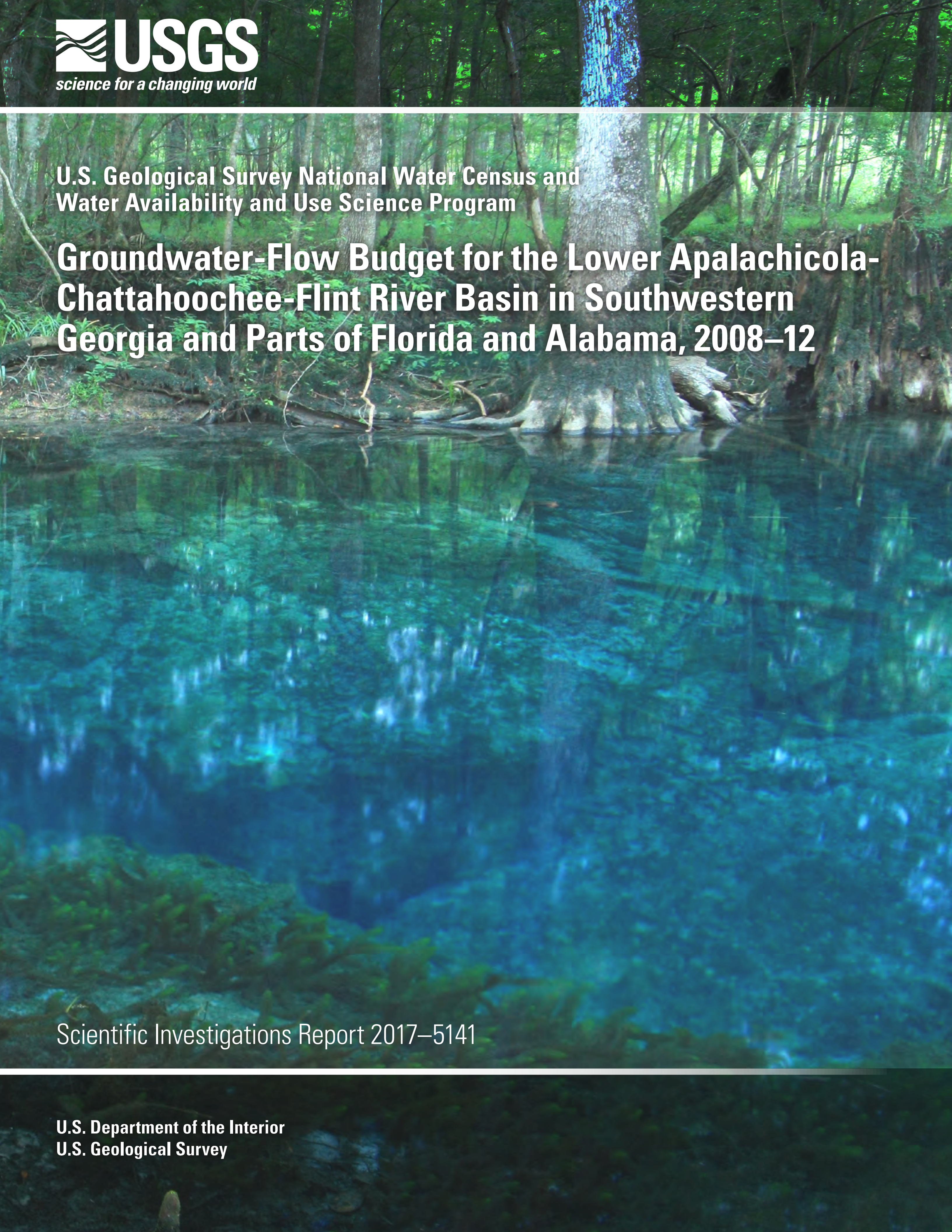

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Groundwater-Flow Budget for the Lower Apalachicola-Chattahoochee-Flint River Basin in Southwestern Georgia and Parts of Florida and Alabama, 2008–12

Scientific Investigations Report 2017–5141

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Cover. Baltzell Spring no. 2, Chipola River drainage, Jackson County, Florida, August 2, 2008. Photograph by Alan M. Cressler, U.S. Geological Survey.

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U.S. Department of the Interior
RYAN K. ZINKE, Secretary

U.S. Geological Survey
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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8.$$

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations

ACF	Apalachicola-Chattahoochee-Flint
DRN	MODFLOW Drain Package
GHB	MODFLOW General-Head Boundary Package
GSWCC	Georgia Soil and Water Conservation Commission
HRU	Hydrologic Response Unit
NHD	National Hydrography Dataset
PRMS	Precipitation-Runoff Modeling System
RCH	MODFLOW Recharge Package
RIV	MODFLOW River Package
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WBD	Watershed boundary dataset
WEL	MODFLOW Well Package

Groundwater-Flow Budget for the Lower Apalachicola-Chattahoochee-Flint River Basin in Southwestern Georgia and Parts of Florida and Alabama, 2008–12

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Abstract

As part of the National Water Census program in the Apalachicola-Chattahoochee-Flint (ACF) River Basin, the U.S. Geological Survey evaluated the groundwater budget of the lower ACF, with particular emphasis on recharge, characterizing the spatial and temporal relation between surface water and groundwater, and groundwater pumping. To evaluate the hydrologic budget of the lower ACF River Basin, a groundwater-flow model, constructed using MODFLOW-2005, was developed for the Upper Floridan aquifer and overlying semiconfining unit for 2008–12. Model input included temporally and spatially variable specified recharge, estimated using a Precipitation-Runoff Modeling System (PRMS) model for the ACF River Basin, and pumping, partly estimated on the basis of measured agricultural pumping rates in Georgia. The model was calibrated to measured groundwater levels and base flows, which were estimated using hydrograph separation.

The simulated groundwater-flow budget resulted in a small net cumulative loss of groundwater in storage during the study period. The model simulated a net loss in groundwater storage for all the subbasins as conditions became substantially drier from the beginning to the end of the study period. The model is limited by its conceptualization, the data used to represent and calibrate the model, and the mathematical representation of the system; therefore, any interpretations should be considered in light of these limitations. In spite of these limitations, the model provides insight regarding water availability in the lower ACF River Basin.

Introduction

The Apalachicola-Chattahoochee-Flint (ACF) River Basin, in Alabama, Florida, and Georgia, is an important water resource of the Southeastern United States (fig. 1), within which there is intense competition for water to provide public and industrial supply, power generation, agricultural water supply, and ecological and recreational needs. Groundwater-level declines during periods of widespread agricultural irrigation and drought have resulted in frequent drying of area streams, leading to population declines and extirpation of federally protected species such as native mussels (Johnson and others, 2001; U.S. Fish and Wildlife Service, 2003; Rugel and others, 2012). To provide information to help manage ACF River Basin groundwater resources, the U.S. Geological Survey (USGS), as part of the National Water Census (authorized by section 9508 of the Secure Water Act of 2009, 42 U.S.C. 10368), is evaluating the availability of freshwater resources to meet current and future human and ecological demands. One of the goals of the National Water Census is to provide stakeholders and resource managers with information about components of the hydrologic budget. To this end, the National Water Census program focused on three themes to provide information for an accurate water budget for the ACF River Basin: (1) water use, (2) surface water-groundwater interactions, and (3) ecologically relevant streamflow statistics.

The lower part of the ACF River Basin (fig. 1) is where the Upper Floridan aquifer, the most prolific and extensive regional aquifer in the Southeastern United States, crops out or is close to land surface (Miller, 1986; Williams and Kuniansky, 2015). The Upper Floridan aquifer (fig. 2), which is composed of highly permeable, predominantly karst limestone, is the primary water supply in the lower ACF River Basin. The exchange between groundwater and surface water in the lower ACF River Basin is substantial because streams cut into and are minimally separated hydrologically from the Upper Floridan aquifer. Land use in the lower ACF River Basin is largely agricultural, and thus groundwater use is dominated by agricultural irrigation supplied by the Upper Floridan aquifer. The lower ACF River Basin is an important agricultural area in Georgia and has been ranked by the U.S. Department of Agriculture as first in peanut production and second in cotton production for the United States (Census of Agriculture, 2012). Prior to enactment of the Georgia Agricultural Water Conservation and Metering Program of 2003 and the subsequent installation of about 4,000 flowmeters on

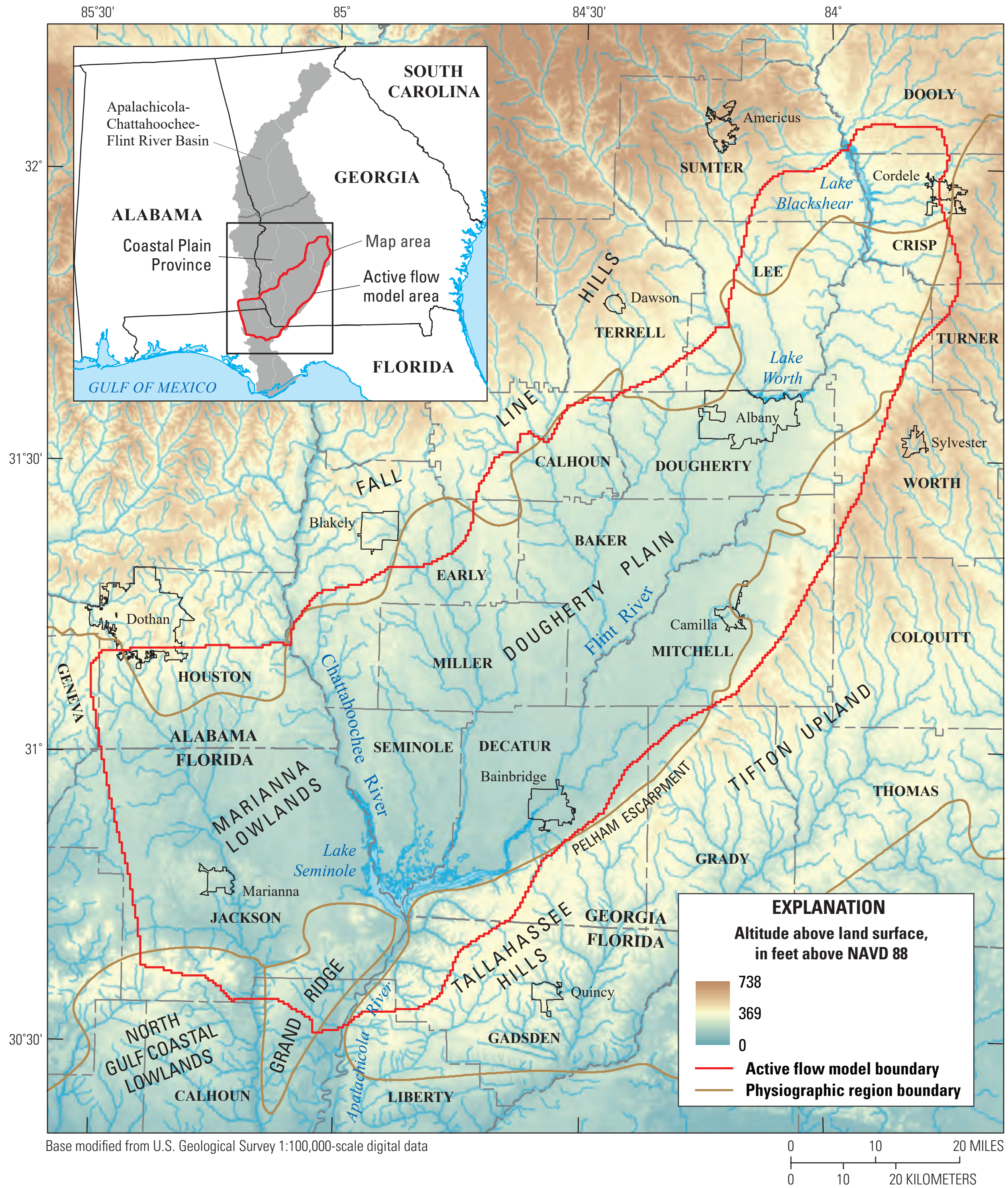

Figure 1. Physiographic regions, land-surface altitude, counties, and municipalities within the study area in southwestern Georgia and adjacent parts of Alabama and Florida. [NAVD 88, North American Vertical Datum of 1988]

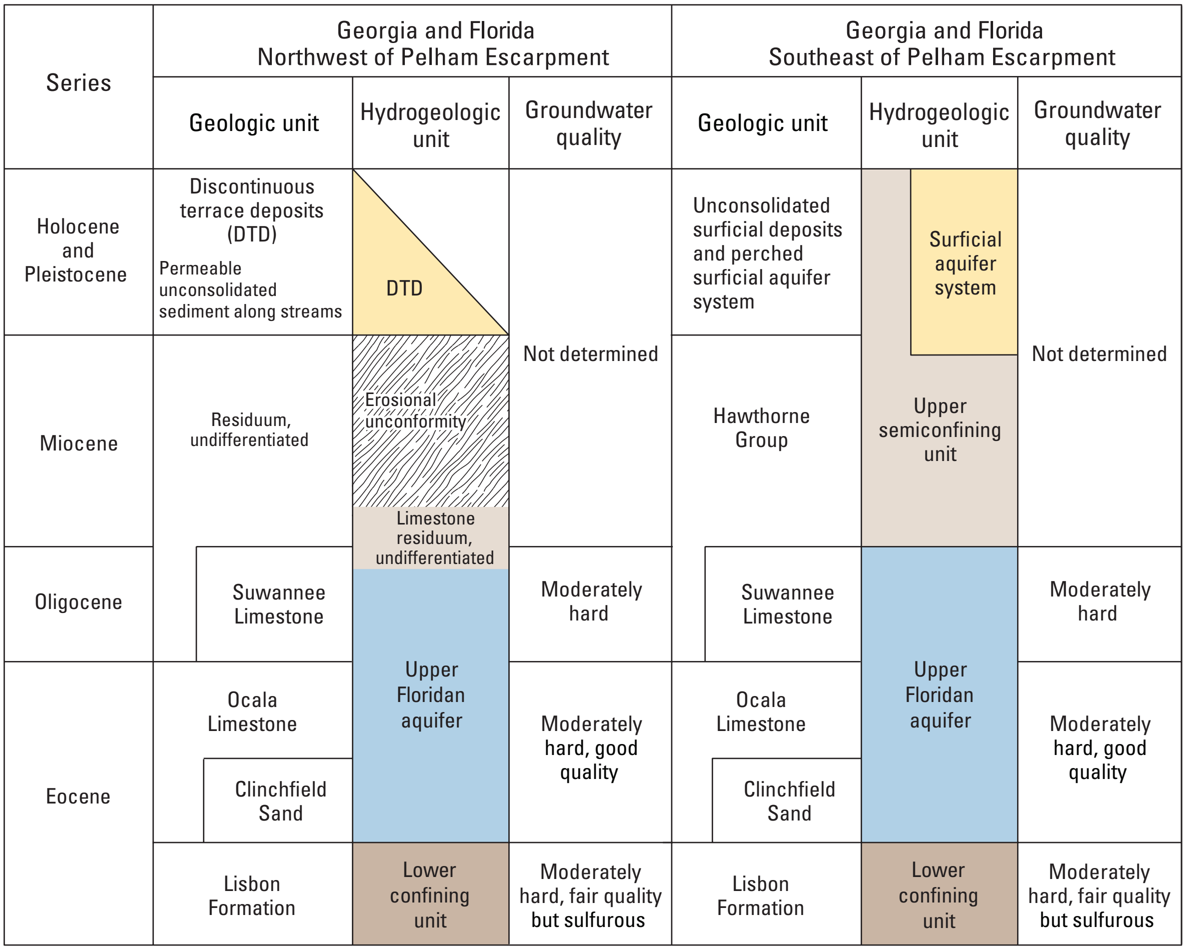

Figure 2. Diagram showing geologic and hydrogeologic units, and general groundwater quality in the lower Apalachicola-Chattahoochee-Flint River Basin (modified from Torak and Painter, 2006).

agricultural irrigation systems in the lower ACF River Basin from 2004 to 2010 (Torak and Painter, 2011), the amount of irrigation water use had not been adequately evaluated. The Apalachicola and Flint Rivers support rare fish and mussel species and are important to the ecology and economy of the region. Downstream from the lower ACF River Basin, the Apalachicola River discharges into the Gulf of Mexico, where adequate freshwater flow is needed to maintain healthy oyster beds in Apalachicola Bay to support a coastal fisheries industry. An accurate evaluation of the flow of water between the Upper Floridan aquifer and the surface waters of the lower ACF River Basin is essential for managing potentially conflicting water demands of agricultural supply, drinking-water supply, instream flows for ecological needs, and downstream freshwater flows needed for Gulf coastal fisheries.

To address the need for an evaluation of freshwater resources in the ACF River Basin, the USGS evaluated recent hydrologic flows throughout the basin and developed tools that resource managers can use to evaluate the availability of freshwater to meet the competing needs throughout the basin. A particular emphasis of the project is on evaluating adequate instream flow for ecological needs throughout the basin and how water use throughout the basin, and in particular groundwater use in the lower ACF River Basin, may affect the availability of adequate instream flow.

Purpose and Scope

The purpose of this report is to evaluate the components of the groundwater budget of the lower ACF River Basin for 2008–12. Particular emphasis was placed on characterizing the spatial and temporal relation between perennial streams, ephemeral streams, and wetland discharges and changes in groundwater in storage, and recharge and groundwater pumping. This evaluation incorporated a process-based estimation of recharge and groundwater-pumping distribution based on data from agricultural metering, field reconnaissance, crop distribution, and spatial analysis. Information gained on groundwater discharge to streams can be used to inform a more accurate accounting of streamflow throughout the ACF River Basin (LaFontaine and others, 2017). The evaluation presented in this report is one element of an overall evaluation of freshwater availability in the ACF River Basin.

This report describes the groundwater hydrology of the lower ACF River Basin and presents a conceptual hydrologic flow model. The simulated hydrologic budget is presented, and effects of estimated recharge and groundwater pumping on groundwater discharges to wetlands, streams, and rivers and changes in groundwater storage are discussed. The model used to evaluate the hydrologic flows and budget of the lower ACF River Basin for 2008–12 is documented, including model construction, calibration, and fit to observed data (appendix 1). Sensitivity tests of the model are presented. Limitations of the evaluation and the model used to evaluate the hydrologic budget are described.

Approach

To evaluate the hydrologic budget of the lower ACF River Basin, a groundwater-flow model was developed for the unconfined and semiconfined Upper Floridan aquifer and overlying semiconfining unit (fig. 2), representing transient conditions during 2008–12 (appendix 1; Sepulveda and Painter, 2017). The model generally extends over the part of the ACF River Basin in which the Upper Floridan aquifer is unconfined to semiconfined (fig. 1). The model was constructed using MODFLOW-2005 (Harbaugh, 2005) and is largely derived from a previously existing groundwater model for the area (Jones and Torak, 2006). Data used for model boundary conditions and calibration were obtained from the U.S. Geological Survey National Water Information System (U.S. Geological Survey, 2015). The model used for the current evaluation improves on the Jones and Torak (2006) model by incorporating detailed irrigation groundwater-pumping data and recharge, estimated using a separate model of precipitation, runoff, streamflow, and is three dimensional.

Agricultural irrigation groundwater pumping is the largest component of groundwater stresses in the study area. The study period was chosen because of the availability of monthly estimates of agricultural irrigation groundwater-pumping rates over most of the study area during 2008–12 (Painter and others, 2015). These irrigation pumping rate estimates were more accurately evaluated than had previously been possible because of the Georgia General Assembly enactment of House Bill 579 (June 4, 2003), granting the Georgia Soil and Water Conservation Commission (GSWCC) the jurisdiction to implement "a program of measuring farm uses of water in order to obtain clear and accurate information on the patterns and amounts of such use, which information is essential to proper management of water resources by the state and useful to farmers for improving the efficiency and effectiveness of their use of water … and [for] improving water conservation" (http://www.legis.ga.gov/Legislation/20032004/27094.pdf). Additional groundwater pumping data were taken or derived from Marella and Dixon (2015) and the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2017). In addition, groundwater-level data are available for three synoptic surveys conducted during the study period (Gordon and Peck, 2010; Kinnaman and Dixon, 2011; Gordon and others, 2012), as well as continuous groundwater-level data at 31 sites and continuous stream stage and streamflow data at 27 sites (appendix 1).

Because of the potential effect of groundwater pumping on streamflow in the lower ACF River Basin (Jones, 2012) and the dominance of agricultural withdrawals relative to other water uses in the region, new techniques were developed to estimate groundwater withdrawals for agricultural irrigation in the study area more accurately than previously estimated (appendix 1; Painter and others, 2015). Agricultural irrigation in the lower ACF River Basin was estimated using a combination of data from metered wells, precipitation data, aerial assessment of irrigated acres, and geostatistical analysis. Data used in the analysis are provided in Sepulveda and Painter (2017).

As part of the overall study of the ACF River Basin, a Precipitation-Runoff Modeling System (PRMS; Leavesley and others, 1983; Markstrom and others, 2015) model was developed to simulate surface-water flows and budget for the entire ACF River Basin (LaFontaine and others, 2017). The PRMS model was used to calculate groundwater-recharge rates in interstream areas, and these values were applied as recharge to the lower ACF River Basin groundwater-flow model. Many of the tributaries simulated in the PRMS model were also incorporated into the lower ACF River Basin groundwater-flow model. Aquifer discharge rates to streams simulated by the lower ACF River Basin groundwater-flow model were then used as base-flow values for the final version of the PRMS model.

Description of the Study Area

The study area includes parts of southwestern Georgia, the north-central panhandle area of Florida, and the southeastern corner of Alabama (fig. 1). The area includes the downstream ends of the Chattahoochee and Flint Rivers, and their termination, and the headwaters of the Apalachicola River at Lake Seminole. The study area includes all or parts of Baker, Calhoun, Crisp, Decatur, Dooly, Dougherty, Early, Grady, Lee, Miller, Mitchell, Seminole, Sumter, Terrell, Turner, and Worth Counties in Georgia; parts of Calhoun, Gadsden, Jackson, and Liberty Counties in Florida; and parts of Geneva and Houston Counties in Alabama.

Precipitation

Annual mean precipitation in the study area for 1981–2012 was 46.8 inches (in.) and for the study period, 2008–12, was 43.7 in., which is about 7 percent lower than the long-term mean, based on data from Daymet (Thornton and others, 1997; Thornton and others, 2016) (fig. 3*A*). Both long-term and study-period data indicate a bimodal seasonal trend with higher precipitation in the winter and summer and lower precipitation in the spring and fall (fig. 3*A*). Rainfall is generally of higher intensity and shorter duration during the summer months than during the winter months (Torak and Painter, 2006). The study-period data show a later and higher spike during the summer rainy period than the long-term data, likely owing to substantial precipitation related to tropical storm Fay, in August 2008, which resulted in a monthly total rainfall of more than 10 in. (fig. 3*B*).

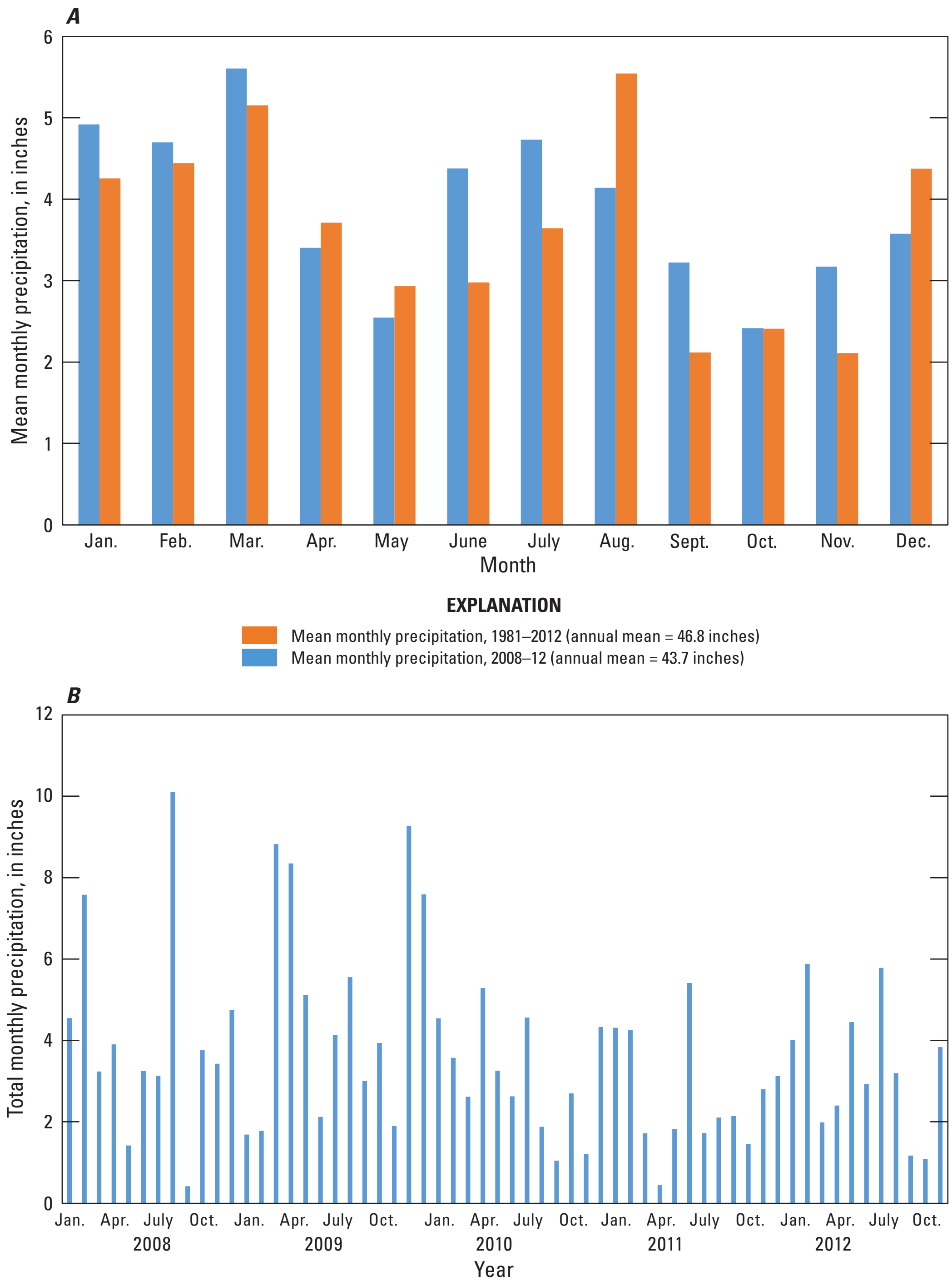

Figure 3. *A*, Mean monthly precipitation for the study area for 1981–2012 and 2008–12, and *B*, monthly total precipitation for the study area from January 2008 to December 2012.

Land Use

Land use in the study area is primarily cultivated crops (about 28 percent), forests (about 32 percent), and woody wetlands (about 12 percent), with sparse urban and suburban areas (about 6 percent), based on the 2011 National Land Cover Database (Homer and others, 2015).

Water Use

In the lower ACF River Basin, groundwater from the Upper Floridan aquifer is used primarily for agricultural irrigation and secondarily for public supply (Lawrence, 2016). Since 1985, groundwater withdrawals in the lower ACF River Basin have generally been increasing (Lawrence, 2016). Data used for study area water-use compilations (appendix 1) indicate that total annual groundwater pumping in the study area during 2008–12 ranged from about 169 million gallons per day (Mgal/d) to about 277 Mgal/d, with an average of about 211 Mgal/d of which an average of about 84 percent was used for agricultural irrigation (fig. 4). Generally, pumping for agricultural irrigation is minimal during November through February and greatest during June and July. During the study period, the maximum monthly groundwater pumping for irrigation was more than 850 Mgal/d, which occurred in June 2009 and June 2011.

Physiography

The physiography of the lower ACF River Basin strongly influences the drainage in the study area, which is located primarily in the Dougherty Plain and adjacent Marianna Lowlands districts of the Coastal Plain physiographic province (fig. 1). The Dougherty Plain and Marianna Lowlands are relatively flat, internally drained lowlands having an irregular and undulating surface characterized by heterogeneous stream-channel development and karst topography, including many shallow surface-water sinks and depressions (Jones and Torak, 2006; Torak and Painter, 2006). In this karst plain, there is an erosional unconformity where the limestones of the Upper Floridan aquifer were exposed at land surface and dissolved, leaving less permeable residuum at land surface, in which more recent erosion and deposition from streams occur (fig. 2). The Dougherty Plain and Marianna Lowlands are bounded along the northwest by the Fall Line Hills physiographic district, a region of rolling hills with dendritic drainage pattern, with a hydraulic gradient that directs flow into the study area. Along this northwest boundary of the karst plain, the sedimentary rocks have graded from carbonates to less permeable clastics. This gradation is shown by the increase in tributary streams along the northwest boundary, in contrast to internal subsurface drainage in the form of large major rivers incised into the carbonate rocks within the

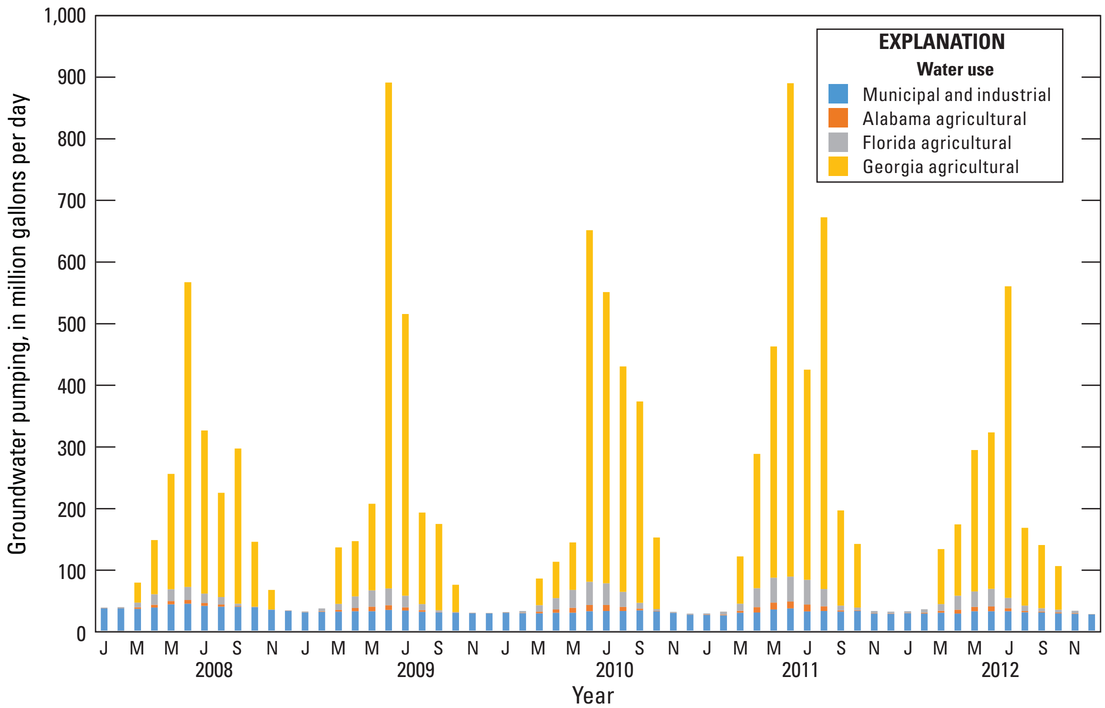

Figure 4. Total monthly pumping rates from the Upper Floridan aquifer for the study area, 2008–12, including agricultural, municipal, and industrial water uses.

karst plain (fig. 1). The Dougherty Plain is bounded along the southeast by the Pelham Escarpment, which separates the Dougherty Plain from the Tifton Upland physiographic district and the adjacent Tallahassee Hills district in Florida. Streams in the Tifton Upland physiographic district flow toward the southeast margin of the study area.

Hydrogeology

This study focuses on the Upper Floridan aquifer and the overlying units, which include the shallowest discontinuous terrace deposits and undifferentiated residuum northwest of the Pelham Escarpment; and the surficial aquifer system, and the semiconfining unit of the Upper Floridan aquifer southeast of the Pelham Escarpment (fig. 2). Northwest of the Pelham Escarpment, the study area is underlain by discontinuous sandy marine and fluvial terrace deposits, and undifferentiated semiconfining to leaky weathered limestone residuum, where the Upper Floridan aquifer is essentially at land surface (Torak and Painter, 2006; Crandall and others, 2013; Miller, 1986; Williams and Kuniansky, 2015; E.L. Kuniansky, U.S. Geological Survey, written commun., September 1, 2017). Southeast of the Pelham Escarpment, the area is underlain by unconsolidated surficial deposits and perched surficial aquifer system (E.L. Kuniansky, U.S. Geological Survey, written commun., September 1, 2017). Where the surficial aquifer system occurs, the thickness ranges from less than 10 feet (ft) to about 100 ft south of Lake Seminole in the southernmost part of the study area (Williams and Kuniansky, 2015). The surficial aquifer system is not a substantial source of water in the study area and was not evaluated individually as a hydrogeologic unit in this study.

Southeast of the Pelham Escarpment, the upper semiconfining unit of the Upper Floridan aquifer is composed of Miocene-age rocks of the Hawthorne Group (fig. 2). Within the Dougherty Plain and Marianna Lowlands, northwest of the Pelham Escarpment, weathered limestone of Eocene and Oligocene age, clayey units, and other younger undifferentiated material of relatively lower permeability than the underlying Upper Floridan aquifer occur (fig. 2). Where present, the top of the upper semiconfining unit is at or close to land surface. As mapped, the upper semiconfining unit is generally less than 50 ft thick beneath the Pelham Escarpment and is thinnest or does not occur within the Dougherty Plain and Mariana Lowlands and in many stream valleys where it has been removed by erosion. Between stream valleys, the residuum and undifferentiated deposits can be as much as 100 ft thick. Along the southeastern and southernmost parts of the study area, where the upper semiconfining unit is intact beneath the Pelham Escarpment, this unit can be more than 300 ft thick (Miller, 1986; Torak and Painter, 2006; Crandall and others, 2013; Williams and Kuniansky, 2015).

The Upper Floridan aquifer extends across the study area and is composed predominantly of late Eocene- to Oligocene-age carbonates (Torak and Painter 2006; Williams and Kuniansky, 2015). In the study area, the Upper Floridan aquifer is primarily equivalent to the Ocala Limestone and also may be equivalent to the Suwannee Limestone where it overlies the Ocala Limestone in the southern and southeasternmost parts of the study area. The top of the Upper Floridan aquifer is unconfined in areas where the upper semiconfining unit has eroded or is thin, and in other areas the Upper Floridan aquifer is semiconfined by the upper semiconfining unit or by the semiconfining to leaky weathered limestone residuum (Miller, 1986; Williams and Kuniansky, 2015; E.L. Kuniansky, U.S. Geological Survey, written commun., September 1, 2017). The Upper Floridan aquifer is characterized by limestone dissolution, which creates cavities, fluid transport conduits, and sinkholes, making the aquifer particularly permeable in the study area. Because of the proximity of the Upper Floridan aquifer to land surface, there is a high degree of hydrologic connectivity between the groundwater system and streams that flow through the area in the Dougherty Plain and Marianna Lowlands (Williams and Kuniansky, 2015). The thickness of the Upper Floridan aquifer ranges from less than 30 ft along the northwestern part of the study area to more than 300 ft along the southeastern boundary, reaching more than 500 ft at the southern end of the model area (Torak and Painter, 2006; Crandall and others, 2013). The base of the Upper Floridan aquifer dips toward the southeast and is marked by the top of the middle Eocene-age Lisbon Formation, which composes the lower confining unit of the Upper Floridan aquifer in the study area (Torak and Painter, 2006).

Conceptualization of Hydrologic Flow

Inflow to the groundwater-flow system in the study area is largely from recharge from precipitation: precipitation directly recharges the Upper Floridan aquifer where it is unconfined and indirectly recharges the aquifer through the upper semiconfining unit and discontinuous terrace deposits (fig. 5). Losing reaches of streams may also provide inflow to the groundwater system (Gordon and Peck, 2010) as well as karstic sinks and lakes, but these sources are likely much smaller components of inflow than direct or indirect recharge (Jones and Torak, 2006). Groundwater may also flow into the study area from adjacent or updip equivalent aquifer units.

Outflow from the groundwater system in the study area is largely from discharges to streams (Gordon and Peck, 2010), springs, and wetlands (fig. 5). Groundwater pumping also removes some water from the groundwater system, although some excess irrigation may recharge the shallow groundwater system. Some groundwater flows out of the study area, likely toward the south and southeast following the dip of the Upper Floridan aquifer and where indicated by potentiometric surfaces (Gordon and Peck, 2010; Kinnaman and Dixon, 2011; Williams and Kuniansky, 2015). Some groundwater may also leave the system through evapotranspiration from the shallow part of the groundwater system.

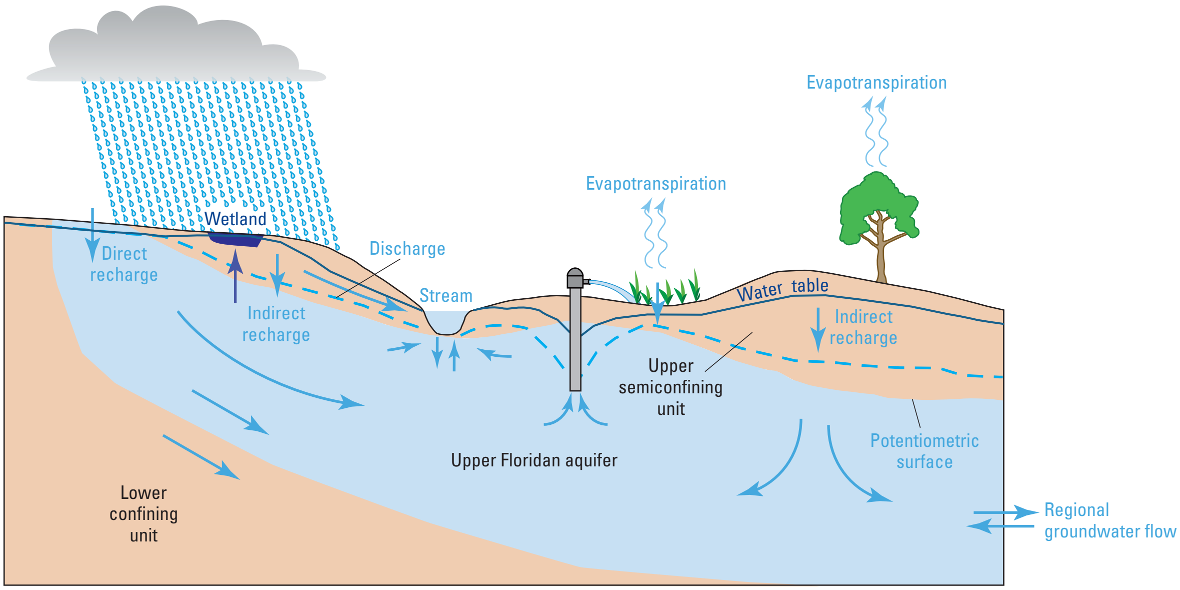

Figure 5. Conceptual diagram of the groundwater-flow system in the lower Apalachicola-Chattahoochee-Flint River Basin showing the groundwater-budget components simulated by the model.

Mean annual recharge in the study area was 8.8 in. during 1981–2012 and 8.1 in. during the study period, 2008–12 (fig. 6*A*), as estimated using a PRMS model, and is spatially variable at the Hydrologic Response Unit (HRU) resolution developed for the study area (LaFontaine and others, 2017) (also see appendix 1, figures 1–7 and 1–8). The PRMS model partitions precipitation into surface water and groundwater, accounting for runoff, infiltration, and evapotranspiration processes, as a function of precipitation, air temperature, and soil permeability (LaFontaine and others, 2013). Mean monthly recharge trends over both the long-term and study periods show similar patterns of highest recharge rates during the winter months, a period of elevated but smaller magnitude recharge during the summer months, and lowest recharge during the spring and fall months (fig. 6*A*). The timing of the bimodal seasonal trends is similar to the bimodal seasonal precipitation trends (fig. 3*A*), but the difference in magnitude of recharge between the summer and the winter is notably greater than the difference in magnitude of precipitation between the summer and winter. Less recharge occurs during the summer rainy season than the winter rainy season, probably because evapotranspiration is much greater in the summer and the summer precipitation events tend to be of shorter duration and higher rate than those in the winter, resulting in greater runoff and less infiltration during the summer than the winter (fig. 6).

Regionally, groundwater flow in the Upper Floridan aquifer is from the northwest toward the southeast as indicated from synoptic potentiometric maps (Gordon and Peck, 2010; Kinnaman and Dixon, 2011), The simulated direction of local flow from recharge areas toward streams in the study area is superimposed on the direction of regional flow (Jones and Torak, 2006). Simulated flow rates in the Upper Floridan aquifer in the study area are highest where the aquifer discharges along major streams.

Hydrologic Budget

The hydrologic budget of the lower ACF River Basin for the groundwater system was evaluated using the MODFLOW-2005 groundwater-flow model, described in appendix 1, for the unconfined and semiconfined Upper Floridan aquifer and overlying semiconfining unit and surficial aquifer, during 2008–12 (table 1; fig. 7). Simulated groundwater-budget components are tabulated as million gallons per day for ease in comparison with conventional units of groundwater pumping, but are displayed graphically in inches per month for ease in comparison with precipitation and recharge. Simulation results show that for the entire model area for the study period, the largest cumulative inflow to the groundwater system is recharge at about 1,878 Mgal/d, with about 191 Mgal/d input from regional boundaries and lakes, and negligible amounts from aquifer recharge from streams, rivers, or wetlands (less than 10 Mgal/d). Simulated outflow is largest for wetlands, about 1,266 Mgal/d, less for minor (ephemeral) streams, 410 Mgal/d, and rivers, 379 Mgal/d. Outflow to wells (214 Mgal/d) and outflow to regional boundaries and lakes (186 Mgal/d) is substantially less than outflow to wetlands (1,266 Mgal/d) and streams and rivers combined (789 Mgal/d). The difference between inflows and outflows is accounted for by a net cumulative loss

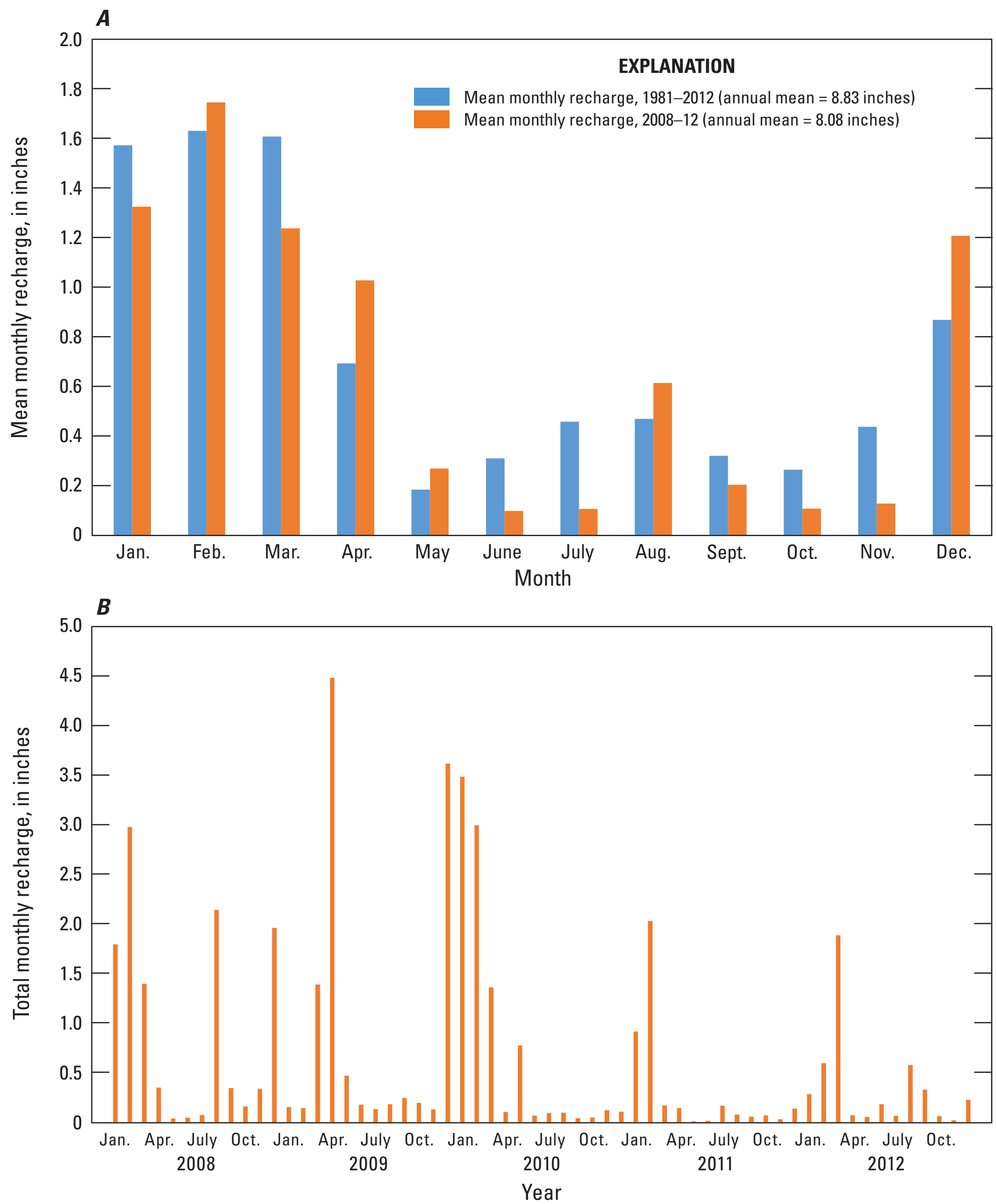

Figure 6. *A*, Mean monthly recharge for the study area for 1981–2012 and 2008–12, and *B*, monthly total recharge for the study area from January 2008 to December 2012.

Table 1. Total simulated flows for evaluated budget components for the study area and for each subbasin (table 2) from January 2008 to December 2012.

[Subbasin locations are shown in figure 8; mi², square miles (one grid cell has an area of 0.0965 mi²); Mgal/d, million gallons per day; in/month, inches per month]

Area in model	Number of grid cells		Inflows						Outflows								Area, mi²
			Recharge	Regional boundaries and lakes	Rivers	Storage loss	Groundwater from other subbasins	Total in	Rivers	Minor streams	Wetlands	Ground-water pumping	Regional boundaries and lakes	Storage gain	Ground-water flow to other basins	Total out	
Entire active model area	47,310	Mgal/d	1,877.74	190.76	7.56	617.20	2,506.76	5,200.02	379.49	409.60	1,265.75	214.35	186.05	529.45	2,215.32	5,200.02	
		in/month	0.72	0.07	0.00	0.24	0.96	1.99	0.15	0.16	0.49	0.08	0.07	0.20	0.85	1.99	4,567
Subbasin 1	4,550	Mgal/d	281.30	42.43	0.50	69.98	165.02	559.23	61.88	35.54	237.50	13.15	34.25	60.17	116.74	559.23	
		in/month	1.12	0.17	0.00	0.28	0.66	2.23	0.25	0.14	0.95	0.05	0.14	0.24	0.47	2.23	439
Subbasin 2	6,311	Mgal/d	168.05	37.14	0.31	68.72	300.74	574.95	27.02	46.51	99.94	13.90	20.90	57.14	309.53	574.95	
		in/month	0.48	0.11	0.00	0.20	0.86	1.65	0.08	0.13	0.29	0.04	0.06	0.16	0.89	1.65	609
Subbasin 3	2,045	Mgal/d	67.18	12.58	2.23	24.70	74.33	181.02	25.37	11.24	36.93	8.14	5.58	20.20	73.56	181.02	
		in/month	0.60	0.11	0.02	0.22	0.66	1.61	0.23	0.10	0.33	0.07	0.05	0.18	0.65	1.61	197
Subbasin 4	12,065	Mgal/d	300.73	69.72	0.18	147.32	736.40	1,254.36	189.42	26.42	109.83	93.38	46.20	132.76	656.36	1,254.36	
		in/month	0.45	0.10	0.00	0.22	1.11	1.89	0.28	0.04	0.17	0.14	0.07	0.20	0.99	1.89	1,165
Subbasin 5	4,803	Mgal/d	142.31	12.61	2.46	52.11	223.59	433.08	34.57	45.90	84.74	15.03	6.18	40.22	206.44	433.08	
		in/month	0.54	0.05	0.01	0.20	0.84	1.64	0.13	0.17	0.32	0.06	0.02	0.15	0.78	1.64	464
Subbasin 6	6,461	Mgal/d	243.77	4.93	0.00	104.60	559.82	913.12	0.00	93.21	124.64	56.87	26.17	92.16	520.07	913.12	
		in/month	0.68	0.01	0.00	0.29	1.57	2.57	0.00	0.26	0.35	0.16	0.07	0.26	1.46	2.57	624
Subbasin 7	2,805	Mgal/d	188.97	3.61	0.82	44.18	141.85	379.43	7.53	37.26	164.59	4.35	17.72	38.87	109.11	379.43	
		in/month	1.22	0.02	0.01	0.29	0.92	2.46	0.05	0.24	1.06	0.03	0.11	0.25	0.71	2.46	271
Subbasin 8	8,270	Mgal/d	485.42	7.74	1.05	105.59	305.02	904.82	33.70	113.52	407.59	9.52	29.04	87.95	223.51	904.82	
		in/month	1.07	0.02	0.00	0.23	0.67	1.99	0.07	0.25	0.89	0.02	0.06	0.19	0.49	1.99	798

Table 2. Subbasins partially contained within the model.

Watershed boundary dataset code	Subbasin name	Subbasin number
03130004	Lower Chattahoochee	1
03130006	Middle Flint	2
03130007	Kinchafoonee-Muckalee	3
03130008	Lower Flint	4
03130009	Ichawaynochaway	5
03130010	Spring	6
03130011	Apalachicola	7
03130012	Chipola	8

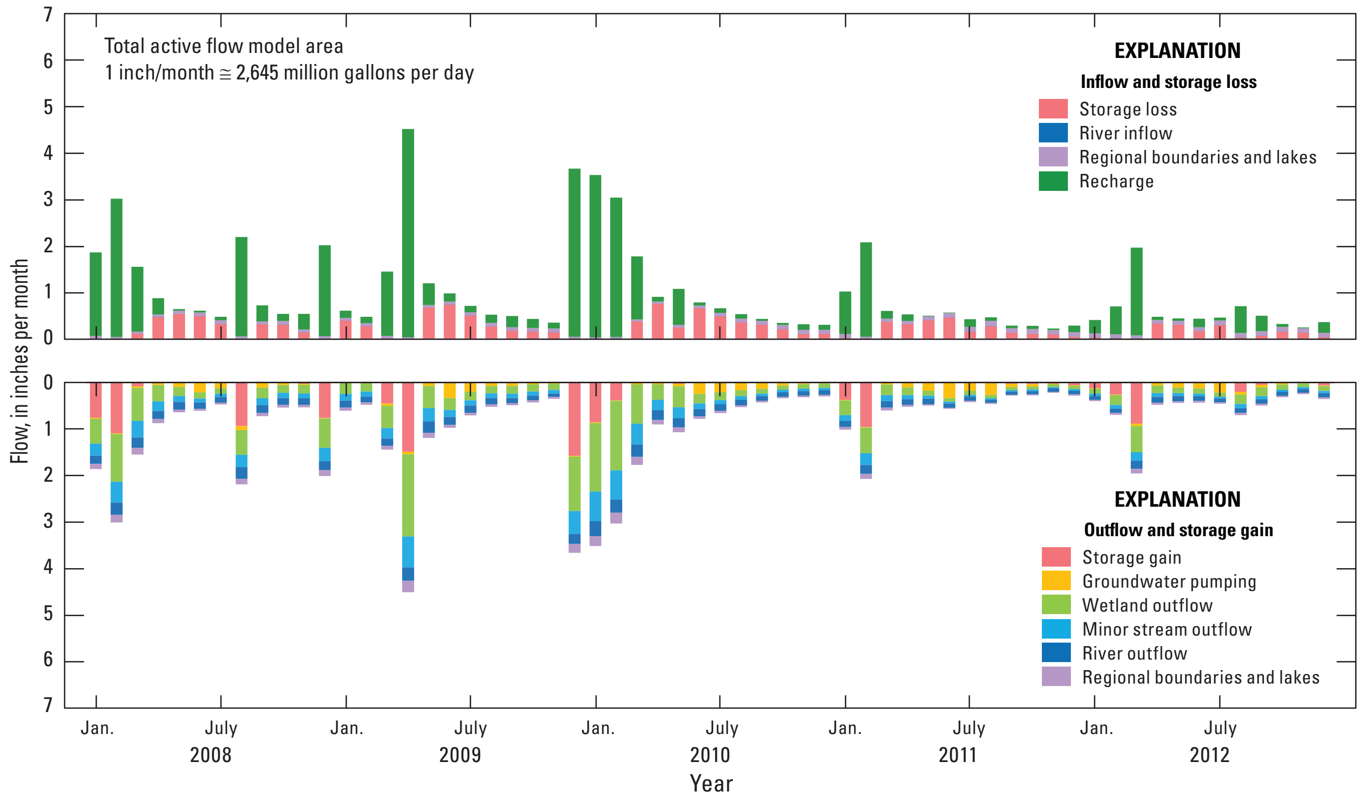

Figure 7. Monthly simulated (*A*) inflows and (*B*) outflows for groundwater-budget components for the study area for January 2008 to December 2012, in inches per month.

in groundwater in storage of about 88 Mgal/d for the study period, or a 17-percent greater depletion than accumulation of groundwater in storage. Net loss of groundwater in storage during the study period represents about 1.7 percent of the total budget.

The magnitudes of inflows, outflows, and changes in groundwater in storage vary temporally during the study period (fig. 7). Recharge inflows tend to occur in large magnitudes relative to other budget components and are concentrated temporally over one to a few months. Much of this recharge inflow occurs during the winter months and results in larger wetland, minor stream, and river outflows, and gains in groundwater in storage. During the longer periods of minimal recharge, which are largely during the spring, summer, and fall, and include the growing season, pumping outflows increase, and progressive declines in wetland, stream, and river outflows occur; these outflows are offset largely by groundwater-storage losses. Following periods of increased recharge, outflows to rivers decrease less substantially than outflows to wetlands and minor streams. In other words, outflow to rivers is temporally less variable than outflows to wetlands and minor streams, which are seasonally more variable. Thus, during dry periods, groundwater levels decline below smaller streams and wetlands, and discharge little groundwater.

Simulated groundwater-budget components were evaluated for the eight subbasins within the model area (figs. 8 and 9). Subbasin 4 is the largest subbasin, measuring 1,165 square miles (mi^2), about 25 percent of the entire model area, and contains the lower part of the Flint River that occurs within the study area. Subbasins 8, 6, and 2 are between 600 and 800 mi^2 each, and the remaining subbasins are smaller than 500 mi^2 each. Subbasin 4 shows the largest magnitude exchanges (fig. 9*B*), and the exchanges are dominated by flows to and from other subbasins along its lengthy western boundary. Subbasin 6, the Spring Creek Basin, has the largest exchanges on a per-unit-area basis (fig. 9*A*), the largest component of which is flows to and from other subbasins.

Exclusive of exchanges with other basins, results show that recharge is the largest magnitude inflow and largest inflow on a per-unit-area basis to all of the subbasins (fig. 9). Recharge applied in the groundwater-flow model is derived from a watershed model, which estimates recharge on the basis of spatially variable precipitation, temperature, vegetation, and soil characteristics (LaFontaine and others, 2017). Recharge is the primary driver of fluxes within the model, as shown by the qualitative correlation between recharge and total exchange, for both total magnitude and on a per-unit-area basis. Total recharge magnitude is greatest in subbasin 8, the Chipola River Basin. Recharge on a per-unit-area basis is greatest in subbasins 1, 7, and 8, in the southwesternmost part of the simulated area.

Exclusive of exchanges with other basins, results show that the largest magnitude outflows and outflows on a per-unit-area-basis are to wetlands, except for subbasin 4 (fig. 9). Outflows to wetlands are greatest in magnitude and on a per-unit-area basis in subbasins 1, 7, and 8, in the southwesternmost part of the simulated area. In subbasin 4, outflows to rivers are greater in magnitude and on a per-unit-area basis than all other outflows. Subbasin 4 is in the lower part of the Flint River Basin (fig. 8).

Some of the large outflows in the southwestern part of the simulated area may be related to Lake Seminole, particularly in subbasin 1. The impoundment of Lake Seminole resulted in the inundation of a large area in the Chattahoochee River, Flint River, and Spring Creek drainage areas, which have been indicated as the primary cause of large groundwater outflows in a simulated hydrologic budget (Jones and Torak, 2004). Land cover in this area is characterized by commonly occurring wetlands (appendix fig. 1–10), and much of the simulated outflows is to those wetlands. The largest simulated outflows to rivers, on both a total magnitude and per-unit-area basis, are in subbasin 4, which discharges to the lower part of the Flint River. There are many springs in the Flint River (Georgia Hometown Locator, http://georgia.hometownlocator.com/features/physical,class,spring.cfm, accessed March 31, 2017), and Torak and others (1996) note that in-channel springs contribute to gaining streamflows along the Flint River. Estimated groundwater pumping, on both a total magnitude and per-unit-area basis, is greatest in subbasins 4 and 6, which include the highest concentration of irrigated agriculture and groundwater withdrawals within the model area (Lawrence, 2016, fig. 7).

During the study period, there was a small net loss in simulated groundwater in storage for each subbasin (table 1; fig. 10). The largest simulated magnitude gains and losses in groundwater in storage occurred in subbasins 4, 6, and 8. Storage losses and gains on a per-unit-area basis were more evenly distributed across the subbasins. The largest simulated net losses of groundwater in storage in magnitude occurred in subbasins 4 and 8, and on a per-unit-area basis in subbasin 5. The overall net losses of groundwater in storage were likely the result of the change in recharge during the simulation period, because conditions changed from wetter, at the beginning of the simulation period, to drier, at the end of the simulation period. While recharge and storage gain decreased notably during the simulation period, storage loss decreased less (fig. 7).

Discussion

Fluxes from recharge dominate the hydrologic system. Recharge inputs to the model, as simulated from the PRMS model (LaFontaine and others, 2017), were more dynamic both temporally and spatially than inputs used in previous models (Jones and Torak, 2006), resulting in larger annual and seasonal changes in water budget components than previously simulated. It is likely that the variability in these water budget components represents the actual dynamics of the system. As the primary input to the system, recharge is the primary driver

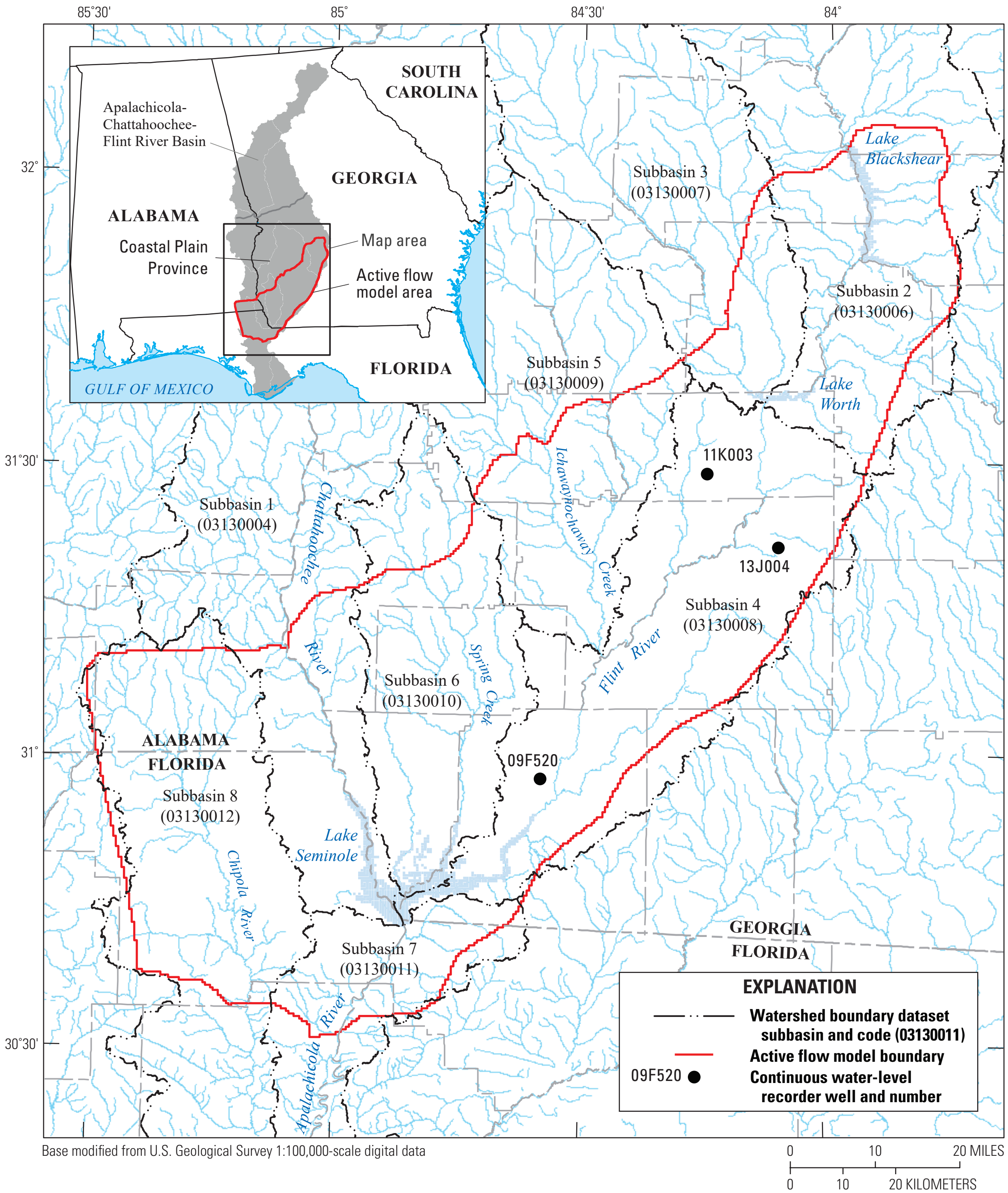

Figure 8. The areal extent of watershed boundary dataset subbasins in the active flow model area. Watershed boundary dataset codes are listed in table 2.

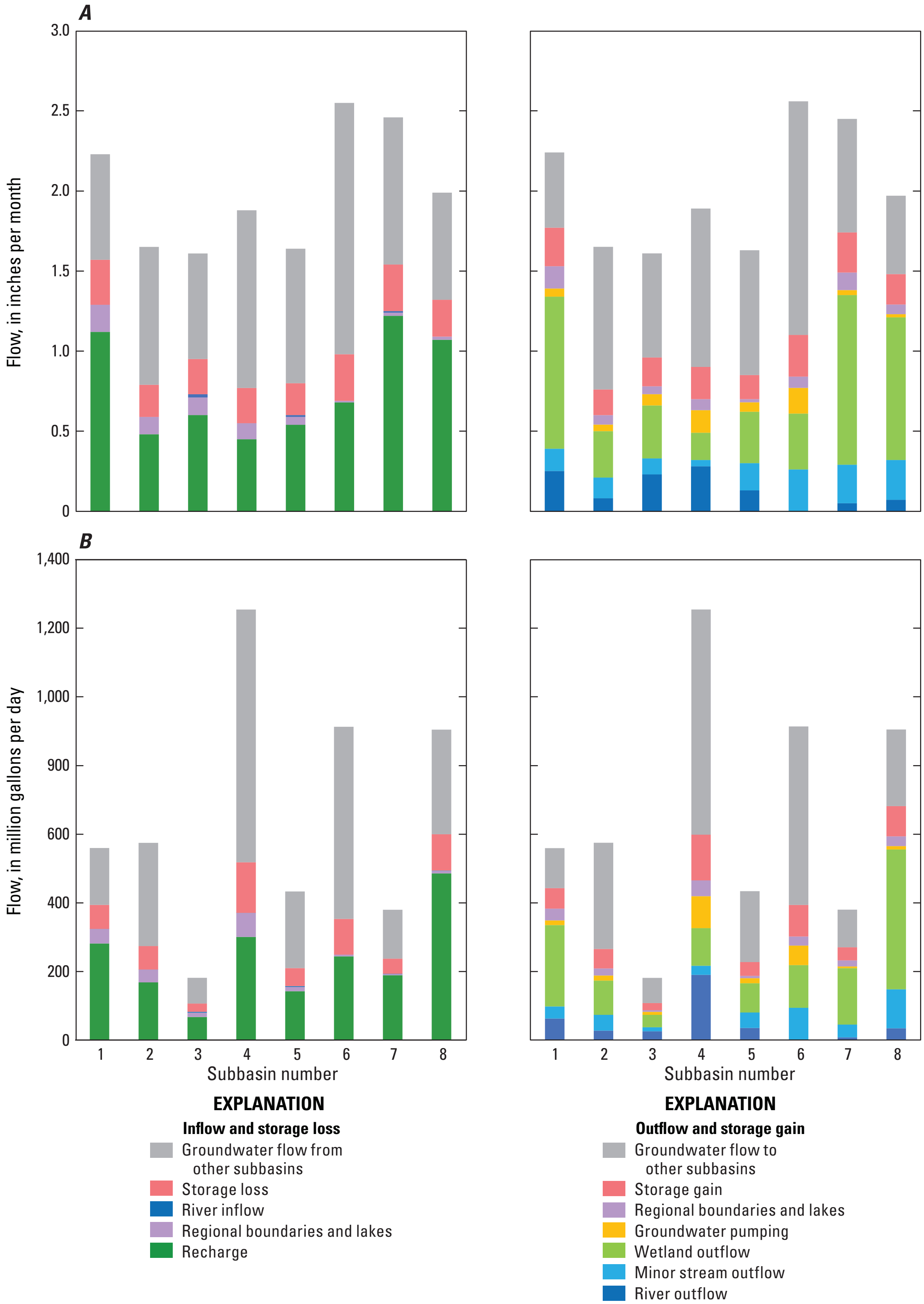

Figure 9. Simulated average inflow and groundwater-storage loss and outflow and groundwater-storage gain for each subbasin in the study area from January 2008 to December 2012, in *A*, inches per month, and *B*, million gallons per day, calculated for the Upper Floridan aquifer and grouped by subbasin number.

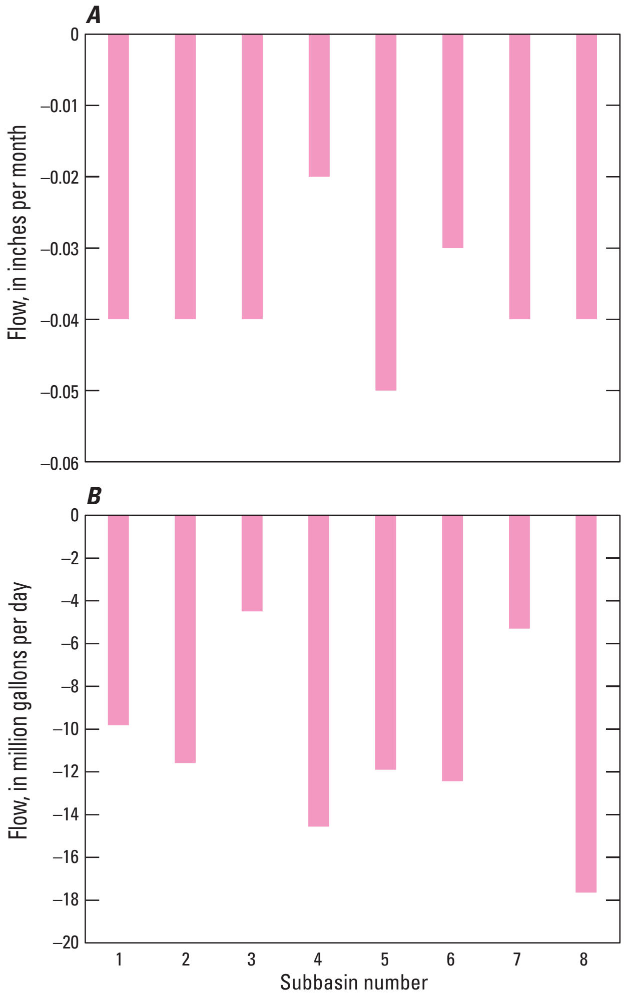

Figure 10. Simulated net changes in groundwater in storage in the Upper Floridan aquifer for each subbasin in the study area from January 2008 to December 2012, in *A*, inches per month, and *B*, million gallons per day, averaged monthly from January 2008 to December 2012 in the active flow model area.

of the system. Cumulative yearly recharge declined substantially during the study period as precipitation declined. In 2008, calculated recharge was about 922,000 million gallons (11.6 in), decreased for 2009 to about 898,000 million gallons (11.3 in), continued declining in 2010 to about 738,000 million gallons (9.3 in), then dropped substantially during 2011 to about 303,000 million gallons (3.8 in), and increased slightly during 2012 to about 345,000 million gallons (4.3 in).

In general, large amounts of recharge on the seasonal time scale (in winter) are balanced by large discharges to wetlands, rivers, and streams and by gains in groundwater in storage. Replenishment of storage is important during the winter season as a long-term supply of water for groundwater pumping as well as for wetland and riparian environments during the summer season when recharge is reduced. The reduction of recharge during the study period likely accounts for most of the net loss of groundwater in storage. The loss of groundwater in storage over the 5-year study period is recorded in groundwater hydrographs that show a decline during the study period (fig. 11). Since 2012, many hydrographs, including hydrographs for sites in the study area (fig. 8), show recovery of the depressed groundwater levels, indicating a replenishment of groundwater in storage, although long-term records at some sites (including those in figure 8) indicate overall declines (Peck and Painter, 2016).

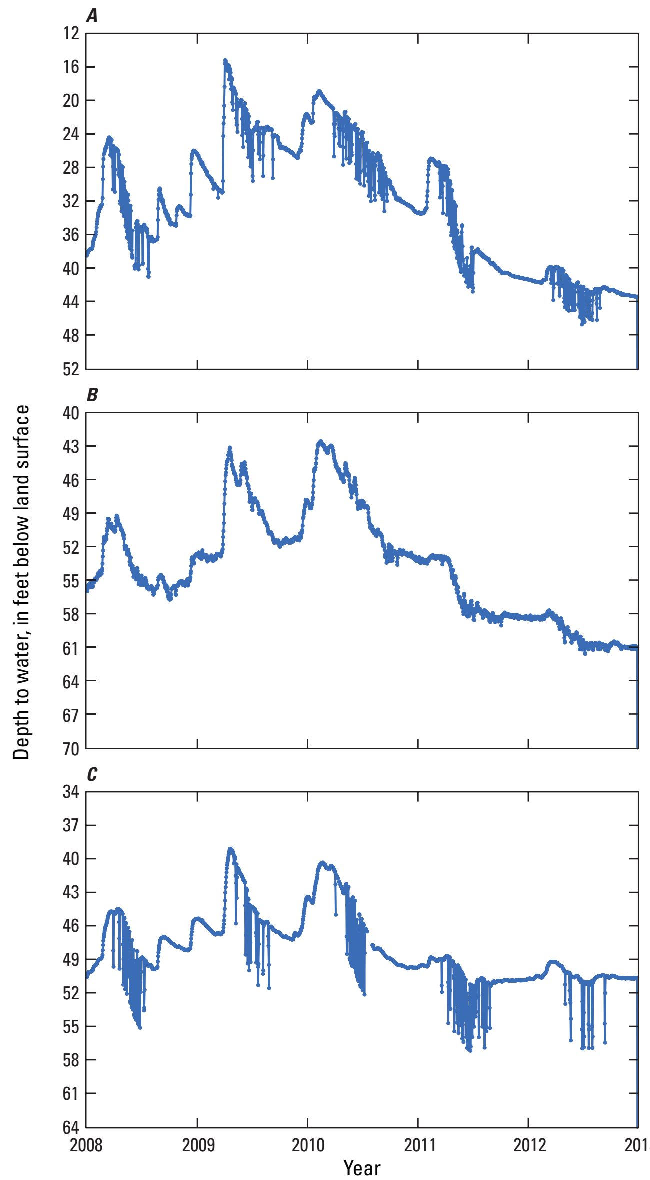

Figure 11. Selected hydrographs for the study period at Upper Floridan aquifer continuous water-level-recorder well sites *A*, 312919084153801 (11K003) in Dougherty County, Georgia; *B*, 312127084065801 (13J004) in Mitchell County, Georgia; and *C*, 305736084355801 (09F520) in Decatur County, Georgia, from January 2008 to December 2012.

Groundwater in storage is reduced by groundwater pumping as well as discharges to wetlands, rivers, and streams. During drier periods, agricultural irrigation tends to increase, as crop demand cannot be met with precipitation, drawing more from groundwater in storage than would be drawn in wetter growing seasons. During periods of decreased recharge, outflows to rivers, streams, and wetlands also draw on groundwater in storage, as does transfer of groundwater outside of the basin, for example to downdip areas of the Upper Floridan aquifer. Thus, during drier periods, the availability of groundwater discharge to support wetland and riparian environments may be reduced by competition with groundwater pumping for groundwater in storage. Although the volume of groundwater removed from the study area by pumping over the simulation period (214 Mgal/d) represents only about 11 percent of the volume of water recharging the system (1,878 Mgal/d; table 1), the storage of groundwater and the discrepancy in timing of replenishment and depletion of groundwater in storage are more important considerations in groundwater availability for the study area.

Potential long-term changes in climatic conditions, for example in magnitude or timing of precipitation, or changes in land use may affect groundwater-recharge rates and distribution, and thus groundwater in storage. Long-term declines in groundwater levels, though not large, have been observed in the study area (Peck and Painter, 2016) and indicate long-term declines in groundwater in storage. Although this model does not address long-term effects of climatic changes, long-term declines in groundwater storage may affect long-term groundwater availability for groundwater pumping and for supporting environmental needs in wetlands and riparian environments. Long-term declines in groundwater storage may thus increase competition between groundwater-pumping demands during drier growing seasons and seasonal availability of groundwater discharge for wetland and riparian environments. An evaluation of the temporal and spatial variability of precipitation and recharge could be used to optimize the management of groundwater use as well as land use, and models such as developed for this study could be used to assist in long-term future land- and water-use planning.

Model Limitations

In general, groundwater-flow models are limited by the conceptualization of the hydrologic system as well as assumptions about the system and uncertainties in how the system is represented in the model. Hydrologic-flow simulations generally are based on conceptual models that are simplified representations of complex, heterogeneous flow systems. The lack of sufficient measurements to fully describe the spatial and temporal variability of hydrologic conditions and the spatial variability of hydraulic properties throughout the model area necessitate these simplifications. Assumptions about hydraulic properties such as isotropy, spatial uniformity, and the absence of preferential flow zones are examples of simplified representations that can be sources of error in a flow model.

The feasibility of this model to represent the lower ACF hydrologic system during the simulation period is limited by the assumptions and simplifications associated with the (1) conceptualization of the lower ACF groundwater-flow system; (2) data available to represent the physical properties of the system, as well as observations of system conditions such as the measured groundwater heads, lake stages, and stream base flows; and (3) equations used to simulate components of the flow system. The model was shown to approximate independently estimated base flow to streams and observed groundwater heads in response to hydrologic stresses and groundwater-pumping rates for monthly stress periods from 2008 to 2012, which included dry, wet, and average hydrologic conditions. Nonetheless, it may be inappropriate to use the model with hydrologic conditions outside the range tested, or to impose groundwater-pumping rates greater than those used in the simulation, or near the boundaries of the model area. Also, although simplifying the actual flow system with the selected conceptualizations does not invalidate model results, model results should not be interpreted at scales smaller than the representative grid cell.

The model layering discretization was based on estimated altitudes and thicknesses of the hydrogeologic units, but was modified to prevent simulated water levels from declining below the top of layers assigned confined storage, specifically layers 2 and 3. This approach accounts for uncertainty in where the Upper Floridan aquifer is actually unconfined or confined. It is possible that changes in how the layers are simulated, if not assigned thicknesses, would have an effect on the model and the resulting calibrated parameters, as well as simulated budget components.

The lower ACF groundwater system is assumed to be recharge driven, which is probably a valid assumption, considering the Upper Floridan aquifer in the study area is near its updip extent, and the aquifer is highly permeable. Recharge rates, however, can only be evaluated indirectly and are, generally, poorly known. Simulated wetland, stream, and river discharges, groundwater in storage, and groundwater levels are most sensitive to recharge rates, compared with all of the input variables tested (appendix figs. 1–25 to 1–38). Recharge rates and distribution were estimated for this model using the companion PRMS model of the ACF River Basin (LaFontaine and others, 2017) and were based on estimated distributions of precipitation, temperature, land cover, evapotranspiration, and soil properties. Each of these factors is based on other assumptions and spatial distribution functions, each of which has an associated error and uncertainty, which would propagate into the estimation of the recharge rate distribution. Uncertainty in the climatic variables that affect the estimation of recharge make unclear the degree to which changes in these climatic variables affect the observed long-term declines in groundwater levels. Furthermore, the approach of specifying recharge to units overlying the Upper Floridan aquifer is based on the assumption that recharge is independent of processes or conditions in those hydrologic units, which is unlikely.

In the model, the general-head boundary cells along lateral boundaries of layer 3 were simulated as spatially variable, but constant in time, although measured values indicate the cells are temporally variable (Gordon and Peck, 2010; Kinnaman and Dixon, 2011; Gordon and others, 2012). This assumption may result in larger or smaller flows across the model boundaries and may result in an inability to accurately simulate groundwater levels near the boundaries. For example, the outlier residuals in the northern part of the model area may be a result of their proximity to boundary conditions that are not reflective of conditions at the observation locations.

Although groundwater pumping is not a large component of the overall budget and although the estimate of groundwater pumping is considered more accurate than estimates used in previous groundwater-flow models of the lower ACF River Basin, there are still uncertainties associated with the estimated pumping rates. Pumping for agricultural irrigation is not determined explicitly through metering for all sites for the entire simulation period. A small, but statistically valid, subset of monthly irrigation water withdrawals used in the model was directly measured, and the rest were extrapolated and estimated on the basis of these data and measured annual totals from the larger population of metered systems. An evaluation of the uncertainty of these estimates is currently not available. In addition, different, yet individually viable, methods of estimating actual irrigation water use produce different values (Painter and others, 2015). Sensitivity testing results indicate that simulated discharges to wetlands, streams, and rivers, and changes in groundwater in storage are not particularly sensitive to substantially larger pumping rates in general, but model results indicate that groundwater availability for discharges to wetlands, rivers, and streams may be temporally affected by groundwater pumping. Another assumption of the model is that groundwater that is pumped and applied to irrigation is consumptively used, when any excess irrigation may in reality be recharging the groundwater system. Much of the irrigation in the region is delivered by center-pivot systems, which are estimated to be generally 75 to 98 percent efficient (Dickens and others, 2011). So it is not likely that these uncertainties in pumping would notably affect the simulation results, as indicated by sensitivity testing, or the resulting interpretation.

The model is calibrated to fit observed groundwater levels in the Upper Floridan aquifer and estimated stream base flow for selected subbasins. Groundwater leakage to wetlands and minor or ungaged streams accounts for more of the simulated discharge than leakage to rivers, but actual groundwater discharge to wetlands and minor streams is unknown. Minor streams may be ephemeral. Any adjustments to the conceptual model or input variables may affect the resulting simulated discharge to wetlands and minor streams. Data to constrain fluxes through these potentially important hydrologic features in the lower ACF River Basin could improve the evaluation of the hydrologic budget. Furthermore, a lack of hydraulic conductivity and water-level data for hydrologic units overlying the Upper Floridan aquifer resulted in these values being adjusted only on the basis of measured water levels in the Upper Floridan aquifer.

The groundwater-flow equation solved by the model for porous-equivalent media is based on Darcy's law and the continuity equation when the velocity of groundwater is low and flow is laminar. In karstic terrains, however, it is possible for flow through caverns and solution channels to be turbulent. The possibility of turbulent flow in some areas may indicate that the base-flow calculations are underestimated, because lower simulated hydraulic conductivity values associated with porous media were used. Kuniansky (2016) noted that comparisons of simulated flow in a karstic area using porous-equivalent media flow versus combined porous-equivalent and non-laminar flow show similar results, and that consideration of turbulent flow may be more important for matching spring-flow hydrographs for short-duration, intense precipitation events.

The lower ACF River Basin groundwater model was calibrated primarily by trial-and-error adjustments of aquifer hydraulic properties, which were derived from previous models and field data. Simulated discharge to rivers and model boundaries and lakes is moderately sensitive to the horizontal hydraulic conductivity of layer 3, which represents most of the Upper Floridan aquifer, and exchanges with groundwater storage in the shallowest unit are moderately sensitive to the specific yield applied to unconfined layer 1. Typically, inherent uncertainty in the distribution of hydraulic properties is addressed during model calibration. By adjusting hydraulic properties, a better model fit can be obtained. It should be noted that the model could be made to fit observed groundwater levels and base flows to the same degree with an entirely different distribution of hydraulic properties. Techniques that quantitatively fit the model to observations using an objective function minimization process can be used to provide a "best fit" within the constraints imposed on the model. This does not necessarily mean a model calibrated using these techniques is more correct. Simulation results show a spatial bias in the largest residuals, indicating the model underestimates simulated groundwater-level values in the north-central part of the model area (appendix figs. 1–17, 1–20, 1–21, 1–22). It is not certain if this spatial bias is the result of incorrect hydraulic properties, boundary conditions, or model conceptualization, or whether a quantitative best-fit approach to calibration could reduce this underestimation.

Summary

The lower Apalachicola-Chattahoochee-Flint (ACF) River Basin is an important agricultural area in the Southeastern United States, for which water for irrigation is supplied primarily by the Upper Floridan aquifer. The aquifer generally is shallow and karstic, and receives much recharge in the area. The lower ACF River Basin has experienced long-term groundwater-level declines and reductions in base flow, which have contributed to declining streamflows in downstream parts of the ACF River Basin. As part of the National Water Census program in the ACF River Basin, the U.S. Geological Survey evaluated the groundwater budget of the lower ACF River Basin, with particular emphasis on recharge, characterizing the spatial and temporal relation between surface water and groundwater, and groundwater pumping.

To evaluate the hydrologic budget of the lower ACF River Basin, a groundwater-flow model was developed for the Upper Floridan aquifer and overlying upper semiconfining unit and undifferentiated shallow units for 2008–12. The study period was chosen because of the availability during this period of monthly estimates of agricultural irrigation groundwater-pumping rates, the largest component of groundwater stresses in the study area. The study period also included a wide range of values of annual precipitation. Hydrologically, the Upper Floridan aquifer in the lower ACF River Basin is characterized as recharge driven, with the most substantial recharge occurring during the winter months. Rivers in the area primarily receive discharge from the aquifer.

The hydrologic budget was computed with a groundwater-flow model, which was constructed using MODFLOW-2005. Model input included temporally and spatially variable specified recharge and pumping, and the model was calibrated to measured groundwater levels and base flows, which were estimated using hydrograph separation. The model was calibrated by adjusting hydraulic properties to fit simulated to measured groundwater levels and estimated base flows, using a trial-and-error approach.

Simulation results show that recharge is the largest inflow to the groundwater system, and simulated outflow is largest for wetlands. Outflow to wells is less than outflow to rivers or minor streams. The model simulates a net cumulative loss in groundwater in storage during the study period, representing about 1.7 percent of the total budget.

Hydrologic budgets of eight subbasins were also evaluated. Exclusive of exchanges with other basins, results show that recharge is the largest component of inflows to all of the subbasins, and that outflow to wetlands is the largest component of outflows for all subbasins, except subbasin 4. The largest outflow in subbasin 4, the lower part of the Flint River Basin, is to rivers. The Flint River is characterized by many in-channel springs. A small net loss in groundwater storage was simulated in all subbasins and is likely attributable to a transition from wetter to drier climatic conditions during the simulation period. The model was not used to estimate long-term changes in groundwater storage.

Recharge occurs predominantly during the winter months, whereas groundwater-pumping withdrawals are greatest during the summer months, so accumulation of groundwater storage from recharge is important for water supply. Although the results of this study do not address long-term changes in groundwater storage, the model could provide insight for planning purposes to optimize water use and land use.

The model is limited by specific assumptions associated with (1) conceptualization of the lower ACF groundwater-flow system, (2) data available to represent the physical properties of the system and to calibrate the model, and (3) mathematical representation of the flow system. Assumptions include the conceptualization of static boundary conditions at the lateral boundaries of the model and the representation of the system as laminar flow through porous media. Uncertainty is introduced in recharge rates and distributions of groundwater pumping.

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Appendix 1. Model Construction and Calibration

Introduction

A groundwater-flow model was developed for the lower Apalachicola-Chattahoochee-Flint (ACF) River Basin in southwestern Georgia and adjacent parts of Florida and Alabama, using MODFLOW-2005, to evaluate the groundwater-flow budget in the lower ACF River Basin and to quantify the water exchanges between the Upper Floridan aquifer and the rivers from 2008 to 2012 (Sepulveda and Painter, 2017). The active flow model area, which extends about 4,567 square miles (mi^2) in the lower ACF River Basin, includes parts of southwestern Georgia and adjacent parts of Florida and Alabama (fig. 1 in main body of report). The active flow model area was further delimited to the lower ACF River Basin where the top of the Upper Floridan aquifer is near land surface and thus has the potential of a high hydraulic connection to surface-water bodies.

The model simulates groundwater flow within and between the Upper Floridan aquifer and the overlying upper semiconfining unit and surficial aquifer (fig. 1–1). The model also simulates stream-aquifer and lake-aquifer flows and accounts for recharge and groundwater pumping for

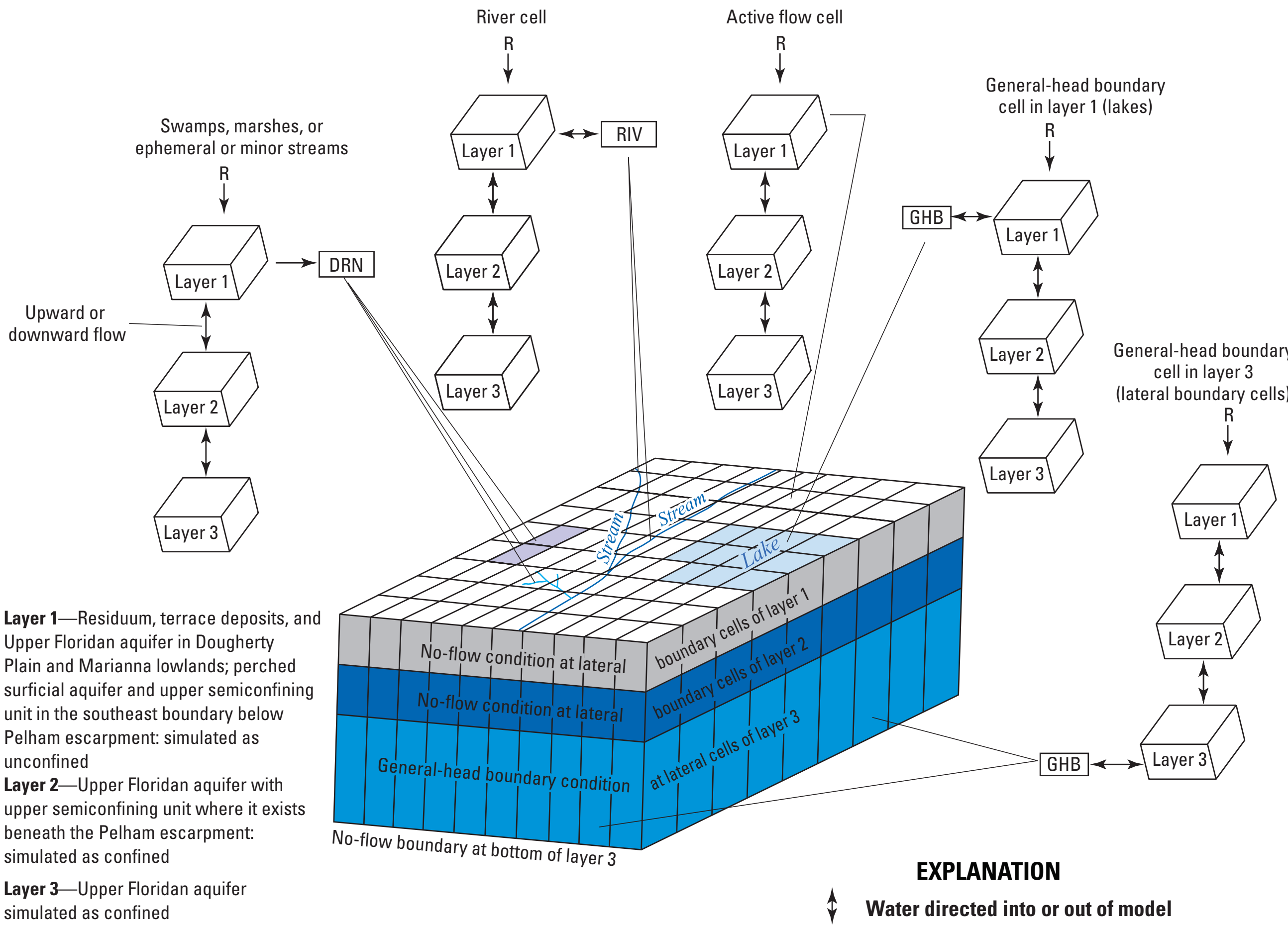


Figure 1–1. Schematic diagram of how the conceptual groundwater-flow model is implemented in MODFLOW-2005 for the lower Apalachicola-Chattahoochee-Flint River Basin.

agricultural irrigation and municipal and industrial supply. Recharge rates were estimated using precipitation data, soil storage capacity information, and a Precipitation-Runoff Modeling System (PRMS, Leavesley and others, 1983) model developed for the ACF River Basin (LaFontaine and others, 2017). The model was calibrated by adjusting hydraulic conductivity values, using a trial-and-error method, such that simulated groundwater levels and stream base flow (the flow contribution from the aquifer to the stream) reasonably matched observed groundwater levels and estimated base flows. Development, calibration, fit of the model, and model sensitivity are described in this appendix.

Table 1–1. Geographic information system coordinates of the corners of the groundwater-flow model grid.

[XALB and YALB coordinates refer to easting and northing of the projection using Albers Equal-Area Conic projection centered east-west at the meridian W84°30', North American Datum of 1983, in meters (Snyder, 1983)]

Grid corner	XALB	YALB
Northwest	–95341.63	1004539.90
Northeast	71658.71	1004539.90
Southwest	–95341.63	826539.54
Southeast	71658.71	826539.54

Simulation Code

The simulation code used to develop the surface-water/groundwater-flow model presented here for the lower ACF River Basin was MODFLOW-2005, version 1.11.0 (Harbaugh, 2005). The model was constructed using the following MODFLOW packages: Drain (DRN), General-Head Boundary (GHB), Observation (OBS), Recharge (RCH), River (RIV), and Well (WEL) (Harbaugh, 2005). Detailed guidelines of the input files required in the use of these packages are explained on the U.S. Geological Survey (USGS) MODFLOW web page at https://water.usgs.gov/ogw/modflow/MODFLOW.html. The RCH Package was used to apply the simulated recharge rates from the PRMS model developed by LaFontaine and others (2017) to the groundwater-flow model developed herein for the lower ACF River Basin.

Extent and Discretization

The southeastern and western lateral model boundaries were delineated adjacent to the lateral boundaries of the lower ACF River Basin (fig. 1 in main body of report). The northwestern lateral model boundary is delineated near the updip extent of the top of the Upper Floridan aquifer. The southern lateral model boundary is in an area where the connection between the Upper Floridan aquifer and the surface-water bodies in the ACF River Basin is diminished because of the increasing depth of the top of the aquifer and increasing thickness of the overlying clayey sediment deposits of low permeability of the Hawthorne Group, which forms the upper confining unit southeast of the Pelham Escarpment, closer to the Gulf of Mexico (Williams and Kuniansky, 2015). The active flow model area included all areas with potentially high stream-aquifer hydraulic connection in the lower ACF River Basin to improve the assessment of water exchanges between the Upper Floridan aquifer and water-surface bodies.

The rectangular numerical grid, with zero degrees rotation, used to develop the model was generated using the Albers Equal-Area Conic map projection coordinate system (Snyder, 1983) and the coordinates of the model grid corners (table 1–1; Details on map projection parameters are provided in Sepulveda and Painter, 2017). The model area was discretized with uniform square grid cells of about 1,640 feet (ft; 500 meters) on each side. The resulting grid contains 47,310 active flow cells and encompasses an area of about 4,567 mi^2 (fig. 1 in main body of report). The model is discretized as three layers, approximately representing the Upper Floridan aquifer and the overlying hydrogeologic units. The uppermost layer, layer 1, is simulated as unconfined, and represents residuum, terrace deposits and the unconfined areas of the Upper Floridan aquifer in the Dougherty Plain and Marianna Lowlands, and the perched surficial aquifer and upper semiconfining unit southeast of the Pelham Escarpment (fig. 1–1). The altitude of the top of layer 1 is land surface. The altitude of the bottom of layer 1 is based on the altitude of the top of the Upper Floridan aquifer (Williams and Kuniansky, 2015), but is adjusted to ensure simulated water levels do not drop below the base of layer 1. Layer 1 ranges from about 13 ft thick to greater than 350 ft thick (fig. 1–2). Layer 1 is thinnest near and beneath Lake Seminole and larger rivers, and is thickest beneath and southeast of the Pelham Escarpment and in interstream areas. Layer 2 is simulated as confined and generally represents a composite of the Upper Floridan aquifer and overlying residuum northwest of the Pelham Escarpment and the uppermost part of the Upper Floridan aquifer and lower part of the upper semiconfining unit southeast of the Pelham Escarpment (fig. 2 in main body of report). Layer 2 ranges in thickness from 0.5 to 64 ft (fig. 1–3). Layer 3 is simulated as confined and generally represents the confined parts of the Upper Floridan aquifer in the study area. Layer 3 ranges in thickness from about 5 to almost 600 ft (fig. 1–4).

The period of groundwater-flow simulation chosen was from January 2008 to December 2012 based on the availability of reproducible and reliable estimates of monthly agricultural irrigation usage from metered agricultural pumping data in Georgia and collaborative analysis between the USGS and the Georgia Soil and Water Conservation Commission (GSWCC), under the Georgia Agricultural Water Conservation and Metering Program. The 5-year period of 2008 to 2012 was divided into 60 transient monthly stress periods with 10 time steps for all monthly stress periods. During this 5-year period, three potentiometric-surface maps for the Upper Floridan

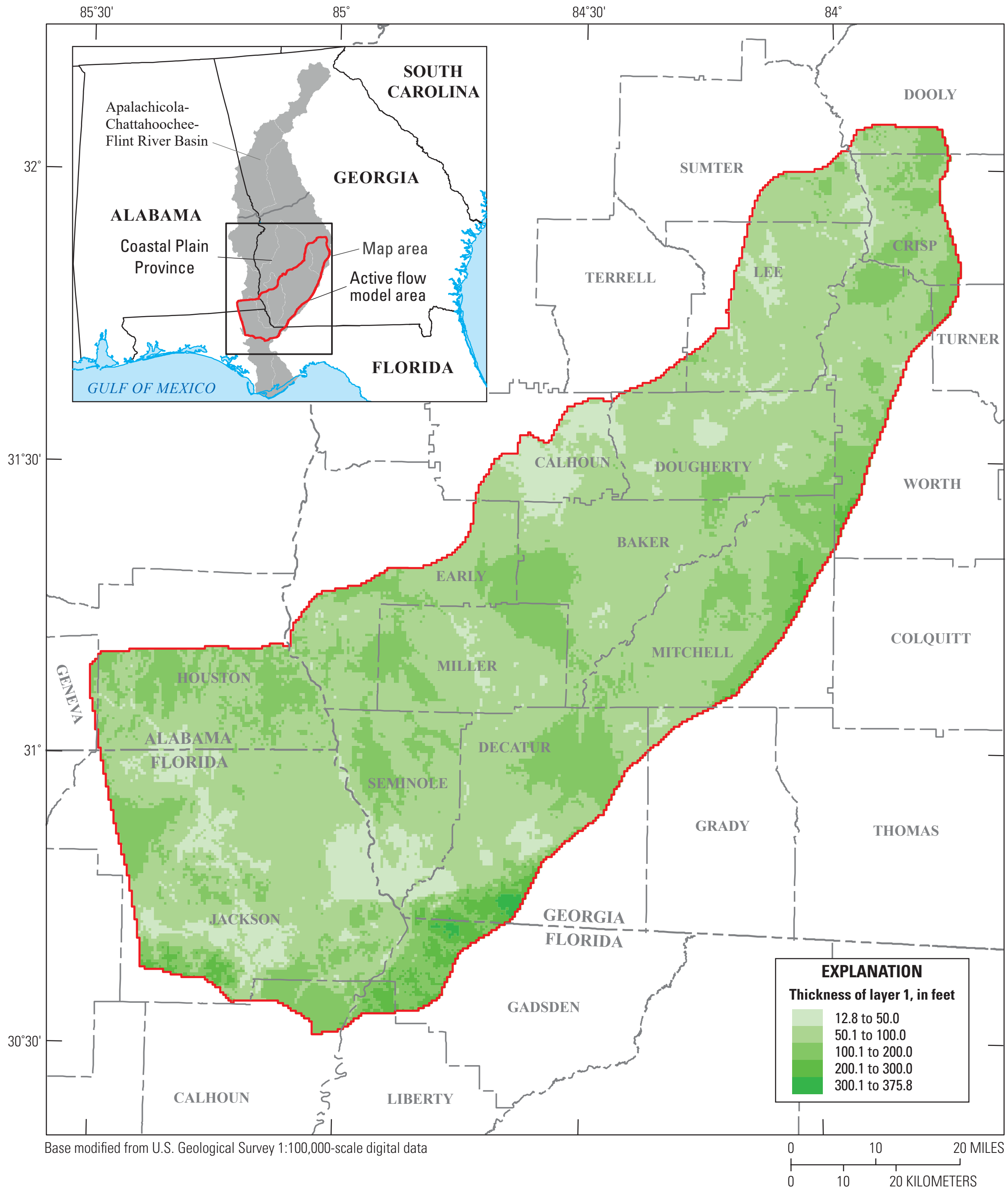


Figure 1–2. The thickness of layer 1 in the active flow model area.

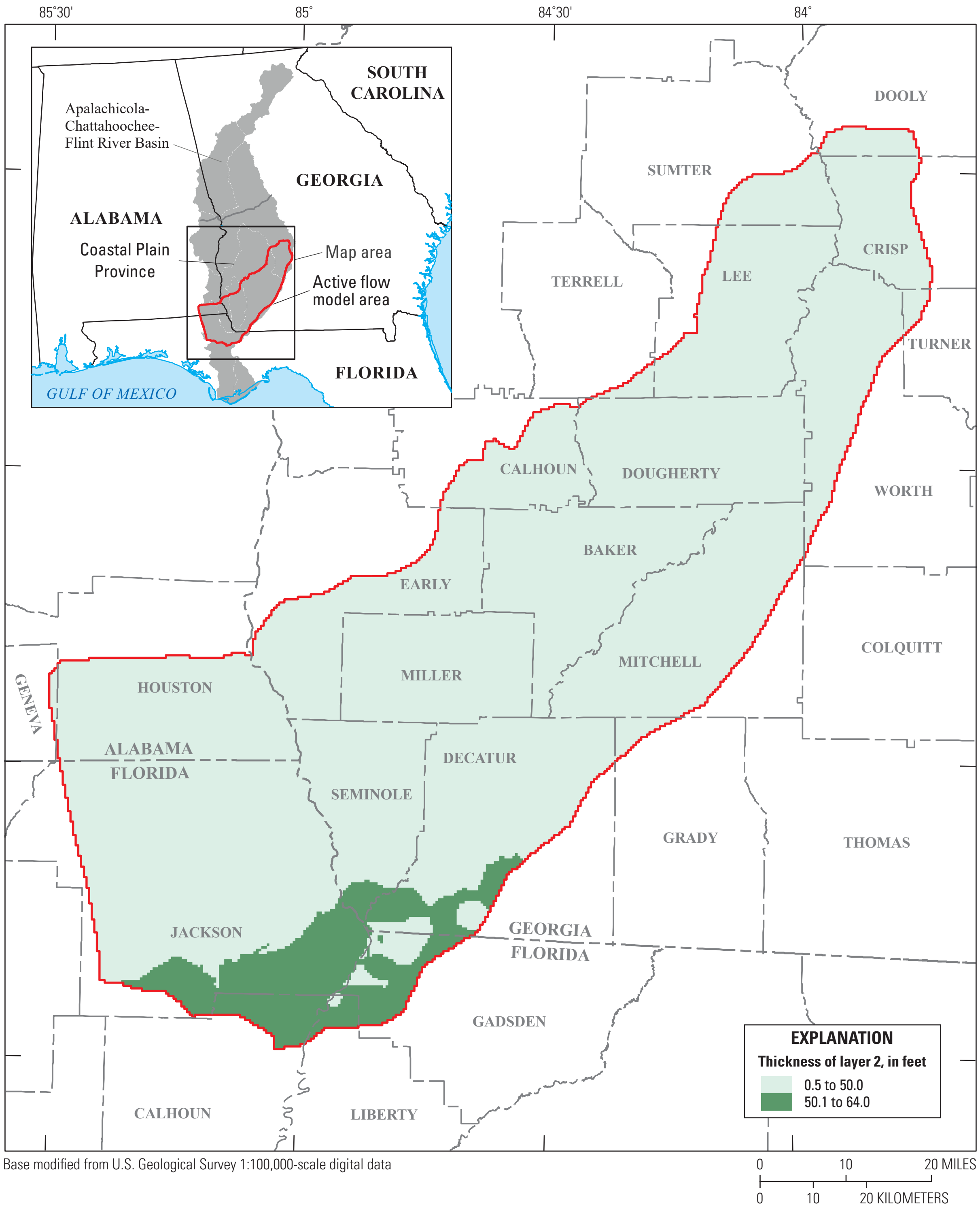


Figure 1–3. The thickness of layer 2 in the active flow model area.

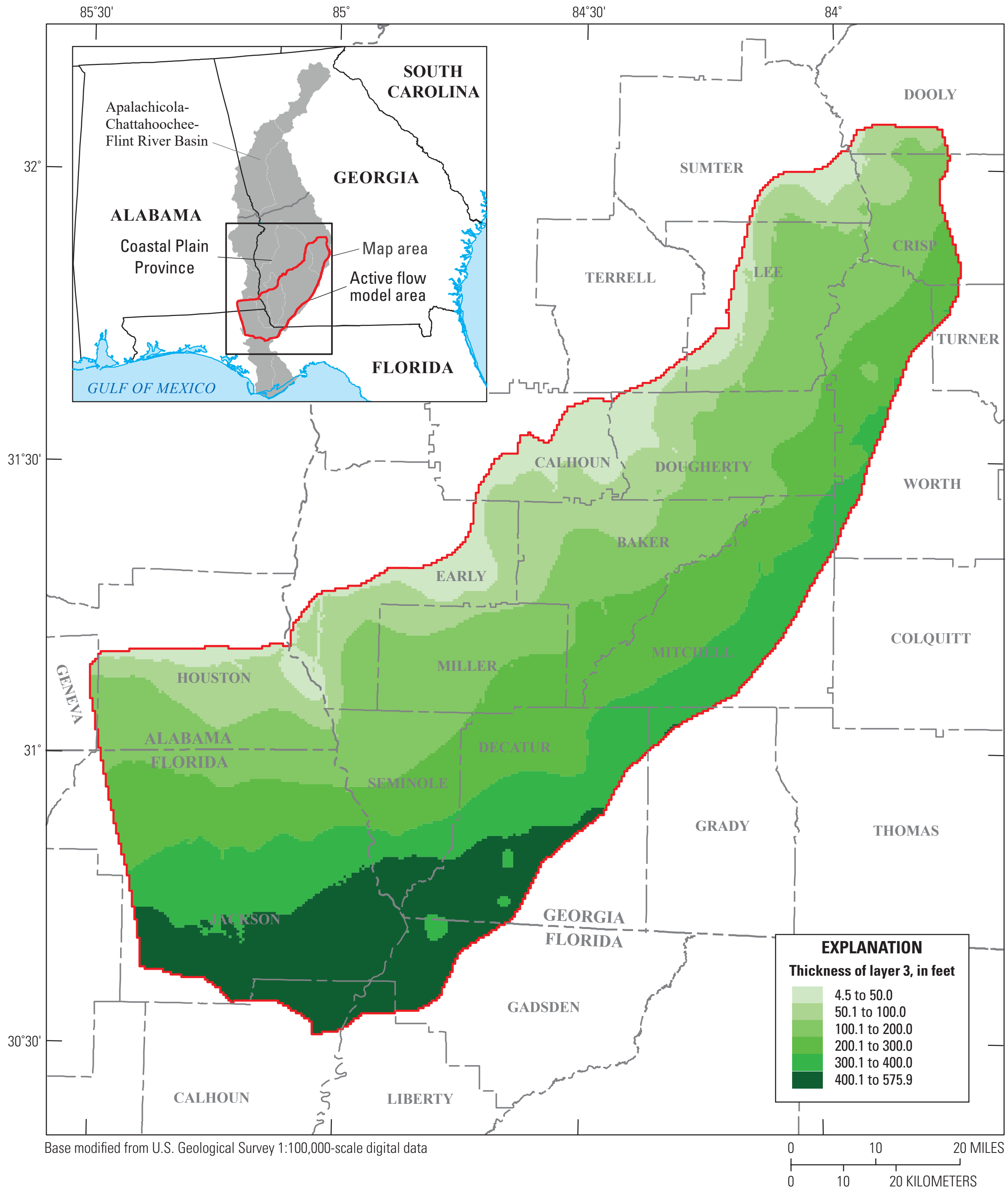


Figure 1–4. The thickness of layer 3 in the active flow model area.

aquifer (November 2008, Gordon and Peck, 2010; May and June 2010, Kinnaman and Dixon, 2011; and July 2011, Gordon and others, 2012) provided groundwater-level measurements for use in calibrating the groundwater-flow model for the three stress periods. Continuous groundwater-level recorders at 31 sites in Georgia provided monthly average water levels for calibration of the remaining stress periods.

Boundary Conditions

No-flow, specified flux, and head-dependent flux boundary conditions were used in the groundwater-flow model (fig. 1–1). No-flow boundaries were imposed at all lateral boundary cells in layers 1 and 2 of the model because of the assumption that the lateral flow in layers 1 and 2, as well as the hydraulic conductivity, are much lower than the lateral flow in layer 3. A no-flow boundary condition was also imposed at the bottom of layer 3 (Upper Floridan aquifer), assuming the Upper Floridan aquifer is confined from below. Boundary conditions other than no-flow are described in the following subsections, and calibrated hydraulic properties assigned to the boundary conditions are presented in the section on hydraulic properties.

Specified Flux

Groundwater-pumping and recharge rates were applied using specified flux boundaries (MODFLOW WEL and RCH Packages).

Groundwater Pumping

Groundwater-pumping data representing agricultural irrigation, and municipal and industrial water use, compiled in various formats and from multiple sources for the study period, were estimated on a monthly basis (fig. 1–5). These data were then summed by model row and column location, and then applied to layer 3 in the WEL Package (Sepulveda and Painter, 2017). Data used for agricultural irrigation groundwater-pumping rates were provided by the Northwest Florida Water Management District, Georgia Department of Natural Resources, and Marella and Dixon (2015), and techniques used to estimate the agricultural groundwater pumping distribution are described in Painter and others (2015) and Sepulveda and Painter (2017). Municipal and industrial groundwater-pumping rates were provided by the Georgia Department of Natural Resources, Environmental Protection Division and the U.S. Geological Survey (2017) and Sepulveda and Painter (2017).

Recharge

The PRMS model partitions precipitation into surface water and groundwater, accounting for runoff, infiltration, and evapotranspiration processes, as a function of precipitation, air temperature, and soil permeability. The monthly recharge rates from the PRMS model (Leavesley and others, 1983; Markstrom and others, 2015) developed for the ACF River Basin focus area study by LaFontaine and others (2017) were spatially uniform within hydrologic response units, but spatially variable across the study area, and were applied to the active flow model area in layer 1 using the Recharge (RCH) Package (Harbaugh, 2005). Monthly recharge rates during the transient simulation of January 2008 to December 2012 ranged from about 0 to about 4.5 inches per month (fig. 1–6). Recharge rates were applied to each active flow model cell in layer 1 on the basis of the output from the simulation of a precipitation and surface-water runoff model developed for the ACF River Basin (LaFontaine and others, 2017). The largest monthly recharge rates occurred in the months of April 2009 and December 2009 (fig. 1–6). The recharge rates in April 2009 ranged from almost 12 inches per month in the southernmost part of the model area to less than 1 inch, just northeast of there (fig. 1–7). Highest recharge rates in the model area in December 2009 were almost 9 inches per month and also occurred in the southwesternmost part of the model area, with less than 1 inch occurring in parts of Decatur, Dougherty, and Mitchell Counties (fig. 1–8).

High values assigned to the maximum allowable water storage in the PRMS (Leavesley and others, 1983) soil zone cause much of the precipitation to be stored in the soil zone, or routed as surface runoff or shallow subsurface flow, instead of infiltrating into the deeper groundwater system as recharge (fig. 1–9). Recharge is a function of precipitation, soil properties, antecedent conditions, and other landscape characteristics, and thus there is no simple relation between soil storage capacity and recharge distribution (figs. 1–7, 1–8, and 1–9).

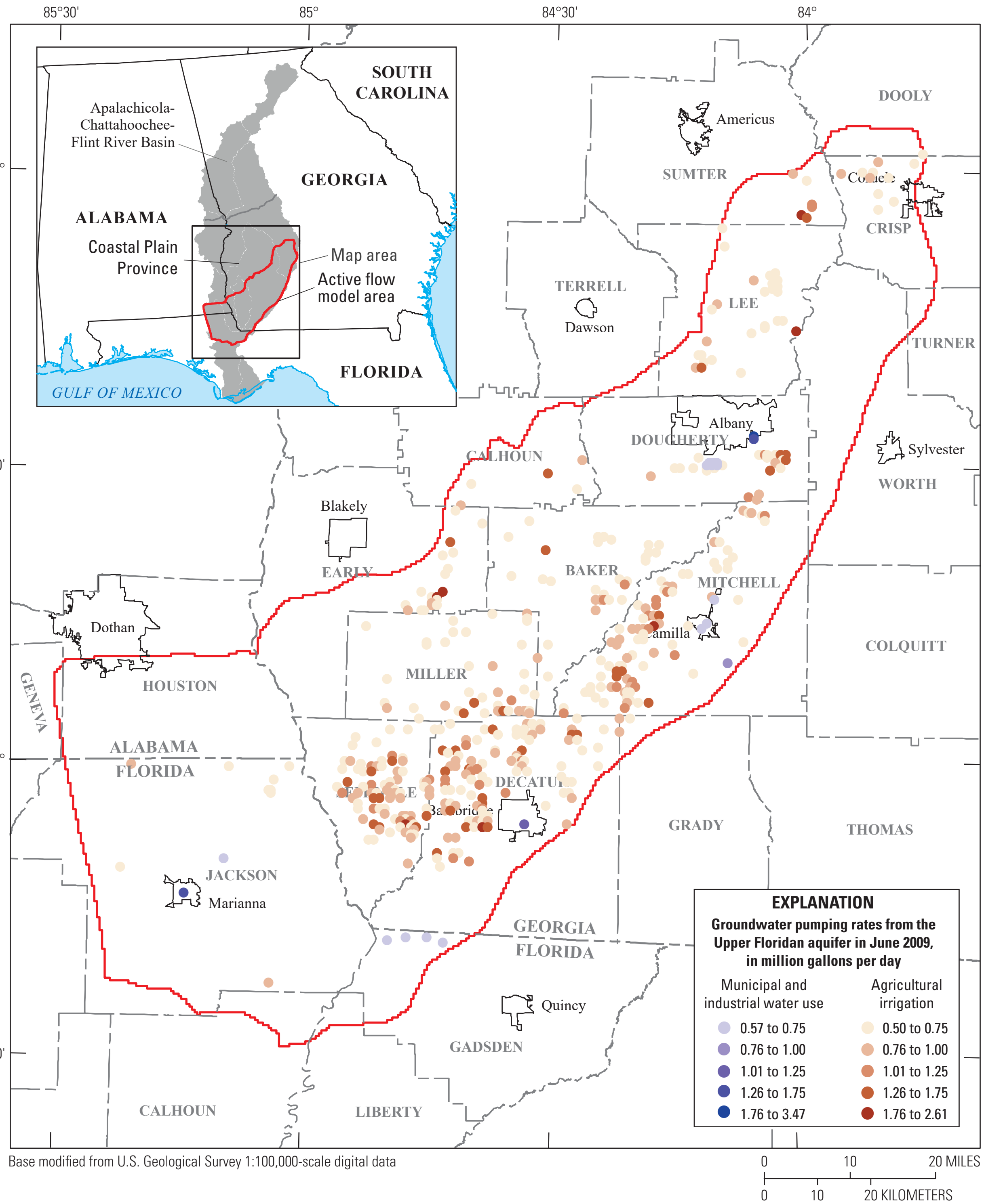


Figure 1–5. Locations where groundwater-pumping rates from the Upper Floridan aquifer in June 2009 in the active flow model area were greater than or equal to 0.5 million gallons per day.

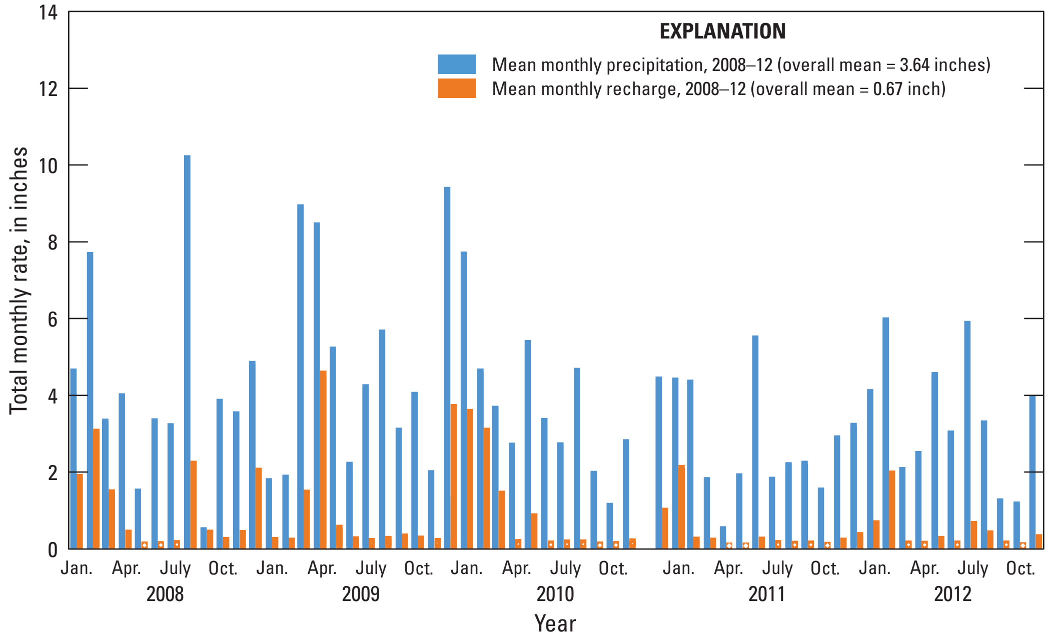


Figure 1–6. The mean monthly precipitation and recharge rates over the active flow model area from January 2008 to December 2012.

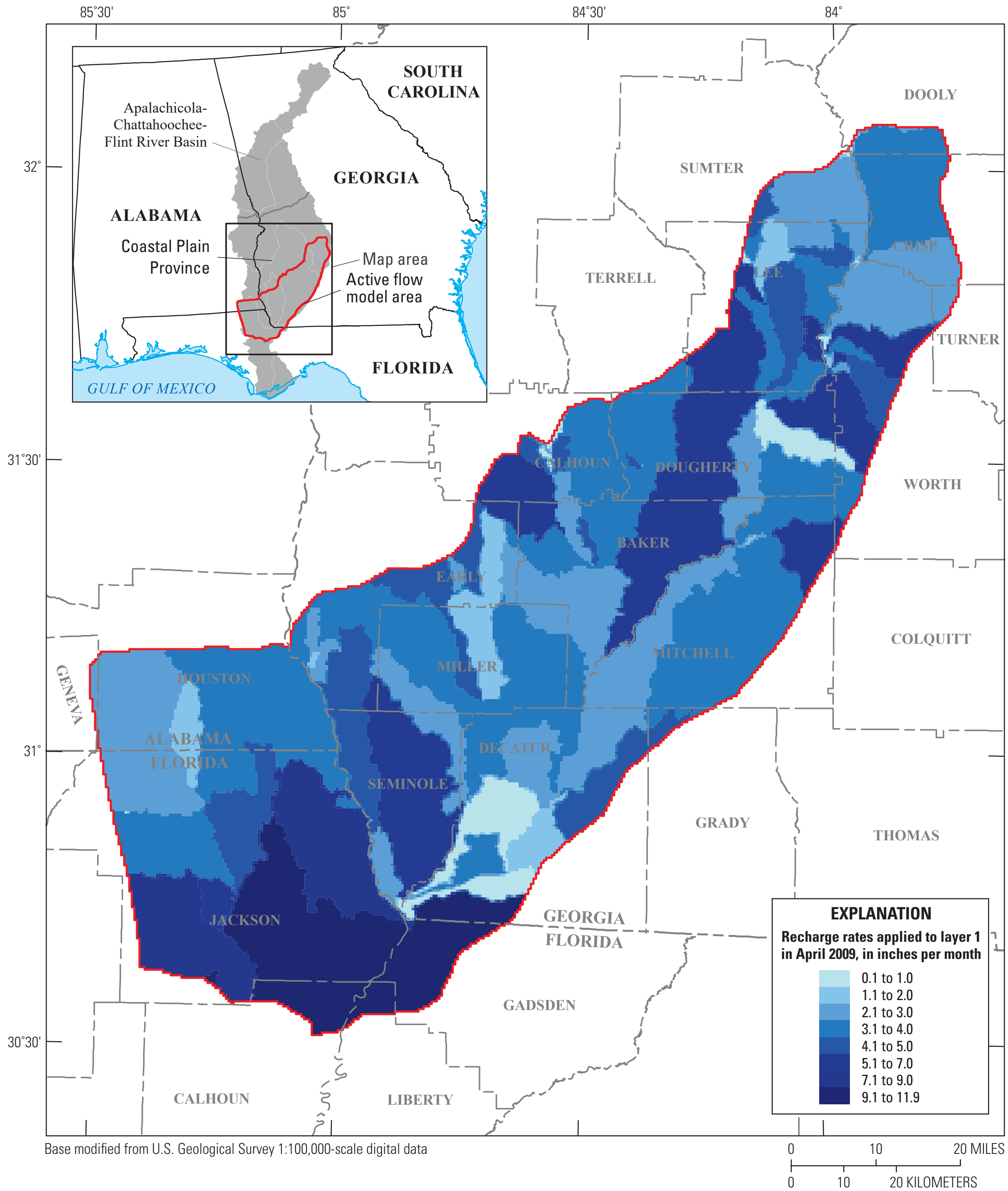


Figure 1–7. The distribution of recharge rates, in inches per month, applied to layer 1 in April 2009 to the active flow model area.

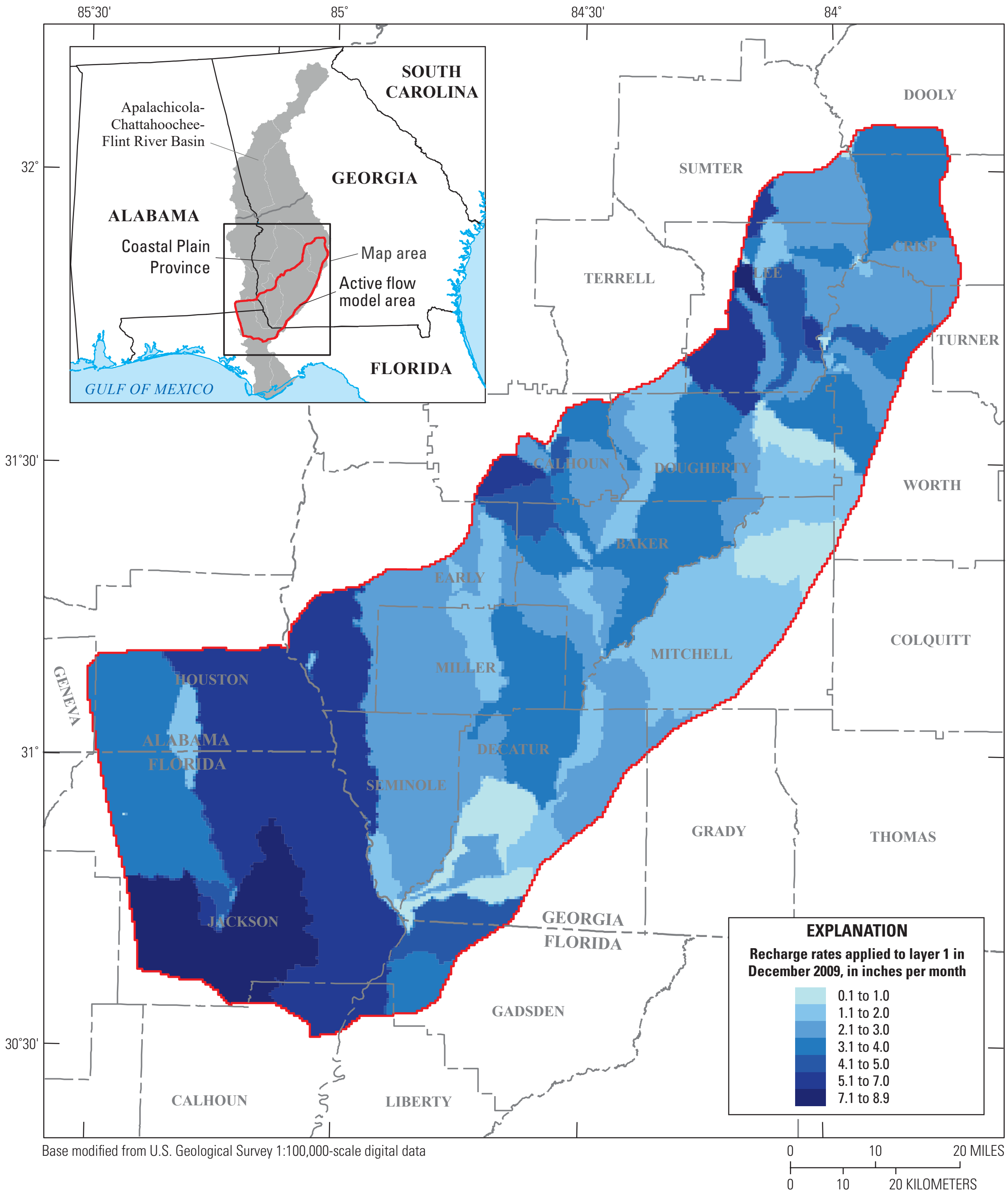


Figure 1–8. The distribution of recharge rates, in inches per month, applied to layer 1 in December 2009 to the active flow model area.

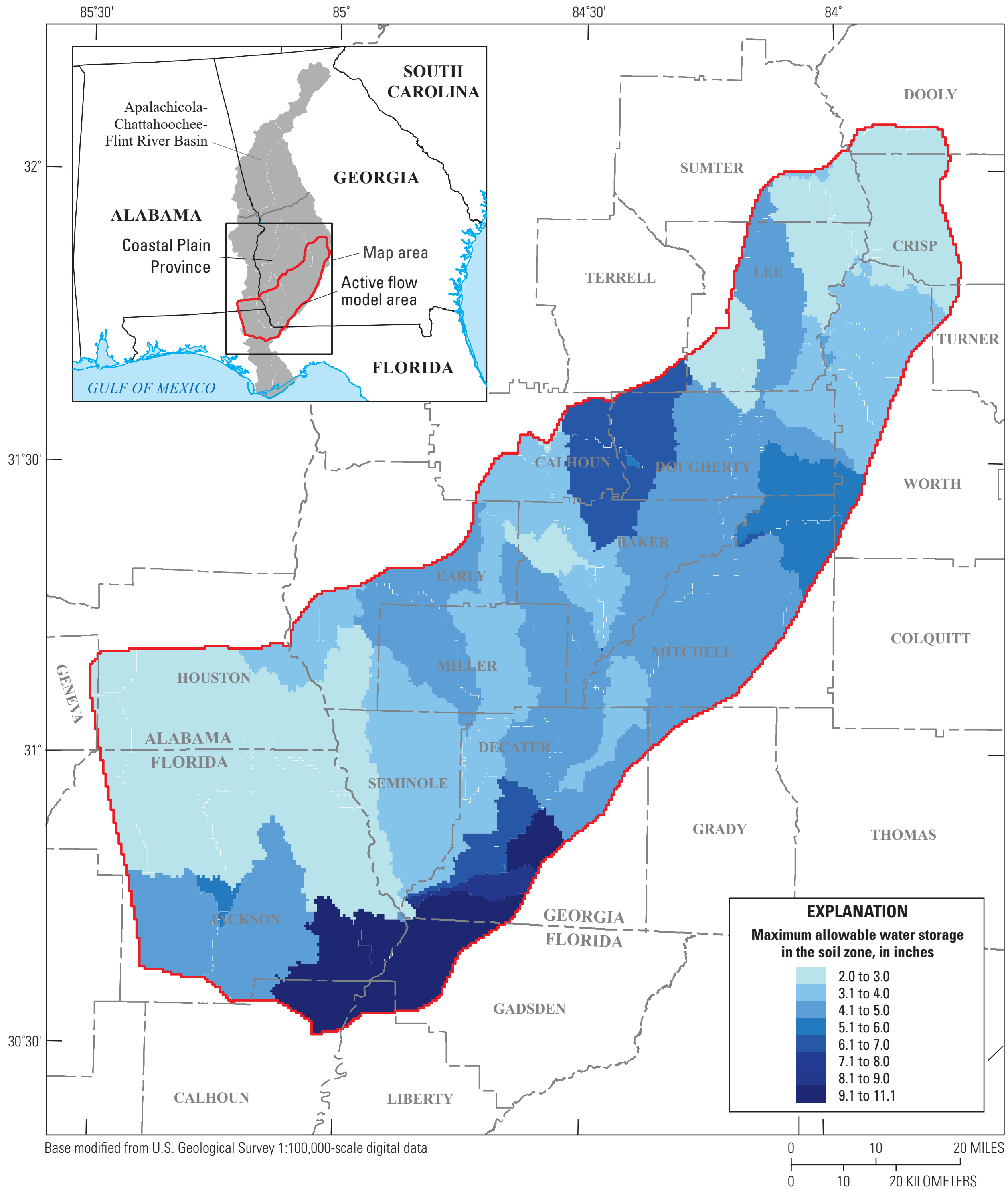


Figure 1–9. The distribution of maximum allowable water storage used in the Precipitation-Runoff Modeling System soil zone in the active flow model area.

Head-Dependent Flux

Water exchanges between surface waters of the lower ACF River Basin and the Upper Floridan aquifer were simulated using head-dependent boundaries for major streams, minor streams, three reservoirs, and wetlands, using the GHB, RIV, and DRN Packages (Harbaugh, 2005; fig. 1–10). Regional groundwater flow in the Upper Floridan aquifer exchanged across the lateral model boundaries was also simulated as a head-dependent flux boundary condition, using the GHB package. Stream stages and groundwater levels used in model boundary conditions were obtained from the U.S. Geological Survey National Water Information System (U.S. Geological Survey, 2015).

Stream-Aquifer Flow

Evaluation of stream-aquifer flow was one of the two primary purposes of constructing the groundwater model of the Upper Floridan aquifer in the lower ACF River Basin for the focus area study. Exchanges between groundwater and tributaries to the Chattahoochee, Flint, and Apalachicola Rivers were simulated for this report. Simulated streams (figs. 1–10 and 1–11) are located in one of eight Watershed Boundary Dataset (WBD) subbasins (fig. 1–12). The stream reaches representing major streams in the model area (fig. 1–10) were simulated by specifying river conductance and riverbed bottom and monthly varying stage using the RIV Package (Harbaugh, 2005) in layer 1, totaling 796 cells. Stream reaches representing minor, or ephemeral, streams (fig. 1–10) were simulated using the DRN Package (Harbaugh, 2005), totaling 3,237 cells. Minor or ephemeral streams generally have substantial fluctuations from dry to wet periods and were simulated assuming that minor or ephemeral streams are considered gaining and not losing reaches. Model cells representing reaches of the major and minor streams were selected by intersecting the numerical groundwater-flow model grid with the locations of streams obtained from the USGS National Hydrography Dataset (NHD).

For major streams, the altitude of the bottom of the riverbed (Rbot) along the trace of each major stream was estimated using measured stream depths when regular transect streamflow measurements were made at the USGS streamflow-gaging stations (fig. 1–12; table 1–2). For minor streams, the drain altitudes were assigned by averaging the minimum measured monthly stage at all streamflow-gaging stations and making adjustments based on altitudes along stream reaches, which were sampled from and interpolated between altitude contours of topographic maps along stream traces.

For major streams, monthly average stream stages were calculated at streamflow-gaging station locations (fig. 1–12), from measured daily stream stage at 27 stations (table 1–2). Along each stream trace, monthly average stream stages were linearly interpolated between stations to calculate the monthly average stream stage along each stream. Monthly average stream stage at each point along a stream trace was averaged within and assigned to the stage for each simulated stream reach.

If the stream length in the grid cell was longer than 820 ft (250 meters), which is half of the cell dimension, the cell was simulated as a river or drain cell. To account for the stream length that was not simulated, the ratio of such stream length divided by the total stream length was determined, and all streambed conductance terms were increased by that factor.

Lake-Aquifer Flow

Exchanges between groundwater and Lake Seminole, Lake Worth, and Lake Blackshear (fig. 1 in main body of report) are simulated as head-dependent flux boundaries using the GHB Package (Harbaugh, 2005) by specifying lakebed conductance and monthly varying stage in layer 1 (fig. 1–10). These lakes represent 2.25 percent of the active flow model area and are represented by 806, 58, and 201 model cells, respectively. Monthly stage data for Lake Blackshear and Lake Worth were not available, and an average constant stage was calculated from sparse available data. Monthly stage data were available for Lake Seminole, and a time-varying stage was assigned to the general-head boundary representing Lake Seminole for each monthly stress period. The maximum lakebed conductance was assigned to cells where the lake extends over the entire grid cell and was calculated as the square area of a grid cell times a calibrated hydraulic conductivity of the lakebed divided by the estimated lakebed thickness. The hydraulic conductivity value of the lakebed resulted in lakebed conductance values that ranged from 1,080 to 21,528 feet squared per day (ft^2/d) after multiplying each maximum conductance by the fraction of the grid cell area covered by the lake's water-surface area. The average stages at Lake Blackshear and Lake Worth were 236.8 and 182.2 ft North American Vertical Datum of 1988 (NAVD 88), respectively, constant stages for the 5-year 2008–12 simulation period. The stage at Lake Seminole ranged from 75.8 to 76.8 ft NAVD 88 over the simulation period.

Wetlands

Locations of wetlands were assigned based on the distribution of Woody Wetlands and Emergent Herbaceous Wetlands categories in the National Land Cover Database (Homer and others, 2015). Exchanges between groundwater and wetlands were simulated using the DRN Package (Harbaugh, 2005) assigned to 14,810 grid cells in layer 1 (figs. 1–1 and 1–10). Like minor streams, the wetlands were assumed to drain the aquifer and not to provide recharge beyond what is provided using the RCH Package. The drain process does not distinguish between physical processes that remove water from the system, for example overland flow, evapotranspiration, or streamflow. For each wetland cell, the drain altitude value assigned in the DRN Package was its altitude from a digital elevation model.

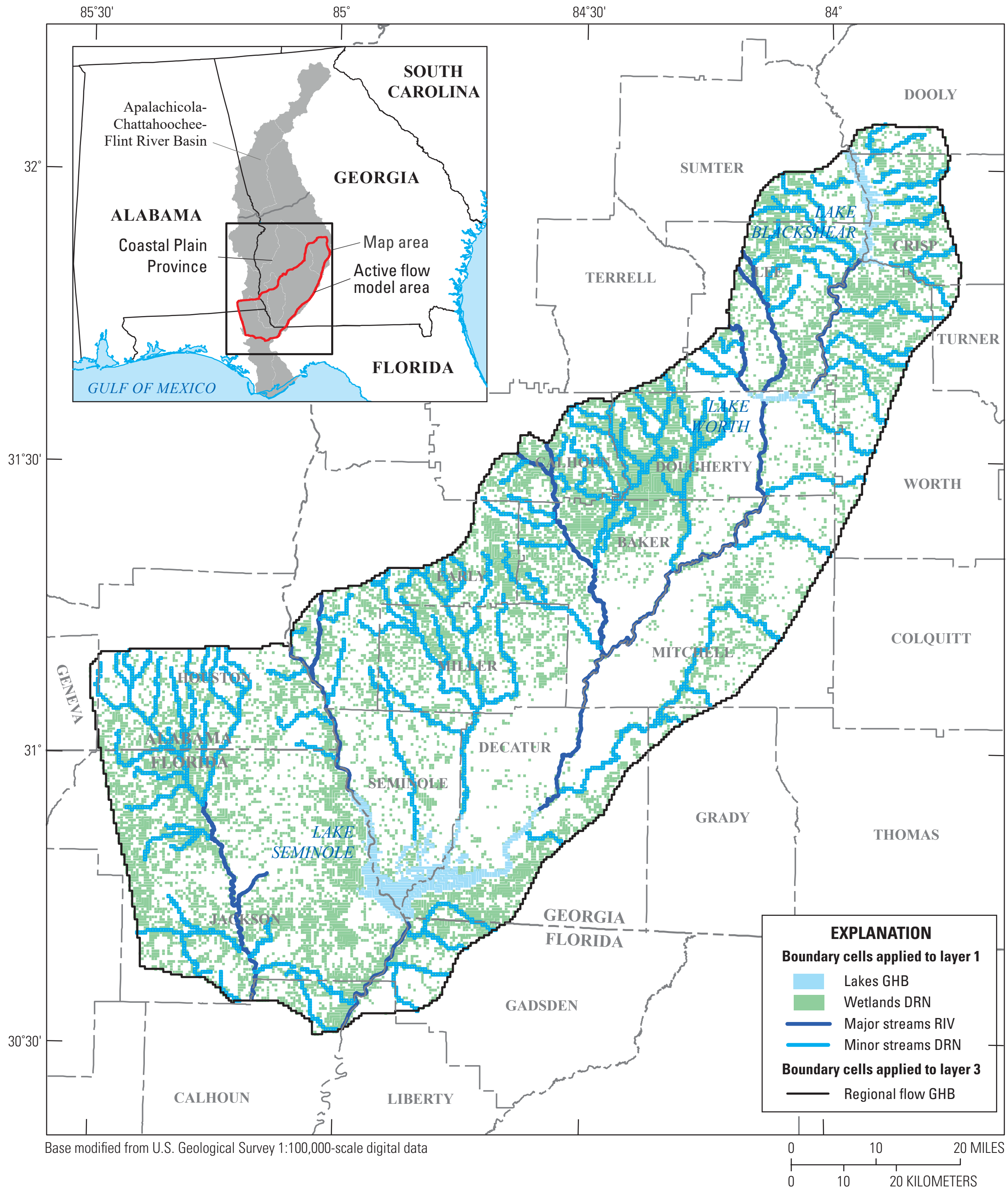


Figure 1–10. Head-dependent flux boundary conditions applied to the model: lateral model boundaries and lakes simulated as general-head boundaries (GHB), major streams simulated as river cells (RIV), and minor streams and wetlands simulated as drain cells (DRN).

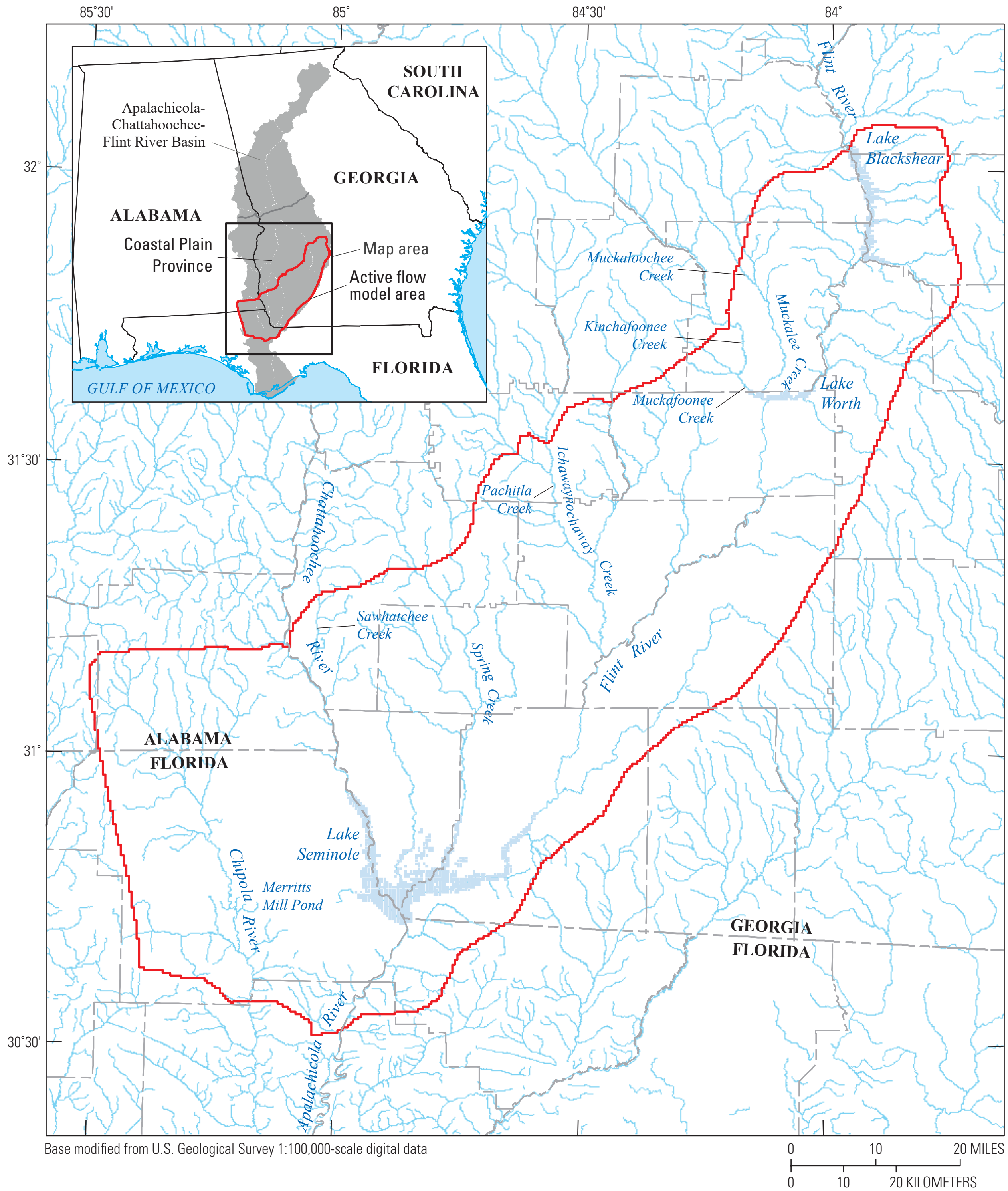


Figure 1–11. Streams and creeks simulated with the River or Drain Packages in the lower Apalachicola-Chattahoochee-Flint River Basin.

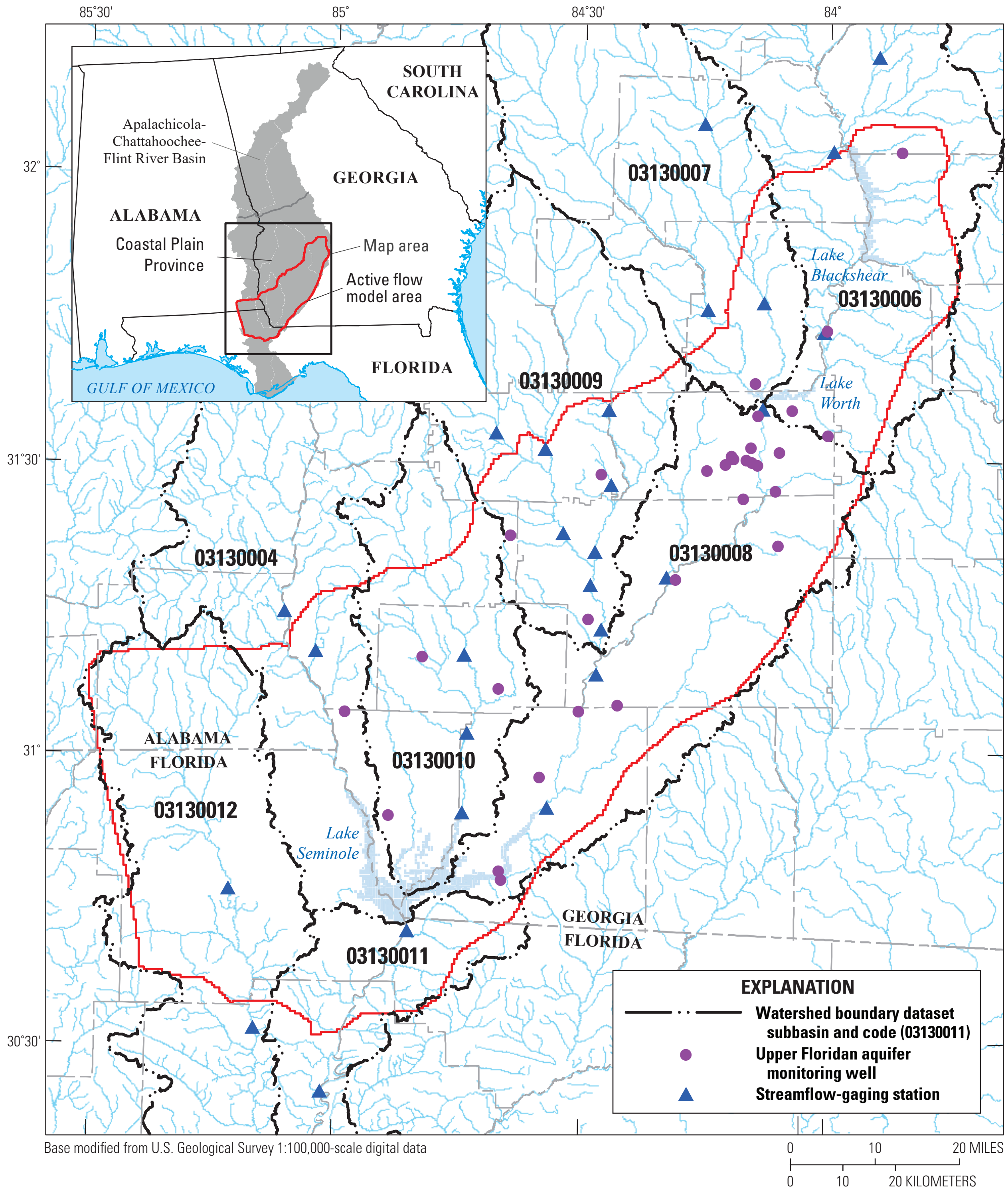


Figure 1–12. Location of Upper Floridan aquifer continuous groundwater monitoring wells, streamflow-gaging stations (table 1–2), and watershed boundary dataset (WBD) subbasins in the active flow model area.

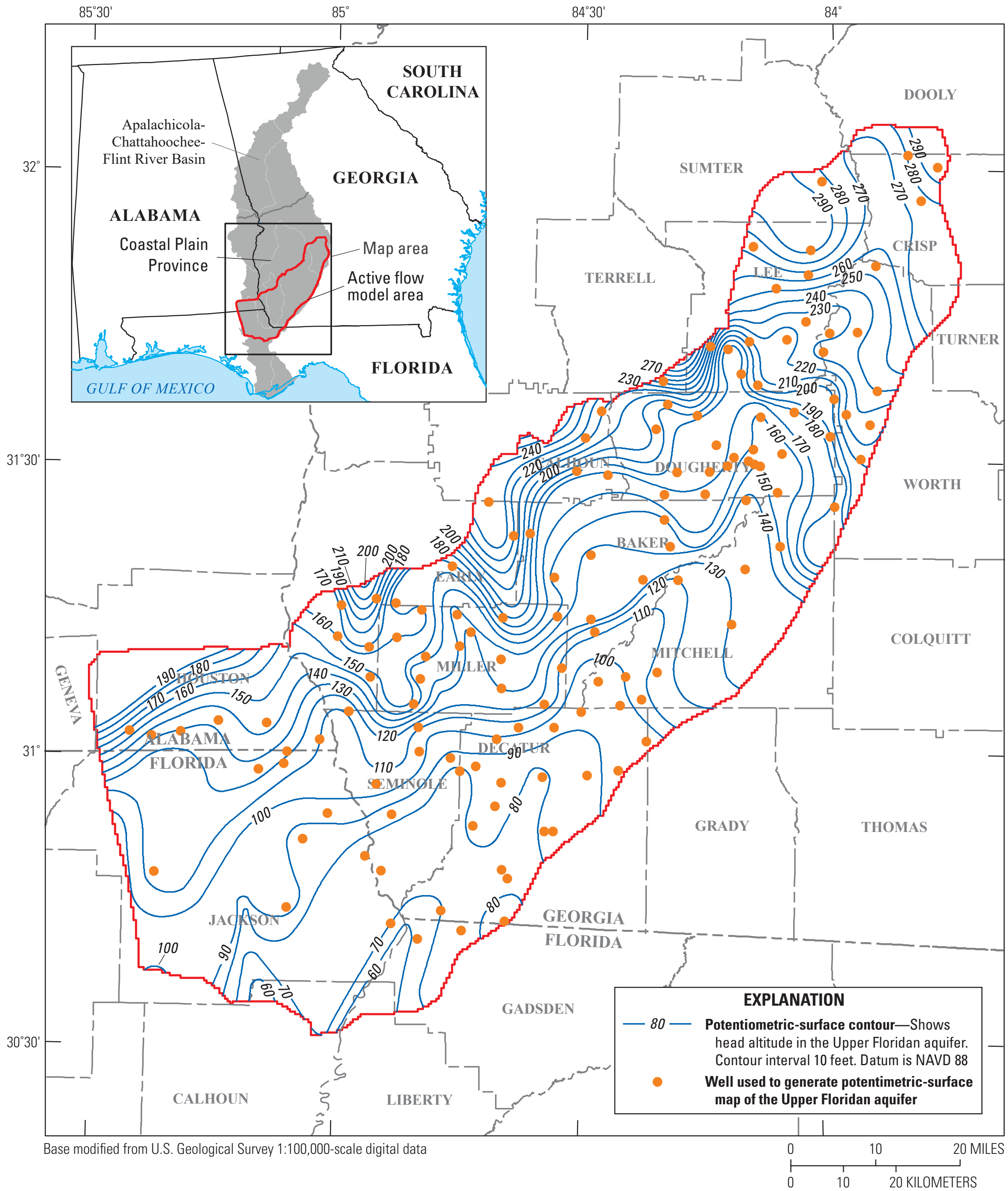
Table 1–2. Streamgaging stations used to assign boundary conditions for the groundwater-flow model for the lower Apalachicola-Chattahoochee-Flint River Basin.

[USGSNum, U.S. Geological Survey (USGS) site number of streamflow-gaging station; USGSNam, USGS site name of streamflow-gaging station; LAT and LON, latitude and longitude of station in decimal degrees referenced to the North American Datum of 1983]

USGSNum	USGSNam	LAT	LON
02343801	CHATTAHOOCHEE RIVER NEAR COLUMBIA, AL	31.259	–85.110
02343940	SAWHATCHEE CREEK AT CEDAR SPRINGS, GA	31.181	–85.044
02349900	TURKEY CREEK AT BYROMVILLE, GA	32.196	–83.902
02350080	LIME CREEK NEAR COBB, GA	32.034	–83.996
02350512	FLINT RIVER AT GA 32, NEAR OAKFIELD, GA	31.725	–84.019
02350900	KINCHAFOONEE CREEK AT PINEWOOD ROAD, NEAR DAWSON, GA	31.764	–84.253
02351500	MUCKALEE CREEK NEAR AMERICUS, GA	32.083	–84.258
02351890	MUCKALEE CREEK AT GA 195, NEAR LEESBURG, GA	31.776	–84.139
02352500	FLINT RIVER AT ALBANY, GA	31.594	–84.144
02353000	FLINT RIVER AT NEWTON, GA	31.307	–84.339
02353265	ICHAWAYNOCHAWAY CREEK AT GA 37, NEAR MORGAN, GA	31.527	–84.583
02353400	PACHITLA CREEK NEAR EDISON, GA	31.555	–84.681
02353500	ICHAWAYNOCHAWAY CREEK AT MILFORD, GA	31.383	–84.546
02354350	CHICKASAWHATCHEE CREEK NEAR ALBANY, GA	31.594	–84.453
02354475	SPRING CREEK NEAR LEARY, GA	31.466	–84.449
02354500	CHICKASAWHATCHEE CREEK AT ELMODEL, GA	31.351	–84.483
02354800	ICHAWAYNOCHAWAY CREEK NEAR ELMODEL, GA	31.294	–84.492
02355350	ICHAWAYNOCHAWAY CREEK BELOW NEWTON, GA	31.218	–84.471
02355662	FLINT RIVER AT RIVERVIEW PLANTATION, NEAR HOPEFUL,GA	31.141	–84.480
02356000	FLINT RIVER AT BAINBRIDGE, GA	30.912	–84.580
02356638	SPRING CREEK APPROX .25 MI US US27 NEAR COLQUITT, GA	31.174	–84.745
02357000	SPRING CREEK NEAR IRON CITY, GA	31.040	–84.740
02357150	SPRING CREEK NEAR REYNOLDSVILLE, GA	30.904	–84.749
02358000	APALACHICOLA RIVER AT CHATTAHOOCHEE, FL	30.701	–84.859
02358700	APALACHICOLA RIVER NEAR BLOUNTSTOWN, FL	30.425	–85.031
02358789	CHIPOLA RIVER AT MARIANNA, FL	30.773	–85.216
02359000	CHIPOLA RIVER NEAR ALTHA, FL	30.534	–85.165

Lateral Groundwater Flow

Groundwater flow entering and leaving the active flow model area in the Upper Floridan aquifer was simulated using the GHB Package (Harbaugh, 2005) and was specified at 968 of the 1,003 lateral boundary cells in layer 3 (fig. 1–10). The heads used in the GHB cells were the average heads from May 2010 and July 2011 potentiometric-surface maps (fig. 1–13; Kinnaman and Dixon, 2011; Gordon and others, 2012). The GHB heads were maintained constant for the January 2008 to December 2012 simulation period as a model simplification. It was assumed that the groundwater levels at model boundaries did not vary during the simulation period, and the values were assigned on the basis of sampling the interpolated potentiometric surface in Gordon and others (2012). Along the northwestern lateral boundary, from Houston County, Alabama, to Calhoun County, Georgia, the published potentiometric contours of Gordon and others (2012) were used to interpolate water levels at the lateral model boundary. GHB cells near valleys of major streams were removed at 35 grid cells to allow the stream stage to determine the water exchanges between these 35 lateral model boundary cells and the stream.



Base modified from U.S. Geological Survey 1:100,000-scale digital data

Figure 1–13. Potentiometric-surface map of the Upper Floridan aquifer for the model area, May 2010 hydrologic conditions (modified from Kinnaman and Dixon, 2011).

Hydraulic Properties

Conductance values for boundary conditions using the GHB, RIV, and DRN Packages (Harbaugh, 2005) were assigned from Jones and Torak (2006) and Torak and others (1996). Conductance values were assigned to lateral boundary cells, 12 major streams and creeks, minor streams, and wetland cells. The assigned conductance specified at the GHB cells ranged from 0 (at 17 of the 968 cells) to 463,992 ft^2/d.

The streambed conductance for each cell was calculated from the product of the hydraulic conductivity of the riverbed material, the length of the stream in the cell, the width of the stream, and the reciprocal of the thickness of the riverbed. Assigned streambed conductance values over all major stream and creek cells ranged from 4.9×10^3 to 3.9×10^6 ft^2/d. The hydraulic conductivity of the streambed material was assigned for each stream section between stations for each of the 12 major streams and creeks from previously generated values by Jones and Torak (2006) and Torak and others (1996). Measured low-flow streamflow and simulated low-flow base flow were compared to adjust the hydraulic conductivity of the streambeds in the ACF River Basin during a previous study conducted by Torak and others (1996). For the model documented in this report, previously generated conductance values of drain cells were multiplied by the fraction of the grid cell occupied by the minor stream reach or the wetland. Assigned conductance values at minor stream cells ranged from 17,121 to 96,476 ft^2/d, and assigned conductance values at wetland cells ranged from 6,048 to 62,424 ft^2/d.

A trial-and-error method was used to calibrate the hydraulic conductivity of all three layers. The calibration of the horizontal hydraulic conductivity (K_h) of layer 1 was based on assigning discrete values of 5, 10, 15, 20, and 40 feet per day (ft/d; fig. 1–14) to active flow cells to minimize stream base-flow residuals and the effects these would have on head residuals in the Upper Floridan aquifer (layer 3). About 72 percent of layer 1 had a calibrated K_h value of 10 ft/d, and about 22 percent had a calibrated K_h value of 40 ft/d (fig. 1–14). The lowest calibrated hydraulic conductivity value in layer 2 was 0.001 ft/d for the upper semiconfining unit where it exists beneath the Pelham Escarpment (fig. 1 in main body of report; fig. 1–15), an area that represents about 24 percent of the active flow model area. The hydraulic conductivity values in layer 2 were calibrated with discrete values of 0.001, 5, 10, 15, 25, 50, and 75 ft/d (fig. 1–15). The largest calibrated hydraulic conductivity values in layer 2 (50 and 75 ft/d) were assigned to more than half of the active flow model area in layer 2 (fig. 1–15). The initial distribution of K_h for layer 3 was derived from estimates of the Upper Floridan aquifer obtained from Jones and Torak (2006), Torak and Painter (2006), and Kuniansky and Bellino (2012), which consist of aquifer-performance tests and specific-capacity tests. The K_h value of layer 3 was subsequently adjusted by a trial-and-error process until the head residuals in the Upper Floridan aquifer could not be further reduced. The resulting final distribution of K_h for layer 3 ranged from 5 to 3,500 ft/d (fig. 1–16). Vertical hydraulic conductivity values were assigned to be equal to one hundredth of the horizontal hydraulic conductivity in each cell of the model.

Layer 1 was treated as an unconfined unit, and layers 2 and 3 were treated as confined units. The calibrated specific yield for layer 1 was 0.018, reflecting the residuum and terrace deposits that compose layer 1. The calibrated specific storage values for layers 2 and 3 were 1.0×10^{-5} and 1.0×10^{-6} /ft, respectively.

Model Calibration

The transient groundwater-flow model for the lower ACF River Basin was calibrated for the January 2008 to December 2012 period by reducing (1) groundwater-level residuals (simulated minus measured groundwater levels) at continuous water-level recorders and monitoring wells (table 1–3 [p. 69]) and (2) base-flow residuals (estimated minus simulated streamflow during low-flow periods) at streamflow-gaging stations. Groundwater-level and stream-stage data used to calibrate the model were obtained from the U.S. Geological Survey National Water Information System (U.S. Geological Survey, 2015). Base flow, which is the flow contribution from the aquifer to the stream, was estimated for low-flow conditions when all streamflow was attributed to aquifer discharge. The goal of model calibration is to have the mean simulated groundwater-level residuals and the mean base-flow residuals as close to zero as possible for a low overall error and to have the standard deviations of each of these two sets of residuals to be normally distributed. Residuals were decreased by adjusting, through trial-and-error, primarily (1) hydraulic conductivity values in layer 3 from initial values from Jones and Torak (2006), and (2) until specific yield and specific storage calibration goals for the overall mean residual and the standard deviation were met.

Groundwater-level residuals were calculated at (1) locations where measurements were made in November 2008, May 2010, and July 2011 to generate estimated potentiometric-surface maps for the Upper Floridan aquifer and (2) locations of continuous water-level recorders in the model area. Groundwater-level measurements used to calibrate the model were monthly averages of measurements made at each continuous water-level recorder and the 1-day measurements made at the sampled wells in November 2008, May 2010, and July 2011. The number of measurements from which the monthly averages were calculated varied depending on the type of monitoring well. Groundwater levels at many wells varied 10 ft or more during a month, particularly during the growing season when pumping is highly variable. The statistical measure used to guide the model calibration of groundwater residuals was the standard deviation of the mean residuals for each distinct well. An additional and quicker verification criterion for the calibration of simulated heads was taken from Kuniansky and others (2004), namely the standard deviation of residuals was divided by the range of the

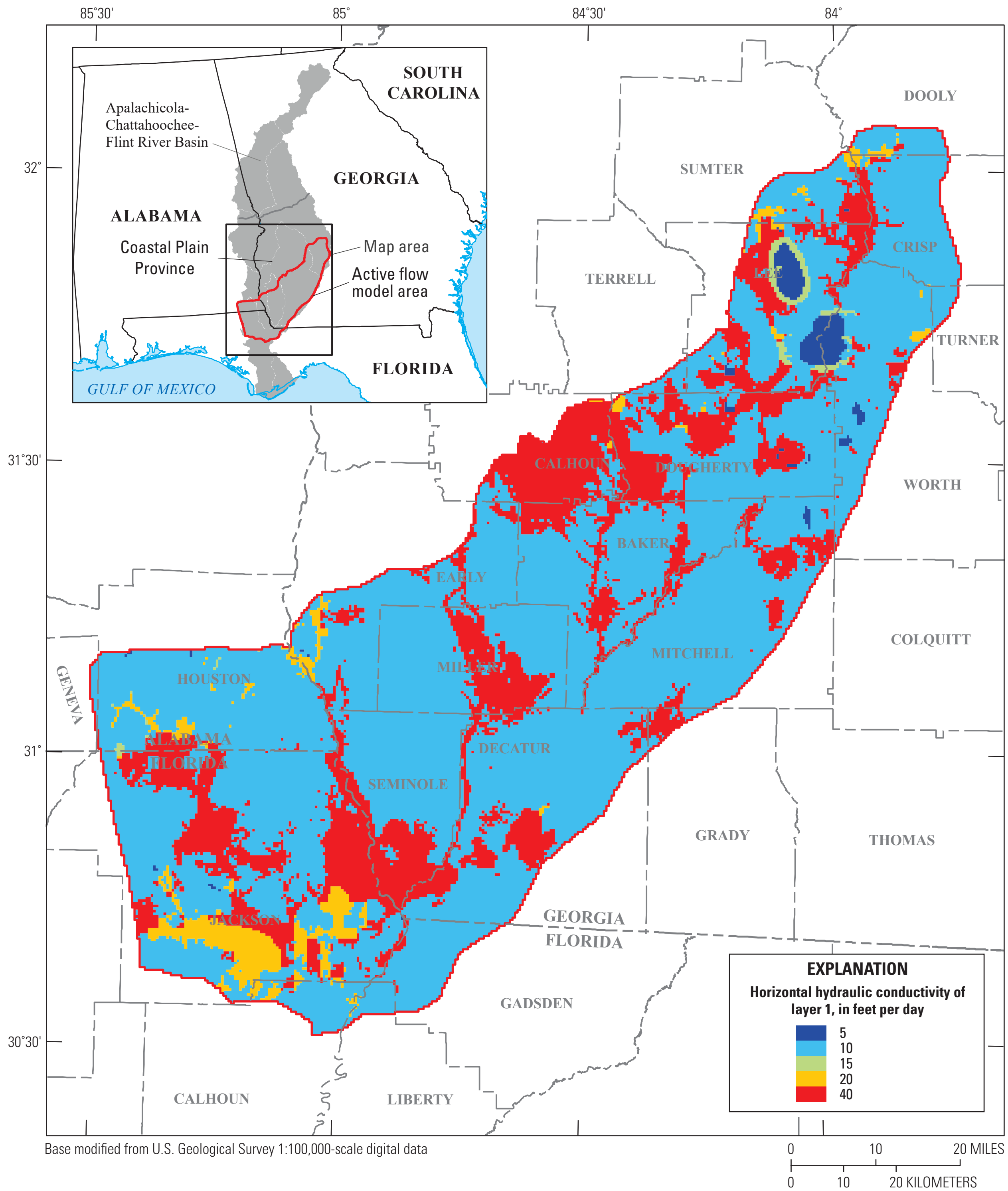


Figure 1–14. The distribution of calibrated horizontal hydraulic-conductivity values of layer 1 in the active flow model area.

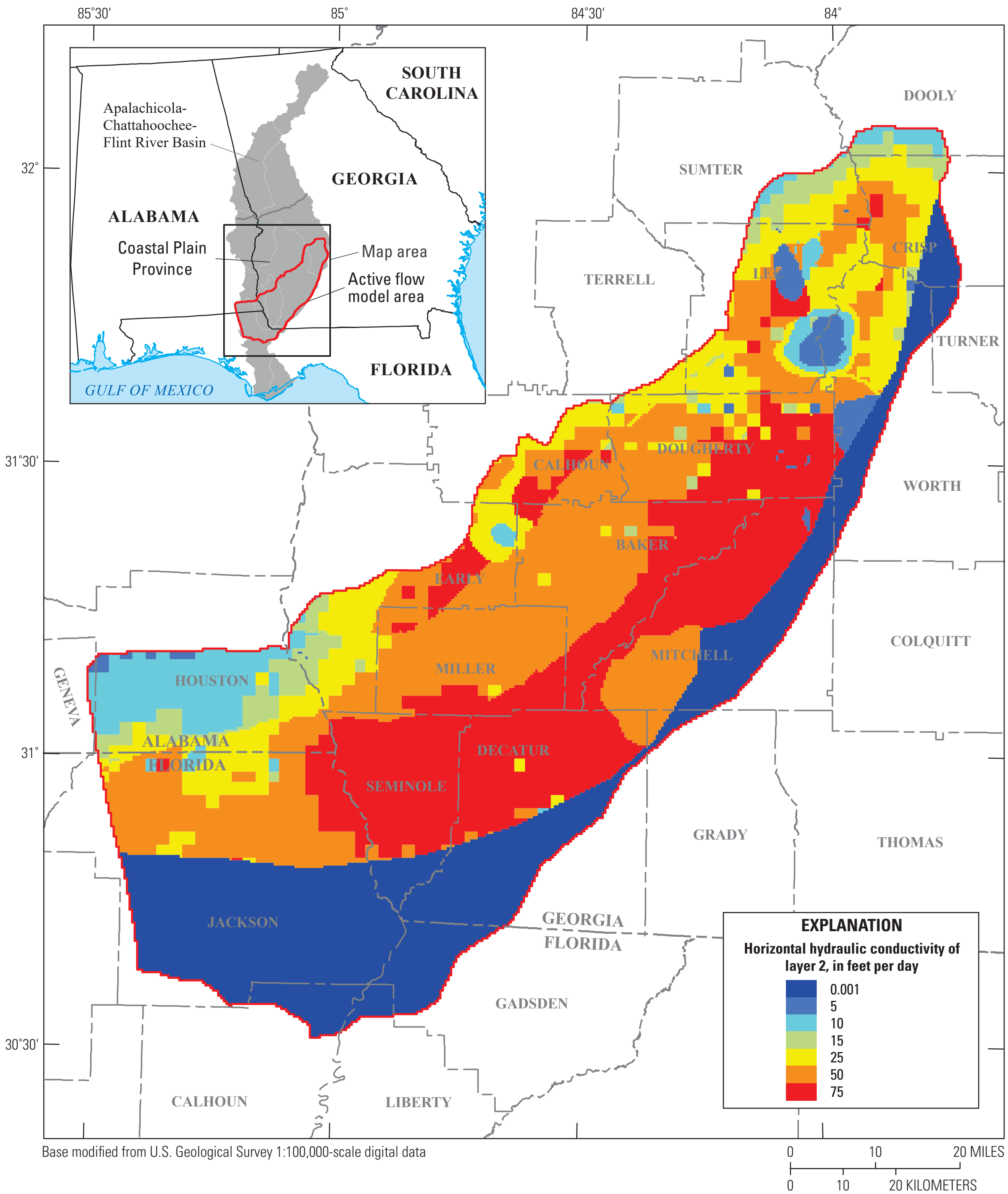


Figure 1–15. The distribution of calibrated horizontal hydraulic-conductivity values of layer 2 in the active flow model area.

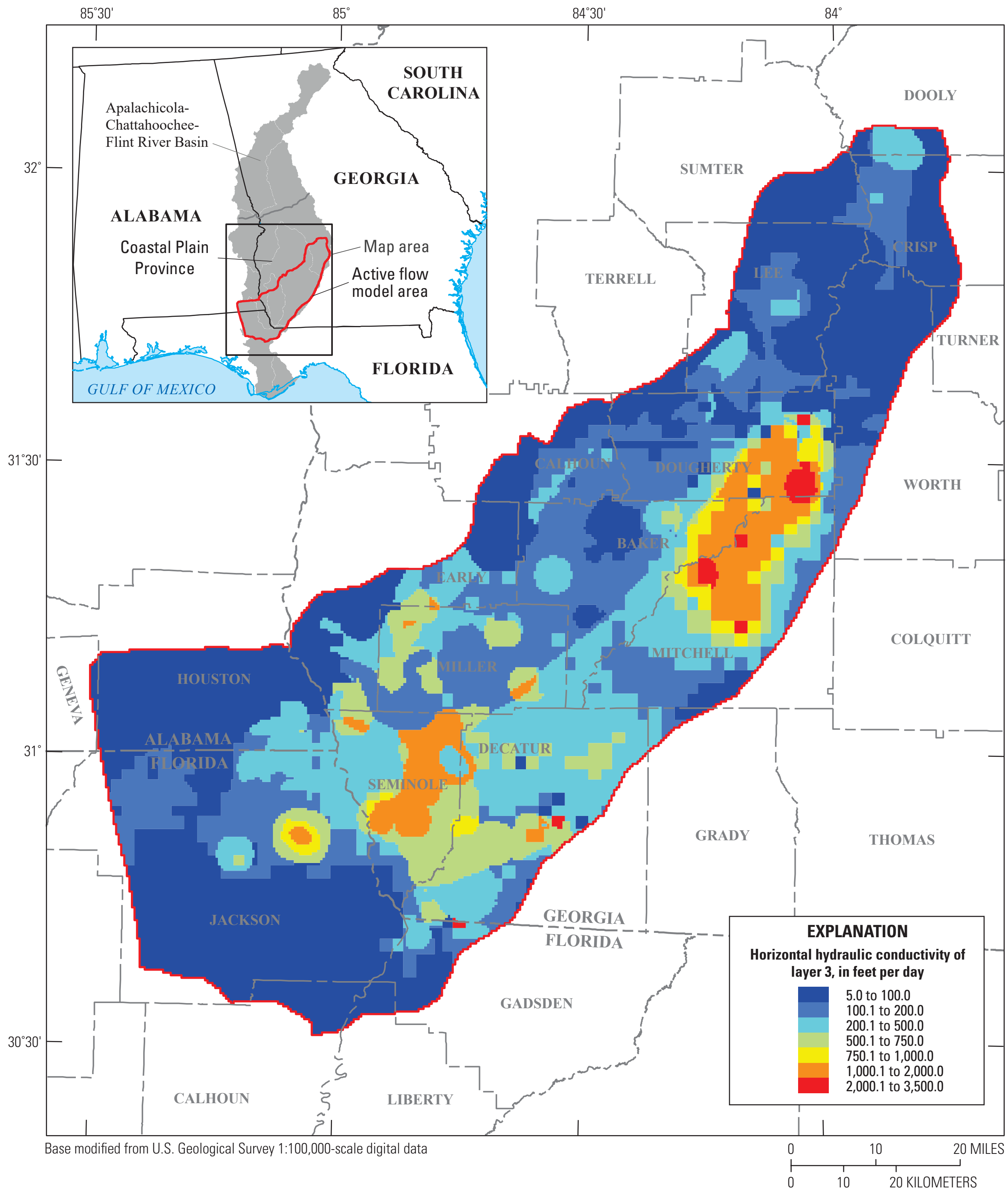


Figure 1–16. The distribution of calibrated horizontal hydraulic-conductivity values in layer 3 in the active flow model area.

water-level measurements, which is dimensionless and should be less than 0.1. This dimensionless statistic is a practical tool to guide model calibration because it considers the range of groundwater-level measurements used for calibration, indicating that the majority of the residuals are less than 10 percent of the range in observations. For the 60 sets of monthly groundwater-level measurements, the maximum range in measured heads was 240.09 ft (for May 2010), the minimum was 164.93 ft (for August 2012), and the overall average range was 190.23 ft. Thus, the standard deviation of the residuals divided by the average range in groundwater-level measurements was required to be less than 0.1, implying the standard deviation of groundwater-level residuals should be less than 19.02 ft.

The Base-Flow Index (BFI) method developed by Wahl and Wahl (1995), as implemented in the USGS Groundwater Toolbox (Barlow and others, 2015), was used to estimate base flow from daily streamflow data for each station. The estimated base flow was compared with simulated streamflow for dry periods and low-flow conditions. Continuous streamflow records were available at 27 streamflow-gaging stations for all or parts of the 60-month transient simulation (fig. 1–12). Twenty-five different drainage areas, partly or wholly within the model area, form a closed system having a downstream gaging station and one or more upstream gaging stations. Base flow at any given time is estimated by subtracting upstream inflow from downstream outflow to derive the base-flow contribution to streamflow occurring within the area. For example, subtracting stream inflow, as measured at one or more upstream streamflow-gaging stations where the stream enters the gaged subbasin, from stream outflow measured at the downstream station, the resulting net streamflow should represent all inflow to the stream originating within the gaged subbasin, whether from overland flow, flow of wholly contained tributaries, or base flow from the groundwater system. Similarly, subtracting estimates of base flow from the one or more upstream gaging stations from the base flow estimated at the downstream gaging station should result in the base flow that enters the contained stream or streams from the groundwater system within the gaged subbasin. Factors that limited the applicability of hydrograph separation to estimate base flow included drainage basin size (basins larger than about 500 mi^2 are typically too non-uniform), regulated streams (eliminating streamflow-gaging stations on the Chattahoochee, Flint, and Apalachicola Rivers), periods of missing record, and periods of zero streamflow. After records affected by these factors were eliminated and the corresponding subbasins were removed from consideration, four gaged subbasins remained in which the hydrograph separation was applied and in which simulated and estimated net base flows could be compared.

Available data from the selected streamflow-gaging stations within and immediately upstream and downstream from the model area during the transient simulation period of January 2008 to December 2012 were used for calibration. In particular, base flow estimated using streamflow data were from periods of low rainfall and low streamflow conditions, when all changes in streamflow from one gaging station to the next one downstream can be assumed to be attributed to the inflow or outflow of groundwater to the stream.

Model Fit

The model performance is evaluated in this section in terms of the mean residuals (MR) calculated for each distinct Upper Floridan aquifer well in the model area—a total of 305 wells. A total of 2,239 mean monthly measurements were calculated from these 305 sites from January 2008 to December 2012. The overall mean simulated groundwater level was calculated from monthly stress periods for which there were measured groundwater levels from January 2008 to December 2012. The overall mean simulated groundwater level was subtracted from the overall mean measured groundwater level for each of the 305 distinct sites. The standard deviation (s) calculated from the 305 groundwater-level residuals was 6.77 ft (table 1–4). Seven groundwater-level residual intervals were used to classify these residuals: less than –3s, [–3s, –2s), [–2s, –s), [–s, s], (s, 2s], (2s, 3s], and greater than 3s. The expected number of wells in each residual interval, assuming a normal distribution, was calculated by multiplying the area under the curve for each interval (http://onlinestatbook.com/2/calculators/normal_dist.html) by the total number of distinct wells (table 1–4). The calculated mean residuals from model calibration fit the expected values of a normal distribution

Table 1–4. Statistics of simulated overall mean head residuals for the calibrated groundwater-flow model for the lower Apalachicola-Chattahoochee-Flint River Basin.

[MR, mean head residual (simulated minus measured) over simulation period, from January 2008 to December 2012, in feet; RESI_INTER, range of values of MR; s, standard deviation calculated from the sample of 305 wells, in feet; NUFW, number of Upper Floridan aquifer wells with MR within given interval; EXP_AREA, normalized area under curve for MR within given interval of normal distribution; EXP_NDIST, expected number of wells with MR within given interval from normal distribution; TOTAL, total number of wells; OMR, overall mean residual, in feet]

RESI_INTER	NUFW	EXP_AREA	EXP_NDIST
MR < –3s	2	0.001	0
MR in [–3s, –2s)	8	0.021	7
MR in [–2s, –s)	28	0.136	41
MR in [–s, s]	225	0.684	208
MR in (s, 2s]	36	0.136	41
MR in (2s, 3s]	6	0.021	7
MR > 3s	0	0.001	0
TOTAL	305	1.000	305
OMR	0.01		
s	6.77		

except for two outliers with mean residuals that were less than three standard deviations (fig. 1–17). The ratio of the standard deviation of groundwater-level residuals from the sample of 305 wells (s=6.77 ft) and the average range in groundwater-level measurements (190.23 ft) is about 0.04, making the ratio less than 0.1 and validating the criterion used by Kuniansky and others (2004) to determine if the simulated groundwater levels are a good fit to the measured levels.

The two outliers with mean groundwater-level residuals less than three standard deviations from the overall mean residual are located in the northern section of the model, near the Lee and Worth County line and in southwest Decatur County in Georgia (fig. 1–17). The overall mean residual for the 2008–12 simulation period was 0.01 ft. A comparison of overall mean measured and simulated groundwater levels shows that most of the wells are aligned closely along the line representing measured and simulated groundwater levels being equal (fig. 1–18).

The statistics of groundwater-level residuals are more representative of the model fit when the wells from which residuals are calculated span most of the active flow model area. The analysis of groundwater-level residuals from a subset of wells that span only a fraction of the model area generally results in the underrepresentation of the model fit. Values of mean and standard deviation of residuals, calculated for each stress period using the monthly mean groundwater-level measurements made for each stress period, indicate temporal variations in the means and standard deviations with a trend of decreasing mean and increasing standard deviations as time increases (fig. 1–19). The means and standard deviations for November 2008, May 2010, and July 2011 together with the overall means and standard deviations of 0.01 and 6.77 ft, respectively, indicate that the overall mean groundwater-level residual generally decreases as more stress periods in the simulation period are considered in the calculation (table 1–4; fig. 1–19).

There is a reason why the overall mean head residual and the standard deviation for the mean residuals for the 2008–12 period, from all 305 wells, could be lower than the mean head residual and the standard deviation of many stress periods (table 1–4; fig. 1–19). The mean head residual and the standard deviation of the residuals, for any stress period, are calculated using a smaller sample than that of the entire period of simulation, which includes all 305 mean heads. The means and standard deviations calculated from larger samples generally result in lower values than those calculated from smaller samples if the square of the difference between the mean head residual and the overall mean head residual are of comparable values.

The development of potentiometric-surface maps for the Upper Floridan aquifer in the lower ACF River Basin for November 2008, May 2010, and July 2011, used 258, 135, and 174 monthly measurements, respectively. The spatial distribution of the simulated groundwater-level residuals for these three stress periods was similar in the residual intervals to those obtained for the mean residuals calculated for each distinct well (figs. 1–17, 1–20, 1–21, and 1–22). The 3 months of November 2008, May 2010, and July 2011 had model-average-applied recharge rates of 0.336, 0.773, and 0.166 inch per month, respectively. Only May 2010 had an above mean monthly model-average-applied recharge rate for the 60-month transient simulation (0.673 inch per month), explaining the higher mean standard deviation of residuals than that of November 2008 or July 2011. For most areas in the plots of the three measurement events, there is an adequate mix of positive and negative residuals, showing the absence of model bias. However, for the November 2008 measurement, an area in northwestern Worth and east-central Lee Counties had only negative residuals and few nearby positive or near-zero residuals (fig. 1–20). The same area also had predominately negative residuals for the May 2010 (fig. 1–21) and July 2011 (fig. 1–22) measurements, but in both cases near-zero residuals were nearby.

The drainage areas of four stations where estimated base flow was compared to simulated base flow were compared using the downstream gaging station number and name as an identifier (fig. 1–23; table 1–5). The net area of the gaged subbasins is also compared to the model area (table 1–5). For each of the four gaged subbasins, a comparison of monthly time series of net estimated base flow, model input recharge, and simulated base flow (fig. 1–24) shows the simulated base flow and the net estimated base flow from hydrograph separation are correlated, with hydrograph peaks coinciding with the timing when recharge input rates were assigned. The net estimated base flow from hydrograph separation may be within a factor of 2 of actual groundwater discharge to the stream (Kinzelbach and others, 2002; Stewart and others, 2007). Pearson's correlation coefficient was calculated for each set of time series (table 1–6) to quantify the correlation between the two base flows. In each of the four subbasins, (fig. 1–24), peaks in the net estimated base-flow graph correspond closely with peaks in the simulated base-flow graph.

The Pearson's correlation coefficients ranged from 0.837 for the drainage area of station 02358789 to 0.701 for the drainage area of station 02359000 (fig. 1–23; table 1–6). The drainage area of station 02359000 has unusual base flows indicated by a high estimated base-flow index (BFIest) of 0.898 (table 1–6). This BFIest implies that net streamflow in streamflow-gaging station 02359000 is almost entirely composed of base flow from groundwater and that the overland flow component occurs only in a few peaks of streamflow. The drainage area of station 02359000 is in the Marianna Lowlands (fig. 1 in main body of report), an area that exhibits common characteristics of a karst terrain, with many springs, sinkholes, and relatively few major linear surface-drainage streams. The absence of incorporation of conduits at reaches with known springs and the assumption of hydraulic conductivity values in the range of unconsolidated clastic sediment in layer 1 (5 to 40 ft/d) is a model simplification. However, it was beyond the scope of the project to attempt to map conduits from the aquifer to springs within the river reach and assign large hydraulic conductivity to cells with

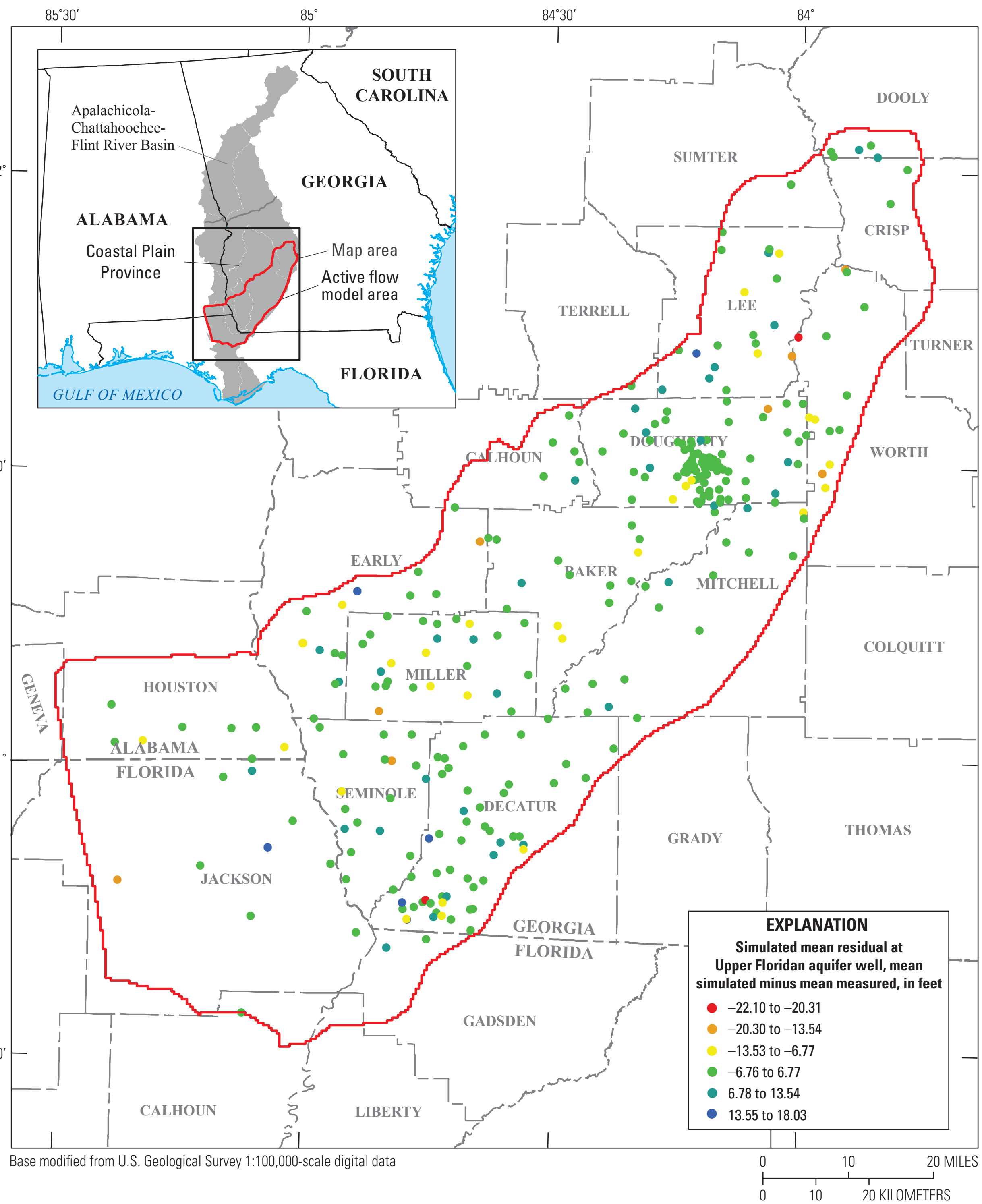


Figure 1–17. Simulated mean residuals at Upper Floridan aquifer wells in the active flow model area calculated for the January 2008 to December 2012 simulation period.

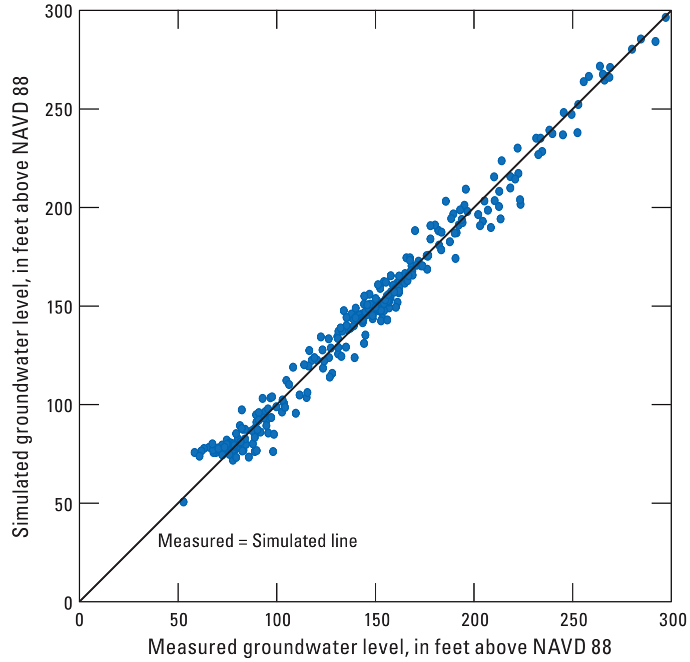


Figure 1–18. Overall mean measured and simulated groundwater levels at the 305 distinct Upper Floridan aquifer wells in the active flow model area from the January 2008 to December 2012 simulation. [NAVD 88, North American Vertical Datum of 1988]

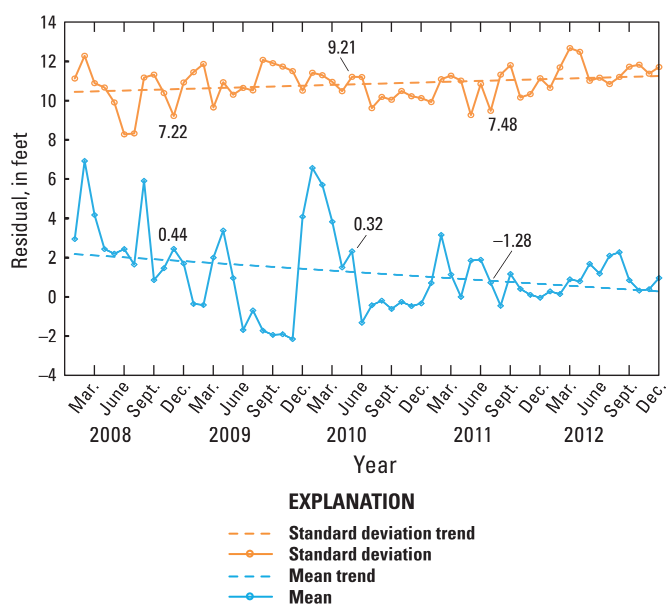


Figure 1–19. Monthly means and standard deviation of residuals (simulated minus measured groundwater level) for each monthly stress period from January 2008 to December 2012 with linear-regression trend lines.

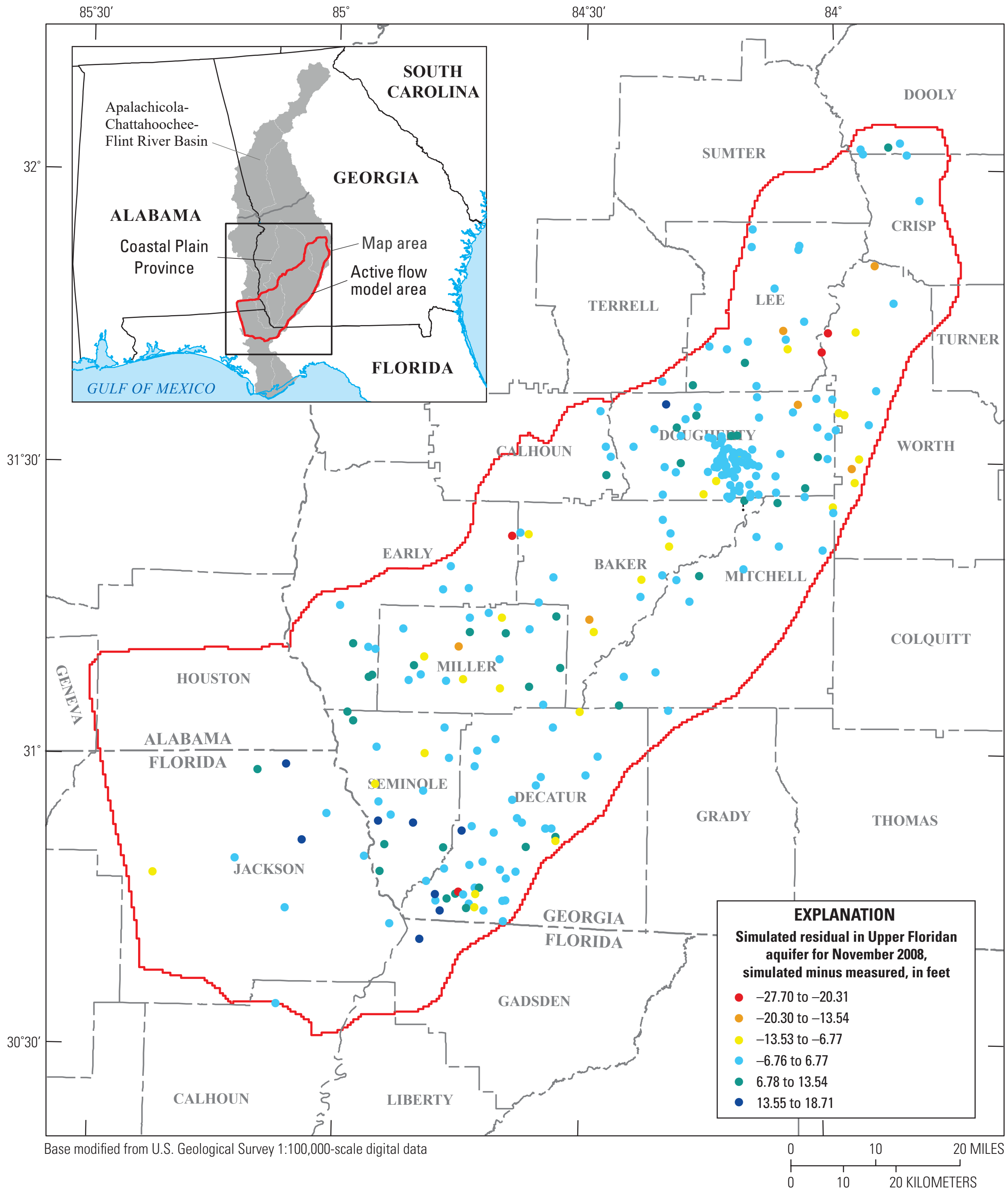


Figure 1–20. Groundwater-level residuals (simulated minus measured) at Upper Floridan aquifer wells for the stress period of November 2008 in the active flow model area.

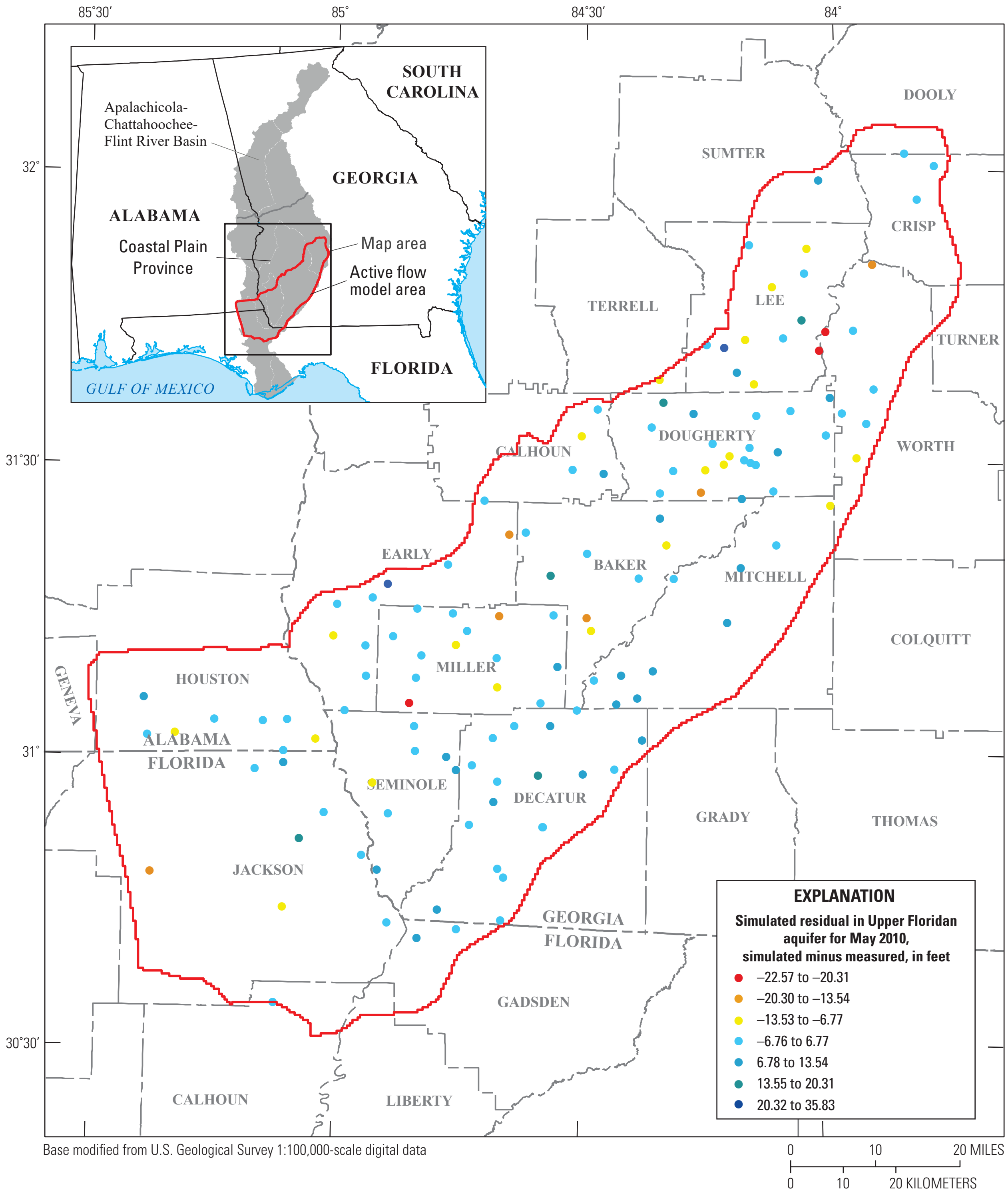


Figure 1–21. Groundwater-level residuals (simulated minus measured) at Upper Floridan aquifer wells for the stress period of May 2010 in the active flow model area.

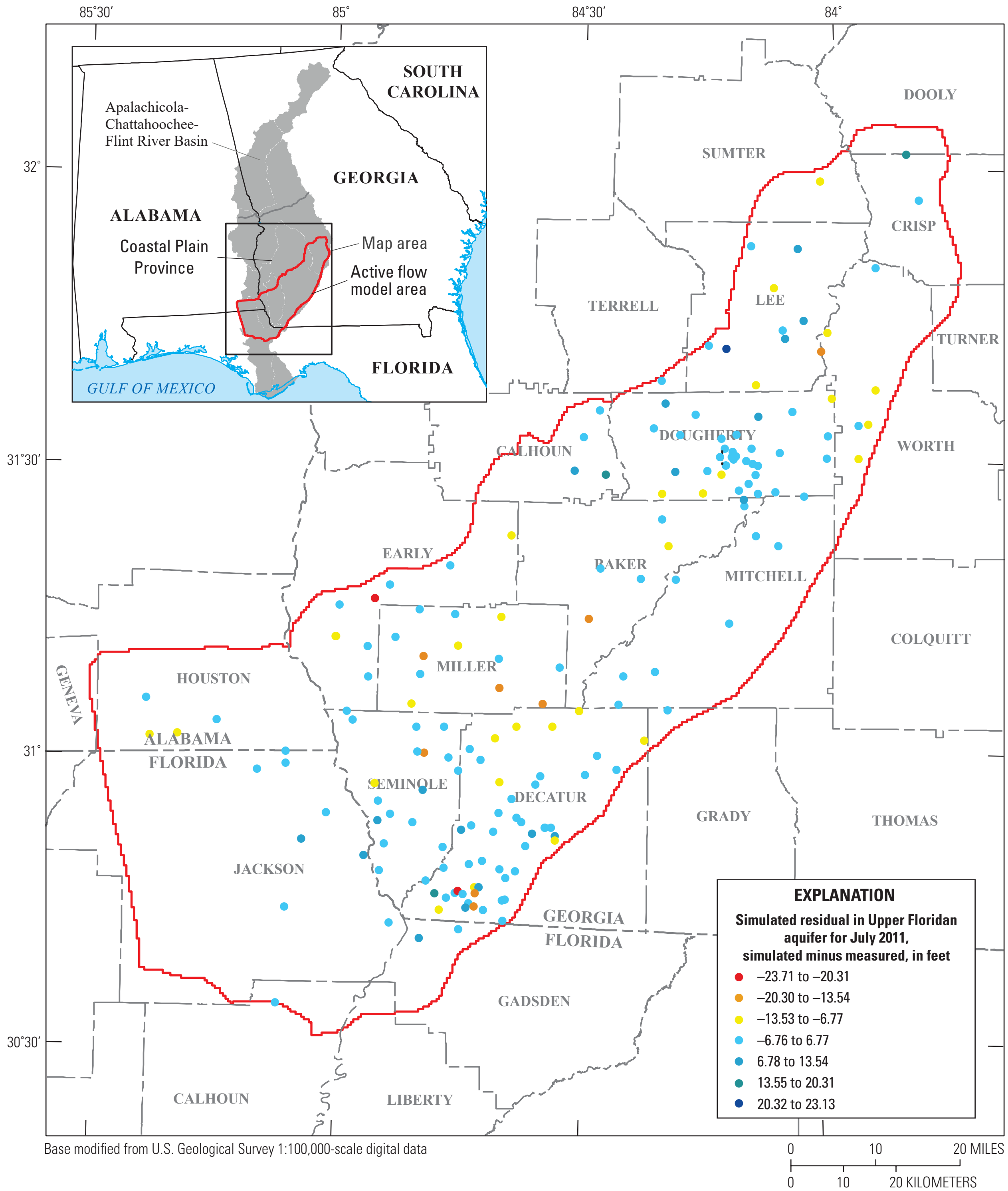


Figure 1–22. Groundwater-level residuals (simulated minus measured) at Upper Floridan aquifer wells for the stress period of July 2011 in the active flow model area.

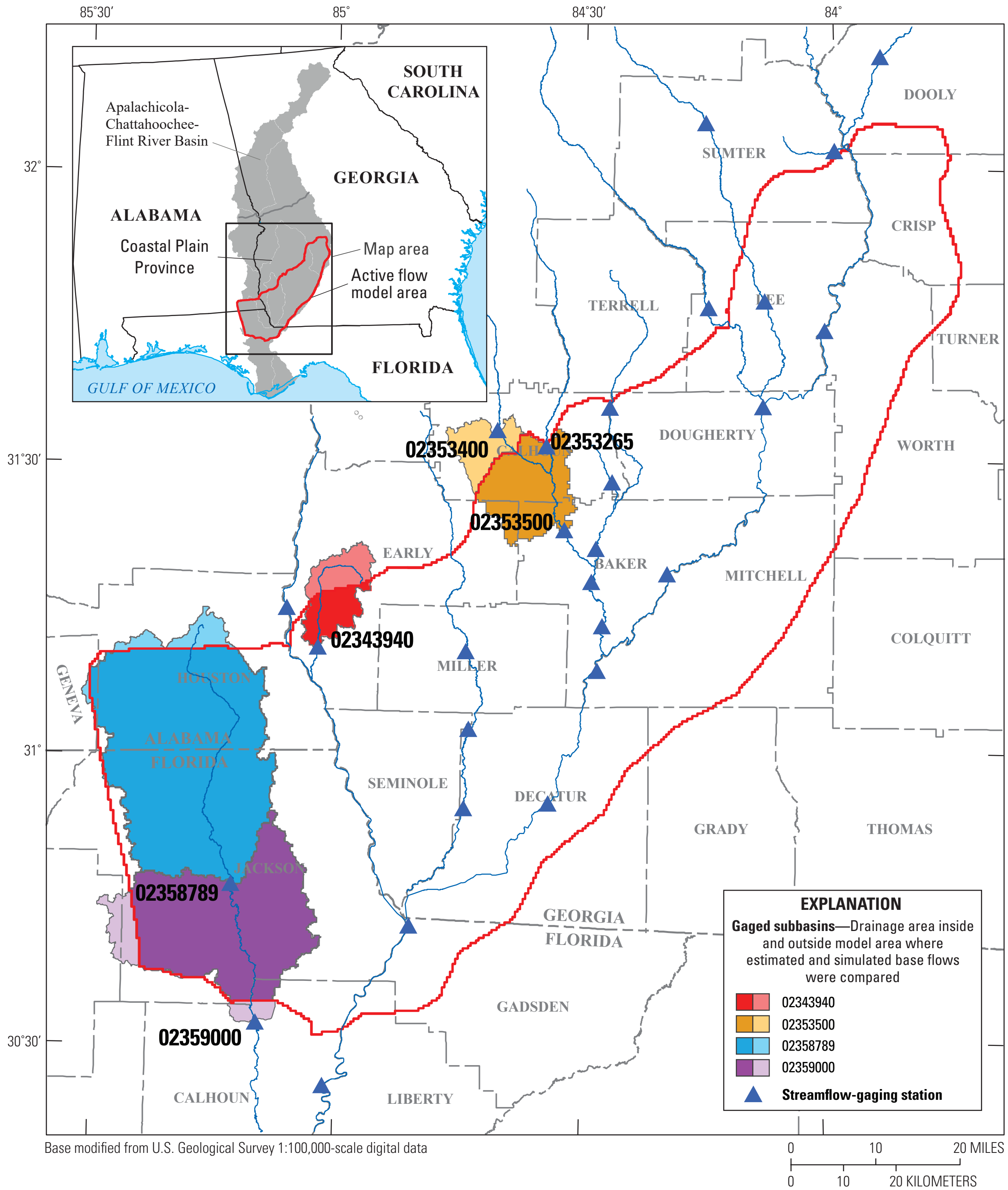


Figure 1–23. Streamflow-gaging stations within and adjacent to the active flow model area with streamflow data from January 2008 to December 2012 and selected drainage areas.

Table 1–5. Selected gaged subbasins, upstream and downstream streamflow-gaging stations, and basin-area statistics in and near the active flow model area.

[Ncells, number of numerical grid cells in the gaged subbasin; Marea, area in grid covered by basin. All areas are shown in square miles]

Downsteam streamflow-gaging station of gaged subbasin	Upstream streamflow-gaging station(s)	Net area	Ncells	Marea	Percentage of net area within model
02343940 Sawhatchee Creek at Cedar Springs, GA	none	65.3	352	34	52.1
02353500 Ichawaynochaway Creek at Milford, GA	02353265, 02353400	144.9	1,083	104.5	72.1
02358789 Chipola River at Marianna, FL	none	514.9	5,033	485.8	94.3
02359000 Chipola River near Altha, FL	02358789	324.5	2,966	286.3	88.2

conduits. This simplification may be partially responsible for under simulation of estimated base flow at station 02359000. The downstream streamflow-gaging station 02359000 has a drainage area of 839 mi^2, exceeding the recommended maximum of 500 mi^2 for the base-flow estimation, and thus may be another source of error in the base-flow estimation. The higher correlations between simulated base flow, Bsim, and estimated base flow, Best, occurred for the time series of the drainage areas of stations 02358789 and 02343940, with $r=0.837$ and $r=0.805$, respectively (table 1–6). These two stations have headwater streams with none of the complications of upstream streamflow-gaging stations and net-flow calculations.

The ratio of net estimated-to-simulated base flow ranged from 1.189 to 6.522 (table 1–6), making the estimated base flow consistently higher than the simulated base flow, but within the uncertainty of the estimate for all but station 02359000. Recharge, Rech (table 1–6), is the primary inflow to the groundwater system and similar in magnitude to the simulated base flow, Bsim, the primary outflow from the groundwater system, with the ratio Rech/Bsim ranging from 0.775 to 5.349 (table 1–6). At the lower end of this range is subbasin station 02343940 on the boundary of the model with a drainage basin that is bisected by a general-head boundary that provides a large part of the inflow to the groundwater system rather than from recharge. Thus, most of the base flow to Sawhatchee Creek (station 02343940) likely occurs in the downstream reaches within the model area. Considering the similarity of the model-input values of Rech and Bsim over the 60-month simulation, an increase in Bsim would require a similar increase in Rech, which was derived from the PRMS model.

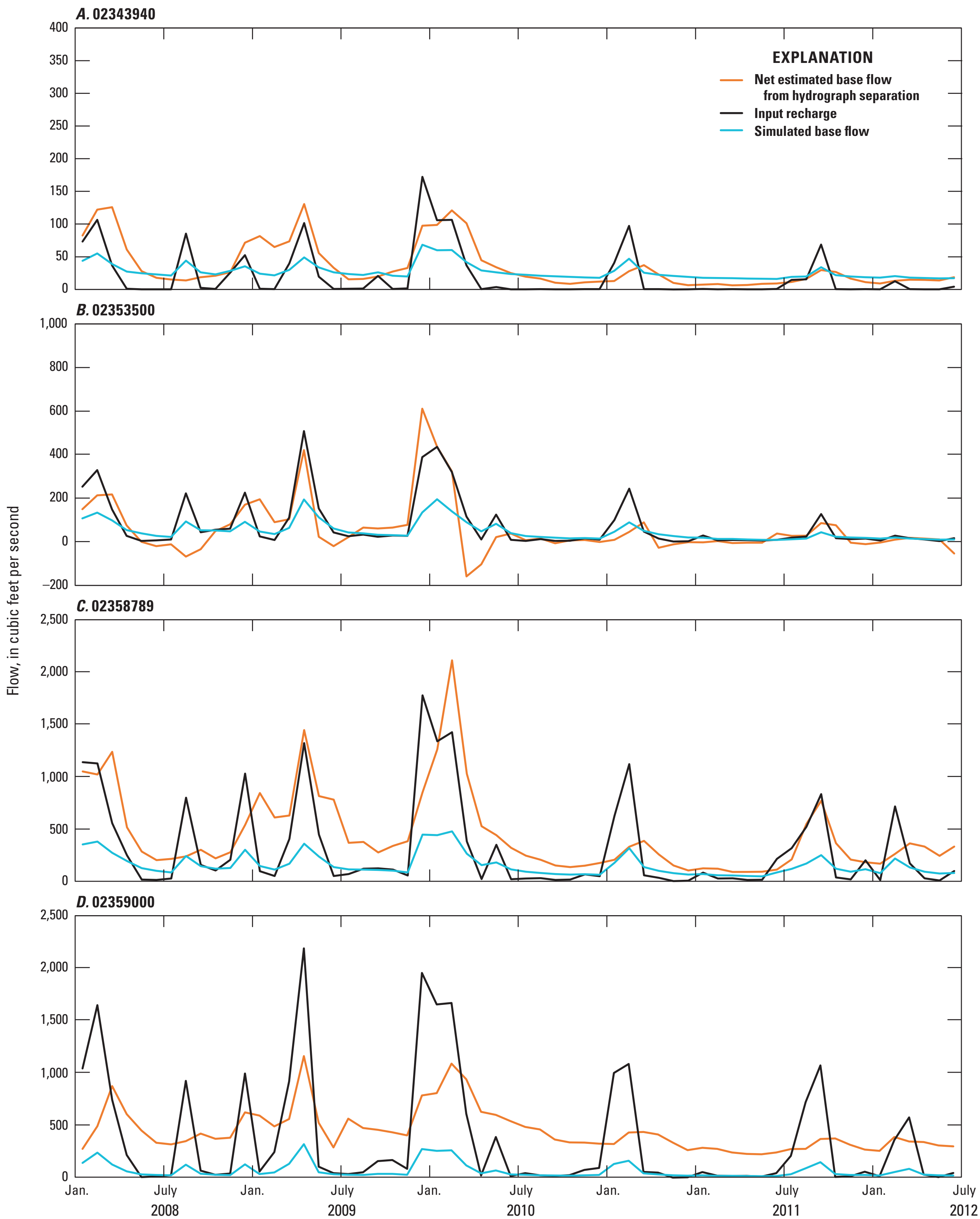


Figure 1–24. Monthly net estimated base flow from hydrograph separation, input recharge, and simulated base flow for the drainage areas of stations (*A*) 02343940, (*B*) 02353500, (*C*) 02358789, and (*D*) 02359000 in the active flow model area.

Table 1–6. Average net estimated and simulated base flow, recharge, and flow statistics for selected gaged subbasins in and near the active flow model area.

[Qs, net measured streamflow; Best, net estimated base flow calculated from measured streamflow data; Bsim, simulated base flow; Rech, model input recharge; BFIest, estimated base-flow index, calculated as the ratio of Best to Qs, dimensionless; BFIsim, simulated base-flow index, calculated as the ratio of Qs to Bsim, dimensionless; Best/Bsim, ratio of estimated to simulated base flow, dimensionless; Rech/Bsim, ratio of input recharge to simulated base flow, dimensionless; r(Bsim,Best), Pearson's correlation coefficient measuring the linear correlation between the simulated and estimated base flows]

Gaged subbasin number	Monthly average, in cubic feet per second				BFIest	BFIsim	Best/Bsim	Rech/Bsim	r(Bsim,Best)
	Qs	Best	Bsim	Rech					
02343940	69.1	35.2	27.1	21.0	0.510	2.550	1.299	0.775	0.805
02353500	91.8	56.5	47.5	75.7	0.615	1.933	1.189	1.594	0.723
02358789	690.5	444.5	157.9	317.1	0.644	4.373	2.815	2.008	0.837
02359000	495.2	444.8	68.2	364.8	0.898	7.261	6.522	5.349	0.701

Sensitivity Analyses

Sensitivity analyses for selected stresses and hydraulic properties were performed to identify how sensitive model fit was to perturbations in each of the stresses or properties. The model-sensitivity analysis was performed by multiplying the selected stress or hydraulic property by factors ranging from 0.1 to 10.0 and evaluating the resulting simulated groundwater levels and hydrologic budget components. Model sensitivity was evaluated by the mean and standard deviation of the simulated groundwater-level residuals and the simulated average monthly model inflow and outflow for each multiplier applied (figs. 1–25 through 1–38).

As recharge is the largest component of the hydrologic budget, groundwater levels and simulated budget components were most sensitive to perturbations in recharge (fig. 1–25). Recharge is a derived component, calculated as a function of precipitation, drainage potential of soil and superficial surfaces, and losses through evapotranspiration, and not directly measurable. Thus, there is a fair amount of uncertainty in the range and spatial distribution of recharge.

In contrast to recharge, pumping is one of the most well-constrained model inputs and can be directly measured, although most inputs are estimates based on measured pumping. Thus, the largest factor used in the sensitivity testing for pumping was 2.0 (fig. 1–26). In general, the simulated groundwater levels are moderately sensitive to perturbations in pumping, but other components of the budget are fairly insensitive.

Hydraulic conductivity values are commonly estimated during model calibration and in this model are qualitatively constrained by values derived from aquifer performance testing, but generally are poorly known. In general, the model is more sensitive to horizontal hydraulic conductivities (figs. 1–27, 1–28, and 1–29) than to vertical hydraulic conductivities (figs. 1–30, 1–31, and 1–32). The model is generally most sensitive to the horizontal hydraulic conductivity of layer 3 (fig. 1–29), compared with horizontal hydraulic conductivities of layers 1 and 2 (figs. 1–27 and 1–28). Specifically, simulated groundwater levels are sensitive to the horizontal hydraulic conductivity of layer 3, likely because most of the observation wells are in the confined part of the Upper Floridan aquifer. Leakage in and out of model boundaries to layer 3 is sensitive to horizontal hydraulic conductivity of layer 3, as is aquifer leakage to rivers. Simulated storage loss is also moderately sensitive to horizontal hydraulic conductivity of layer 3.

The model is relatively insensitive to conductivity values applied to the boundary condition drain beds (fig. 1–33), riverbeds (fig. 1–34), and regional boundaries and lakebeds (fig. 1–35), compared with other parameters. Among these three boundary condition parameters, simulated groundwater levels show moderate sensitivity to drain conductivities (fig. 1–33), as does flow out of groundwater storage.

Storage parameter values are also poorly known and, thus, commonly estimated during model calibration. Of the storage parameters—specific yield of layer 1 (fig. 1–36) and specific storage of layers 2 and 3 (figs. 1–37 and 1–38), the model is most sensitive to specific yield of layer 1. Groundwater storage in unconfined units generally accounts for much larger fluxes than groundwater storage in confined units, and volumes of flow in and out of a unit, than groundwater storage in confined units. Other than model sensitivity to recharge (fig. 1–25), the model is most sensitive to specific yield of layer 1 (fig. 1–36) and horizontal hydraulic conductivity of layer 3 (fig. 1–29).

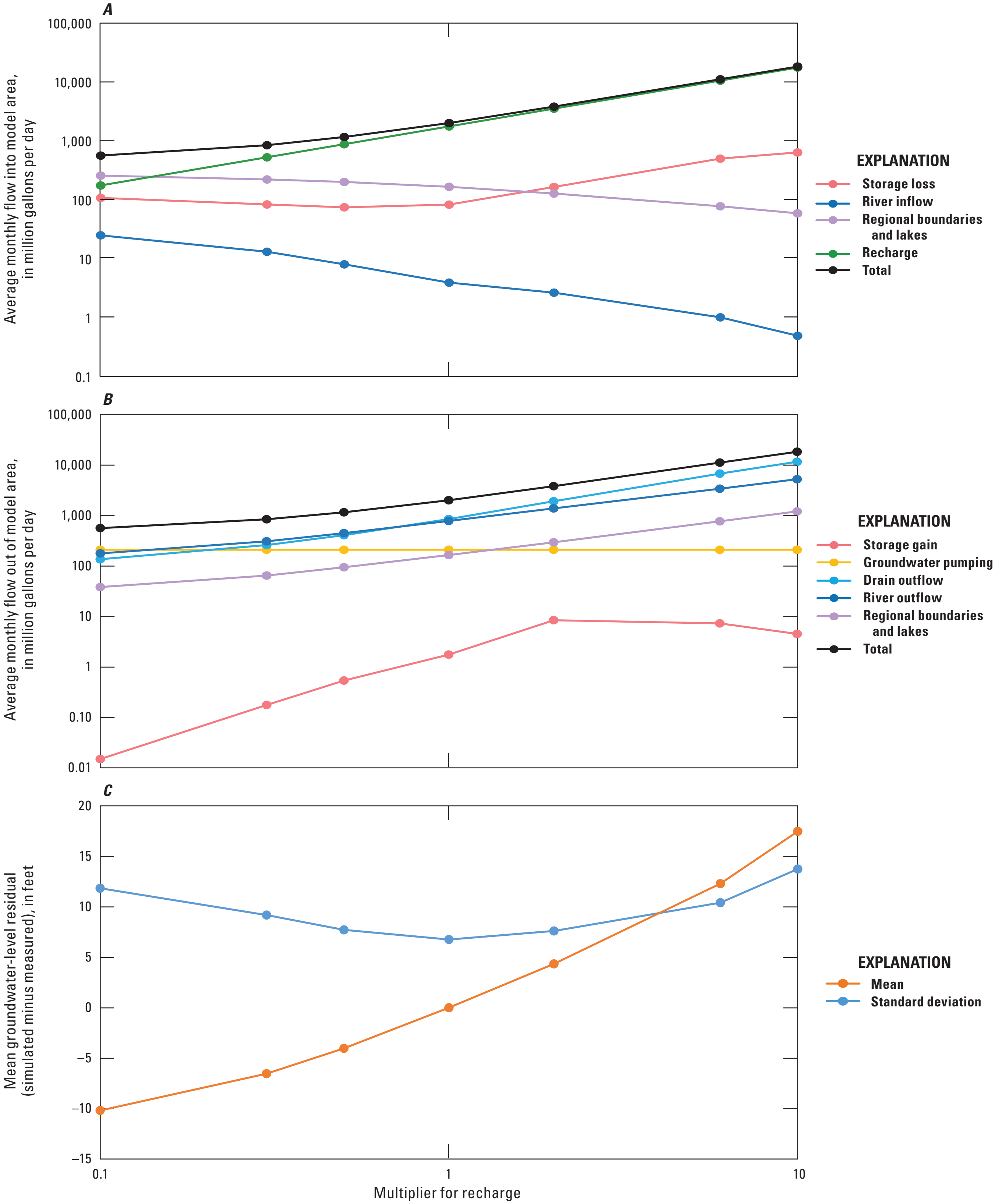


Figure 1–25. Changes in average monthly budget components and groundwater-level-residual (simulated minus measured) statistics due to changes in multiplier for recharge.

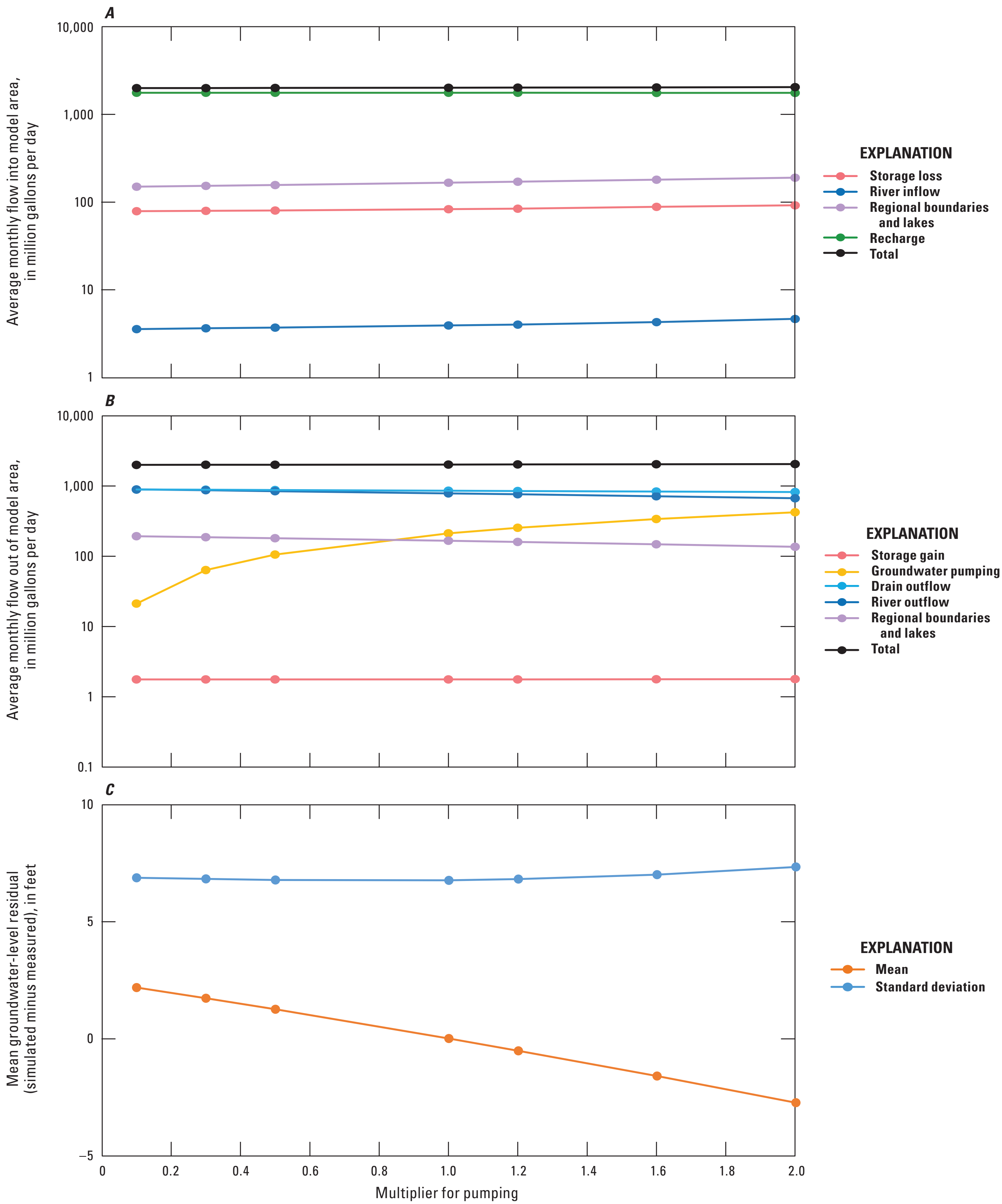


Figure 1–26. Changes in average monthly budget components and groundwater-level-residual (simulated minus measured) statistics due to changes in multiplier for pumping.

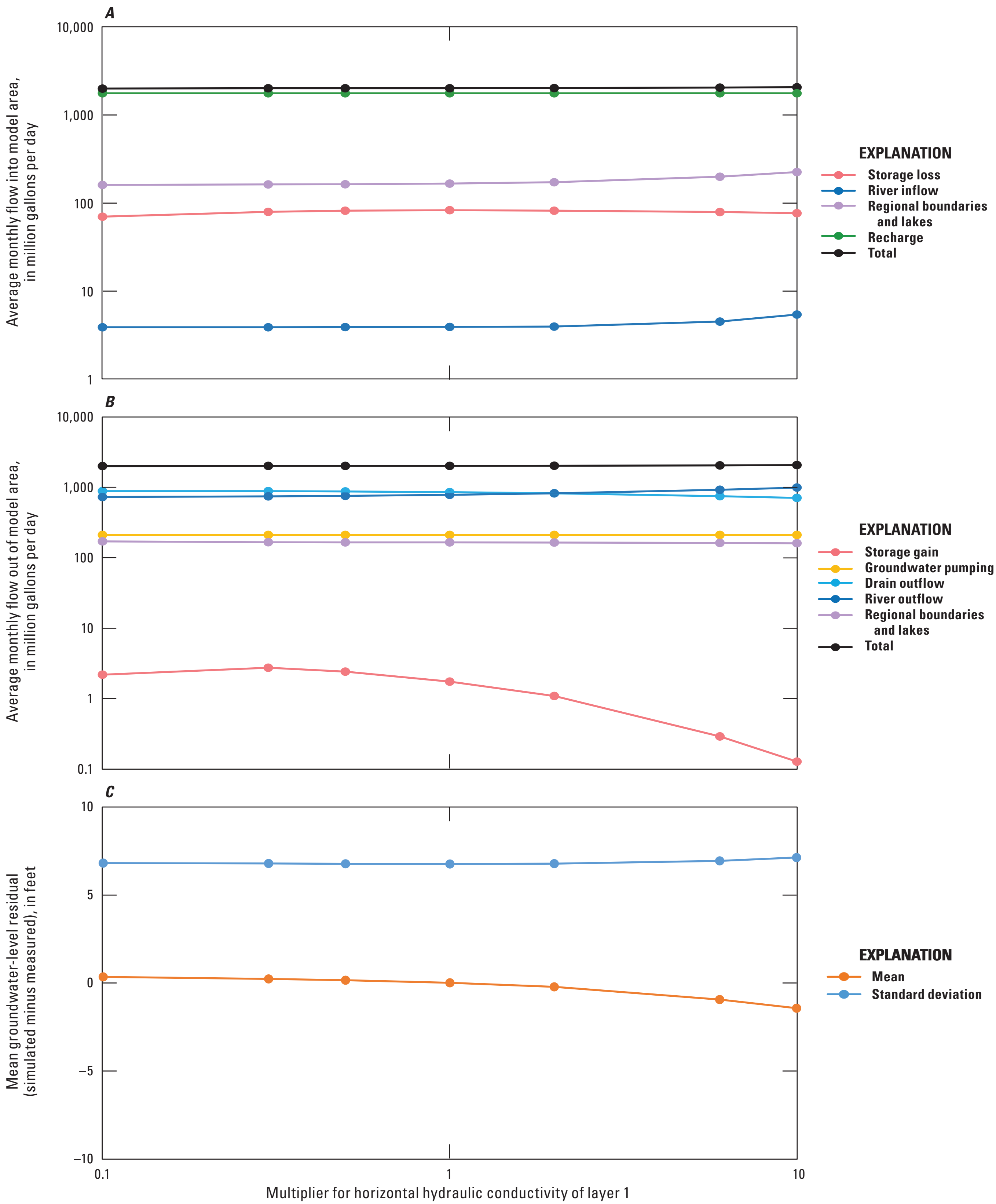


Figure 1–27. Changes in average monthly budget components and groundwater-level-residual (simulated minus measured) statistics due to changes in multiplier for horizontal hydraulic conductivity of layer 1.

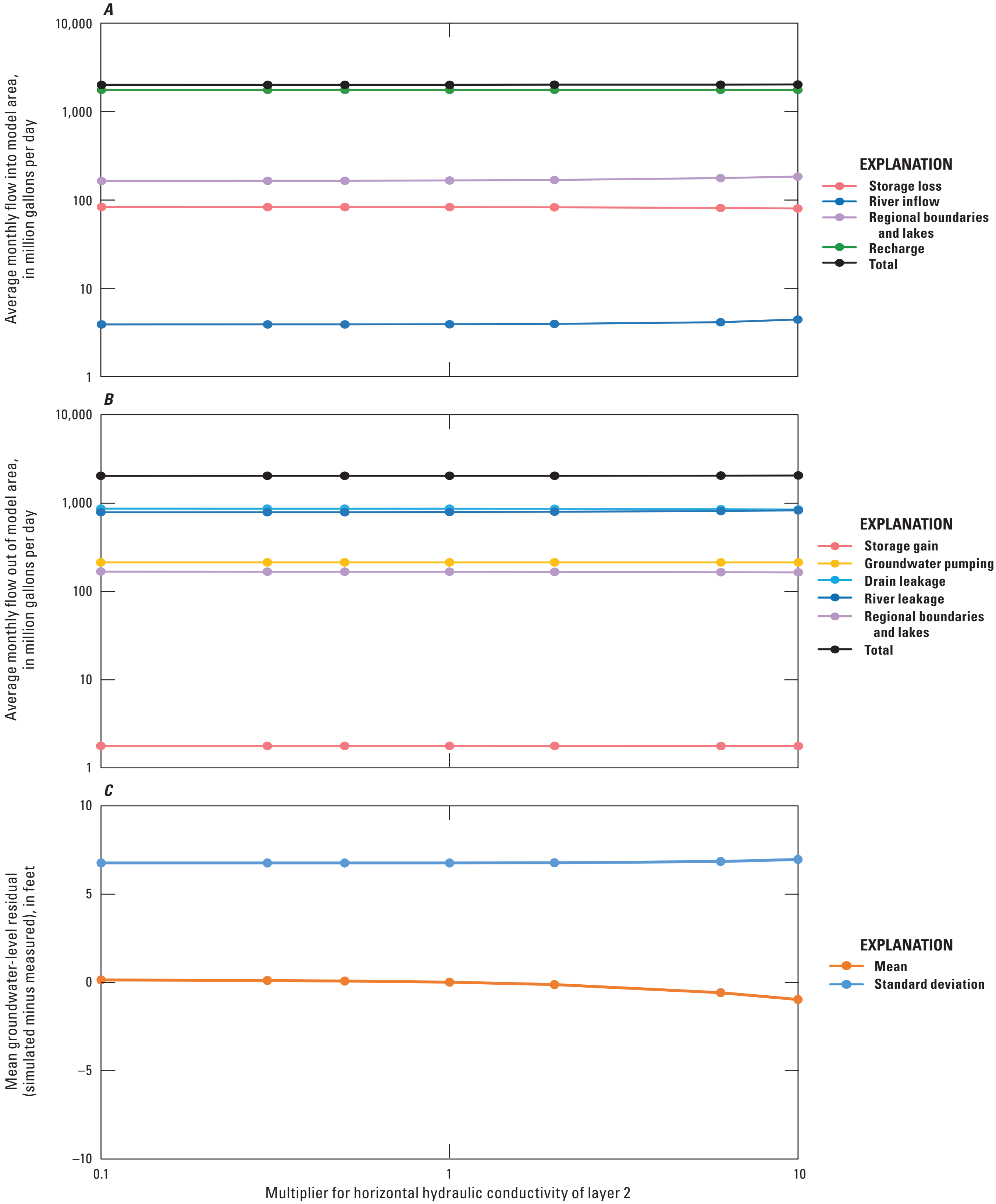


Figure 1–28. Changes in average monthly budget components and groundwater-level-residual (simulated minus measured) statistics due to changes in multiplier for horizontal hydraulic conductivity of layer 2.

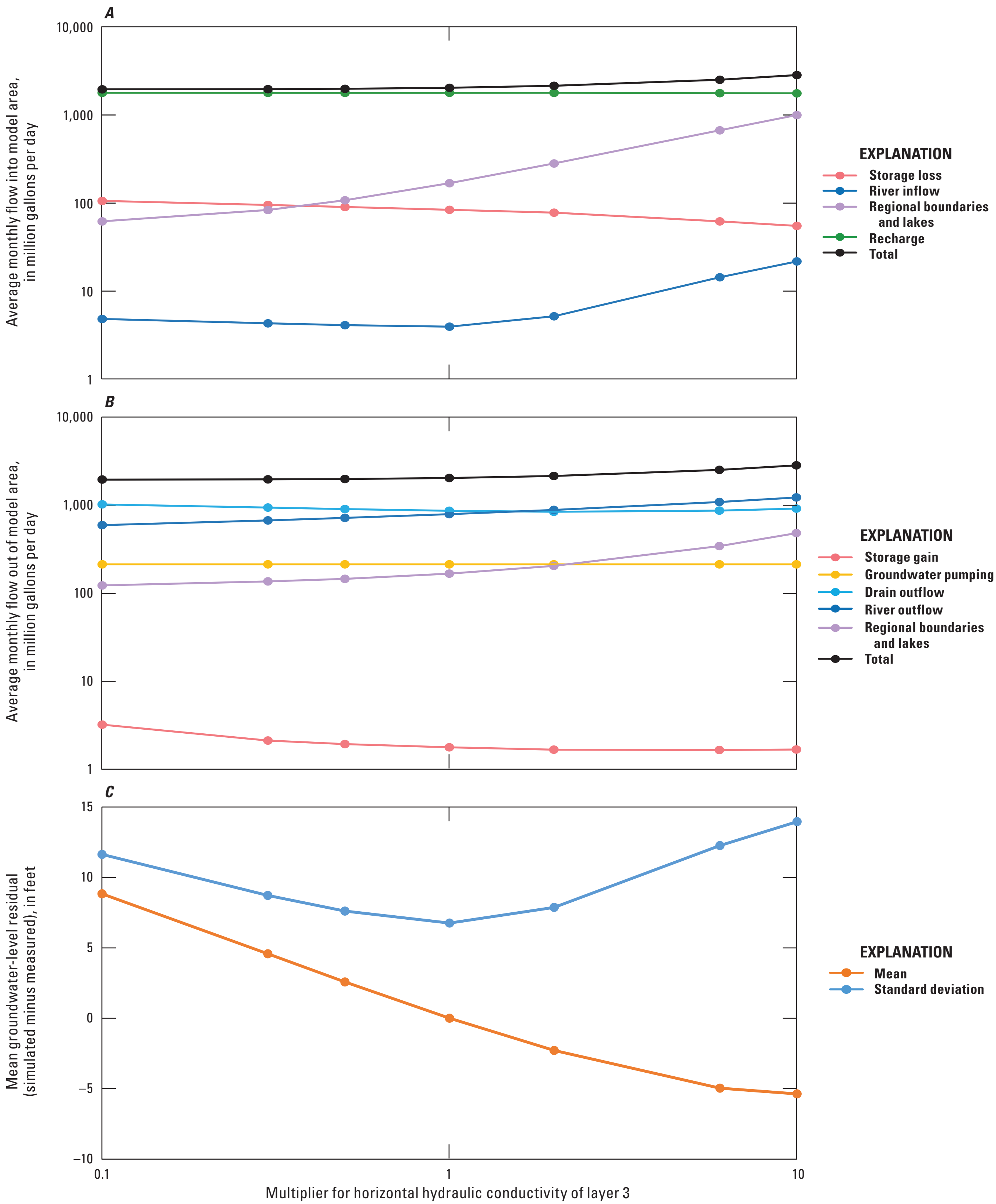


Figure 1–29. Changes in average monthly budget components and groundwater-level-residual (simulated minus measured) statistics due to changes in multiplier for horizontal hydraulic conductivity of layer 3.

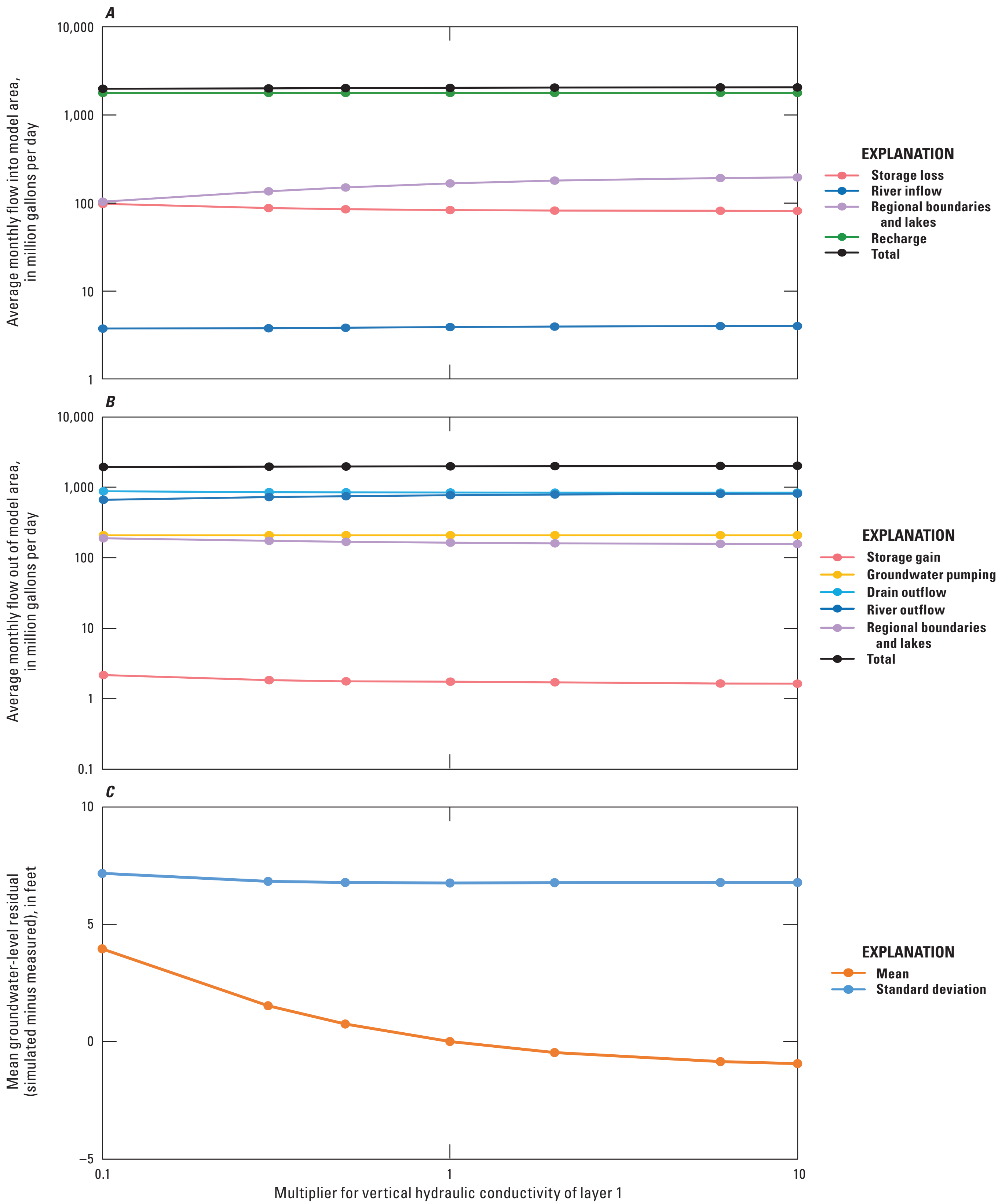


Figure 1–30. Changes in average monthly budget components and groundwater-level-residual (simulated minus measured) statistics due to changes in multiplier for vertical hydraulic conductivity of layer 1.

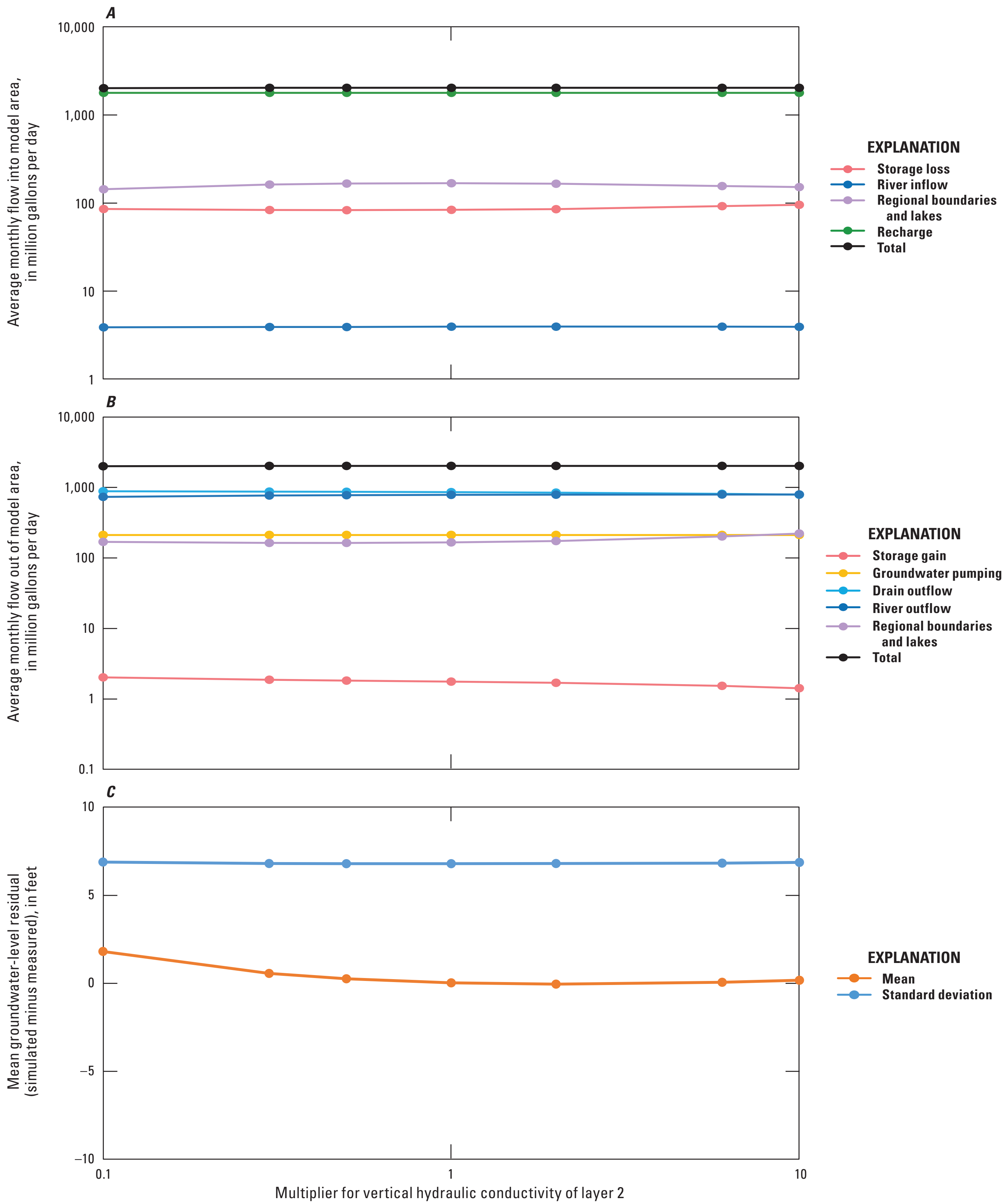


Figure 1–31. Changes in average monthly budget components and groundwater-level-residual (simulated minus measured) statistics due to changes in multiplier for vertical hydraulic conductivity of layer 2.

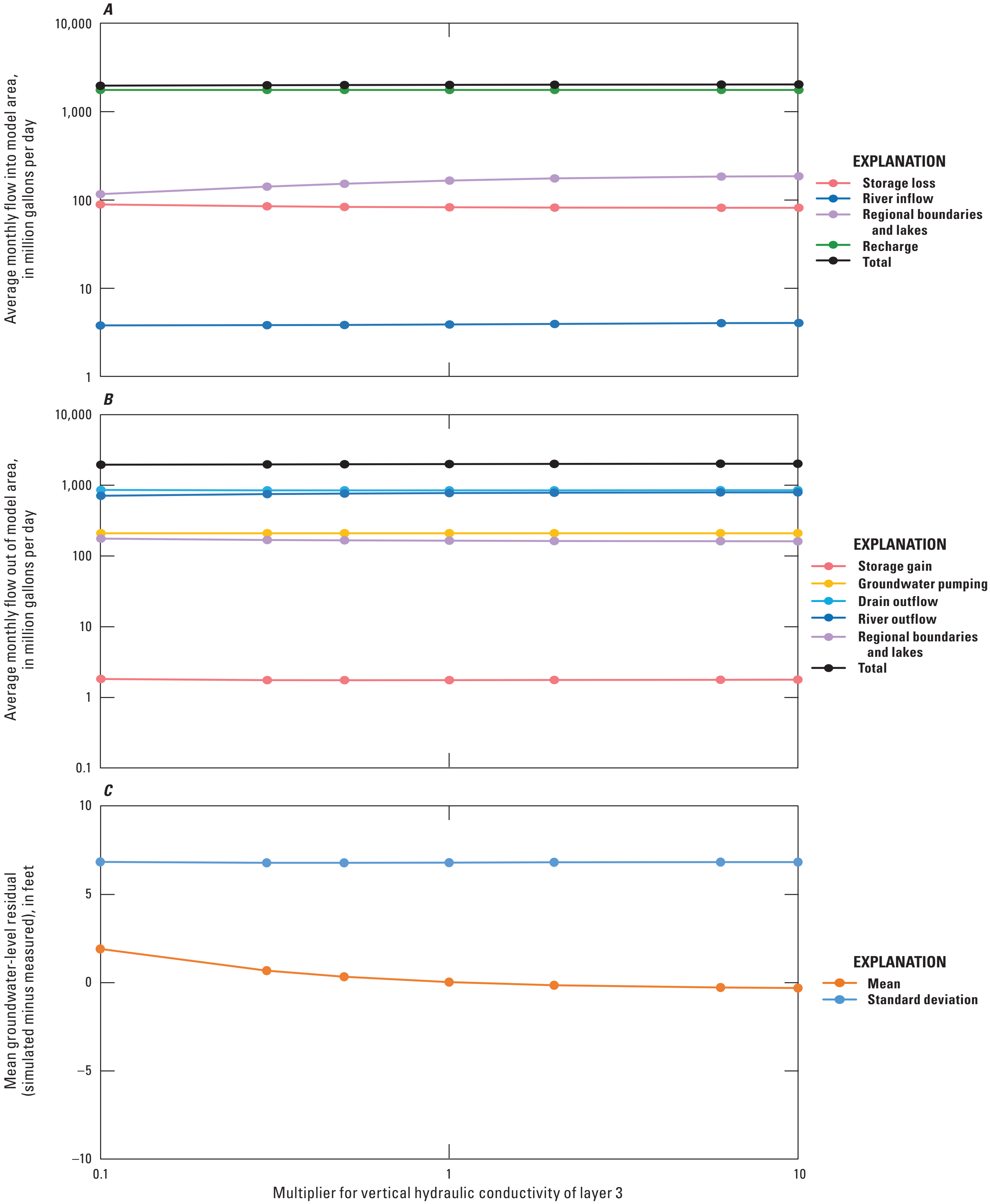


Figure 1–32. Changes in average monthly budget components and groundwater-level-residual (simulated minus measured) statistics due to changes in multiplier for vertical hydraulic conductivity of layer 3.

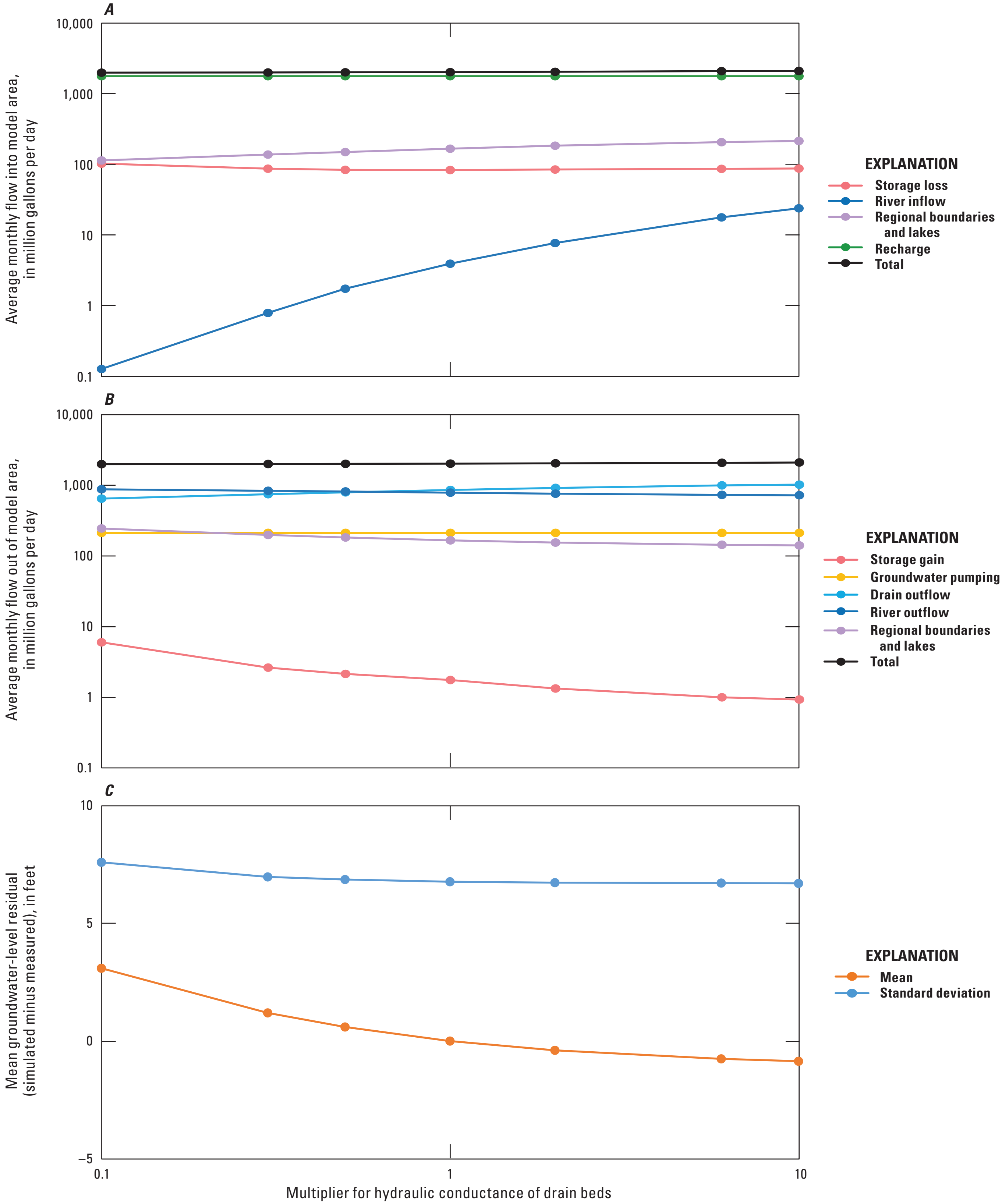


Figure 1–33. Changes in average monthly budget components and groundwater-level-residual (simulated minus measured) statistics due to changes in multiplier for hydraulic conductance of drain beds.

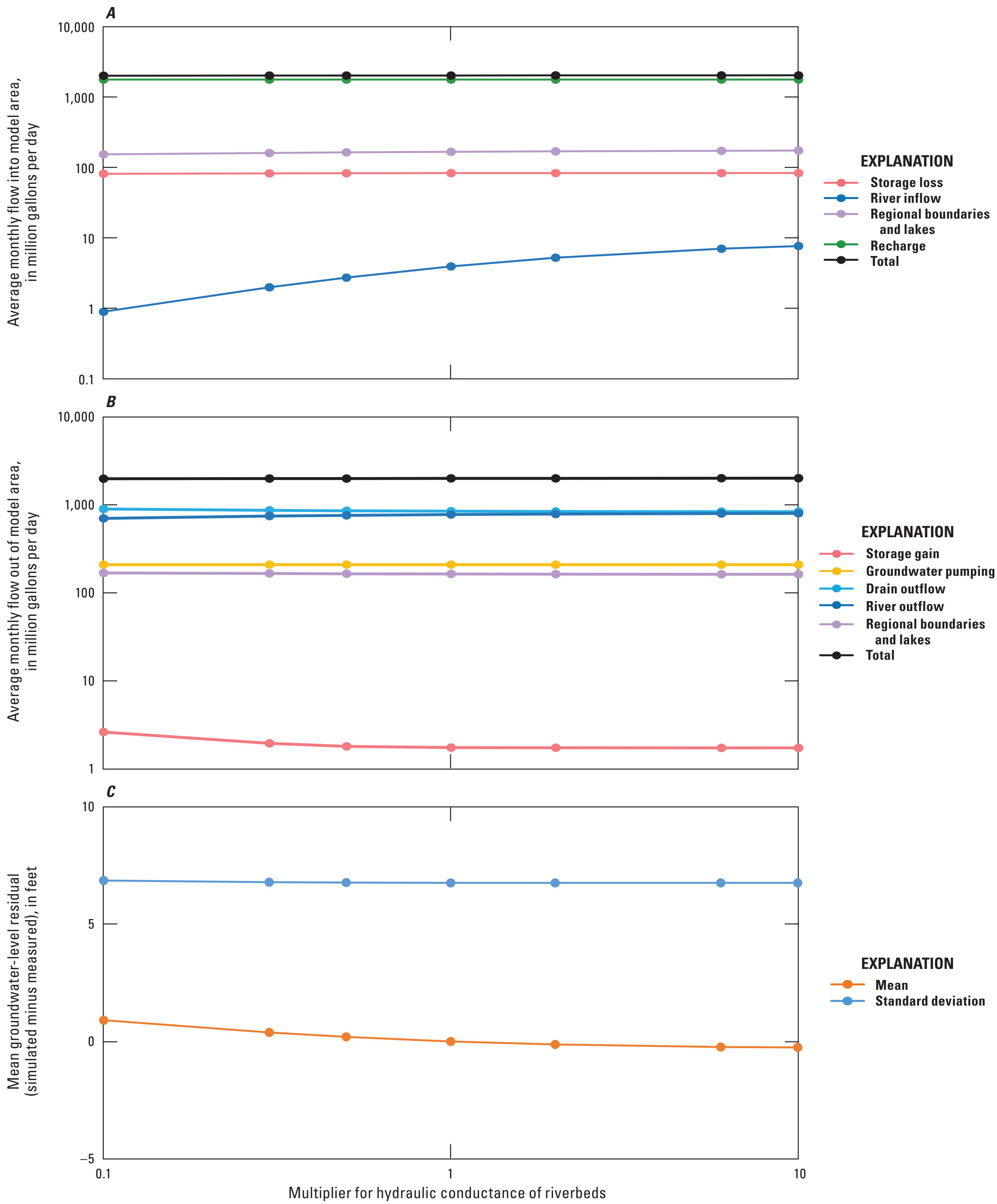


Figure 1–34. Changes in average monthly budget components and groundwater-level-residual (simulated minus measured) statistics due to changes in multiplier for hydraulic conductance of riverbeds.

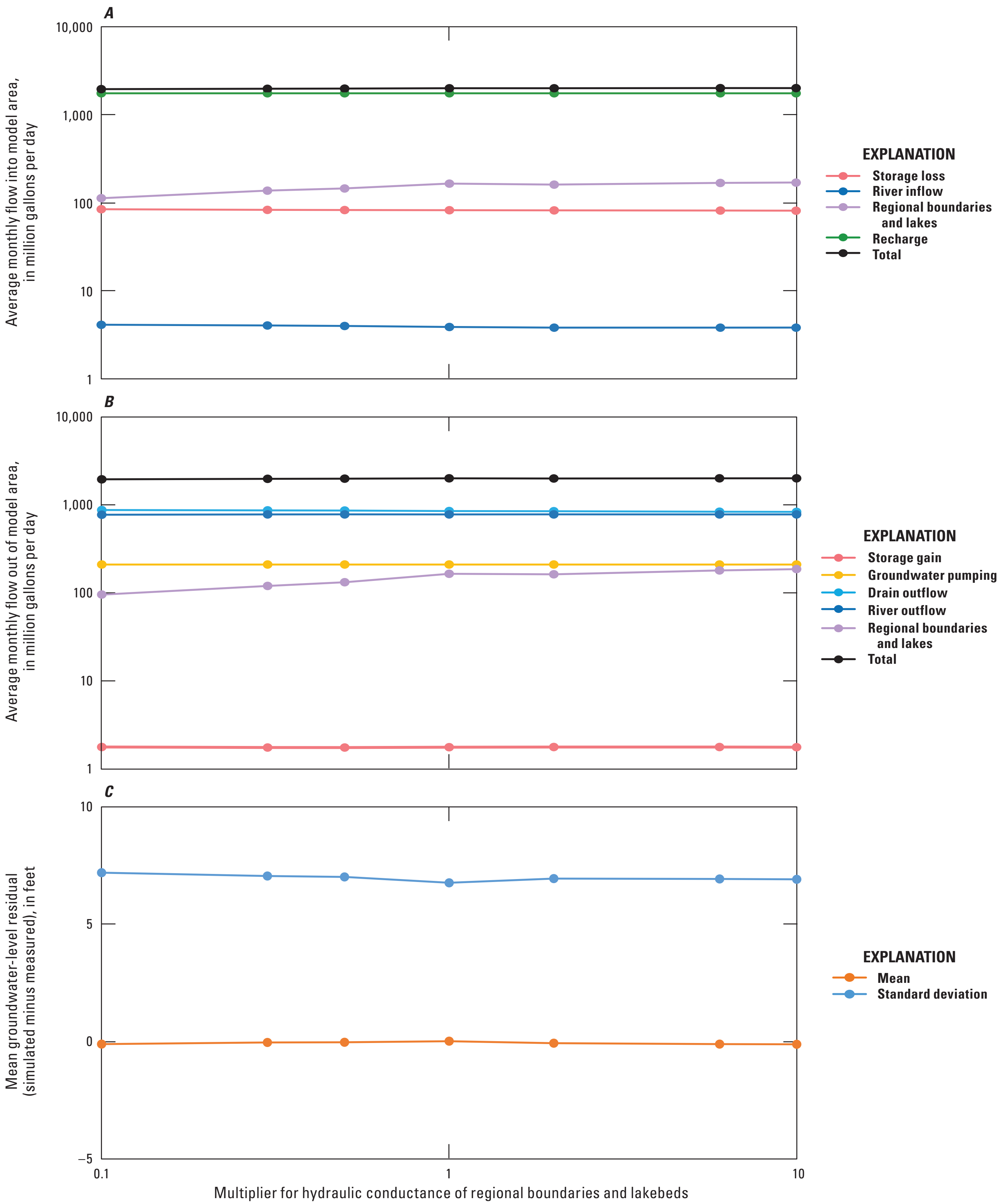


Figure 1–35. Changes in average monthly budget components and groundwater-level-residual (simulated minus measured) statistics due to changes in multiplier for hydraulic conductance of regional boundaries and lakebeds.

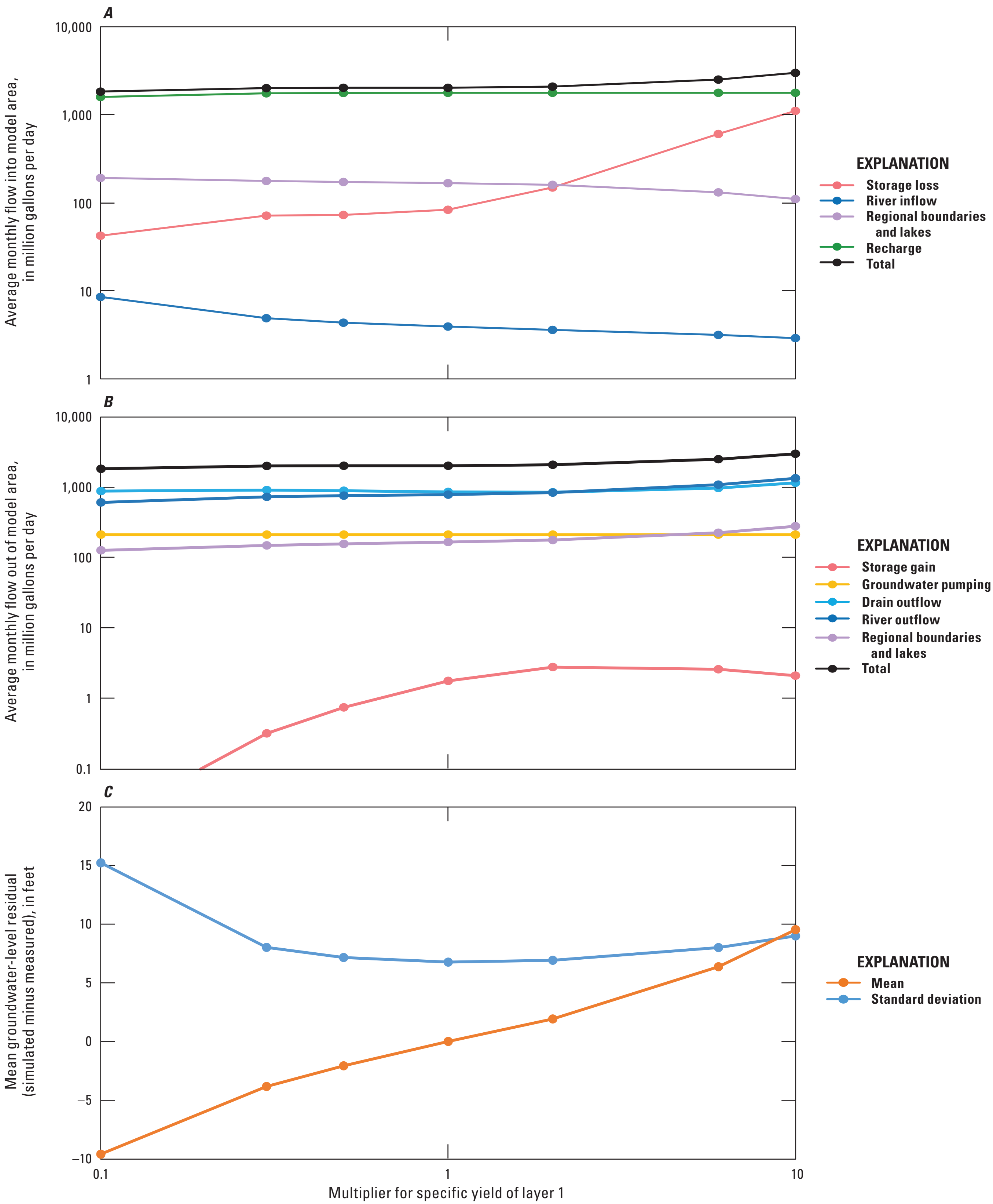


Figure 1–36. Changes in average monthly budget components and groundwater-level-residual (simulated minus measured) statistics due to changes in multiplier for specific yield of layer 1.

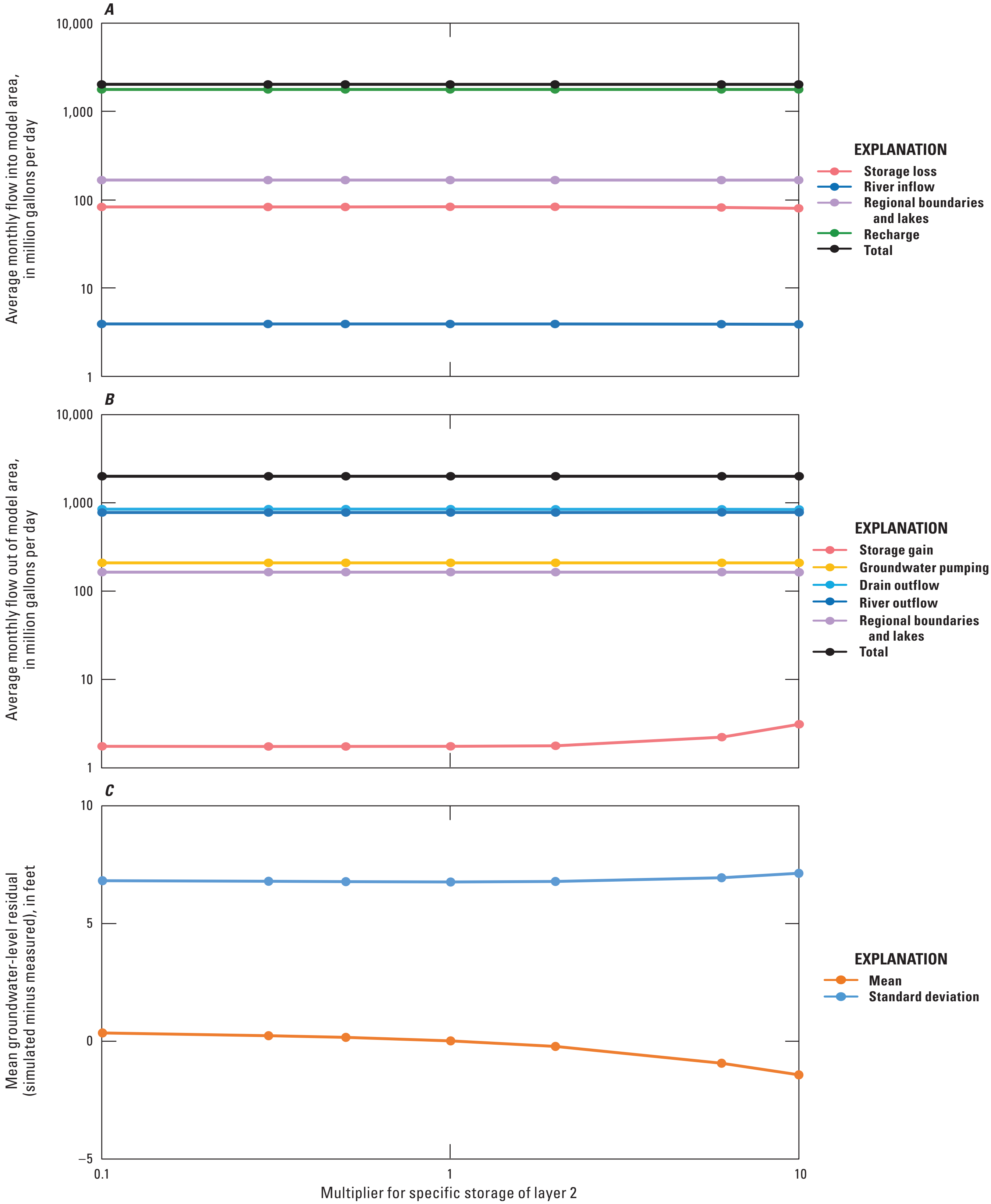


Figure 1–37. Changes in average monthly budget components and groundwater-level-residual (simulated minus measured) statistics due to changes in multiplier for specific storage of layer 2.

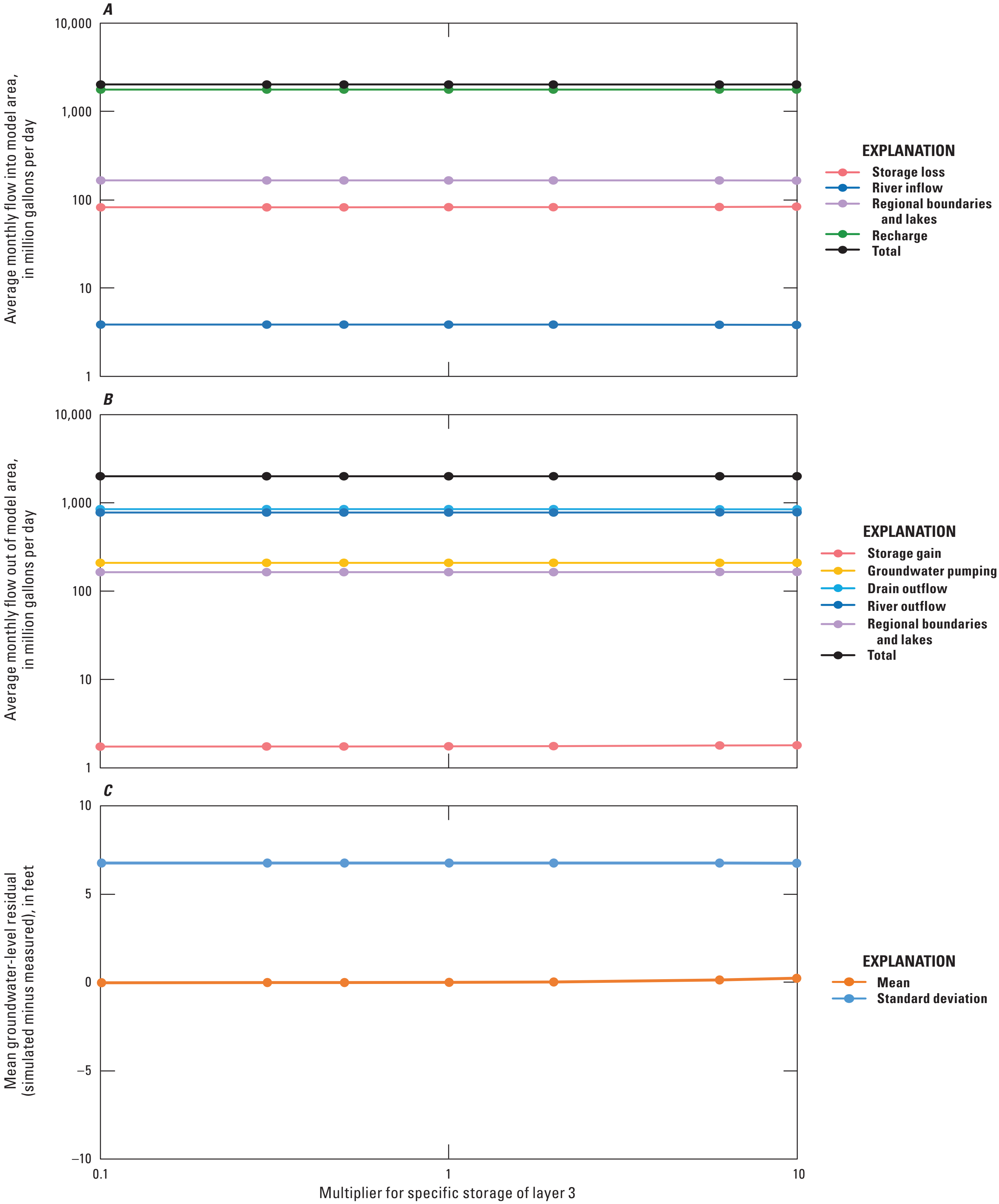


Figure 1–38. Changes in average monthly budget components and groundwater-level-residual (simulated minus measured) statistics due to changes in multiplier for specific storage of layer 3.

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Table 1–3. Wells in the Upper Floridan aquifer used in the calibration of the groundwater-flow model for the lower Apalachicola-Chattahoochee-Flint River Basin.

[WNAME, code identifier of Upper Floridan aquifer well; XALBS, YALBS, well coordinates in Albers centered at meridian W84°30'; MEANMEAS, mean measured head from monthly means calculated from January 2008 to December 2012 measurements, in feet North American Vertical Datum of 1988 (NAVD 88); MEANSIMU, mean simulated head from simulation period, in feet NAVD 88; MEANRESI, mean residual (MEANSIMU minus MEANMEAS) head, in feet NAVD 88; NOBS, number of monthly mean measurements calculated from January 2008 to December 2012, maximum number is 60, number greater than 53 indicates a continuous water-level recorder well; SITE-ID, U.S. Geological Survey identification number of well]

WNAME	XALBS	YALBS	MEANMEAS	MEANSIMU	MEANRESI	NOBS	SITE-ID
05H008	–48358.59	903151.00	153.60	143.73	–9.87	1	311209085003301
05H021	–48384.64	903212.94	161.21	151.75	–9.46	2	311212085003401
05J007	–47666.87	909235.69	176.02	175.38	–0.64	3	311526085000801
06E019	–39164.46	863409.19	73.82	77.79	3.97	2	305044084543801
06E023	–40114.59	858287.25	72.34	78.88	6.55	3	304758084551301
06F001	–38001.11	869117.62	80.45	82.42	1.98	53	305356084534601
06F005	–40320.48	871598.50	82.47	78.99	–3.48	2	305509084552301
06F007	–40416.43	867892.69	65.76	78.24	12.48	2	305309084552601
06F084	–40967.20	874937.19	95.69	85.54	–10.15	3	305657084554801
06G006	–46268.34	888864.19	96.73	103.41	6.68	55	310427084591101
06G008	–45140.78	887128.38	94.17	96.24	2.07	2	310330084582801
06G012	–40696.93	882071.62	102.66	96.09	–6.57	1	310048084553901
06H006	–41479.86	895854.81	134.04	147.56	13.52	1	310809084561001
06H008	–40823.69	900826.94	160.18	160.68	0.50	1	311055084554701
06H009	–42299.57	901235.44	161.25	161.85	0.60	3	311108084564301
06H012	–45119.95	901867.12	154.40	162.30	7.90	1	311128084583001
06H013	–42141.96	895425.31	138.13	143.87	5.74	3	310800084563601
06H022	–36988.45	902973.62	159.01	160.44	1.43	2	311206084532201
06J009	–37974.83	913084.12	170.13	188.16	18.03	2	311733084540101
06J010	–40885.55	910469.62	212.57	200.42	–12.15	2	311608084555101
07D002	–29431.02	852559.31	79.05	77.20	–1.85	1	304454084483001
07D004	–28574.88	850609.06	63.11	77.64	14.53	2	304351084475701
07D005	–28631.53	850740.75	85.88	73.25	–12.63	1	304356084475901
07E001	–25544.41	853942.50	70.15	75.97	5.82	2	304539084460301
07E003	–27218.41	852990.25	69.10	75.62	6.51	2	304508084470601
07E006	–27957.67	862750.06	71.06	76.72	5.66	2	305024084473501
07E008	–25065.99	854280.88	98.15	76.09	–22.06	2	304550084454501
07E009	–24086.08	853722.44	74.85	76.12	1.27	2	304532084450801
07E044	–24344.86	866013.12	61.74	76.45	14.71	2	305210084451901
07E045	–31159.69	856337.62	76.44	76.08	–0.36	2	304656084493501
07E046	–27731.33	858765.88	74.17	76.42	2.25	2	304815084472601
07E062	–29470.80	853769.19	58.36	75.64	17.28	2	304533084383201
07F002	–31709.08	873633.69	77.02	79.95	2.93	2	305616084495801
07F003	–24949.36	877350.00	74.69	81.87	7.18	2	305816084454201
07F004	–26793.98	879857.38	82.91	87.28	4.37	3	305938084465301
07F006	–33663.97	867525.38	70.58	77.96	7.38	2	305258084510201
07G005	–27675.14	885791.38	88.81	87.80	–1.01	2	310250084472701
07G007	–31419.31	880860.81	98.57	84.90	–13.67	2	310010084494801

Table 1–3. Wells in the Upper Floridan aquifer used in the calibration of the groundwater-flow model for the lower Apalachicola-Chattahoochee-Flint River Basin.—Continued

[WNAME, code identifier of Upper Floridan aquifer well; XALBS, YALBS, well coordinates in Albers centered at meridian W84°30'; MEANMEAS, mean measured head from monthly means calculated from January 2008 to December 2012 measurements, in feet North American Vertical Datum of 1988 (NAVD 88); MEANSIMU, mean simulated head from simulation period, in feet NAVD 88; MEANRESI, mean residual (MEANSIMU minus MEANMEAS) head, in feet NAVD 88; NOBS, number of monthly mean measurements calculated from January 2008 to December 2012, maximum number is 60, number greater than 53 indicates a continuous water-level recorder well; SITE-ID, U.S. Geological Survey identification number of well]

WNAME	XALBS	YALBS	MEANMEAS	MEANSIMU	MEANRESI	NOBS	SITE-ID
07G026	–32909.02	885747.12	103.77	100.32	–3.45	2	310249084504501
07G027	–33843.83	890230.44	139.43	123.79	–15.65	2	310514084512101
07G028	–32767.45	881050.94	95.03	92.24	–2.79	2	310017084503901
07H002	–31513.51	899337.25	152.86	142.41	–10.45	56	311009084495502
07H005	–24082.20	894957.44	128.12	115.69	–12.43	1	310747084451201
07H006	–27383.80	894719.62	126.52	123.71	–2.81	1	310738084471701
07H008	–32159.28	895878.62	127.42	128.64	1.22	2	310816084501801
07H009	–34486.64	894867.56	143.57	142.70	–0.87	1	310743084514601
07H011	–35583.23	904729.50	162.10	162.16	0.06	1	311302084522901
07H012	–24962.46	901325.44	144.31	130.88	–13.43	3	311113084454701
07H014	–33499.18	897675.75	138.02	145.90	7.88	1	310914084510901
07H025	–32273.24	908302.12	160.12	158.61	–1.51	2	311459084502501
07H026	–25473.11	907384.06	135.94	137.84	1.90	2	311430084460701
07H027	–32560.48	895102.00	146.36	146.20	–0.16	1	310752084503301
07J012	–26395.25	916659.25	163.62	162.59	–1.03	3	311929084464301
07J013	–27936.96	912181.94	146.85	149.39	2.54	1	311704084474101
08D001	–23001.78	851922.75	72.61	75.95	3.34	2	304450084442701
08D002	–21969.72	851339.69	88.93	76.04	–12.89	2	304415084434801
08D003	–23535.75	851127.44	67.87	75.64	7.77	2	304408084444701
08D005	–20220.02	850656.25	75.74	76.35	0.61	2	304353084424201
08D006	–16455.66	848611.06	79.57	78.45	–1.13	3	304247084402001
08D007	–15970.91	852593.00	74.90	78.66	3.76	2	304456084400201
08D090	–16554.67	852532.25	73.96	78.20	4.23	2	304454084402401
08E019	–21828.25	854982.62	83.11	76.73	–6.38	2	304613084434301
08E022	–21032.59	854980.75	67.65	76.90	9.25	2	304614084431401
08E024	–21751.42	853840.00	89.79	76.59	–13.20	2	304536084434101
08E031	–14078.81	858055.00	84.33	79.67	–4.66	2	304753084385101
08E032	–12057.44	862807.62	72.35	79.34	6.99	2	305227084373501
08E034	–20331.56	860074.06	75.48	77.25	1.77	2	304858084424701
08E035	–22851.53	859400.69	75.49	76.84	1.34	2	304836084442201
08E037	–18252.82	865597.38	75.17	77.38	2.21	2	305157084412901
08E038	–15857.52	856761.12	76.18	80.55	4.37	57	304712084395801
08E039	–16994.57	858461.50	77.02	80.26	3.24	60	304806084404101
08F006	–21904.47	878299.75	83.89	87.28	3.39	2	305848084434801
08F009	–13718.57	868338.00	77.06	78.24	1.18	2	305326084383901
08F012	–14692.76	871860.44	78.03	77.14	–0.89	2	305523084391401
08F017	–17239.21	869239.62	77.81	71.62	–6.19	1	305355084405101
08F018	–22435.52	866811.19	78.57	79.05	0.48	3	305236084440701

Table 1–3. Wells in the Upper Floridan aquifer used in the calibration of the groundwater-flow model for the lower Apalachicola-Chattahoochee-Flint River Basin.—Continued

[WNAME, code identifier of Upper Floridan aquifer well; XALBS, YALBS, well coordinates in Albers centered at meridian W84°30'; MEANMEAS, mean measured head from monthly means calculated from January 2008 to December 2012 measurements, in feet North American Vertical Datum of 1988 (NAVD 88); MEANSIMU, mean simulated head from simulation period, in feet NAVD 88; MEANRESI, mean residual (MEANSIMU minus MEANMEAS) head, in feet NAVD 88; NOBS, number of monthly mean measurements calculated from January 2008 to December 2012, maximum number is 60, number greater than 53 indicates a continuous water-level recorder well; SITE-ID, U.S. Geological Survey identification number of well]

WNAME	XALBS	YALBS	MEANMEAS	MEANSIMU	MEANRESI	NOBS	SITE-ID
08F499	–12845.82	867471.94	78.46	78.73	0.27	2	305258084380501
08F512	–17730.95	871248.44	81.28	89.18	7.90	1	305501084411001
08F513	–17016.30	875107.62	83.89	82.47	–1.41	2	305706084404401
08F514	–20632.04	879439.69	79.47	73.05	–6.42	1	305926084425901
08G001	–17008.72	893211.00	115.10	103.48	–11.62	60	310651084404501
08G005	–17899.53	883480.62	94.78	89.31	–5.47	3	310136084411701
08G006	–21368.23	881294.81	87.56	86.66	–0.90	1	310025084432801
08G013	–13745.08	885759.50	97.16	93.35	–3.81	2	310251084384001
08G015	–22663.58	881514.25	82.54	76.43	–6.11	1	310033084441701
08H003	–22818.23	904039.25	126.35	133.28	6.94	2	311241084442501
08H005	–22837.64	906789.81	133.07	137.27	4.20	1	311410084442201
08H006	–15933.48	903869.94	122.32	134.27	11.95	1	311236084400401
08H007	–19169.91	907739.31	143.62	141.46	–2.16	1	311441084420701
08H009	–16693.04	906807.25	156.00	142.91	–13.09	3	311411084403401
08H010	–17103.77	898804.00	120.40	122.42	2.02	3	310952084404801
08J015	–22981.41	912446.12	150.23	149.33	–0.90	1	311713084443201
08K001	–14663.32	922475.00	213.44	194.13	–19.31	60	312232084391701
08K013	–13082.99	923059.94	192.26	190.97	–1.29	1	312257084381701
08K023	–19433.11	928994.88	231.46	235.03	3.57	1	312610084421901
09E003	–8397.16	866354.94	81.61	80.95	–0.66	3	305223084351701
09E004	–8291.20	866385.75	81.75	80.96	–0.79	3	305223084351301
09E005	–7125.69	866353.81	78.04	80.06	2.02	2	305222084343001
09E006	–6438.09	864778.31	67.33	80.06	12.72	2	305132084340301
09E007	–6412.19	863944.50	87.85	80.00	–7.85	2	305104084340201
09E518	–10808.95	865307.44	70.42	77.60	7.18	1	09E518
09F004	–582.13	876574.31	82.26	87.76	5.50	3	305752084302201
09F005	–10162.64	874664.94	78.40	79.26	0.86	2	305651084362401
09F520	–9155.37	876239.12	79.39	85.16	5.77	60	305736084355801
09G001	–1717.58	888776.88	91.74	85.90	–5.84	58	310428084310501
09G005	–8745.04	890140.38	104.17	98.48	–5.70	3	310512084353201
09G006	–11461.92	893604.00	92.86	103.00	10.14	1	310705084371501
09G010	–6898.96	885751.69	89.66	90.98	1.33	3	310250084342001
09H007	–11316.10	904604.56	130.68	134.46	3.78	1	311300084370901
09H009	–6249.88	906948.50	137.29	138.55	1.26	2	311416084335701
09H012	–5464.76	897089.94	97.55	103.80	6.25	3	310857084332701
09J004	–6797.99	914552.19	147.05	155.93	8.88	2	311823084341801
09J009	–9596.08	909702.12	142.96	145.76	2.80	1	311545084360601
09K010	–11503.77	922872.25	191.19	187.00	–4.19	2	312251084371701

Table 1–3. Wells in the Upper Floridan aquifer used in the calibration of the groundwater-flow model for the lower Apalachicola-Chattahoochee-Flint River Basin.—Continued

[WNAME, code identifier of Upper Floridan aquifer well; XALBS, YALBS, well coordinates in Albers centered at meridian W84°30'; MEANMEAS, mean measured head from monthly means calculated from January 2008 to December 2012 measurements, in feet North American Vertical Datum of 1988 (NAVD 88); MEANSIMU, mean simulated head from simulation period, in feet NAVD 88; MEANRESI, mean residual (MEANSIMU minus MEANMEAS) head, in feet NAVD 88; NOBS, number of monthly mean measurements calculated from January 2008 to December 2012, maximum number is 60, number greater than 53 indicates a continuous water-level recorder well; SITE-ID, U.S. Geological Survey identification number of well]

WNAME	XALBS	YALBS	MEANMEAS	MEANSIMU	MEANRESI	NOBS	SITE-ID
09K012	–2550.06	934830.31	181.80	188.33	6.53	2	312919084313701
09L029	–840.65	941230.88	212.71	208.09	–4.62	2	313246084303201
10F001	1745.64	880188.56	90.25	87.26	–2.99	2	305950084285401
10F004	5397.22	877471.69	93.41	93.10	–0.31	2	305822084263601
10G001	10734.93	883036.81	99.84	98.85	–0.98	2	310117084231501
10G313	5759.68	889983.56	89.61	94.70	5.09	59	310507084262201
10G317	9805.03	891060.06	104.87	112.19	7.32	1	310543084234901
10H004	923.27	904041.25	115.53	106.01	–9.52	2	311243084292601
10H006	6759.56	895453.12	95.53	97.76	2.23	3	310804084254401
10H009	131.87	906451.81	126.92	113.86	–13.07	60	311400084295502
10H012	1547.47	894492.50	90.92	95.76	4.84	1	310734084290101
10J002	9884.87	910815.06	123.52	118.42	–5.10	1	311622084234501
10J003	10118.50	914029.88	131.09	125.65	–5.44	3	311806084233701
10J009	2397.34	916095.44	131.09	128.90	–2.19	1	10J009
10J010	193.77	918794.56	139.06	139.92	0.86	1	312040084295301
10K005	3391.64	934057.62	165.75	174.39	8.65	57	312853084275101
10L003	4231.25	937644.75	187.74	182.54	–5.20	1	313049084271801
10L004	2231.70	946395.62	218.31	215.56	–2.75	3	313532084283501
10L016	3258.13	939592.50	194.20	192.16	–2.04	1	313152084275601
10L018	8618.29	939627.00	182.11	187.96	5.85	1	313153084243201
11G002	15193.61	888882.19	102.96	102.30	–0.66	2	310431084202501
11H003	12805.05	896263.06	106.18	110.03	3.86	3	310830084215501
11J003	15377.67	920374.06	144.87	135.10	–9.77	3	312129084201701
11J005	14043.39	914869.69	123.98	122.01	–1.97	1	311832084210601
11J012	16785.21	913947.00	117.66	122.29	4.62	60	311802084192302
11J016	21158.25	914730.19	116.52	127.40	10.88	1	311827084161801
11J018	19323.58	909872.25	119.05	123.74	4.69	1	311550084174701
11K003	22872.11	934704.44	161.88	156.68	–5.20	60	312919084153801
11K011	15662.89	922940.38	143.22	145.30	2.08	1	312250084201001
11K015	22014.93	930466.31	160.37	149.25	–11.12	3	312709084161701
11K016	14210.89	925565.75	144.23	150.79	6.56	3	312418084210001
11K028	14589.31	935645.69	176.52	175.16	–1.36	1	312944084204501
11K033	14176.95	930388.75	164.92	161.48	–3.44	3	312654084210104
11K043	16667.76	934690.75	168.31	170.34	2.03	3	312913084192601
11L019	17637.02	936455.19	167.50	174.30	6.80	1	313010084184901
11L020	17653.02	941681.12	183.54	187.40	3.86	2	313300084184901
11L077	16914.62	943195.00	189.49	196.60	7.11	1	313348084191601
11L092	20586.38	945522.06	188.37	194.34	5.98	3	313504084165701

Table 1–3. Wells in the Upper Floridan aquifer used in the calibration of the groundwater-flow model for the lower Apalachicola-Chattahoochee-Flint River Basin.—Continued

[WNAME, code identifier of Upper Floridan aquifer well; XALBS, YALBS, well coordinates in Albers centered at meridian W84°30'; MEANMEAS, mean measured head from monthly means calculated from January 2008 to December 2012 measurements, in feet North American Vertical Datum of 1988 (NAVD 88); MEANSIMU, mean simulated head from simulation period, in feet NAVD 88; MEANRESI, mean residual (MEANSIMU minus MEANMEAS) head, in feet NAVD 88; NOBS, number of monthly mean measurements calculated from January 2008 to December 2012, maximum number is 60, number greater than 53 indicates a continuous water-level recorder well; SITE-ID, U.S. Geological Survey identification number of well]

WNAME	XALBS	YALBS	MEANMEAS	MEANSIMU	MEANRESI	NOBS	SITE-ID
11L111	12607.55	942940.50	193.75	193.77	0.02	3	313340084220001
11L112	14858.49	947706.56	195.87	209.18	13.31	3	313614084203401
11L113	22907.67	941374.44	176.84	175.62	–1.22	1	313251084152901
11L115	20845.35	947099.88	195.13	201.07	5.94	1	313554084164601
11L116	18539.71	944806.38	192.92	198.64	5.72	1	313440084181402
11M010	19943.28	951335.00	213.97	223.60	9.63	1	313813084171801
11M017	23099.43	958735.12	238.14	239.04	0.90	3	314210084151901
11M025	14064.08	952097.12	239.66	237.41	–2.26	3	313836084210401
12H008	27034.62	905472.44	123.17	127.70	4.53	2	311328084130701
12J002	29637.42	916051.06	131.27	137.03	5.76	2	311909084111501
12K001	32170.61	922273.19	133.14	137.27	4.13	2	312253084100001
12K009	29913.55	928077.50	135.32	139.99	4.67	2	312538084110301
12K010	28904.27	931042.31	141.80	142.89	1.08	2	312714084114001
12K011	31062.68	930554.81	141.58	144.09	2.51	1	312650084102101
12K012	28874.90	932000.75	142.31	145.17	2.86	1	312745084114701
12K013	32536.11	930405.44	148.68	143.44	–5.23	2	312650084092301
12K014	29828.03	929273.75	135.37	144.13	8.75	59	312617084110701
12K016	27825.69	931131.69	143.61	144.43	0.82	1	312719084123101
12K037	30906.74	929997.75	141.12	143.28	2.16	1	312641084102401
12K063	24155.17	935650.81	157.69	153.99	–3.70	1	312944084144001
12K101	26054.79	934171.94	153.60	148.65	–4.95	1	312857084132901
12K107	26598.19	929999.44	140.33	143.61	3.28	1	312634084131301
12K108	30386.89	935932.62	145.38	146.78	1.40	1	312953084104401
12K109	27923.20	933605.50	145.67	146.57	0.90	1	312839084121601
12K110	30793.66	932285.38	140.35	144.38	4.03	2	312747084102901
12K115	32076.29	933959.50	141.82	145.23	3.41	2	312848084094101
12K117	24431.74	933007.31	156.93	149.03	–7.90	1	312821084142701
12K118	24657.04	935545.38	154.98	153.04	–1.94	1	312941084140301
12K124	27136.00	932205.56	145.78	145.58	–0.20	1	312751084124901
12K129	27611.85	934816.62	151.40	147.63	–3.77	1	312917084123001
12K132	26922.74	929669.62	143.33	143.23	–0.10	1	312629084125701
12K134	30899.09	929935.94	139.06	143.19	4.13	1	312638084102601
12K137	27434.27	930110.12	142.88	143.56	0.68	1	312645084123701
12K141	26365.31	935858.06	156.80	151.88	–4.92	59	312950084131801
12K142	26339.01	935858.00	152.10	147.55	–4.55	1	312950084131802
12K168	28444.16	935172.69	152.43	147.21	–5.22	1	312929084115801
12K170	30281.14	936117.75	147.53	146.80	–0.73	1	312957084104901
12K171	26916.31	934440.44	152.11	147.94	–4.17	1	312904084130501

Table 1–3. Wells in the Upper Floridan aquifer used in the calibration of the groundwater-flow model for the lower Apalachicola-Chattahoochee-Flint River Basin.—Continued

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WNAME	XALBS	YALBS	MEANMEAS	MEANSIMU	MEANRESI	NOBS	SITE-ID
12K172	24691.04	935806.88	156.85	153.50	–3.35	1	312948084142001
12K173	25529.25	934062.25	154.34	147.57	–6.77	2	312852084135001
12K180	32543.05	935754.56	145.69	148.19	2.50	58	312947084092201
12L028	28396.95	941770.50	155.29	161.99	6.70	2	313302084120301
12L029	32614.07	945155.62	152.41	158.89	6.48	53	313450084091801
12L030	31269.76	939058.75	151.57	150.54	–1.03	59	313130084101001
12L045	32232.19	949112.94	182.25	180.77	–1.48	1	313658084093201
12L061	24635.74	936787.00	158.26	156.19	–2.07	1	313020084142501
12L268	23775.34	941107.62	171.86	172.60	0.74	1	313240084145501
12L269	27301.78	941683.62	157.73	165.25	7.52	1	313300084124302
12L270	30420.62	937630.31	145.95	147.69	1.74	1	313047084104201
12L272	28357.52	937626.62	151.96	148.03	–3.93	2	313048084120101
12L273	28859.44	938466.25	152.79	149.98	–2.81	1	313117084114201
12L277	27517.05	937438.50	156.27	152.64	–3.63	59	313040084125901
12L309	25535.95	940957.81	165.22	164.07	–1.15	1	313235084134801
12L310	25914.66	938970.56	162.07	159.34	–2.73	1	313132084133201
12L311	24225.20	939902.81	170.86	170.54	–0.32	2	313202084143801
12L319	25437.09	941523.50	173.30	170.24	–3.06	1	313255084135201
12L324	25536.10	940896.06	168.78	167.69	–1.09	1	313234084134801
12L326	25295.46	940244.12	165.09	166.32	1.23	1	313212084135701
12L339	29354.31	936594.00	145.99	146.88	0.89	1	313014084112201
12L340	28914.72	936778.00	146.79	146.97	0.18	1	313023084113201
12L342	27831.23	937841.50	153.29	150.83	–2.46	1	313055084122101
12L343	29696.32	938097.94	149.41	148.49	–0.92	1	313104084111001
12L344	26224.50	939073.50	157.86	157.04	–0.82	2	313135084132201
12L345	26772.64	939243.38	159.33	157.76	–1.57	1	313140084130101
12L347	30839.27	936642.25	144.89	146.99	2.10	1	313016084102701
12L348	28151.51	936265.44	152.89	147.76	–5.13	1	313005084121401
12L350	27886.54	936944.88	148.67	145.02	–3.65	7	313026084121901
12L351	27724.07	938490.50	153.31	151.30	–2.01	2	313115084122701
12L352	26047.20	936784.81	154.31	151.14	–3.17	2	313019084133101
12L353	25256.85	937431.81	155.77	154.86	–0.92	2	313043084131401
12L355	25226.87	936126.25	155.08	153.08	–2.00	1	313001084140101
12L356	25663.99	937516.56	156.61	155.67	–0.94	1	313043084134301
12L357	25659.63	938110.19	161.89	157.38	–4.51	1	313102084134301
12L370	30331.63	936736.38	146.47	148.74	2.27	59	313019084104601
12L373	31463.87	936152.75	146.54	148.52	1.97	60	313000084100301
12L375	24225.20	939902.81	168.01	167.77	–0.24	1	313202084143801

Table 1–3. Wells in the Upper Floridan aquifer used in the calibration of the groundwater-flow model for the lower Apalachicola-Chattahoochee-Flint River Basin.—Continued

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WNAME	XALBS	YALBS	MEANMEAS	MEANSIMU	MEANRESI	NOBS	SITE-ID
12M011	30490.12	959716.19	202.05	196.35	–5.70	2	314241084103701
12M017	32119.47	951277.50	190.24	186.83	–3.41	60	313808084093601
12M024	29900.71	955631.06	180.27	191.02	10.75	1	314029084110001
12M027	26457.05	958218.50	185.70	202.99	17.29	3	314153084131101
12M060	28905.33	953428.62	177.96	190.61	12.65	1	313919084113801
12N004	31265.54	977879.50	266.17	264.46	–1.71	3	315228084100601
12P010	31384.62	981221.81	280.02	280.16	0.14	1	315417084100001
13J004	36416.74	920403.62	139.85	144.02	4.17	60	312127084065801
13J008	44846.51	919699.75	159.62	156.90	–2.72	1	312105084013701
13K011	41473.62	931586.19	144.38	154.95	10.57	1	312731084034101
13K014	35875.12	930758.25	147.43	150.87	3.44	57	312704084071601
13K017	41402.37	929916.25	150.79	152.77	1.97	2	312636084034601
13K019	35783.71	933911.62	145.92	150.58	4.66	1	312846084071901
13K022	46778.79	927933.00	176.23	168.50	–7.72	2	312531084002201
13K023	46863.29	926851.25	168.85	165.54	–3.31	1	312456084001901
13K091	36198.55	928811.69	140.03	148.84	8.81	1	312601084070401
13L012	36712.69	938213.44	150.17	153.67	3.50	58	313105084064302
13L028	43916.71	937534.50	151.43	160.74	9.31	1	313041084020801
13L047	46697.52	948619.81	196.62	197.84	1.22	3	313640084002101
13L048	45758.12	937203.62	166.32	162.72	–3.60	2	313031084005901
13L049	39122.15	946140.31	166.80	165.32	–1.47	57	313521084051001
13L052	40034.48	947628.88	190.61	174.06	–16.55	1	313609084043502
13L054	43652.14	948697.25	177.84	183.99	6.15	1	313643084021701
13L057	43836.22	943255.00	161.97	165.07	3.10	1	313347084021101
13L180	45973.16	941410.25	173.75	170.36	–3.39	60	313247084005001
13M006	45845.21	961297.25	223.61	201.50	–22.10	57	314330084005402
13M027	37724.41	960083.88	210.14	215.38	5.24	3	314252084060102
13M056	44631.06	957702.81	223.33	203.80	–19.53	3	314134084013801
13M065	38151.65	958260.62	218.44	209.82	–8.62	1	314153084054501
13M066	37245.70	961721.44	222.53	217.11	–5.42	2	314345084061901
13M086	41274.03	963502.38	222.01	230.08	8.07	3	314442084034501
13N003	35640.56	969882.19	245.04	236.82	–8.22	3	314809084071901
13N007	40189.95	977327.25	258.17	266.43	8.26	2	315209084042501
13N009	42257.55	977212.94	291.97	284.16	–7.81	1	315205084030501
13N014	41772.73	972447.25	267.17	266.35	–0.82	1	314932084032401
13P005	40317.62	978039.44	268.95	270.96	2.01	1	315232084040901
13P019	44442.90	990282.69	284.62	285.30	0.68	2	315908084013901
14K006	50447.02	935342.44	208.51	189.66	–18.85	1	312930083580101

Table 1–3. Wells in the Upper Floridan aquifer used in the calibration of the groundwater-flow model for the lower Apalachicola-Chattahoochee-Flint River Basin.—Continued

[WNAME, code identifier of Upper Floridan aquifer well; XALBS, YALBS, well coordinates in Albers centered at meridian W84°30'; MEANMEAS, mean measured head from monthly means calculated from January 2008 to December 2012 measurements, in feet North American Vertical Datum of 1988 (NAVD 88); MEANSIMU, mean simulated head from simulation period, in feet NAVD 88; MEANRESI, mean residual (MEANSIMU minus MEANMEAS) head, in feet NAVD 88; NOBS, number of monthly mean measurements calculated from January 2008 to December 2012, maximum number is 60, number greater than 53 indicates a continuous water-level recorder well; SITE-ID, U.S. Geological Survey identification number of well]

WNAME	XALBS	YALBS	MEANMEAS	MEANSIMU	MEANRESI	NOBS	SITE-ID
14K011	50935.58	932624.19	204.40	192.88	–11.52	1	312802083574301
14L005	47892.41	946059.06	203.01	190.64	–12.37	1	313517083593601
14L006	53630.52	943710.19	220.77	214.38	–6.39	3	313400083555801
14L011	49050.04	945632.31	210.48	203.38	–7.10	2	313503083585201
14L013	51803.77	937112.75	206.96	198.46	–8.50	3	313027083570901
14L014	55035.41	950182.50	234.55	228.33	–6.22	3	313729083550301
14L048	47332.53	942685.25	183.41	178.44	–4.97	1	313328083595801
14L059	51793.68	943421.12	205.27	203.25	–2.02	1	313352083570801
14M006	51165.12	961511.56	232.57	226.80	–5.77	2	314336083572801
14N012	54766.82	974138.94	252.49	237.84	–14.66	2	315024083550801
14N013	58377.39	967010.31	252.88	252.08	–0.80	1	314633083525101
14N015	55074.88	973631.50	233.65	235.01	1.36	1	315008083545601
14Q005	52088.21	996514.12	245.46	247.99	2.53	1	320227083564501
14Q006	52511.36	995588.06	249.39	247.09	–2.30	1	320157083562901
14Q009	57386.37	996856.12	255.63	263.73	8.10	1	320237083532201
15P018	63359.78	986590.12	268.58	265.97	–2.61	3	315703083493601
15Q011	66578.85	993081.88	297.12	296.33	–0.79	1	320021083473401
15Q012	59626.01	997706.56	265.34	267.55	2.21	1	320304083515701
15Q016	60895.35	995331.75	263.84	271.55	7.71	60	320139083511602
AL0101	–58023.73	881177.56	116.02	119.45	3.42	2	310017085063401
AL0102	–51822.01	883457.00	111.63	104.75	–6.88	1	310132085024001
AL0103	–84045.42	884347.69	135.04	129.08	–5.97	2	310153085225901
AL0104	–78780.41	884763.75	132.76	124.37	–8.40	2	310208085194001
AL0105	–61924.44	887011.44	150.18	149.23	–0.95	1	AL0105
AL0106	–71200.07	887203.38	131.01	133.42	2.41	2	310329085145401
AL0107	–57298.12	887166.38	132.34	138.75	6.41	1	AL0107
AL0108	–84718.75	891491.06	167.44	173.18	5.74	2	310539085232601
FL3775	–60087.57	832990.06	52.70	50.57	–2.13	3	303415085074001
FL4566	–32498.88	845227.50	60.78	73.69	12.91	3	304056084502501
FL4681	–38221.47	848213.50	72.51	74.30	1.79	3	304230084535901
FL4795	–58240.79	851286.62	88.83	83.32	–5.51	3	304413085064401
FL5062	–83592.48	858187.50	109.62	95.53	–14.09	2	304746085223201
FL5147	–43105.28	861187.12	74.59	79.60	5.01	3	304918084565601
FL5151	–67827.91	860884.25	73.48	78.22	4.74	1	FL5151
FL5266	–55046.06	864365.94	82.27	97.23	14.96	3	305113085043601
FL5408	–50314.07	869332.06	90.97	92.05	1.08	3	305351085013903
FL5671	–63522.15	877785.62	113.87	120.19	6.32	3	305822085095701
FL5718	–58039.21	878894.56	108.35	118.94	10.59	3	305905085063401
FL8152	–24926.95	846963.25	75.99	74.63	–1.36	2	304154084453901

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