

Section 6

Regional Groundwater Flow Model Calibration

6.1 Approach to Groundwater Flow Model Calibration

Calibration of a groundwater flow model refers to a demonstration that the model is capable of producing field-measured groundwater heads and flows, which are the calibration values (Anderson and Woessner, 1992). Acceptable flow model calibration is accomplished by finding a set of hydrogeologic parameters, boundary conditions, and stresses that produce simulated heads and fluxes (flows) that match field-measured values within a pre-established range of error.

Both quantitative and qualitative metrics are used to assess calibration. Quantitative calibration is most commonly accomplished by a systematic *trial-and-error* adjustment of hydrogeologic parameters within the range of published or measured values for the hydrogeologic units being modeled. More recently, automated programs such as the Parameter Estimation code, or PEST (Doherty, 2005), have been used to assist in calibrating models.

After the regional groundwater flow model was developed (Section 5) and prior to using it to assess sustainable yields for the prioritized aquifers in the Coastal Plain of Georgia, model simulation results were compared to observed groundwater elevations at monitor well locations and to estimated groundwater baseflow in major surface water bodies such as rivers.

6.2 Calibration Criteria and Metrics

There are many documents that provide guidance on model calibration, but there are no set standards that apply to all locations. In general, it is desirable to adjust the model's hydrogeologic parameters such that the model simulated heads (groundwater elevations) and groundwater fluxes to major rivers (baseflow) are within a reasonable range of measured, published, or estimated values. The concept of a "reasonable range" is dependent on the objectives of the simulations being made. For example, the range might be more stringent for a site scale contaminant transport model (e.g., smaller observed head decline over the model area would require a smaller difference between simulated and observed groundwater heads), and less stringent for a regional model designed to estimate a water balance (e.g., larger observed head decline over the model area would suggest that larger difference between simulated and observed groundwater heads would be acceptable). The range will also depend on the quality of the data available (the data also represents a range).

The American Society of Testing and Materials (ASTM) suggests several quantitative and qualitative criteria that can be used to judge groundwater flow model calibration. These criteria include the following:

- Average and standard deviation of residuals between computed and observed heads;
- Average and standard deviation of residuals between computed and observed flows (for head-dependent boundaries);
- Directions and residuals for vertical gradients;
- Water budgets and mass balances;
- Groundwater flow paths;
- Head and flow matching under different hydrologic conditions; and
- Input aquifer hydraulic properties.

The first three of these seven criteria are the most commonly used for groundwater model calibration.

6.2.1 Calibration Criteria

Model calibration for this project was considered complete when the following criteria were met by the regional groundwater flow model:

- The average of residuals (the difference between observed and model computed) in groundwater elevations was less than 10 feet across all model layers;
- The standard deviation of residuals, or Root Mean Squared Error (RMSE), in groundwater elevations was less than 20 feet across all model layers; and
- The average of residuals and standard deviation of residuals in vertical heads across aquifers at monitor well cluster locations were less than 5 feet and 15 feet, respectively.

In addition to these numerical criteria, some subjective criteria were also considered:

- The model needed to match the measured flow patterns both laterally and vertically; and
- There should be limited to no spatial bias in residuals (i.e., differences between measured and modeled heads).

The aquifer hydraulic parameters were varied systematically until these criteria were met.

6.2.2 Calibration Parameters

The model hydrogeologic parameters were modified until the model-computed groundwater levels closely matched observed groundwater levels at monitor well locations. Hydrogeologic parameters that were modified included:

- Horizontal hydraulic conductivity/transmissivity;
- Leakance (vertical hydraulic conductivity divided by layer thickness). As discussed in Section 5.1, leakance was used rather than specifying separate layers for confining units; and
- River/Drain bed conductance (hydraulic conductivity multiplied by the river or drain width and length within a given grid cell).

6.3 Well Pumping Data

Selection of time periods for model calibration are influenced by a number of factors such as hydrologic conditions (i.e., steady-state or transient), availability and reliability of pumping data, availability and reliability of water level data and availability and reliability of climatological/hydrological data needed to calculate aquifer recharge. It is necessary that synchronous pumping data, water level data and recharge data be available and reliable for the time periods selected for model calibration.

For steady-state calibration purposes, the time period selected should be a period where there has been very little or no changes in pumping, recharge, and water levels. For this project the 20-year period from 1989 through 2009 was selected. The pumping rate from wells in the Coastal Plain Aquifer system in Georgia over this period averaged 1,167 mgd (see Table 5-6). From Table 4-2, groundwater use in the Georgia Coastal Plain in 2000 (low rainfall year) and 2005 (high rainfall year) was 1,312 mgd and 1,012 mgd, respectively. The pumping rate in Georgia used for the steady-state model calibration (1,167 mgd) is close to the average between a high and low rainfall year (1,162 mgd). Recharge used for model calibration in the outcrop areas and through surficial aquifer recharge (the constant head boundary) to the Coastal Plain Aquifer System was derived from average rainfall, evapotranspiration and runoff data for 1989 to 2009.

6.4 Available Water Level Data

Average groundwater and surface water levels within the Coastal Plain of Georgia, north Florida, east Alabama, and western South Carolina over the last 20 years were used to calibrate the regional groundwater flow model.

6.4.1 Monitor Wells

Groundwater elevation data for the Coastal Plain aquifers for the last 20 years were used to calibrate the regional groundwater flow model. A total of 320 monitor wells

were identified within the regional model domain as shown on **Figure 6-1**. The distribution of monitor wells used for calibration by aquifer is given below:

- 249 monitor wells in Upper Floridan Aquifer (Layer 2);
- 31 monitor wells in Claiborne/Gordon/Lower Floridan Aquifers (Layer 3);
- 20 monitor wells in Clayton- Dublin Aquifer (Layer 4);
- 7 monitor wells in Providence Sand-Peedee-Dublin Aquifers (Layer 5);
- 13 monitor wells in Eutaw-Midville Aquifer (Layer 6), and
- 0 monitor wells in Upper Atkinson-Upper Tuscaloosa Aquifer (Layer 7).

Table 6-1 presents the number of monitor wells by model layer for each State in the regional model domain. There are few monitor wells located within the portions of Alabama and South Carolina simulated in the regional model. The majority of the monitor wells (97 percent) in Florida and Georgia are located in the Upper Floridan Aquifer (Layer 2). The remaining model layers (3 through 6) contained 10 percent, 6 percent, 2 percent, and 4 percent, respectively, of the monitor wells. Annual rainfall during the period from 1989-2009 (49.31 inches) is very close to the historical long-term average rainfall for Georgia (1891 through 2008) of 50.79 inches suggesting that this time period is representative of steady-state conditions.

Table 6-1 Monitor Well Distribution for the Georgia EPD Regional Groundwater Model Area

State	Number of Wells						
	Model Layer ¹						
	2	3	4	5	6	7	Total
Georgia	145	31	20	7	12	0	216
Florida	95	0	0	0	0	0	95
Alabama	0	0	0	0	1	0	1
South Carolina	9	0	0	0	0	0	9
Total	249	31	20	7	13	0	321

¹Notes:

Model Layer 1 - Surficial/Brunswick Aquifer (constant head)

Model Layer 2 - Upper Floridan Aquifer

Model Layer 3 - Claiborne/Gordon/Lower Floridan Aquifers

Model Layer 4 - Clayton-Dublin Aquifer

Model Layer 5 - Providence Sand-Peedee-Dublin Aquifers (Cretaceous Aquifer System)

Model Layer 6 - Eutaw-Midville Aquifer (Cretaceous Aquifer System)

Model Layer 7 - Upper Atkinson-Upper Tuscaloosa Aquifer (Cretaceous Aquifer System)

Measured groundwater elevations at the 320 monitor well targets are presented in **Table D-1** in **Appendix D**. As shown, measured groundwater levels vary from approximately -116.8 feet NGVD to 328.1 feet NGVD, with a groundwater drop (328.1 ft NGVD minus -116.8 ft NGVD) of about 445 feet within the model domain.

6.4.2 Staff Gauges

It was very important to use accurate surface water levels that were measured concurrently with the groundwater levels. Surface water levels in the Coastal Plain Aquifer System outcrop areas for the 1989-2009 time period were represented as head-dependent boundaries (see section 5.1) in the upper most aquifer. The MODFLOW River Package was used to represent portions of the major rivers and their tributaries in the model domain. Model river cell stages were assigned using surface water elevation data based on 97 USGS gauging stations (Figure 5-15 and Table 5-7) to represent these rivers and their tributaries. Water levels at gauging stations varied from approximately 4 feet NGVD at Fort Pulaski in Chatham County on the Savannah River to 334 feet NGVD at Culloden in Upson County on the Flint River.

6.4.3 Baseflow

Comparison of groundwater flow model output to known baseflows (observed or calculated from observed data), as well as observed groundwater levels, is very important in steady-state calibration because known flows in combination with observed groundwater levels provide a unique solution. In order to assess the contribution of groundwater to major rivers and streams within the outcrop areas and provide the data for calibration of the groundwater flow model, baseflow separation analysis was performed for this project.

6.4.3.1 Selection of Stations and Discharge Data

Fifty-four USGS flow monitoring stations in southern Georgia were selected for the baseflow separation analysis. These stations were located on the major rivers and their tributaries within the model domain. These rivers and the tributaries include:

- Saluda River;
- South Fork Edisto River;
- North Fork Edisto River;
- Edisto River;
- Brier Creek;
- Ogeechee River;
- Ocmulgee River;
- Oconee River;
- Altamaha River;
- Satilla River;

- Suwannee River;
- Alapaha River;
- Little River;
- Withlacoochee River;
- Ochlockonee River;
- Chattahoochee River;
- Flint River;
- Apalachicola River;
- Choctawhatchee River;
- Pea River; and
- Savannah River.

The locations of these stations are shown on **Figure 6-2**. The portions of the subbasins in the model area associated with these stations are also displayed on Figure 6-2. The drainage areas contributing to these stations were obtained from the USGS National Water Information System (NWIS) database. The USGS station IDs are shown on Figure 6-2, **Table 6-2**, and **Table 6-3**. These ID numbers are related to stream order and not to Hydrologic Unit Codes (HUCs). Watersheds are delineated by the USGS using a nationwide system based on surface hydrologic features. This system divides the country into 21 regions (2-digits), 222 subregions (4-digits), 352 accounting units (6-digits), and 2,262 cataloguing units (8-digits). Each hydrologic unit is assigned an 8-digit attribute code (referred to as a HUC8) that uniquely identifies each of the four levels of classification within four two-digit fields. The USGS assigns the streamflow station IDs independent of the HUCs. Additionally, the discharge data for these rivers were obtained from the USGS NWIS database.

6.4.3.2 PART Analysis

Baseflow in the modeled area was estimated using PART, a computer program developed by the USGS (Rutledge, 1993 and 1998). This program uses stream partitioning to estimate a daily record of baseflow under the streamflow record. The program scans the record for days that fit the requirement of antecedent recession. The program then designates baseflow to be equal to streamflow on these days and linearly interpolates the daily record of baseflow, or days that do not fit the requirement of antecedent recession. The program is applied to a sufficiently long continuous period of record to give an estimate of the mean rate of groundwater discharge.

Table 6-2 Results of Long-Term Baseflow and Recharge Analysis¹

USGS Station ID	Station Name	State Plane GA West (ft)		Drainage Area mi ²	Modeled Period of Record		Mean Streamflow		Mean Recharge (in/yr)	Mean Baseflow		Normalized Baseflow (cfs/mi ²)	Baseflow Percentage of Total Streamflow %	Net Recharge in/yr
		X	Y		Start	Finish	cfs	in/yr		cfs	in/yr			
2339500	CHATTAHOOCHEE RIVER AT WEST POINT	1,984,835	1,051,275	3,550	1960	2008	5,491	21.0	9.2	2,207	8.5	0.62	40.2	0.7
2341505	CHATTAHOOCHEE RIVER AT US 280, NEAR COLUMBUS, GA	2,040,993	893,219	4,670	2003	2008	6,001	17.5	7.1	3,080	9.0	0.66	51.3	-1.9
2343801	CHATTAHOOCHEE RIVER NEAR COLUMBIA, AL	2,001,767	459,267	8,210	1976	2008	10,039	16.6	5.9	2,916	4.8	0.36	29.0	1.1
2344872	FLINT RIVER BELOW BIG BRANCH, NEAR MOLENA, GA	2,186,213	1,108,525	794	2005	2008	634	10.9	6.4	361	6.2	0.45	56.9	0.2
2347500	FLINT RIVER AT US 19, NEAR CARSONVILLE, GA	2,276,337	989,853	1,850	1960	2008	2,199	16.1	11.0	1,267	9.3	0.68	57.6	1.7
2349500	FLINT RIVER AT MONTEZUMA	2,334,519	835,862	2,900	1960	2002	3,479	16.3	12.3	2,305	10.8	0.79	66.3	1.5
2349605	FLINT RIVER AT GA 26, NEAR MONTEZUMA, GA	2,334,607	834,044	2,920	1960	2008	3,396	15.8	11.9	2,252	10.5	0.77	66.3	1.5
2350512	FLINT RIVER AT GA 32, NEAR OAKFIELD, GA	2,342,615	627,414	3,880	1988	2008	4,071	14.3	7.7	2,099	7.4	0.54	51.6	0.4
2352500	FLINT RIVER AT ALBANY	2,303,589	579,794	5,310	1960	2008	5,800	14.8	8.0	3,002	7.7	0.57	51.8	0.3
2353000	FLINT RIVER AT NEWTON	2,242,799	475,363	5,740	1960	2008	6,325	15.0	9.6	3,985	9.4	0.69	63.0	0.2
2355662	FLINT RIVER AT RIVERVIEW PLANTATION, NR HOPEFUL, GA	2,198,472	414,940	7,080	2003	2008	6,456	12.4	8.3	4,434	8.5	0.63	68.7	-0.2
2356000	FLINT RIVER AT BAINBRIDGE	2,166,965	331,692	7,570	1960	1970	8,760	15.7	10.9	6,099	10.9	0.81	69.6	-0.1
					2002	2008	6,560	11.8	8.4	4,758	8.5	0.63	72.5	-0.1
2358000	APALACHICOLA RIVER AT CHATTAHOOCHEE FLA	2,078,970	255,614	17,200	1960	2007	22,036	17.4	11.3	14,741	11.6	0.86	66.9	-0.4
2359170	APALACHICOLA RIVER NR SUMATRA, FLA.	2,027,776	-17,417	19,200	1978	2007	24,530	17.4	13.9	20,047	14.2	1.04	81.7	-0.2
2210500	OCMULGEE RIVER NEAR JACKSON, GA	2,396,921	1,203,391	1,420	1976	1981	1,781	17.04	9.6	991	9.5	0.70	55.6	0.1
					1988	2008	1,908	18.26	11.9	1,046	10.0	0.74	54.8	1.9
2213000	OCMULGEE RIVER AT MACON	2,464,312	1,032,927	2,240	1960	2008	2,722	16.50	11.3	1,538	9.3	0.69	56.5	2.0
2215500	OCMULGEE RIVER AT LUMBER CITY	2,759,755	700,899	5,180	1960	2008	5,417	14.20	11.2	4,201	11.0	0.81	77.6	0.2
2218300	OCONEE RIVER NEAR PENFIELD, GA	2,561,490	1,354,744	940	1978	2008	1,184	17.11	13.4	803	11.6	0.85	67.8	1.8
2223000	OCONEE RIVER AT MILLEDGEVILLE	2,587,880	1,125,072	2,950	1960	2008	3,045	14.02	7.6	1,160	5.3	0.39	38.1	2.3
2223056	OCONEE RIVER AT AVANT MINE NEAR QUITMAN	2,633,967	1,071,040	3,100	2006	2006	1,468	6.43	4.2	814	3.6	0.26	55.5	0.6
2223248	OCONEE RIVER NEAR OCONEE	2,668,266	1,015,922	3,770	1993	2008	3,446	12.42	7.0	1,821	6.6	0.48	52.9	0.4
2223500	OCONEE RIVER AT DUBLIN	2,688,533	927,815	4,400	1960	2008	4,365	13.47	8.9	2,399	7.4	0.55	55.0	1.5
2225000	ALTAMAHA RIVER NEAR BAXLEY	2,859,018	709,895	11,600	1971	2007	11,208	13.12	9.6	8,369	9.8	0.72	74.7	-0.2
2226000	ALTAMAHA RIVER AT DOCTORTOWN	3,024,315	609,515	13,600	1960	2008	13,701	13.68	10.7	10,611	10.6	0.78	77.5	0.1
21973269	SAVANNAH RIVER NEAR WAYNESBORO, GA	3,034,823	1,154,237	8,300	2006	2008	5,775	9.5	6.1	4,634	7.6	0.56	80.2	-1.5
2198000	BRIER CREEK AT MILLHAVEN	3,068,383	1,076,169	646	1960	2007	605	12.73	10.4	471	9.9	0.73	77.8	0.5
2173000	SOUTH FORK EDISTO RIVER NEAR DENMARK, S.C.	3,222,550	1,247,715	720	1960	1970	931	17.56	15.7	791	14.9	1.10	85.0	0.8
					1981	2008	650	12.27	11.2	570	10.8	0.79	87.6	0.5
2173030	SOUTH FORK EDISTO RIVER NEAR COPE, SC	3,245,401	1,235,940	757	1992	2008	679	12.18	11.1	585	10.5	0.77	86.2	0.6
2173051	SOUTH FORK EDISTO RIVER NEAR BAMBERG, SC	3,258,118	1,228,325	807	1992	2008	862	14.51	13.2	739	12.4	0.92	85.7	0.8
2173500	NORTH FORK EDISTO RIVER AT ORANGEBURG, SC	3,300,880	1,283,054	683	1960	1987	850	16.90	15.7	736	14.6	1.08	86.6	1.0
					1989	2008	651	12.94	12.4	570	11.3	0.83	87.6	1.1
2174000	EDISTO RIVER NEAR BRANCHVILLE, SC	3,326,524	1,172,008	1,720	1960	1995	2,100	16.58	14.7	1,845	14.6	1.07	87.9	0.2
2175000	EDISTO RIVER NR GIVHANS, SC	3,453,879	1,122,114	2,730	1960	2008	2,547	12.67	10.9	2,149	10.7	0.79	84.4	0.2
2168504	SALUDA RIVER BELOW LK MURRAY DAM NR COLUMBIA, SC	3,192,409	1,486,564	2,420	1989	2008	2,280	12.80	4.4	779	4.4	0.32	34.2	0.1
2201230	OGEECHEE RIVER AT MIDVILLE, GA	2,890,026	1,029,181	1,300	2004	2007	764	7.99	6.2	545	5.7	0.42	71.4	0.5
2202040	OGEECHEE RIVER AT ROCKY FORD RD, NR ROCKY FORD, GA	3,012,566	971,375	2,040	2003	2007	1,410	9.39	7.1	1,038	6.9	0.51	73.6	0.1
2202500	OGEECHEE RIVER NEAR EDEN	3,147,582	807,925	2,650	1960	2008	2,297	11.77	9.8	1,837	9.4	0.69	80.0	0.4
2198000	BRIER CREEK AT MILLHAVEN	3,068,383	1,076,169	646	1960	2007	605	12.73	10.4	471	9.9	0.73	77.8	0.5
2318000	LITTLE RIVER NEAR ADEL, GA	2,491,472	420,806	577	1960	1970	508	12.0	8.6	289	6.8	0.50	56.8	1.8
					2003	2007	502	11.8	6.6	226	5.3	0.39	45.0	1.3
23177483	WITHLACOOCHEE RIVER AT MCMILLAN RD, NEAR BEMISS, GA	2,578,129	347,612	502	1989	2008	450	12.2	7.5	226	6.1	0.45	50.2	1.4
2318500	WITHLACOOCHEE RIVER AT US 84, NEAR QUITMAN, GA	2,520,469	289,127	1,480	1989	1991	1,488	13.7	8.5	766	7.0	0.52	51.5	1.5
					1994	2007	1,162	10.7	6.9	678	6.2	0.46	58.4	0.7
2316000	ALAPAHA RIVER NEAR ALAPAHA, GA	2,600,606	504,826	663	1960	1975	567	11.6	9.5	404	8.3	0.61	71.3	1.2
					2003	2008	444	9.1	6.4	303	6.2	0.46	68.2	0.2
2317500	ALAPAHA RIVER AT STATENVILLE	2,652,763	257,783	1,400	1960	2008	1,123	10.9	8.9	864	8.4	0.62	76.9	0.6
2314500	SUWANNEE RIVER AT US 441, AT FARGO, GA	2,801,483	251,110	1,130	1960	2008	969	11.7	10.5	839	10.1	0.74	86.6	0.4
2315500	SUWANNEE RIVER AT WHITE SPRINGS, FLA.	2,747,271	121,311	2,430	1960	2008	1,798	10.1	9.1	1,482	8.3	0.61	82.4	0.8
2319500	SUWANNEE RIVER AT ELLAVILLE, FLA	2,610,267	141,265	6,970	1960	2008	6,357	12.4	11.1	5,561	10.8	0.80	87.5	0.3
2319800	SUWANNEE RIVER AT DOWLING PARK, FLORIDA	2,586,152	90,243	7,190	1997	2008	4,913	9.3	8.3	4,360	8.2	0.61	88.7	0.0
2320000	SUWANNEE RIVER AT LURAVILLE, FLA.	2,611,261	37,716	7,280	1997	2008	5,242	9.8	8.9	4,685	8.7	0.64	89.4	0.2
2320500	SUWANNEE RIVER AT BRANFORD, FLA.	2,688,958	-13,960	7,880	1960	2008	7,118	12.3	10.9	6,533	11.3	0.83	91.8	-0.3
2361000	CHOCTAWHATCHEE RIVER NEAR NEWTON, AL.	1,845,835	491,371	686	1960	2008	916	18.1	12.8	596	11.8	0.87	65.0	1.0
2361500	CHOCTAWHATCHEE RIVER NEAR BELLWOOD AL	1,790,564	425,331	1,280	2001	2008	1,525	16.2	12.0	976	10.4	0.76	64.0	1.7
2363000	PEA RIVER NEAR ARITON AL	1,793,324	583,775	498	1960	1969	564	15.4	9.8	321	8.8	0.64	56.9	1.0
					1988	2008	555	15.1	9.7	303	8.3	0.61	54.5	1.5
2327500	OCHLOCKONEE RIVER NEAR THOMASVILLE, GA	2,334,610	318,509	550	1960	1970	571	14.1	9.6	307	7.6	0.56	53.7	2.0
					2001	2008	552	13.6	8.6	293	7.2	0.53	53.0	1.4
2226500	SATILLA RIVER NEAR WAYCROSS	2,872,276	455,064	1,200	1960	2008	1,063	12.0	8.9	698	7.9	0.58	65.6	1.0
2228000	SATILLA RIVER AT ATKINSON	3,015,340	451,579	2,790	1960	2008	2,338	11.4	9.7	1,721	8.4	0.62	73.6	1.3
Overall Avg							2,432	13.48	9.7	1,570	8.8	0.65	66.3	0.9
Avg for outcrop areas							2,854	14.60	9.2	1,476	8.1	0.60	56.2	1.0
Avg for non-outcrop areas							2,067	12.51	10.1	1,652	9.4	0.69	75.0	0.7

Note: Yellow shaded cells denote stations located in areas where the surficial aquifer is the uppermost aquifer. All other stations located in the outcrop areas of Coastal Plain Aquifer System

¹ Long-Term refers to period of record, as noted.

Net recharge it mean recharge minus baseflow

Table 6-3 2003-2008 Results of Baseflow and Recharge Analysis

USGS Station ID	Station Name	State Plane GA West (ft)		Drainage Area	Modeled Period of Record		Mean Streamflow		Mean Recharge	Mean Baseflow		Normalized Baseflow	Baseflow Percentage of Total Streamflow	Net Recharge
		X	Y		Start	Finish	cfs	in/yr		cfs	in/yr			
2339500	CHATTAHOOCHEE RIVER AT WEST POINT	1,984,835	1,051,275	3,550	2003	2008	4,804	18.4	10.7	2,408	9.2	0.68	50.1	1.5
2341505	CHATTAHOOCHEE RIVER AT US 280, NEAR COLUMBUS, GA	2,040,993	893,219	4,670	2003	2008	6,001	17.5	3.0	3,080	9.0	0.66	51.3	-6.0
2343801	CHATTAHOOCHEE RIVER NEAR COLUMBIA, AL	2,001,767	459,267	8,210	2003	2008	8,721	14.4	2.2	3,878	6.4	0.47	44.5	-4.2
2344872	FLINT RIVER BELOW BIG BRANCH, NEAR MOLENA, GA	2,186,213	1,108,525	794	2005	2008	634	10.9	6.4	361	6.2	0.45	56.9	0.2
2347500	FLINT RIVER AT US 19, NEAR CARSONVILLE, GA	2,276,337	989,853	1,850	2003	2008	1,804	13.3	8.4	1,000	7.3	0.54	55.4	1.1
2349605	FLINT RIVER AT GA 26, NEAR MONTEZUMA, GA	2,334,607	834,044	2,920	2003	2008	2,803	13.0	9.8	1,874	8.7	0.64	66.9	1.1
2350512	FLINT RIVER AT GA 32, NEAR OAKFIELD, GA	2,342,615	627,414	3,880	2003	2008	3,723	13.0	8.3	1,972	6.9	0.51	53.0	1.4
2352500	FLINT RIVER AT ALBANY	2,303,589	579,794	5,310	2003	2008	4,712	12.1	5.7	2,660	6.8	0.50	56.4	-1.1
2353000	FLINT RIVER AT NEWTON	2,242,799	475,363	5,740	2003	2008	5,321	12.6	6.8	3,362	8.0	0.59	63.2	-1.2
2355662	FLINT RIVER AT RIVERVIEW PLANTATION, NR HOPEFUL,GA	2,198,472	414,940	7,080	2003	2008	6,456	12.4	8.3	4,434	8.5	0.63	68.7	-0.2
2356000	FLINT RIVER AT BAINBRIDGE	2,166,965	331,692	7,570	2003	2008	6,986	12.5	9.0	5,071	9.1	0.67	72.6	-0.1
2358000	APALACHICOLA RIVER AT CHATTAHOOCHEE FLA	2,078,970	255,614	17,200	2003	2007	19,177	15	10.1	13,031	10	0.76	67.9	-0.2
2359170	APALACHICOLA RIVER NR SUMATRA,FLA.	2,027,776	-17,417	19,200	2003	2007	24,530	17	12.3	20,047	14	1.04	81.7	-1.9
2210500	OCMULGEE RIVER NEAR JACKSON, GA	2,396,921	1,203,391	1,420	2003	2008	1,851	17.7	11.4	1,004	9.6	0.71	54.2	1.8
2213000	OCMULGEE RIVER AT MACON	2,464,312	1,032,927	2,240	2003	2008	2,373	14.4	9.9	1,401	8.5	0.63	59.1	1.4
2215500	OCMULGEE RIVER AT LUMBER CITY	2,759,755	700,899	5,180	2003	2008	4,507	11.8	9.5	3,479	9.1	0.67	77.2	0.4
2218300	OCONEE RIVER NEAR PENFIELD, GA	2,561,490	1,354,744	940	2003	2008	1,079	15.6	12.3	740	10.7	0.79	68.6	1.6
2223000	OCONEE RIVER AT MILLEDGEVILLE	2,587,880	1,125,072	2,950	2003	2008	2,336	10.8	5.2	940	4.3	0.32	40.2	0.8
2223056	OCONEE RIVER AT AVANT MINE NEAR QUITMAN	2,633,967	1,071,040	3,100	2006	2006	1,468	6.4	5.3	814	3.6	0.26	55.5	1.7
2223248	OCONEE RIVER NEAR OCONEE	2,668,266	1,015,922	3,770	2003	2008	2,938	10.6	4.4	1,439	5.2	0.38	49.0	-0.8
2223500	OCONEE RIVER AT DUBLIN	2,688,533	927,815	4,400	2003	2008	3,273	10.1	4.7	1,692	5.2	0.38	51.7	-0.5
2225000	ALTAMAHA RIVER NEAR BAXLEY	2,859,018	709,895	11,600	2003	2007	9,687	11.3	7.5	6,931	8.1	0.60	71.6	-0.6
2226000	ALTAMAHA RIVER AT DOCTORTOWN	3,024,315	609,515	13,600	2003	2008	10,998	11.0	8.8	8,705	8.7	0.64	79.2	0.2
21973269	SAVANNAH RIVER NEAR WAYNESBORO, GA	3,034,823	1,154,237	8,300	2006	2008	5,775	9.5	5.4	4,634	7.6	0.56	80.2	-2.1
2198000	BRIER CREEK AT MILLHAVEN	3,068,383	1,076,169	646	2003	2007	452	9.5	7.5	346	7.3	0.54	76.7	0.2
2173000	SOUTH FORK EDISTO RIVER NEAR DENMARK, S.C.	3,222,550	1,247,715	720	2003	2008	552	10.41	9.4	483	9.1	0.67	87.5	0.3
2173030	SOUTH FORK EDISTO RIVER NEAR COPE, SC	3,245,401	1,235,940	757	2003	2008	592	10.6	9.5	503	9.0	0.66	84.9	0.5
2173051	SOUTH FORK EDISTO RIVER NEAR BAMBERG, SC	3,258,118	1,228,325	807	2003	2008	674	11.4	10.4	582	9.8	0.72	86.3	0.6
2173500	NORTH FORK EDISTO RIVER AT ORANGEBURG, SC	3,300,880	1,283,054	683	2003	2008	518	10.3	9.9	455	9.1	0.74	87.9	0.8
2175000	EDISTO RIVER NR GIVHANS, SC	3,453,879	1,122,114	2,730	2003	2008	1,818	9.1	7.6	1,493	7.4	0.21	82.1	0.1
2168504	SALUDA RIVER BELOW LK MURRAY DAM NR COLUMBIA, SC	3,192,409	1,486,564	2,420	2003	2008	1,782	10.0	4.3	705	4.0	0.19	39.6	0.3
2201230	OGEECHEE RIVER AT MIDVILLE, GA	2,890,026	1,029,181	1,300	2004	2007	764	7.99	6.2	545	5.7	0.42	71.4	0.5
2202040	OGEECHEE RIVER AT ROCKY FORD RD, NR ROCKY FORD, GA	3,012,566	971,375	2,040	2003	2007	1,410	9.39	7.1	1,038	6.9	0.51	73.6	0.1
2202500	OGEECHEE RIVER NEAR EDEN	3,147,582	807,925	2,650	2003	2008	1,736	8.9	6.9	1,369	7.0	0.52	78.9	-0.1
2198000	BRIER CREEK AT MILLHAVEN	3,068,383	1,076,169	646	2003	2007	452	9.5	7.5	346	7.3	0.54	76.7	0.2
2318000	LITTLE RIVER NEAR ADEL, GA	2,491,472	420,806	577	2,003	2,007	508	12.0	6.9	289	6.8	0.50	56.8	0.1
23177483	WITHLACOOCHEE RIVER AT MCMILLAN RD,NEAR BEMISS, GA	2,578,129	347,612	502	2,003	2,008	488	13.2	8.1	218	5.9	0.43	44.8	2.2
2318500	WITHLACOOCHEE RIVER AT US 84, NEAR QUITMAN, GA	2,520,469	289,127	1,480	2003	2007	1,253	11.5	6.7	682	6.3	0.46	54.4	0.5
2316000	ALAPAHA RIVER NEAR ALAPAHA, GA	2,600,606	504,826	663	2003	2008	444	9.1	6.9	303	6.2	0.46	68.2	0.7
2317500	ALAPAHA RIVER AT STATENVILLE	2,652,763	257,783	1,400	2003	2008	979	9.5	7.5	742	7.2	0.53	75.8	0.3
2314500	SUWANNEE RIVER AT US 441, AT FARGO, GA	2,801,483	251,110	1,130	2003	2008	844	10.2	9.1	715	8.6	0.63	84.7	0.5
2315500	SUWANNEE RIVER AT WHITE SPRINGS, FLA.	2,747,271	121,311	2,430	2003	2008	1,599	8.9	7.8	1,306	7.3	0.54	81.6	0.5
2319500	SUWANNEE RIVER AT ELLAVILLE, FLA	2,610,267	141,265	6,970	2003	2008	5,645	11.0	9.8	4,907	9.6	0.70	86.9	0.2
2319800	SUWANNEE RIVER AT DOWLING PARK, FLORIDA	2,586,152	90,243	7,190	2003	2008	5,474	10.3	9.7	4,846	9.2	0.67	88.5	0.6
2320000	SUWANNEE RIVER AT LURAVILLE, FLA.	2,611,261	37,716	7,280	2003	2008	5,922	11.1	9.7	5,221	9.7	0.72	88.2	0.0
2320500	SUWANNEE RIVER AT BRANFORD, FLA.	2,688,958	-13,960	7,880	2003	2008	6,581	11.3	10.3	5,873	10.1	0.75	89.2	0.2
2361000	CHOCTAWHATCHEE RIVER NEAR NEWTON, AL.	1,845,835	491,371	686	2003	2008	757	15.0	11.2	474	9.4	0.69	62.6	1.8
2361500	CHOCTAWHATCHEE RIVER NEAR BELLWOOD AL	1,790,564	425,331	1,280	2003	2008	1,628	17.3	12.6	1,030	10.9	0.80	63.2	1.7
2363000	PEA RIVER NEAR ARITON AL	1,793,324	583,775	498	2003	2008	484	13.2	8.9	267	7.3	0.54	55.1	1.6
2327500	OCHLOCKONEE RIVER NEAR THOMASVILLE, GA	2,334,610	318,509	550	2003	2008	604	14.9	9.1	319	7.9	0.58	52.8	1.2
2226500	SATILLA RIVER NEAR WAYCROSS	2,872,276	455,064	1,200	2003	2008	900	10.2	7.0	555	6.3	0.46	61.7	0.7
2228000	SATILLA RIVER AT ATKINSON	3,015,340	451,579	2,790	2003	2008	2,008	9.8	8.1	1,437	7.0	0.52	71.6	1.1
Overall Avg							2,141	11.6	8.6	1,548	7.8	0.56	68.4	0.8
Avg for outcrop areas							1,886	13.1	8.7	1,036	7.5	0.54	56.8	1.2
Avg for non-outcrop areas							2,301	10.7	8.5	1,868	8.0	0.58	75.7	0.5

Note: Yellow shaded cells denote station located in areas where the surficial aquifer is the uppermost aquifer. All other stations located in the outcrop areas of Coastal Plain Aquifer System
Net recharge is mean recharge minus baseflow.

The antecedent recession, defined in PART, is the time increment between the peak and a day during the groundwater flow recession period after the peak or the time in which baseflow is calculated. The requirement of antecedent recession used in PART is the result (N) of the equation $N=A^{0.2}$ rounded to the next larger integer, in which N is the number of days after the peak, and A is the drainage area in square miles. PART should be used for estimating recharge or baseflow only if the drainage area is larger than one square mile. Therefore, the requirement of antecedent recession will exceed the time increment of the data (one day).

6.4.3.3 PART Results

The long-term results of the baseflow analysis using PART are provided in Table 6-2. Additionally, an evaluation of the baseflow over the period from 2003 to 2008 was completed, and the results are summarized in Table 6-3. The tables present the drainage areas for each station, the period of record, mean streamflow, mean baseflow, areally averaged (normalized) baseflow, and the percent of total streamflow that comes from baseflow.

Based on Table 6-2, the unit-area mean-annual baseflow ranges from approximately 3.6 inches per year at the Oconee River at Avant Mine near Quitman, Georgia, to about 14.9 inches per year at South Fork of the Edisto River near Denmark, South Carolina. This result is relatively consistent with a baseflow analysis conducted by the USGS for 67 USGS gauging stations in the Apalachicola-Chattahoochee-Flint and the Alabama-Coosa-Tallapoosa River Basins portion of the Coastal Plain. The USGS analysis found that most of the baseflow estimates ranged from 8.3 to 14.8 inches per year (Jones and Mayer, 1997).

Results from the USGS PART baseflow separation analysis are shown on two example hydrographs from two gauging stations on the Chattahoochee and Flint Rivers in western Georgia (**Figures 6-3 and 6-4**). **Figures E-1 through E-9 in Appendix E** depict the streamflow and baseflow for the downstream stations located closest to the boundary of the surficial aquifer.

6.4.3.4 Comparison to Simulated Baseflow

As stated in Section 5.4.6, groundwater baseflow to major rivers and streams was simulated using the MODFLOW River Package. Groundwater contributions to baseflow for a given river or stream in the model were determined by calculating the difference between baseflow between the downstream and upstream flow monitoring stations. The comparisons could only be made in the active portions of the model, and only reflect a portion of the total baseflow. Thus, a comparison of the difference in baseflow estimated from streamflow records and simulated baseflow showed that the regional model was only simulating anywhere from 1/3 to 1/10 of the total baseflow to rivers and streams. There are several reasons why the model is only simulating a portion of the total baseflow:

- The model did not represent all of the tributaries to the major rivers, but instead only includes the higher order rivers and streams;

- The model only included rivers and streams that are connected to hydrogeologic units other than the surficial aquifer system, which were aquifers whose groundwater elevations responded to hydrologic stresses (active model layers). As stated in Section 5.4.6, rivers and streams that are connected to the surficial aquifer were not included in the model because the surficial aquifer was modeled as a constant head boundary and therefore did not receive simulated baseflow discharge. More than half of the rivers and streams are directly connected to the surficial aquifer system in the Coastal Plain of Georgia and therefore contribute baseflow to the rivers.

One consequence of modeling stream baseflow in only the active layer is that for a stream that crossed the outcrop of an active aquifer layer and then crossed the surficial aquifer, the modeling only reduced the baseflow of the portion of the stream that crossed an active aquifer layer.

Based on Table 6-3, the unit-area mean-annual baseflow ranges from approximately 4.0 inches per year at the Saluda River below the Lake Murray Dam near Columbia, South Carolina, to about 10.9 inches per year at the Choctawhatchee River near Bellwood, Alabama. In general, there has been an overall reduction in the unit-area mean-annual baseflow over the last five years compared to the long term baseflow estimates.

Baseflow to streams and rivers varies with the geology and the stream. For example, in much of south central Georgia there is no direct recharge from streams to the upper Floridan Aquifer or groundwater baseflow contribution from the Upper Floridan Aquifer to streams (discharge) because the aquifer is deep and confined. **Figure 6-5** shows where major rivers and tributaries are in direct hydraulic connection with the prioritized aquifers and where interactions of surface and groundwater were simulated. Comparison of modeled-rivers and all of the rivers and their tributaries shows that the model only represents the major rivers and some of the larger tributaries, and it only represents the rivers and streams that are in direct hydraulic connection with aquifers other than the surficial aquifer (since the surficial aquifer was modeled as a constant head boundary in the project models) such as in the outcrop areas. As noted above, the regional model predictably underestimated total baseflow to all rivers and streams by a factor of 3 to 10 times. As discussed in Section 6.5.4 below, this will likely result in a conservatively low estimate of the range of sustainable yield.

6.4.4 Estimated Recharge in the Outcrop Areas

Published average annual hydrologic (rainfall and evapotranspiration) and hydraulic (stormwater runoff) data were used to estimate aquifer recharge in the outcrop areas as discussed in Section 2.1. Aquifer recharge in the areas where the surficial aquifer is present was calculated by the model using constant head (estimated average water table elevation data) for the surficial aquifer, published leakance values and computed groundwater elevations for model layer 2 (Upper Floridan-Barnwell Aquifers).

To check the aquifer recharge values in the outcrop areas used in the model, the USGS streamflow data described in Section 6.4.1 and contained in Tables 6-2 and 6-3 were used to estimate recharge within the respective contributing areas. The USGS RORA Program (Rutledge, 1993 and 1998) was used to estimate aquifer recharge from USGS streamflow data.

This program uses the recession-curve-displacement method to estimate the recharge for each peak in the streamflow record. The method is also called the Rorabaugh Method. It is based on measuring the change in the total potential groundwater discharge. This is estimated at the critical time after the peak, by the extrapolation of discharge values from the pre-peak and the post-peak recession periods. The method is applied to a long period of record and gives an estimate of the mean rate of groundwater recharge.

The results indicated that aquifer recharge rates range from low to moderate in the outcrop areas. A comparison of groundwater recharge at Taylor Creek (average of 4.55 inches per year) to baseflow to Taylor Creek (3.5 inches per year) also indicated that approximately 1.0 inches per year remained in the surficial aquifer

6.5 Regional Georgia EPD Groundwater Flow Model Calibration Results

ASTM D 5490-93 (Reapproved 2002) titled "*Standard Guide for Comparing Ground-Water Flow Model Simulations to Site-Specific Information*" provides industry-accepted guidance for calibration. This guide covers techniques that should be used to compare the results of groundwater flow model simulations to measured field groundwater levels as part of the process of calibrating a groundwater flow model. This guide was used to present groundwater calibration results. This ASTM standard includes several calibration metrics. CDM followed this guide to present groundwater calibration results, including comparison of simulated and measured groundwater level residuals, and standard deviation of residuals, as well as several other calibration metrics.

6.5.1 Groundwater Levels

As part of the process of calibrating groundwater models, scattergram comparisons of the observed and model-computed groundwater elevations are recommended. A comparison between the observed and model-computed groundwater elevations across all model layers is depicted on **Figure 6-6** using a scattergram at 320 monitor wells. Comparisons between the observed and model-computed groundwater elevations in Layer 2 through Layer 6 are displayed on **Figures F-1 through F-5** in **Appendix F**, respectively. The 45 degree red line on Figure 6-6 and the figures in Appendix F represents a perfect head calibration where the residuals are zero. A scattergram was not developed for Layer 7 since there are no existing monitor wells in that aquifer unit. The corresponding statistical analysis, such as groundwater level residuals, standard deviation of residuals, and RSME of residuals, are also presented on these figures.

Comparisons between the observed and model-computed groundwater elevations at each monitor well are presented in **Table F-1** in Appendix F. The model calibration statistics for all of the aquifer layers and each individual layer are summarized in **Table 6-4**. The model calibration statistics for Layers 2 through 6 are presented on Figures F-1 through F-6, respectively. As shown in these figures and tables, there is a very strong correlation between observed and model-computed groundwater elevations across all model layers.

Table 6-4 Georgia EPD Regional Groundwater Model Calibration Statistics

Calibration Statistics	Value/Unit					
	Model Layer ¹					
	Overall	2	3	4	5	6
No. of Monitor Wells	320	249	31	20	7	13
Average of Residuals (ft)	0.23	0.21	4.73	-2.40	-0.17	-6.00
Standard Deviation of Residuals (ft)	13.28	13.32	7.76	14.64	11.57	18.99
Root Mean Square Error of Residuals (ft)	13.27	13.30	8.98	14.47	10.72	19.21
Head Difference across layers (ft)	445	398	369	223	167	119
Average of Residuals/Head Difference across layers (%)	0.05	0.05	1.28	1.07	0.10	5.04
Standard Deviation of Residuals/Head Difference across layers (%)	2.98	3.35	2.10	6.57	6.92	15.96

¹Notes:

Model Layer 1 - Surficial/Brunswick Aquifer (constant head)

Model Layer 2 - Upper Floridan Aquifer

Model Layer 3 - Claiborne/Gordon/Lower Floridan Aquifers

Model Layer 4 - Clayton-Dublin Aquifers

Model Layer 5 - Providence Sand-Peedee-Dublin Aquifers (Cretaceous Aquifer System)

Model Layer 6 - Eutaw-Midville Aquifer (Cretaceous Aquifer System)

Model Layer 7 - Upper Atkinson-Upper Tuscaloosa Aquifers (Cretaceous Aquifer System)

As shown in Table 6-4, the average residual (model-computed minus observed) for all layers is about 0.23 feet. Overall standard deviation and RMSE of residuals are approximately 13.28 feet and 13.27 feet, respectively. As shown in Table F-1, the groundwater levels varied from about -117 to 328 feet NGVD, representing a head difference of 445 feet across the entire model domain. The ratio of average residual to head difference across the model is approximately 0.05 percent. The ratio of standard deviation of residual to head difference across the model is approximately 3 percent. Average residuals for Layers 2 through 6 range from approximately 0.21 feet in Layer 2 to -6.0 feet in Layer 6. Standard deviations of residuals for Layers 2 through 6 range from approximately 7.76 feet in Layer 3 and 18.99 feet in Layer 6. The RMSE of residuals for Layers 2 through 6 ranges from approximately 8.98 feet in Layer 3 and 19.21 feet in Layer 6.

According to the model calibration criteria established for this project, the regional groundwater flow model calibration met the average of residuals and the standard

deviation of residuals criteria. These two criteria should be related to the head difference across the simulated Study Area. As shown in Table F-1, the groundwater levels varied from about -117 to 328 feet NGVD, representing a difference of 445 feet across the entire model domain. Thus, the criterion for mean residual was about 0.05 percent of the head difference, and the criterion for the standard deviation was about 3 percent. Modeling efforts in similar settings have used criteria in the range of 5 percent or more with success; therefore, the criteria stated above are seen as relatively strict and this model can be considered a well calibrated model.

6.5.2 Groundwater Flow Patterns

Using the calibrated regional groundwater model, the simulated long-term average groundwater elevation contours in the Upper Floridan Aquifer (Layer 2) through the Upper Atkinson Aquifer (Layer 7) are presented on **Figures 6-7** through **6-12**. As shown on these figures, the predominant groundwater flow direction in all of the aquifers occurs from the outcrop areas south of the Fall Line toward the southeast to the Atlantic Ocean and south to the Gulf of Mexico. This pattern is consistent with regional groundwater flow patterns in the Coastal Plain of Georgia (Figures 2-20 through 2-24).

As shown on Figures 6-7 and 6-8, groundwater flows in the Upper Floridan Aquifer (Layer 2) and the Claiborne/Gordon/Lower Floridan Aquifers (Layer 3) are significantly influenced by the Gulf Trough. The calibrated regional groundwater model clearly represents this hydrogeologic feature.

Comparisons of the groundwater elevation contours in the Upper and Lower Floridan Aquifers between the calibrated regional groundwater model and the USGS Georgia Coastal groundwater model are shown on **Figures 6-13** and **6-14**, respectively. As shown, the calibrated regional model duplicates the groundwater flow patterns in the Upper and Lower Floridan Aquifers in the Georgia coastal areas.

6.5.3 Vertical Head Differences

Comparisons of Figures 6-7 through 6-12 indicate simulated vertical head differences between each layer (i.e., Layers 2 through 7) within southwestern Georgia. Vertical head differences generally indicate that there is a confining or semi-confining layer between each hydrogeologic unit, which is consistent with field exploration and regional hydrogeologic studies. **Table 6-5** and **Figure 6-15** summarize model-computed and observed groundwater levels in 35 monitor well clusters installed in different aquifers at 15 locations (**Figure 6-16**). As shown in this table, simulated vertical head differences between the aquifers vary as follows:

- From approximately -12 feet (upward gradient) to 64 feet (downward gradient) with an average downward gradient of about 17 feet (downward gradient) between the Upper Floridan Aquifer (Layer 2) and the Claiborne/Gordon/ Lower Floridan Aquifers (Layer 3) in the model domain;

Table 6-5 Comparison Between Observed and Simulated Vertical Head Differences in the Regional Model

MW Cluster	Aquifer	USGS ID	Model Layer	Groundwater Elevation (ft NGVD)		Residual (ft)
				Measured	Computed	
1	UFA	13L012	2	152.8	165.9	13.1
	Claiborne	13L011	3	119.1	123.5	4.4
	Clayton	13L013	4	86.4	84.4	-2.1
	Δ Head	-	-	66.4	81.6	-
2	Claiborne	06K010	3	234.3	230.5	-3.8
	Clayton	06K009	4	140.6	156.5	15.8
	Δ Head	-	-	93.7	74.1	-
3	Claiborne	09M009	3	292.1	299.7	7.6
	Clayton	09M007	4	152.7	159.4	6.7
	Δ Head	-	-	139.3	140.3	-
4	Claiborne	11L001	3	196.6	198.6	2.1
	Clayton	11L002	4	114.2	127.7	13.6
	Δ Head	-	-	82.4	70.9	-
5	Claiborne	11P015	3	300.3	304.1	3.8
	Clayton	11P014	4	230.8	207.9	-23.0
	Δ Head	-	-	69.5	96.2	-
6	Claiborne	12M001	3	130.8	139.4	8.6
	Clayton	12M002	4	90.3	100.0	9.7
	Δ Head	-	-	40.5	39.4	-
7	UFA ¹	12L029	2	153.9	171.9	18.0
	Claiborne	12L019	3	114.8	129.7	14.9
	Clayton	12L020	4	55.8	40.4	-15.3
	Providence	12L021	5	65.1	65.0	-0.1
	Δ Head	-	-	88.7	106.9	-
8	UFA ²	13L049	2	170.8	178.3	7.5
	Claiborne ²	13L015	3	108.7	114.3	5.6
	Clayton ²	13L002	4	100.5	85.2	-15.3
	Δ Head	-	-	70.3	93.1	-
9	UFA	13M006	2	228.6	195.2	-33.4
	Claiborne	13M005	3	224.7	207.2	-17.6
	Δ Head	-	-	3.9	-12.0	-
10	Claiborne	11K002	3	157.6	155.6	-2.0
	Clayton	11K005	4	123.0	127.4	4.4
	Δ Head	-	-	34.6	28.2	-
11	UFA	11J012	2	119.1	130.9	11.9
	Claiborne	11J011	3	124.5	137.0	12.5
	Δ Head	-	-	-5.4	-6.1	-
12	Claiborne	14P015	3	229.6	234.4	4.7
	Clayton	14P014	4	205.5	225.2	19.8
	Δ Head	-	-	24.2	9.1	-
13	Gordon	32Y033	3	115.5	127.0	11.6
	Clayton	32Y031	4	158.8	143.5	-15.3
	Eutaw-Midville	32Y030	6	177.8	173.6	-4.3
	Δ Head	-	-	-62.4	-46.6	-
14	UFA	35P110	2	-19.1	-8.1	11.0
	LFA	35P109	3	-19.1	-4.5	14.5
	Δ Head	-	-	0.0	-3.6	-
15	UFA	33H207	2	4.6	8.2	3.6
	LFA	33H206	3	11.7	16.1	4.4
	Δ Head	-	-	-7.0	-7.9	-
Average of Residuals						2.8
Standard Deviation of Residuals						12.4
Root Mean Square Error of Residuals						12.5

Note:

¹ Monitor well is about 7,000 feet from cluster wells.

² Monitor wells are within about 3,000 feet radius.

- From approximately -17 feet (upward gradient) to 140 feet (downward gradient) with an average downward gradient of about 68 feet (downward gradient) between the Claiborne (Layer 3) and Clayton Aquifers (Layer 4);
- At monitor well clusters 12L029 and 12L021, a downward gradient between the Upper Floridan Aquifer (Layer 2) and the Providence Aquifer (Layer 5) was approximately 107 feet; and
- At monitor well clusters 32Y033 and 32Y030, an upward gradient between the Gordon Aquifer (Layer 3) and the Eutaw-Midville Aquifer (Layer 6) was approximately -47 feet.

From review of the data in Table 6-5, most of the downward vertical head loss usually occurs between the Upper Floridan Aquifer and the Clayton-Lower Floridan Aquifers with smaller vertical head differences between the Clayton-Lower Floridan Aquifers and the Providence Sand-Peedee and Eutaw Midville aquifers that comprise the Cretaceous Aquifer System.

Based on the model simulation results, the vertical head differences criteria of having the average of residuals and standard deviation of residuals in vertical heads across aquifers at monitor well cluster locations of less than 5 feet and 15 feet, respectively was met.

6.5.4 Baseflow Comparison

Based on the calibrated regional groundwater model, a water budget analysis was performed on the River Package inflow and outflows to determine model-computed baseflow on the major rivers in the outcrop areas. Two examples are discussed here, the Chattahoochee and Flint Rivers, because nearly the entire river surface water basin is located in the outcrop area and therefore the model would be expected to simulate a higher percentage of the total baseflow than in rivers with significant contributions from the surficial aquifer. The baseflow to the Chattahoochee River between Stations 2341505 and 2343801 (see Figure 6-5 for station locations) was computed to be approximately 300 cubic feet per second (cfs), which indicates that the model was not simulating about 2/3 of the baseflow likely originating in tributaries not included in the model. The baseflow to the Flint River between Stations 2356000 and 2349605 was computed to be approximately 725 cfs, which indicates that the model was not simulating about 3/4 of the baseflow likely originating in tributaries not included in the model.

As discussed in Section 6.3.3.4, these differences are primarily attributed to the fact that not all of the river tributaries were represented as actively contributing baseflow in the model. Comparisons of modeled-river lengths and a total of lengths of all rivers and their tributaries (Figure 6-5) show that the model only represents 25 percent of the major rivers and some of the larger tributaries in the Flint River Basin. The model includes only 1,465 miles of river and tributaries in the outcrop areas out

of a total of 21,526 miles (~7%) of total rivers and tributaries in the Coastal Plain of Georgia.

The regional model only simulates a portion of the groundwater contribution to baseflow for the sections of the rivers and streams in the outcrop areas. However, this does not invalidate the use of baseflow reduction as a sustainable yield metric if the model limitations are recognized and accounted for. It should be recognized that applying baseflow reduction constraints to only those portions of stream reaches that receive simulated baseflow discharge from active model layers, and ignoring the contributions to baseflow of stream tributaries, will result in an conservatively low estimate of sustainable yield. If pumping sustainability is defined as pumping that results in less than a 40% reduction in groundwater contribution to stream baseflow, the sustainable pumping range would be lower if the stream baseflow being affected is only a fraction of the actual total baseflow.

Thus, though the model is not currently configured to simulate the entire stream system, underestimating the groundwater contribution to stream baseflow available to contribute to sustainable yield would result in smaller and therefore conservative ranges of sustainable yield, when those ranges are defined relative to the percent reduction of groundwater contributions to stream baseflow sustainable yield metric.

Based on the model calibration results presented above and due consideration to the limits of the model with regard to baseflow simulation, the calibrated Georgia EPD regional groundwater flow model represents a reasonable representation of the Coastal Plain Aquifers in Georgia that can be used to evaluate conservatively low estimates of the sustainable yield of the various aquifers.

Since completion of the 2009 sustainable yield modeling described herein, the regional model was calibrated to groundwater withdrawal data that became available during 2010. An analysis of the 2010 pumping data resulted in an increased baseline pumping rate from the Claiborne (67 mgd in 2009 vs. 93 mgd in 2010) and Cretaceous Aquifers (124 mgd in 2009 vs. 219 mgd in 2010). Since the internal (River) and perimeter (general head) boundary conditions of the regional model had to be changed with new baseline pumping data, the regional model was updated and calibrated to the 2010 input (pumping) data. The MODFLOW Well file in the regional model was changed to reflect the revised pumping data for all of the Coastal Plain Aquifers. The regional model calibration consisted of a series of model simulations by systematically adjusting the boundary conditions and hydrogeologic properties until the groundwater head and baseflow calibration criteria were satisfied. In this 2010 calibration it was found that after adding additional River cells and adjusting transmissivity and leakance between aquifers, additional recharge was needed to match the observed groundwater heads and estimated groundwater contribution to surface water features with the increased 2010 pumping. This afforded the opportunity to adjust recharge within the outcrop areas (within the range of values in the literature) and to increase the model's representation of the river reaches and tributaries.

Once the refined regional model was calibrated to the 2010 pumping data, the regional model was used to revise the boundary conditions and hydrogeologic properties of the Claiborne and Cretaceous Aquifer subregional models. The Claiborne and Cretaceous Aquifer models were then calibrated to the 2010 input data. Subsequently, the revision of model calibration to the 2010 input data dictated a re-assessment of the sustainable yield estimates of both the Claiborne and Cretaceous Aquifers. From this re-assessment, the sustainable yield range estimates for the Claiborne and Cretaceous Aquifers increased significantly between 2009 and 2010 modeling efforts (150 % low end /354% high end for the Claiborne Aquifer and 58 % low end /103% high end for the Cretaceous Aquifer). This affirmed that the 2009 model calibration resulted in conservatively low sustainable yield estimates for these aquifers.

6.6 Calibrated Hydrogeologic Properties

As discussed in Section 5.4.4, initial hydrogeologic values were assigned to each model layer based on several sources. During the model calibration, spatial changes in hydraulic conductivity, transmissivity and leakance were made. The variations of the horizontal hydraulic conductivities, transmissivity, and leakance of the calibrated groundwater flow model are shown on **Figures G-1** through **G-12** in Layers 2 through 7 in **Appendix G**, respectively. Variations of hydrogeologic properties within the model area can also be found in the GMS-MODFLOW output file.

As discussed in Section 5.4.8, net recharge was used in the calibrated Georgia EPD regional model. Net recharge, as shown on Figure 5-16, ranged from 0.1 to 6 inches/year and was assigned to the highest active model layer of the model. As shown on Figure 5-16, the range of recharge estimates is consistent with the range of recharge estimates from the USGS for the Upper Floridan Aquifer (0 to 15 inches/year on Figure 2-10) and the Claiborne, Clayton, and Cretaceous Aquifers (0 to 5 inches/year on Figure 2-13) in the outcrop areas.

6.7 Model-Wide Water Budget

A model-wide water budget for the 2009 calibrated steady-state regional groundwater model was developed from the MODFLOW output file. **Table 6-6** presents the model-wide water budget following model calibration to existing conditions. Based on the model-wide water budget, recharge and river leakage are the largest inflow terms. The largest outflow terms are river leakage (baseflow), followed by pumping. The MODFLOW Well Package was used to represent recharge of surface water from the Suwannee River to the Upper Floridan Aquifer.

The unit area water budget inflow and outflow terms (in inches per year) were calculated over the areas in which each water budget component was applied rather than the entire model domain so that the model simulated values could be compared to published values (Faye and Mayer, 1996) or values estimated using other techniques such as the baseflow separation and aquifer recharge analyses.

Table 6-6 Model-Wide Water Budget for the Georgia EPD Regional Groundwater Model

Water Budget Component	Inflow to Model (Sources)		Outflow from Model (Sinks)		Difference	
	(mgd)	(in/yr)	(mgd)	(in/yr)	(mgd)	(in/yr)
Storage	0	0	0	0	0	0
Constant head (surficial aquifer) ^{1,2}	1,208	1.13	-785	-0.98	424	0.15
Well Pumping ³	29	0.01	-1,622	-0.58	-1,593	-0.57
River leakage (in outcrop areas) ⁴	3,481	3.48	-4,830	-4.83	-1,349	-1.35
Recharge in outcrop areas ⁵	2,519	1.77	0	0	2,519	1.77
Total	7,236	6.39	-7,236	-6.39	0	0

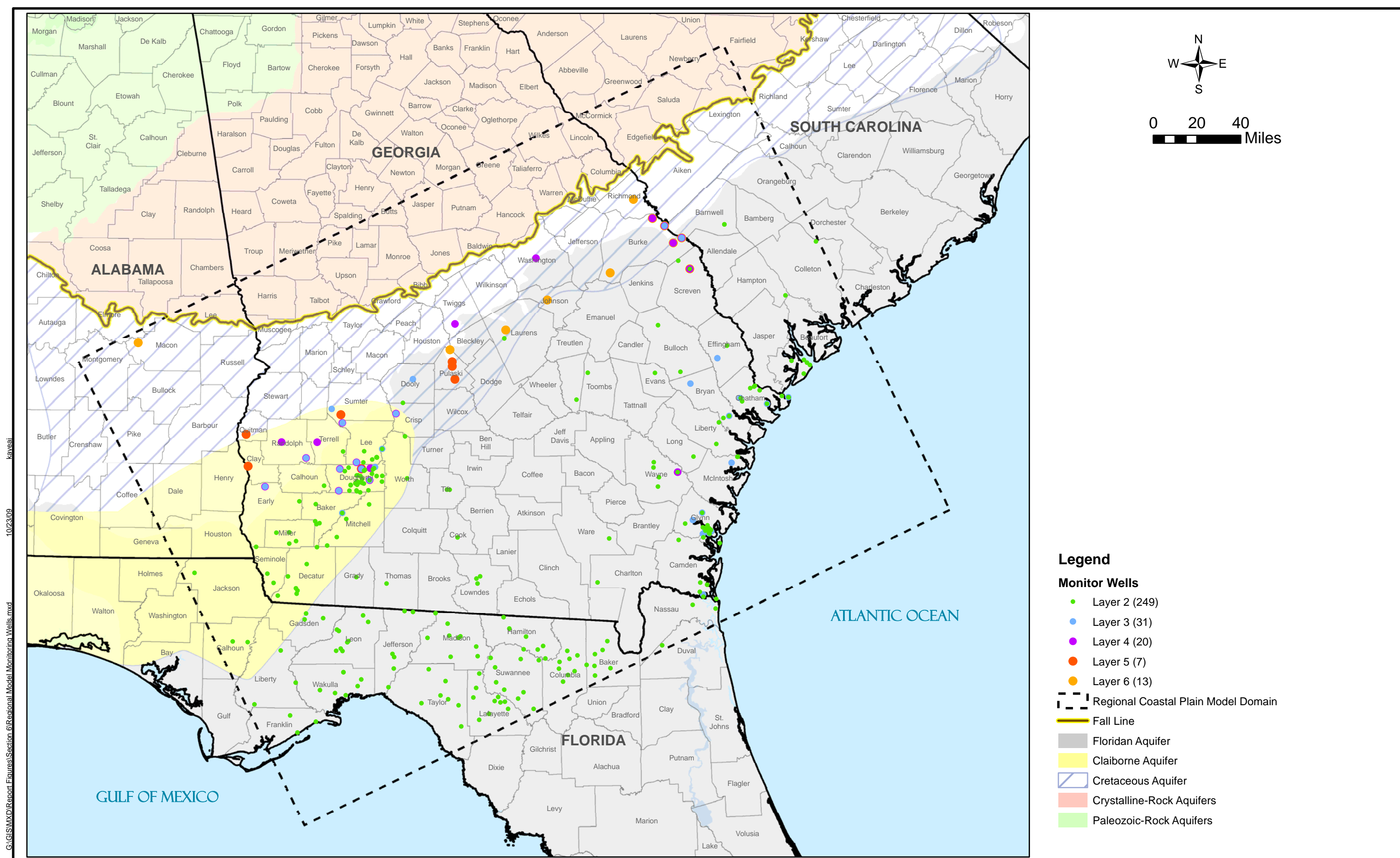
¹Constant head inflows are from the surficial aquifer (model layer 1) to underlying aquifers and constant head outflows are from deeper aquifers to model layer1 in the portions of the model that covers the coastal areas, the Atlantic Ocean and the Gulf of Mexico

²The land-based areas (recharge) used to calculate the inflow in inches per year is 22,470 square miles. The discharge areas of model layer 1 used to calculate outflow in inches per year is 16,790 square miles.

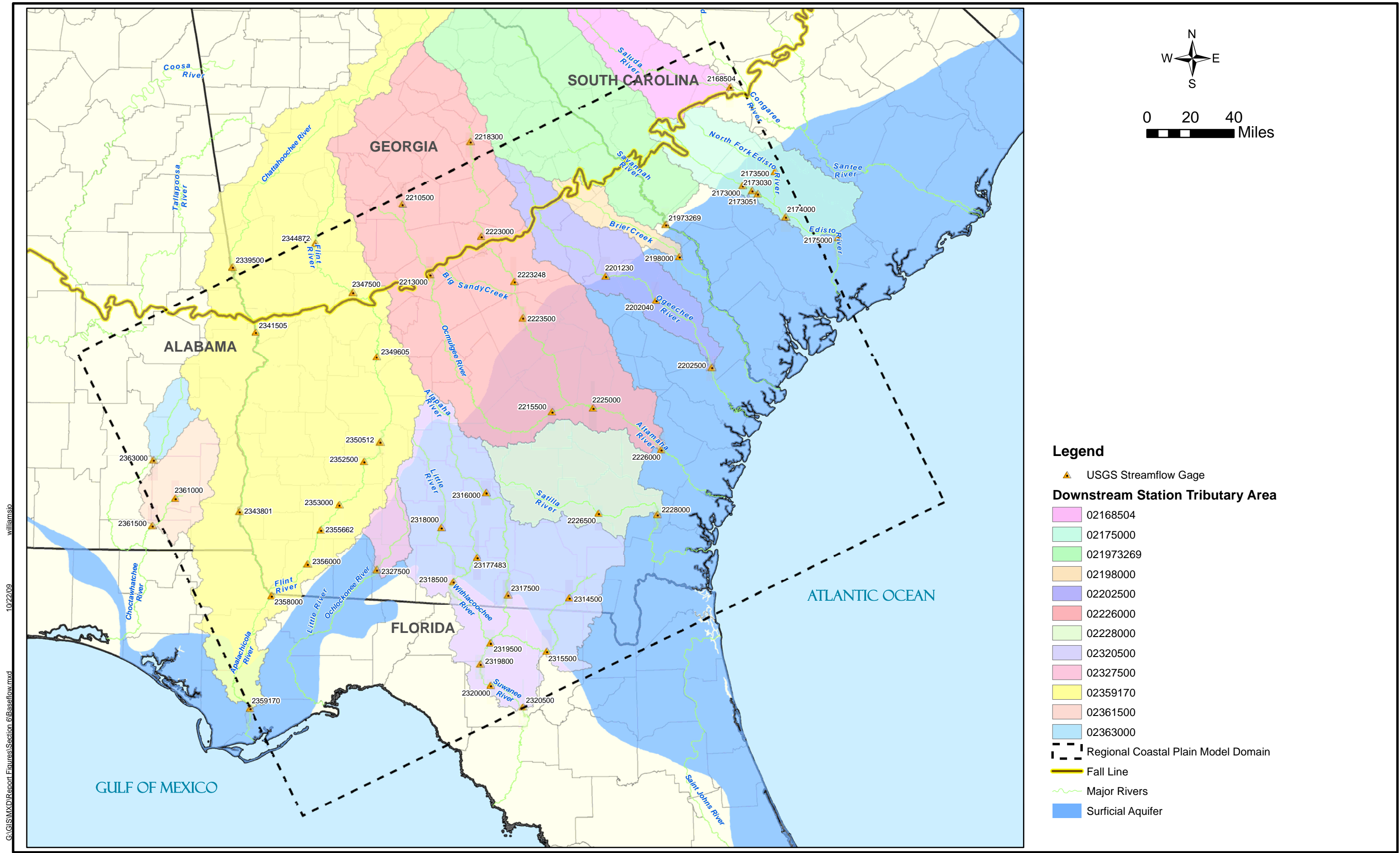
³Well pumping occurs over the entire active portion of the model domain, which corresponds to an area of approximately 58,640 square miles

⁴River leakage only occurs within the drainage basins in the outcrop areas, which covers a land area of approximately 21,000 square miles

⁵Recharge was specified only in the outcrop areas, which covers a land area of approximately 29,890 square miles

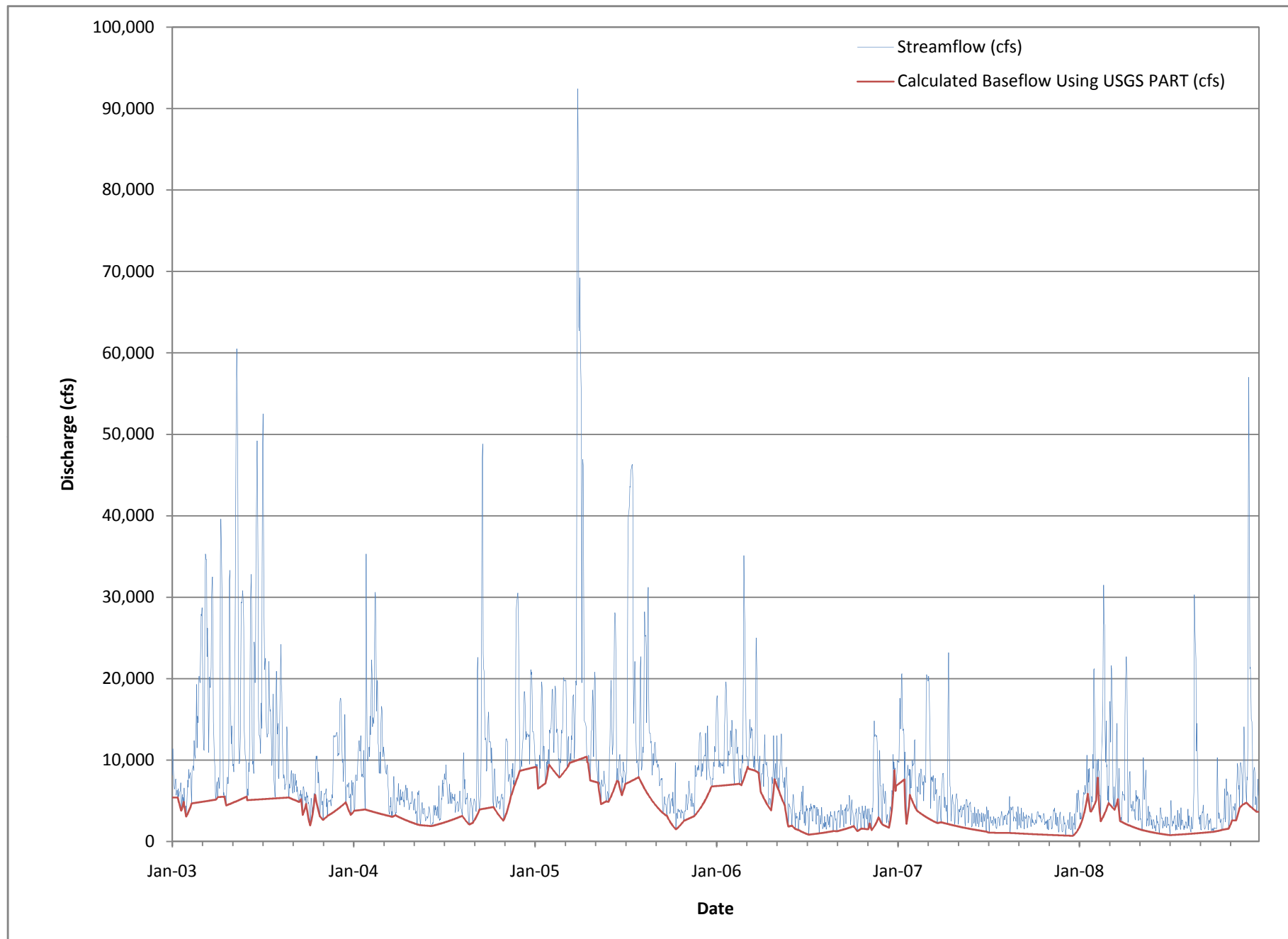


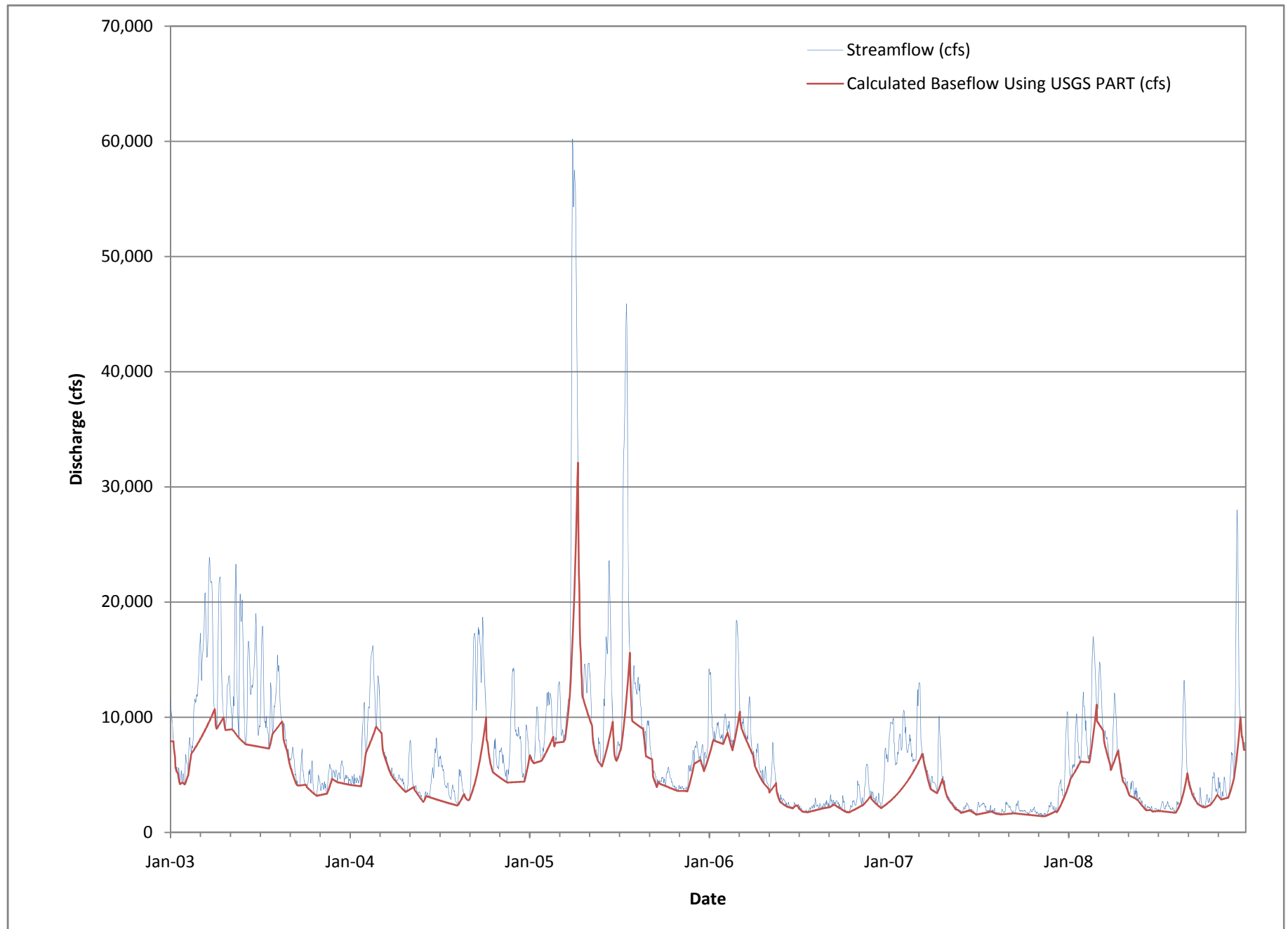
CDM **Figure 6-1**
Monitor Well Locations in Regional Groundwater Flow Model Domain

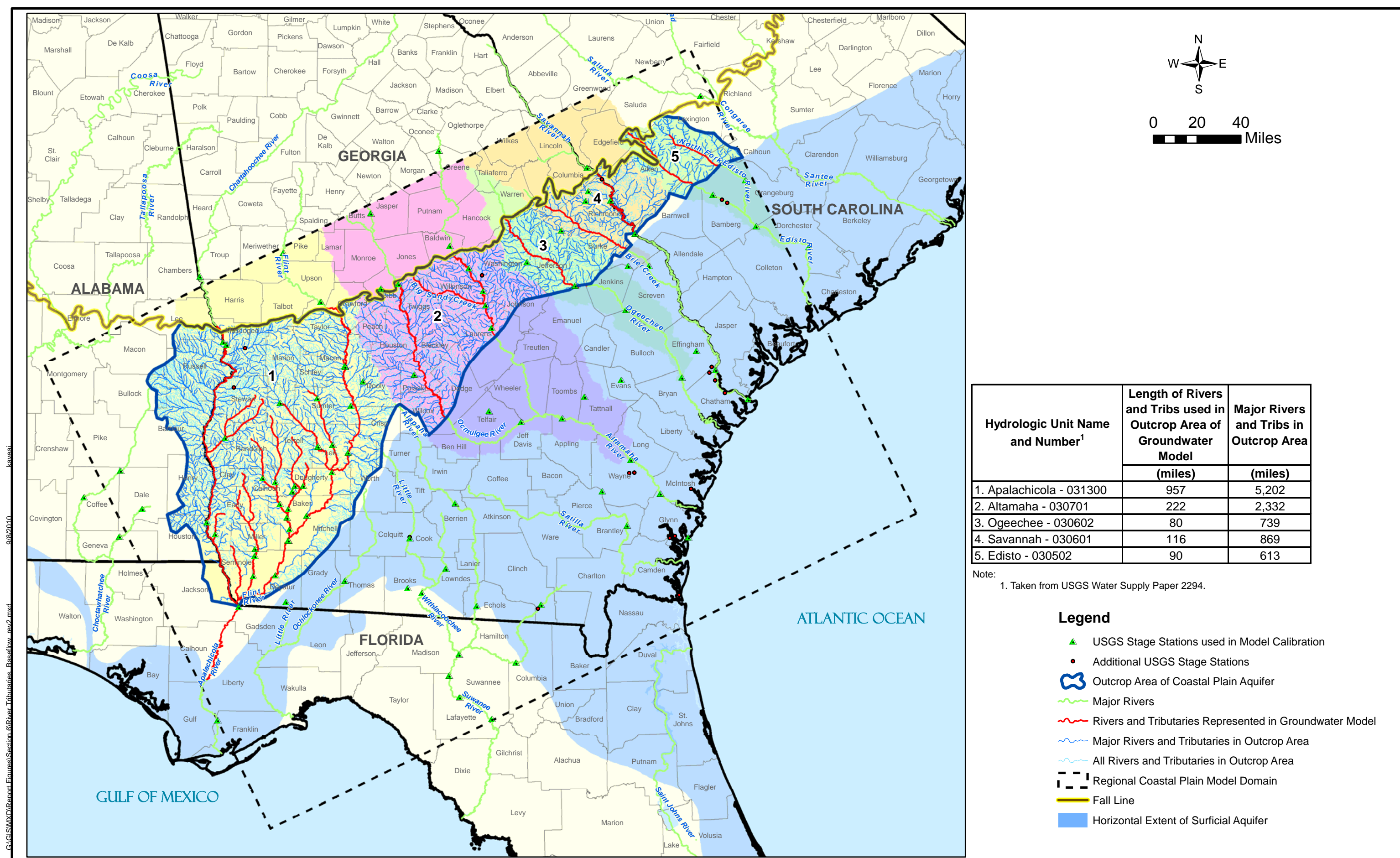


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CDM **Figure 6-2**
Selected USGS Streamflow Gages for Baseflow Separation Analysis







CDM **Figure 6-5**
Major Rivers and Tributaries Represented in the Regional Groundwater Flow Model

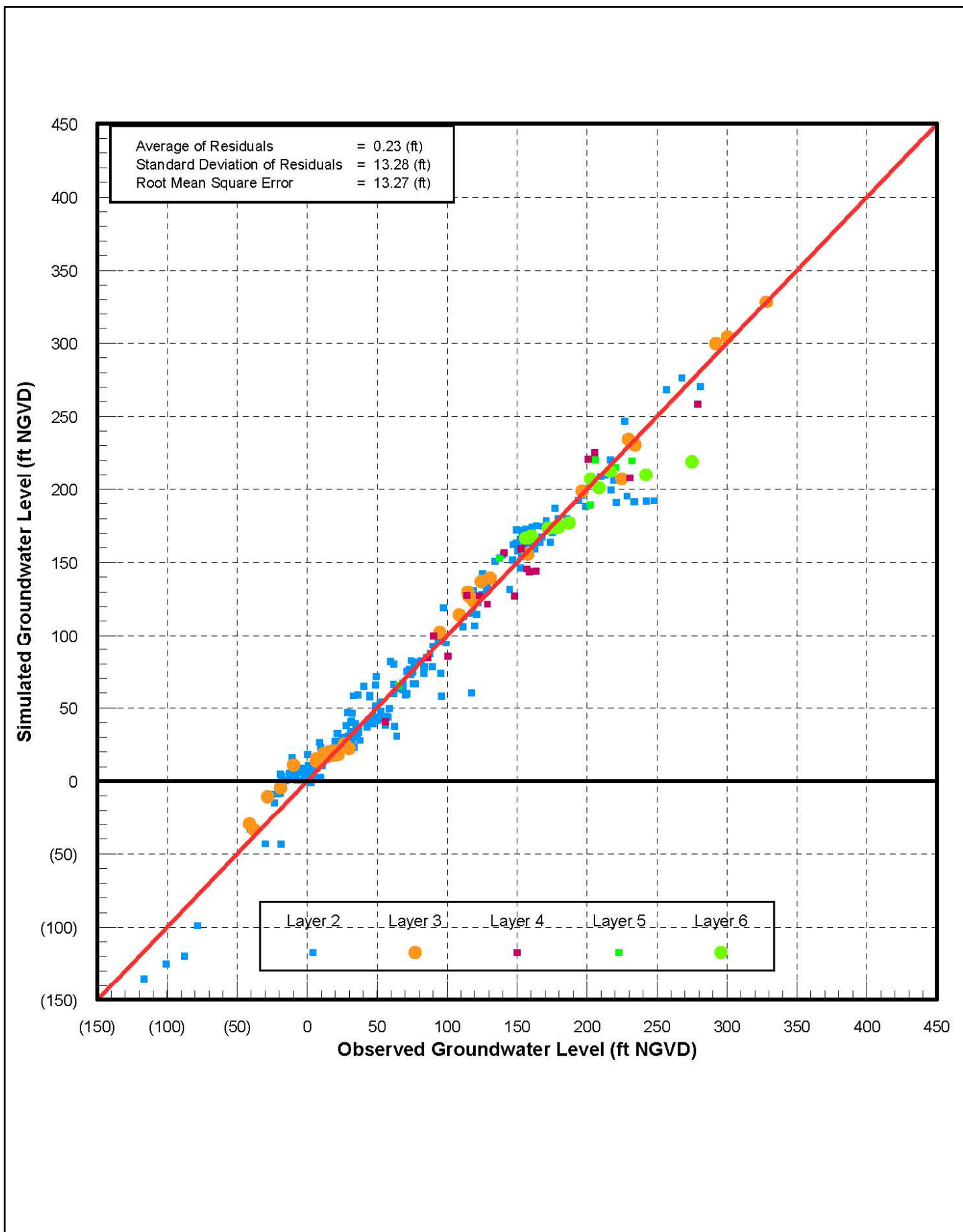
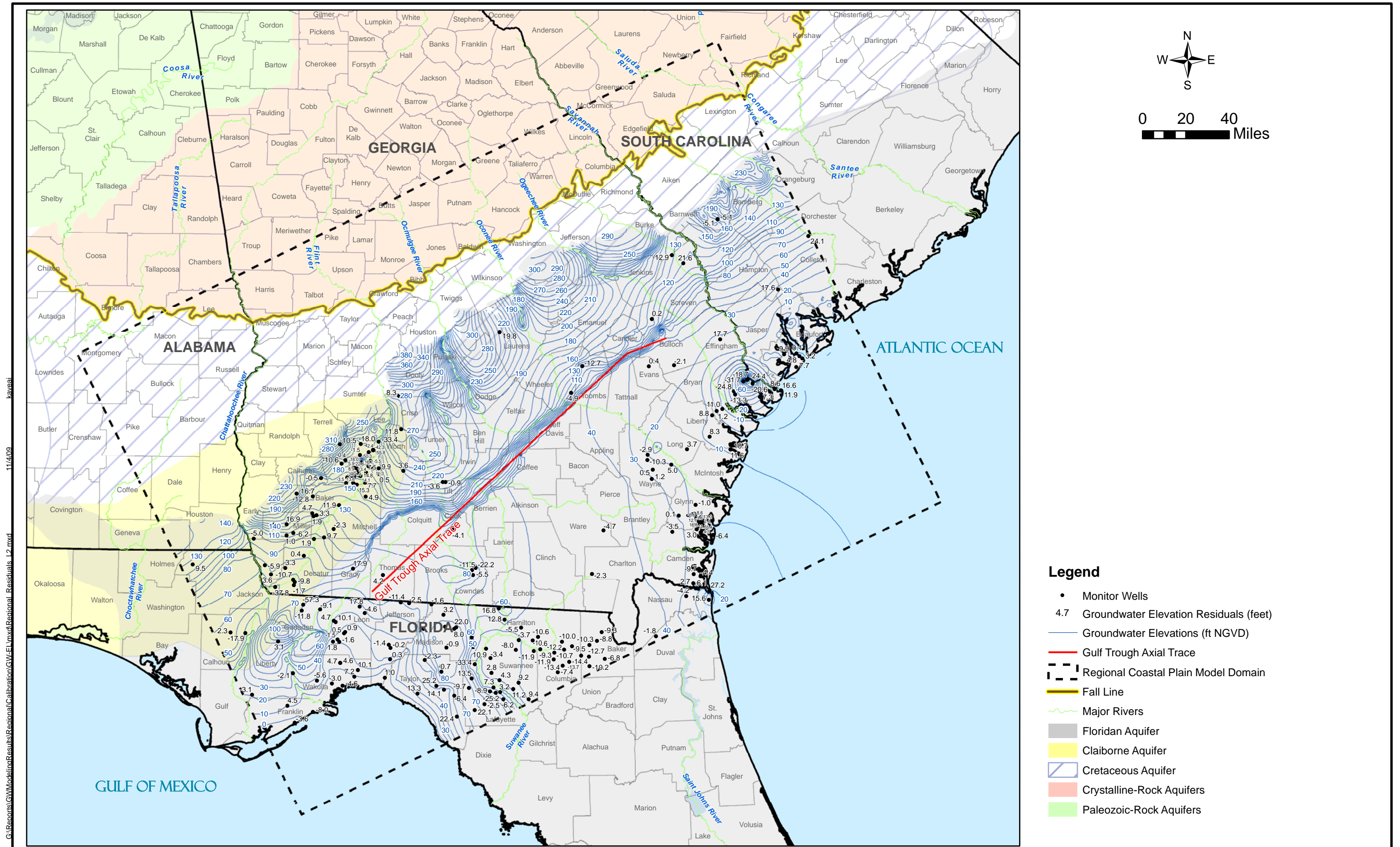
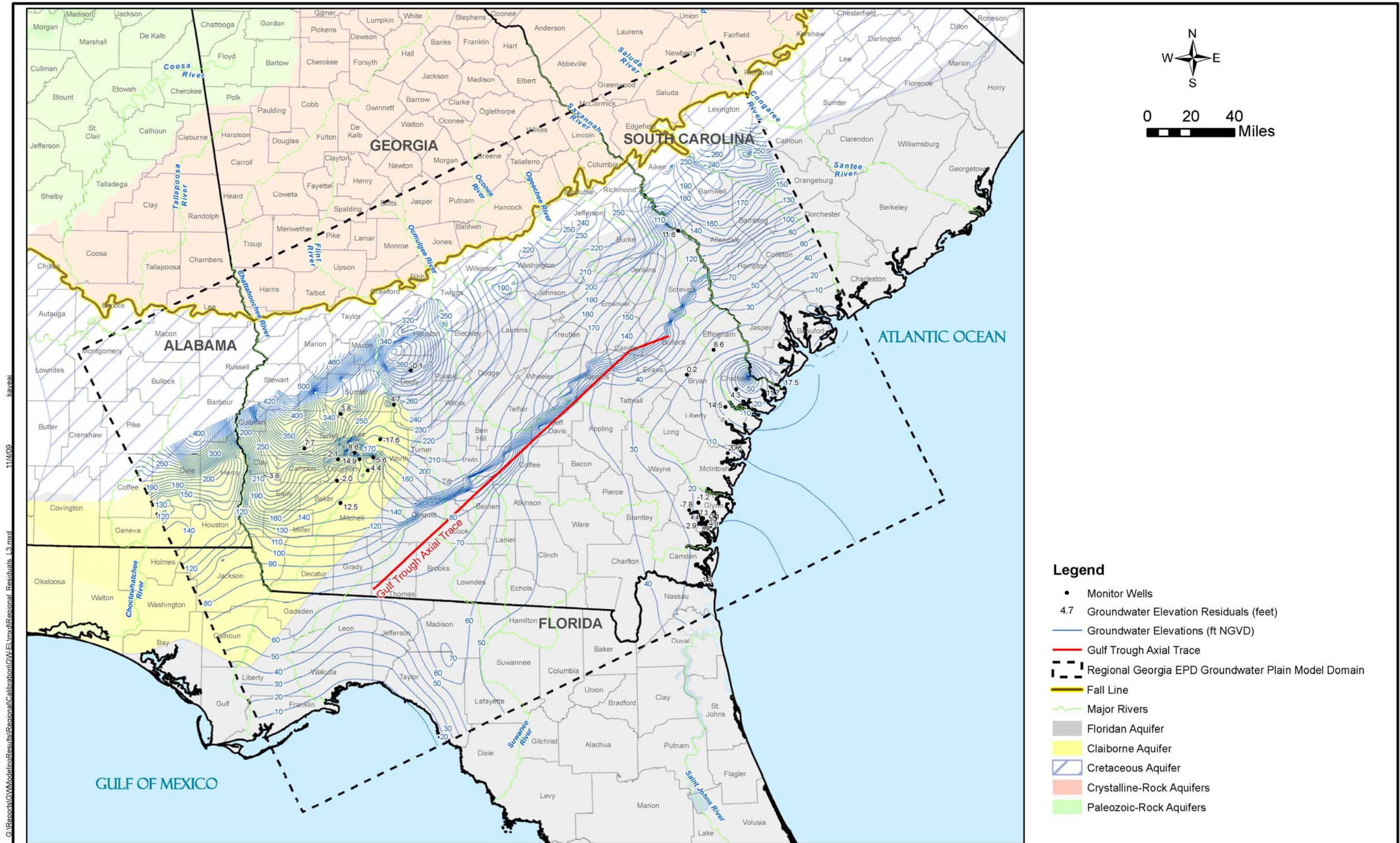


Figure 6-6
Scattergram Comparison of Observed and Simulated Groundwater Elevations
For Regional Georgia EPD Groundwater Model Calibration



CDM

Figure 6-7
Simulated Groundwater Elevation Contours with Average Residuals (computed minus observed)
in Upper Floridan Aquifer (Layer 2)



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CDM **Figure 6-8**
Simulated Groundwater Elevation Contours with Average Residuals (computed minus observed)
in Claiborne/Gordon/Lower Floridan Aquifers (Layer 3)

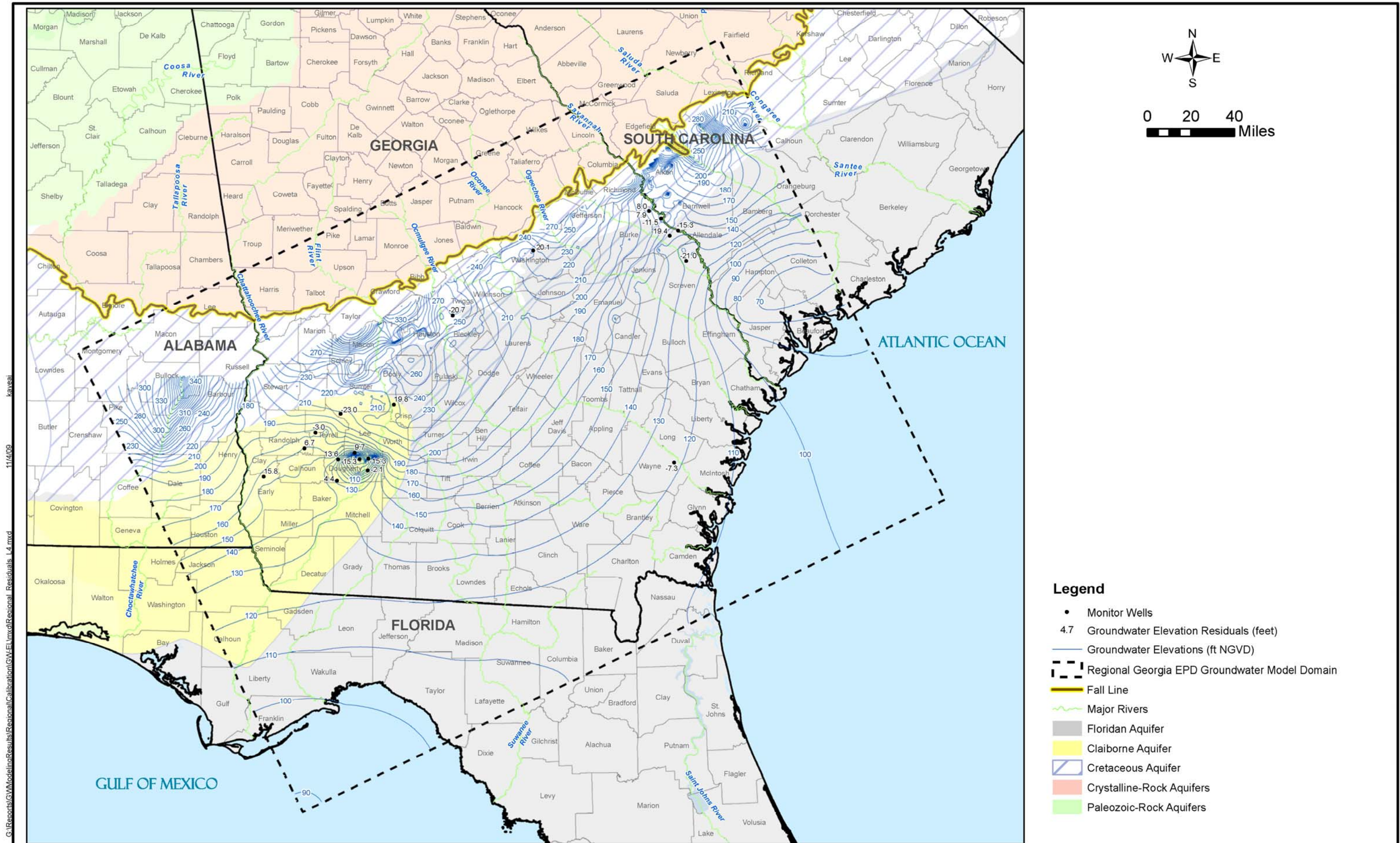
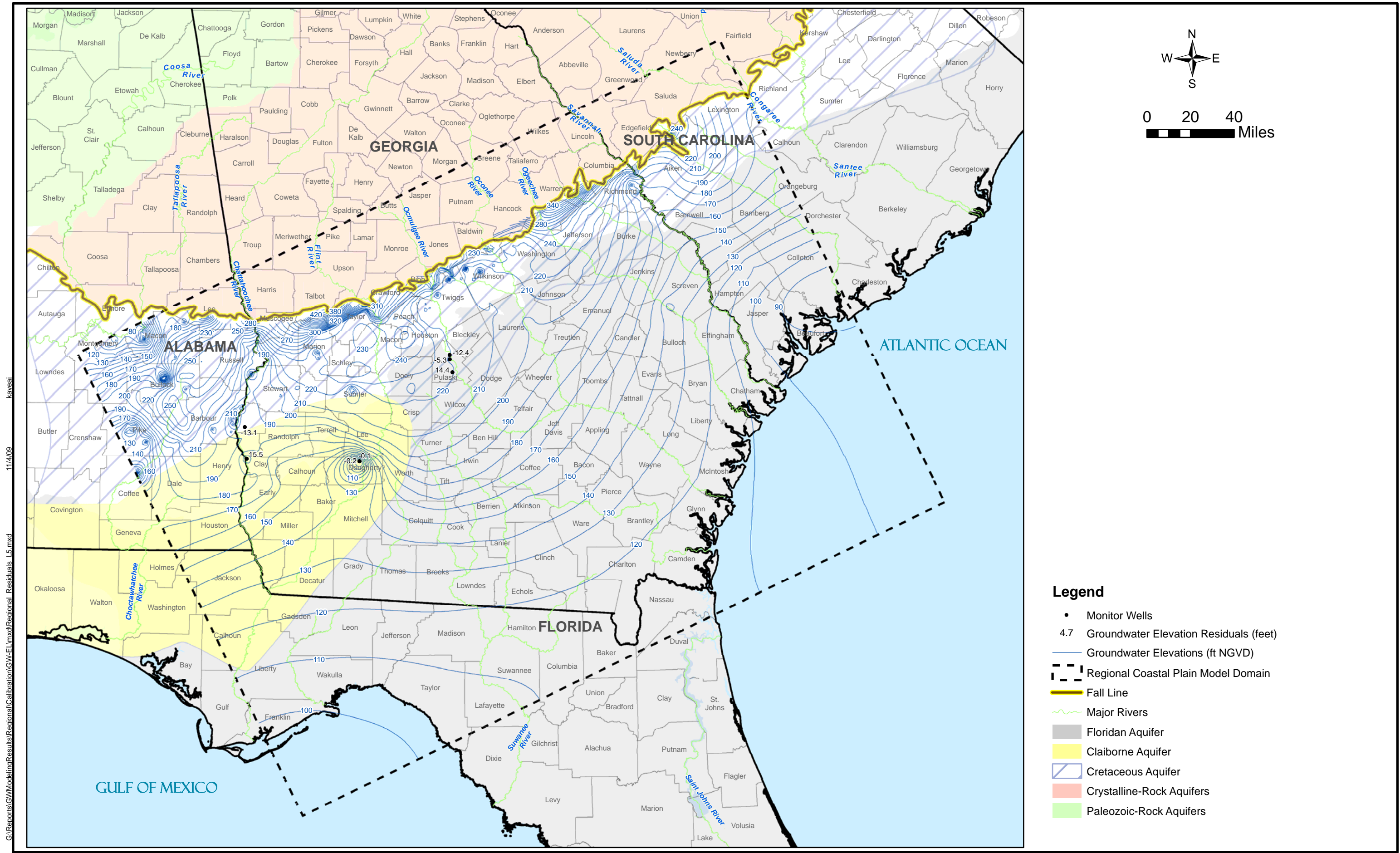
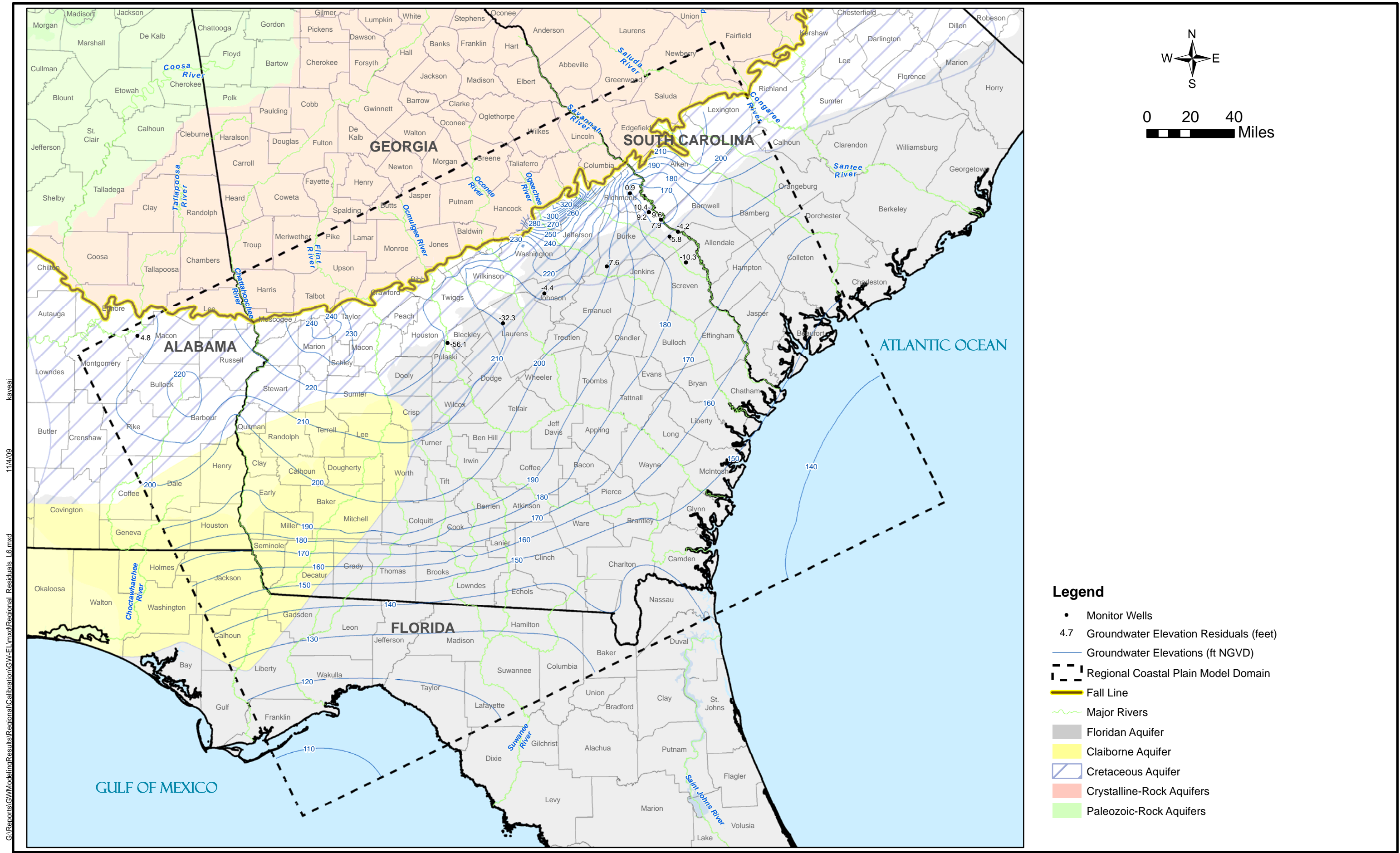


Figure 6-9
Simulated Groundwater Elevation Contours with Average Residuals (computed minus observed)
in Clayton-Dublin Aquifers (Layer 4)



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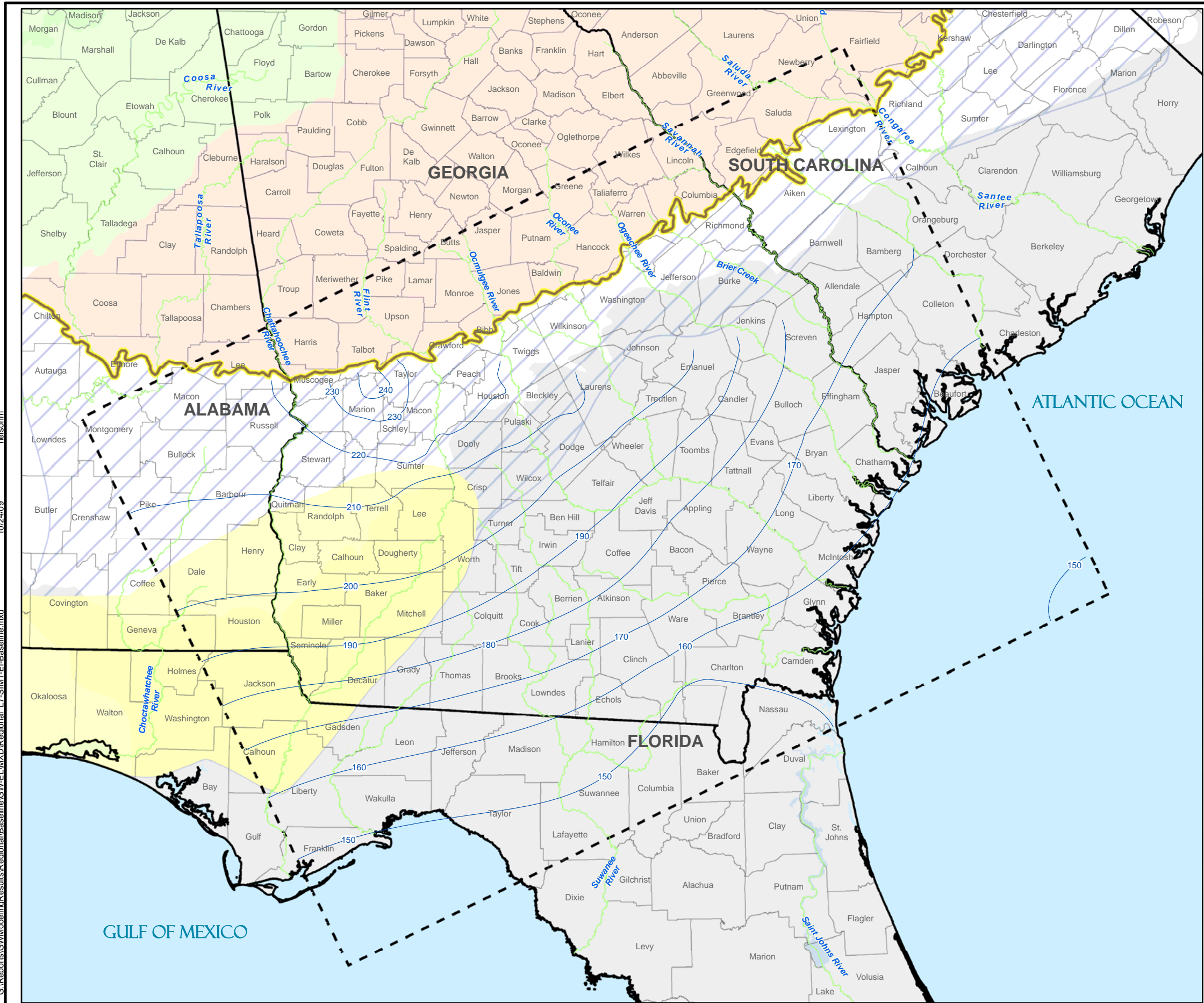
CDM **Figure 6-10**
Simulated Groundwater Elevation Contours with Average Residuals (computed minus observed)
in Providence Sand-Peedee-Dublin Aquifers (Cretaceous Aquifer System) (Layer 5)



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CDM **Figure 6-11**
Simulated Groundwater Elevation Contours with Average Residuals (computed minus observed)
in Eutaw-Midville Aquifer (Cretaceous Aquifer System) (Layer 6)

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Legend

- Groundwater Elevations (ft NGVD)
- Regional Coastal Plain Model Domain
- Fall Line
- Major Rivers
- Floridan Aquifer
- Claiborne Aquifer
- Cretaceous Aquifer
- Crystalline-Rock Aquifers
- Paleozoic-Rock Aquifers

Figure 6-12
Simulated Groundwater Elevation Contours
in Upper Atkinson-Upper Tuscaloosa Aquifers (Cretaceous Aquifer System) (Layer 7)

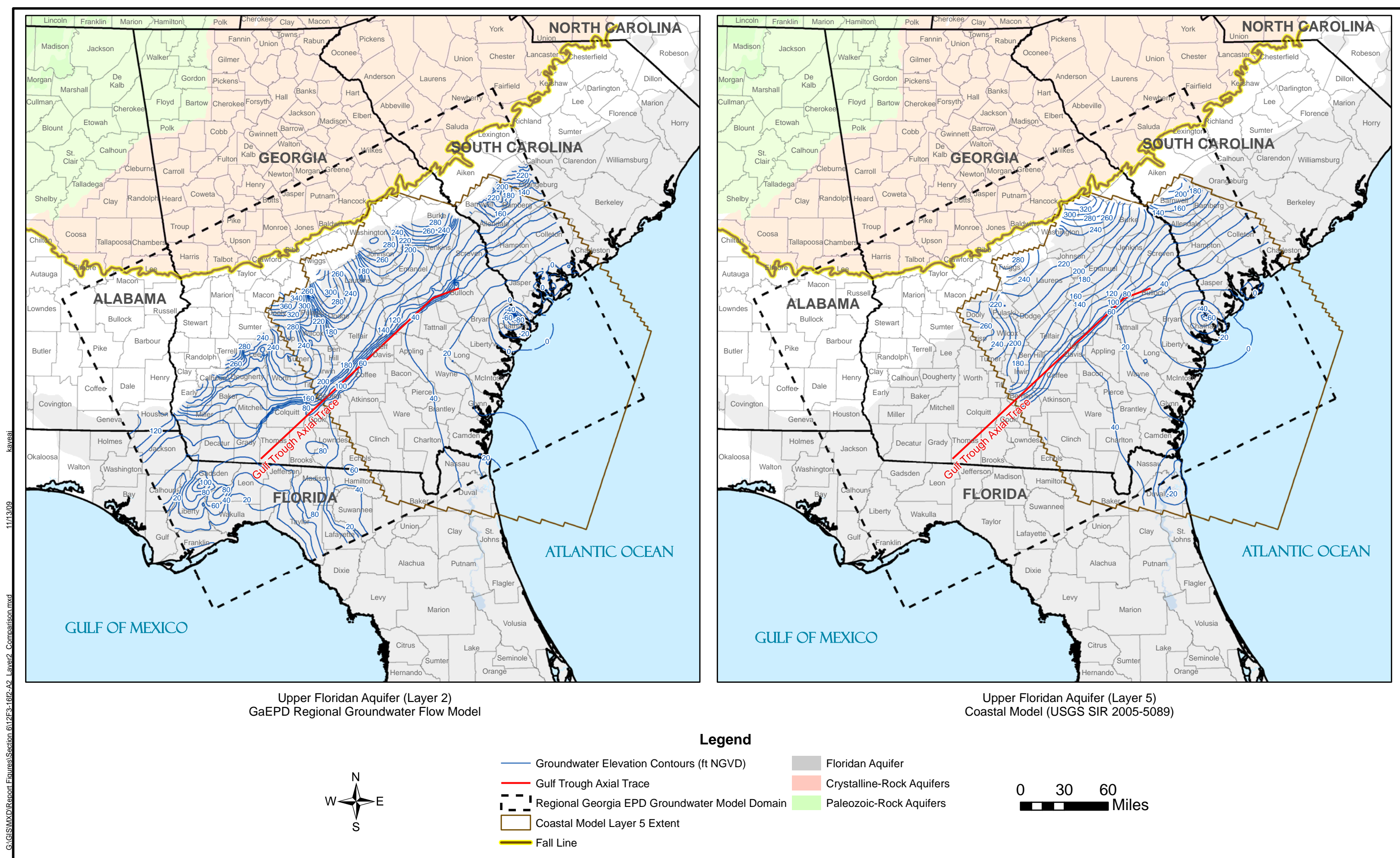
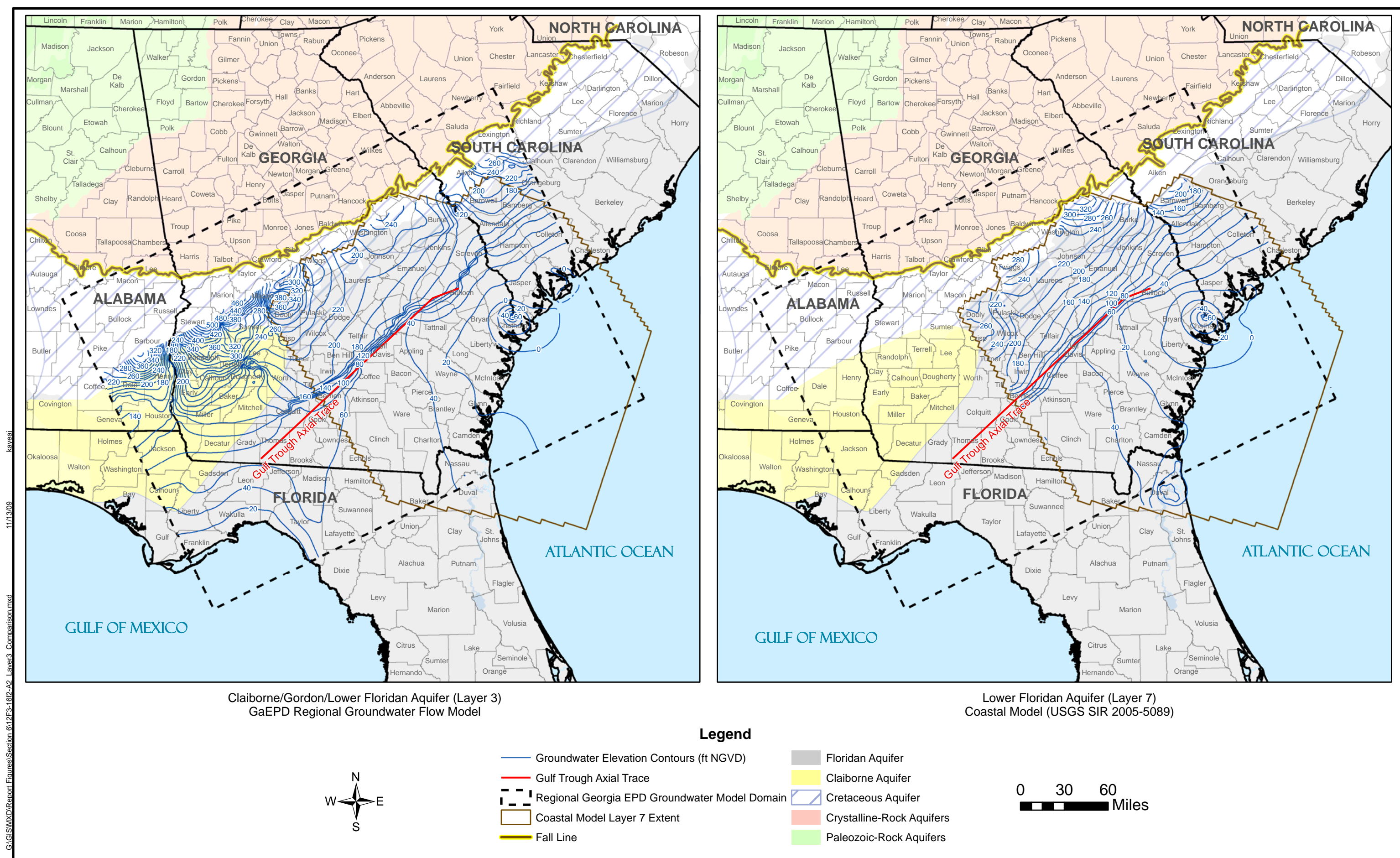
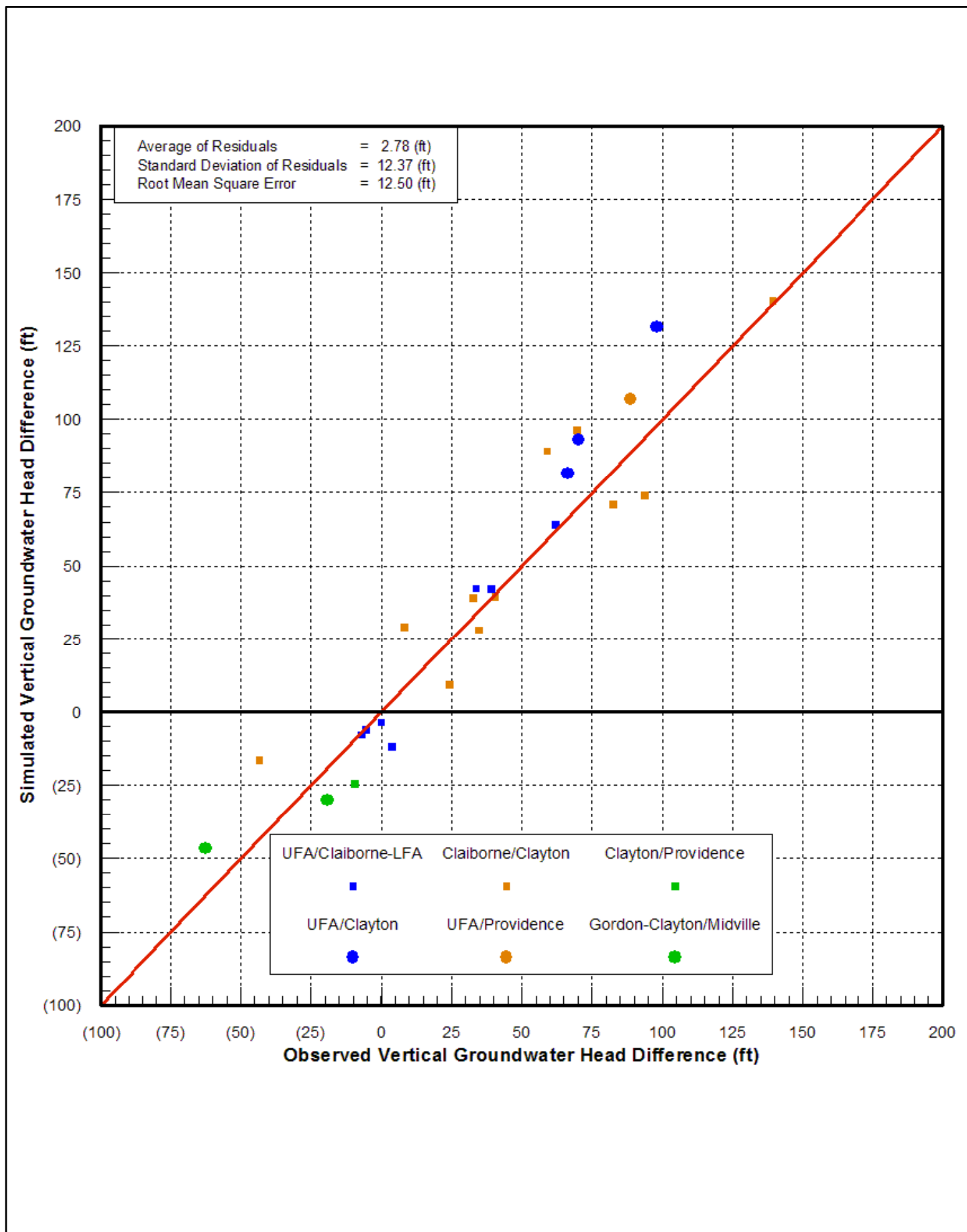


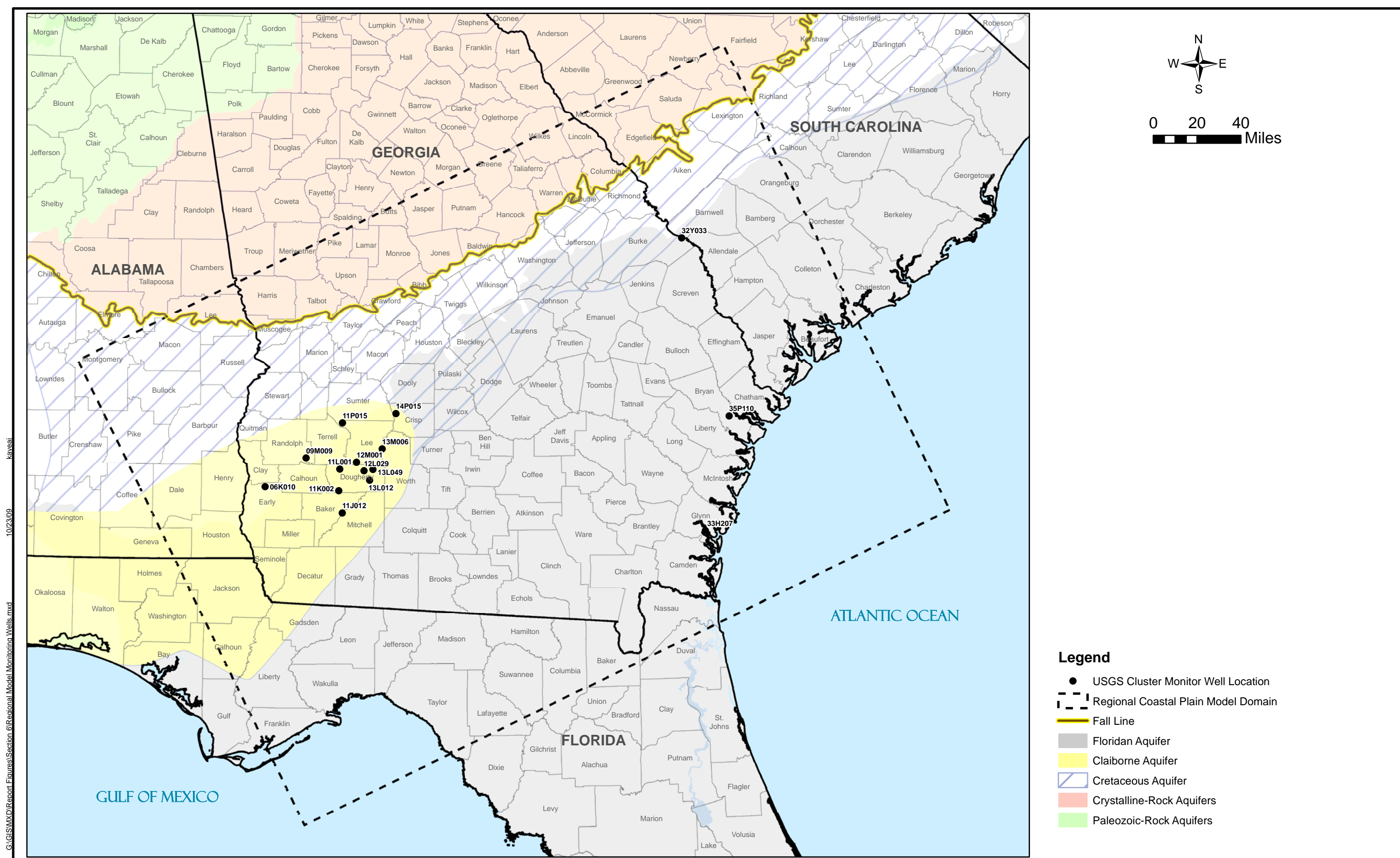
Figure 6-13
Comparison of Groundwater Elevations
in Upper Floridan Aquifer



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Figure 6-14
Comparison of Groundwater Elevations
in Lower Floridan Aquifer





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Figure 6-16
Monitor Well Cluster Locations in Regional Groundwater Flow Model Domain