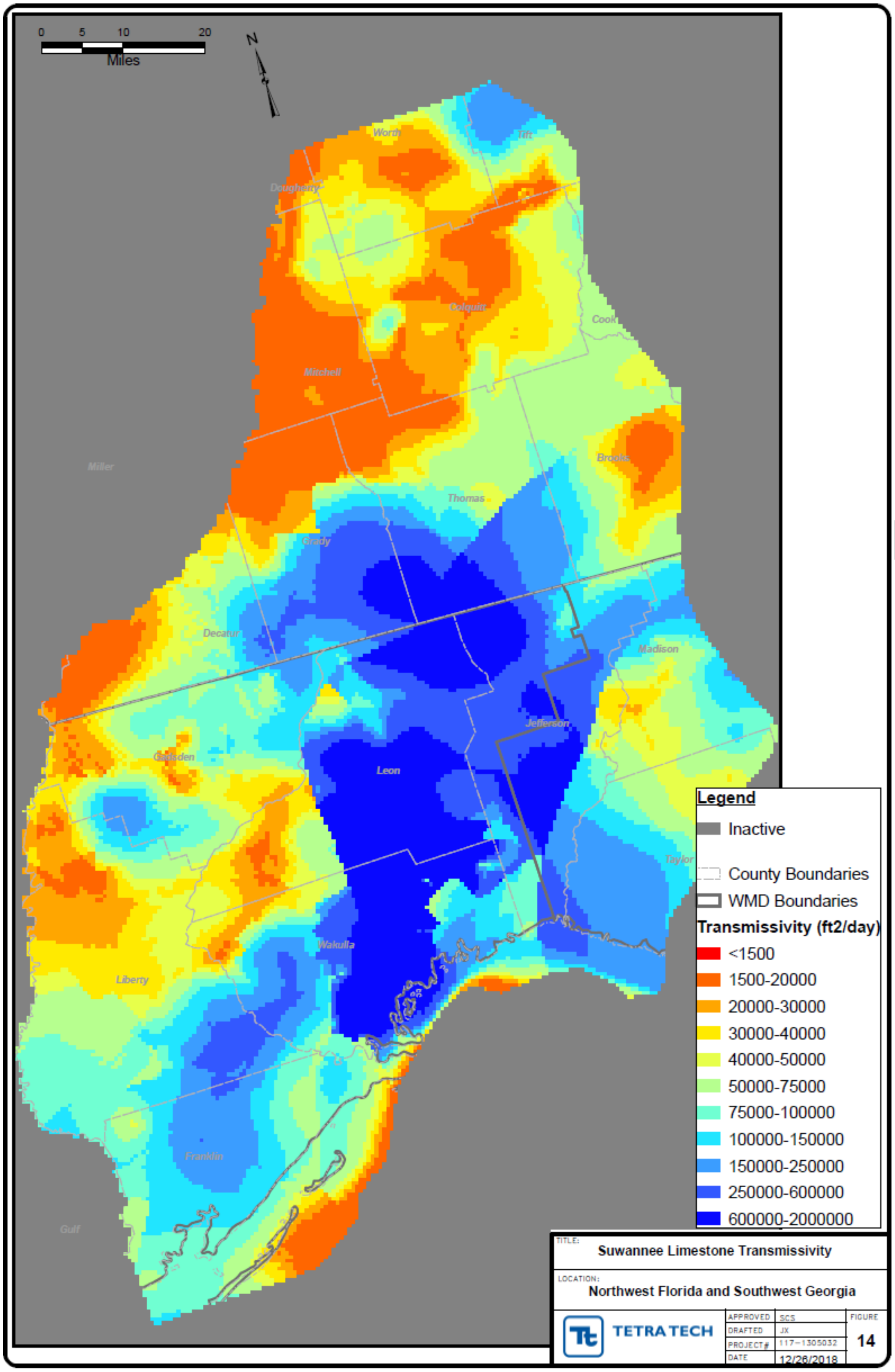

Figure 37. Calibrated Transmissivities of the Oligocene-Age Formations (from Appendix I)

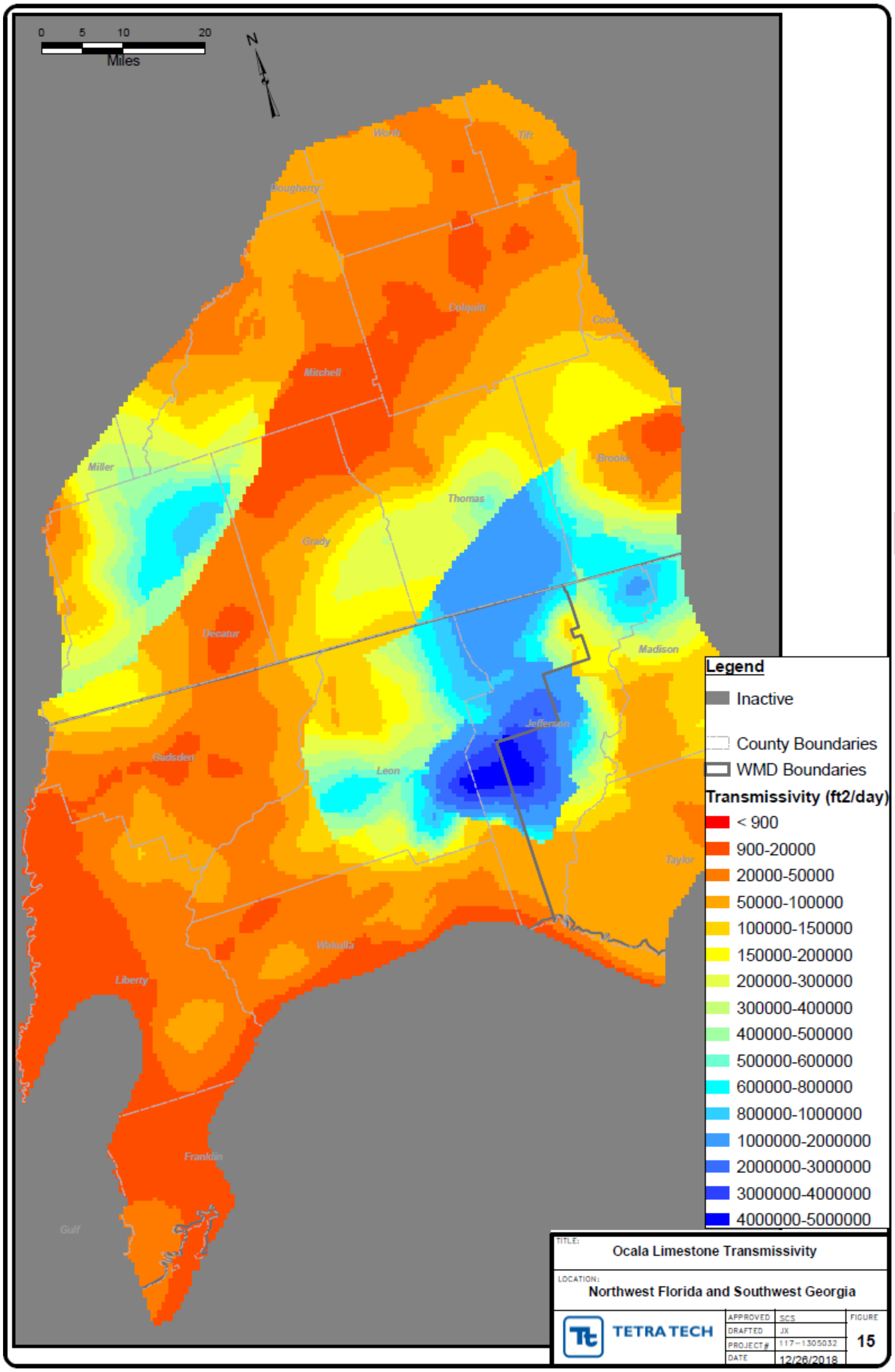

Figure 38. Calibrated Transmissivities of the Ocala Limestone (from Appendix I)

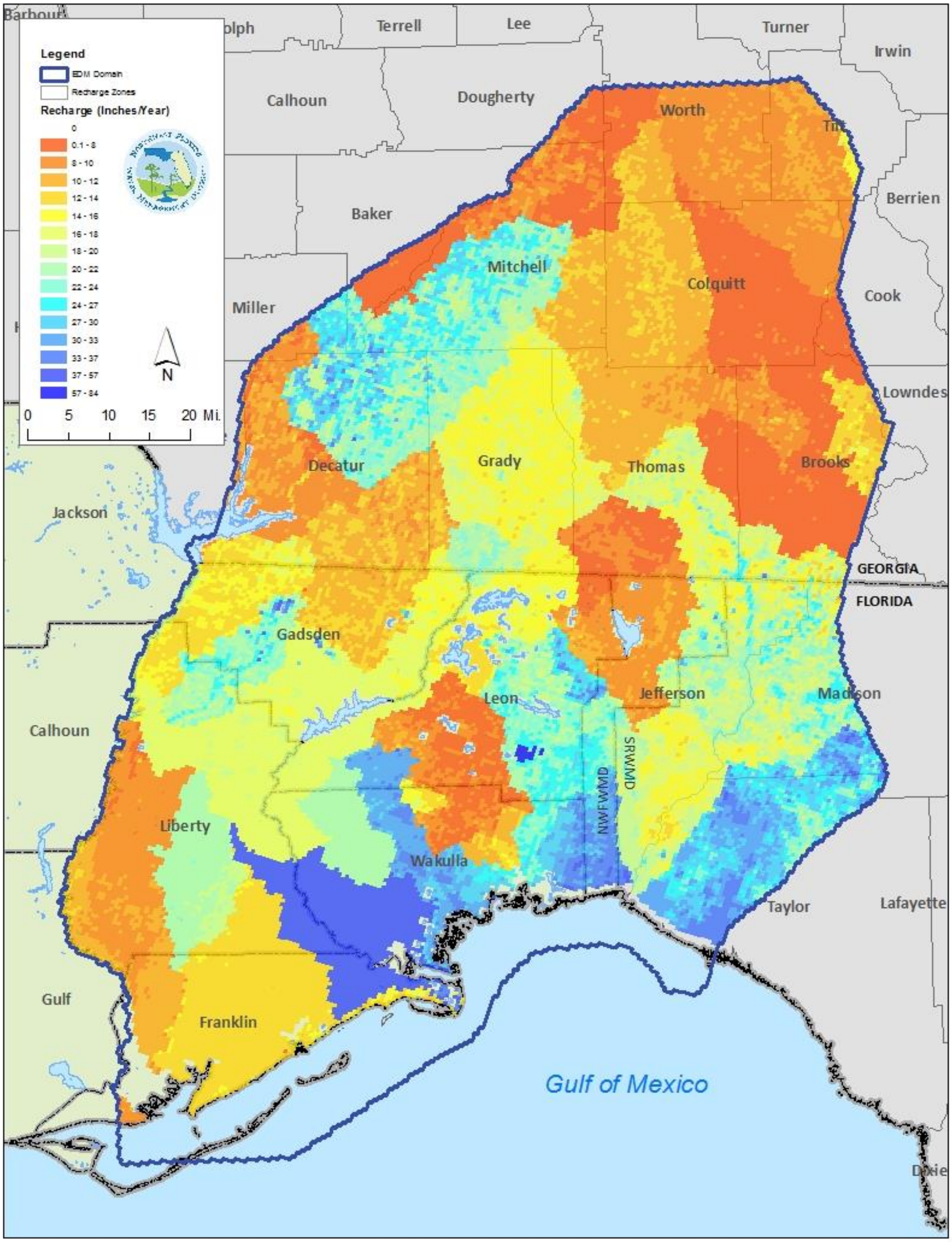

Figure 39. Calibrated Recharge Rates for 2009

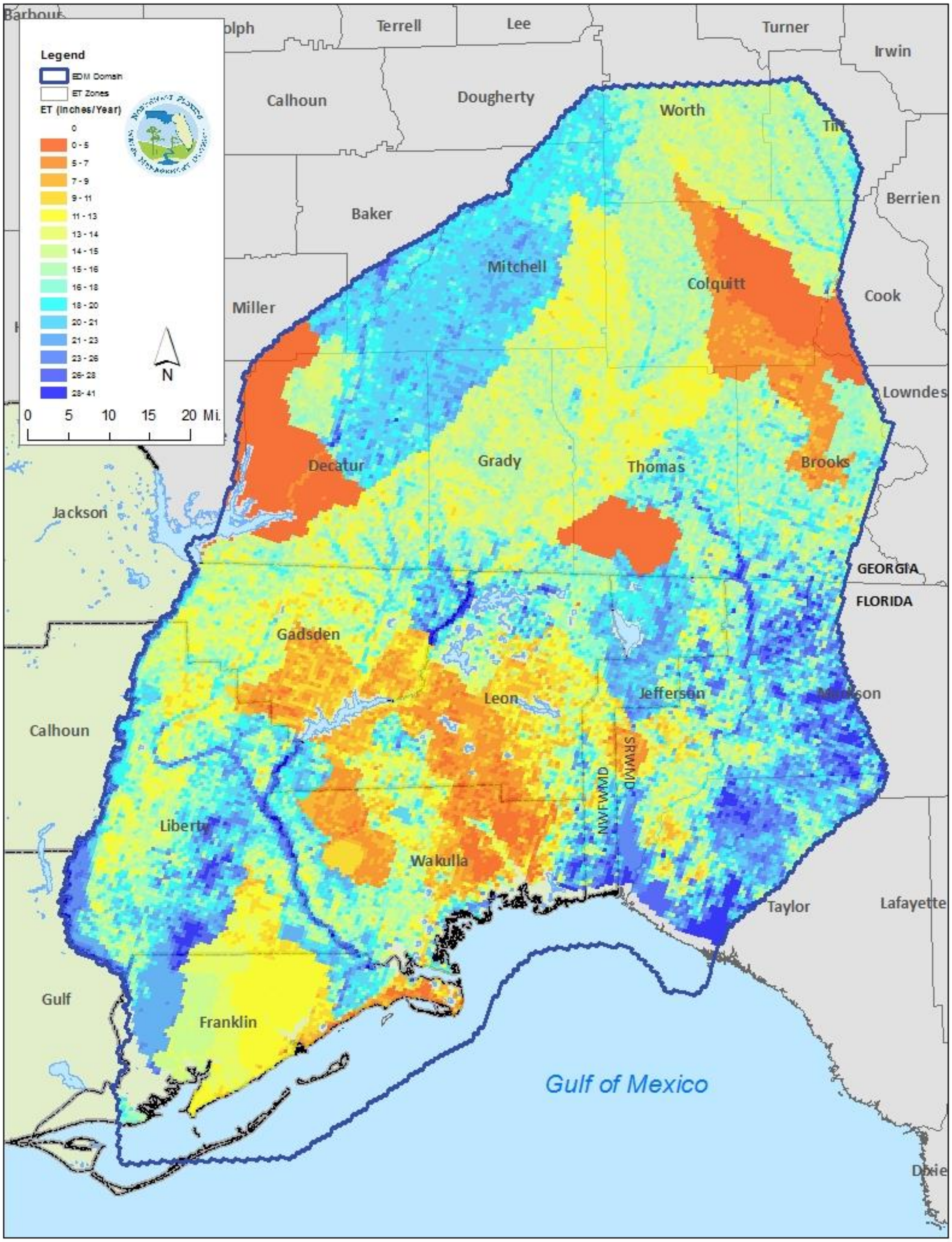

Figure 40. Calibrated Maximum Groundwater ET Rates for 2009