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Scientific Investigations Report 2018–5011

U.S. Department of the Interior
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Cover. The North Valdosta Road bridge over the Withlacoochee River overflow channel in Lowndes County, Georgia.

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RYAN K. ZINKE, Secretary

U.S. Geological Survey
William H. Werkheiser, Deputy Director
exercising the authority of the Director

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88), and National Geodetic Vertical Datum of 1929 (NGVD 29).

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

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

Stage, as used in this report, is the height of water surface above an arbitrary datum established at the gage (gage datum).

Abbreviations

AHPS	Advanced Hydrologic Prediction Service
DEM	digital elevation model
DFIRM	Digital Flood Insurance Rate Map
FEMA	Federal Emergency Management Agency
ft	feet
Ga.	Georgia
GIS	geographic information system
HEC–RAS	Hydrologic Engineering Center's River Analysis System
HWM	high water mark
lidar	light detection and ranging
mi	mile
NAVD 88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
NWISWeb	National Water Information System Web Interface
NWS	National Weather Service
USGS	U.S. Geological Survey

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Abstract

Digital flood-inundation maps for a 12.6-mile reach of the Withlacoochee River from Skipper Bridge Road to St. Augustine Road (Georgia State Route 133) were developed to depict estimates of the areal extent and depth of flooding corresponding to selected water levels (stages) at the U.S. Geological Survey (USGS) streamgage at Withlacoochee River at Skipper Bridge Road, near Bemiss, Ga. (023177483). Real-time stage information from this streamgage can be used with these maps to estimate near real-time areas of inundation. The forecasted peak-stage information for the USGS streamgage at Withlacoochee River at Skipper Bridge Road, near Bemiss, Ga. (023177483), can be used in conjunction with the maps developed for this study to show predicted areas of flood inundation.

A one-dimensional step-backwater model was developed using the U.S. Army Corps of Engineers Hydrologic Engineering Center's River Analysis System (HEC–RAS) software for the Withlacoochee River and was used to compute flood profiles for a 12.6-mile reach of the Withlacoochee River. The hydraulic model was then used to simulate 23 water-surface profiles at 1.0-foot (ft) intervals at the Withlacoochee River near the Bemiss streamgage. The profiles ranged from the National Weather Service action stage of 10.7 ft, which is 131.0 ft above the North American Vertical Datum of 1988 (NAVD 88), to a stage of 32.7 ft, which is 153.0 ft above NAVD 88. The simulated water-surface profiles were then combined with a geographic information system digital elevation model—derived from light detection and ranging (lidar) data having a 4.0-ft horizontal resolution—to delineate the area flooded at each 1.0-ft interval of stream stage.

Introduction

Lowndes County is a rural county in southern Georgia with the City of Valdosta located near its center (fig. 1). The estimated population of Lowndes County was 114,628 in 2016 (U.S. Census Bureau, 2017), and the estimated population of Valdosta was 54,518 (Suburban Stats, 2017). Within the county, the Withlacoochee River floodplain is primarily woody wetlands with areas of deciduous, evergreen, and mixed forest (Homer and others, 2015). Some developed areas within Valdosta encroach on the east side of the floodplain. The Withlacoochee River generally flows southward through Lowndes County (fig. 1). South of the junction with the Little River, the Withlacoochee River forms the western boundary of Lowndes County. Peak flood flows of greater than 15,000 cubic feet per second (ft^3/s) were recorded at the U.S. Geological Survey (USGS) streamgage Withlacoochee River at Skipper Bridge Road, near Bemiss, Georgia (Ga.; station 023177483), in 1948, 1984, 1986, 2009, 2013, 2014, and 2016; the largest peak flow was recorded on April 4, 1948, at 37,500 ft^3/s (U.S. Geological Survey, 2017). Before October 1, 2017, this streamgage was named Withlacoochee River at McMillan Road, near Bemiss, Ga.

Before this study, Lowndes County and Valdosta officials relied on several online information sources to decide how to alert the public and mitigate flood damages along the Withlacoochee River. One source was the Federal Emergency Management Agency (FEMA) Digital Flood Insurance Rate Map (DFIRM) (Federal Emergency Management Agency, 2008). A second source was the following set of USGS streamgages (table 1): Withlacoochee River at Skipper Bridge Road, near Bemiss, Ga. (023177483), Withlacoochee River at US 41 near Valdosta, Ga. (02317755), Withlacoochee River at US 84, near Quitman, Ga. (02318500), and Little River at Ga. 122, near Hahira, Ga. (02318380). From these sites, current and historical water levels (stage) can be obtained through the USGS National Water Information System web portal (NWISWeb; https://doi.org/10.5066/F7P55KJN). Stage is the height of the water surface above an arbitrary datum established at the gage (gage datum). A third source of usable information was the National Weather Service (NWS) Withlacoochee River above Valdosta (Skipper Bridge Road) streamgage (forecast site VDSG1) available through the Advanced Hydrologic Prediction Service (AHPS) web page (https://water.weather.gov/ahps/).

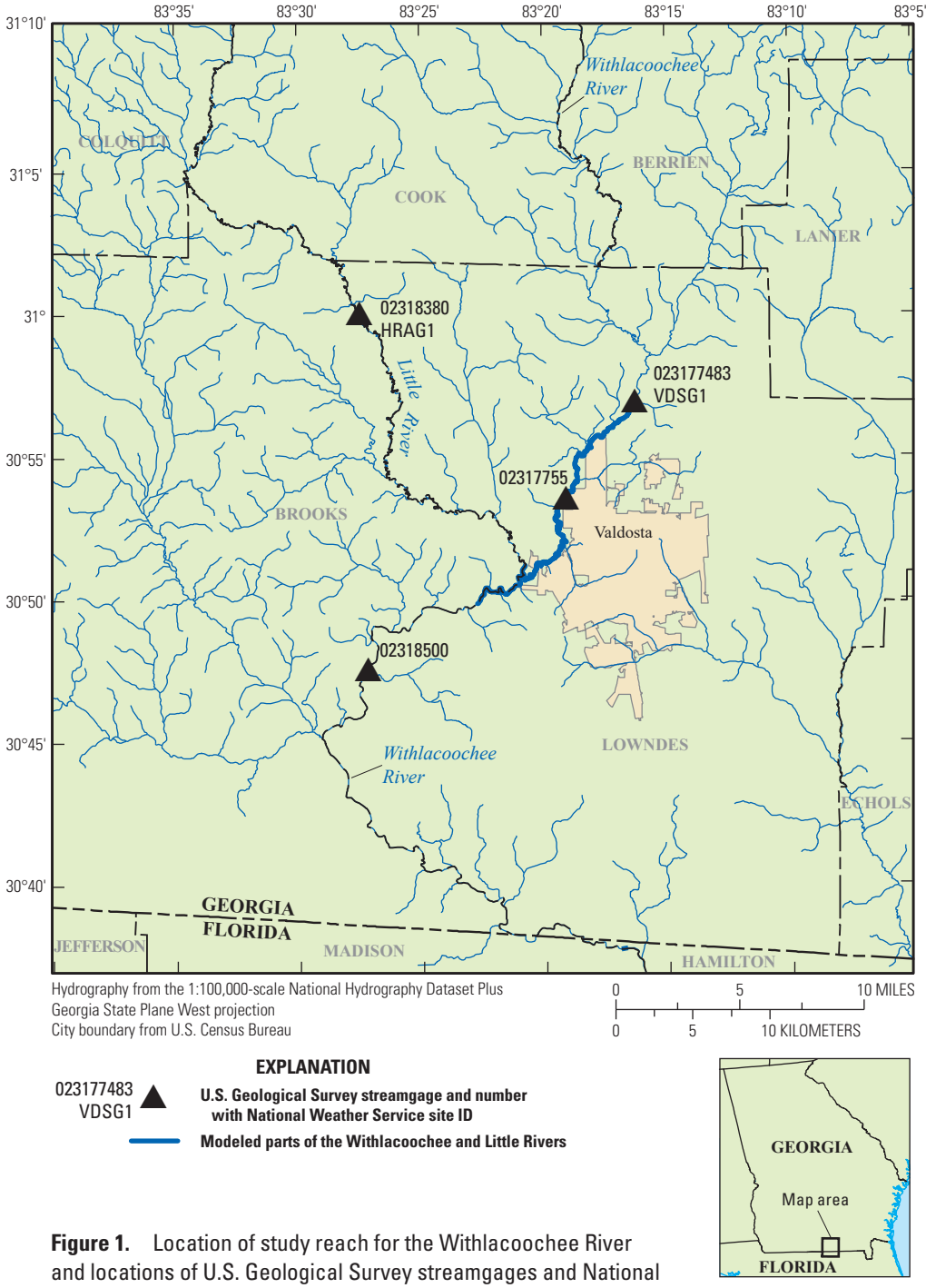

Figure 1. Location of study reach for the Withlacoochee River and locations of U.S. Geological Survey streamgages and National Weather Service (NWS) forecast sites, Lowndes County, Georgia. NWS site identifiers (HRAG and VDSG) are included.

Although USGS real-time stages are useful for residents in the immediate vicinity of a streamgage, the data are of limited use to residents upstream or downstream because water-surface elevation is not constant along an entire stream channel. Likewise, depth varies locally along stream channels, and FEMA and State emergency management mitigation teams or property owners typically lack information on water depth in areas not near USGS streamgages or NWS flood-forecast points. To help the general public take individual safety precautions and give local officials a tool to help manage emergency flood operations and mitigation efforts, a series of digital flood-inundation maps for a 12.6-mile (mi) reach of the Withlacoochee River was developed by the USGS in cooperation with the City of Valdosta and Lowndes County, Georgia.

Table 1. Site information for selected U.S. Geological Survey streamgages in the Withlacoochee River Basin in Georgia.

[Data for this table were compiled from U.S. Geological Survey (2017) and National Weather Service (2017). USGS, U.S. Geological Survey; Ga., Georgia; ft, foot; ft^3/s, cubic foot per second; *, elevation above National Geodetic Vertical Datum of 1929]

Station name (fig. 1)	USGS station number	Drainage area, in square miles	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Period of record	Maximum recorded stage and corresponding flow at streamgage and date
Withlacoochee River at Skipper Bridge Road, near Bemiss, Ga.	023177483	502	30° 56' 57"	83° 16' 18"	1988 to current year (2017)	33.00 ft 37,500 ft^3/s Apr. 4, 1948
Withlacoochee River at US 41, near Valdosta, Ga.	02317755	537	30° 53' 33"	83° 19' 08"	1976 to current year (2017)	138.9 ft* 38,000 ft^3/s Apr. 4, 1948
Withlacoochee River at US 84, near Quitman, Ga.	02318500	1,480	30° 47' 35"	83° 27' 13"	1928 to current year (2017)	34.67 ft 60,700 ft^3/s Apr. 5, 2009
Little River at Ga. 122, near Hahira, Ga.	02318380	776	31° 00' 03"	83° 27' 30"	2009 to current year (2017)	155.8 ft* 45,000 ft^3/s Apr. 3, 1948

Purpose and Scope

This report describes the development of estimated flood-inundation maps for the Withlacoochee River in Lowndes County, Ga. Inundation maps and other flood-related data are available on the USGS Flood Inundation Mapping Science web page (https://water.usgs.gov/osw/flood_inundation/). Users can select estimated inundation maps at or near (1) the current stage at the USGS streamgage near Bemiss, Ga. (023177483), (2) the NWS forecasted peak stage or (3) other desired stages at the USGS streamgage near Bemiss, Ga. (023177483).

The study covers a 17.2-mi reach of the Withlacoochee River from 0.1 mi upstream of Skipper Bridge Road to 4.5 mi downstream of St. Augustine Road (Georgia State Route 133), including a 0.6-mi reach of the Little River from 0.1 mi upstream of St. Augustine Road to its junction with the Withlacoochee River (fig. 2). The mapped area, the 12.6-mi reach of the Withlacoochee River from Skipper Bridge Road to St. Augustine Road, is the primary focus of the study.

Development of the flood-inundation maps included (1) analysis of the flow and stage data collected at four USGS streamgages—Withlacoochee River at Skipper Bridge Road, near Bemiss, Ga. (023177483), Withlacoochee River at US 41, near Valdosta, Ga. (02317755), Withlacoochee River at US 84, near Quitman, Ga. (02318500), and Little River at Ga. 122, near Hahira, Ga. (02318380) (table 1); (2) collection of topographic and geometric data for floodplains, bridges, and the stream channel; (3) determination of energy-loss factors (roughness coefficients) in the stream channel and floodplain; (4) computation of water-surface profiles using the Hydrologic Engineering Center's River Analysis System (HEC–RAS) computer program, created by the Hydrologic Engineering Center at the U.S. Army Corps of Engineers Institute for Water Resources (U.S. Army Corps of Engineers, Hydrologic Engineering Center, 2017); (5) production of estimated flood-inundation maps based on simulated stream stages at the Withlacoochee River at Skipper Bridge Road, near Bemiss, Ga. (023177483), streamgage, using the geographic information system (GIS) program ArcGIS Desktop (Esri, 2016a); and (6) development of a web interface that links to USGS real-time streamgage information.

Methods

Most methods used here are cited from published reports (Bales and others, 2007; Whitehead and Ostheimer, 2009). If techniques varied substantially because of local hydrologic conditions or available data, the variances are described in detail within this report. Inundation maps for 23 water-surface profiles referenced to the stage and water-surface elevation at the streamgage Withlacoochee River at Skipper Bridge Road, near Bemis, Ga. (023177483), were produced. These profiles ranged from the NWS action stage of 10.7 feet (ft), which is 131.0 ft above NAVD 88, to a stage of 32.7 ft, which is 153.0 ft above NAVD 88.

Study Area Description

The Withlacoochee River is located in southern Georgia in the Tifton Upland District within the Coastal Plain physiographic province (Clark and Zisa, 1976). The drainage area ranges from 502 square miles (mi^2) at the upstream end of the study reach at the Withlacoochee River at Skipper Bridge Road, near Bemiss, Ga. (023177483), streamgage to 537 mi^2 at the Withlacoochee River at US 41, near Valdosta, Ga. (02317755), streamgage to 556 mi^2 at the St. Augustine Road bridge, which is at the downstream end of the mapped reach

Figure 2. Withlacoochee River bridge crossings, mapped river extent, flood-inundation mapping boundary, and direction of surface-water flow, Lowndes County, Georgia.

(fig. 2). The study reach of the Withlacoochee River is located entirely in Lowndes County, Ga. (fig. 1). The Withlacoochee River generally flows south through Lowndes County until it joins with the Little River, where it then flows westward, then southward, and finally flows southeastward where it forms the western boundary for Lowndes County. The river then flows southward into Florida. The major tributaries flowing into the Withlacoochee River along the mapped reach are Bay Branch, Cherry Creek, and Sugar Creek. Other streamgages in the Withlacoochee River Basin include Withlacoochee River at US 84, near Quitman, Ga. (02318500), and Little River at Ga. 122, near Hahira, Ga. (02318380). The Withlacoochee River Basin terrain has a well-developed, dendritic drainage pattern and is formed on the undifferentiated Neogene sediments in the Tifton Upland District (Clark and Zisa, 1976). The Withlacoochee River study reach is about 17.2 mi long, is fairly consistent in slope and width (with local variations), and has an average channel slope of about 1.8 feet per mile (ft/mi). The land contiguous to the study reach is mostly classified as woody wetlands with some areas of deciduous, evergreen, and mixed forest. Developed areas are located near and along the edge of the floodplain, primarily in the southern half of the study reach on the eastern side (Homer and others, 2015). Within the study reach there are 11 road bridges and 1 railroad bridge that cross either the main channel or the adjacent floodplain.

Previous Studies

Similar studies that provide flood-inundation maps for a range of stream stages in Georgia were completed by the USGS in Albany, Ga., for the Flint River (Musser and Dyar, 2007); Atlanta, Ga., for Peachtree Creek (Musser, 2012a); Gwinnett County, Ga., for Suwanee Creek (Musser, 2012b); Cobb County, Ga., for Sweetwater Creek (Musser, 2012c); Alpharetta and Roswell, Ga., for Big Creek (Musser, 2015a); and DeKalb County, Ga., for South Fork Peachtree Creek (Musser, 2015b). The methods for the Flint River model used a finite-element, two-dimensional model, which differed from those used to develop the Withlacoochee River model. The methods used for the Peachtree Creek, Suwanee Creek, Sweetwater Creek, Big Creek, and South Fork Peachtree Creek models were similar to those used to develop the Withlacoochee River model. Additionally, the current—as of 2017—DFIRM for Lowndes County, Ga., was published on September 26, 2008 (Federal Emergency Management Agency, 2008), but it was not used in this study, other than to define a general area of the floodplain for modeling purposes.

Constructing Water-Surface Profiles

The water-surface profiles used to produce the 23 flood-inundation maps in this study were computed using HEC–RAS, version 5.0.3 (U.S. Army Corps of Engineers, Hydrologic Engineering Center, 2017). HEC–RAS is a one-dimensional, step-backwater model used for simulation of water-surface profiles with gradually varied, steady-state, or unsteady-state flow computation options. Inputs into the HEC–RAS model include cross sections representing the land surface, bridge geometry, roughness coefficients, and multiple flow values. For this study, the HEC–RAS analysis was completed by using the steady-state flow computation option.

Hydrologic and Steady-Flow Data

The hydrologic network in the study area consists of two USGS streamgages operated within the study reach, one USGS streamgage downstream on the Withlacoochee River, and one USGS streamgage on the Little River (fig. 1; table 1). Water level (stage) is measured continuously at each site, and continuous records of streamflow are computed. Stage is the height of the water surface above an arbitrary datum established at the gage (gage datum). All water-surface elevations are referenced to NAVD 88. The streamgages are equipped with a satellite radio transmitter that allows data to be transmitted routinely and made available online within 1 hour of collection. The streamgages are also equipped with recording rain gages. Steady-flow data for the study reach were calibrated in the model using the rating curve (stage-streamflow or stage-discharge relation) at the streamgages Withlacoochee River at Skipper Bridge Road, near Bemiss, Ga. (023177483), and Withlacoochee River at US 41, near Valdosta, Ga. (02317755). Downstream boundary conditions in the model were determined using a normal depth based on slope (U.S. Army Corps of Engineers, Hydrologic Engineering Center, 2017).

A comparison was made between the peak flows at the two Withlacoochee River streamgages within the modeled reach. During some events, the peak flow was higher at the downstream streamgage, and at other events, it was lower. In most hydrologic settings, peak flows increase with the ratio of the drainage area (Gotvald and Knaak, 2011), but the wetlands and (or) the close interaction with groundwater in the study area complicate the hydrology and could be reducing peak flows downstream. Table 2 shows the peak-flow values for each Withlacoochee River streamgage, the date of the peaks, and the ratio of the downstream peak-flow value to the upstream peak flow value. Because of this variable hydrologic response during flooding it was decided that the flows in the HEC–RAS model would have a 1.2 ratio at the US 41 streamgage compared with the Skipper Bridge Road streamgage, up to a flow of 20,000 ft^3/s, then linearly decrease to a 1.0 ratio at 30,000 ft^3/s, and stay at 1.0 for any higher flows. This ratio reflects the potential for increasing flows in the Withlacoochee and the worst case for flooding downstream. Figure 3 is a graph of this HEC–RAS model-flow ratio as it varies with the peak flow at the Skipper Bridge Road streamgage, showing peak-flow ratios from recorded events.

Flow-change points were added in the HEC–RAS model at stream tributaries in the reach where the drainage area increased abruptly. The ratio of the drainage area at

Table 2. Comparison of peak streamflows at the Withlacoochee River at Skipper Bridge Road, near Bemiss, Georgia, (023177483) streamgage, and the Withlacoochee River at US 41, near Valdosta, Georgia (02317755), streamgage.

[*, gage at different site and (or) datum; —, no gage height recorded]

Withlacoochee River at Skipper Bridge Road, near Bemiss, Georgia (023177483)			Withlacoochee River at US 41, near Valdosta, Georgia (02317755)			Ratio of peak streamflow at the US 41 streamgage to the Skipper Bridge Road streamgage
Date	Streamflow, in cubic feet per second	Gage height, in feet	Date	Streamflow, in cubic feet per second	Gage height, in feet	
Apr. 4, 1948	37,500	—	Apr. 4, 1948	38,000	138.90*	1.01
Dec. 2, 1976	4,810	—	Dec. 2, 1976	5,390	16.32	1.12
Mar. 12, 1978	3,440	—	Mar. 13, 1978	3,700	15.30	1.08
Mar. 15, 1980	7,080	—	Mar. 15, 1980	6,580	17.55	0.93
Mar. 8, 1984	16,000	—	Mar. 8, 1984	16,000	22.11	1.00
Feb. 12, 1986	19,500	—	Feb. 12, 1986	19,500	28.00	1.00
July 26, 1989	1,140	9.91	July 26, 1989	1,120	11.86	0.98
July 19, 2011	1,280	11.34	July 20, 2011	1,020	12.31	0.80
Feb. 27, 2013	17,300	21.77	Feb. 28, 2013	21,300	22.20	1.23
Apr. 21, 2014	6,200	17.35	Apr. 21, 2014	4,230	16.46	0.68
Dec. 26, 2014	12,700	20.09	Dec. 26, 2014	8,890	18.86	0.70
Apr. 4, 2016	12,500	20.02	Apr. 4, 2016	9,550	19.11	0.76

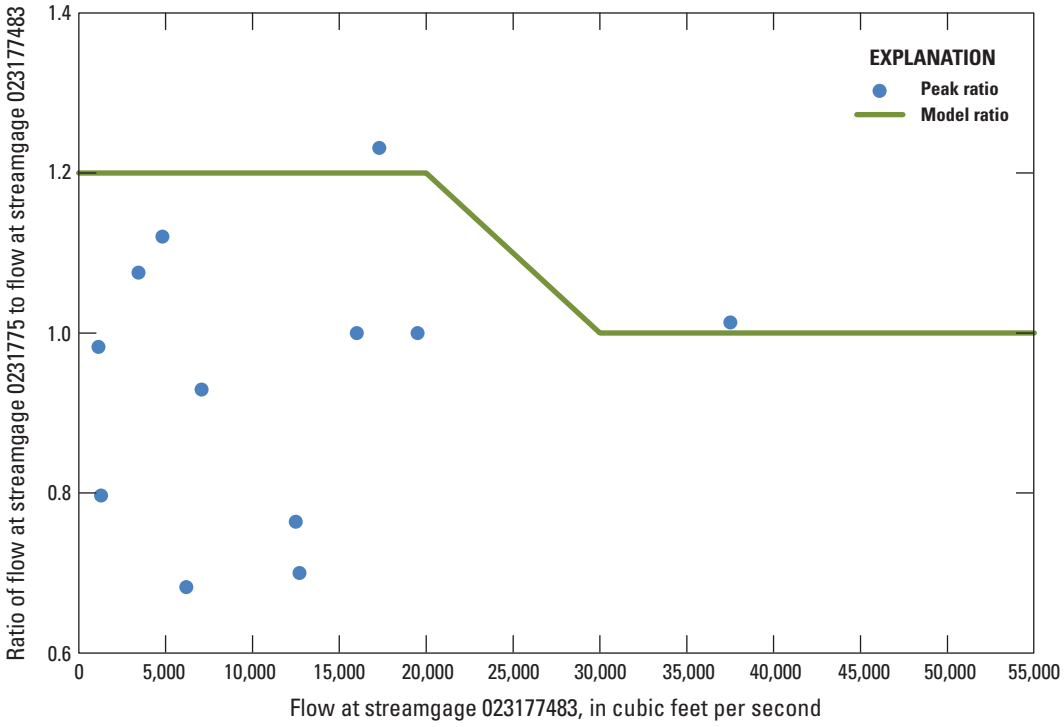

Figure 3. Ratio of peak flows at Withlacoochee River at US 41, near Valdosta, Georgia (02317755) streamgage to peak flows at Withlacoochee River at Skipper Bridge Road, near Bemiss, Georgia (023177483) streamgage and ratio line for generating flows in a Hydrologic Engineering Center's River Analysis System (HEC–RAS) model between the two streamgages.

these points, with the drainage area at the Skipper Bridge Road streamgage raised to the power of 2.55 multiplied by the flow at the Skipper Bridge Road streamgage, is the model flow at these points. The power of 2.55 was selected by adjusting its value until a flow ratio of 1.2 resulted at the US 41 streamgage. The equation for the flow values along the Withlacoochee River is

$$flowPoint = \left(\frac{DAPoint}{DASBR} \right)^{2.55} * flowSBR,$$

where the downstream flow is flowPoint, with the drainage area at that point being DAPoint, and the drainage area and flow at Skipper Bridge Road are DASBR and flowSBR, respectively. For flows between 20,000 and 30,000 ft^3/s, the power factor was reduced until it was 1.0 above 30,000 ft^3/s, resulting in constant model flow values along the reach. Table 3 shows model flow values for selected locations.

Comparisons were also made with peak-flow values on the Little River at the streamgage Little River at Ga. 122, near Hahira, Ga. (02318380), and downstream on the Withlacoochee River at the streamgage Withlacoochee River at US 84, near Quitman, Ga. (02318500). Table 4 shows recorded peaks at these two streamgages, along with peaks from the Withlacoochee River at Skipper Bridge Road, near Bemiss, Ga. (023177483), streamgage when all three streamgages had peaks that coincided. In all coincident sets of peaks, the sum of peaks upstream from the junction between the two rivers is more than the peak downstream on the Withlacoochee River near Quitman, Ga. This result indicates that the peaks on the Little River and the Withlacoochee River do not arrive at the junction of the two rivers near the same time. Due to the long distance between the Little River streamgage and the junction with the Withlacoochee River, the decision was made to not create a flood-inundation model with variable flow inputs on the Little River. Instead, single flow inputs were used for the Little River in the HEC–RAS model. To determine the single flow values, the ratios of peak flows at the Little River streamgage were compared with the peak flow at the Withlacoochee River at Skipper Bridge Road streamgage. The ratios of peak flows ranged from 0.94 to 1.89 with the Little River streamgage having the higher peak flows, except for the April 2016 peak flows. A flow ratio of 1.8 was selected for the Little River model flows to account for the backwater effects from the Little River on the Withlacoochee River. With this 1.8 ratio, the higher model flows on the Withlacoochee River at Skipper Bridge Road were causing the model flow on the Little River to be significantly greater than any historical recorded flow, so the maximum Little River model flow was capped at 55,000 ft^3/s, which is 10,000 ft^3/s greater than the highest recorded peak. The Little River model flows are shown in table 3.

Table 3. Water-surface elevations (and stages) with corresponding streamflow estimates for selected simulated water-surface profiles at selected locations for the Withlacoochee River at Skipper Bridge Road, near Bemiss, Georgia (023177483), streamgage.

Location of streamflow estimate	Water-surface elevation, in feet above North American Vertical Datum of 1988 (Stage, in feet above gage datum)								
	131.0 (10.7)	134.0 (13.7)	137.0 (16.7)	140.0 (19.7)	143.0 (22.7)	145.0 (24.7)	148.0 (27.7)	150.0 (29.7)	153.0 (32.7)
Streamflow, in cubic feet per second, Withlacoochee River									
Near Bemiss streamgage (023177483)	1,250	2,230	4,910	11,700	19,600	24,400	34,300	41,700	52,500
Below Bay Branch	1,280	2,290	5,040	12,000	20,100	24,800	34,300	41,700	52,500
Below Cherry Creek	1,490	2,660	5,860	14,000	23,400	27,100	34,300	41,700	52,500
Near Valdosta streamgage (02317755)	1,500	2,680	5,900	14,100	23,600	27,200	34,300	41,700	52,500
Below Sugar Creek	1,630	2,900	6,390	15,200	25,500	28,500	34,300	41,700	52,500
Below junction of Withlacoochee and Little Rivers	3,890	6,940	15,300	36,500	61,000	67,400	80,300	93,100	108,000
Streamflow, in cubic feet per second, Little River									
Little River above St. Augustine Road	2,250	4,010	8,840	21,100	35,300	38,800	46,000	51,400	55,000

Table 4. Comparison of peak streamflows at the Withlacoochee River at Skipper Bridge Road, near Bemiss, Georgia (023177483), streamgage, the Little River at Ga. 122, near Hahira, Georgia (02318380), streamgage, and the Withlacoochee River at US 84, near Quitman, Georgia (02318500), streamgage.

[Ga., Georgia]

Withlacoochee River at Skipper Bridge Road, near Bemiss, Ga. (023177483)		Little River at Ga. 122, near Hahira, Ga. (02318380)		Ratio of peak streamflows at Little River at Ga. 122 to Withlacoochee, near Bemiss	Withlacoochee River at US 84, near Quitman, Ga. (02318500)	
Date	Streamflow, in cubic feet per second	Date	Streamflow, in cubic feet per second		Date	Streamflow, in cubic feet per second
Apr. 4, 1948	37,500	Apr. 3, 1948	45,000	1.20	Apr. 4, 1948	62,000
Feb. 27, 2013	17,300	Feb. 27, 2013	30,600	1.77	Mar. 1, 2013	41,000
Apr. 21, 2014	6,200	Apr. 11, 2014	11,700	1.89	Apr. 23, 2014	13,000
Dec. 26, 2014	12,700	Dec. 26, 2014	21,700	1.71	Dec. 28, 2014	26,200
Apr. 4, 2016	12,500	Apr. 3, 2016	11,700	0.94	Apr. 5, 2016	22,300

Topographic-Bathymetric Data

The base for the HEC–RAS model was a raster elevation dataset obtained from the National Oceanic and Atmospheric Administration (NOAA). The source for the raster elevation was a 4.0-ft by 4.0-ft cell raster digital elevation model (DEM) derived from light detection and ranging (lidar) data collected in 2015. The Bare-Earth DEM Fundamental Vertical Accuracy yielded an average accuracy of 0.384 at a 95-percent confidence level (National Oceanic and Atmospheric Administration, 2016). The NOAA DEM did not extend far enough west along the Withlacoochee and Little Rivers downstream of St. Augustine Road, so an approximate 1,500-ft-wide area of 1/3 arc-second DEM from the USGS's The National Map was downloaded for the west side of the river floodplains (https://viewer.nationalmap.gov/basic/). This DEM was resampled and merged into the NOAA DEM.

Cross sections for HEC–RAS were created from the merged DEM using the HEC–GeoRAS software (Esri, 2016b) within ArcGIS. HEC–GeoRAS is a set of tools developed for ArcGIS to translate data to and from HEC–RAS. The cross sections were created for a 17.2-mi reach of the Withlacoochee River, ranging from 13.9 mi upstream of the Little River junction to 3.3 mi downstream of the junction. This 17.2-mi reach includes the 12.6-mi reach between Skipper Bridge Road and St. Augustine Road, which is the primary focus of the study, a 0.1-mi reach upstream of Skipper Bridge Road, and a 4.5-mi reach downstream of St. Augustine Road. Cross sections were also created on a 0.6-mi reach of the Little River from 0.1 mi upstream of St. Augustine Road to its junction with the Withlacoochee River. Reaches outside the primary focus area were part of the HEC–RAS model to account for backwater effects from the Little River and to model the inundation of Skipper Bridge Road. Initially, a shorter reach on the Withlacoochee River, downstream of the Little River, was used for creating cross sections, but the backwater effect on the water-surface elevation in the model from the river junction was not high enough to match the high-water marks (HWM) collected in April 2009 and February 2013 by Lowndes County and the City of Valdosta, so the reach was extended to where the Withlacoochee floodplain narrows. Downstream stream lengths were computed within HEC–GeoRAS. Because the DEM does not accurately show the ground-surface elevations within the river channel, USGS field crews measured 81 river channel cross sections from boats using an acoustic Doppler current profiler. These river channel cross sections were inserted into the cross sections within HEC–RAS by replacing the channel areas from the merged DEM.

Various drainage structures (bridges, culverts, roadway embankments, levees, and dams) in and along the stream can affect water-surface elevations during floods. To account for these structural features in the model, the structural dimensions of 13 bridges were measured and surveyed in the field. Using data obtained from the surveys, the bridges were inserted between the cross sections in the HEC–RAS model. Most of the bridge crossings over the rivers contained multiple bridge structures. From upstream to downstream on the Withlacoochee River, the bridge crossing location and number of bridge structures are as follows: Skipper Bridge Road (1), Staten Road (3), U.S. Highway 41 (North Valdosta Road) (4), Norfolk Southern Railway (1), Interstate 75 (1), and St. Augustine Road (Georgia State Route 133) (2). On the Little River, there is one bridge structure on St. Augustine Road, (Georgia State Route 133) (fig. 2). A detailed description of the methods used to acquire and process the topographic and bathymetric data is provided in Bales and others (2007).

Energy-Loss Factors

Field observations and high-resolution aerial photographs were used to select initial (precalibration) Manning's roughness coefficients (*n* values) for energy (friction) loss calculations. The final Manning's *n* values ranged from 0.039 to 0.04 for the main channel. The Manning's *n* values ranged from 0.085 to 0.15 for the overbank areas modeled in the reach.

Model Calibration and Performance

The hydraulic model was calibrated using the most current (2017) stage-discharge relations at the Withlacoochee River at Skipper Bridge Road, near Bemiss, Ga. (023177483), and Withlacoochee River at US 41, near Valdosta, Ga. (02317755), streamgages in conjunction with adjusting the Manning's *n* value for the channel and overbank areas until the results of the hydraulic computations closely agreed with the expected water-surface elevations at the two streamgages. The current rating curve for Withlacoochee River at US 41 has a maximum stage of 22.19 ft (132.49 ft above NAVD 88); no model calibrations were performed at the US 41 streamgage when the stage was greater than 22.19 ft. Table 5 shows the stage, the actual water-surface elevations at the streamgages, the corresponding modeled water-surface elevations, and the differences between actual and modeled elevations up to a water-surface elevation of 146.0 ft.

During the initial calibration for 147.0 ft, the modeled water-surface elevation was below the expected water-surface elevation using the flow value from the rating curve, and initial attempts to adjust the roughness coefficients to raise the model water-surface elevations to 147.0 ft were unsuccessful. This low model water-surface elevation was likely the result of water overtopping Skipper Bridge Road to the west of the bridge. Additionally, in 2011, after the April 2009 peak flow, which had a gage height of 25.66 ft (145.96 ft elevation), the Skipper Bridge Road bridge was rebuilt. The current rating curve for the Skipper Bridge Road streamgage has a maximum stage of 27.39 ft with an elevation of 147.69 ft, but the bridge replacement affected the upper end of the rating curve. To calibrate the model for the 147.0 ft water-surface elevation, the *n*-values from the calibration at 146.0 ft were used, and the flow value was increased until the model water-surface elevation was 147.0 ft. This calibration method was also used for the model water-surface elevations from 148.0 to 153.0 ft.

Table 5. Comparison of hydraulic-model output and water-surface elevations at the Withlacoochee River at Skipper Bridge Road, near Bemiss, Georgia (023177483), streamgage and the Withlacoochee River at US 41, near Valdosta, Georgia, (02317755) streamgage.

[Stage listed in feet above the gage datum; Elevation listed in feet above the North American Vertical Datum of 1988; —, no calibration value]

Withlacoochee River at Skipper Bridge Road (023177483)				Withlacoochee River at US 41 (02317755)			
Stage, in feet	Actual water-surface elevation, in feet	Modeled water-surface elevation, in feet	Elevation difference, in feet	Stage, in feet	Actual water-surface elevation, in feet	Modeled water-surface elevation, in feet	Elevation difference, in feet
10.7	131.0	131.2	0.2	13.5	123.8	123.8	0.0
11.7	132.0	132.1	0.1	14.1	124.4	124.5	0.1
12.7	133.0	133.0	0.0	14.7	125.0	125.0	0.0
13.7	134.0	133.8	–0.2	15.2	125.5	125.5	0.0
14.7	135.0	134.8	–0.2	15.8	126.1	126.2	0.1
15.7	136.0	135.7	–0.3	16.6	126.9	126.9	0.0
16.7	137.0	136.9	–0.1	17.5	127.8	127.7	–0.1
17.7	138.0	138.2	0.2	18.6	128.9	128.8	–0.1
18.7	139.0	139.2	0.2	19.7	130.0	129.9	–0.1
19.7	140.0	140.1	0.1	21.3	131.6	131.6	0.0
20.7	141.0	141.1	0.1	22.0	132.3	132.4	0.1
21.7	142.0	142.1	0.1	—	—	—	—
22.7	143.0	143.2	0.2	—	—	—	—
23.7	144.0	143.9	–0.1	—	—	—	—
24.7	145.0	145.1	0.1	—	—	—	—
25.7	146.0	145.9	–0.1	—	—	—	—

Once the model was calibrated, a sensitivity analysis was done to compare flow ratios in the Little River. The flow selected for this analysis—at the Withlacoochee at Skipper Bridge Road streamgage—was 17,300 ft^3/s, which was the peak on February 27, 2013. Different flows in the Little River were selected based on the ratio of the flow in the Little River to the flow in the Withlacoochee River at Skipper Bridge Road. These ratios ranged from 1.3 to 2.1. The resulting water-surface elevations on the upstream side of bridges were—St. Augustine Road, 1.93 ft; Interstate 75, 1.6 ft; and Norfolk Southern Railroad, 1.26 ft. This sensitivity analysis shows that the backwater from the Little River does have an impact upstream on the Withlacoochee River that varies with the flow in the Little River. During a flood event, if the Little River's flow is significantly different from the HEC–RAS model, then the inundated area downstream of the Norfolk Southern Railroad bridge could be slightly larger or smaller than what is modeled. Table 6 shows Little River modeled flows, and the modeled water-surface elevations at locations on the Withlacoochee River based on the flow ratios.

Development of Water-Surface Profiles

Profiles were developed for 23 water-surface elevations at 1.0-ft intervals between 131.0 and 153.0 ft above NAVD 88 as referenced to the Withlacoochee River at Skipper Bridge Road, near Bemiss, Ga. (023177483), streamgage. Streamflows corresponding to profiles at water-surface elevations were obtained from the most current (2017) rating curve in use at the streamgage (rating no. 7.0, effective February 28, 2013; U.S. Geological Survey, 2017) up to 146.0 ft. These streamflow values were used in the model. Streamflow values from 147.0 to 153.0 ft were calculated from the model during the calibration. The streamflow values for all profiles were adjusted along the Withlacoochee River, primarily at junctions with smaller tributaries.

Simulated stage and streamflow estimates for selected locations and profiles are in table 3. A normal depth, based on slope of the streambed method, was used for the downstream boundary conditions (U.S. Army Corps of Engineers, Hydrologic Engineering Center, 2017). All streamflow and water-elevation data used for the model are available in U.S. Geological Survey, 2017.

Flood-Inundation Mapping

Flood-inundation GIS layers were created based on simulated water-surface elevations at the Withlacoochee River at Skipper Bridge Road, near Bemiss, Ga. (023177483), streamgage, which has the NWS designation VDSG1. For each 1.0-ft interval in water-surface elevation from 131.0 ft to 153.0 ft above NAVD 88, a polygon layer showing the inundated area, and a raster showing the depth of inundation, were created. Additionally, a boundary polygon layer showing the extent of the inundation area was created. The layers were created in ArcGIS by exporting a 4.0-ft by 4.0-ft cell depth raster from HEC–RAS and selecting all cells with a depth greater than 0.05 ft. The resulting polygon inundated area was cleaned up by deleting all polygons smaller than 400 square feet (ft^2) and filling all holes in the inundated layer smaller than 400 ft^2. Any polygon pieces not directly connected to the river were deleted. The boundary layer was created to limit the extent of the inundation polygons and depth rasters to the Withlacoochee River from Skipper Bridge Road to St. Augustine Road. The tributaries of the Withlacoochee River, which are shown as inundated, are a result of backwater effects from the Withlacoochee River. At the lower flow values of the Withlacoochee River, the tributaries may not be shown as inundated, but it is likely water is still flowing in them. Though the depth rasters are rounded to the nearest 0.1 ft, the resulting inundation maps have a vertical accuracy of about 0.5 ft.

Table 6. Comparison of modeled water-surface elevations on the Withlacoochee River for different ratios of streamflow in the Little River at St. Augustine Road, based on a streamflow of 17,300 cubic feet per second at Withlacoochee River at Skipper Bridge Road, near Bemiss, Georgia (023177483), streamgage.

[Ga., Georgia]

Upstream side bridge location of modeled elevation for the Withlacoochee River	Streamflow in cubic feet per second in the HEC–RAS model for the Little River (ratio of Little River streamflow to Withlacoochee River streamflow)						
	22,500 (1.3)	26,000 (1.5)	29,400 (1.7)	31,100 (1.8)	32,900 (1.9)	34,600 (2.0)	36,300 (2.1)
Modeled elevation, in feet above the North American Vertical Datum of 1988							
St. Augustine Road (Ga. SR 133) bridge	127.8	128.3	128.8	129.0	129.3	129.5	129.7
Interstate 75 bridge	128.9	129.3	129.7	129.9	130.1	130.3	130.5
Norfolk Southern Railway bridge	130.4	130.7	131.0	131.1	131.3	131.5	131.7

The final step in the creation of the inundation polygons was to remove the area of the non-inundated bridges from the inundation polygon. During this process, it was determined which inundation polygons show inundation at bridges and (or) the roads near the bridges. The St. Augustine Road (Ga. State Route 133), Interstate 75, and Skipper Bridge Road bridges over the Withlacoochee River, and also Baytree Road over Sugar Creek, were not flooded by any inundation polygon. The 143.0-ft inundation polygon shows inundation on Gornto Road west of the bridge over Sugar Creek, and the 144.0-ft inundation polygon shows that the bridge is inundated. The 146.0-ft inundation polygon shows inundation on Skipper Bridge Road west of the bridge. The 147.0-ft inundation polygon shows that the Norfolk Southern Railway bridge is inundated, and the 151.0-ft inundation polygon shows that the U.S. Highway 41 (North Valdosta Road) bridges are inundated. The 151.0-ft inundation polygon shows inundation on Staten Road north of the three bridges over the Withlacoochee River, while the 153.0-ft inundation polygon shows inundation on the low sides of the bridges. The two bridges over Sugar Creek were not part of the HEC–RAS model, so their flooding status was determined by whether or not the land surface at the ends of the bridges was flooded.

Once the inundation polygons were created, they were compared with HWMs, which were collected in April 2009 and February 2013. The HWMs were collected as latitude and longitude at the edge of inundation, with no vertical elevation, so they could only be used for a final check of accuracy, not for calibration of the model. The April 2009 peak was 26,200 ft^3/s, which is close to flow at the 146.0 ft water-surface elevation inundation layer. Most of the HWMs were within about 20 ft of the inundation polygon edge. Figure 4 shows the HWMs near the area of Gornto Road. The February 2013 peak was 17,300 ft^3/s, which is between the flows at 142.0 and 143.0-ft water-surface elevation inundation layers. The HWMs, some of which are shown in figure 5, were all between the two inundation polygon edges. The 23 inundation polygons, 23 depth rasters, boundary polygon, and all associated metadata are available for download in Musser, 2017.

Withlacoochee River, Georgia, Flood-Inundation Maps on the Internet

The USGS Flood Inundation Mapping Program website (https://water.usgs.gov/osw/flood_inundation/) was established by the USGS to provide estimated flood-inundation information to the public. The GIS layers from this study are viewable on the Flood Inundation Mapper (available from the above link) over selected base maps linked from the website. The GIS layers can also be downloaded in commonly used electronic file formats. Each stream reach displayed on the website contains links to the NWISWeb graphs of the current stage and streamflow at the USGS Withlacoochee River at Skipper Bridge Road, near Bemiss, Ga. (023177483), streamgage, to which the inundation maps are referenced. A link is also provided for the NWS AHPS web page (https://water.weather.gov/ahps/). The estimated flood-inundation maps are displayed in sufficient detail to note the extent of flooding concerning individual structures so preparations for flooding and decisions about emergency responses can be completed efficiently.

Disclaimer for Flood-Inundation Maps

Inundated areas shown should not be used for navigation, regulatory, permitting, or other legal purposes. The USGS provides these maps "as-is" for use as quick-reference emergency planning tools but assumes no legal liability or responsibility resulting from the use of this information.

Uncertainties and Limitations Regarding Use of Flood-Inundation Maps

The flood boundaries shown were estimated based on water stages and streamflows at the USGS streamflow gaging station, (Withlacoochee River at Skipper Bridge Road, near Bemiss, Ga. (023177483)), steady-state hydraulic modeling (assuming unobstructed flow), and a digital elevation model. The hydraulic model reflects the land-cover characteristics and any bridge, dam, levee, or other hydraulic structures existing in August 2017. Unique meteorological factors (timing and distribution of storm) could cause actual streamflows along the modeled reach to vary from those assumed during a flood, which may lead to deviations from the water-surface elevations and inundation boundaries shown here. Additional areas could be flooded due to unanticipated backwater from major tributaries along the main stem or localized debris- or ice-jams. Inundated areas shown should not be used for navigation, regulatory, permitting, or other legal purposes. Although the USGS intends to make this server available 24 hours a day, 7 days a week, timely delivery of data and products from this server through the Internet is not guaranteed. The USGS provides these maps "as-is" for use as quick-reference emergency planning tools but assumes no legal liability or responsibility resulting from the use of this information.

If this series of flood-inundation maps is to be used in conjunction with NWS river forecasts, the user should be aware that additional uncertainties may be inherent or factored into NWS forecast procedures. The NWS uses river forecast models to estimate the quantity and timing of water flowing through selected river reaches in the United States. These forecast models (1) estimate the amount of runoff generated by a precipitation event, (2) compute how the water moves downstream, and (3) predict the flow and stage (water-surface elevation) for the river at a given location (Advanced Hydrologic Prediction Service (AHPS) forecast point) throughout the forecast period (3 to 5 days, at 6-hour intervals in many locations). For information on AHPS forecasts, please visit the NWS Precipitation and River Forecasting overview web page (https://water.weather.gov/ahps/pcpn_and_river_forecasting.pdf).

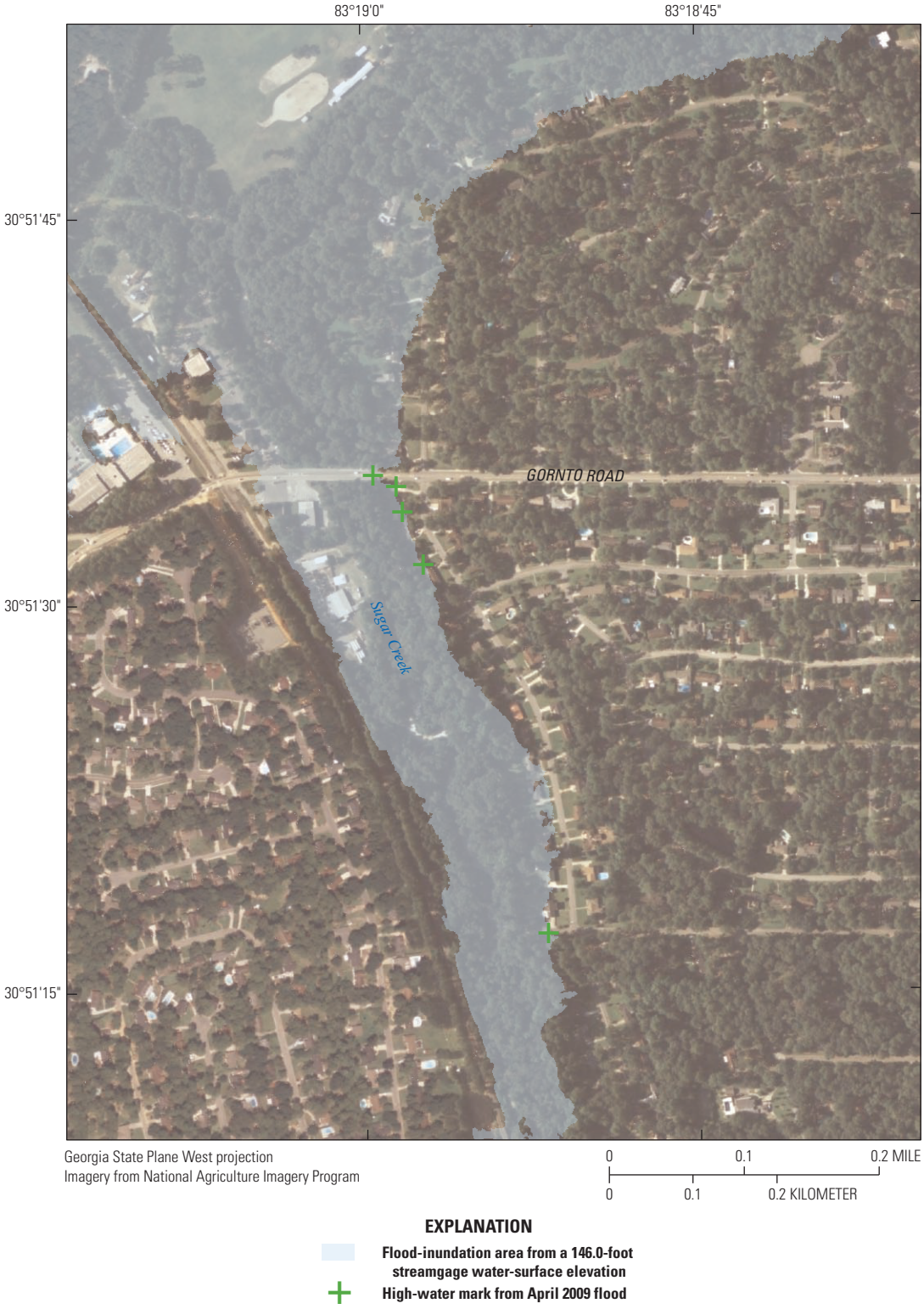

Figure 4. High-water marks from April 2009 and flood-inundation areas based on water-surface elevation at the Withlacoochee River at Skipper Bridge Road, near Bemiss, Georgia (023177483) streamgage, Lowndes County, Georgia.

Figure 5. High-water marks from February 2013 and flood-inundation areas based on water-surface elevation at the Withlacoochee River at Skipper Bridge Road, near Bemiss, Georgia (023177483) streamgage, Lowndes County, Georgia.

Summary

A series of estimated GIS flood-inundation layers was developed by the USGS, in cooperation with the City of Valdosta, Ga., and Lowndes County, Ga., for a 12.6-mi reach of the Withlacoochee River that extends from Skipper Bridge Road to St. Augustine Road (Georgia State Route 133). These GIS flood-inundation layers, available at the USGS Flood Inundation Mapping Program website, in conjunction with the real-time stage data from the USGS streamgage Withlacoochee River at Skipper Bridge Road, near Bemiss, Ga. (023177483), and NWS flood-stage forecasts, can help the general public take individual safety precautions and provide local officials with a tool for managing emergency flood operations and flood-mitigation efforts.

The GIS flood-inundation layers were developed using the U.S. Army Corps of Engineers HEC–RAS computer program to compute water-surface profiles and delineate estimated flood-inundation areas for selected stream stages. The layers show estimated flood-inundation areas overlain on selected base maps of the study area for 1.0-ft increments of water-surface elevation between 131.0 and 153.0 ft above NAVD 88 (stage of 10.7 to 32.7 ft) at the Withlacoochee River at Skipper Bridge Road, near Bemiss, Ga. (023177483), streamgage.

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