Prepared in cooperation with the U.S. Fish and Wildlife Service

Hydraulic Model and Flood-Inundation Maps Developed for the Pee Dee National Wildlife Refuge, North Carolina

Scientific Investigations Report 2015–5137

U.S. Department of the Interior
U.S. Geological Survey

Cover. Brown Creek at the Pee Dee National Wildlife Refuge, North Carolina. (Photograph by Mike Landrum, U.S. Geological Survey)

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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Director

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Contents

Figures

Tables

Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Pressure	
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)

Datum

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

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

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

Abbreviations

ADCP	acoustic Doppler current profiler
DEM	digital elevation model
DGPS	differential global positioning system
GIS	geographic information system
GPS	global positioning system
HEC-RAS	Hydrologic Engineering Center River Analysis System
kHz	kilohertz
lidar	light detection and ranging
mm	millimeter
Pee Dee NWR	Pee Dee National Wildlife Refuge
USGS	U.S. Geological Survey

Hydraulic Model and Flood-Inundation Maps Developed for the Pee Dee National Wildlife Refuge, North Carolina

By Douglas G. Smith and Chad R. Wagner

Abstract

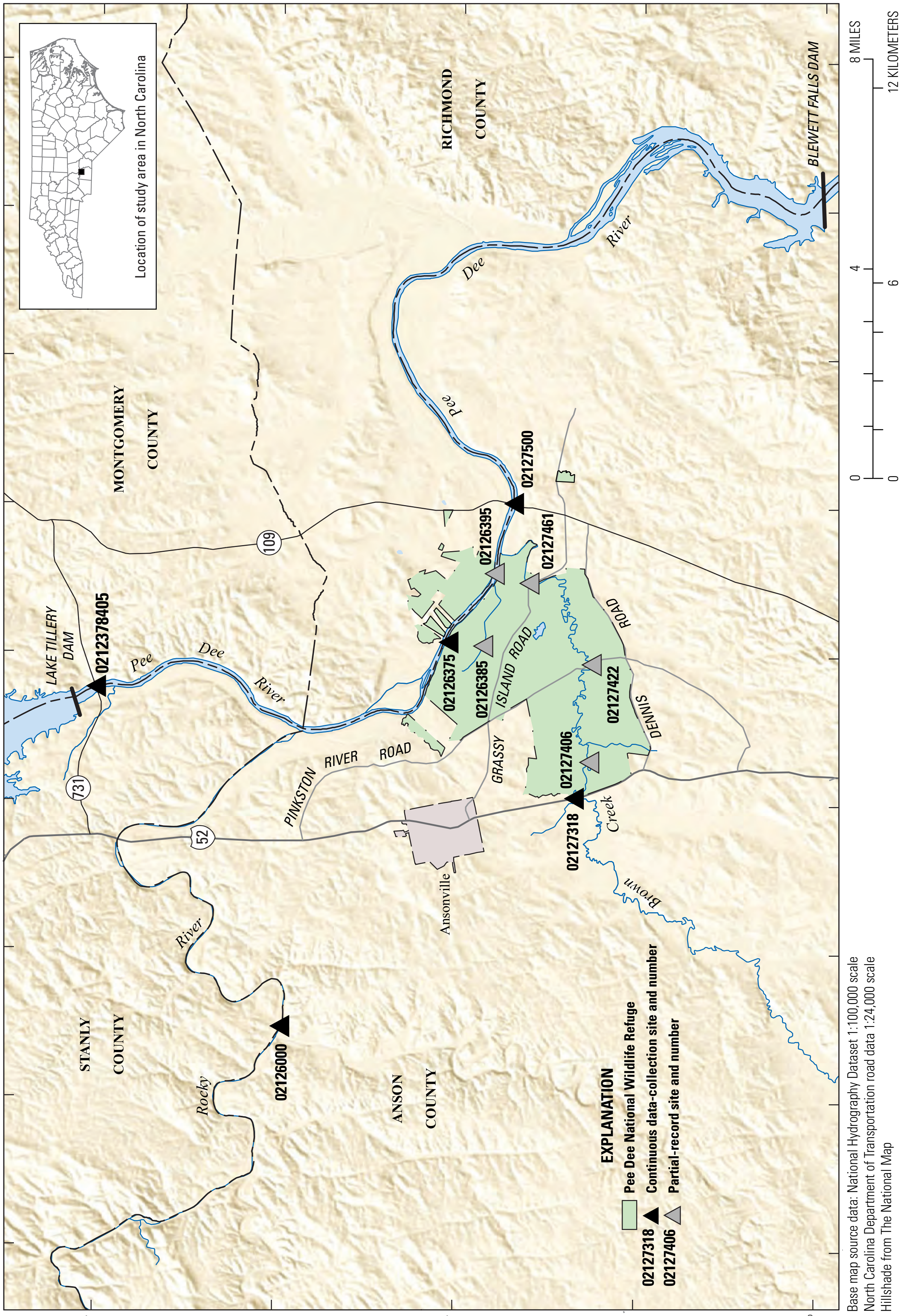
A one-dimensional step-backwater model was developed by the U.S. Geological Survey (USGS) in cooperation with the U.S. Fish and Wildlife Service, Pee Dee National Wildlife Refuge, North Carolina, to provide a means for predicting flood-plain inundation. The model was developed for selected reaches of the Pee Dee River, Brown Creek, and Rocky River, using the U.S. Army Corps of Engineers Hydrologic Engineering Center River Analysis System (HEC-RAS) software. Multiple cross sections were defined on each modeled stream, and hydrologic data were collected between August 2011 and August 2013 at selected locations on the Pee Dee River and on its tributaries Brown Creek, Rocky River, and Thoroughfare Creek. Cross-section, stage, and flow data were used to develop the model and simulate water-surface profiles at 1.0-foot increments at the USGS streamgage Pee Dee River at Pee Dee Refuge near Ansonville, N.C. The profiles were produced for 31 selected water levels that ranged from approximately 193.0 feet to 223.0 feet in elevation at the Pee Dee River at Pee Dee Refuge streamgage.

A series of digital flood-inundation maps were developed on the basis of the water-surface profiles produced by the model. The inundation maps, which can be accessed through the USGS Flood Inundation Mapping Program Web site at http://water.usgs.gov/osw/flood_inundation/, depict estimates of the areal extent and depth of flooding corresponding to selected water levels at the USGS streamgage Pee Dee River at Pee Dee Refuge near Ansonville, N.C. These maps, when combined with real-time water-level information from USGS streamgages, provide managers with critical information to help plan flood-response activities and resource protection efforts.

Introduction

The Pee Dee River is part of the Yadkin-Pee Dee River basin, the second largest river basin in North Carolina. The Pee Dee River flows from northwest to southeast through the central part of the State and is regulated by dams that provide flood control, electric power generation, recreation, water storage, irrigation, debris containment, and navigation opportunities. The Pee Dee National Wildlife Refuge (Pee Dee NWR) is managed by the U.S. Fish and Wildlife Service and is located in Anson and Richmond Counties in North Carolina. The refuge lies along the banks of the Pee Dee River between the Lake Tillery and Blewett Falls Lake hydroelectric dams (fig. 1). Some areas within the Pee Dee NWR are subject to flooding and can become inundated by flood waters from the Pee Dee River and Brown Creek.

Prior to this study, resource managers had limited information available regarding the potential for flooding in the Pee Dee NWR area. As a result, some refuge assets have been damaged by flooding in the past. Those damages may have been reduced or avoided entirely if information about the potential for flooding and inundation in the refuge area had been available. One-dimensional hydraulic models can be used to predict the extent of flood-plain inundation (Bates and De Roo, 2000; Horritt and Bates, 2002; Alho and Aaltonen, 2008). To provide a means for predicting and responding to periods of inundation in the Pee Dee NWR, a one-dimensional hydraulic model with geographic information system (GIS) mapping capabilities was developed using the U.S. Army Corps of Engineers Hydrologic Engineering Center River Analysis System (HEC-RAS) software (U.S. Army Corps of Engineers, 2010). The model was used to simulate water-surface elevations at 1.0-foot (ft) increments. A series of estimated flood-inundation maps was produced for the study area based on the results of the model.



Base map source data: National Hydrography Dataset 1:100,000 scale
North Carolina Department of Transportation road data 1:24,000 scale
Hillshade from The National Map

Figure 1. Locations of U.S. Geological Survey data-collection sites in the Pee Dee National Wildlife Refuge study area in North Carolina.

Background

The Pee Dee NWR is located on the Pee Dee River between the Lake Tillery and Blewett Falls hydroelectric dams. The relation between river flow and flood-plain inundation along the Pee Dee River between these dams is poorly understood. Because flow in the Pee Dee River is highly regulated, flooding and flood-plain inundation along the river do not follow natural patterns in which high stages solely are produced by heavy precipitation within the drainage area. In addition to precipitation patterns, flooding along the Pee Dee River can also be influenced by releases made from the dams to produce hydroelectric power. When the water level in the Pee Dee River is already elevated, releases from the dam can make the stage rise more rapidly and increase the possibility of flooding. Resource managers have a need for advance knowledge or warning of the potential for flooding and an improved understanding of the likely extent of inundation from such releases in order to plan effective responses and ensure the protection of natural and manmade assets. The extent of flood-plain inundation within the Pee Dee NWR is an important consideration that affects accessibility, habitat use and reproductive success of wildlife, regeneration of bottomland hardwood trees, and land-use decisions. With an improved understanding of the relation between river flow and flood-plain inundation, management decisions can be made to improve and sustain the land, conserve wildlife, and provide for wildlife-dependent recreational uses in the Pee Dee NWR for future generations.

Purpose and Scope

The purpose of this report is to describe the development of a one-dimensional step-backwater hydraulic model for the Pee Dee NWR area that was used to generate a series of flood-inundation maps produced on the basis of results of the model. The maps can be used to provide resource managers with advance knowledge of the extent of inundation that may result from various hydrologic conditions in the Pee Dee River and its major tributaries in the vicinity of the Pee Dee NWR. These maps and other flood information are available at the U.S. Geological Survey (USGS) Flood Inundation Mapping Program Web site at http://water.usgs.gov/osw/flood_inundation/. Users can select estimated inundation maps with water levels in the Pee Dee River at a specific elevation, or corresponding gage height, at the USGS streamgage Pee Dee River at Pee Dee Refuge near Ansonville, N.C. (site number 02126375).

The scope of the model development was limited to an 11.2-mile reach of the Pee Dee River, a 10.8-mile reach of Brown Creek, and a 1-mile reach of Rocky River (figs. 2 and 3). Multiple cross sections were defined within the specified reach of each stream. Stage and streamflow data collected between August 2011 and August 2013 on each of the modeled streams were used to calibrate the model. The calibrated model was then used to simulate water-surface elevations in the Pee Dee NWR area at a series of projected high flows. A series of estimated inundation maps of the study area were produced on the basis of model results.

Study Area

The study area encompassed the region near the Pee Dee NWR in south-central North Carolina (fig. 1). The model developed for the study included a reach of the Pee Dee River that extended from N.C. Highway 731 to N.C. Highway 109, a reach of Brown Creek that extended from U.S. Highway 52 downstream to the mouth, and a reach of Rocky River that extended 1 mile above its confluence with the Pee Dee River (fig. 2). An effort was made to include a separate reach for Thoroughfare Creek in the hydraulic model (fig. 3); however, due to a lack of flow in the creek for most of the study period and the probability that its channel would become inundated by the Pee Dee River at high stages, a separate model reach for Thoroughfare Creek was not developed.

General Description of the Study Area

The Pee Dee NWR is located in south-central North Carolina (fig. 1). The Lake Tillery hydroelectric power dam impounds the Pee Dee River about 7 miles upstream from the Pee Dee NWR (fig. 2). The Blewett Falls hydroelectric dam (fig. 1) impounds the Pee Dee River about 16 miles downstream from the Pee Dee NWR area but appears to have little effect on flow patterns near the refuge. The refuge area includes 8,443 acres of rolling hills covered with upland pine forest and a mosaic of croplands, fields, and mixed pine-hardwood forest that intermingles with creeks, ponds, lakes, and the Pee Dee River (U.S. Fish and Wildlife Service, 2006). The bottomland hardwood forests, uplands, and waterways provide excellent habitat for many animals, including more than 180 species of birds (U.S. Fish and Wildlife Service, 2006).

The Pee Dee NWR manages manmade waterfowl impoundments and agricultural lands within the Pee Dee River and Brown Creek flood plains. Flooding from hydrologic events can inundate the fields and impoundments within the refuge area and cause damage to refuge assets. When the Lake Tillery hydroelectric dam releases water to generate electricity, stage data collected at the USGS streamgage located about 0.5 mile downstream from the dam (0212378405; fig. 2) indicate that the water level in the Pee Dee River can increase by more than 2 ft in as few as 15 minutes at that site. Releases from the dam may be unavoidable during hydrologic events. Because the Lake Tillery dam is located about 7 miles upstream from the Pee Dee NWR, a period of time will pass before releases made at the dam cause water levels in the Pee Dee River to rise at the refuge area. Given this delay or lag time, if refuge personnel are made aware of existing high-stage conditions in the river and have advance knowledge of the extent of possible inundation, there may be adequate time to secure refuge assets, close flow-control structures, and protect sensitive areas before flooding occurs.

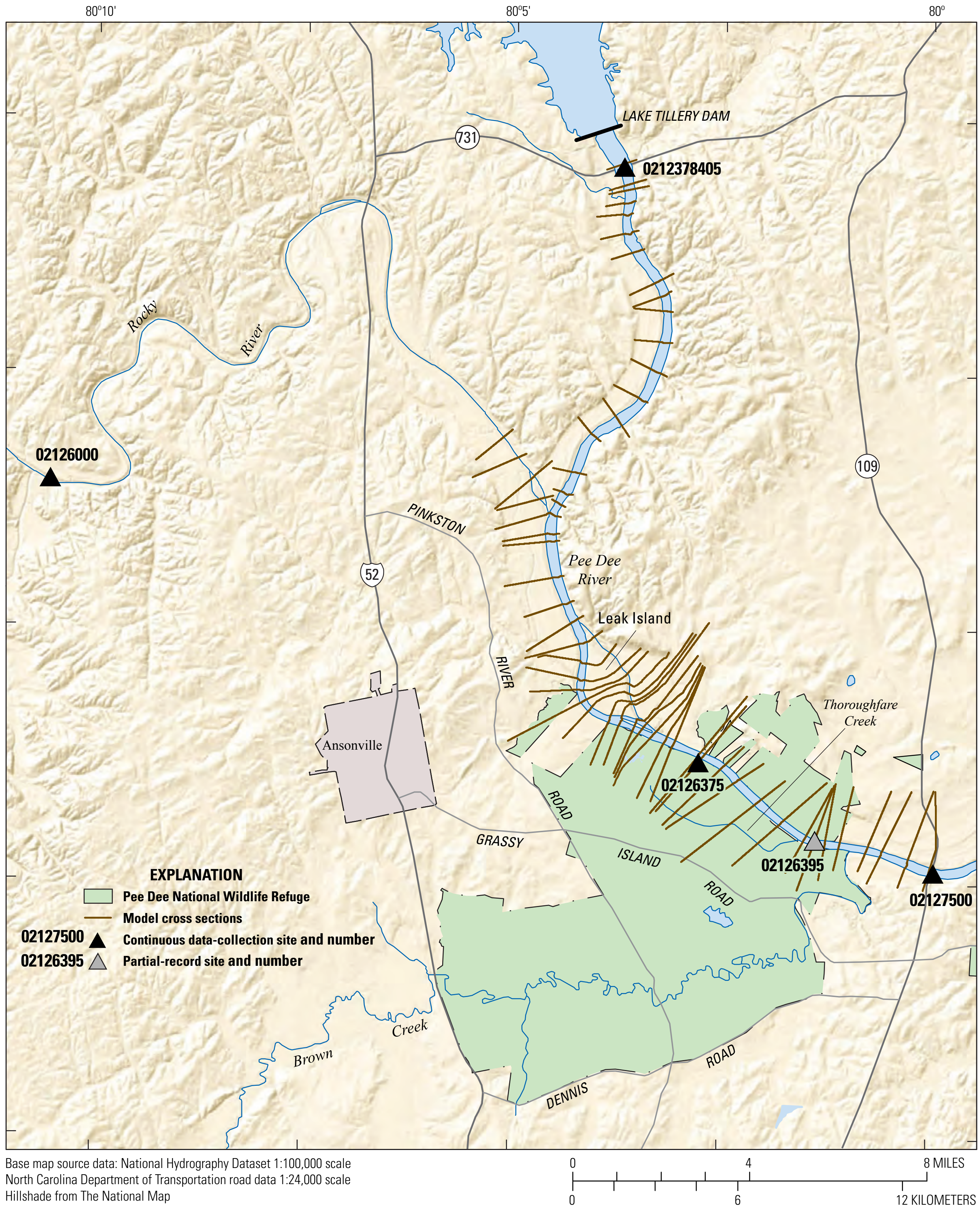


Figure 2. Model extent, cross sections, and data-collection sites on the Pee Dee and Rocky Rivers, North Carolina.

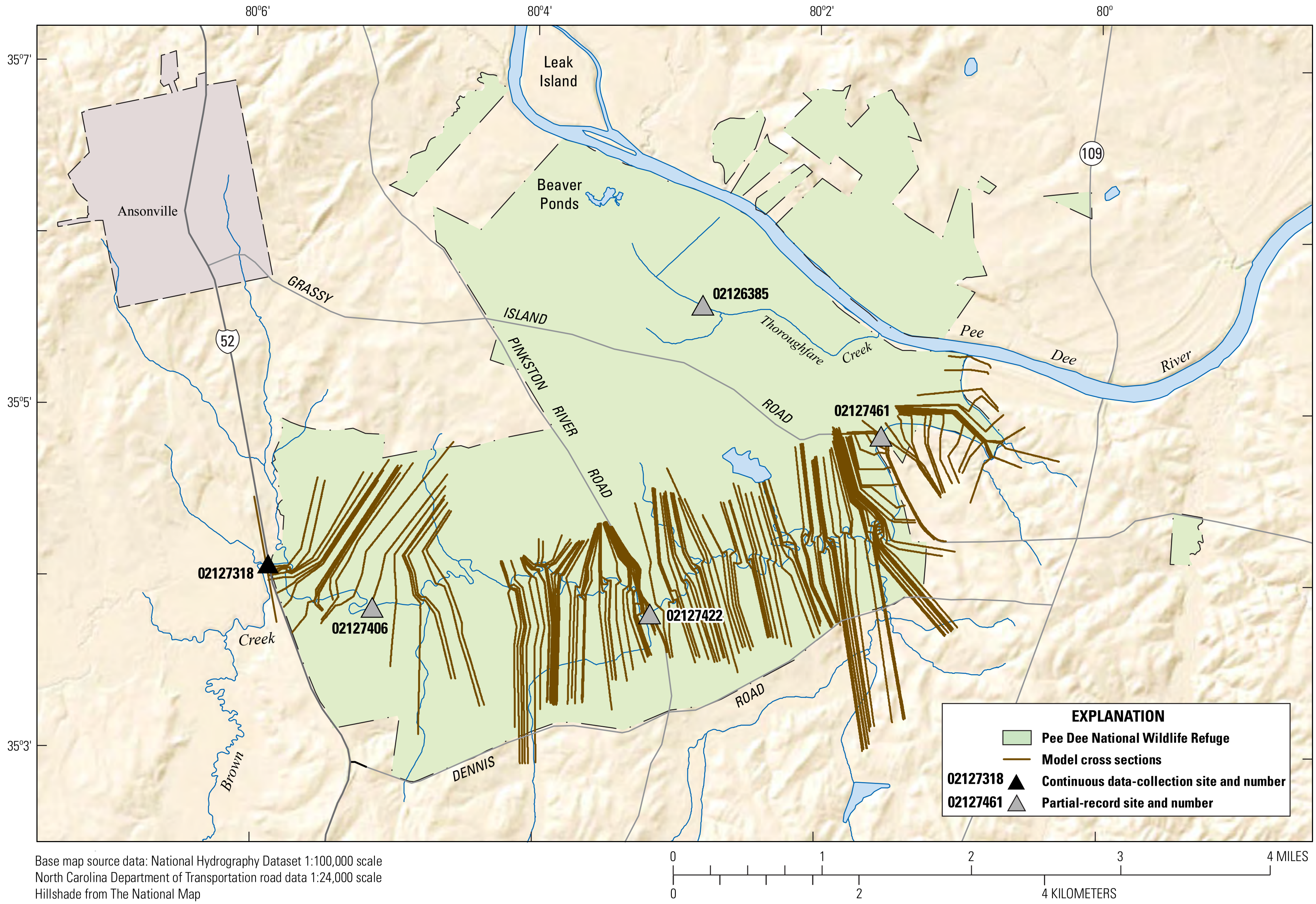


Figure 3. Model extent and cross sections for Brown Creek and data-collection sites on Brown and Thoroughfare Creeks, North Carolina.

Pee Dee River

The Pee Dee River is one of the largest rivers in North Carolina. The river flows from northwest to southeast, gently meandering through the study area. An 11.2-mile reach of the Pee Dee River that extended from N.C. Highway 731 at the upstream boundary to N.C. Highway 109 at the downstream boundary was selected for model development (fig. 1). At the upstream end of the reach, the drainage area of the Pee Dee River is 4,694 square miles (mi^2; table 1). At the downstream end of the reach, the drainage area of the river is 6,320 miles. The channel bottom of the Pee Dee River is rocky in some parts of the study area and is about 700 ft wide near the N.C. Highway 731 bridge and about 450 ft wide near the N.C. Highway 109 bridge. Agricultural fields and wooded areas are present in the flood plains on both sides of the channel for much of the study area.

Water levels in the Pee Dee River can fluctuate rapidly in response to releases from the Lake Tillery Dam, which is about 0.5 mile upstream from the N.C. Highway 731 site. In addition to flows released from the Lake Tillery Dam, the modeled reach of the Pee Dee River also receives inflow from Rocky River and Brown Creek. Between the mouths of Rocky River and Brown Creek, a small secondary channel departs from the main stem of the Pee Dee River and flows around Leak Island before rejoining the main channel again about 1.8 miles downstream (fig. 2). Inflows from Rocky River and Brown Creek as well as conveyance in the small channel around Leak Island were included in the model.

Table 1. List of U.S. Geological Survey data-collection sites in the Pee Dee National Wildlife Refuge study area in North Carolina.

[Sites are listed by USGS downstream order number. PR, partial record; Q, streamflow; Cont., continuous, mi^2, square miles; *, periodic streamflow measurements also made at this site from 1985 to 1995]

Site number	Site name	Drainage area (mi^2)	Data type	Period of record
	Pee Dee River			
0212378405	Pee Dee River at N.C. Highway 731 near Norwood, N.C.	4,694	Cont. stage, Q	Mar. 2009 to present
02126375	Pee Dee River at Pee Dee Refuge near Ansonville, N.C.	6,134	Cont. stage	Aug. 2011 to present
02126395	Pee Dee River above Brown Creek near Ansonville, N.C.	6,138	PR stage	Aug. 2011 to Aug. 2013
02127500	Pee Dee River at N.C. Highway 109 near Ansonville, N.C.	6,320	Cont. stage	Nov. 2011 to Aug. 2013
	Brown Creek			
02127318	Brown Creek at U.S .Highway 52 near Pinkston, N.C.	152	Cont. stage	Nov. 2011 to Aug. 2013
02127406	Brown Creek below U.S. Highway 52 near Ansonville, N.C.	156	PR stage	Aug. 2011 to Feb. 2012
02127422	Brown Creek at Bennett Bridge near Ansonville, N.C.	163	PR stage, Q	Aug. 2011 to Aug. 2013*
02127461	Brown Creek at Grassy Island Road near Ansonville, N.C.	179	PR stage	Apr. 2012 to Aug. 2013
	Rocky River			
02126000	Rocky River near Norwood, N.C.	1,372	Cont. stage, Q	Oct. 1929 to present
	Thoroughfare Creek			
02126385	Thoroughfare Creek near Ansonville, N.C.	0.57	PR stage	Aug. 2011 to Aug. 2013

Brown Creek

Brown Creek flows generally from west to east through a heavily wooded region in the study area (fig. 3). The channel meanders sharply throughout the refuge area, forming a very sinuous pattern. Close examination of aerial photography reveals the existence of oxbows in places where the Brown Creek channel has shifted its course over time, leaving remnant channel features behind. The model reach of Brown Creek extends from U.S. Highway 52 at the upstream boundary to the mouth where it empties into the Pee Dee River. The drainage area of Brown Creek is about 152 mi^2 at the U.S. Highway 52 bridge and about 182 mi^2 at its confluence with the Pee Dee River. Brown Creek flows into the Pee Dee River near the downstream boundary of the Pee Dee NWR. The Brown Creek channel has a relatively gentle slope with a sandy bottom present in many areas. The width of the channel varies locally but generally is about 30 to 40 ft wide. The wooded area through which Brown Creek flows has thick vegetation in many areas and is generally low lying and irregular. Wide flat flood plains are present on both banks of the creek. Beaver activity and numerous fallen trees form snags in the Brown Creek channel that affect flow conditions in many places. Although the drainage area of Brown Creek contributes less than 3 percent of the total flow from the refuge watershed, during large precipitation events flow from Brown Creek can increase the water level in the Pee Dee River as well as inundate the flood plain of the creek. Flow in Brown Creek is unregulated but is affected by backwater from the Pee Dee River, especially near its mouth. On multiple occasions during this study, the effects of backwater from the Pee Dee River were observed on Brown Creek at the bridge on Grassy Island Road (fig. 3).

Rocky River

Rocky River generally flows in a southeasterly direction across the southern areas of central North Carolina. Flow within Rocky River is unregulated and, as its name implies, the channel bottom is very rocky in many areas. The Rocky River channel meanders gently along its course as it approaches the Pee Dee River (fig. 1). A USGS streamgage has been in operation on the Rocky River since 1929 at a location 11 miles upstream from the confluence of Rocky River with the Pee Dee River. The drainage area of the Rocky River at the streamgage (02126000) is 1,372 mi^2. At its mouth, the confluence with the Pee Dee River, the drainage area of the Rocky River is 1,420 mi^2. Cross sections surveyed in the Rocky River channel were limited to a reach that extended from 1 mile upstream from its mouth down to where it empties into the Pee Dee River.

Thoroughfare Creek

Thoroughfare Creek is a small stream that originates and flows entirely within the boundaries of the Pee Dee NWR. This creek drains the area near the "Beaver Ponds" (fig. 3) in the refuge and empties into the right bank of the Pee Dee River approximately 3,200 ft upstream from the mouth of Brown Creek. A stage data-collection site was installed and operated on Thoroughfare Creek during this study. The drainage area of Thoroughfare Creek at the data-collection site (02126385; fig. 3) is about 0.57 mi^2. Field observations indicate the channel of Thoroughfare Creek may serve as an overflow channel and receive waters from the Pee Dee River during periods of high flow. Although the stream channel was never found to be dry during the study, no flow was observed in Thoroughfare Creek during some site visits. Because appreciable flow in this stream likely occurs only after receiving water from the Pee Dee River, a separate reach for Thoroughfare Creek was not simulated in the model; however, the overbank areas of some Pee Dee River cross sections included the Thoroughfare Creek channel.

Constructing Water-Surface Profiles

A one-dimensional step-backwater hydraulic model was developed using HEC-RAS computer software for the three main streams in the Pee Dee NWR area: Pee Dee River, Rocky River, and Brown Creek. Multiple cross sections were developed within specific reaches of each modeled stream to define the shape and elevation of the channel and flood-plain areas. Stage and (or) streamflow data were collected at multiple sites on the Pee Dee River and Brown Creek, at one site on Rocky River, and at one site on Thoroughfare Creek (figs. 2, 3). Stage, flow, and cross-section data collected between August 2011 and August 2013 were used to develop the model. The model was calibrated using stage and flow data collected during the study. The model was then used to simulate water-surface elevations at a series of selected high flows. A series of estimated inundation maps were developed for the study area on the basis of simulated water-surface elevations produced by the model.

Bathymetric/Topographic Data

More than 200 cross sections were developed for the three modeled stream reaches. For the Pee Dee River, 50 cross sections were used to define the reach between the bridge at N.C. Highway 731 and the bridge at N.C. Highway 109 (fig. 2). Five cross sections were used in the model of the Rocky River reach from about 1 mile upstream from its mouth down to its confluence with the Pee Dee River (fig. 2). For Brown Creek, 153 cross sections were used to define the reach between the bridge at U.S. Highway 52 and the mouth of the creek at its confluence with the Pee Dee River (fig. 3).

Elevation data used to define the geometry of each cross section were determined by combining bathymetric surveys of the stream channels at selected locations with bank and flood-plain elevation data derived from remote sensing technology using light detection and ranging (lidar). The bathymetry surveys were used to determine the streambed elevations for each section from edge-of-water to edge-of-water. From water's edge at both banks, lidar-based land-surface elevation data were used to extend each section landward or laterally out and onto the overbank areas. The combination of these two types of data was used to develop all cross sections in the model.

The bathymetry surveys of the modeled stream channels were performed in January of 2012. Bathymetry data were collected from a moving boat by using an acoustic Doppler current profiler (ADCP) equipped with a 200-kilohertz (kHz) single-beam echo sounder. The echo sounder is specified by the manufacturer to have an accuracy of 1 percent of the measured depth and a resolution of 1 millimeter (mm). A differential global positioning system (DGPS) was used to establish horizontal stationing for bathymetry surveys in the Pee Dee River and Rocky River channels and lower areas of the Brown Creek channel. The accuracy of the DGPS unit used to complete these channel surveys is specified by the manufacturer to be within 3.3 ft at two standard deviations.

Various equipment was used for bathymetry surveys in the Brown Creek reach. The same equipment that was used for the bathymetry surveys in the Pee Dee and Rocky River channels was used to survey six cross sections in the Brown Creek channel near the mouth of the creek. For the remainder of the cross sections in the Brown Creek reach, bathymetry data were measured by an ADCP and then transmitted through wireless communications to a field computer operated by personnel on the streambank. At the same time channel bathymetry data were collected, a handheld GPS unit was used to pinpoint the location of each section. The horizontal accuracy of the handheld GPS unit used to mark the location of most Brown Creek cross sections was reported by the manufacturer to be within 49 ft.

Bathymetry surveys were coordinated with the dam operator at the Lake Tillery dam to maintain a steady or constant stage in the Pee Dee River while the surveys were being performed in the field. Water-level data recorded during bathymetry surveys at the Pee Dee River and Brown Creek data-collection sites were used to calculate a water-surface elevation at the surveyed bathymetry sections. By assuming a constant slope in the water surface between data-collection sites, a water-surface elevation was interpolated for the location of each cross section. The water-surface elevation derived for each cross section subsequently was used to calculate channel bottom elevations on the basis of depths measured by the ADCP.

Upon completion of the bathymetry surveys, all channel bathymetry sections were plotted and ground-truthed using GIS software. The locations of a few bathymetry sections in the Brown Creek reach were manually adjusted to improve the alignment of the section with the stream channel when superimposed on high-resolution aerial photography.

The overbank areas of each cross section were delineated manually and were positioned to be generally perpendicular to the stream channel where the section intersected the stream. Despite the sinuosity of the stream channel in some areas, care was taken to keep cross-section lines from intersecting or crossing one another. The elevation data that were used to define the overbank areas are referenced vertically to the North American Vertical Datum of 1988 (NAVD 88); all horizontal data are referenced to the North American Datum of 1983. The vertical accuracy of the elevation data is less than or equal to 9.9 inches (in.). Cross-section elevation data were obtained from a digital elevation model (DEM) that was derived from lidar data collected between February and April 2003 by the North Carolina Floodplain Mapping Program (North Carolina Floodplain Mapping Program, 2003). The DEM was created from the bare earth points with a 10-ft by 10-ft cell size.

Stage and Streamflow Data

When first established, a USGS streamgage typically is set to monitor water levels so that the range of stage values recorded by the instrumentation is relatively low. To achieve this, recording equipment is set to an arbitrary datum plane that is selected after some consideration is given to unique channel characteristics and conditions. Stage (also referred to as gage height) values that are recorded at streamgages typically are reported by the USGS in this arbitrary gage datum. The USGS commonly determines the elevation at streamgage sites and relates the arbitrary gage datum to mean sea level elevation, thereby providing a means to convert recorded stage values to water-surface elevation. The arbitrary datum of each USGS streamgage used in this study is listed under the heading “Gage datum” in table 2. A user can convert stage values to water-surface elevation by adding the gage datum value to recorded stage values.

Stage and streamflow data were collected for this study between August 2011 and August 2013 using electronic instrumentation operated by the USGS at sites on the Pee Dee River, Rocky River, Brown Creek, and Thoroughfare Creek. Four data-collection sites were in operation on the Pee Dee River during the study (fig. 1). Data-collection sites were also operated at four sites on Brown Creek, at one site on Rocky River, and at one site on Thoroughfare Creek during the study (fig. 1). The mean sea level elevation was determined for each data-collection site using a DGPS. The DGPS unit used to determine elevations of the streamgages was reported by the manufacturer to be capable of producing vertical accuracy to within 0.05 ft.

A previously existing USGS streamgage—Pee Dee River at Highway 731 below Lake Tillery near Norwood, N.C. (0212378405; fig. 1)—was in operation at the beginning of the data-collection period at the upstream boundary of the Pee Dee River model reach. This streamgage had been established in 2009 in cooperation with Duke Energy (formerly Progress Energy) and was located at the N.C. Highway 731 bridge about 0.5 mile downstream from the Lake Tillery dam (fig. 1). A stage-discharge relation was developed to quantify streamflow at this site for the period of study. Continuous stage and streamflow data collected at the site were used as the upstream boundary condition for the Pee Dee River reach in the model. This streamgage is currently (August 2015) still in operation and is equipped with satellite telemetry that transmits real-time data that are available through the USGS South Atlantic Water Science Center (SAWSC) – North Carolina Office Web site at http://nc.water.usgs.gov/.

Three additional streamgages were installed and operated on the Pee Dee River to provide water-level data during this study (figs. 1, 2). One of these sites was installed within the refuge boundary at a wooden bulkhead located on the right bank about 3 miles upstream from N.C. Highway 109. This site, Pee Dee River at Pee Dee Refuge near Ansonville, N.C. (02126375), was equipped with real-time satellite telemetry that provided continuous stage data at 15-minute intervals throughout the period of study. This streamgage is currently (August 2015) still in operation and is equipped with satellite telemetry that transmits real-time data that are available through the USGS SAWSC – North Carolina Office Web site at http://nc.water.usgs.gov/. Inundation maps developed for this study are based on model results for the location of this streamgage.

Farther downstream, stage data were recorded only during periods of high flow at another site on the Pee Dee River that was also located within the refuge boundary. This site, Pee Dee River above Brown Creek near Ansonville, N.C. (02126395), was installed on the left bank of the river at a steel bulkhead located about 2,000 ft upstream from the mouth of Brown Creek and approximately 1.4 miles upstream from N.C. Highway 109 (fig. 2). The equipment installed at this site was set to record stage data only when the sensor became inundated. Therefore, water levels at this partial-record site were only recorded when the water-surface elevation in the river rose above 182.1 ft. All equipment was removed and data collection was discontinued at this site in August 2013.

At the downstream end of the Pee Dee River reach, another USGS streamgage was installed and operated at the N.C. Highway 109 bridge (fig. 2). This streamgage, Pee Dee River near Ansonville, N.C. (02127500), was also equipped with satellite telemetry that provided continuous stage data at 15-minute intervals throughout the period of study; these data were used as the downstream boundary condition for calibration of the model. Equipment was removed and data collection was discontinued at this site in August 2013.

Data were collected at four sites on Brown Creek during this study (fig. 3). The upstream end of the Brown Creek reach was located at the U.S. Highway 52 bridge. A USGS streamgage, Brown Creek at U.S. Highway 52 near Pinkston, N.C. (02127318), was installed at the site and provided continuous stage data at 15-minute intervals throughout the period of study.

At the other three Brown Creek sites, stage data were recorded only when the stage sensor installed at each site became inundated by rising water in the creek. The farthest upstream partial-record site on Brown Creek was located approximately 1.2 miles downstream from the U.S. Highway 52 bridge and near the Pee Dee NWR office (02127406; fig. 3). Water levels at this site were only recorded when water-surface elevations in the creek rose above 201.9 ft. Another partial-record site on Brown Creek was in operation near the upstream side of Bennett Bridge on Pinkston River Road (02127422). Water levels at this site were only recorded when water-surface elevations in the creek were above 191.4 ft. The farthest downstream partial-record site on Brown Creek was installed downstream from the bridge on Grassy Island Road (02127461; fig. 3). Water levels at this site were only recorded when water-surface elevations in the creek were above 181.0 ft.

Data were collected without interruption at only two of the four Brown Creek sites during the period of study (02127318 and 02127422; fig. 3). After observing considerable backwater effects from the Pee Dee River near the mouth of Brown Creek, the data-collection site that had been installed on Brown Creek near the refuge office downstream from U.S. Highway 52 (02127406; fig. 3) was discontinued. The equipment removed from that site was subsequently installed at the site downstream from Grassy Island Road (02127461; fig. 3) to monitor backwater effects from the Pee Dee River.

Streamflow data were estimated for the site on Brown Creek at Bennett Bridge on Pinkston River Road (02127422; fig. 3) using a stage-discharge relation developed from 32 streamflow measurements made at that site. Twenty-eight of those streamflow measurements were made by the USGS between 1985 and 1995 during a variety of flow conditions. In 2012 and 2013, additional streamflow measurements were made during medium-to high-flow conditions at the Brown Creek at Bennett Bridge site (02127422). The streamflow data that were estimated on the basis of the stage-discharge relation developed for this site were used for the upstream boundary condition for the Brown Creek reach in the model. Data collection ended and equipment was removed from all of the sites on Brown Creek in August 2013.

In addition to the sites that were installed and operated on Pee Dee River and Brown Creek, one previously existing USGS streamgage on Rocky River remained in operation throughout the period of study. The Rocky River near Norwood, N.C., streamgaging station 02126000 (fig. 1) was established in 1929 and provided continuous streamflow data that were used for the upstream boundary condition of the Rocky River reach in the model. This streamgage is currently (August 2015) still in operation and is equipped with satellite telemetry that transmits real-time data that are available through the USGS SAWSC – North Carolina Office Web site at http://nc.water.usgs.gov/.

One streamgage was installed on Thoroughfare Creek (02126385) to collect stage data only during periods of high flow (figs. 1, 3). However, due to a lack of flow during the study period and characteristics of the stream, stage data collected at the Thoroughfare Creek site were not used in the model. The equipment was removed and data collection ended at the Thoroughfare Creek site in August 2013.

No high-stage events occurred during the period of study that resulted in widespread inundation within the study area. Several of the highest peaks recorded by the streamgages during this study occurred during the months of June and July of 2013. The highest water level recorded at all of the Pee Dee River data-collection sites occurred on June 8, 2013. The streamflow produced by the event on June 8 at the streamgage on the Pee Dee River at N.C. Highway 731 (0212378405) was 64,100 cubic feet per second (ft^3/s). The highest streamflow recorded during the period of study for the streamgage on Rocky River near Norwood, N.C. (02126000) occurred on July 1, 2013, and was 17,400 ft^3/s. The highest water levels recorded at the Brown Creek sites at U.S. Highway 52 and Bennett Bridge (02127318 and 02127422; fig. 3) occurred on July 1, 2013. The maximum flow estimated during the study for the Brown Creek at Bennett Bridge site occurred on July 1, 2013, and was about 2,800 ft^3/s. The highest water level recorded at the farthest downstream site on Brown Creek (near Grassy Island Road, site 02127461) occurred on June 8, 2013, but was affected by backwater from the Pee Dee River (fig. 2; table 2).

Table 2. Data-collection sites and maximum peak stage, corresponding water-surface elevations, and flow recorded during period of study, August 2011 through August 2013, at the Pee Dee National Wildlife Refuge, North Carolina.

[—, not available; *, affected by backwater from Pee Dee River; n/r, not reported (information not used in model); †, limited data available (site not used in model)]

Site number	Station name	Maximum recorded peak stage (feet)	Maximum corresponding water-surface elevation (feet)	Maximum recorded peak flow (ft^3/s)	Date of maximum peak stage and flow	Gage datum (feet)
	Pee Dee River					
0212378405	Pee Dee River at N.C. Highway 731 near Norwood, N.C.	17.98	215.43	64,100	06/08/13	197.45
02126375	Pee Dee River at Pee Dee Refuge near Ansonville, N.C.	25.51	201.14	—	06/08/13	175.63
02126395	Pee Dee River above Brown Creek near Ansonville, N.C.	24.90	198.84	—	06/08/13	173.94
02127500	Pee Dee River at NC Highway 109 near Ansonville, N.C.	27.11	197.31	—	06/08/13	170.20
	Brown Creek					
02127318	Brown Creek at US Highway 52 near Pinkston, N.C.	19.23	212.67		07/01/13	193.44
02127406†	Brown Creek below US Highway 52 near Ansonville, N.C.	—	—	—	—	n/r
02127422	Brown Creek at Bennett Bridge near Ansonville, N.C.	14.06	201.20	2,800	07/01/13	187.14
02127461	Brown Creek at Grassy Island Road near Ansonville, N.C.	22.41*	197.90	—	06/08/13*	175.49
	Rocky River					
02126000	Rocky River near Norwood, N.C.	n/r	n/r	17,400	07/01/13	n/r
	Thoroughfare Creek					
02126385†	Thoroughfare Creek near Ansonville, N.C.	—	—	—	—	n/r

Model Development

The step-backwater hydraulic model was created using HEC-RAS, software version 4.1.0 (U.S. Army Corps of Engineers, 2010). Cross sections that were developed by combining measured channel bathymetry with high-resolution elevation data for the flood-plain areas were used to model the Pee Dee River, Rocky River, and Brown Creek reaches. The Pee Dee River reach extended approximately 11.2 miles with no bridges or flow control structures located within the reach. The Rocky River reach included only the lower mile of the river and ended at its confluence with the Pee Dee River. No flow control structures were located within the Rocky River reach. The Brown Creek reach extended approximately 10.8 miles with two highway bridges located within the reach. These two bridges were surveyed, and characteristics of the structures were entered into the model.

Roughness coefficients were initially assigned to each cross section on each stream using an automated procedure that was based on land cover. These Manning's "n" values were assigned to the channel and overbank areas and were varied horizontally along each cross section according to changes in vegetation and other natural features. Adjustments were made to some of the original roughness coefficients to improve calibration of the model.

Model Calibration and Performance

The model was developed and calibrated using data that were collected during the study. Stage and streamflow data recorded from August 2011 to August 2013 at sites on Pee Dee River, Rocky River, and Brown Creek were used in the model. Stage values were recorded continuously at some sites and only during periods of relatively high flow at other sites (table 1). Multiple rises in water levels were monitored on each stream; however, none of the high-stage events that occurred during the period of study resulted in widespread inundation within the refuge area. Several of the highest peak stages recorded during the study period occurred between June 1 and July 31, 2013. The dynamic nature of the responses of the three modeled streams to precipitation and variable timing of the peak-flow hydrographs on the Pee Dee River, Rocky River, and Brown Creek limited the applicability of steady-state flow simulations for model calibration. As a result, recorded stage and streamflow data and unsteady-state flow simulation were used to calibrate the model.

After entering the geometry and characteristics of cross sections and bridge structures into the HEC-RAS software, the model was run using data that were recorded at 15-minute intervals from June 1 to July 31, 2013, as input. Flow data were used as the upstream boundary condition for the Pee Dee River, Rocky River, and Brown Creek reaches, and recorded stage data were used as the downstream boundary condition of the model. The water-surface elevations that were simulated by the model were compared to the stage data that had been recorded at all Pee Dee River and Brown Creek sites. The water-surface elevations of several peak stage values that were recorded between June 1 and July 31, 2013, on each of the modeled streams were compared to the simulated water-surface elevations that were produced by the model.

To achieve improved agreement between the recorded data and simulated water-surface elevations produced by the model, some Manning's roughness coefficients were adjusted in the Pee Dee River and Brown Creek reaches. The final Manning's n values used for the Pee Dee River reach ranged from 0.017 to 0.058 in the channel areas and generally from 0.04 to 0.172 in the overbank areas. For the Rocky River reach, a Manning's n value of 0.031 was used for the main channel on all five cross sections. For the overbank areas of the Rocky River reach, roughness coefficient values used in the model ranged from 0.04 to 0.14. Manning's n values for the Brown Creek reach were generally higher due to the highly sinuous nature of the stream channel, extensive snags formed by downed trees that were observed in many parts of the reach, irregular channel and overbank areas, and dense vegetation that occurred along both banks in much of the study area. For the Brown Creek reach, final Manning's n values used in the model ranged from 0.04 to 0.132 for the main channel and from 0.07 to 0.24 for the overbank areas.

After adjusting the Manning's n values in some areas of the Pee Dee River and Brown Creek reaches, simulated peak water-surface elevations produced by the model were compared to peak stages that were recorded during June 1 to July 31, 2013. For the Pee Dee River sites, the simulated maximum water-surface elevation produced by the calibrated model matched the highest recorded peak at each data-collection site to within 0.03 ft. The calibrated model also matched the highest recorded peak at each of the Brown Creek sites to within 0.08 ft.

At the upstream end of the Pee Dee River reach, the highest simulated peak stage matched the highest recorded peak stage at the streamgage Pee Dee River at N.C. Highway 731 (0212378405; fig. 2). At this site, the median difference between the simulated water-level elevations and the five highest peaks recorded from June 1 to July 31, 2013, was 0.35 ft. At the Pee Dee River at Pee Dee Refuge streamgage (02126375; fig. 2), the highest simulated peak stage matched the highest recorded peak stage to within 0.03 ft. At this site, the median difference between the simulated water-level elevations and the five highest peaks recorded from June 1 to July 31, 2013, was –0.55 ft. Farther downstream at the partial-record streamgage on the Pee Dee River above Brown Creek (02126395; fig. 2), the highest simulated peak stage matched the highest recorded peak stage to within 0.02 ft. At this site, the median difference between the simulated water-level elevations and the five highest peaks recorded from June 1 to July 31, 2013, was –0.26 ft.

At the upstream end of the Brown Creek reach, the highest simulated peak stage matched the highest recorded peak stage at the streamgage Brown Creek at U.S. Highway 52 (02127318; fig. 3) to within 0.01 ft. At this site, the median difference between the simulated water-level elevations and the five highest peaks recorded from June 1 to July 31, 2013, was 0.79 ft. For the partial-record streamgage Brown Creek at Bennett Bridge (02127422; fig. 3), the highest simulated peak stage matched the highest recorded peak stage to within 0.01 ft. At this site, the median difference between the simulated water-level elevations and the five highest peaks recorded from June 1 to July 31, 2013, was 0.02 ft. For the partial-record streamgage, Brown Creek at Grassy Island Road (02127461; fig. 3), the highest simulated peak stage matched the highest recorded peak stage to within 0.08 ft. At this site, the median difference between the simulated water-level elevations and the five highest peaks recorded from June 1 to July 31, 2013, was –0.41 ft.

Substantial flooding did not occur during the period of study. In order to simulate water-surface elevations that were higher than the stage values measured during the study, the calibrated model was used to project higher water levels using steady-state flow simulation. To accomplish this, a normal depth condition (U.S. Army Corps of Engineers, 2010, p. 17–24) was used for the downstream boundary condition of the model rather than a measured water-surface elevation as was used in the unsteady-state simulation. Downstream boundary conditions were established using the normal depth with a friction slope estimated from the streambed slope through the reach. The normal depth is calculated by using the Manning equation with user-provided data for slope, geometry, and Manning's n roughness coefficients. With an approximated streambed slope value of 0.0001727 foot per foot, as determined from bathymetry surveys and assigned at the downstream boundary, the model was run at a series of selected flows. Corresponding water-surface elevations were produced by the model. The input flow values and the corresponding simulated water-surface elevations subsequently were used to develop a simulated stage-discharge rating for the Pee Dee River at Pee Dee Refuge streamgage site (02126375; fig. 2). Further details about the methods used to define this rating curve are described in Bales and others (2007).

Development of Water-Surface Profiles

By using steady-state flow simulation and the simulated stage-discharge rating curve for the Pee Dee River at Pee Dee Refuge streamgage (02126375, figs. 1, 2), as described in the preceding paragraph, a series of 31 water-surface profiles in the study area were generated at 1.0 ft intervals. These profiles define the estimated extent of inundation corresponding to selected water-level elevations at the Pee Dee River at Pee Dee Refuge streamgage (02126375; fig. 2). The water-surface elevations range from 193.0 ft (stage = 17.37 ft) to 223.0 ft (stage = 47.37 ft), with corresponding flow values ranging from 32,200 to 261,000 ft^3/s. These profiles represent a wide range of flow conditions in the Pee Dee River at Pee Dee Refuge streamgage site (02126375; fig. 2). The lowest profile simulates water levels that are below bankfull conditions, and the highest profile simulates extensive flooding as shown in figure 4.

Inundation Mapping

Estimated flood-inundation maps were created using the final series of water-surface profiles that were developed as described in the preceding paragraphs. Maps were created in GIS by combining the water-surface profiles with a DEM of the study area. The digital elevation data are from a high-resolution dataset derived from lidar. The maps show estimated flood-inundated areas overlain on high-resolution, georeferenced aerial photographs of the study area for each of the water-surface profiles that were generated by the hydraulic model. Estimated boundaries for each simulated profile were developed using HEC-GeoRAS software, version 10.2 (U.S. Army Corps of Engineers, 2009). HEC-GeoRAS is a set of procedures, tools, and utilities for processing geospatial data in ArcGIS (Esri, 2015) by using a graphical user interface. The interface allows the preparation of geometric data for import into HEC-RAS and processes simulation results exported from HEC-RAS (U.S. Army Corps of Engineers, 2010). HEC-GeoRAS results were modified to ensure a hydraulically reasonable transition of the boundary between modeled cross sections relative to the contour data for the land surface (Whitehead and Ostheimer, 2009).

Pee Dee River Flood-Inundation Maps

A USGS Flood Inundation Mapping Program Web site (http://water.usgs.gov/osw/flood_inundation/) has been established by the USGS to provide estimated flood-inundation information to the public. The maps from the current study are available in several commonly used electronic file formats that can be downloaded from the Web site. The Pee Dee River reach displayed on the Web site contains links to the USGS National Water Information System graphs of the current stage at the Pee Dee River at Pee Dee Refuge streamgage (02126375), to which the inundation maps are referenced. The estimated flood-inundation maps are displayed in sufficient detail to note the extent of flooding so that preparations for flooding and decisions for emergency response can be performed effectively.

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 a quick reference and emergency planning tool but assumes no legal liability or responsibility for any direct, indirect, incidental, consequential, special, or exemplary damages or lost profit resulting from the use or misuse of this information.

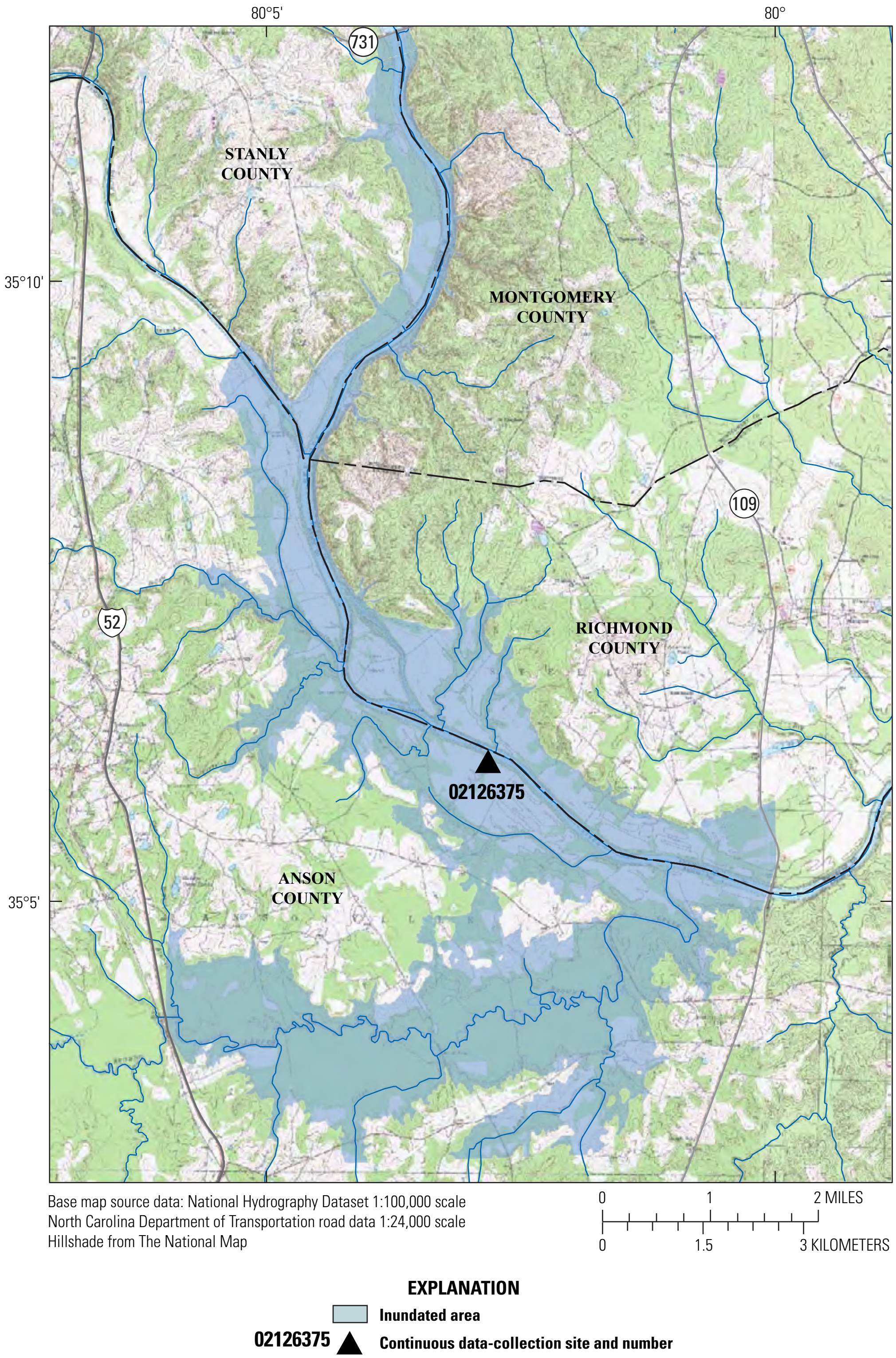


Figure 4. Extent of maximum inundation produced by the model, using a water-surface elevation of 223.00 feet and a stage of 47.37 feet at Pee Dee River at Pee Dee Refuge streamgage (02126375).

Uncertainties and Limitations Regarding Use of Flood-Inundation Maps

Although the flood-inundation maps represent the estimated boundaries of inundated areas with a distinct line, some uncertainty is associated with these maps. The flood boundaries shown were estimated on the basis of stage and streamflow data collected at sites on the Pee Dee River, Rocky River, and Brown Creek. The water-surface elevations along the stream reaches were estimated by steady-state hydraulic modeling, assuming unobstructed flow, and by using flows at selected hydrologic conditions at the Pee Dee River at Pee Dee Refuge streamgage (02126375).

The hydraulic model reflects the land-cover characteristics and characteristics of bridges, dams, levees, or other hydraulic structures that existed as of January 2012 when field surveys were performed. Changes to these characteristics may cause streamflow patterns within the study area to vary from those simulated by the model. Unique meteorological factors, such as the timing and distribution of precipitation, may also cause actual streamflows in the study area to vary from those simulated by the model, which may lead to deviations in the water-surface elevations and inundation boundaries. Additional areas may be flooded due to unanticipated conditions such as changes in the structure or operation of the Lake Tillery Dam, changes in the streambed elevation or roughness, considerable erosion or deposition in the channel areas, backwater into major tributaries, or backwater from localized debris or ice jams. The accuracy of the floodwater extent portrayed on the inundation maps will vary with the accuracy of the DEM used to simulate the land surface. Additional uncertainties associated with this study include limitations in the accuracy of cross-section data and water-level and flow data recorded by the streamgages.

Summary

A hydraulic model was developed by the U.S. Geological Survey (USGS), in cooperation with the U.S. Fish and Wildlife Service, for an 11.2-mile reach of the Pee Dee River from N.C. Highway 731 to N.C. Highway 109, a 1-mile reach of the Rocky River, and a 10.8-mile reach of Brown Creek from U.S. Highway 52 to the mouth of the creek. The model was based on cross-section, stage, and streamflow data that were collected during the period of study—August 2011 to August 2013. The model was used to produce a series of estimated flood-inundation maps that were developed using the U.S. Army Corps of Engineers HEC-RAS and HEC-GeoRAS software to compute water-surface profiles and to delineate estimated flood-inundation areas at selected water-surface elevations. The maps show estimated inundation areas overlain on high-resolution, georeferenced, aerial photographs of the study area for selected 1.0-foot increments of water-surface elevation in the Pee Dee River between 193.0 and 223.0 feet at the Pee Dee River at Pee Dee Refuge near Ansonville, N.C., streamgage (02126375). These maps, available at a USGS Web site, in conjunction with the real-time stage data available from the USGS streamgage at Pee Dee River at Pee Dee Refuge near Ansonville, N.C. (02126375), can help guide resource managers to take necessary precautions to more effectively and efficiently plan emergency flood response operations and flood-mitigation efforts.

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