FLOOD DYNAMICS IN THE BERTIE WATER CRESCENT

INTEGRATING THE DYNAMICS OF COMPLEX DRAINAGE SYSTEMS TO MINIMIZE STORM IMPACTS AND MAXIMIZE AQUATIC ENVIRONMENT VIABILITY, BERTIE COUNTY, NC

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COVER PHOTOGRAPHS: Top panel shows the Cashie River flood waters flowing over the King Street Bridge in the Town of Windsor as a result of Hurricane Matthew on October 10, 2016. Photograph is by S. Sauer. Bottom panel shows the sheet flow across the Weeping Mary Road during the six month period from mid-September 2018 to mid-March 2019 when the USACE was discharging over 30,000 cfs from the upstream dams to the Lower Roanoke River. Photograph is by S. Riggs.

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SUMMARY

Small towns in North Carolina's Land of Water are hard-pressed to create new economic opportunities. Today they face major challenges that include destructive floods, rising sea level, loss of jobs, population declines, high poverty rates, and crumbling infrastructure. In an effort to stimulate new economic opportunities, NC LOW's strategy is to focus on the natural and cultural, resource-based science, eco-tourism and environmental education as a means of diversifying the rural economy while minimizing the stifling impact of flooding and drought. NC LOW brings this vision to the Bertie County region with the expectation of improving the local quality of life through sustainable economic development that enhances and protects the environment and culture of the region.

Bertie County is water-bound by a complex of different kinds of drainage systems encircling three sides of the county and dissecting it through the interior. The great Roanoke River forms the entire western and southern boundary, while the estuarine waters of Albemarle Sound and the Chowan River embayed estuary forms the southeastern and entire eastern boundary, respectively. The interior of Bertie County is dominated by the dendritic valley of the Cashie River and its tributary network. Several smaller and incised, black-water tributary streams flow into Albemarle Sound and include the Salmon, Black Walnut, and Cashoke creeks. The high, east-facing bluffs of the Wicomoco and Talbot Terraces contain numerous small and deeply incised, ephemeral drainages characterized by small delta plains and cypress headlands where they discharge into the Chowan River and Albemarle Sound. The dynamics of this world-class, integrated water system is generally passive and beautiful, while at certain times it can become extremely energetic and angry. This report considers the complex interactions and dynamic responses that occur to turn this positive situation into a negative one for the regions inhabitants. The general findings are based on the patterns of water-level dynamics through time at water-level gages and on available weather data throughout the Bertie region.

1. The lower Roanoke River has two major parts, joined by a fluctuating transition zone, that function differently. The region from the Roanoke Lake dam in Roanoke Rapids to Williamston is totally dependent on the dam discharge that is a function of upstream weather in combination with management policies associated with the engineered dam system. The Roanoke River from Williamston east to Westover Hwy 45 is generally the transition zone. Flooding is controlled by the dam discharge.

2. The river segment from Westover Hwy 45 to Albemarle Sound is dominated by the dynamics of Albemarle Sound (storm surge, wind tides, and astronomical tides that overwhelms a minor base signal from dam discharge). Flooding is minimal except when there is a major storm surge.

3. The Cashie River also has two major parts joined by a fixed transition zone. The upper Cashie River is riverine with a moderate gradient and totally dependent on rainfall to feed the stream system, which the School Rd. gage measures.

4. The Town of Windsor occupies the transition zone which is generally between the Hwy 17 Bypass Bridge and the Hwy 17 King St. Bridge. The lower Cashie River is an estuary that is basically at sea level and is driven by the dynamics of Albemarle Sound. The Windsor King St. gage more closely records Albemarle Sound signals that are similarly recorded at two other downstream sites (Bowling Farm and Westover Hwy 45). Only when there is a major rainfall on the School Rd. gage is there a significant upstream record at the King St. gage.

5. Thus, flooding on the Cashie River in Windsor appears to be generally dependent on the interaction of a large rain water input at the same time that there is either a major wind set up or storm surge on the Albemarle Sound that produces a backflow up the Cashie River.

6. Consequently, when large-scale upstream (rainfall) and/or downstream (storm surge) events occur, then the smaller-scale processes can affect the extent of flooding. Inches to feet of increase or decrease in vertical water levels translate into significantly larger or smaller flooded areas.

7. Thus, it makes a substantial difference in flooding potential if water levels in the lower Cashie River channel are low and there is a dry primary floodplain with abundant storm-water storage capacity or if there has been a prior and/or extended wet weather period with a high groundwater level, full river channels, and wet primary floodplains. When the latter situation exists there is a substantial potential for increased flooding in Windsor and the lower Cashie River.

8. Flooding and shoreline erosion on the eastern banks of Bertie County are totally dependent on the interaction of storm dynamics (storm surge, wind, and rainfall) and associated weather patterns through time on the very large water bodies of the Albemarle and Chowan estuaries.

RECOMMENDATIONS

1A. Status of Water-Level Recorders and Local Weather Stations.

In coastal NC, floods don't just happen in response to upstream rainfall. Any given flood event is dictated by a complex of interacting dynamics between all interconnected water bodies and their response to the changing weather system, and human modifications. The present monitoring sites within the Bertie Water Crescent are as follows.

a. The US Geological Survey operates 8 relevant water-level gages on the lower Roanoke River between the Roanoke River dam at Roanoke Rapids and Westover Hwy 45 bridge located just west of where the lower Roanoke River enters Albemarle Sound.

b. The US Geological Survey operates 1 water-level gage on the upper Cashie River north of Windsor at School Rd. Bridge. This gage is located high enough above mean sea level that it only measures upstream rain input into the Cashie River and rarely records any activity from the Roanoke River, Albemarle Sound, Chowan River, or lower Cashie River.

c. The NC Division of Emergency Management operates 1 FIMAN water-level gage on the King St. Bridge (Hwy 17 Business) over the Cashie River in Windsor. This gage is basically at sea level and records the wind tides and astronomical tides of the Albemarle Sound and Chowan River.

d. No permanent water-level recorders are located on the lower Cashie River, in western Albemarle Sound, or within the Chowan River Estuary. It is very clear that Albemarle-Chowan water does move upstream on the Cashie River and can turn a moderate flood into a catastrophic event. The downstream dynamics can not only add feet of flood water, but can slow down the discharge of flood waters.

e. Obtaining water level and weather data on these water bodies is critical for understanding the interaction between the downstream and upstream components of the Cashie River, predicting potential impacts of future storms, and minimizing the flooding potential for the town of Windsor, lower Cashie River, and western Chowan River and Albemarle Sound shore zones.

f. Only a few scattered weather stations occur throughout the Bertie region that are owned by specific organizations (small air strips, TV stations, or private groups) who do not have direct connections to specific water-level gages, nor do they make their data readily available or store their data.

1B. Recommendations: Water-Level Recorders and Local Weather Stations.

Install four new and/or upgrade permanent water-level recorders and weather stations to monitor the downstream water systems relevant to the Cashie River flooding and to be utilized in combination with the upstream Cashie River and Roanoke River data.

a. Install one system on the lower Cashie River at the Sans Souci Ferry House on NC Dept. of Transportation property.

b. Install one system in western Albemarle Sound at the Salmon Creek State Natural Area on property of the NC Division of State Parks. This location is semi-protected area just inside the mouth of Salmon Creek and on a heavy duty dock.

c. Either reactivate an existing water-level gage or install a new one in central Albemarle Sound at Leonard's Point on the south side of the NC highway 32/94 bridge over the Sound. Supposedly there already is a water-level gage located at Leonard's Point, but a NC DEM site states that there has been no data collected for the past 7 months or more.

d. Install a water-level recorder on the west bank of the Chowan River, possibly on the Colerain waterfront. There is a possibility of cooperating with a private beach club at the east end of NC Hwy 42 where there is a major boat dock inside two rock jetties.

e. Each of these stations should have electronic feeds to the various local emergency management centers. It is essential to provide adequate personnel and funding not only to maintain the new gages, but aid in interpreting and managing the data.

2. Recommendations: The Lower Roanoke River

The summary recommendation is to approach the entire regional system with a more holistic management approach that equally includes the tripartite of waterscape, landscape, and atmoscape within the entire Roanoke Drainage Basin (upper and lower Roanoke Rivers) and not just lake levels, power supply, or rain on the ground.

a. The present policy of “no dam water discharge until there is rain on the ground” is not an adequate policy in this day and age of weather science. Storm science has now become relatively good so that policy decisions can be modified sooner than previously when “rain on the ground” was adequate.

b. At the time when storm water decisions need to be made, the policy of weekly discharge schedules should be shifted to daily scheduling. This would allow more flexibility in ramping up or ramping down discharge patterns.

c. The dam discharge should not be operated as an on-off switch. But rather as a variable switch where the discharge can be slowly ramped up well before there is “rain on the ground”. This could alleviate the possibility of getting to the “fishbowl effect” where the dams can’t hold any more water, forcing massive dumping.

d. In making dam discharge decisions, it is equally important to consider lower Roanoke River water level conditions as considering the Kerr Lake water levels. Discharging large volumes on top of a normal to full river channel will exacerbate downstream flooding.

e. The Roanoke River stakeholder groups should work with each downstream county to help evaluate and develop a geo-zone plan for Roanoke floodplain based upon potential flooding and best land-uses.

f. The geo-zone plan should recommend policies for specific land-use practices for each part of the most flood-prone lands within the lower Roanoke River system. This plan should include the potential for reclaiming the lowest and most seriously flooded agricultural fields from production utilizing procedures such as buyouts, conservation easements, and/or partnerships for eco-tourism, recreation, and educational-research programs.

g. Dam discharge policies should factor in the downstream valley geometry and geomorphology based upon a geo-zone plan for the lower Roanoke River floodplain.

3A. The Cashie River

The Doll et al. report (2018) recommendations for flooding in the Town of Windsor considered the hydrologic dynamics within the upstream portion of the Cashie River. However, it is equally critical to focus on the downstream dynamics. Thus, an integrated approach should be built around both upstream and downstream hydrologic dynamics, the unique physical and environmental settings of inter-connected water bodies, and the ongoing changes in climate and sea level. These efforts must be integrated with a well-defined land-use management plan that includes geo-zoning and preserving substantial natural buffer areas along each stream channel, particularly in the broad upland headwaters.

<u>3-1. Recommendations: Upper Cashie River</u>

a. Utilize an integrated set of natural and historic water control structures in the upstream portions of the black-water drainage systems (e.g., conservation easements, vegetation buffer zones, design road dams to slow down the water and create temporary holding ponds, etc.). The purpose is to temporarily slow down and/or store portions of flood-waters in the upstream wetlands and let the groundwater reservoir store and evapotranspiration processes utilize major portions of storm water runoff. This will slow down flash-flooding discharges, store water for periods of drought, and provide opportunities of expanding sustainable ecosystems and their services. This should build on findings of the NCSU 2018 report.

b. Develop community partnerships with one or more non-profit, land conservancy groups to implement an integrated drainage system program of conservation easements and best-land use management practices.

c. Revisit the Hoggard mill dam site, as well as other historic mill dam locations in the upper Cashie watershed to determine if re-occupation of one or more sites would work as water storage facilities to manage both flood and drought waters and to provide a basis for expanding sustainable ecotourism opportunities similar to Merchants Mill Pond State Park.

<u>3-2. Recommendations: Town of Windsor</u>

a. Define the "geo-zones" for the Town of Windsor based upon detailed topographic features of both the drainage system and the upland "Windsor Ridge". High- and low-risk zones and past flooding history for the town should determine future land use. Structures within the high-risk geo-zone should be demolished, raised, or moved with development of a set of land uses for these vacated risk zones that are compatible with flooding and can lead to expanding sustainable businesses (see NC LOW 2018 report on the Windsor Water Hub).

b. In order for a long-term flood management program to happen, there should be a series of public workshops to increase the understanding of inter-relationships between the basics of coastal system science, healthy resource systems, and high quality, sustainable economics. The business and agricultural communities, as well as private land owners, must buy into the program or it won't work. This component should partner with pre-existing programs such as NCSU extension and outreach programs, as well as ECU, CU, and the regional community colleges.

c. Develop a regionally focused concentration/curriculum within the STEM education programs for teachers in the regional schools. This program should integrate the coastal landscape, hydrology, climate change, and cultural history of the unique northeastern NC coastal region. A major field component should be included to get students involved in their backyard with mapping and various types of monitoring projects (see NC LOW "Rivers to Sounds" Science Education Report, 2019).

d. The NCSU (2018) report had its most downstream boundary condition at Windsor and did not address downstream controls on water levels and flooding in Windsor. Their conclusions were not based on the possibility that downstream water levels do fluctuate independently of upstream flows. Possibly a re-evaluation should be undertaken to determine the impact of Hwy 17 Business bridge (King Street Bridge) on floodplain connectivity, flushing, and water quality during various flow conditions.

e. If the re-evaluation warrants it, work with both the NC and US DOT to remove segments of the Hwy 17 Business (King Street) road dam across the primary floodplain of the Cashie River to allow a larger portion of the primary floodplain to be used for moderate flow river discharges that don't overtop the road dam.

f. Develop an emergency management protocol that includes observations of downstream conditions along with the upstream monitoring. If possible, develop a mathematical model that includes both conditions to aid in predictions of flooding.

<u>3-3. Recommendations: Lower Cashie River Estuary</u>

The lower Cashie River channel at Windsor drops well below sea level making it a "drowned-river estuary" that is in sync with the dynamics of Albemarle Sound. With its low gradient and strong tidal signal (storm surges, wind tides, and astronomical tides), the valley floor has produced an exceptionally wide floodplain dominated by a vast swamp forest. Consequently, the lower Cashie represents a critical "water sponge" that plays a significant role in buffering storm dynamics, upgrading water quality, and supplying a sustainable future.

a. Consequently, the recommendation is to establish both policies and organizational oversight structures that will 1) <u>protect</u> the resource, 2) <u>preserve</u> the ecosystem function, 3) <u>prepare</u> the resource for utilization as a key part of a sustainable eco-tourism destination, and 4) <u>partner</u> with key land trusts, government agencies, and non-profits to help build the "Bertie Water Crescent" (the 4 P's).

b. Foster education of residents about the importance of the riverine resources and swamp forest ecosystems of the Cashie and Roanoke river systems.

4A. The Chowan and Albemarle Shorelines

4-1. Wicomoco and Talbot Terrace Shorelines

From Colerain south to Batchelor Bay, the shoreline consists of 20- to 80-foot high bluffs and associated narrow strand-plain beaches. Erosion of the Wicomoco and Talbot terrace bluffs respond to rain, wind, and storm surges causing massive slumps that are subsequently reworked into the associated beaches. Along with the land slumps is abundant vegetation that can regrow and form natural vegetation buffers that temporarily protect the shoreline. The bluffs are generally composed of marine strata including a basal bed of highly burrowed clay that often grades upward into an extremely fossiliferous marine bed full of finger corals, scallops, oysters, and clams. Above the clay is a thick layer of sand that is often cross-bedded and full of crab burrows. The contact between the sand and clay beds are many small springs that continuously weep water and precipitate orange iron oxide that forms a bed of ironstone up to two to three feet thick. The bluffs are more susceptible to erosion than the cypress headlands and result in a series of cuspate-shaped embayments between the headlands.

4-2. Ravines, Delta Flats, and Cypress Headlands

The drainage system off the eastern side of the Wicomoco and Talbot terraces (east of hwy 45) is dominated by dozens of short steep ravines deeply incised into the bluffs and filled with upland hardwood forests. Each ravine flows into the Chowan River estuary with a shallow delta flat deposited into the river. The deltas are generally surrounded and protected by a cypress fringe where many of the older shoreline communities occur.

4-3. Remnant Riverine Swamp Forests

The Cow Island Swamp Forest acts as a natural storm buffer for the Wicomoco Bluff and associated uplands to the west and should be protected as a “significant natural area”. With its vast and wild wetlands, riddled with creeks and fronted by an extensive cypress fringe, it is a key natural resource as a portion of a sustainable eco-tourism program for recreation, education, and scientific investigation.

4B. Recommendation for Chowan and Albemarle Shorelines

a. The Albemarle and Chowan River shoreline environments are limited natural resources that are being bulldozed and converted into developments due to their awesome waterfronts and associated viewscapes. This is in spite of the severe erosion, major flooding, and potential total loss of these unique ecosystems. Consequently, the following approach is recommended.

b. Due to the extreme dynamics, spectacular geology, and unique ecology, it is recommended to establish the policies and organizational oversight structure that will 1) protect some of the remaining natural resource, 2) preserve the ecosystem function and dynamics, 3) prepare for utilization as key components of a sustainable eco-tourism destination, and 4) partner with key land trusts, government agencies, and non-profits to help build the “Bertie Water Crescent” (the 4 P’s).

5. Recommendations: Modern and Historic Storm Data

The detailed historical water level and storm data from events during the 20th century, and even into the first decade of the 21st century (Barnes, 2013), is scattered, poorly preserved, or totally non-existent. Consequently, it is recommended that Bertie County and the Town of Windsor either invest in a professional weather person or collaborate with the NC Climate Center at NCSU and the NC Emergency Management Division to explore and mine preserved historic data for the events that were catastrophic within the Bertie region. There are critical lessons to be learned in the history of each event.

a. Secure adequate funding to maintain the new gages, make live data available to the public and emergency management personnel, and archive and preserve all data as historical records for future use.

b. Use the resources cited in Appendices A and B to extend the amount of information for both short-term and long-term decision making. Sources should include existing NOAA weather and storm data, Kerr Lake water level and US ACE dam discharge data, USGS and NC DEM water gage stations, data from the NC Climate Office, regional weather data from local airports, military sites, and other agencies for changing environmental conditions within the Bertie region.

c. Mine historical storm data for the Bertie region from pre-existing sources including the US Geological Survey, US NOAA, US DOA, Library of Congress, NC Archives and History and any other potential source of detailed storm information. Historical data represents a gold mine of understanding!

INTRODUCTION

NC LOW and Vision for NC's Coastal System

The northeastern coastal system is "North Carolina's Land of Water" (NC LOW) dominated by the world-class riverine-estuarine-oceanic water system. Figure 1-1 displays the lowlands of the Inner Banks (green shades) are separated from the higher land areas of the middle and upper Coastal Plain (gray shades) by the paleo-ocean Suffolk Shoreline (red dashed line) and from the Piedmont uplands (white) by the Fall Line (black). The Inner Banks is the great mixing zone where the fresh riverine water arrives at sea level and begins mixing with ocean water. This transition zone is incredibly rich in diversity of ecosystems, vast variety of fauna and flora, and extreme fluctuations in the flow of energy. It is the dynamic intersection between the landmass of North Carolina and the Atlantic Ocean!

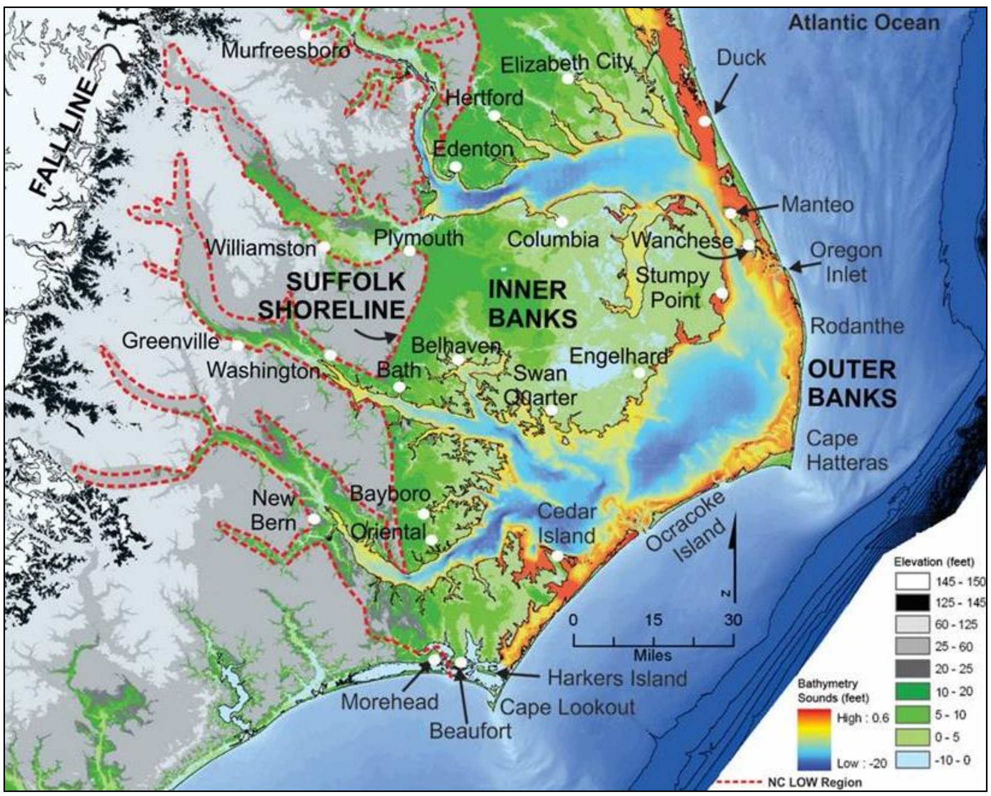


FIGURE 1-1. This color topography (land elevation) and bathymetric (water depth) map of the North Carolina Land of Water (NC LOW) coastal system includes the Inner and Outer Banks of northeastern North Carolina. The area defined as NC LOW occurs between the red dashed line (the Suffolk Shoreline and associated river bottoms) on the west and the Outer Banks barrier islands on the east. Land elevations and water depth are color-coded as indicated in the legend. The locations of some major towns are indicated. The black zone (Fall Line) on the western side of the map is the contact between the Piedmont Province (west) and Coastal Plain Province (east). Topographic data are from the NC DOT's 2007 LiDAR program. Map prepared by D. Ames.

NC LOW is a 501 c 3 that has completed a drainage basin-wide study for Bertie County and the Town of Windsor. This study evaluates the dynamic interactions and underlying forces operating within and between water bodies and the landscape with a three-pronged approach: understanding the scientific framework of the regional landscape and waterscape; implementing a sustainable eco-tourism program based on the regions natural resources; and educating the local population about the natural resources of the region. More specifically the goals of this study were as follows.

1. Address three major flooding and erosion problem areas associated with the Bertie-Water Crescent: a) upstream dam discharge flooding of the Roanoke River; b) severe riverine flooding events of the Cashie River; and c) erosion along the bluff and delta shorelines of the Wicomoco and Talbot Terraces on the western side of the Chowan River Estuary.

2. Produce the scientific framework for developing a storyboard of the history and dynamics of the coastal resources of the regional waterscape and landscape. This serves as a "sustainable eco-tourism" plan that focuses on minimizing flood impacts and maximizing utilization of natural waterscape resources.

3. Implement the "Rivers to Sounds" environmental education program for the Bertie-Windsor school system that focuses on the regional science of "what's in your backyard".

The world-class natural resources of the Bertie landscape and waterscape form the basis of the concept of the "Bertie Water Crescent". It's all about developing an "environmental water vision" for a region at the confluence of five spectacular coastal water systems surrounding and dissecting the Bertie Peninsula of northeastern North Carolina (Figure 1-2).

1. Roanoke River: A large, brown-water trunk river along the western and southern boundaries of the Bertie Peninsula.

2. Black-Water Tributary Streams: Cashie River and Salmon Creek dissect the high Wicomoco and low Talbot Terraces.

3. Chowan River Estuary: A vast, fresh-water estuary along the eastern Peninsula boundary.

4. A multitude of Bluff Ravines: deep, spring-fed canyons incised into and rim the Wicomoco and Talbot terraces.

5. Albemarle Sound: Drowned river valleys of the Paleo-Roanoke and Chowan Rivers.

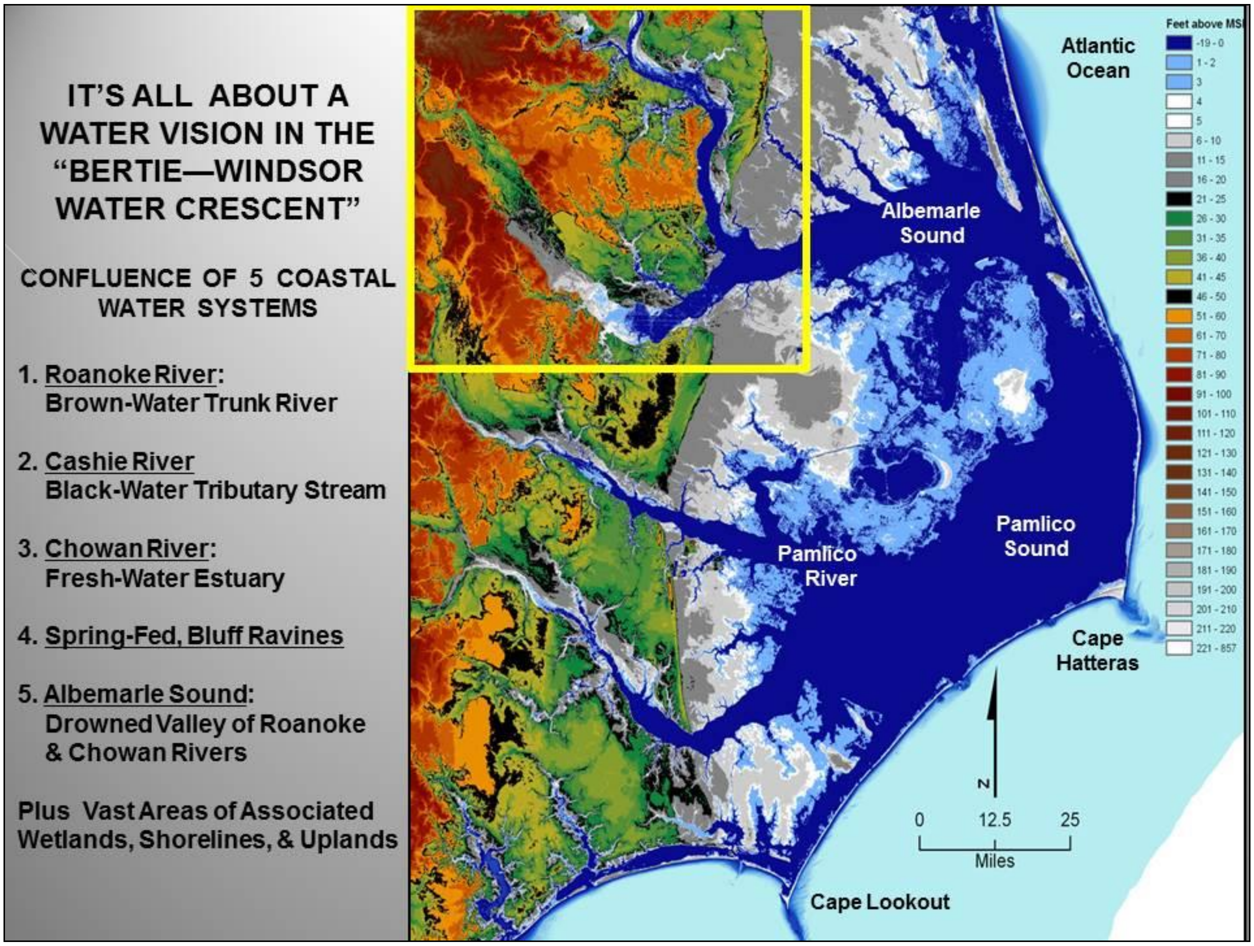


FIGURE 1-2. A color topography map shows the northeastern North Carolina Coastal Plain, the Bertie-Windsor study area (yellow box). The Ravines listed as item 4 and not visiable at the scale of this map. Topographic data are from the NC 2015 LiDAR program. Map prepared by D. Ames.

On the large scale, the complex Bertie waterscape results from two major processes: 1) the waterscape is incised deeply into the surrounding landscape system and 2) the outer portion of the waterscape is slowly being drowned by rising sea level. The evolutionary history of the Bertie Peninsula landscape and associated waterscape determined the different types of water bodies and include the following components.

1. Previous Ice Age climatic conditions including storm dynamics and rain input.
2. Present Interglacial climatic conditions.
3. Underlying Coastal Plain geologic framework.
4. Inherited paleo-drainage topography.
5. Downstream level of the Atlantic Ocean.
6. Continuity of the barrier islands.
7. Ecosystems and their services.

All of the drainages associated with the Bertie Peninsula have been deeply incised into the paleo-topographic landscape during major climatic changes in the glacial and interglacial climates of the past 2.5 million years. Through the entire Lower Roanoke River, the active or modern channel and associated active floodplain is cut into older meander and braidplain terraces that were formed during very different climatic conditions of the last ice age. Both the meander and braidplain terraces are dominated by alternating ridges of sand and swales containing low swamp forest wetlands. This is dramatically expressed in the distribution patterns of upland/wetland ecosystems and the human utilization of the sand ridges for farming and sand mining. Only when major dam discharges take place do some of these paleo-wetland swales flood along with the farm fields on the lowest paleo-sand ridges that are adjacent to the active or modern river system.

The present NC LOW study considers the long-term, sustainable management of the Bertie County natural drainage systems and produced a set of recommendations to help minimize the impacts of severe flooding events. Implementation efforts must seriously consider both the impacts on the natural ecosystems, the ecosystem services to society, and the economic resource base that presently exists in this dynamic and complex coastal drainage system. This report develops and integrates a network of inter-basinal and regional monitoring sites for hydrologic conditions in the lower Roanoke River, upper and lower Cashie River, and Albemarle Sound-Chowan River estuarine systems. Knowing how the complex drainage system works in response to the atmospheric events is crucial for understanding how to minimize the negative impacts of future hazard events and their economic impacts throughout the drainage system.

Bertie Peninsula Landscape and Bertie Water Crescent

The Bertie Peninsula is a topographic landscape that is delineated and dissected by a diverse waterscape system (Figure 1-3). The northern portion of the County consists of the high Wicomoco Terrace (45 to 80 feet above sea level) where the towns of Roxobel, Kelford, Lewiston-Woodville, Aulander, Powellsville, and Askewville are located. This high terrace also forms the interstream divide between the south-flowing Cashie River drainage system of Bertie County and the north-flowing Wiccacon River drainage system that dominates Hertford County. The west-east oriented Wicomoco Terrace is truncated on the east by the Chowan River estuary to form a seven mile stretch of north-south, high shoreline bluffs. The Cashie River system lies totally within the boundaries of Bertie County with its headwaters incised into the pocosin uplands of the high terrace. The Cashie River slopes down onto the intermediate Talbot Terrace (elevations of 20 to 45 feet above sea level) where the town of Windsor is located. Bertie county’s southern portion is low (0 to 20 feet above sea level) and consists of the Roanoke River valley with the Cashie River as a tributary. The Roanoke, North Carolina’s largest river, discharges into the Albemarle Sound at Batchelor Bay, a drowned-river estuarine valley of the paleo-Roanoke and Chowan Rivers.

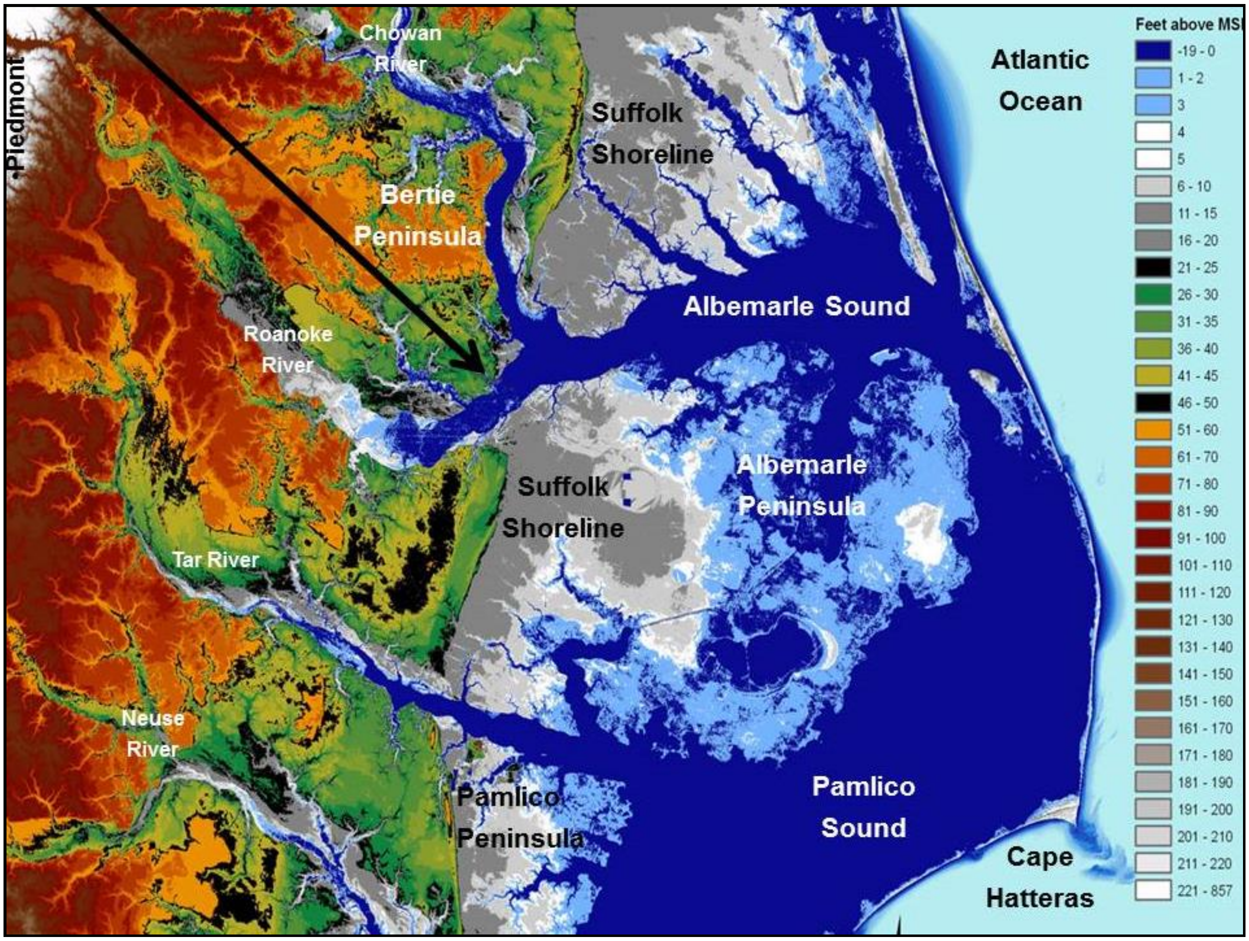


FIGURE 1-3. A color topography map shows the northeastern North Carolina Coastal Plain, the Bertie Peninsula, and the associated water bodies. The black arrow generally indicates the highest crest or inter-stream divide of the Peninsula. Topographic data are from the NC 2015 LiDAR program. Map prepared by D. Ames.

Bertie County is water-bound by the "Bertie Water Crescent" a complex of different kinds of drainages that encircle three sides of the county and dissect it through the interior. The great Roanoke River forms the entire western and southern boundary, the estuarine waters of Albemarle Sound and Batchelor Bay embrace the southeastern boundary, and the embayed estuary of the Chowan River forms the entire eastern boundary. The interior of Bertie County is dominated by the dendritic valley of the 55 mile long, black-water Cashie River which is subdivided into the Upper Cashie (from Roxobel to Hwy 17 By-pass Bridge in north Windsor) and the Lower Cashie River from north Windsor south to the "Thorofare" channel of the Roanoke River (Figure 1-4). The town of Windsor is situated on the Cashie at the transition zone where the upper channel bottom drops below modern sea level to become an estuary. Numerous tributary streams flow into the Upper Cashie including Whatom Swamp, Connarista Swamp, Whiteoak Swamp, Cucklemaker Creek, Flat Swamp Creek, and Hoggards Mill Run, which account for about 52% of the flow in the Upper Cashie. The remaining 48% represents the flow from the headwater streams of the uppermost portion of the mainstem Cashie (Doll et al. 2018). The downstream inputs of freshwater into the Lower Cashie are primarily from Roquist and

Wadling Place Creeks. As will be demonstrated, flows in the lower Cashie are also greatly influenced by Albemarle Sound.

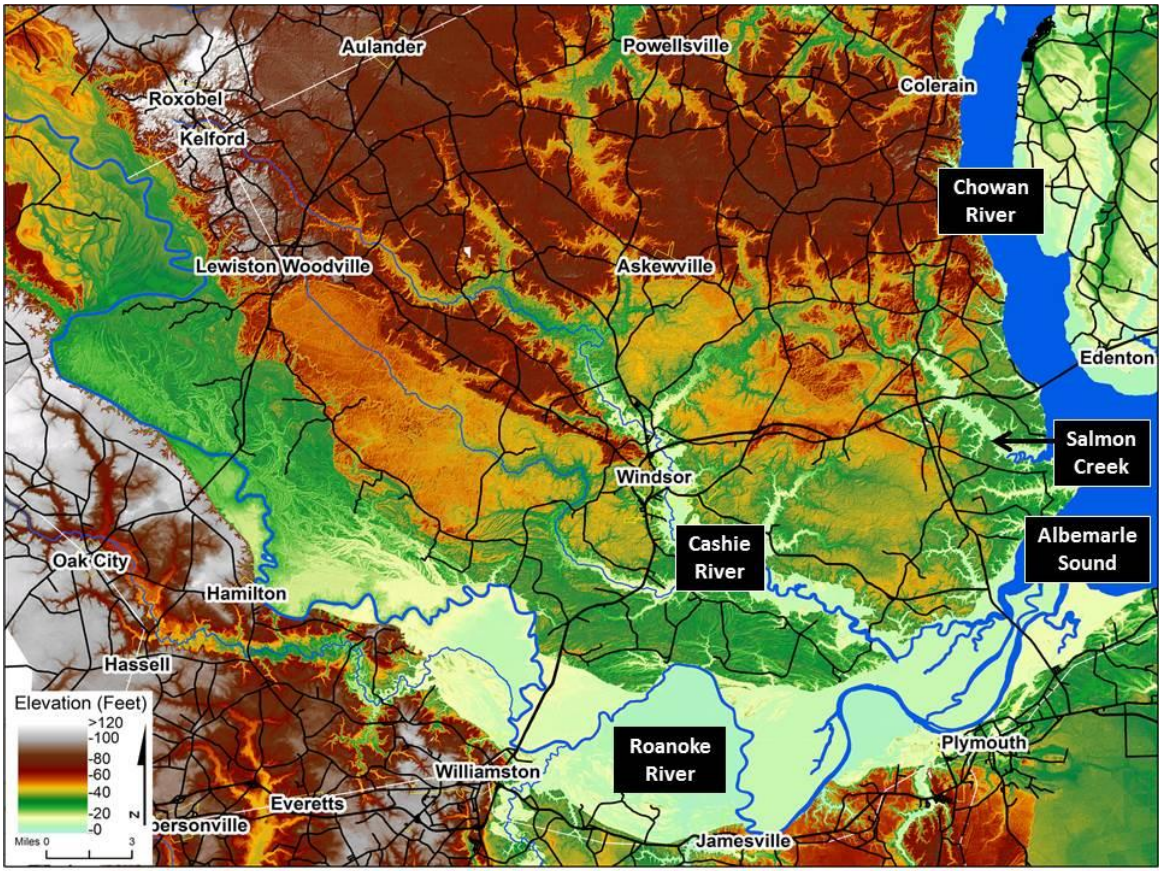


FIGURE 1-4. A color topography map shows the southern portion of the Bertie Peninsula in the northeastern North Carolina Coastal Plain and including all of Bertie County and the associated Bertie Water Crescent. The black labels identify the five water bodies included in the present report. Topographic data are from the NC 2015 LiDAR program. Map prepared by D. Ames.

Bertie-Windsor Water Hubs

The world-class natural resources of the Bertie landscape and waterscape form the basis for development of short- and long-term, sustainable eco-tourism in the "Bertie-Windsor Water Crescent". Based on this unique land of water system, Bertie County and the Town of Windsor have defined five water hubs (see the previous report by Riggs et al., 2018). This 2018 report provides the foundation for implementation of these water hubs as centers for sustainable eco-tourism and form the basis for requesting a US National Park Service designation as a National Water Trail for the "Bertie-Windsor Water Crescent". Four of the five water hubs already exist in various stages of development, while the fifth one is in the early discussion stages.

1. Windsor: An urban waterfront park on the Upper Cashie River that includes four boat ramps, fishing piers, boardwalks, campground, four tree houses, two museums, kayak rental facility, and a National Wildlife Refuge Visitors Center and meeting facility.

2. Sans Souci: A two car cable ferry and public boat ramp that opens up the black-water wilderness of the Lower Cashie and vast Roanoke River floodplains with their abundant camping platforms.

3. Salmon Creek State Natural Area (995 acres) and County Recreational Area (147 acres) occurs at the confluence of three different water bodies with over 5 miles of waterfront and provides the framework for the "Rivers to Sounds" environmental education program. The possible acquisition of an additional 300 acre parcel, that connects the two existing parcels, is presently in progress.

4. Weeping Mary on the Roanoke River, with its vast wilderness and important climate history, is situated within the historic Moratico Floodplain that already has developed a public fishing platform and boat ramp.

5. Colerain's Wicomoco Bluffs and Northern Cow Island Swamp Forest Natural Areas on the west bank of the Chowan River Estuary are in the early discussion phase.

WATERSCAPE OF THE "BERTIE WATER CRESCENT"

Flooding and erosion problems within the Bertie Water Crescent must consider five different kinds of water bodies and four basic processes that are all integrated and work together. The five types of water bodies are the Upper and Lower Roanoke River, Upper and Lower Cashie River, Chowan River Estuary, Chowan River bluffs and ravines, and Albemarle Sound. The four basic processes include the various storm dynamics including the following: 1) upstream rainfall, 2) downstream wind tides and storm surge, 3) release policies on the upstream dams of the Roanoke River (discharge amount, duration, and pattern), and 4) status of ecosystems to provide the services of water storage and removal.

ROANOKE RIVER SYSTEM

The Roanoke River Watershed

The Roanoke River has the largest discharge of all North Carolina rivers with a 10,000 square mile watershed (Fig. 2-1). The headwaters are in the Valley and Ridge, Blue Ridge, and Piedmont provinces of Virginia and North Carolina (DWQ, 2001). The river flows generally southeast for about 400 miles, and discharges into Albemarle Sound. The upper Roanoke River watershed is that portion west of the Fall Line and constitutes 80% of total drainage basin (8,000 square miles). The lower watershed is that portion east of the Fall Line where the river flows across the Coastal Plain and constitutes 20% (2,000 square miles) of the drainage basin.

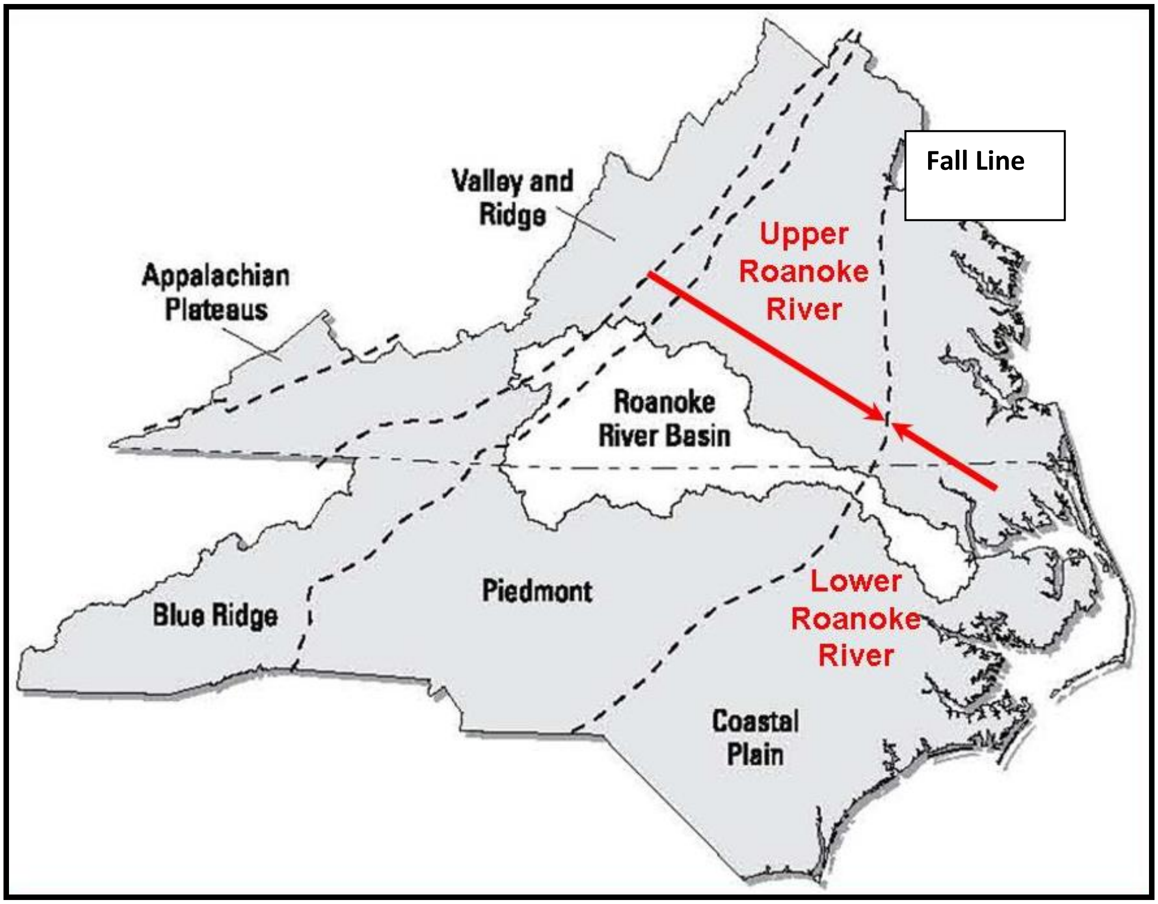


FIGURE 2-1. Location of the Roanoke River drainage basin in North Carolina and Virginia with the upper Roanoke River situated in the Appalachian Mountain and Piedmont provinces and the lower Roanoke River situated in the Coastal Plain Province. Figure is modified from Bales and Walters (2003).

The upper portion of the Roanoke watershed contains three large reservoirs (Kerr, Gaston, and Roanoke lakes in Figure 2-2), three intermediate size reservoirs (Belews, Hyco, and Mayo lakes, and at least five additional small reservoirs (DWQ, 2001). These reservoirs were built for public water supplies, hydroelectric power, flood control structures, and for recreation and development. The water stored in the lake above the dam contains potential energy. The elevation difference is known as the hydraulic head and allows water to fall through passage ways connecting the lake above to the tail race below using the force of gravity. Thus, potential energy is converted to kinetic energy as the water flows through the blades of turbines, which in turn spin generators to produce electricity—this is hydroelectric power.

Piedmont Dams and the Fall Line

Water flow management from the dams is a major controversy for the disparate user groups since this represents a major influence upon both downstream water quantity and quality, as well as the pattern of flows and water levels. Since the present project is primarily interested in the lower Roanoke River, the Kerr Lake dam is most critical. It was built in 1952 as a water storage basin and a discharge control structure to manage downstream flooding. The downstream Roanoke Rapids and Gaston dams were completed in 1955 and 1963, respectively, as hydro-power plants to generate electricity. These latter two dams are substantially smaller and only act as pass-through dams. Thus, it is the Kerr Lake dam discharge that dictates the water flow of the entire Lower Roanoke River. Together these three dams captured the free-flowing Roanoke River and drowned over 70 miles of the river valley to produce the Kerr, Gaston, and Roanoke Rapids lakes.

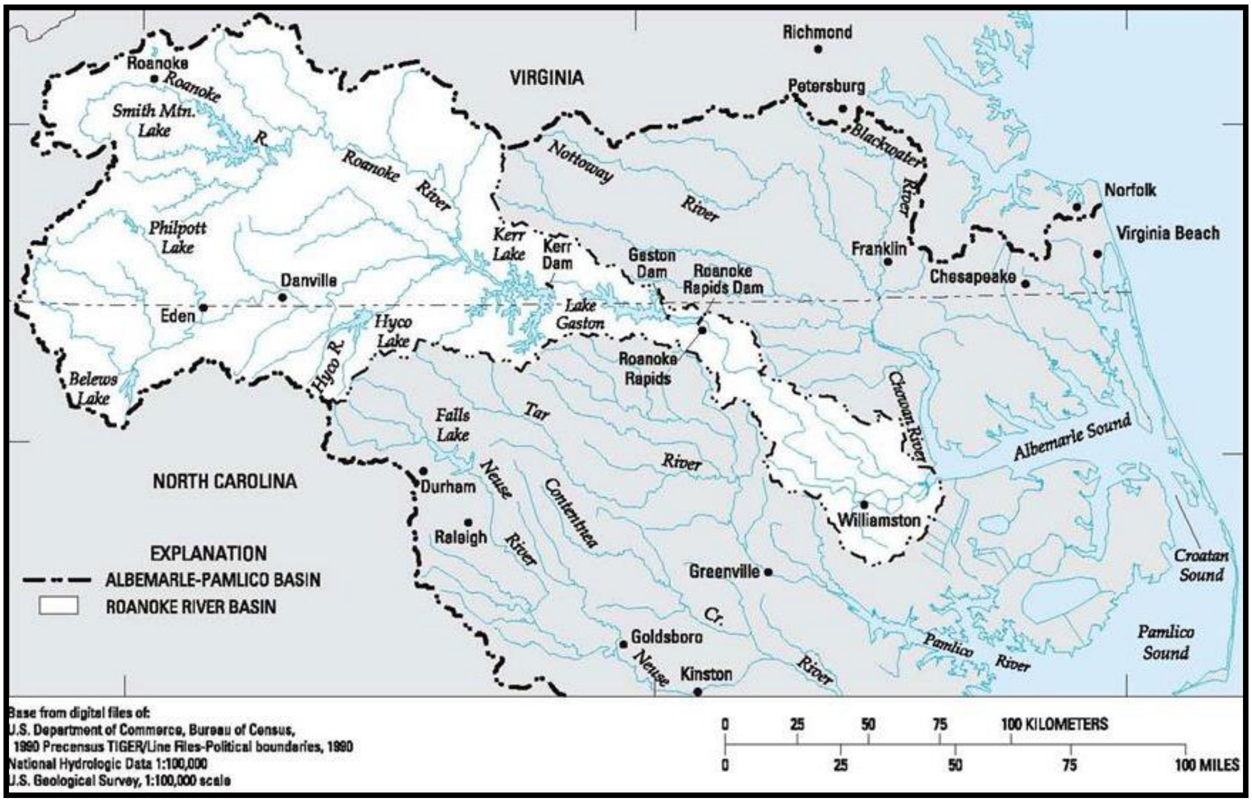


FIGURE 2-2. The map shows the relation of the Roanoke River drainage basin in North Carolina and Virginia to the other Albemarle-Pamlico sound trunk drainage systems. Notice the three large lakes and three small lakes in the upper Roanoke River drainage system. Figure is from Bales and Walters (2003).

Timing and volume of water discharge through the dams determines floodplain water levels and in-stream dissolved-oxygen concentrations (Bales and Walters, 2003). Consequently, flooding and floodplain inundation no longer occur according to natural seasonal patterns, but rather, are determined by upstream reservoir releases. This can have both negative and positive impacts upon various aspects of fisheries, water quality, floodplain plant and animal resources, farming, and recreational uses including hunting, boating, kayaking, and camping. Because the floodplains of the lower Roanoke River contain nationally significant wetland habitats with large and diverse populations of plants and animals, the conflicts between various stakeholder groups have been and continue to be severe at times.

When the Roanoke Rapids hydroelectric dam was built in 1955 (Figure. 2-3), it became the major control of the Lower Roanoke River flow. This dam eliminated many of the “rapids” through Roanoke Rapids, except for the lower falls at Weldon. The top of the dam has an elevation of 142 ft above MSL that forms an 8-mile long lake encompassing 4,600 acres of water surface with 47 miles of shoreline. The average annual flow with a maximum and minimum river flow recorded <u>prior to dam construction</u> was 261,000 $feet^3$/second and 250 $feet^3$/second, respectively (Figure 2-4).

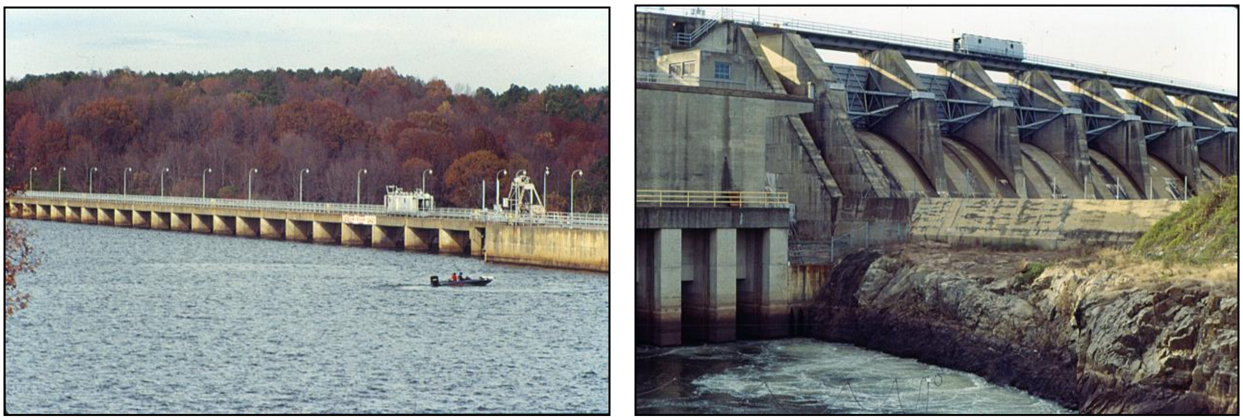


FIGURE 2-3. Photographs show the hydroelectric dam that forms the Roanoke Rapids Lake at the eastern edge of the Piedmont Province. Panel A is a photo above the dam and Panel B is a photo of the tailrace below the dam. Notice the crystalline granite that the raceway has been cut into.

The hydrographic data from the gaging station located just downstream of the Roanoke Lake dam is presented in Figure 2-4. The data from this gaging station indicates that mean water level is 44 feet above mean sea level (MSL) and the area drained through this station is 8,384 $miles^2$. The pre-dammed river was characterized by periodic seasonal episodes of high and low flow that were quite regular with only an occasional diversion from this pattern due to anomalous storms and droughts. The downstream ecosystem had evolved based on this pattern and was in equilibrium with it. However, since 1955 the Roanoke River Dam has been managed with a water control and release program based primarily on energy demand and storm water discharge from Kerr Dam. This changed pattern of water flow has had major impacts on the natural character of the downstream ecosystems and economy of people living in the area. The impacts on farming, forestry, hunting, and boating have resulted in extremely controversial water management problems.

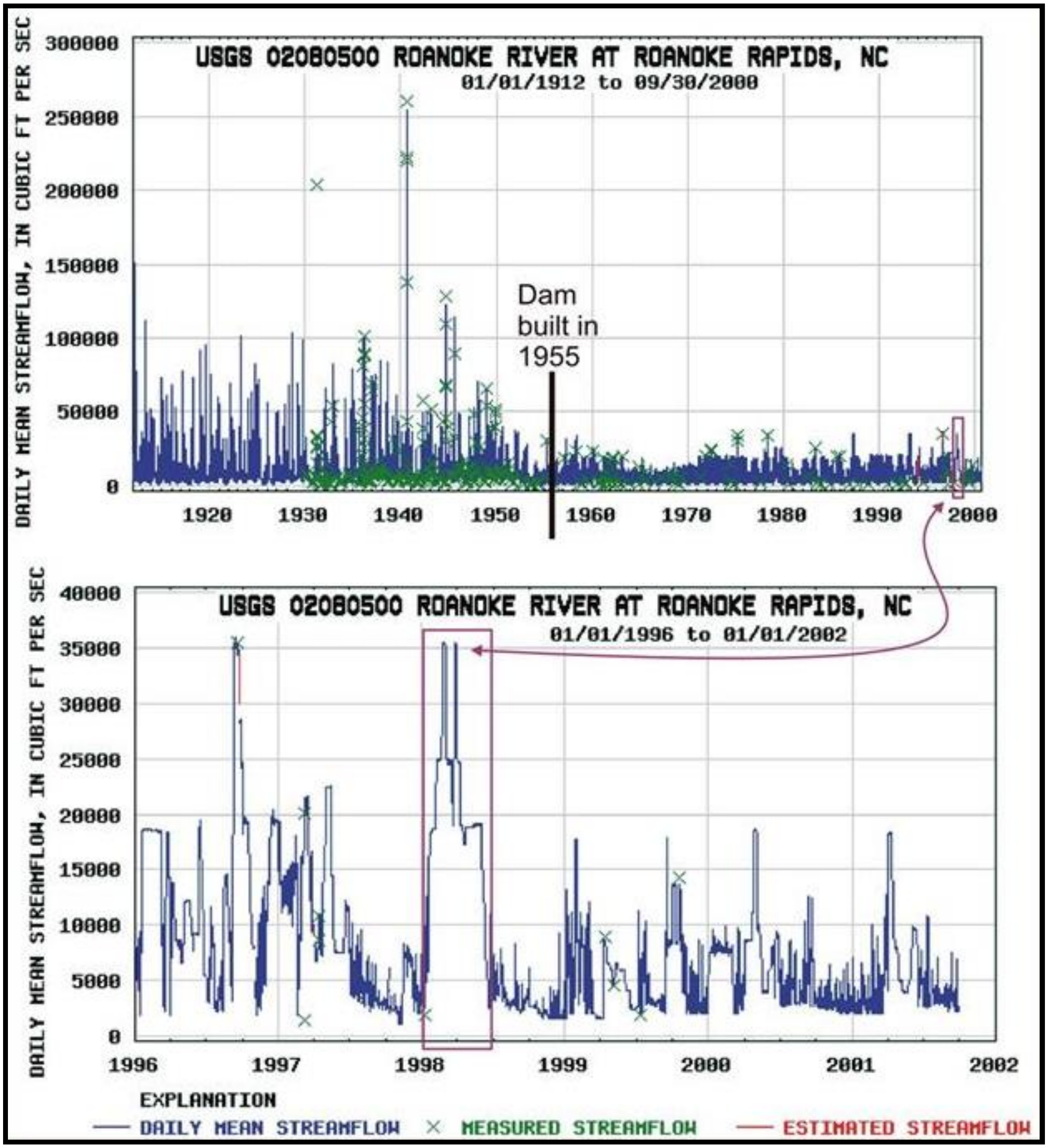


FIGURE 2-4. USGS hydrograph shows the daily mean stream flow for the Roanoke River at Roanoke Rapids below the dam. The upper record shows the natural river flow from 1912 to 1955 and after construction of the dam from 1955 to 2000. The lower panel shows an expanded section of the hydrograph from 1996 to 2002 and includes numerous small storm events when the rates and duration of discharge were substantially increased. The two periods of 35,000 feet^3/second discharge resulted primarily from hurricanes Bertha and Fran in 1996 and hurricane Bonnie in 1998. Data are from the U.S. Geological Survey (http://nwis.waterdata.usgs.gov/nc/nwis/sw).

Increased withdrawals of water from the reservoir for industrial and urban utilization diminish the net water flow within the riverine hydrologic system. Starting in 1968 several Virginia communities began efforts to tap Roanoke River water to support their rapid population growth rates. A pipeline was completed in 1998 from Lake Gaston to Hampton and Virginia Beach and began delivering 60 million gallons of water per day to these booming coastal cities. As growth continues, Virginia Beach, as well as others in the region, will want to increase water withdrawals in the future. Since Hampton and Virginia Beach are located within another drainage basin, this volume of water is permanently lost to the lower Roanoke River system.

The average annual flow at the dam today is determined by the John H. Kerr Reservoir Guide Curve based on agreed upon lake levels with two basic categories: the first is the "conservation (power) pool" for lake elevations of 268 to 300 feet and second is the "controlled flood stage pool" for lake elevations of 300 to 320 feet above sea level (US ACE, June 2016). The "Water Control Plan" describes the discharge operations for "flood control, hydropower generation, low flow regulation, and other project purposes" including fish and wildlife, water supply, and recreation. In order to accomplish these objectives, the "Guide Curve" varies through the seasons and is determined by lake elevations. Based on the current Final Environmental Assessment and subsequent "Water Control Plan" (USACE, May 2016; June 2016) "flood waters in the Reservoir are released in accordance with the following schedule: only up to 20,000 cfs is released between reservoir elevations 300 ft to 320 ft NGVD29. For reservoir levels between 315 and 320 feet NGVD 29, flood releases may be increased to 35,000 cfs. Since dam construction, flood releases from Roanoke Rapids Dam have not exceeded 35,000 cfs since the Reservoir water level has not exceeded elevation of 320 feet." When lake level is below 300 feet, water discharge can be up to 8,000 feet^3/second with drought minimum flows of 1,500 cfs to 2,000 cfs, depending on the season. These low flow rates supposedly "mimic the unregulated river discharges" (US ACE, May 2016).

Since the Kerr Lake Reservoir is the flood storage area for the Lower Roanoke River, its discharged waters pass through the Lake Gaston and Roanoke dams into the Lower Roanoke River. Legislatively, the primary objective of the "Water Control Plan" is to control and reduce flood risk along the Lower Roanoke River. Flood waters temporarily stored in the reservoir are generally released through the dams at the maximum rate possible. However, the lower Roanoke River channel conveyance capacity is approximately 20,000 cfs before substantial floodplain flooding occurs over the existing natural levee (US ACE, May 2016). Significant long-term damage begins to impact portions of the downstream system as the discharge occurs in the 20,000 to 25,000 cfs range, particularly if the floodwaters occur over an extended period of time. This was the situation that occurred during a significant portion of 2018 and the first half of 2019. The Lower Roanoke River experienced an extended series of 30,000 to 35,000 cfs discharges over a six month period (mid-September through mid-March) even though the Kerr Lake levels only ranged between maximums of 307 to 314 feet above sea level (Figures 2-5 and 2-6). This resulted in extensive and economically significant downstream flooding that severely impacted four downstream counties.

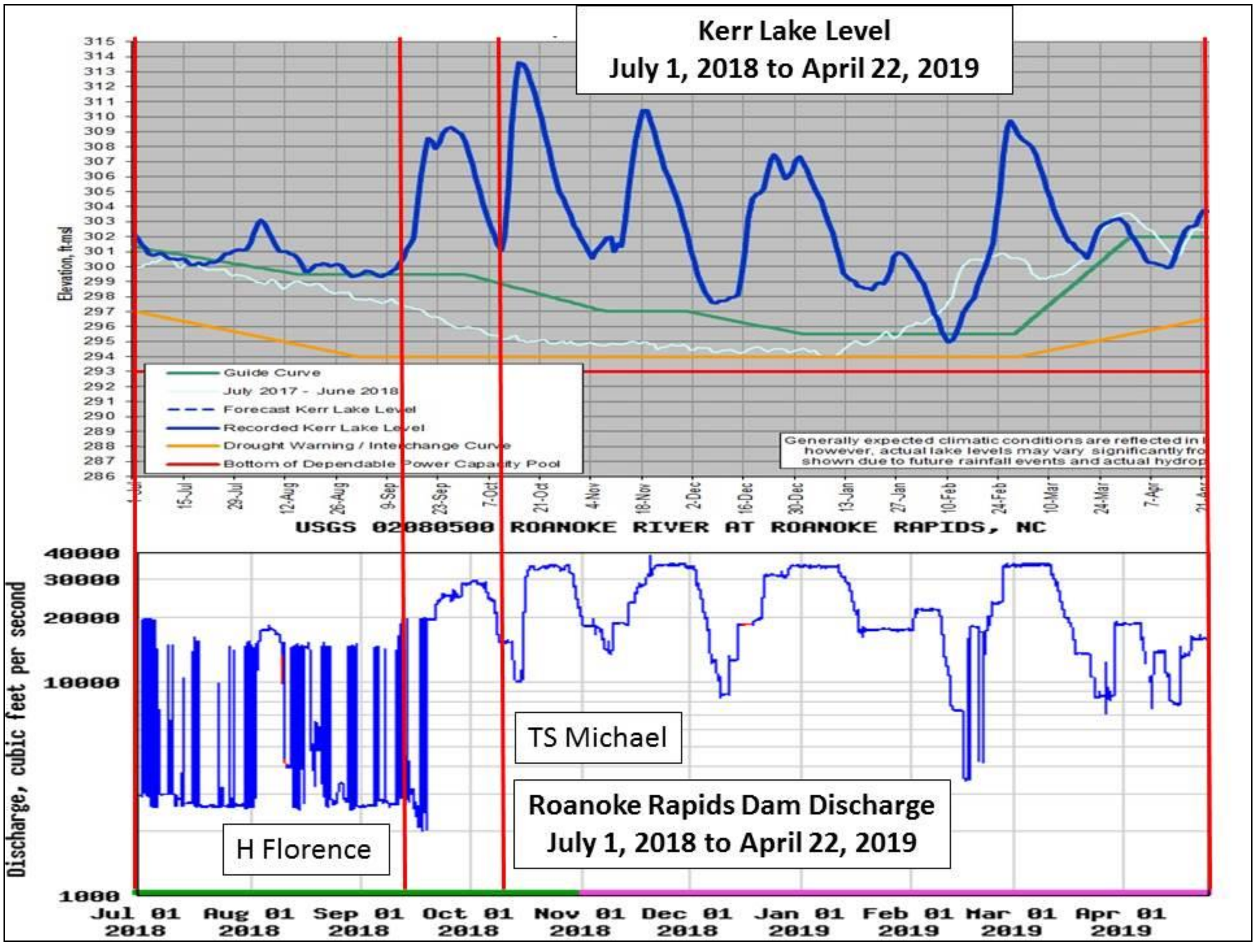


FIGURE 2-5. This plot shows the USGS water level records for the Kerr Reservoir water elevation in feet above sea level vs the water discharge rate in cubic feet per second at the Roanoke Rapids gage for the period from July 1, 2018 to April 15, 2019. The high rate of discharge has generally continued through June, 2019.

Dam Discharge Controls in the Lower Roanoke River

The historic to present day water level data for the Bertie Water Crescent study has been mined and monitored from 15 different gages that are indicated on Figure 2-6 and in Appendix A. The relevant gages utilized in this study include 9 maintained by the USGS, 1 maintained by NC FIMAN, and 4 NC LOW gages were utilized. For the purposes of this study, what is important is the vertical height of water and the fluctuation pattern of water level that are based on the relative stage height (measured in feet) of the water that will be utilized from the different water level recorders. Since many groups studying and working in the NC river systems utilize the water flow data measured in cubic feet per second (cfs), it is important to recognize that the **patterns** of water flow measured in discharge (feet^3/second) and gage height (feet) at any given site are similar as indicated in Figures 2-7 and 2-8 for the Roanoke and Cashie Rivers, respectively. When dealing with flooding and the public, it is the water height in feet and inches that matter.

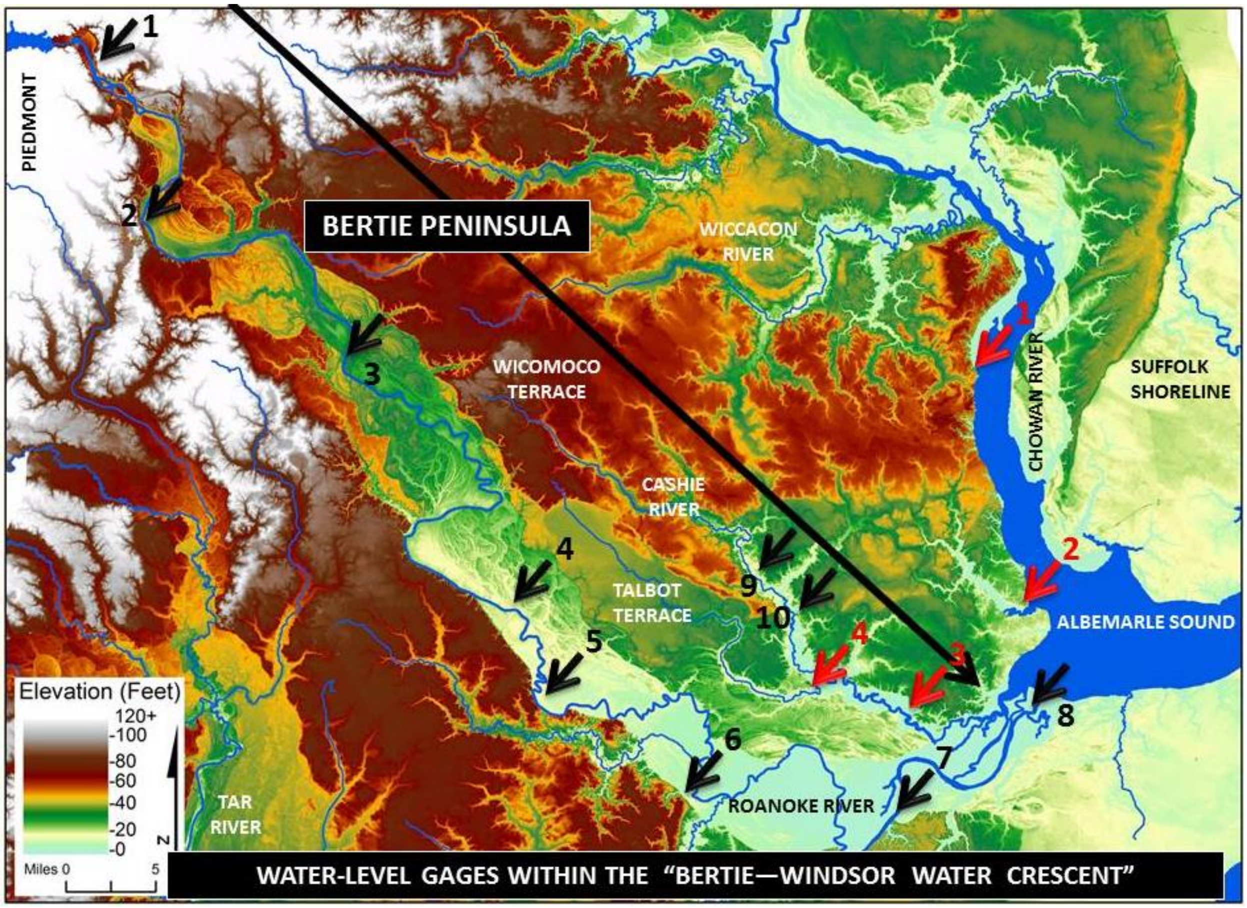


FIGURE 2-6. A color topography map of the Bertie Peninsula and surrounding Bertie-Windsor Water Crescent shows the general location of the 15 water-level gage sites utilized for the present NC LOW study. The black arrow sites 1 through 9 are maintained by the US Geological Survey in Raleigh, site 10 is maintained by NC FIMAN in Raleigh, and the 4 red sites are temporary HOBO sites maintained by the authors and NC LOW in Greenville. Location information is in Appendix A. Topographic data are from the NC 2015 LiDAR program. Map prepared by D. Ames.

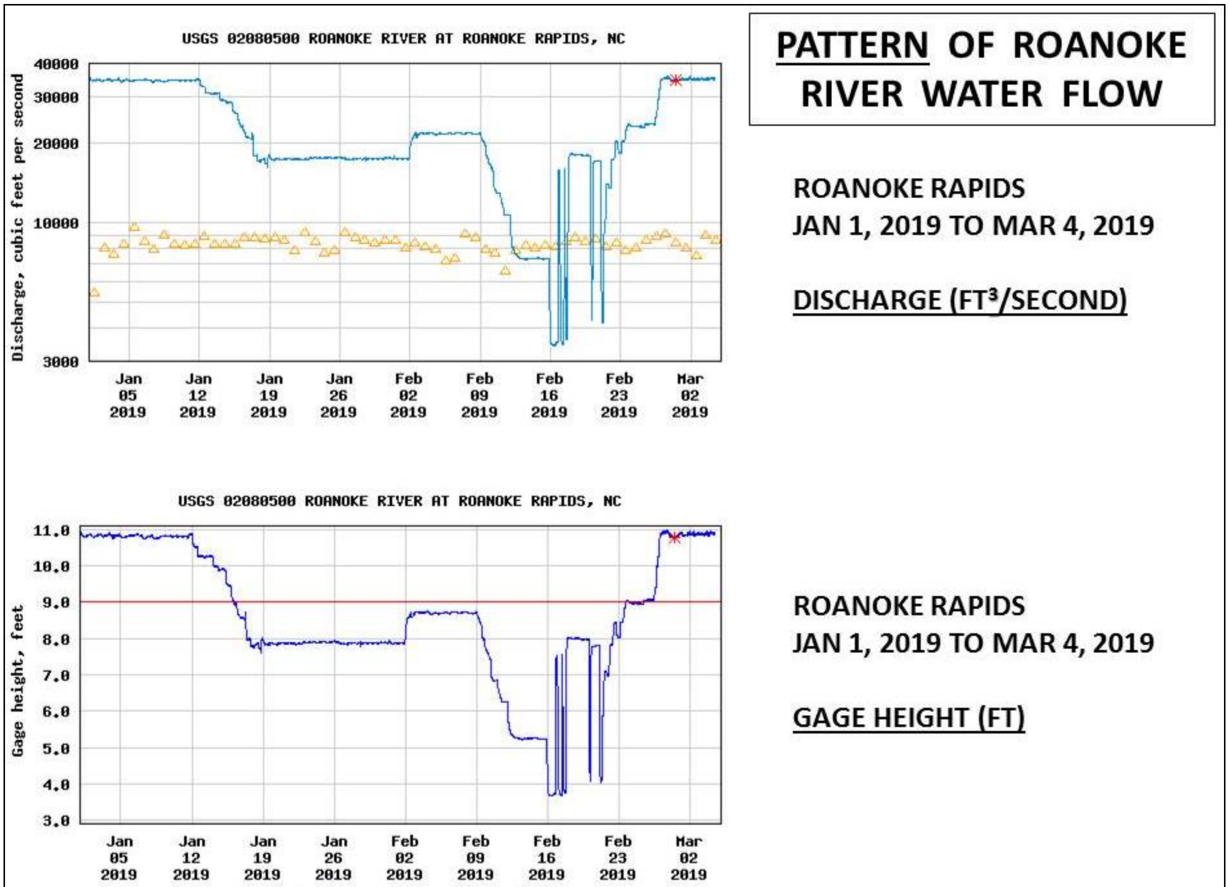


*FIGURE 2-7. Plot compares the gage pattern of Roanoke River dam discharge rate in feet^3 per second (upper panel) with the water level gage height in feet (lower panel) at the USGS water gage site in Roanoke Rapids for the period of January 1, 2019 to March 4, 2019. Since it is the downstream pattern of flow that is important, **NONE** of the water-level plots in this report are corrected for absolute elevation.*

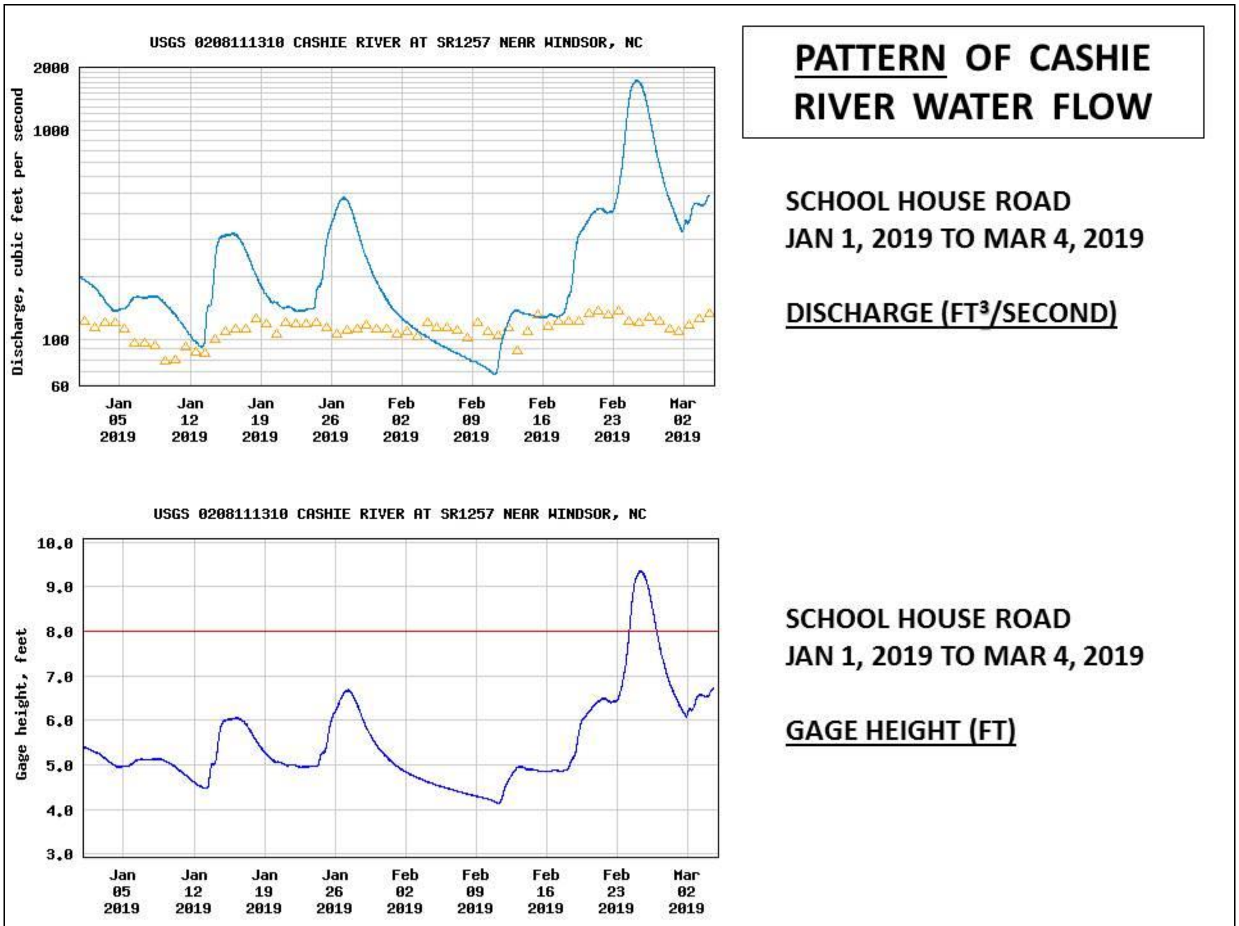


FIGURE 2-8. Plot compares the gage pattern of rate of discharge in feet^3 per second (upper panel) with the water level gage height in feet (lower panel) at the USGS water gage site in at School House Road on the Upper Cashie River for the period of January 1, 2019 to March 4, 2019. Since it is the downstream pattern of flow that is important, ***NONE*** *of the water-level plots in this report are corrected for absolute elevation.*

The Lower Roanoke River has eight US Geological Survey water level recorders (Figure 2-6) that extend from the Roanoke Rapids recorder, three miles below the Roanoke Lake dam, and downstream to Halifax, Scotland Neck (highway 258 bridge), Oak City (highway 11 bridge), Hamilton, Williamston (highways 13-17 bridge), Jamesville, and Westover (highway 45 bridge). Figures 2-9 and 2-10 demonstrate how a series of normal daily dam discharges produce individual water waves that coalesce and propagate downstream to Jamesville. The top panel in Figure 2-9 shows the daily dam discharges between 15,000 to 20,000 cfs from Sep. 1 through Sep 19, 2018. When the upstream lake levels began to rise towards 309 feet dam discharge was increased to 35,000 cfs flow rates. Exceedingly high flows continued through 2018 and lasted until mid-March 2019 (Figure 2-7). As the river flows downstream, each wave set becomes less distinct and coalesces down to the Williamston gage where the Hwy 13-17 gage is located (middle panel in Figure 2-10).

During high discharge flows at the Roanoke Rapids dam (Figure. 2-9) there is no evidence of an Albemarle Sound water level signal at Williamston (Figures 2-10 middle panel and 2-11). However, the Jamesville gage still carries the dam discharge signal, as well as a small tidal signature from Albemarle Sound superimposed on the dam signal. The bottom pane in Figure 2-10 is dominated by the Albemarle Sound signature of both wind and astronomical tides. The Roanoke dam signal is generally lost as the flood waters spread out through an extremely broad, sea-level based, floodplain swamp forest. Thus, the Roanoke dam discharge pulses probably form a very low background that represents less than a foot of gage height flow on the Westover Hwy 45 water-level gage.

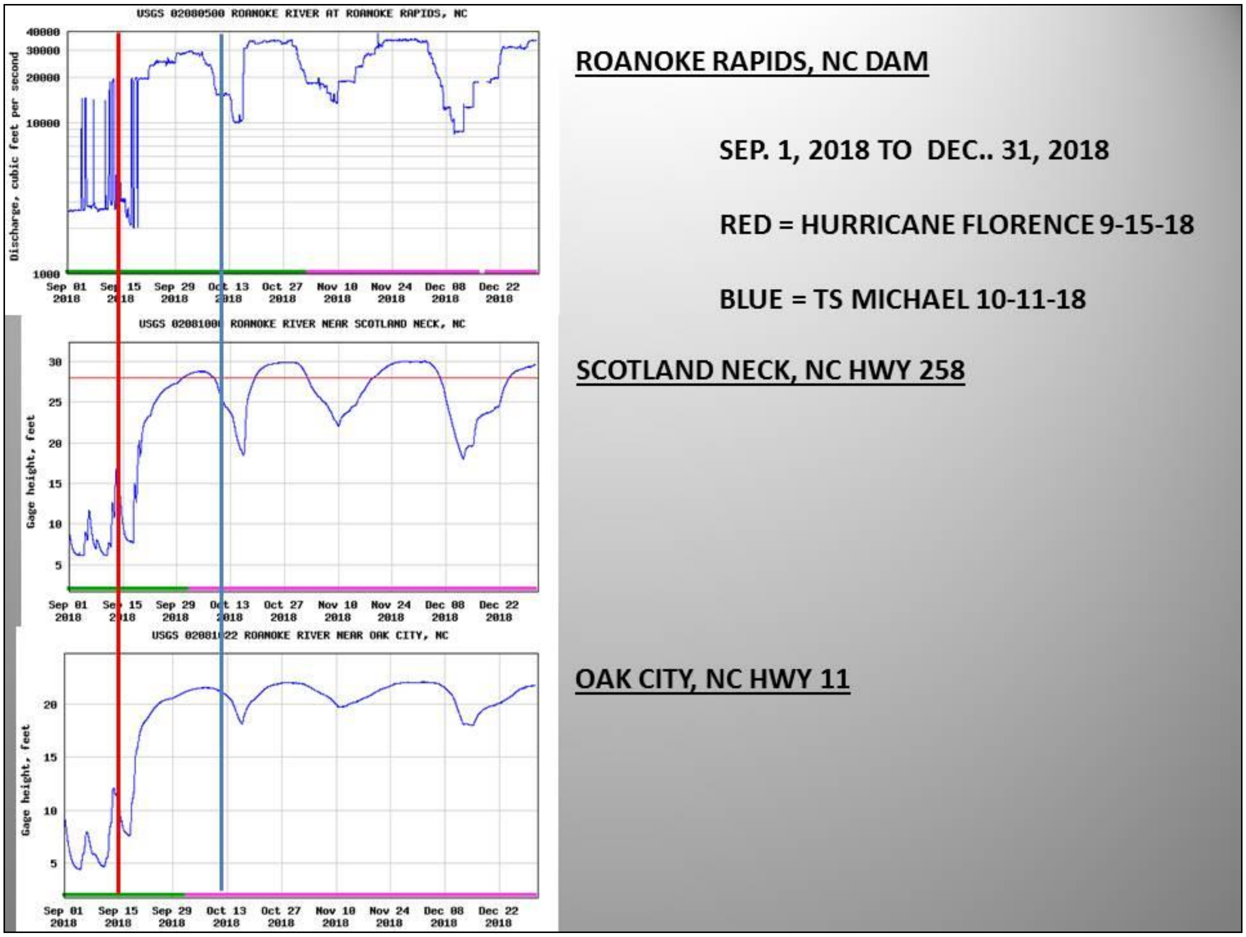


FIGURE 2-9. Plot compares the USGS gage patterns for the Roanoke River from the dam discharge rate in feet^3 per second (top panel) with the water level gage height in feet at the Scotland Neck (middle panel) and the Oak City (bottom panel) for the period of September 1, 2018 to December 31, 2018. Since it is the <u>downstream pattern of flow</u> that is important, none of these plots are corrected for absolute elevation and each plot has a different vertical scale (stage height).

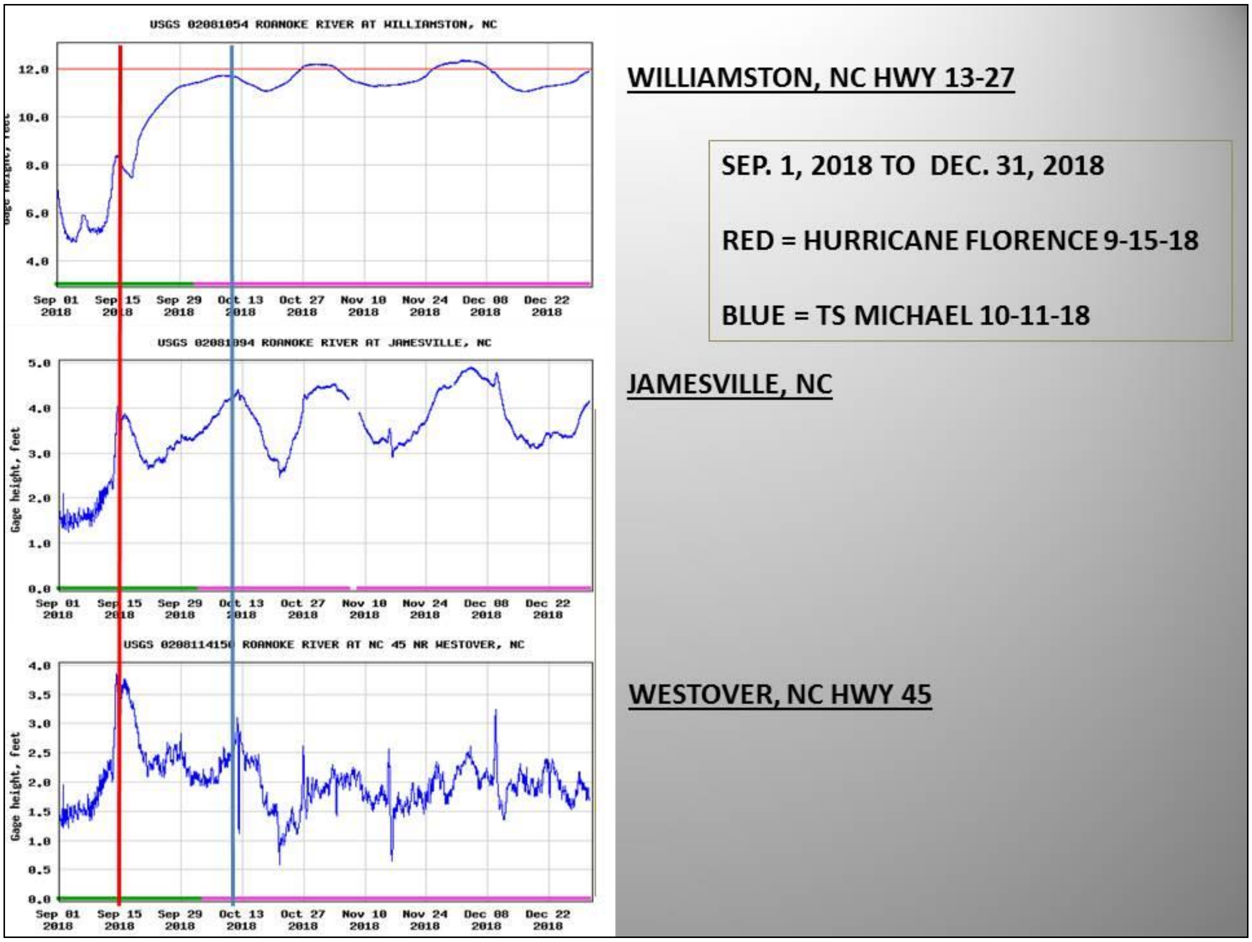


FIGURE 2-10. Plot compares the USGS gage patterns for the Roanoke River from the Williamston water level gage height in feet (top panel) with the water level gage height in feet at the Jamesville (middle panel) and Westover (bottom panel) for the period of September 1, 2018 to December 31, 2018. Since it is the downstream pattern of flow that is important, none of these plots are corrected for absolute elevation and each plot has a different vertical scale (stage height).

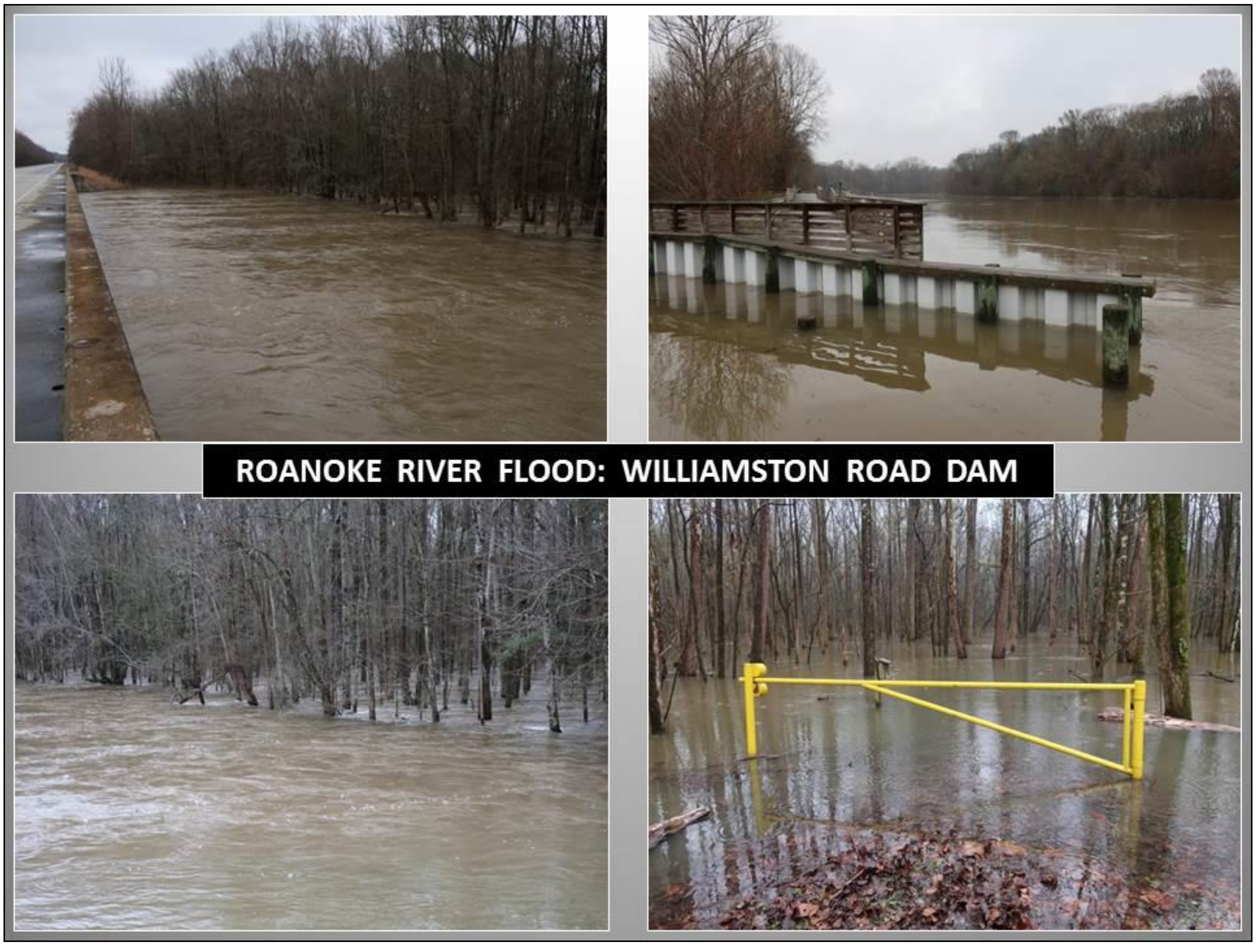


FIGURE 2-11. High flood waters at the Williamston Highway 13-17 road dam (3 floodplain panels) and the NC WRC boat ramp (primary channel in upper right panel) during the period when the Roanoke Rapids dam discharge was up to 35,000 cfs from Sep. 21, 2018 through mid-March 2019. Photographs are by S. Riggs.

Figure 2-10 plots the Williamston Highway 13-17, Jamesville, and Westover Highway 45 gages that demonstrate the change in water flow patterns from the dominant Kerr Lake dam discharge pattern at Williamston, through the transition zone to Albemarle Sound dynamics at the Westover Highway 45 gage. Figure 2-11 provides a visual sense of high water levels at Williamston. The Highway 13-17 road dam across the primary floodplain modifies water flows and levels. Figure 2-12 illustrates the minimal impact of the Kerr Lake dam discharge signal at the lowermost gage in the mouth of the Roanoke River (Westover Highway 45 Bridge). Rather, the signal at this gage reflects the mixed semi-diurnal astronomical tides as seen in Figure 2-13. Superimposed on the tidal signals are the larger, but less regular wind and storm tides associated with several frontal systems and two tropical storms passing through the region. It is clear that if the Roanoke River discharge is at normal or low rates, the Albemarle Sound tidal signals reach Williamston and with larger Albemarle wind surges, the Albemarle signal can reach up the Roanoke River to Hamilton.

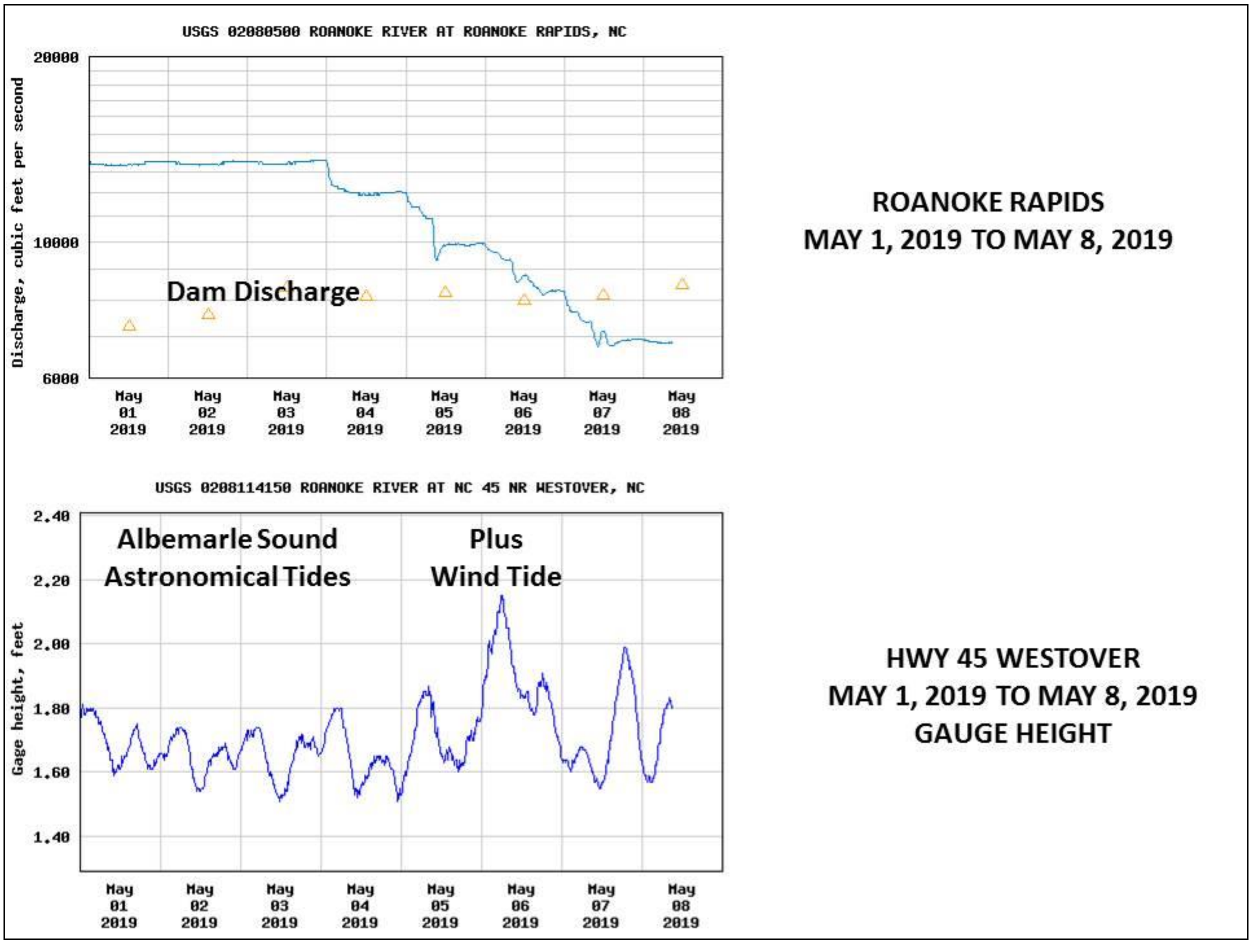


FIGURE 2-12. Plot compares the USGS gage patterns for the Roanoke River from the dam discharge at Roanoke Rapids (upper panel) with the Hwy 45 Westover water level gage height in feet (lower panel) for the period of May 1 to May 8, 2019. Notice that there is no dam discharge signal downstream in panel 11B which is dominated by semi-diurnal astronomical tides and wind tides. Since it is the downstream pattern of flow that is important, none of these plots are corrected for absolute elevation.

The upper left panel in Figure 2-13 shows a four month record (Sept. 1 to Dec. 31, 2018) of water level fluctuations at the Westover Highway 45 water level gage. The lower left panel zooms into the Dec. 1 to Dec. 31 portion of the plot and the upper right panel shows the same data for Dec. 24 to Dec. 31. The first plot shows a minimal storm surge from two different tracked, small-scale tropical systems (Hurricane Florence and Tropical Storm Michael), both of which were peripheral to the Lower Roanoke-Albemarle Sound region. The record of wind tides and storm surges from numerous frontal systems and small-scale storms is also documented in the water level record highlighted in subsequent plots. The different patterns of wind/storm tides reflect the differences in wind direction, intensity, and duration that dictate the size and pattern of the wind/storm tides. The detail at the weekly scale demonstrates the high and low of a small wind tide with the semi-diurnal astronomical tides superimposed on the larger-scale wind tide.

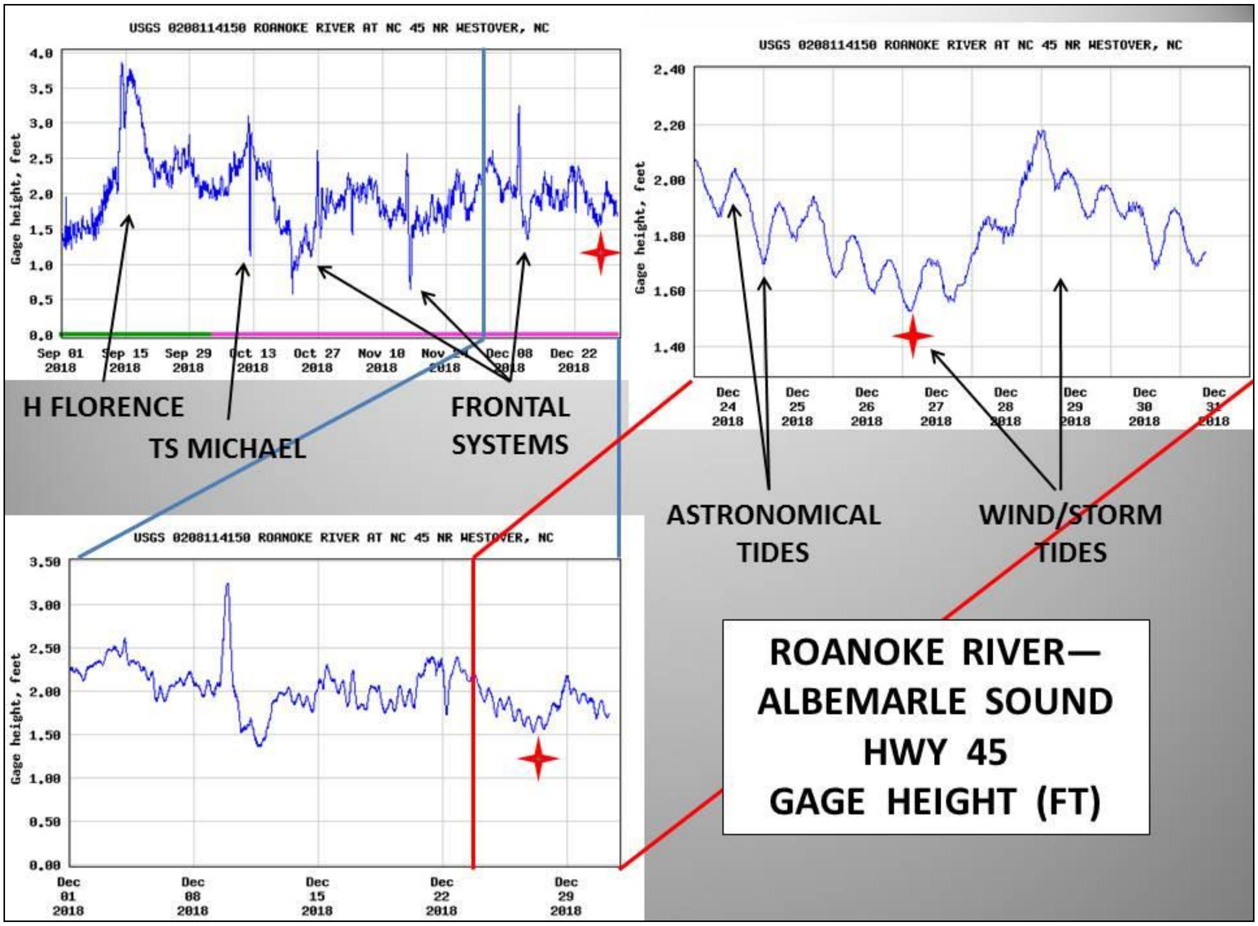


FIGURE 2-13. The upper left plot shows the USGS Westover Highway 45 water level gauge record from Sep. 1, 2018 to Dec. 31, 2018. The lower left plot zooms in and shows the Dec. 1 to Dec. 31 portion of the plot, while the upper right plot shows the same data for the period of Dec. 24 to Dec. 31. Notice that some wind/storm tides are couplets, while others occur as westerlies or easterlies depending on the direction, intensity, and duration of the weather event. The red star identifies the same time in all three panels. Since it is the flow pattern that is important, this plot has not been corrected for absolute elevation.

Consequently, if the Roanoke River is in flood due to large volume Kerr Lake discharges (25,000 to 35,000 cfs rates), the entire river from Roanoke Rapids down to the Williamston highway 13-17 road dam is in flood conditions (Figure 2-14). The Williamston road dam is about 3.4 miles in length with only one main channel bridge and six overflow bridges resulting in a road dam across about 89% of the Roanoke River floodplain. The road dam appears to initiate the decline of the Kerr Lake dam discharge signal. The Jamesville gage represents the transition zone as the flood waters reach sea level and spread out over the extremely broad floodplain. However, the Westover gage at Highway 45 shows only slight increase in water level from the Kerr Lake dam discharge and is dominantly controlled by the Albemarle Sound dynamics of the small astronomical tides superimposed on the larger-scale wind tides (Figure 2-14).

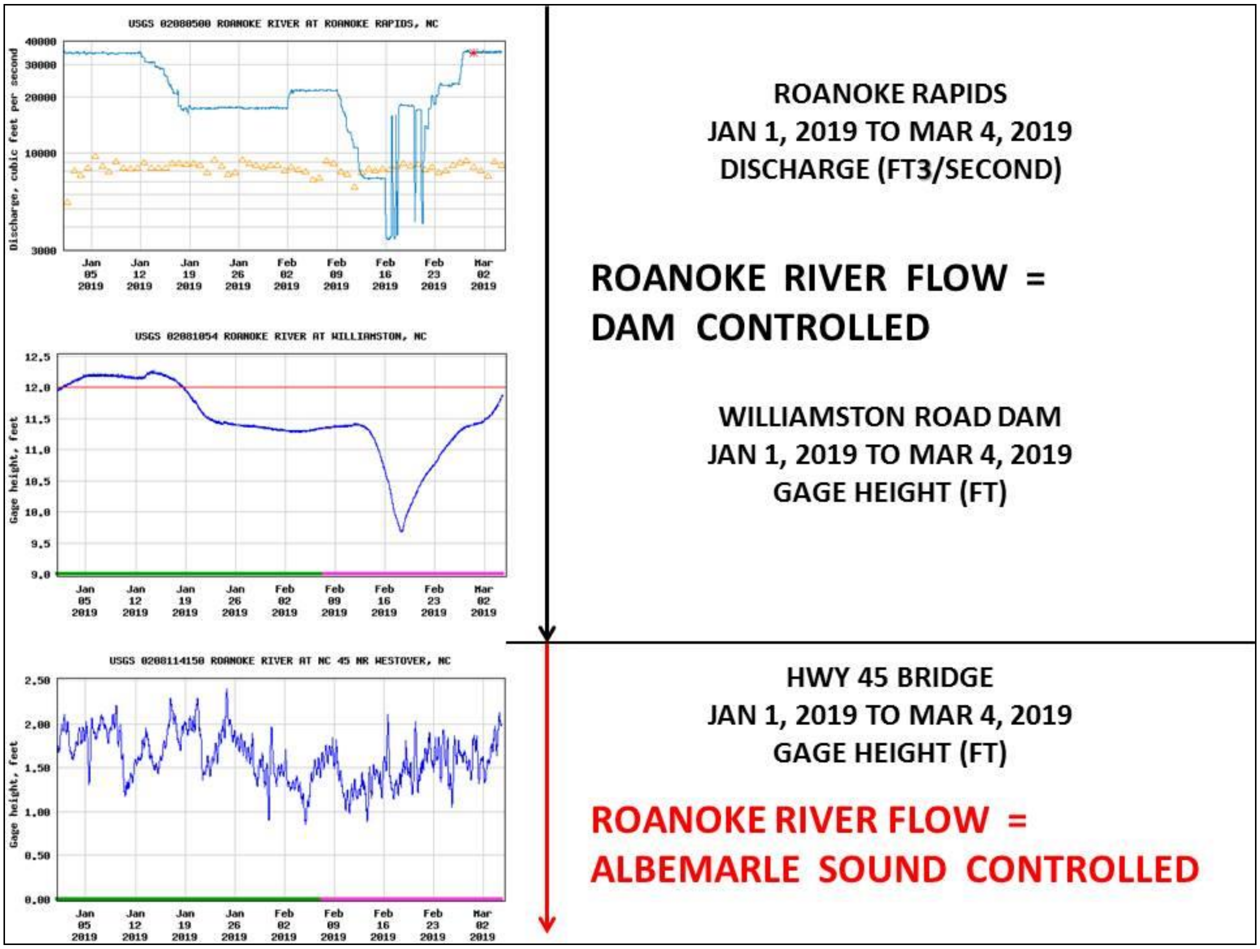


FIGURE 2-14. The three plots summarize the Lower Roanoke River water level gage records from Jan. 1, 2019 to Mar. 4, 2019. Under high flow conditions, the records from the Roanoke Rapids gage to the Williamston Hwy 13-17 gage are totally dam discharge controlled. Whereas, the Westover Hwy 45 record is totally controlled by Albemarle Sound dynamics. The Jamesville gage is in the transition zone and reflects the Albemarle (low dam discharge), records both signals (intermediate dam discharge), or has no Albemarle signal (high dam discharge) (middle panel in Figure 2-10). The red line in panel B is the flood stage at Williamston. Since it is the flow pattern that is important, this plot has not been corrected for absolute elevation and each plot has a different vertical scale (stage height).

Valley Geometry and Flooding in the Lower Roanoke River

The Roanoke River valley is quite different than the modern and active Roanoke River channel and associated floodplain that change dramatically downstream from the Roanoke Lake dam and Roanoke rapids at Weldon. The Lower Roanoke River segment from the Roanoke dam to Mush Island (Figure 2-15) is narrow, steep, and rock-bound by the crystalline rocks of NC’s Piedmont Province (Figure 1-3). This segment is called the “Fall Zone”, is less than a mile wide, dominated by river rapids and small water falls during low water flow, and little to no floodplain (Figure 2-16). The active river system in riverine zone 1 extends from the sediment deposits of

Mush Island to just below Caledonia and is incised into the surrounding terrace deposits with a modern channel and active floodplain that is generally about a mile wide and a channel bottom that is well above sea level. The Roanoke valley in this river segment is filled with the higher terraces of Occoneechee Neck and Caledonia composed of older glacial age meander deposits (Figures 2-15 and 2-16).

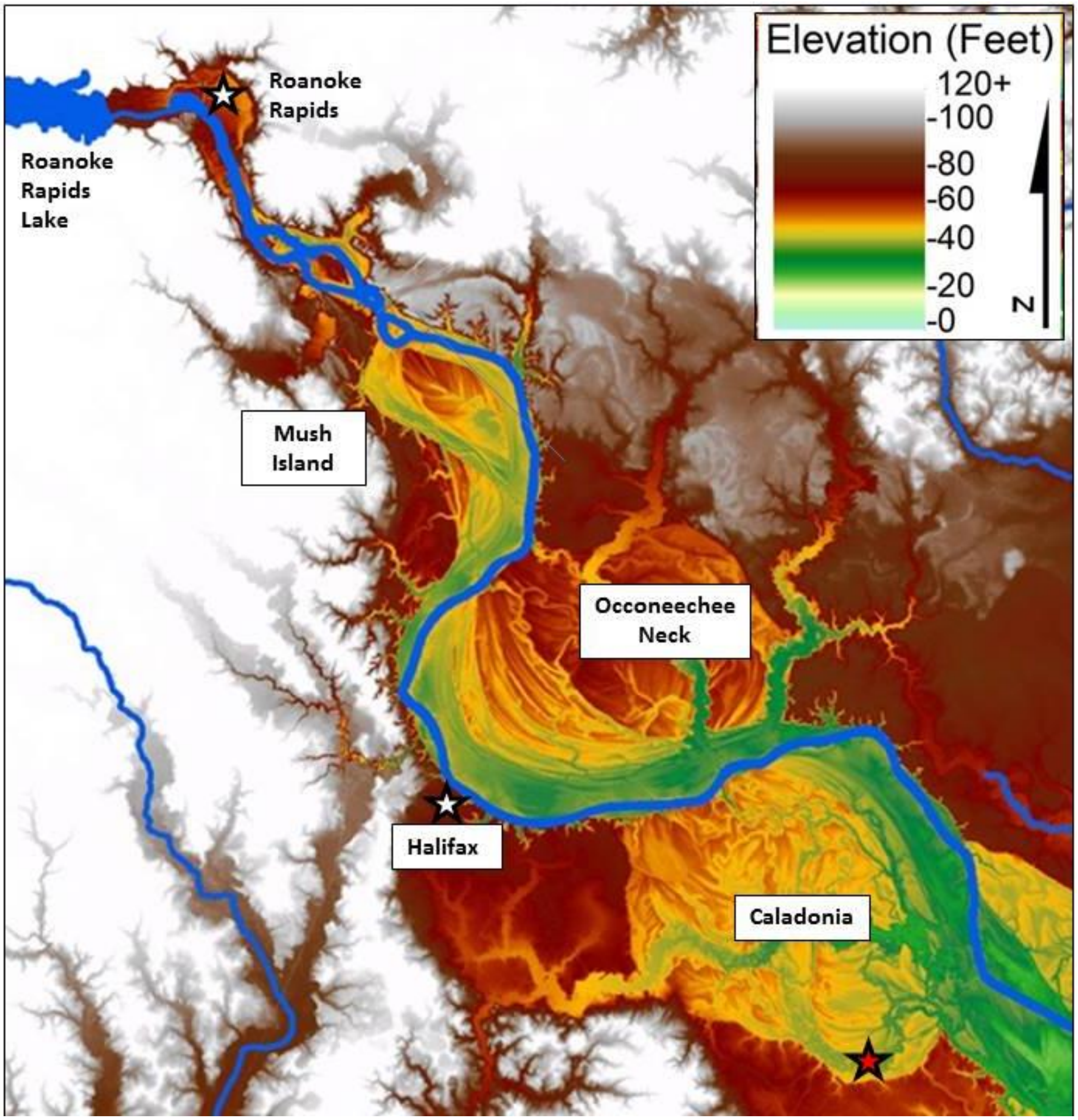


FIGURE 2-15. A color topography map shows the two upper river segments of the Lower Roanoke River. The fall line segment is cut deeply into the crystalline rocks of the Piedmont Province and extends from the dam at Roanoke Rapids Lake downstream to the western edge of Mush Island. River segment 2 begins to flatten out onto the Coastal Plain and extends from the paleo-meander terraces at Mush Island to the downstream edge of the Caledonia paleo-meander terrace. The white stars show the locations of USGS water level gages and the red star is the overlap with Figure 2-17. Topographic data are from the NC DOT's 2007 LiDAR program. Map prepared by D. Ames.

WATER LEVEL PROFILE ON TOP OF THE ROANOKE RIVER FROM THE FALL ZONE TO ALBEMARLE SOUND

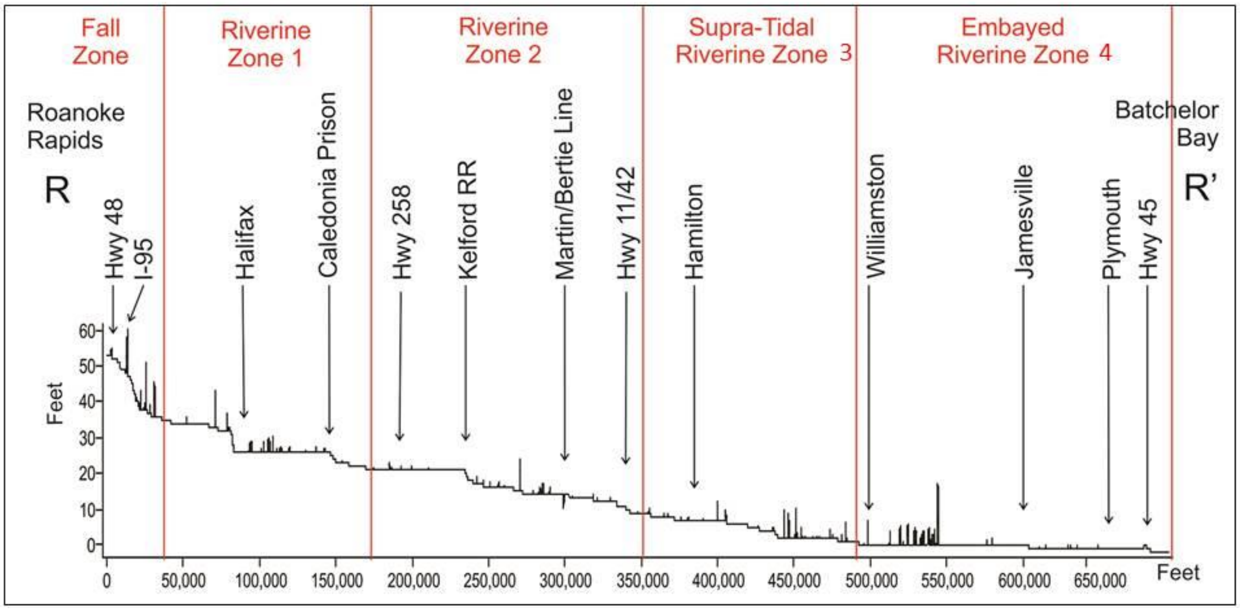


FIGURE 2-16. A generalized section down the lower Roanoke River water surface from Roanoke Rapids to Batchelor Bay shows the four geomorphic river zones between the Fall Zone and Batchelor Bay in Albemarle Sound.

Riverine zone 2 has a straight and narrow, active floodplain and a primary channel dominated by small-scale meanders (~1/2 mile amplitude) which extends from the northern edge of Figure 2-17 to the Bertie County line and old railroad bed (near Kelford). This river segment has generally increased to about one mile in width with the channel bottom approaching modern sea level in the Kelford area. River zone 3 extends from the Bertie County line to Williamston (Figures 2-17 and 2-18) and dramatically changes as the modern channel bottom gradually drops below modern sea level (Figure 2-16). The river has developed two scales of meanders: a very large scale (2 to 3 mile amplitude) meander pattern with a smaller scale meander (~1/2 mile amplitude) superimposed on portions of the larger meanders. The active floodplain widens irregularly to about one to two miles in this segment. In river zone 4, east of the Williamston road dam (Fig. 2-18), the active floodplain system widens to greater than three miles as the modern Roanoke River system approaches modern sea level of Albemarle Sound. The dramatic downstream change into river zones 3 and 4 is due to the increased influence of Albemarle Sound storm surge flooding in combination with the long-term rise in sea level (Figure 2-18).

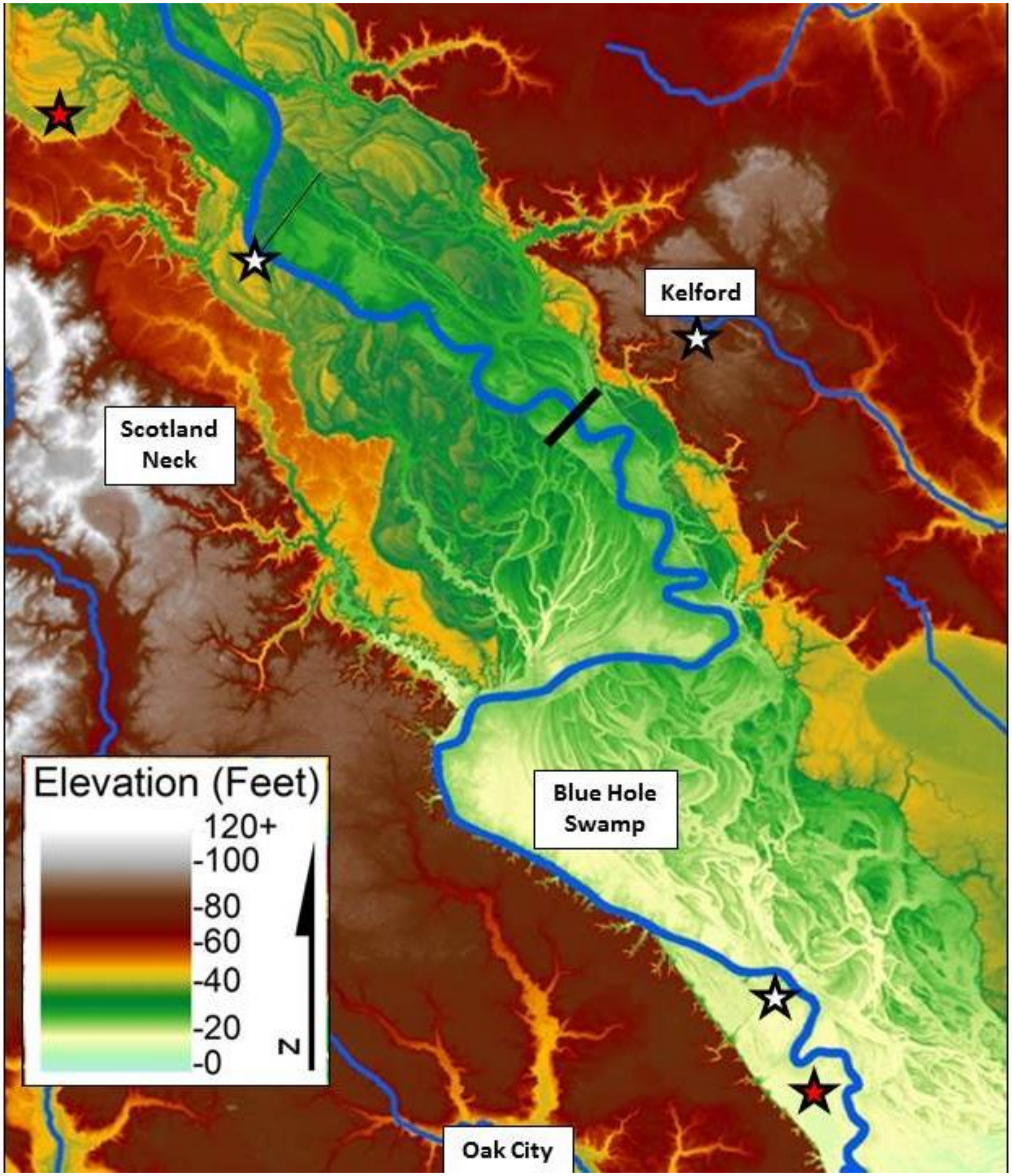


FIGURE 2-17. A color topography map shows the Lower Roanoke River segment 3 and a portion of segment 4. River segment 3 begins at the red star in the upper left corner and extends southeast to the Kelford area. River segment 4 starts on the north side of Blue Hole Swamp and extends downstream into Figure 2-18. The white stars show the locations of USGS water level gages and the red stars are the overlaps with Figures 2-17 and 2-18. Topographic data are from the NC DOT's 2007 LiDAR program. Map prepared by D. Ames.

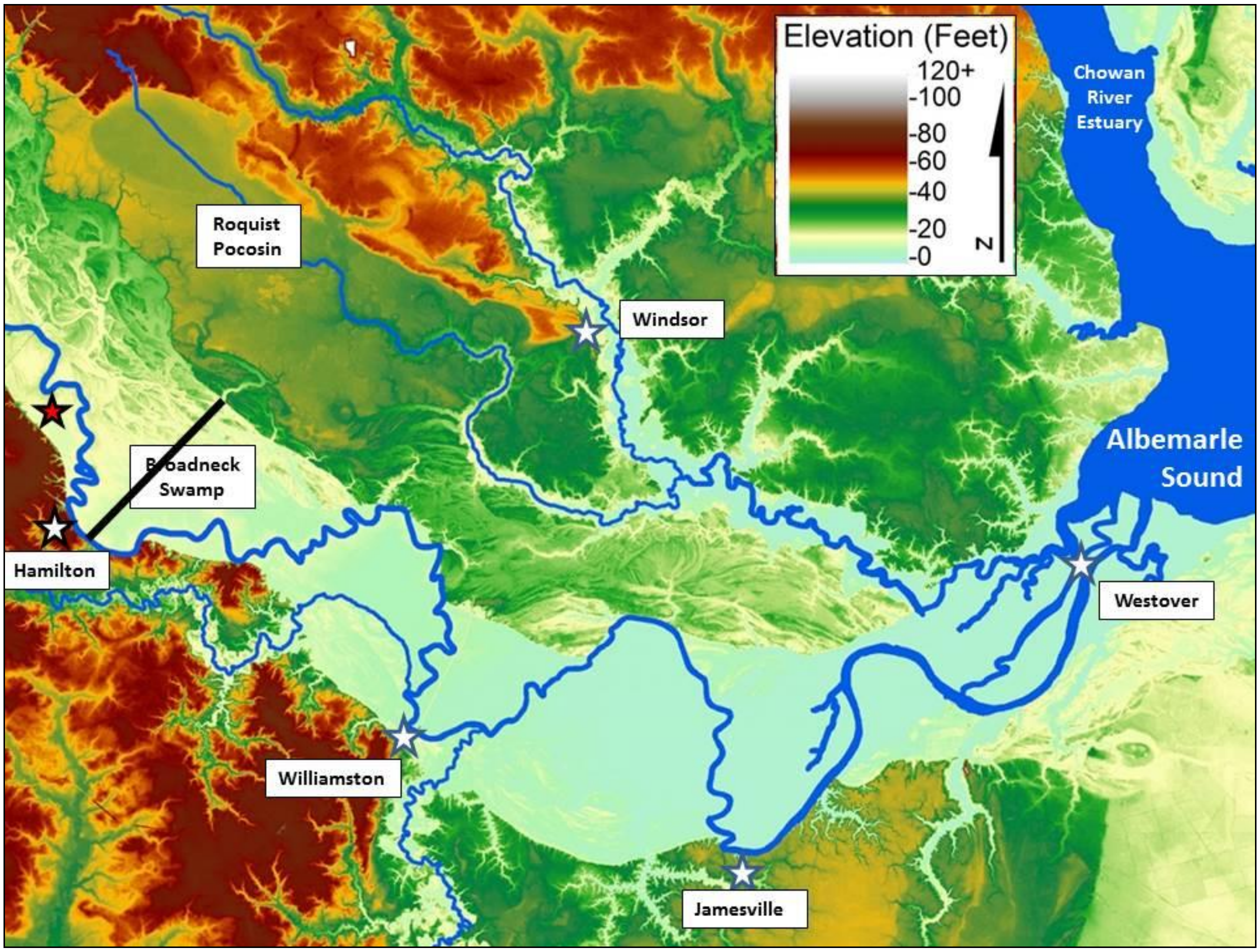


FIGURE 2-18. A color topography map shows the lower portion of river segment 3 and river segment 4 of the Lower Roanoke River. River segment 3 begins on Figure 2-17 and extends southeast to Williamston. River segment 4 starts on the east side of the Hwy 13-17 road dam and extends downstream to Batchelor Bay in western Albemarle Sound. The white stars show the locations of USGS water level gages and the red star is the overlap with Figure 2-17. Topographic data are from the NC DOT's 2007 LiDAR program. Map prepared by D. Ames.

Albemarle Sound and Roanoke Floodplain Storm-Water Buffer

The ongoing drowning process of the lower Roanoke River valley by rising sea level produces the Albemarle Sound drowned river estuary. The lower-most river zone 4 extends from Williamston to Bachelor Bay (Figures 2-16 and 2-18), known as the "embayed riverine zone", consists of a broad swamp forest that is essentially at sea level. From Bachelor Bay to Jamesville, the river is dominated by long meanders with straight primary channels, no natural levees, and common inter-meander black-water streams extending southwestward into the interior of the large-scale meanders. The large-scale meanders of the primary river channel still persist through the river zone from Jamesville west to the Hwy 13-17 Bridge and road dam at Williamston. But here the large meanders are characterized by a superimposed set of smaller-scale meanders with small levees along the primary channel and minor development of internal black-water streams. ***The overall result is an extremely broad, heavily vegetated floodplain allowing increased water flow to spread laterally and provide an incredible energy buffer and storm-water storage area. Thus, the portion of the Roanoke River floodplain east of Williamston acts as a great storm-water sponge.***

The water level within the entire embayed riverine zone 4 (Figure 2-18) feels the imprint of both the small and regular astronomical tides and larger more irregular wind tides from Albemarle Sound. Flood waters from upstream are no longer constrained by terraced braidplains and natural levees and spill out into the broad swamp forest. In addition, large storm surges off of Albemarle Sound are largely buffered by the heavy vegetative cover of the broad swamp forests within this "embayed riverine zone". Consequently piers, fish cabins, homes, and farms built at the water's edge rarely see major flooding impacts. The great volumes of water surging downstream, discharged from the Roanoke River dam at Roanoke Rapids, are rapidly dispersed and minimized within this vast "embayed riverine zone".

Consequences of Lower Roanoke River Flooding

The Roanoke River dams above Roanoke Rapids regulate the volume of water surging downstream into the narrow active floodplain with high river levees and even higher terraces of paleo-meander and paleo-braidplain ridge and swale topography. Large discharge rates cause flooding and shoreline erosion along the river banks within the riverine zones (Figure 2-16). Flooding occurs frequently as a result of large and often long duration discharges of lake waters from the Roanoke River reservoirs due to upstream storm and rain events. Because of the large Roanoke drainage basin and small primary channel and active floodplain, severe flooding can spread into the upper paleo-floodplain terraces causing major economic impacts to the farming, timber, fishing, and hunting industries, as well as impacting the associated ecosystems.

The dam discharge history for the USGS Roanoke Rapids water level gage from Jan. 1, 2017 through May 8, 2019 is presented in Figure 2-19. Two major sets of storm water discharge occurred during the spring months of April through June of 2017 and 2018. Both discharge periods had some flooding impact on downstream riverine sections when the discharge exceeded 20,000 cfs. However, a really severe period of downstream flooding occurred when the dam discharge put the entire Roanoke River (Roanoke Rapids to Jamesville) in continuous flood conditions from mid-September 2018 through mid-March 2019 (Figures 2-9, 2-10, and 2-19).

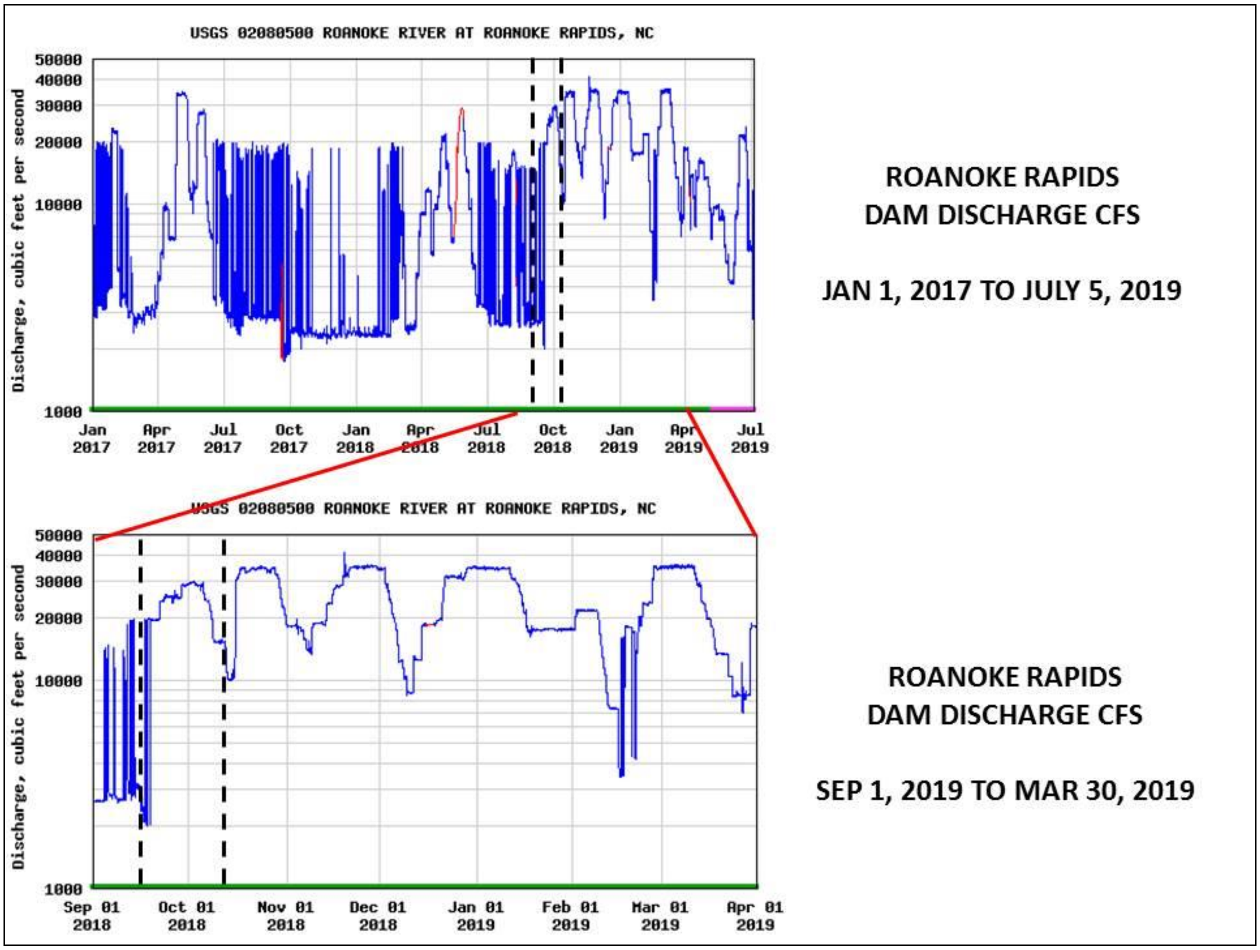


FIGURE 2-19. Plot records the pattern of dam water discharge (in cubic feet per second) to the Lower Roanoke River at the USGS gage at Roanoke Rapids (panel 18A) for the period of January 1, 2017. Panel 18B expands the record for the period seven month period from September 1, 2018 to March 31, 2019. The two dashed black lines show the time of Hurricane Florence (left) and Tropical Storm Michael (right). Since it is the pattern of flow that is important, these plots are not corrected for absolute elevation.

The six month flooding event in the Lower Roanoke River (Figure 2-19) began with Hurricane Florence and Tropical Storm Michael on Sept. 15 and Oct. 11, 2018, neither of which directly impacted the Lower Roanoke River. In Bertie County, these two tropical storms dropped about 3.5 inches of total rain (Figure 2-20). Rather both storms crossed the Piedmont and Appalachian portions of the Roanoke River Basin dropping substantial amounts of rain into Kerr Lake to bring the lake elevation from 300 to 309 and 314 feet, respectively (Figure 1-5). Subsequent rains through March maintained a high lake level requiring major discharge levels to continue into July 2019. The rainfall amounts for 2018 (Figure 2-21) in the Appalachians (Climate Division 2) and North Piedmont (Climate Division 3) (Figure 2-22) were the “wettest on record since 1895” according to NOAA.

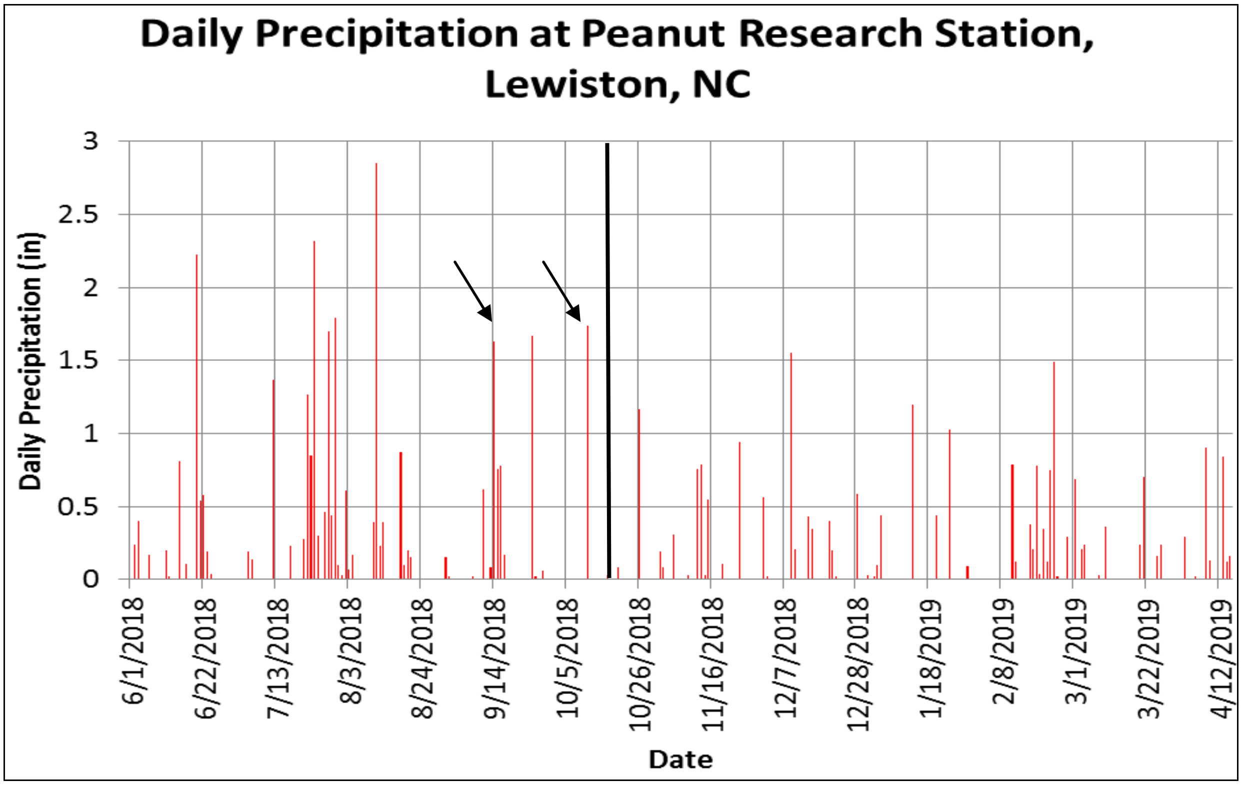


FIGURE 2-20. Plot of daily precipitation (in inches) occurring at the Lewiston Peanut Research Station in NW Bertie County from June 1, 2018 through April 12, 2019. The two arrows indicate rain amounts from Hurricane Florence (Sep. 15) and Tropical Storm Michael (Oct 11).

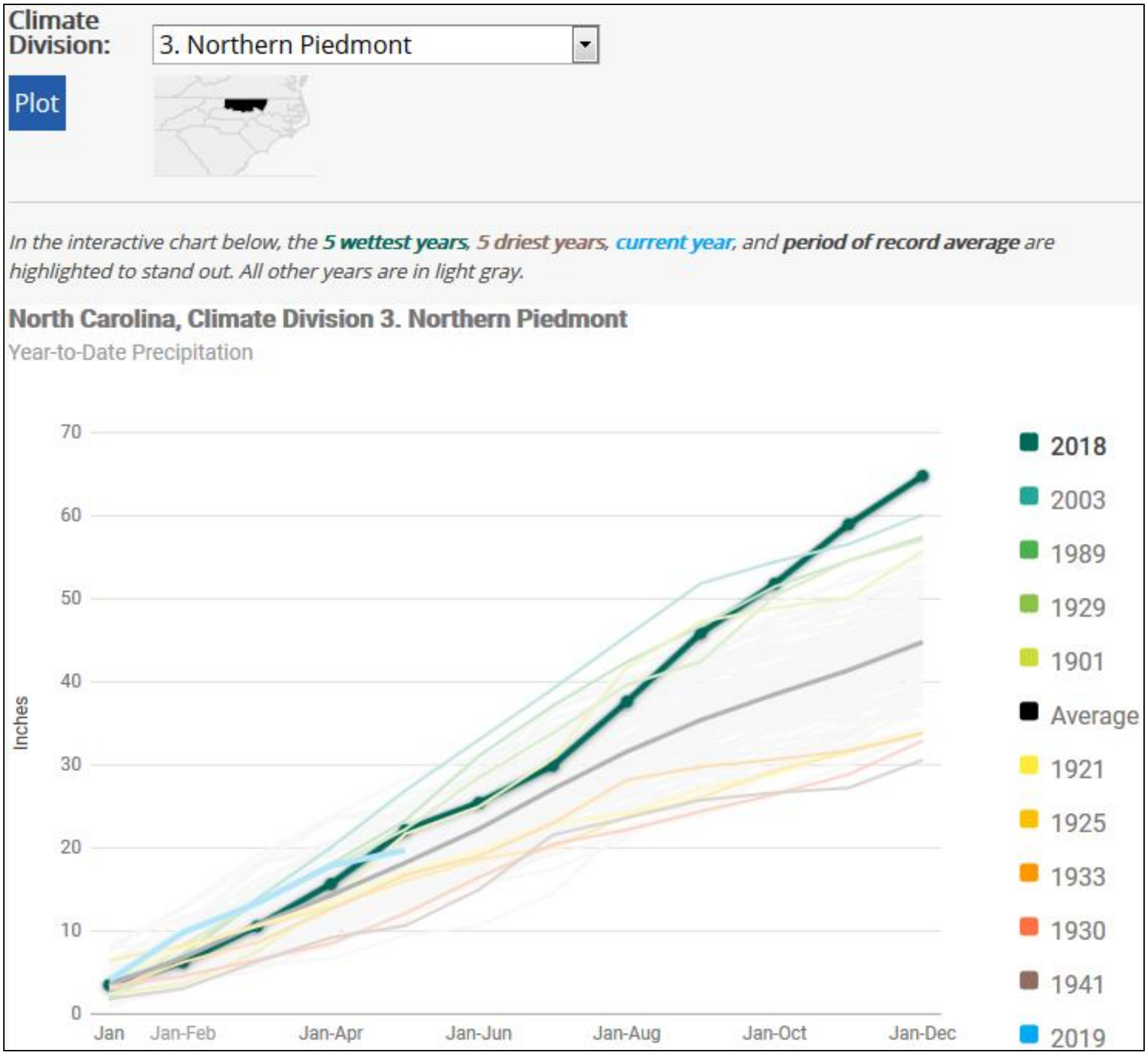
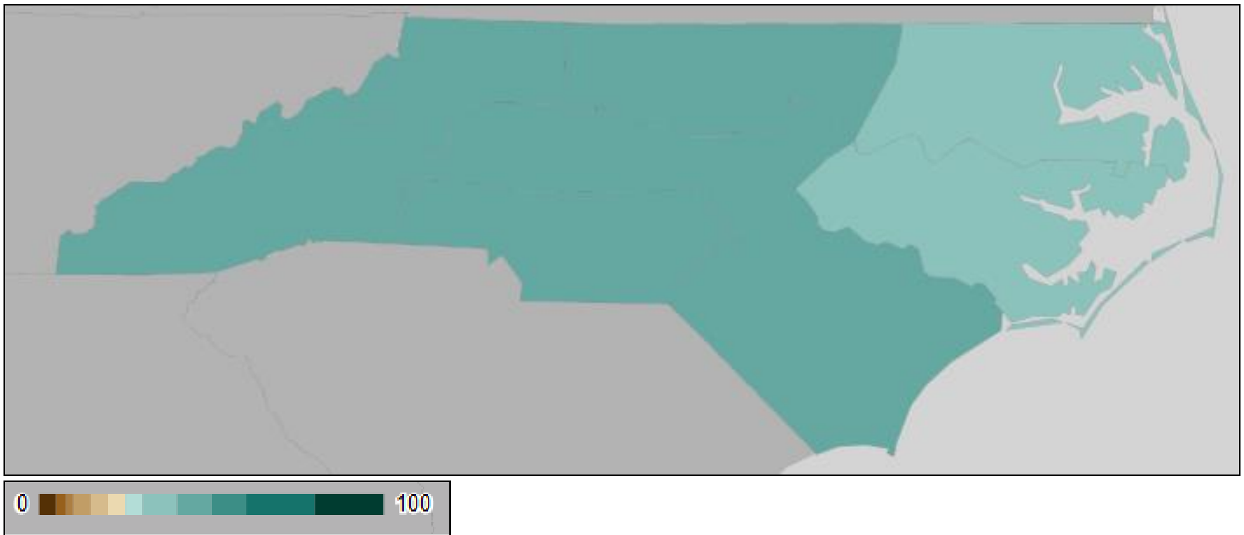


FIGURE 2-21. Plot shows the record amounts of precipitation that occurred with 64.81 inches in 2018 in the Northern NC Piedmont Climate Division 3 (dark green). This is the largest amount recorded since 1895. Also, the head-waters in the Northern Mountain Climate Division 2 received record precipitation amounts. The Northern Coastal Plain had 59.39 inches of rainfal for 2018. Data are from NOAA National Centers for Environmental information, Climate at a Glance: Divisional Mapping, published June 2019 (https://www.ncdc.noaa.gov/cag/).



CLIMATE DIVISION	VALUE	RANK (124 YEARS)	1901-2000 MEAN	ANOMALY
North Carolina CD 1. Southern Mountains	48.80"	124	32.04"	16.76"
North Carolina CD 2. Northern Mountains	43.33"	124	27.00"	16.33"
North Carolina CD 3. Northern Piedmont	40.53"	124	23.98"	16.55"
North Carolina CD 4. Central Piedmont	40.51"	124	25.05"	15.46"
North Carolina CD 5. Southern Piedmont	42.69"	124	25.38"	17.31"
North Carolina CD 6. Southern Coastal Plain	41.35"	124	25.07"	16.28"
North Carolina CD 7. Central Coastal Plain	38.10"	121	26.21"	11.89"
North Carolina CD 8. Northern Coastal Plain	30.28"	106	25.18"	5.10"

FIGURE 2-22. Rainfall data are for NC Climate Division for the period of September 1, 2018 through March 31, 2019. Notice how anomalously high above the mean all climate divisions are with CD 1 through CD 6 ranking as the wettest on record since1895. Data are from NOAA National Centers for Environmental information, Climate at a Glance: Divisional Mapping, published June 2019 (https://www.ncdc.noaa.gov/cag/) .

During the months following the two (Sept. and Oct.) tropical storms of 2018 and extending into April 2019, Bertie County experienced a regular pattern of frontal systems that dropped less than 1.5 inches of rain per event (Figure 2-20). With this rain pattern, the entire Lower Roanoke River from Roanoke Rapids to Jamesville would not have normally been in full flood stage. However Figures 2-19 and 2-23 demonstrate that water levels for the Lower

Roanoke River have generally remained in flood stage from mid-September 2018 through to mid-March, 2019. Figure 2-21 shows the record amounts of precipitation that occurred with 64.81 inches in 2018 in the Northern NC Piedmont Climate Division 3. This is the largest amount recorded since 1895. The Roanoke River water-level gages for the month of June 2019 (Figure 2-23), which NOAA declared was 125 to 200% above the 20th century average within the Upper Roanoke River drainage basin. Since the dam discharge rate barely exceeded the 20,000 cfs and the downstream river system was still full, the ongoing sequence of frontal rain systems, as demonstrated in the Albemarle signal, kept the lower Roanoke River to Williamston in flood stage. Overall, the 9 to 10 month time period (from mid-Sept. 2018 through June, 2019) with record rainfalls from a weather pattern producing numerous frontal systems, kept the "fish bowl" of Kerr Reservoir full, even though there were no direct and major storm events.

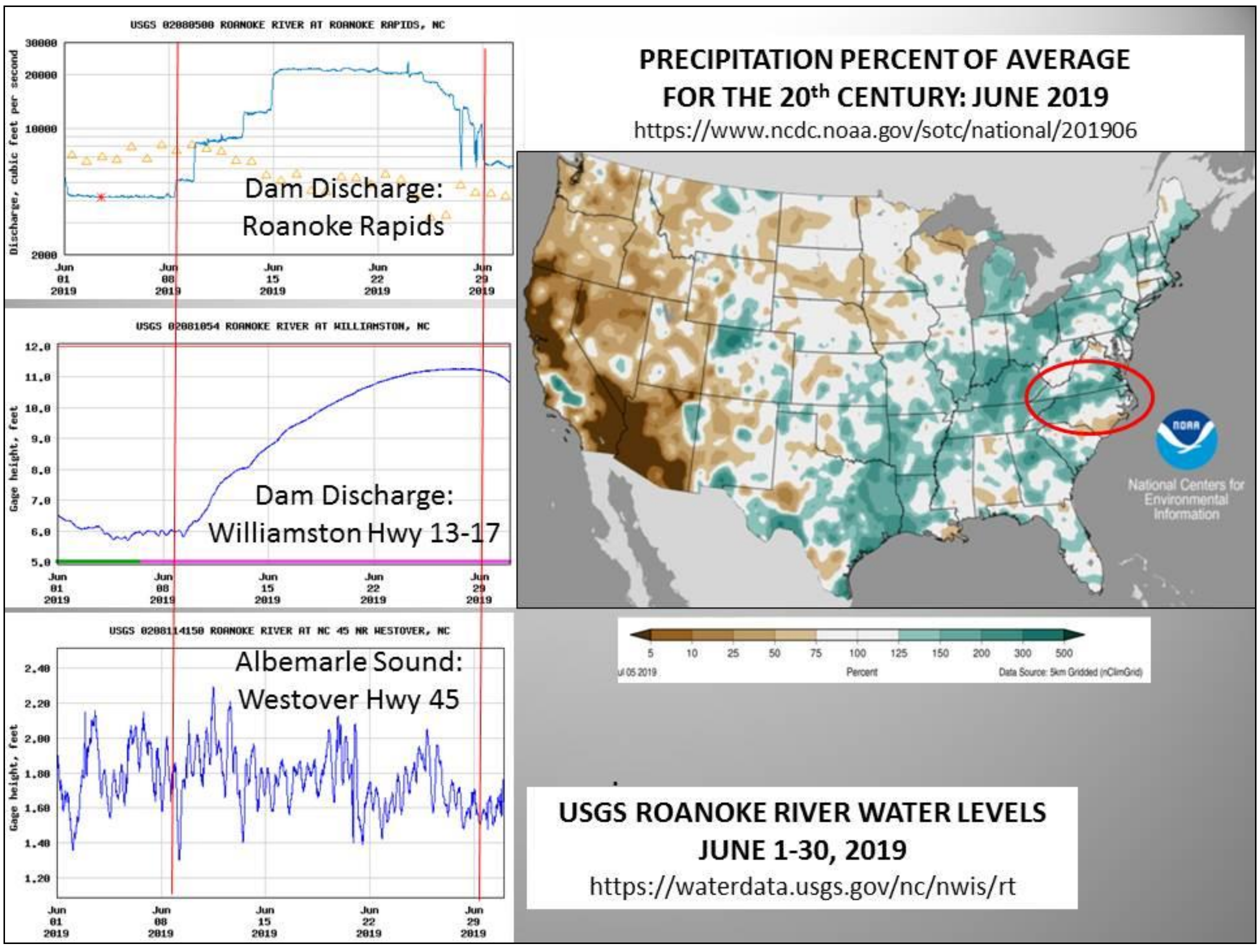


FIGURE 2-23. USGS Lower Roanoke River water level gages for June 1-30, 2019 show a major dam discharge from June 9-29 in response to abnormally high rainfalls within the Roanoke River drainage basin that were from 125% to 200% above the 20th century average for the month of June based on NOAA precipitation data. Notice that there is no apparent record of the dam discharge in the pattern at the Westover Hwy 45 gage, which is dominated by the Albemarle Sound signals. Since it is the pattern of flow that is important, these plots are not corrected for absolute elevation.

Summary of Issues for the Lower Roanoke River

Controlled water flow for production of hydroelectric power and storm-water management has many downstream consequences to the Lower Roanoke River. The overall wetness of 2018, along with two backdoor tropical storms (Florence and Michael), were partly responsible for the severe flooding of the Lower Roanoke River that started in September 2018 and lasted through the middle of March 2019. There is no question that the highly engineered Upper Roanoke River had some real limitations to their storm water management that required major downstream discharging. However, based on discussions with the US ACE dam managers there are a few management suggestions that could help to minimize such an event in the future. Some of the environmental and economic loss due to extreme flooding can be better managed through a more thorough understanding of the climatic dynamics and the physical characteristics of the riverine system, as well as improved land-use measures and recognition of ecosystem limitations. The major impacts can be summarized as follows.

1. Downstream Riverine Processes and Ecosystems. When the natural dynamics of river flooding are engineered for economic purposes, there are severe modifications to the amount, duration, and pattern of water within the natural riverine channel and floodplain swamp forest. Holding and releasing water based upon economic and cultural needs rather than the natural seasonality impacts the natural ecosystems, habitats, and species composition. Changes in the hydraulic regime result in major shifts within the swamp forest ecosystem eliminating many flood-tolerant plant species and allowing non-flood tolerant species to move into the floodplain. There is also a major impact on the water storage capacity within the groundwater system of the floodplain as follows (Figure 2-24).

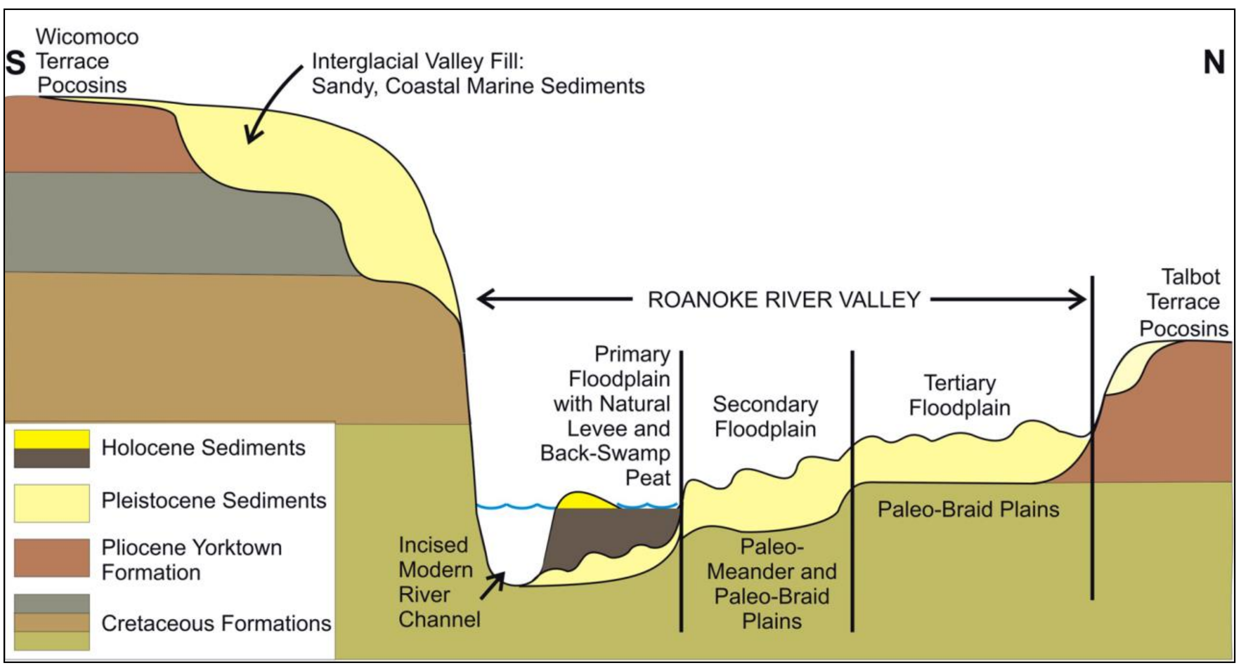


FIGURE 2-24. A schematic drawing of the Lower Roanoke River valley and the major landscape features. The presence of secondary and tertiary components and adjacent uplands vary downstream from Roanoke Rapids to Albemarle Sound. Figure is from Riggs 2006.

A. Decreasing Groundwater Levels over Extended Periods. Significant modification in downstream flow over extended periods affects the groundwater table within the floodplain. Lowering of groundwater levels also leads to major changes in ecosystem composition and loss of critical spawning grounds for some fish species. Decreasing the level of stored groundwater in the floodplain also seriously decreases the downstream base flow since shallow groundwater input is what keeps water in the river flowing through dry climate periods.

B. Increasing Groundwater Levels over Extended Periods. Long duration rates of high discharge can lead to a substantial rise in groundwater levels within the primary and secondary floodplains that cause major ecosystem stress and may result in die-offs of specific plant, tree, and wildlife species. The subsequent rapid decrease in discharge initially drops the water level within the channels and surface water in the floodplain. This is followed by the slow release of groundwater from the floodplain into the lower channel that can cause extensive slumping and erosion of the river banks.

C. Discharge to Full vs Empty Downstream River System. The status of the water levels in the Lower Roanoke River at the time of major dam discharges can dictate the magnitude and economic and environmental consequences of downstream flooding. If water levels in the lower river channel are low and the primary floodplain is dry, a large release will be more readily absorbed by the system. However, a large and extended dam discharge into river channels that are full and a primary floodplain that is wet, there will be a substantial increase in the flooding potential and impact.

2. Agriculture: The sand ridges of the upper meander and braidplain terraces within the Roanoke River valley have rich agricultural soils with abundant ground water under normal river flow conditions. Consequently they have been extensively farmed for several hundreds of years. The ridges have a crest and slope laterally into the adjoining swales. These swales are what floods first under high water flow conditions. Thus, as farmers have cleared and expanded their ridge fields over time, the edges are often in the lower and wetter portions of the ridge crests and frequently flood. In addition, access roads that cross the swales flood, limiting access during spring planting, summer activities during the growth period, and/or fall harvesting. Farmed areas on these lowermost sand ridges that are most subjected to the impacts of flooding should be taken out of production to minimize the impact of flooding.

3. Sylvaculture: The primary Roanoke River floodplain, as well as the upper meander and braidplain terraces, contain many different types of ecosystems, each characterized by different flora and fauna. The wet-dry composition of these ecosystems has changed substantially through time due to the damming of the Upper Roanoke River, controlled nature of the dam discharge, and changing climatic conditions. A highly engineered system can not always reproduce the natural system nor respond to all user groups correctly or equally. Consequently, ecosystem services will be impacted and will change. Some native and valuable timber species become stressed and disappear while less valuable invasive species move in. The results of flooding

highs and drought lows within forestry zones have more extreme and longer lasting economic impacts due to the much longer time scale than annual, agricultural crops.

4. Wildlife. Many small scale economies within rural Bertie County are based on the abundant fauna within the vast wetlands and wildlands of the Roanoke River valley. Extreme flooding and/or drought events will impact the supporting wildlife and fisheries habitats, food supplies, and spawning grounds. The extended flooding that occurred for six months in 2018-2019 has severely impacted many individuals livelihood based on fishing and hunting.

Consequently, the Lower Roanoke River would have been at or above normal water level with a full channel and high ground-water levels within the active floodplain prior to mid-September, 2018. Subsequently, the very high levels of dam discharge put extreme flood waters on top of an already full Lower Roanoke River with no groundwater storage space in the active floodplain. The result was severe flooding of the Lower Roanoke River for an unprecedented six continuous months from mid-September 2018 through mid-March 2019, the entire season with minimal evapotranspiration. This long duration of flood water was environmentally and economically catastrophic for the Lower Roanoke River valley and the associated counties.

Management of the downstream riverine system and the major economic activities (agriculture, sylvaculature, and wildlife issues) require longer term and more detailed monitoring of changing weather conditions long before a given weather event is in close proximity to impacting North Carolina and Virginia. Policy must be flexible and should be dictated by changing conditions for each specific storm event and sets of events, as well as based upon existing conditions and storm predictions and projections, and initiated well before there is “rain on the ground” at the dam. The predictions and projections do not represent a 100% probability of being correct, but the technology has come a long way in the past few years. **Thus, our summary recommendation is to approach the entire regional system with a more holistic management approach that equally includes the tripartite of waterscape, landscape, and atmoscape within the entire Roanoke Drainage Basin (upper and lower Roanoke Rivers) and not just lake levels, power supply, or rain on the ground!**

CASHIE RIVER SYSTEM

NC LOW Study of Cashie River Flooding

The impacts of repeated flooding of Windsor from the Cashie River have been devastating economically and personally. The town has responded to minimize future impacts. One major approach has been to move valuable property away from the lowlands near the river. This effort is ongoing and recommendations for future efforts are in the first NC LOW report (2018). Another approach by the town was to investigate engineering projects that can reduce elevations of flood crests, durations of flooding, and flow paths of flood waters. These were addressed by the NCSU (2018) report. Their report includes cost analyses for the various potential engineering projects. The NCSU analyses focused on upstream processes and ways of temporarily storing water; controlling flow around the town with dikes, opening an additional waterway through town, and removing the King St. road dam. Further, they considered how upstream land use and land cover have changed over recent time and whether such change may be enhancing the flooding. The NCSU report states that downstream processes may be important but this was beyond the scope of their study. Thus, the present NC LOW study focuses on the downstream factors.

A diagram was created to highlight the many factors that affect local water levels in the Cashie River (Figure 3-1). These factors range in both spatial and temporal scales. The diagram is organized to indicate increased size or length of time at the top; so global factors serve as context for those below. Upstream to downstream factors are shown from left to right. The diagram also identifies the factors studied in the NCSU report in blue (NCSU, 2018), the current report in red (NC LOW, 2019), and purple addressed in both reports. Factors in black were not addressed in either report. Thus, the NCSU focus was on the upper Cashie River, whereas the NC LOW focus is on the integration of the lower Cashie River with the associated Roanoke and Chowan Rivers, and Albemarle Sound. The NC LOW approach is to address questions moving from small to large scales and from Windsor centric to broader issues.

1. What are the critical physical changes of the Cashie River watershed from the headwaters downstream to the mouth at the Roanoke River and Albemarle Sound?
2. What local and downstream factors contribute to current water-level patterns at Windsor?
3. How do water-level patterns at Windsor relate to contemporaneous water levels upstream and downstream? This was done using water level data from three sites along the Cashie River (School Rd. upstream of Windsor, King St. in Windsor, and Bowling Farm downstream of Windsor; and one site at the mouth of the Roanoke River (Westover Hwy 45). The data begin June 19, 2018 when measurements were available at all four sites see Appendix for details).
4. Can these relationships provide help in predicting future flooding in Windsor?
5. How do water-level patterns of the Cashie River link to the contemporaneous patterns in the Roanoke River, Albemarle Sound, and Chowan River?
6. Is there evidence of an increase in flooding of Windsor in recent years?

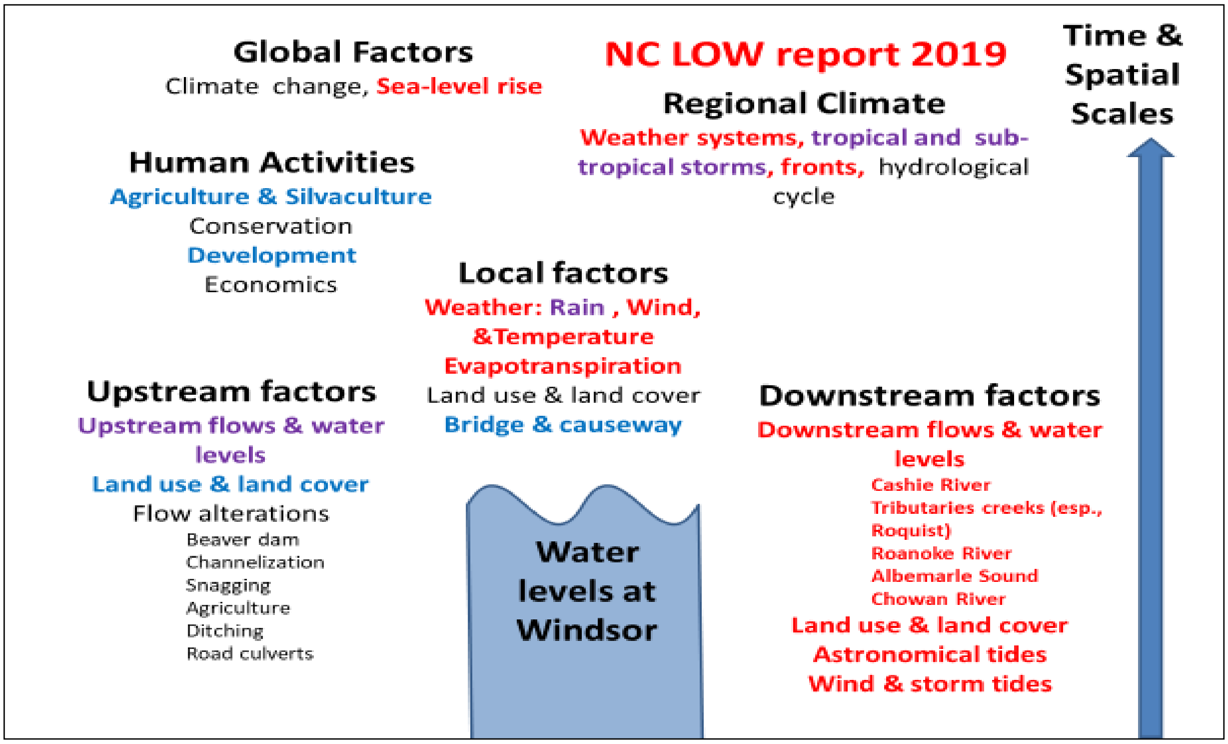


FIGURE 3-1. Diagram shows the factors that potentially control water levels at Windsor. Factors in blue were addressed by NCSU (2018 report), red addressed by this NC LOW (2019 report), and purple addressed in both reports. Factors in black were not extensively addressed in either report.

Cashie River Watershed

The Cashie River watershed is a world-class, black-water drainage system that flows into the Roanoke River and lies totally within the boundaries of one county. Its' headwaters are in the upland swamps and flows southeast for 55 miles where it flows into the west end of Albemarle Sound estuary (Figure 3-2). The entire drainage basin is 307 mi^2 in size (including 17 mi^2 of water) with 30 miles of main stem river above the Town of Windsor and 25 miles of navigable channel below Windsor. The Cashie River flows from about 88 feet of elevation down to sea level at the Thoroughfare, a small distributary channel of the Roanoke River (Figure 3-4). The major tributaries to the Cashie River above Windsor include the Wahtom Swamp, Connarista Swamp, White Oak Swamp, and Hoggard's Mill Run, the largest tributary. Together the upper Cashie constitutes 180 mi^2. Downstream of Windsor the lower Cashie River has two tributaries that include the Wading Place and Roquist Creeks.

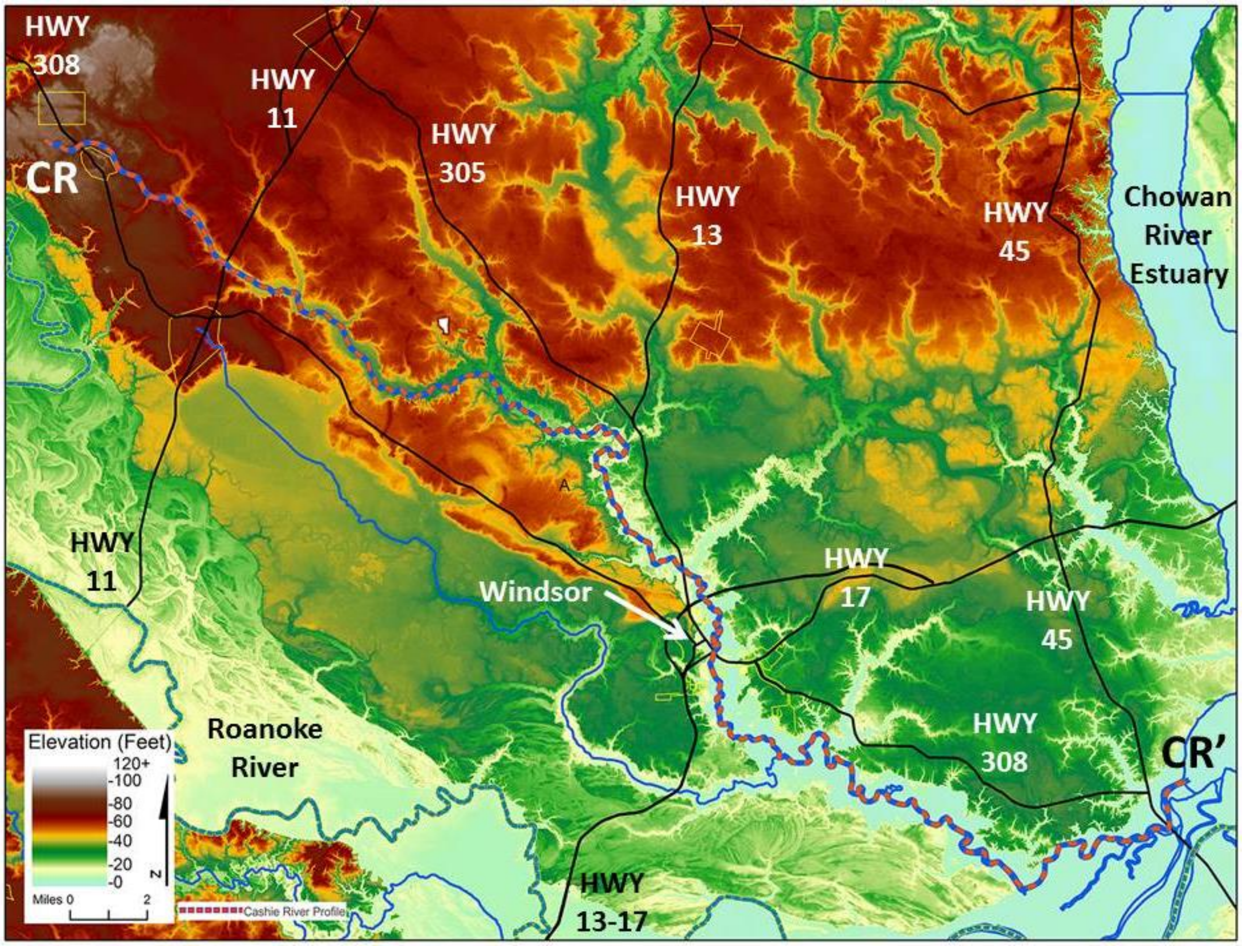


FIGURE 3-2. A color topography map shows the southern portion of the Bertie Peninsula in the northeastern North Carolina Coastal Plain and including all of Bertie County. The trace of the CR-CR' profile of the Cashie River in Figure 3-3 occurs as a red-blue dashed line. Topographic data are from the NC 2015 LiDAR program. Map was made by D. Ames.

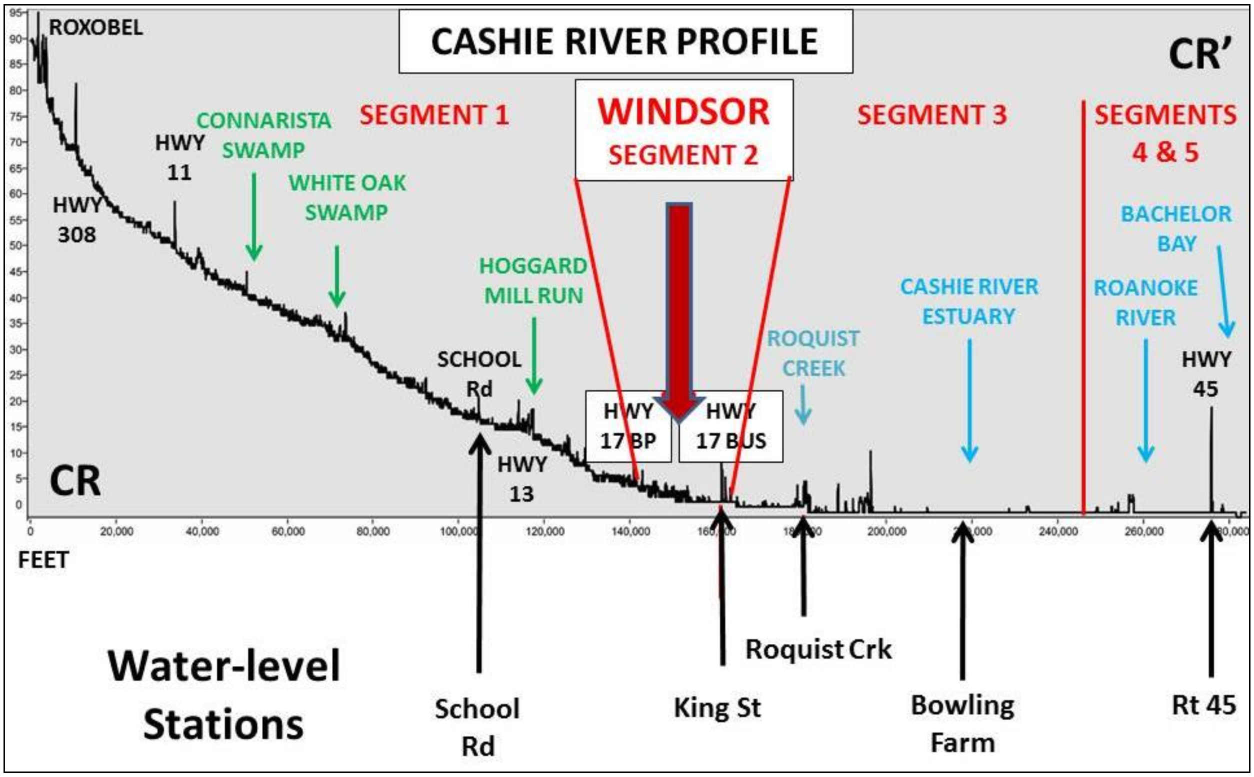


FIGURE 3-3. Topographic profile is along the water surface of the Cashie River during normal water flow conditions. The profile starts at the headwaters near Roxobel and goes into the estuarine waters of Albemarle Sound at Bachelor Bay. Elevation data were obtained from the NC 2015 LiDAR data, USGS topographic data, and 5 water-level recorder gages (in black). Key locations are indicated in green and blue and the river segments are in red (segments 1 and 2 were primarily covered by the NCSU (2018 report) and segments 1 (at School Rd. to segment 5 in Albemarle Sound) are covered by the NC LOW (2019 report). The profile location is indicated in Figure 3-2. Profile was made by D. Ames.

The Cashie River watershed begins in the many pocosins (Native American for "swamps on a hill") on the flat Wicomoco Terrace uplands. As the tributaries drain off the upland terrace, they become deeply incised through the intermediate elevations of the Talbot Terrace, lower elevations of the paleo-braidplains, and into the primary floodplain of the Roanoke River just before it empties into the estuarine waters of Albemarle Sound (Figures 3-2 and 3-3). Windsor occupies a unique position at the intersection where the riverine component of the Cashie River drops below mean sea level and becomes a drowned-river estuary. Consequently, the lower Cashie is at mean sea level and influenced by astronomical tides and storm surges of the Atlantic Ocean and Albemarle Sound, whereas the upper Cashie is totally dependent on regional rainfall.

Additional complicating hydrodynamic factors that could affect the Cashie River are fluctuations in Roanoke River discharge and ongoing sea-level rise of about 2 feet since the colonists sailed the lower Cashie River in the early 1700s (Figure 3-4). Thus, the downstream dynamics of a storm dominated coastal system in combination with the changing land-use patterns within the upstream portion of the drainage basin, are together responsible for the apparent increased frequency and severity of flooding events in Windsor. Both dynamics are becoming of increasing importance due to the ongoing slow changes in land use and changing frequencies and intensities of climate and storms.

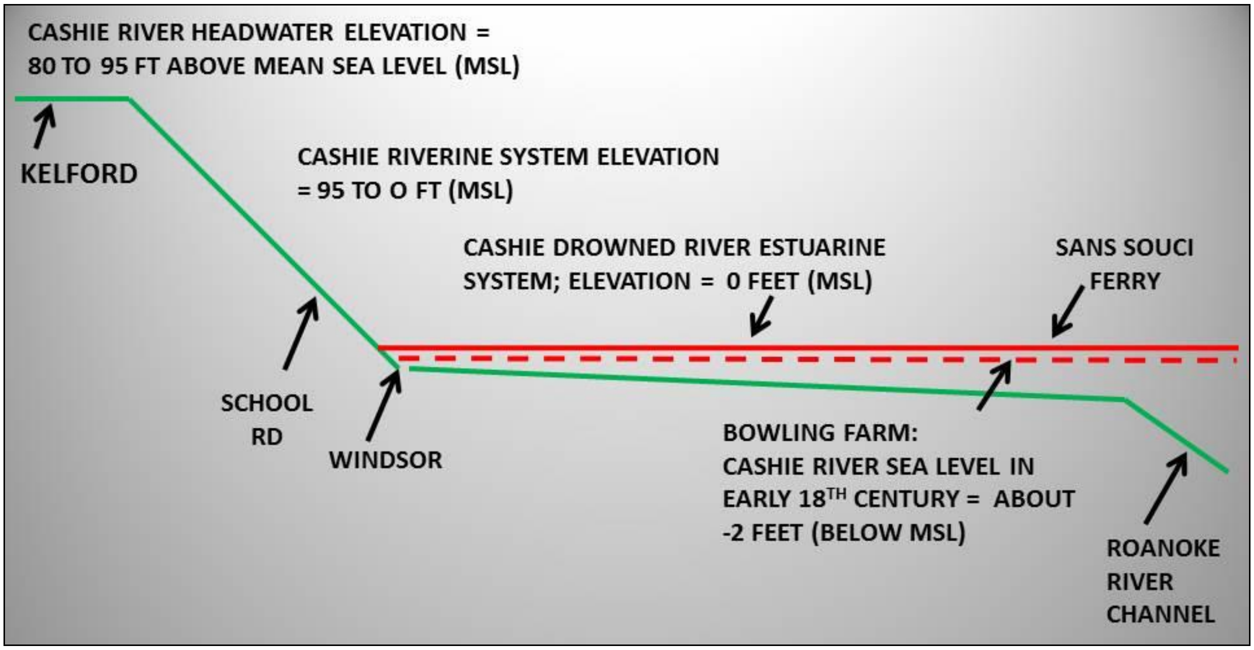


FIGURE 3-4. Schmatic profile of the Cashie River system shows the relative changes in slope between the upper and lower Cashie River and the relative rise of mean sea level since the early 1700s in North Carolina (red lines). Windsor is located at the leading edge of flooding by rising sea level; this is the transition zone (segment 2 in Figure 3-3).

Three River Segments of the Cashie River

On the Cashie River profiles (Figure 3-3) three segments are shown in red and include the upper Cashie (segment 1), the transition zone (segment 2), and the lower Cashie River (segment 3). Segments 4 and 5 are the lowermost portion of a Roanoke River distributary channel (the Thoroghfare) and the western end of Albemarle Sound (Bachelor Bay), respectively.

Upper Cashie River Segment

The landscape topography, upstream of Windsor, determines the drainage pattern and land uses that are dominated by agriculture, forestry, and small industries and villages. The uper Cashie River drains the high (90 to 70 feet above sea level) sloping topography of the Wicomoco Terrace that trends west to east through the northern portion of Bertie County (dark red on Figure 3-2). The river is incised into the terrace and flows off the flats with high gradients and small primary floodplains. Location of most of the headwater branches that feed the main stem of the Cashie River start in swamp pocosins perched on top of the upland terrace. Occasionally strong storm wind driven, sheet-flow moves vast pocosin surface waters across the flat inter-stream divide. For example, during Hurricane Matthew in 2016, pocosin-sourced flood waters located on top of the Wicomoco Terrace blew out the railroad tracks on a high rock dam and adjacent

Harrell's Siding Road. This large rain event resulted in a natural inter-basin water transfer, adding increased flash-flood waters to the Cashie River that severely impacted the Town of Windsor with record flooding.

The USGS School Rd. water level gage is located within the lower portion of segment 1 and is located just above the input of Hoggard Mill Run in Figure 3-3. Consequently, this gage only measures what water is coming down the main stem. The Town of Windsor from the new highway 17 bypass bridge to the King St. highway 17 business bridge, is located in segment 2 of the Cashie River. This is the zone where the channel bottom drops below modern sea level and the river transitions from riverine flow conditions to estuarine back-flooding. The river gradient decreases in segment 3 and the Cashie River spreads out latterly to develop a broad, primary floodplain swamp forest. The water surface expands downstream as the adjacent upland decreases in elevation into the Roanoke River valley. Segment 3 is an estuarine mixing basin where the riverine waters interact with the sea level waters of Albemarle Sound (Figure 3-5). When the black estuarine water of the Cashie reaches the Roanoke River, it flows into a small side channel (Thoroughfare Channel) of brown-river water (segment 4) and shortly flows into Batchelor Bay and Albemarle Sound (segment 5 in Figure 3-3).

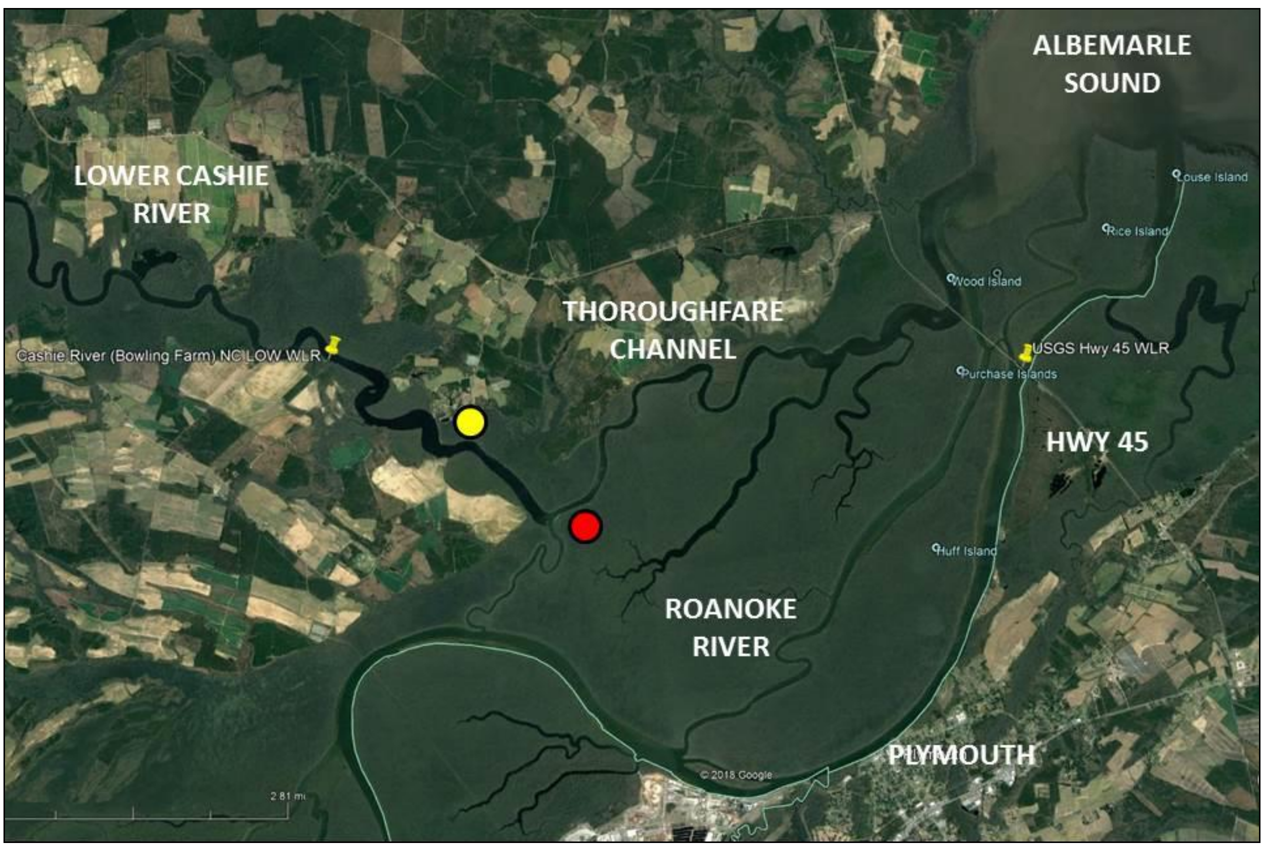


FIGURE 3-5. Google Earth image shows the black-water lower Cashie River (segment 3) that flows southeast into a much smaller Thoroughfare channel (segment 4) of the Roanoke River (red dot) and then northeast into Bachelor Bay of Albemarle Sound (segment 5). The yellow dot locates the San Souci Ferry and the two yellow pins locate the NC LOW and USGS water level recorders. The blue line is the Bertie-Martin county line.

Windsor Segment and Windsor Ridge Transition Zone

Location within the topographic valley of the Cashie River dictates the dynamics and impact of different climatic conditions (floods and droughts) affecting the water flow within that river system. The original town was located at Hoggard Mill in 1722. But this was too far upstream for shipping; the condition of the river channel was too "crooked and narrow" from Gray's Landing to Hoggard Mill (windsornc.com/history-of-windsor/). Consequently, the shipping trade slowly retreated downstream to the present site of Windsor at Gray's Landing by 1768. Figure 3-6 clearly demonstrates the reason why the Town of Windsor is located on the "Windsor Ridge" where the Cashie River transitions from riverine to estuarine conditions. The eastern tip of "Windsor Ridge" is the southernmost piece of high land with elevations that range up to 60 feet above sea level. The topography decreases in elevation to 5 to 10 feet along the floodplain fringes where the main part of downtown has been developed over the past 200 years (Figure 3-7). To the north of Windsor the river is shallow with relatively steep gradients, whereas to the south there is a relatively deep-water channel with very low stream gradients and little high land due to the very broad floodplain (Figure 3-8).

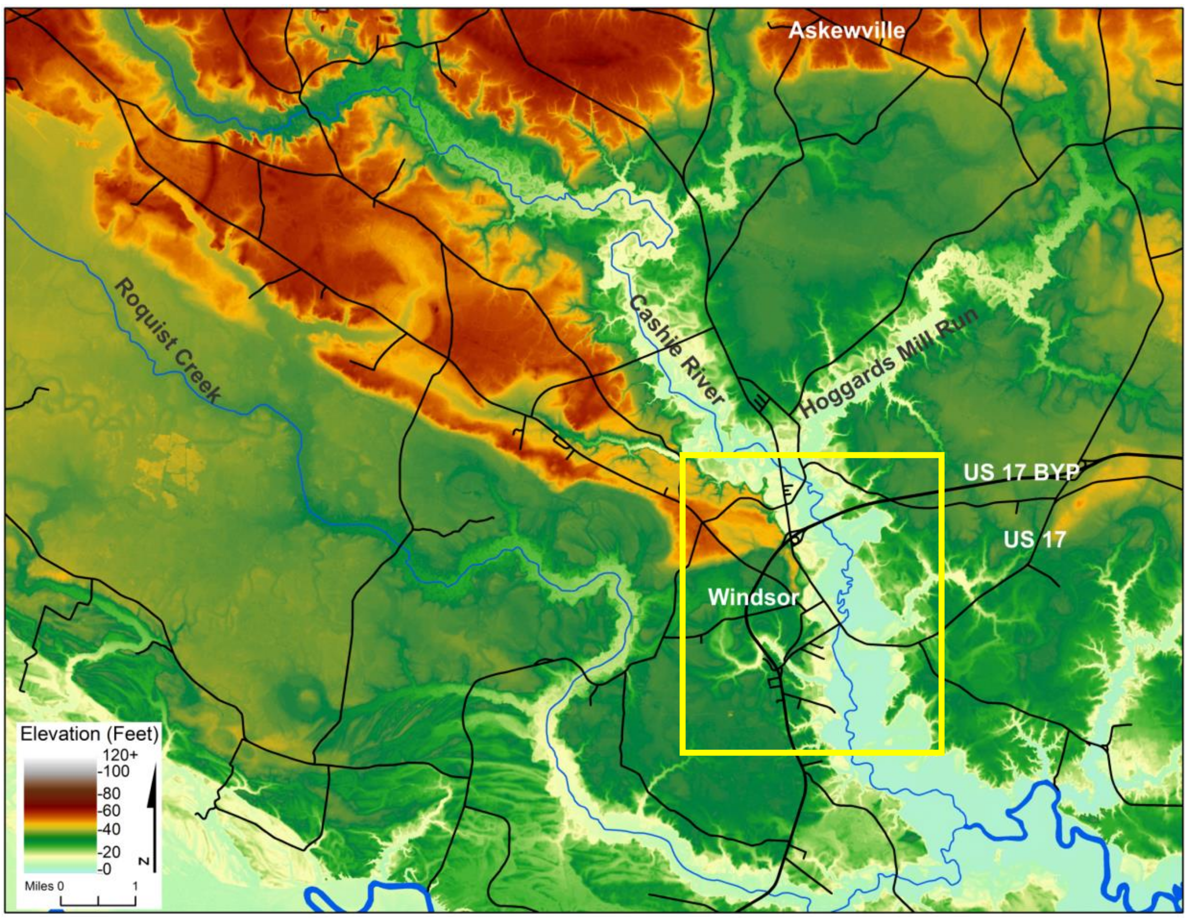


FIGURE 3-6. A color topography map shows the central portion of the Cashie River valley with the Town of Windsor within the yellow box. Notice the location of Windsor relative to the Windsor Ridge, the main stem of the Cashie River, and the Hoggard Mill Run tributary stream. Topographic data are from the NC 2015 LiDAR program. Map was made by D. Ames.

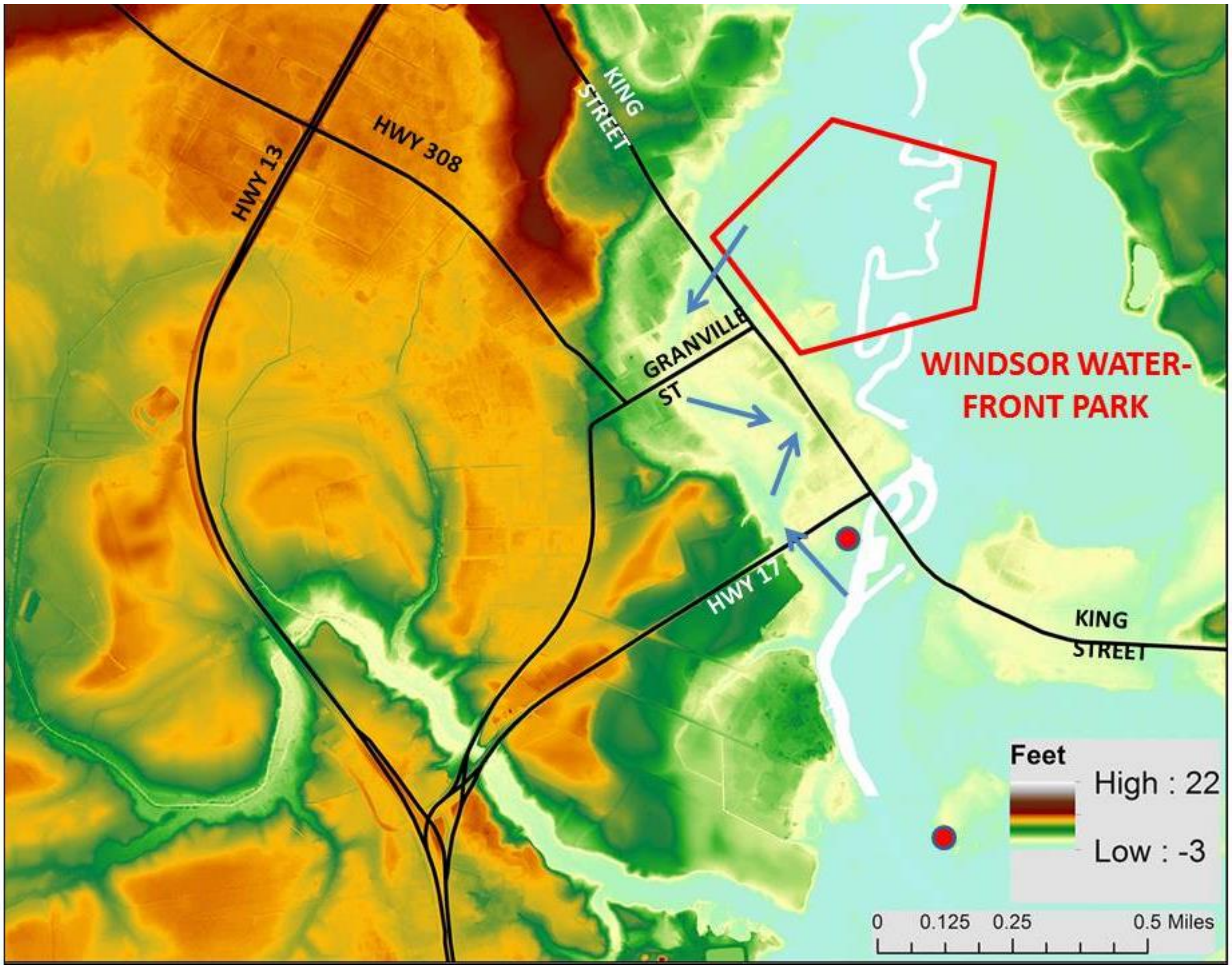


FIGURE 3-7. A color topography map is a close up view of the Town of Windsor. Pale blue color is the primary floodplain of the Cashie River (white). The flood-prone section of Windsor is cream to pale green and the upland is dark green, orange, and dark red (about 20 to 60 feet elevation). Notice the low flood-way shown by blue arrows that cause flooding of the center of Windsor downtown. The red dots, along with the red pentagon, are part of the town's eco-tourism program to utilize the flood-prone areas. Topographic data are from the NC 2015 LiDAR program. Map was made by D. Ames.

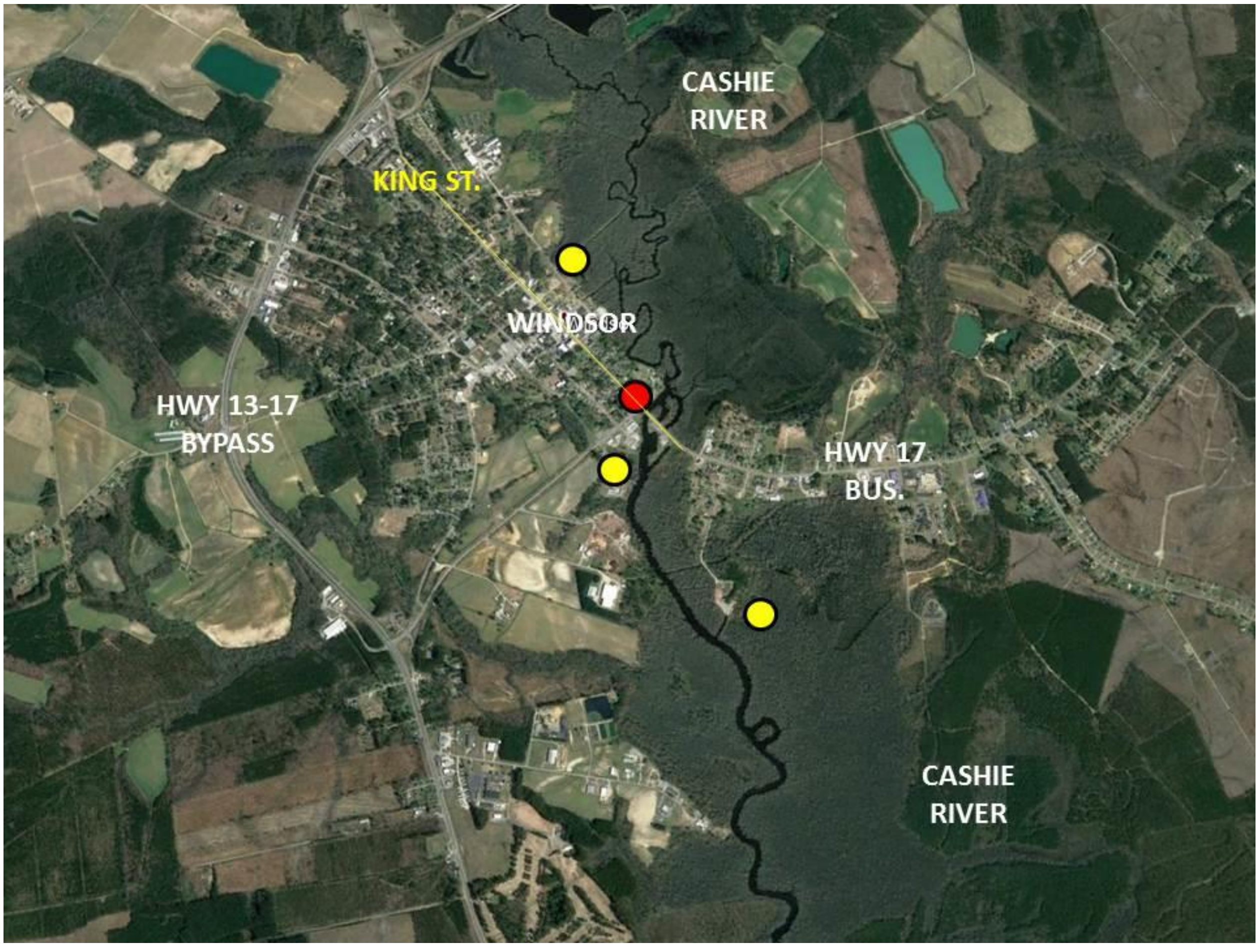


FIGURE 3-8. Google Earth image shows the black-water Cashie River at Windsor with the narrow and highly meandering channel and wide floodplain north of King St., a major pinch point at the King St. bridge (red dot), and a wider estuarine channel south of King St.. The yellow line indicates King St. and the yellow dots locate portions of Windsor's Cashie River related eco-tourism facilities. The red dot at the King St. Bridge is adjacent to the NC water-level recorder on the NW side of the bridge. Notice the dredged cutoff channel south of the lowermost yellow dot and the dredged turning basin just south of the King St. Bridge. This dredging was done in the 1930s to eliminate 3 tight meanders downstream of Windsor

The susceptibility of Windsor to flooding has generally been acknowledged through the recognition of its lowlands and their frequent flooding from upstream high flows. Figure 3-7 shows the lowland portions of Windsor (in cream to very light green colors) that are susceptible to frequent and catastrophic flooding. Since the lower Cashie River estuary is basically at the water level of Albemarle Sound and the lowermost Roanoke River systems, could the dynamics of either of these systems affect the frequency and magnitude of flooding on the lower Cashie River? Do storm surges and wind tides from Albemarle Sound and/or the Roanoke River change the lower Cashie River gradients and increase back-flooding in Windsor? Figure 3-9 shows the extent of flooding in Windsor in response to storm water levels of +3, +6, +8, and +10 feet above normal based on NOAA's "sea-level rise viewer". The bad news is that Windsor has a major portion of the downtown area (cream to pale green colors) that is extremely flood prone;

however, the good news is that they have an abundance of very high ground (dark green to orange and dark red colors) available for the towns future. Figures 3-10 and 3-11 show two plots of historic high river levels at the upstream School Road gage over the past 3 decades. There has been a trend of increase in the annual number of events during this period.

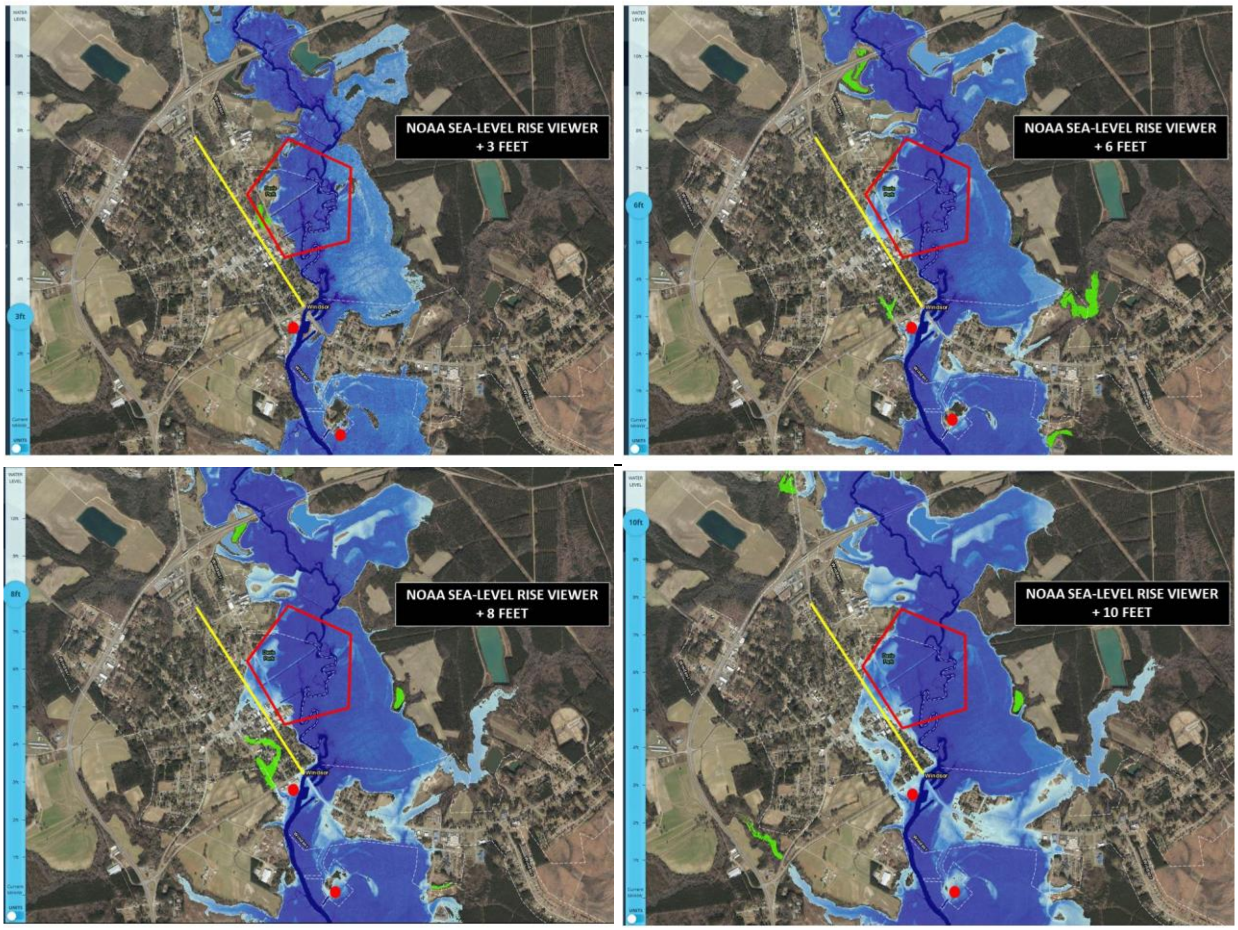


FIGURE 3-9. Four panels show the extent of flooding in Windsor in response to storm-water levels of +3, +6, +8, and +10 feet above normal based on NOAA's "sea-level rise viewer". The red pentagon is the site NC LOW's proposed Windsor Waterfront Park that connects to the two waterfront sites at the red dots (NC LOW, 2018). The yellow line is King St.

MAJOR: +12 FEET		
18.52 ft	09/16/1999	Dennis
12.52 ft	10/19/1999	Floyd
12.07 ft	06/17/2001	Allison
12.24 ft	08/16/2004	Gaston
15.69 ft	10/01/2010	Earle & Nicole
12.14 ft	08/28/2011	Irene
15.00 ft	09/22/2016 (P)	Julia
16.63 ft	10/09/2016 (P)	Matthew

MODERATE: +10 FEET	
11.51 ft	08/18/1992
10.07 ft	03/04/1994
11.49 ft	02/06/1998
11.78 ft	09/20/2003
11.41 ft	06/16/2006
10.54 ft	09/03/2006

MINOR: +8 FEET	
9.57 ft	05/03/1989
8.66 ft	10/04/1989
8.76 ft	07/31/1991
9.13 ft	01/10/1993
8.67 ft	09/05/1996
8.92 ft	10/10/1996
8.65 ft	11/14/2006
8.87 ft	11/23/2006
8.33 ft	12/10/2009
9.51 ft	02/07/2010
9.24 ft	08/05/2014
8.63 ft	12/25/2014
8.33 ft	03/31/2010
8.40 ft	01/02/2016
8.07 ft	01/25/2016
9.80 ft	02/06/2016
8.15 ft	02/26/2016
8.83 ft	04/27/2017 (P)

FIGURE 3-10. List of historical crests that occurred at the USGS Cashie River water-level gage at School Rd. (see Figure 3-3 for the gage location). The National Weather Service flood stage at this gage is +8 feet. However, this gage is at a substantially higher elevation than the Windsor King St. gage that was only established in 2013. Thus, there were 32 storm events with flood waters greater than 8 feet at the School Rd. gage between 1989 and 2017 (28 years). However, this does NOT equate to 32 flooding events in Windsor as will be discussed in detail later in this section. Data are from the US Geological Survey website.

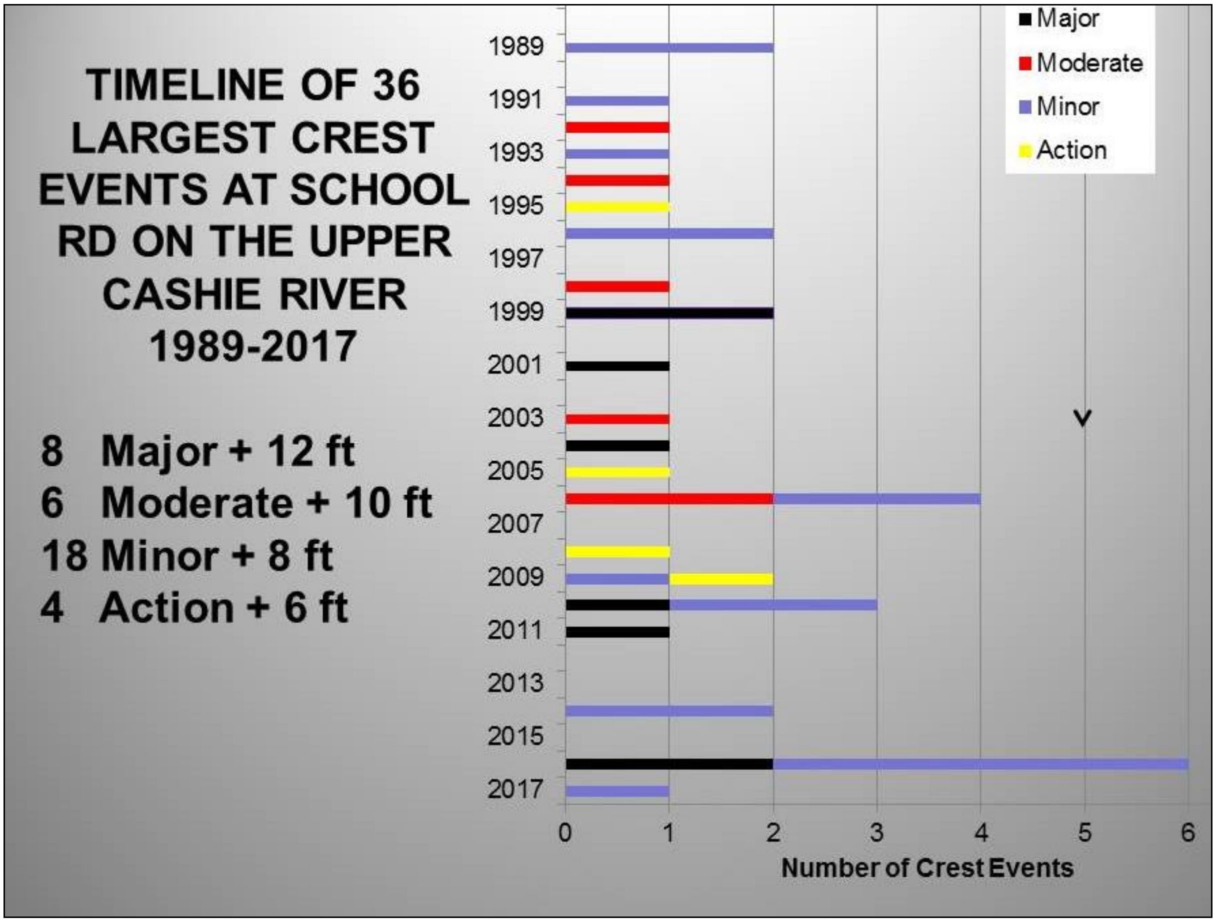


FIGURE 3-11. Graphic representation shows 36 historical crests that occurred at the USGS Cashie River water-level gage at School Rd. with a general increasing frequency through time (see Figure 3-3 for the gage location). Plot includes four +6 foot "Action" events and 1 less +12 foot "Major" event in 2017. The National Weather Service flood stage at this gage is +8 feet, which is a substantially higher elevation than the Windsor King St. gage that was established in 2013. However, this does <u>NOT</u> equate to 36 flooding events in Windsor as will be discussed in detail later in this section. Plot is from the US Geological Survey website.

Lower Cashie River Segment

Windsor's low elevation makes it susceptible to numerous sources of water level changes. This section highlights factors that affect water levels at Windsor other than the upstream flows and water levels (Figure 3-1). Upstream flows (or discharge) and the factors affecting them were a major part of the NCSU (2108) report. These factors are obviously critical, especially during flooding events, but there are other factors that result from local or downstream processes.

Besides upstream rainfall, there are a series of other major contributors to flooding on the Cashie River. Albemarle Sound has a long east/west dimension and Chowan River, as an appendage of Albemarle Sound, has a long north/south dimension. Albemarle Sound, perhaps in conjunction with the Roanoke and Chowan Rivers, is conducive to the setup of high or low water at the mouth of the Cashie River. These high or low water events may occur as small wind tides (few inches up to 2 feet) or large storm tides (2 to 10 feet or higher). Wind tides can occur briefly with a passing weather front, last for days with sustained winds, or be devastating events associated with larger non-tropical nor'easters or tropical storms. In all cases the winds can raise or lower the lower Cashie River as water is pushed in or out. If a storm event drops enough rainfall upstream, the flooding potential (Figure 3-3) at and below Windsor can be significantly modified by 1) downstream wind tides, 2) storm surges, 3) astronomical tides, 4) valley floor groundwater levels, 5) evapotranspiration in the short-term, and 6) ongoing sea-level rise in the long-term. Because of Windsor's location in the transition zone, these variables are important factors that can determine the degree of flooding resulting from any given storm.

Downstream Factors Contributing to Water-Level Patterns at Windsor

This report provides evidence for the effects of local and downstream variables on water level, and the next section extends the analysis to the comparison of water levels in the lower Cashie River with the associated water bodies. All of these variables may not be the critical factor in a specific flooding event in Windsor, but each may alter the magnitude and extent of flooding. **The bottom line is that the characteristics of flooding in Windsor are more complex than simple upstream discharge.**

Astronomical and Wind/Storm Tides

Astronomical tides are relatively small within the sounds, tributary estuaries, and rivers of northeastern North Carolina. Astronomical tides are those resulting largely from the position of the moon and sun relative to the Earth. In North Carolina these occur in semi-diurnal cycles with different sized highs and lows and a wavelength of about 12.3 hours. These semi-diurnal tides have very low amplitudes of less than 6 inches. Both the Hwy 45 gage in the lowermost Roanoke River and the Bowling Farm gage in the lowermost Cashie River display similar semi-diurnal tidal signals. However, as the semi-diurnal tide at the Bowling Farm gage in the lower Cashie River moves upstream to Windsor (King St.) it transitions into a diurnal tide with an amplitude of 6 inches to 1 foot (Figure 3-12). These smaller waves appear as humps on a larger wave that could reflect the moon phases as it cycles between spring and neap tides.

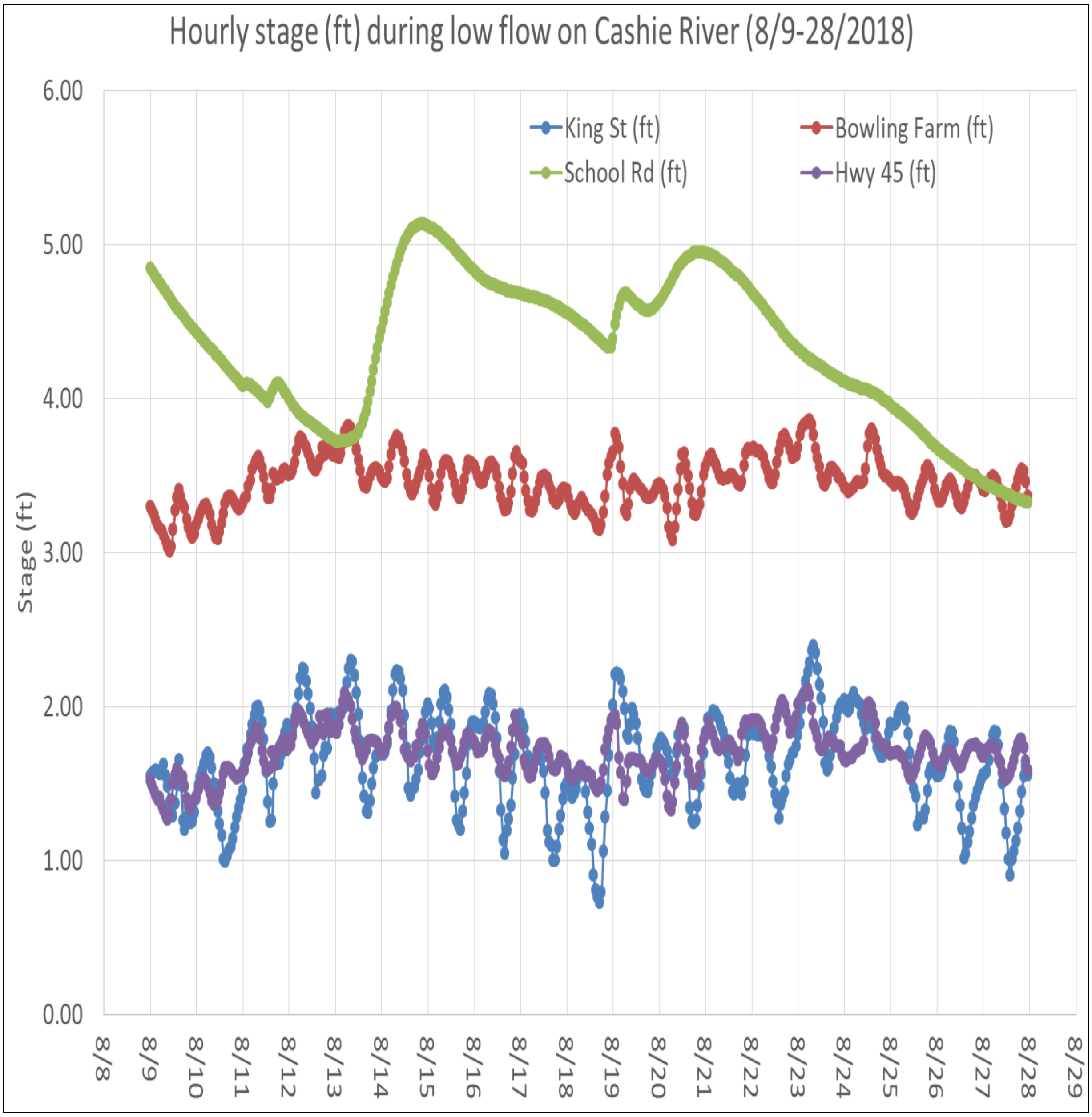


*FIGURE 3-11. Patterns of average hourly stage heights (water levels in feet) at each of four sites are shown over time during a low streamflow period. Notice that stage heights represent the bottom of the river as zero feet at each site. Therefore, the overall vertical positions of the lines are not comparable. School Road signal is **green** and dominantly driven by upstream rainfall. The Windsor King Street (**blue)**, Bowling Farm (**red)**, and Westover Hwy 45 (**purple)** display both astronomical tide and wind tide signals.*

The small astronomical and wind tides do not reach the School Rd. gage where the channel bottom is well above mean sea level (Figure 3-3). The upstream signals result totally from normal rainfall events that fill the narrow upper Cashie River channel and raise the water level. As this increased water level in the more confined channel flows downstream from river segment 1, it spreads out rapidly into the broad floodplain with its vast swamp forests of river segments 2 and 3. The fluctuations in stage height at School Rd. are not seen at the other three downstream sites and vice versa. There is one exception that occurred at all four sites on 8/19 (Figure 3-11). This one day rise in water levels probably represents a frontal system with a wind tide that preceded the river rise from the associated rain event by a few hours. The astronomical tides, wind tides, and rainfall events in Figure 3-11 represent the normal situation and are not by themselves problems with flooding in Windsor.

Wind tides, by contrast, may be large within the sounds and estuaries as wind blows across these wide, long and shallow water bodies. Daily wind tides, as well as longer scale periods of high and low water, can range from inches to a foot or two as displayed in water level signals from three downstream gages in Figure 3-11. During major storm events, storm tides can commonly reach up to 4 to 5 feet and rarely up to 10 feet or more along the western shorelines of the Albemarle Sound and Chowan River. These latter tides have wavelengths that are irregular and vary with wind direction, strength, and duration, relative to the water body configuration. Depending on the duration of a storm event, these storm surges often have time to migrate up the smaller river valleys such as the Cashie River with the possibility of adding multiple feet of storm surge base in Windsor to couple with the downstream river flood. This storm surge rise could precede or occur simultaneously with the arrival of upstream discharge from the storms torrential rainfall. Combining a downstream storm surge event of several feet or more simultaneously with a major upstream rainfall could change the net impact from a small or moderate flooding event in Windsor into a catastrophic flooding event. **Consequently, when large-scale upstream (rainfall) and/or downstream (storm surge) events occur, then the smaller-scale processes can affect the extent of flooding. Inches of increase or decrease in vertical water levels translate into significantly larger or smaller flooded areas. This interpretation is based on the results in this and following sections.**

During this project, there were no major wind storm events to document the cumulative impact. However, the section in this report titled "Historical Flooding Events" briefly documents recent storm scenarios that impacted northeastern NC. Some storms were catastrophic for just the Cashie and Roanoke Rivers, others were major events that impacted the Chowan and Albemarle Shorelines. However, rarely was there good storm tide information recorded for the latter water bodies. The detailed historical water level and storm data from events during the 20th century, and even into the first decade of the 21st century (Barnes, 2013), is scattered, poorly preserved, or totally non-existent. **Consequently, a recommendation for Bertie County is to either invest in a weather expert or enlist the help of the NC Climate Office at NCSU to explore and mine preserved historic data for the events that were catastrophic within the Bertie region; each flooding event is different and there are critical lessons to be learned in the history of each event (see section 5 of this report).**

Groundwater Levels, Seasonal Weather, and Evapotranspiration

The broad floodplain swamp forests that occur within segments 2 and 3 of the Cashie River play a role in the potential impact of flooding events. These floodplains have a huge amount of surface water storage capacity, as well as a vast groundwater storage capacity. The wet or dry condition of the floodplain makes a difference during major flooding events. If the floodplain system is dry and the base flow is low, the system can absorb a substantial amount of storm water. But if it is already full then the storm waters are additive and move through the system as sheet flow through adjacent floodplains. The ultimate impact of a storm in the upper Cashie River and the seriousness of its downstream flooding will be influenced by storm tides on the Albemarle and Chowan estuaries and whether the groundwater storage system is full or empty.

Changing weather patterns over extended periods can change the groundwater level and either fills or empties the downstream surface- and ground-water storage capacity of the floodplain. Long durations of high discharge during the non-growth seasons (low rates of evapotranspiration) and extended episodes of nor'easterly to sou'easterly winds produce high wind set up in western Albemarle. These conditions also can maintain high water levels in the lower Cashie River and its vast floodplains. Thus, surface- and ground-water levels are high with no storage capacity for flooding events. On the other hand long-duration of low discharge rates during growth seasons (high rates of evapotranspiration) and extended episodes of nor'westerly to so'westerly winds (low wind set up in western Albemarle) will tend to decrease the level of surface- and ground-water, increasing the downstream storage capacity for flood waters and increase the discharge flow rate in response to a greater hydraulic head. The differences of whether a system is wet or dry will not prevent major flooding events, but will help determine the potential impact and severity of any given storm event. These processes could feasibly represent several feet of difference and change an event from minor flooding impact to moderate or visa-versa. The status of the water levels in the lower Cashie River at the time of major storm events can dictate the magnitude and economic and environmental consequences of flooding.

An evapotranspiration signal possibly occurs within the detailed water-level fluctuations at Windsor. Evapotranspiration has a diurnal 24 hour cycle and yearly seasonal cycle that would interact with the tidal signal. Evapotranspiration is the process by which plants take in water through their roots and release it from their leaves during photosynthesis and is an important process within riverine floodplain swamp forest ecosystems. For example, Eggleston et al. (2018) estimated that over half of the water entering the Great Dismal Swamp left via evapotranspiration. Doll et al. (2018) calculated similar contributions by evapotranspiration for the upper Cashie. In riparian swamp forest systems, water is removed from the floodplain soil during the day and is replenished at night from the adjacent riverine waterways or shallow perimeter uplands. The result would be a signal of increasing riverine water levels at night, reaching a peak in early morning followed by a decrease throughout the day (Figure 3-12).

The water-level pattern at Windsor King St.gage (Figure 3-12) shows diurnal excursions of water level in August 2018 that were as much as one foot and often nearly 1.5 feet. These fluctuations are primarily due to astronomical and wind tides along with a possible component of evapotranspiration. Calculations of actual evapotranspiration rates are beyond this project. Since evapotranspiration naturally removes water from a river's riparian swamps, this process increases the groundwater storage capacity and can reduce the extent of flooding event during growth seasons. Plus, primary floodplain vegetation baffles the flow of floodwaters and provides surface water storage. Thus, the protection and conservation of vegetated floodplains are critical in helping to reduce the impact of flooding in Windsor.

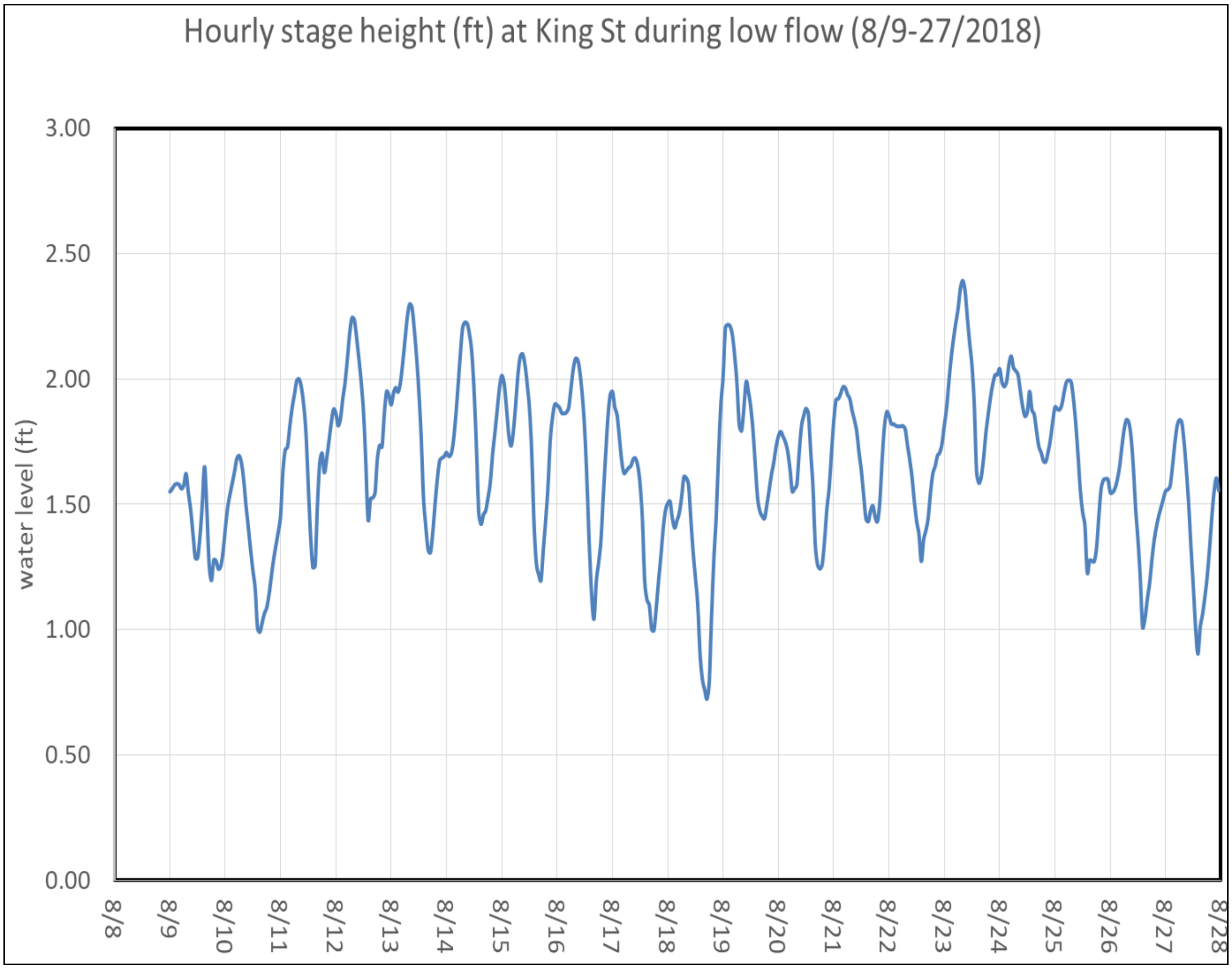


FIGURE 3-12. Hourly water level fluctuations at the King St. gage in Windsor illustrate the daily astronomical diurnal tidal signal, a weekly wind tide signal, and possibly a component of daily evapotranspiration signal. The period represented in the plot extends from August 8 to 28, 2018. The plot is not corrected for elevation.

In summary, a stream system has more storm water storage capacity if water levels in the river channel are low and there is a dry floodplain. However, if there has been an extended wet weather period and the river channels are full with a wet primary floodplain, there can be a substantial increase in the flooding potential and impact. There is a cumulative impact for the second or third storm in a series; weather patterns are critical.

Cashie River Water-Level Patterns

Comparison of Upstream and Downstream Water Levels

Stage heights (equivalent to water levels) were measured at four water-level stations (Figures 3-11, 3-13, 3-14, and 3-15). The School Road site is about 10 river miles upstream of Windsor, is maintained by the U.S. Geological Survey in Raleigh, and sampled at 15 minute intervals. The King Street gage is on the Hwy 17 Business Bridge in Windsor, is maintained by NC Division of Emergency Management in Raleigh, and sampled at 5 minute intervals. NC LOW installed a HOBO data logger at Bowling Farm, about 16 river miles downstream of Windsor, on a dock in the Cashie River, and sampled at 5 minute intervals. The Westover Hwy 45 Bridge gage is about 2.5 river miles to the junction of the Roanoke River and Albemarle Sound, is maintained by the U.S. Geological Survey in Raleigh, and sampled at 15 minute intervals. Average hourly stages (i.e., water levels) at each site were computed to facilitate comparisons. Note: what is important in each figure is the pattern of relative water-level heights through time; the site plot data are NOT corrected for gage elevation.

Four periods in 2018 representing different hydrological conditions were analyzed for site comparisons. The four periods range from 11 to 19 days.

1. Low streamflow period (August 8 to 27, 2018) when the School Road conditions had daily discharge ranging from a minimum of 20 cfs to a maximum of 195 cfs (Figure 3-11).
2. High streamflow period (November 20 to December 20, 2018) when School Road conditions had daily discharges ranging from a minimum of 83 cfs to a maximum of 621 cfs (Figure 3-13).
3. The second period spanned the passage of Hurricane Florence (September 7 to 24, 2018) (Figure 3-14).
4. The third period spanned the passage of Tropical Storm Michael (October 6 to 20, 2018) (Figure 3-15).

All four sites contained data for the selected time period and each figure compares water level stage (height in feet) record for the four sites. **The overall finding is that the pattern of water level dynamics at King St. in Windsor are more closely related to the two other downstream sites (Bowling Farm and Hwy 45) than it is to the upstream School Road. This was true for all four time periods.**

The responses of specific weather events are often subtle depending on the direction, speed, and intensity of the frontal system that determines the character and intensity of the water body response at all sites. Much of the period of late November through December was characterized by relatively small changes in water level (Figure 3-13). Normal rain events are recorded with increased levels at School Rd. and if large enough will impact the three downstream sites with a slightly delayed pattern. Frontal systems that produce small storm surges generally affect the three downstream sites with decreasing magnitude upstream. The largest changes in water level in the time period shown on Figure 3-13 was on 12/10 when a frontal system with both a substantial rainfall and minor storm surge occurred. Windsor King St. showed the least increase at this time, while School Rd. stage heights continued to rise for 3 days in response to upstream runoff. The downstream water level rise was abrupt, whereas the following water level fall was minimal and then overwhelmed by the downstream arrival of rain water.

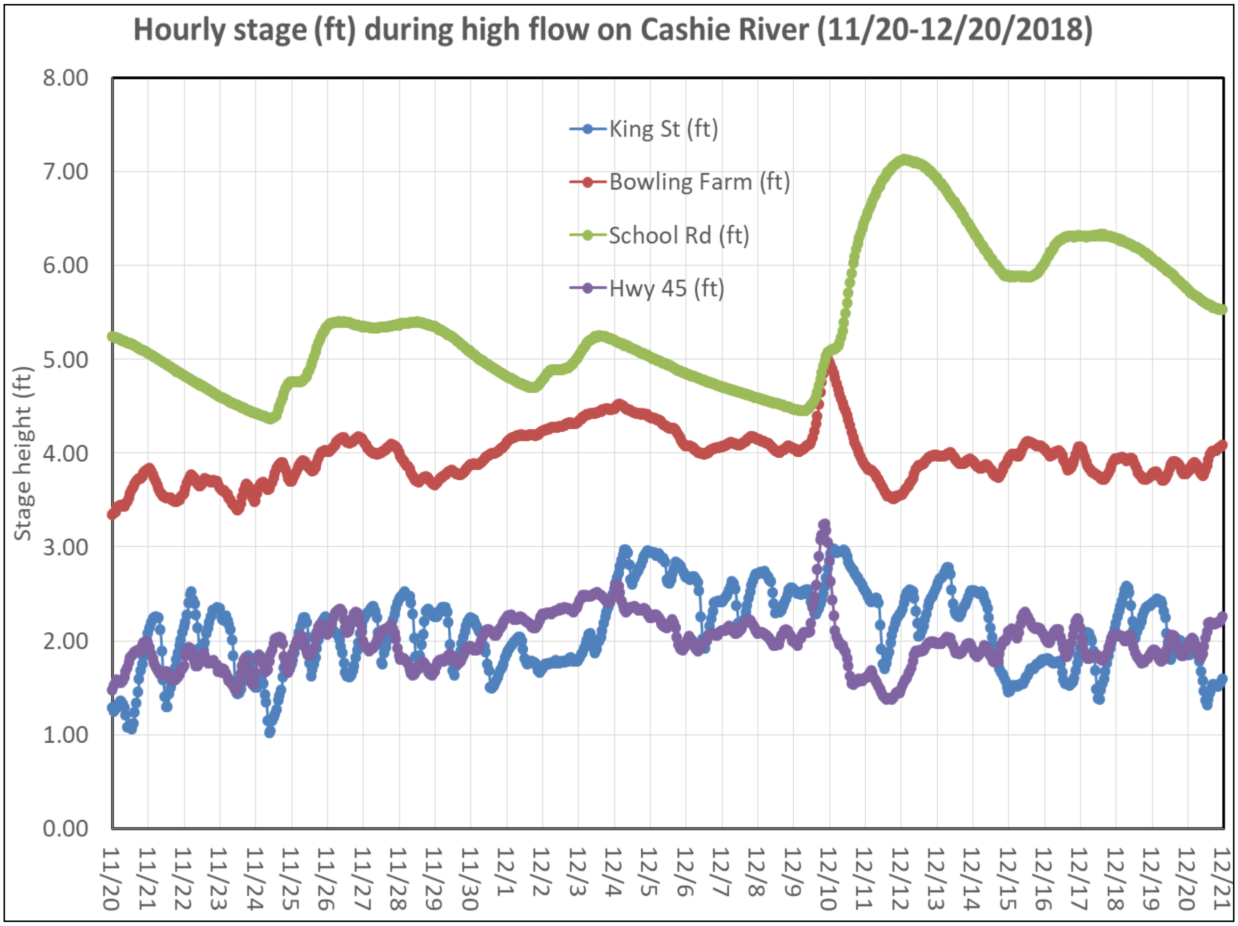


*FIGURE 3-13. Patterns of average hourly stage heights (water levels in feet) at each of the four sites are shown over time during the high flow period including frontal systems. Note that stage heights represent the bottom of the river as zero feet at each site. Therefore, the overall vertical positions of the lines are not comparable. School Rd is represented as **green**, Windsor as **blue**, Bowling Farm as **red**, and Hwy. 45 is **purple**. The frontal event on 12/10 was both a rain event (School Rd.) and small storm tide event that affected the three downstream sites.*

Hurricane Florence was traveling NW towards Cape Lookout and Bertie County. As the storm approached NC it turned W and made landfall in SE North Carolina and moved NW across western NC. Consequently, the Albemarle region was on the outermost fringe of the storm and received only a small, but important storm surge. The King St. gage in Windsor and the two downstream sites (Bowling Farm and Westover Hwy 45) responded to the storm with increases in stage height beginning 9/13, a day before landfall (Figure 3-14). Water levels at these sites rose approximately 1.5 feet in response to the easterly storm winds. These three sites have peak water levels before or at the beginning of the increase in water level at School Rd. The increase of approximately 2.5 feet at School Rd. is a day later with a lower slope. Stage height was declining at the 3 downstream storm tide sites while water levels at the School Rd. continued to increase through 9/21, as a sole function of small amounts of rain runoff associated with diminishing impact of Florence. As the track of the storm changed through time, there was first a minor backflow and then the storm surge was re-established as the storm moved northward across western NC in combination with the small rain-surges on both the Cashie and Roanoke

Rivers moved downstream (see Hurricane Florence section in Historic Storms). Notice that the semi-diurnal tidal cycle continues to occur at the two most downstream gages with diurnal tides occurring at King St. gage; no tidal signal occurs at the School Rd. gage.

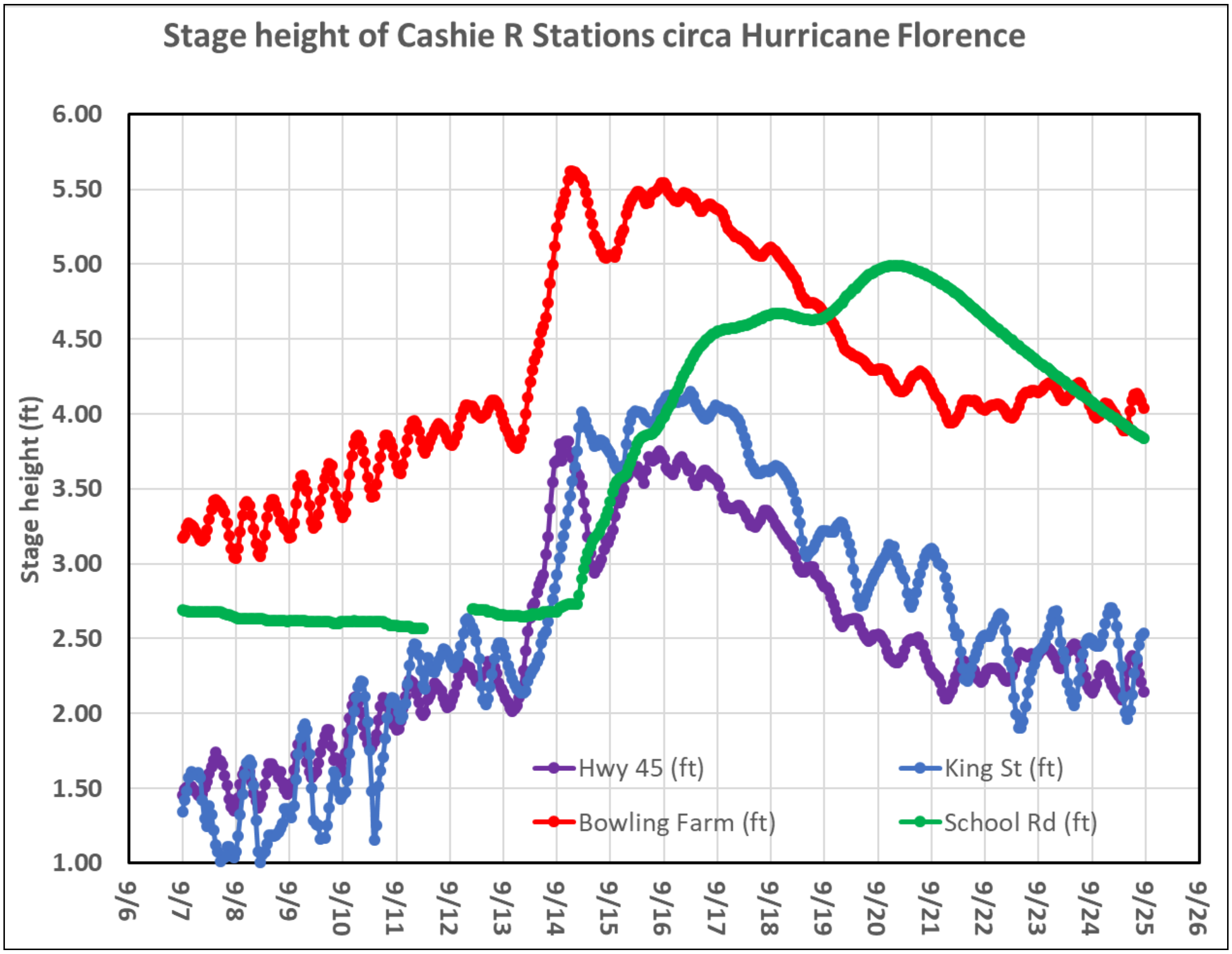


FIGURE 3-14. Patterns of average hourly stage heights (water levels in feet) at each of the four sites are shown over time during the period associated with Hurricane Florence. Note that stage heights represent the bottom of the river as zero feet at each site. Therefore, the overall vertical positions of the lines are not comparable. School Rd is represented as ***green****, Windsor at King St. as* ***blue****, Bowling Farm as* ***red****, and Hwy. 45 is purple.*

Hurricane Michael became a tropical storm by time it reached North Carolina. It produced a similar pattern as Hurricane Florence, but at a much smaller scale and on top of an already saturated groundwater system (Figure 3-15). Multiple days of increasing water levels at King Street and downstream preceded the arrival of Michael. Water levels were higher prior to the arrival of Michael than for Florence. Levels started falling at King Street on 10/9. The largest increases associated with the storm were less than 1.5 ft. Also, School Road and King Street tracked each other more similarly during passage of this storm. King Street patterns diverged from downstream on 10/11-12, the day of and day after Michael reached North Carolina. King Street, Bowling Farm and Hwy 45 showed rapid decreases in water levels.

Again, there is a strong diurnal cycle at King St. with a less evident semi-diurnal cycle. Thus, the influence of upstream conditions appeared more prominent at Windsor during this period than others, but King Street still maintained a downstream signal.

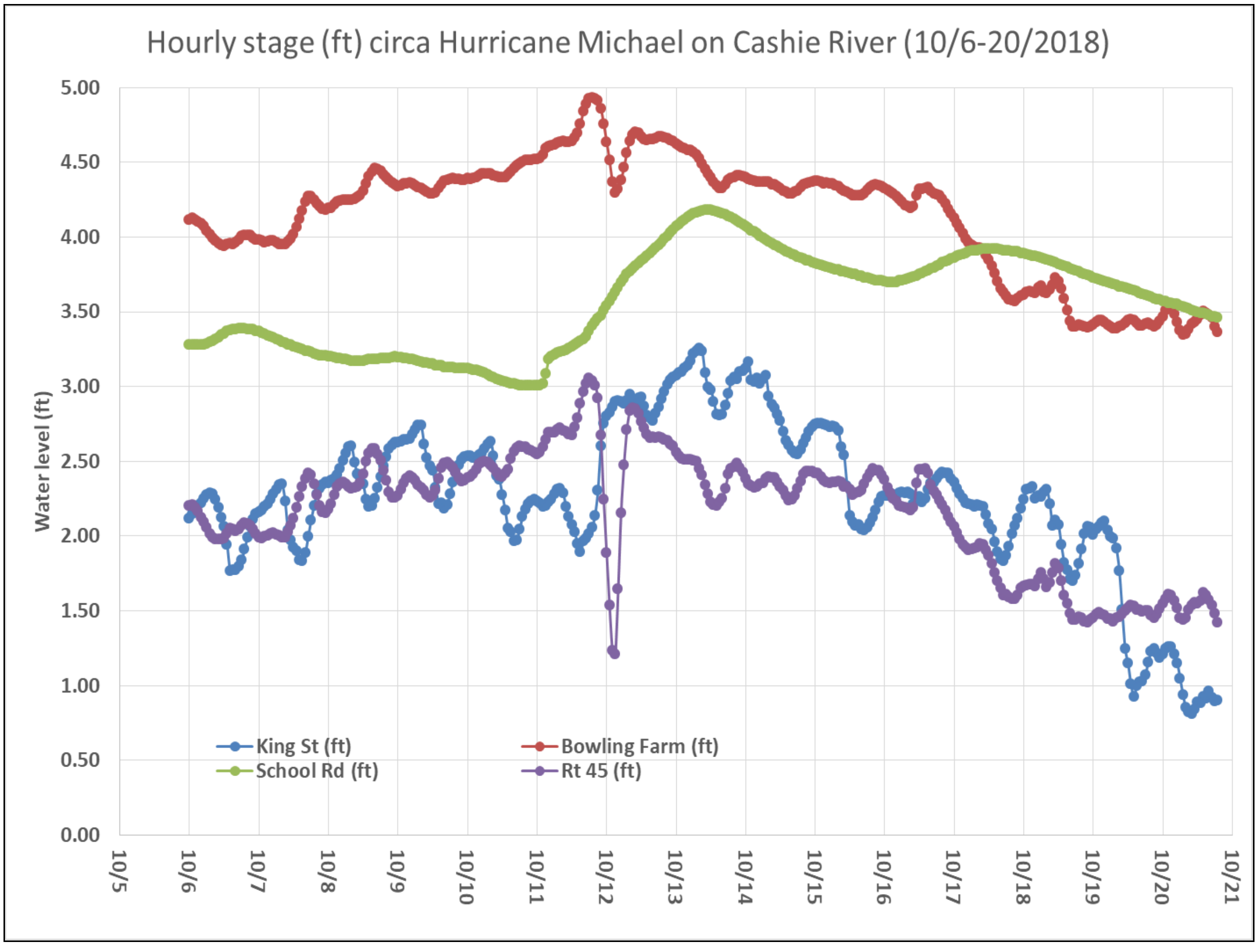


FIGURE 3-15. Patterns of average hourly stage heights (water levels in feet) at each of the four sites are shown over time during the period associated with Tropical Storm Michael. Note that stage heights represent the bottom of the river as zero feet at each site. Therefore, the overall vertical positions of the lines are not comparable. School Rd is represented as ***green****, Windsor as* ***blue****, Bowling Farm as* ***red****, and Rt. 45 is* ***purple****.*

Statistical Analyses of Variability and Site Similarity

Two statistical indices are utilized to summarize water level patterns across periods. First, is the assessment of how variable water levels are at each site by calculating the standard deviation of all average hourly stage heights for each site and period (Figure 3-16). Standard deviations increase as the variation around the average increases. One standard deviation estimates that the value where approximately 34% of samples are away from the average (above or below). For this report, a large standard deviation indicates greater variability in water levels at each site through time.

The second analysis compares hourly stage heights (water level height) at a site with the others for the same time (Figure 3-17). This is done through "Pearson correlation" analysis.

Correlation coefficients are an index of similarity in patterns between sites and range from -1 to +1. Zero indicates no relationship. A larger coefficient in a positive direction indicates more similarity between a pair of sites (e.g., both sites increase or decrease at the same time). A larger coefficient in a negative direction indicates more dissimilarity between sites.

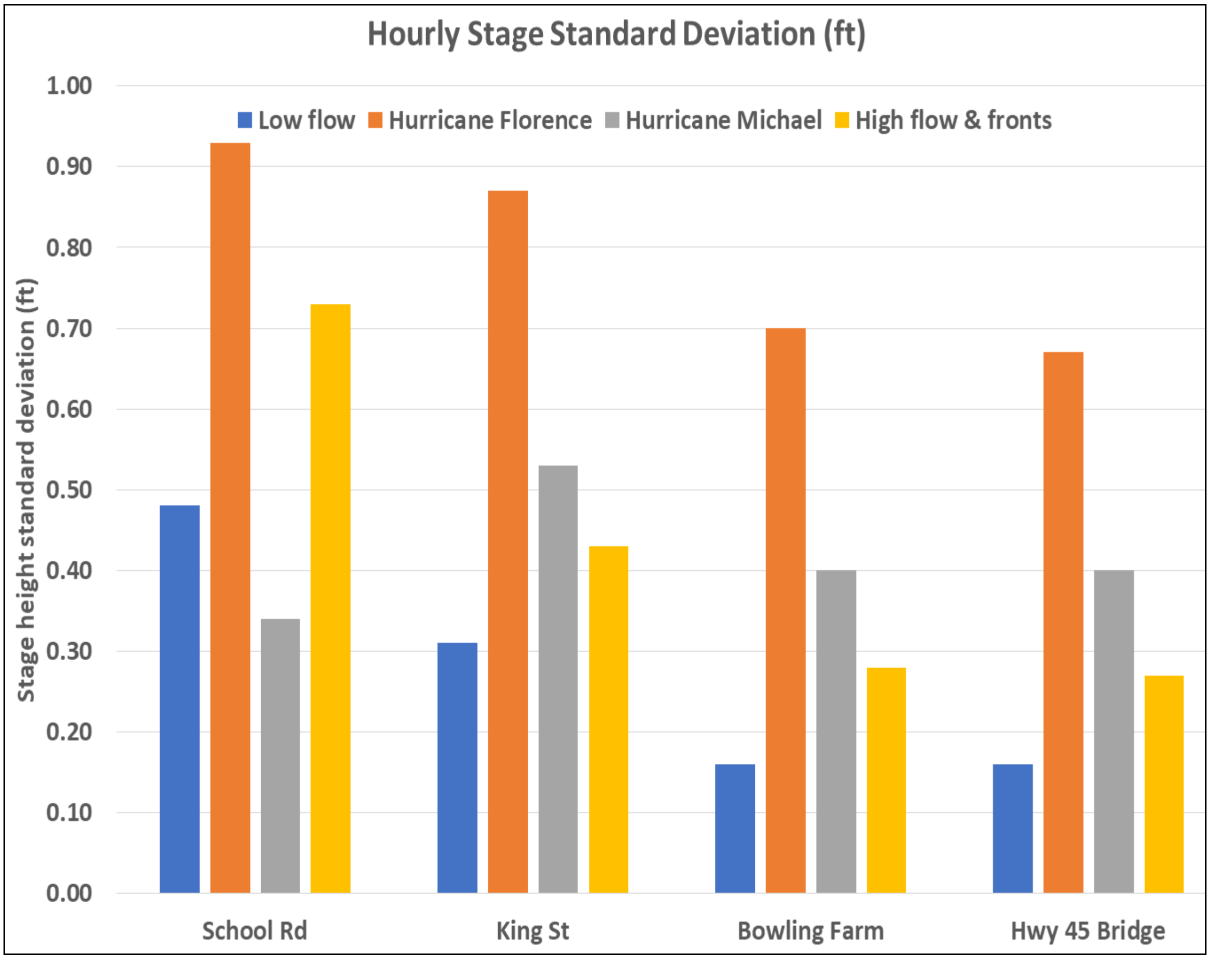


FIGURE 3-16. This plot shows the standard deviations of stage height for each site and the four time periods. Each bar represents the variation of water level through time for a period at each site. A longer bar indicates more variation in height through a time period. The low f low period (Aug. 8-27, 2018) is displayed in ***blue****, Hurricane Florence (Sept. 7-24, 2018) is in* ***orange****, Tropical Storm Michael (Oct. 6-20, 2018) is in* ***grey****, and high flow and frontal periods (Nov. 20 to Dec. 20, 2018) is in* ***yellow****.*

Variation was greatest during the Hurricane Florence period at all sites (Figure 3-16). This is associated with the storm surge as the storm arrived in NC. During this period at King St., 34% of measured water levels (i.e., 1 standard deviation) were almost 0.9 feet above the average water level for the period. The order of periods with decreasing variation was the same for all sites, except School Road; from Hurricane Florence, Tropical Storm Michael, High flow and frontal systems, and Low flow. The order for School Road was Hurricane Florence, High flow and frontal system, Low flow, and then Tropical Storm Michael. A greater similarity in patterns occurs at downstream sites and sites at or near sea level. School Road had the highest variation and the two most downstream sites the least with King Street intermediate. This is an indication of the transitional position of Windsor.

Correlations with King St water levels are shown in the first three clusters of bars in Figure 3-17. Similarities with King St water levels decreased from Bowling Farm to Westover Hwy 45 to School Rd. This pattern of similarities occurred for all four periods. In other words, the patterns in water level change at Windsor tracked downstream better than upstream for all periods studied. The strength of correlations (i.e., similarity) with King Street decreased among periods from Hurricane Florence to Tropical Storm Michael to Low flow to High flow and frontal systems. Thus, during the two tropical storms the patterns at Windsor were most similar to all sites, especially the downstream site.

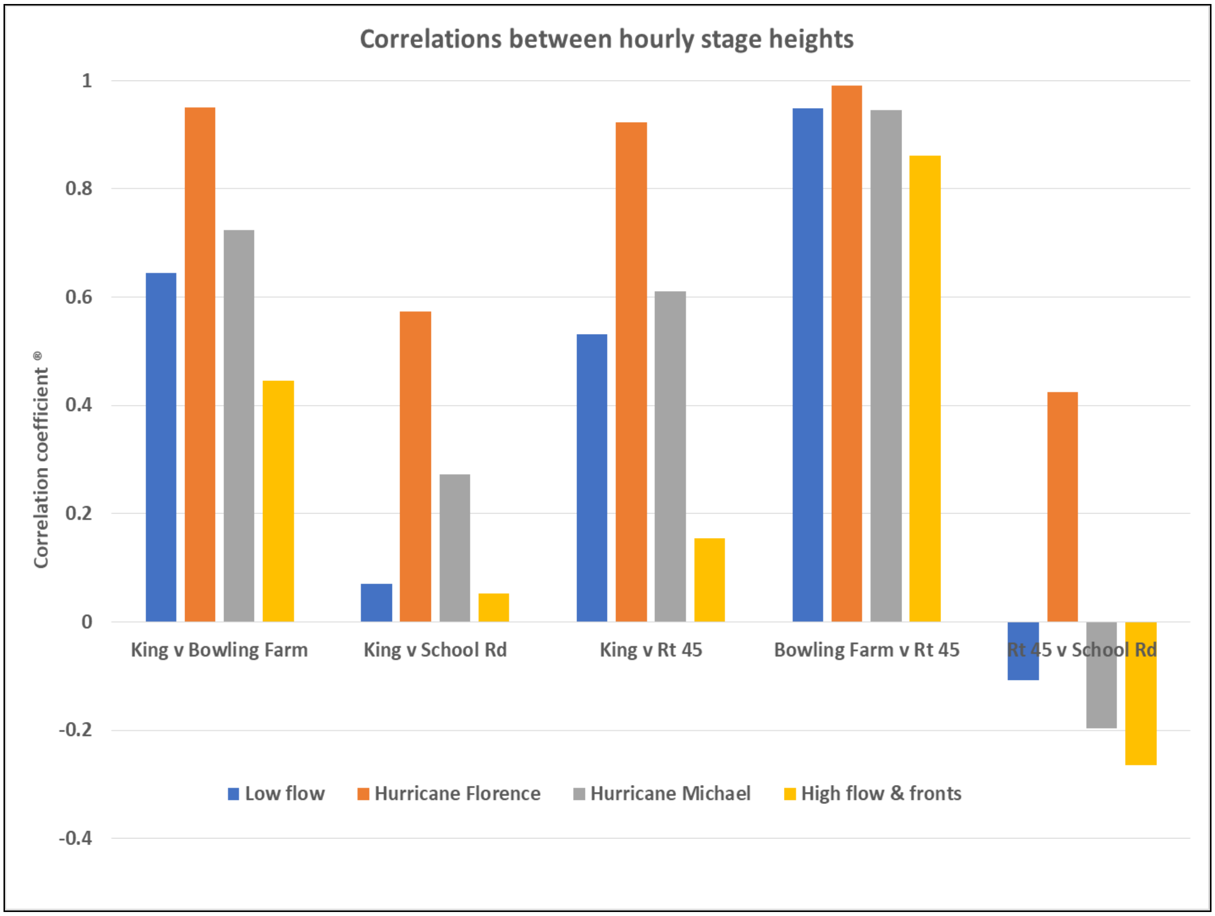


FIGURE 3-17. This plot shows the correlations (degree of similarity) of stage height (water level) between each site and time period (colored bars). Each bar represents the similarity of water levels through time within each period for each site pair. A longer bar in the positive direction indicates more similarity in patterns across a time period. The more negative a bar indicates more dissimilarity across a time period. The low flow bars (Aug. 8-27, 2018) are in ***blue****, Hurricane Florence bars (Sept. 7-24, 2018) are in* ***orange****, Tropical Storm Michael bars (Oct. 6-20, 2018) are in* ***grey****, and high flow and frontal bars (Nov. 20 to Dec. 20, 2018) are in* ***yellow****.*

Similarities were assessed between Westover Hwy 45 water levels with the most downstream site in the Cashie River (Bowling Farm) and with the upstream site (School Rd.) in the fourth and fifth bar clusters in Figure 3-17. Overwhelmingly and expectedly, the greatest similarities were between Westover Hwy 45 and Bowling Farm, while there was little to no similarity between Westover Hwy 45 and School Rd. This latter relationship is further supported by Figure 3-18 that shows how the lower Roanoke River Jamesville tracks a mixed signal of dam discharge and Albemarle Sound weather, while Hwy 45 tracks only the Albemarle Sound weather conditions similar to the lower Cashie River. Notice the striking difference between lower Roanoke signals and the upper Cashie River at School Road, which is dominated only by upstream rainfall.

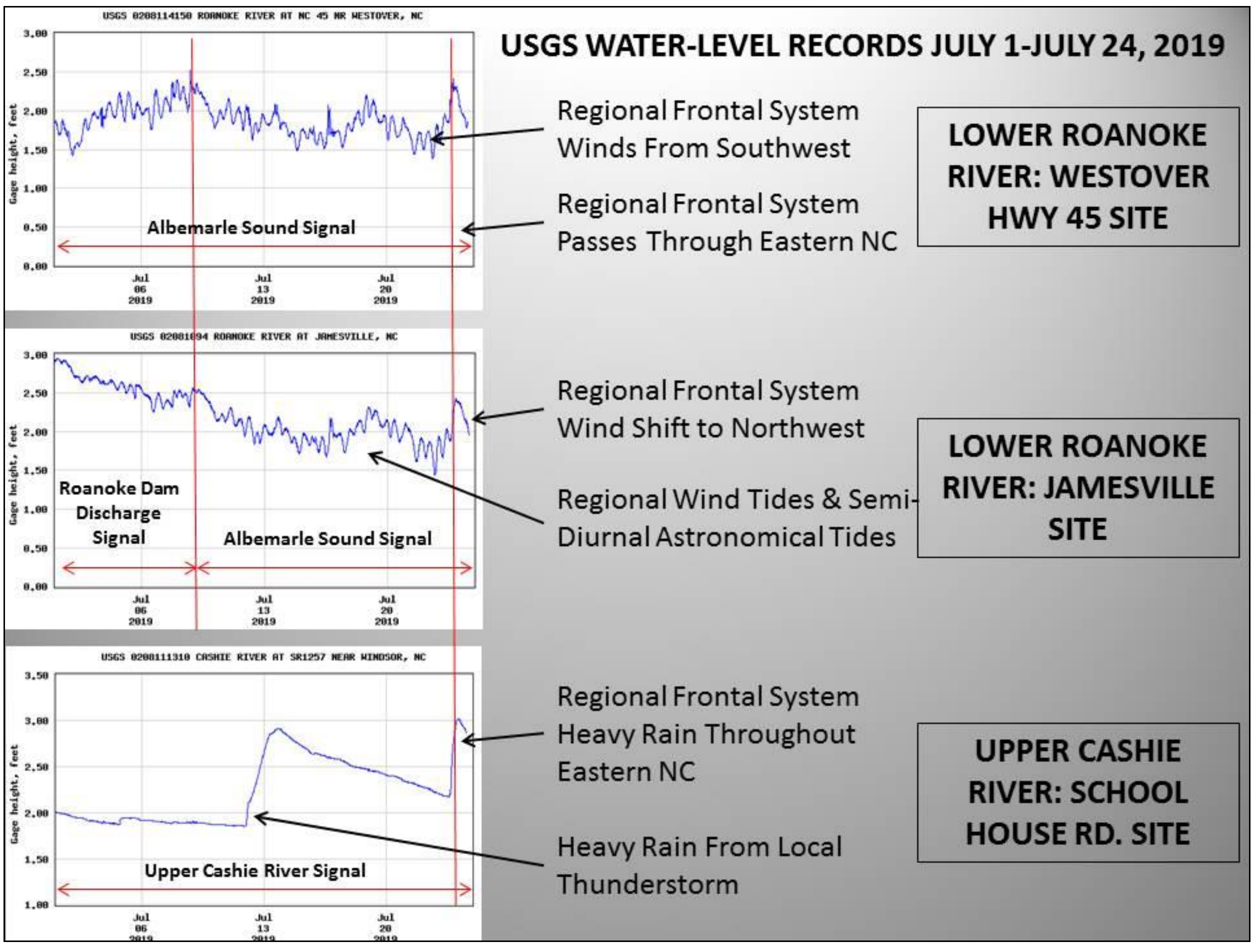


FIGURE 3-18. Plot compares the water-level gage patterns on the two lowermost gages in the lower Roanoke River with the uppermost gage on the upper Cashie River (School Road) for the period of July 1 through July 24, 2019. The upper panel is dominated by the Albemarle Sound signals of frontal systems, wind tides, and semi-diurnal astronomical tides. The middle panel is in the transition zone reflecting the decline of a dam discharge and a small Albemarle Sound signal superimposed on top for the first week. Then the second and third weeks are identical to the top panel. The bottom panel represents the upstream rainfall signal from a local heavy thunderstorm and one regional frontal system recorded on all three gages. None of these plots are corrected for absolute elevation.

In summary, water levels at King St. had temporal patterns that were consistently more similar to downstream sites than the one upstream site during the four periods of record. In fact, King St. patterns were more similar to those on the lower Roanoke River at the Westover Hwy 45 Bridge near the western end of Albemarle Sound than a few miles upstream at School Rd. Bowling Farm results are most similar to King St., both of which display astronomical tidal signatures. Figure 3-18 demonstrates the extreme difference between the lowermost gage on the Roanoke River (Westover Hwy 45) that mimics the lower Cashie River gages as compared to the upper Cashie River at School Road. **These findings all demonstrate that downstream and local processes are as important in controlling water levels in Windsor as upstream processes, at least under the circumstances studied.**

Comparing Water Levels of Roquist Creek to Lower Cashie River

A HOBO was maintained in the lower Roquist Creek to determine the creek's water-level dynamics and its similarity and contribution to the lower Cashie River. The HOBO was placed 1.2 miles from the creek's mouth with the Cashie River. Comparisons were made with the water-level measurements at the Bowling Farm on the lower Cashie River, which was located 7.8 miles downstream from the confluence of the Roquist with the lower Cashie River. Two periods from the Roquist water-level data were evaluated: November 12, 2018 to January 3, 2019 (Figure 3-19) and February 26 to April 15, 2019 (Figure 3-20). The figures show the water levels at Roquist Creek (top panels) and Bowling Farm (bottom panels) in the lowermost portion of the Cashie River during the respective periods. These data plots also include the shallow water temperature at Roquist Creek that equates to water-level changes and associated weather patterns.

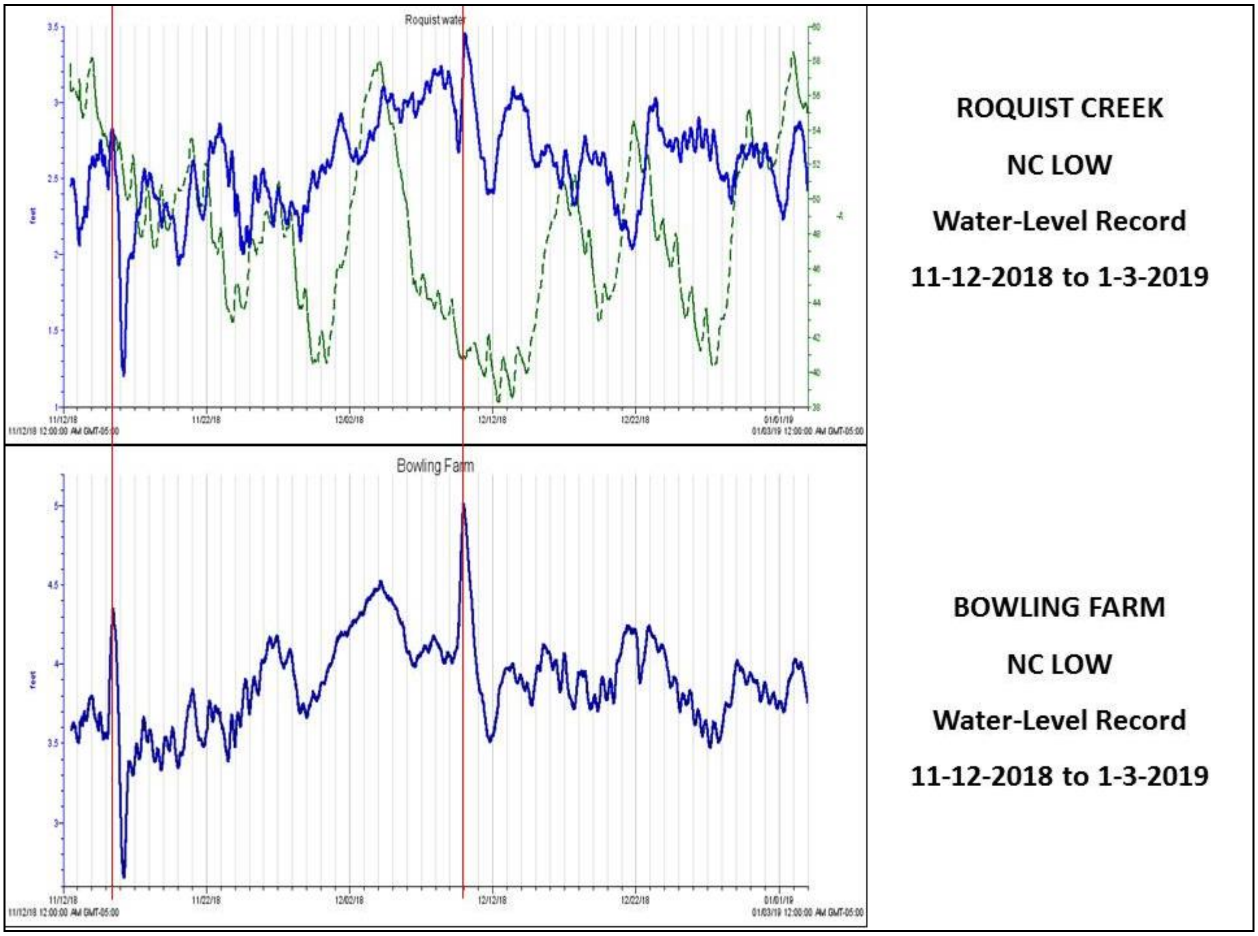


Figure 3-19. Plot compares the water-level gage patterns (in blue) for Roquist Creek (top panel) with the Bowling Farm gage (bottom panel and lowermost Cashie River) for the period 11-12-2018 (in blue) to 1-3-2019. Water temperatures at Roquist Creek are in green. The red lines are two examples of small storm surges that first blew Albemarle Sound waters to the west and then back to the east as the front passed through the region. Neither of these plots is corrected for absolute elevation.

Overall, the water-level patterns were very similar between the two sites during each of the two periods. Both sites displayed short time-scale fluctuations at the similar times that are linked to both astronomical tides and a series larger peaks and valleys due to wind/storm tides associated with frontal systems. These larger excursions are often associated with large changes in water temperature (4/3/2019 on Figure 3-20), but small-scale fluctuations show little temperature change (11/16/2018 on Figure 3-19). Similar longer time-scale (weeks) patterns occur. Discounting short-term fluctuations, the pattern of water level change at both sites remained relatively constant during 11-12-2018 to 1-3-2019 period (Figure 3-19). While the differences in water level were nearly contemporaneous, changes in temperature were dramatic over the nearly two month period. Some changes in temperature coincided with changes in water level, but as with the short-term fluctuations no clear pattern emerged.

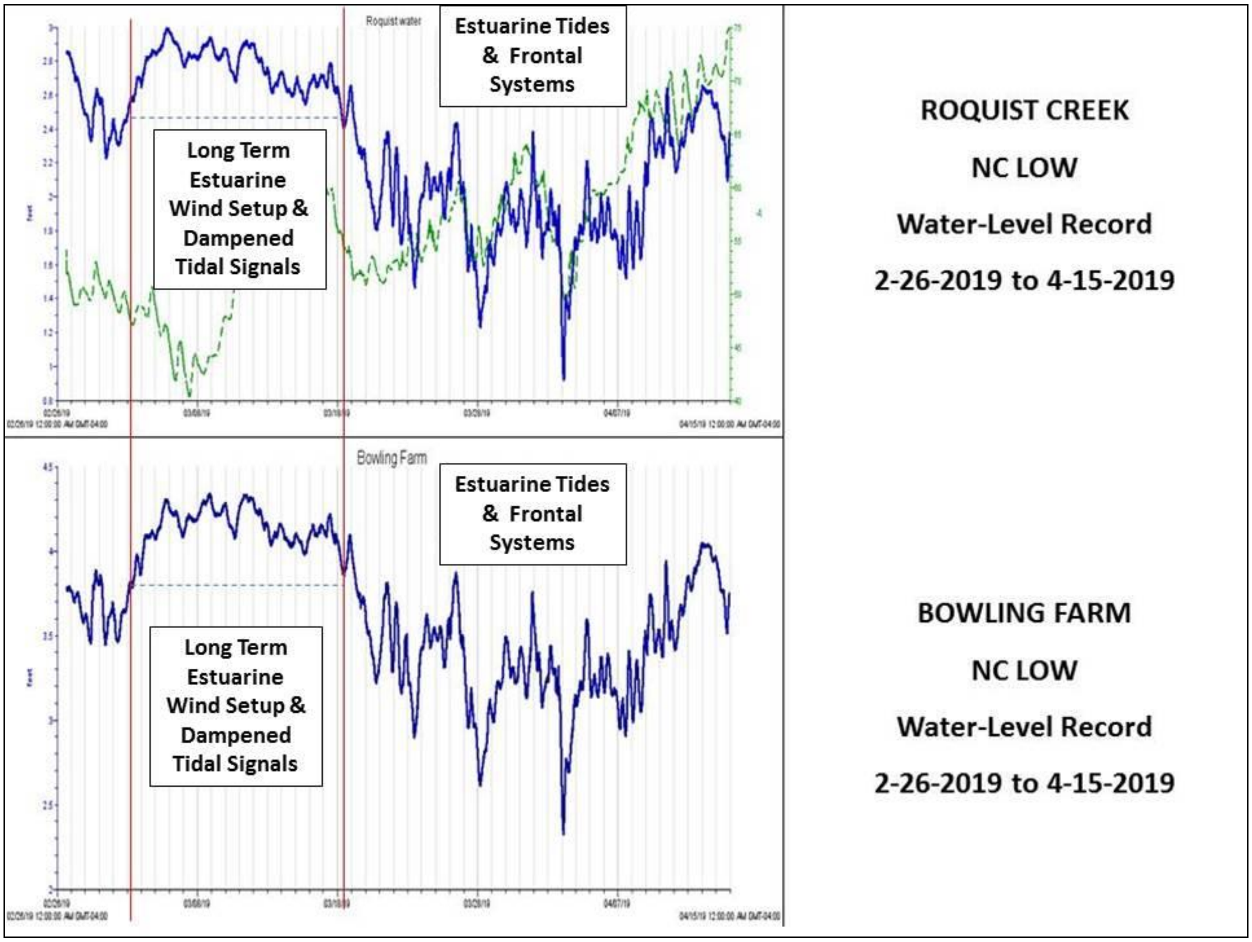


FIGURE 3-20. Plot compares the water-level gage patterns (in blue) for Roquist Creek (top panel) with the Bowling Farm gage (bottom panel and lowermost Cashie River) for the period 2-26-2019 (in blue) to 4-15-2019. Water temperatures at Roquist Creek are in green. The two red lines delineate an extended period of high water set up by a persistent wind pattern on Albemarle Sound. The higher water level caused a dampened tidal signal superimposed on top as compared to more prominent tidal signals and frontal systems during period of lower water levels on the right side. Neither of these plots is corrected for absolute elevation.

During the 2/26/2019 to 4/15/2019 period (Figure 3-20), water levels at both sites were high from about 3/5 to 3/18/2019, then declined and rose again around 4/8 or 4/9. The increase in water levels by about 2/3 feet equates to a general backflow resulting from the rise in increased downstream water level due to extremely high dam discharge of the Roanoke River. Notice how the astronomical tide signal is reduced slightly on top of the high water segment and how the water temperature declines. Temperatures began to generally rise on 3/9 and continued through 4/16 with deviations from frontal systems. From about 3/19 to 4/12, the Roanoke River flow had receded to more normal conditions with a general lowering of water level in the lower Cashie River and a major increase in amplitude of both astronomical tides and the frontal system wind/storm tides. During this latter period, fluctuations in water level at the two sites appeared contemporaneous with no obvious evidence of Roquist Creek providing any control of the Bowling Farm site.

Thus, water levels at the lower Roquist Creek and lower Cashie River (Bowling Farm) appear to be subject to comparable forces of control. Patterns from hours to weeks were similar and in most instances occurred simultaneously. Previously a strong correlation was demonstrated between the water-level patterns in the lower Cashie River with the lower Roanoke River at Westover Hwy 45 and Albemarle Sound. Figure 3-21 demonstrates the declining influence of dam discharged flood waters at Jamesville with an extremely small influence of Albemarle Sound just beginning to show up. As the Roanoke River flood waters (3/3 to 3/19) wane and spread out across the vast floodplain, the Westover Hwy 45 gage shows a background level up to about 0.5 feet high with an intermediate Albemarle Sound tidal signal. From about 3/20 to 4/12 Albemarle Sound dynamics are generally in control in both the lower Cashie River and lowermost Roanoke River. This larger scale pattern is perpetuated into the Cashie River and the Roquist Creek tributary.

However, nothing at present suggests the dynamics of Roquist Creek will significantly aid in predicting water levels at Windsor. This can be better achieved by knowledge of water levels in the lower Cashie River, Roanoke River, and Albemarle-Chowan estuaries.

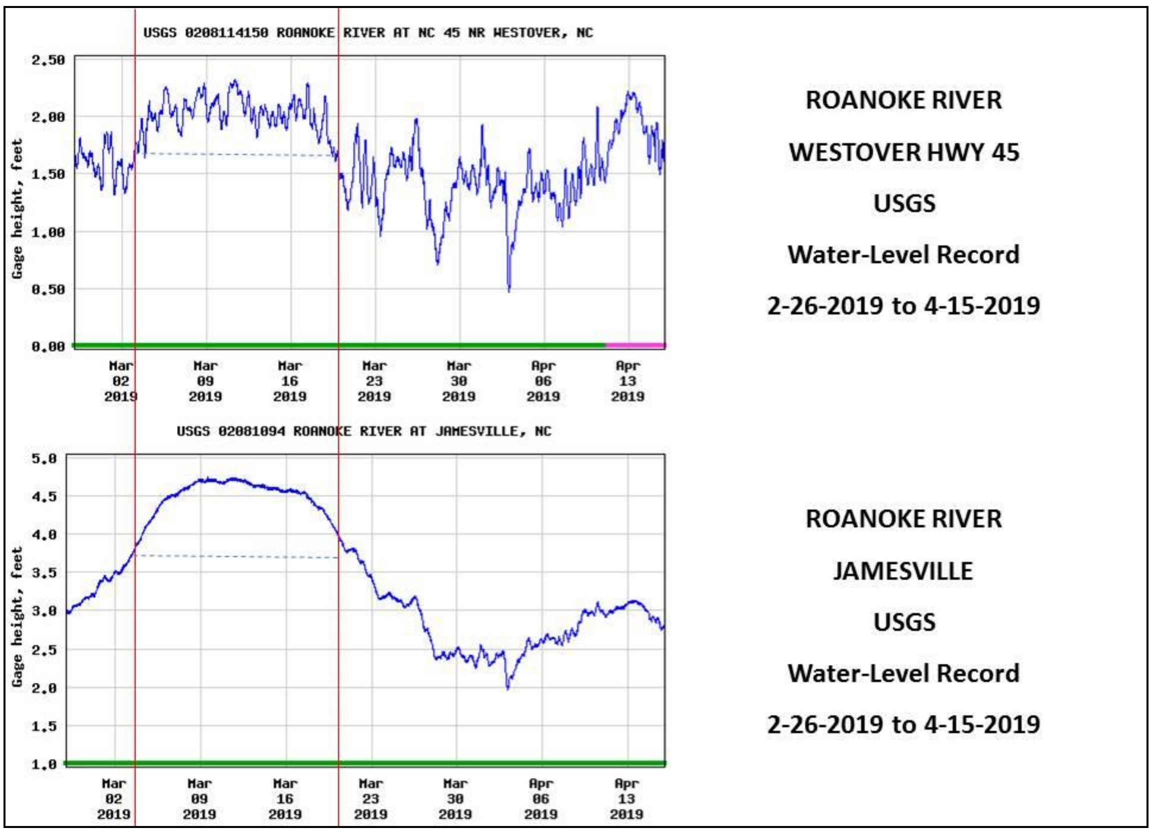


FIGURE 3-21. Plot compares the water-level gage patterns for the lowermost Roanoke River including the Westover Hwy.45 gage (top panel) with the upstream Jamesville gage (bottom panel) for the period 2-26-2019 to 4-15-2019. Notice that the Hwy 45 gage displays the maximum Albemarle Sound signal on top of a minimum Roanoke Dam signal, whereas, the slightly upstream gage at Jamesville is totally opposite. It is the Hwy 45 signal that is mimicked in both the Bowling Farm and Roquist Creek gages in the lower Cashie River. Neither of these plots is corrected for absolute elevation.

Comparing High Crest Water Levels at Windsor to School Rd. and Hwy 45 Gages

This report demonstrates stronger relationships between water levels at Windsor with downstream levels and processes than upstream at School Road. Doll et al. (2018) and general knowledge indicate that high discharge (and water levels) upstream at School Rd. greatly influences and may control flooding of Windsor. Thus, one might expect that at low and normal water levels the Cashie River at Windsor would track downstream conditions. While under flood conditions, upstream processes would dominate. This report has tried to determine whether there is a transition from one dominant input to the other and how downstream conditions might influence flooding in Windsor resulting from upstream during high crests at School Road.

This question was addressed using data from a list of stages during high water crests at School Rd. from 2013 through 2017 when data were also available from both King St and Hwy. 45 Bridge gage stations. The initial list for School Rd. came from the USGS gage station web site and was culled to match the duration when King St. gage station was active (from 2013 on but with interruptions). The list was supplemented with recent high water levels in 2018 for a total of 15 crests. Stage (water level) variation during crests varied less than ten-fold at any site and decreased from upstream to downstream. Stages considered at School Rd. ranged from 3.3 to 16.6 ft., at King St. from 1.5 to 12 ft., and at Hwy. 45 from 1.6 to 4.3 ft. Two events exceeded 16 ft. at School Rd. (9/22/2016 and 10/9/2016). The two largest events exceeding 10 ft. were at King St. No stages reached 5 ft. at Hwy. 45 among the dates considered.

The relationship between King St. stage and School Rd. (Figure 3-22) differed from the pairing between King St. and Hwy. 45 (Figure 3-23). Stage at School Rd. had little relationship to King St. for all times except the two highest levels. King St. stage largely stayed between 2 and 4 ft. while School Rd. stage varied from <4 to 10 ft. The two highest stages ($\geq$16 ft.) at School Rd. were linked to high water levels at King St. (>11 ft.). Stages at King St. were almost always less than those at School Rd.

A number of regression analyses were run. The results of line fitting analyses (i.e., correlation with regression) are shown on Figures 3-22 and 3-23. Of general importance is that these relationships are more complicated than just a linear or straight line. The complex relationship between stages at King Street and School Road is evident in Figure 3-22. There is a lack of change in King Street levels with most School Road crests and then a significant rise with only the two highest crests. The lack of correlation during lower flows (low water levels) is similar to the other findings using hourly information for the sampling period. The link occurs between the two highest crests conform to the expectations of Doll et al. (2018).

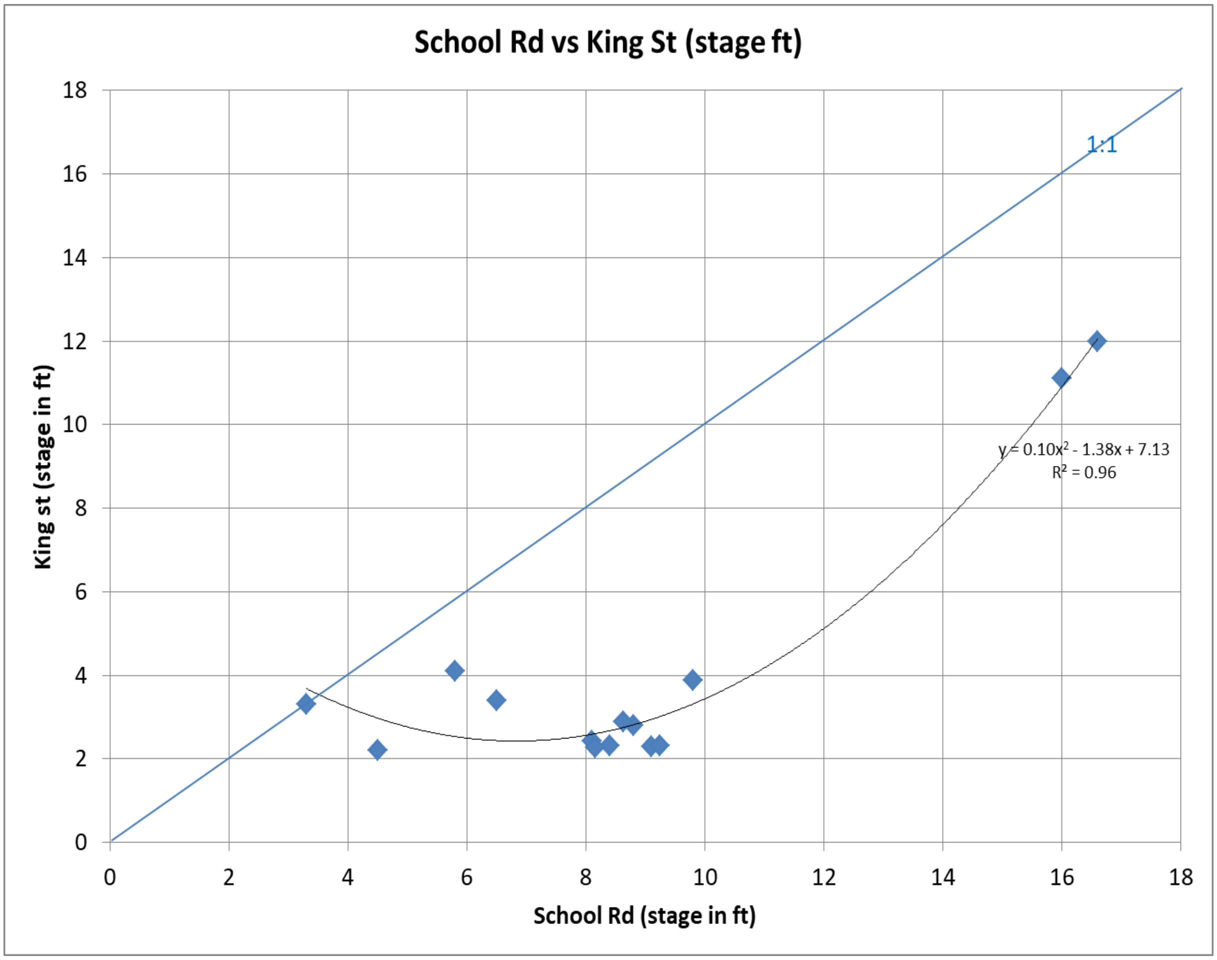


FIGURE 3-22. Cashie River water-level stages at King St. in Windsor and School Rd. during 15 high crest conditions. The blue line represents the 1:1 relationship between the two sites. A 4th order polynomial regression is used to predict the relationship between sites (black line).

Water-level stages at King Street showed closer, but still weak, association with those in the lower Roanoke River at Hwy 45 during all but the highest stages (Figure 3-23). The relationship at all but the two highest levels at the two sites is nearly 1 to 1. This means there is a similar quantitative change in water level at King Street as there is at Hwy 45. This is similar to the strong correlations that occurs in the 2018 data. The two highest crests at Windsor, however, were much higher than those at Hwy 45. The complexity of transition found in the King Street vs School Road comparison is shown again here; a complex equation is necessary to explain the stage relationship for all crests.

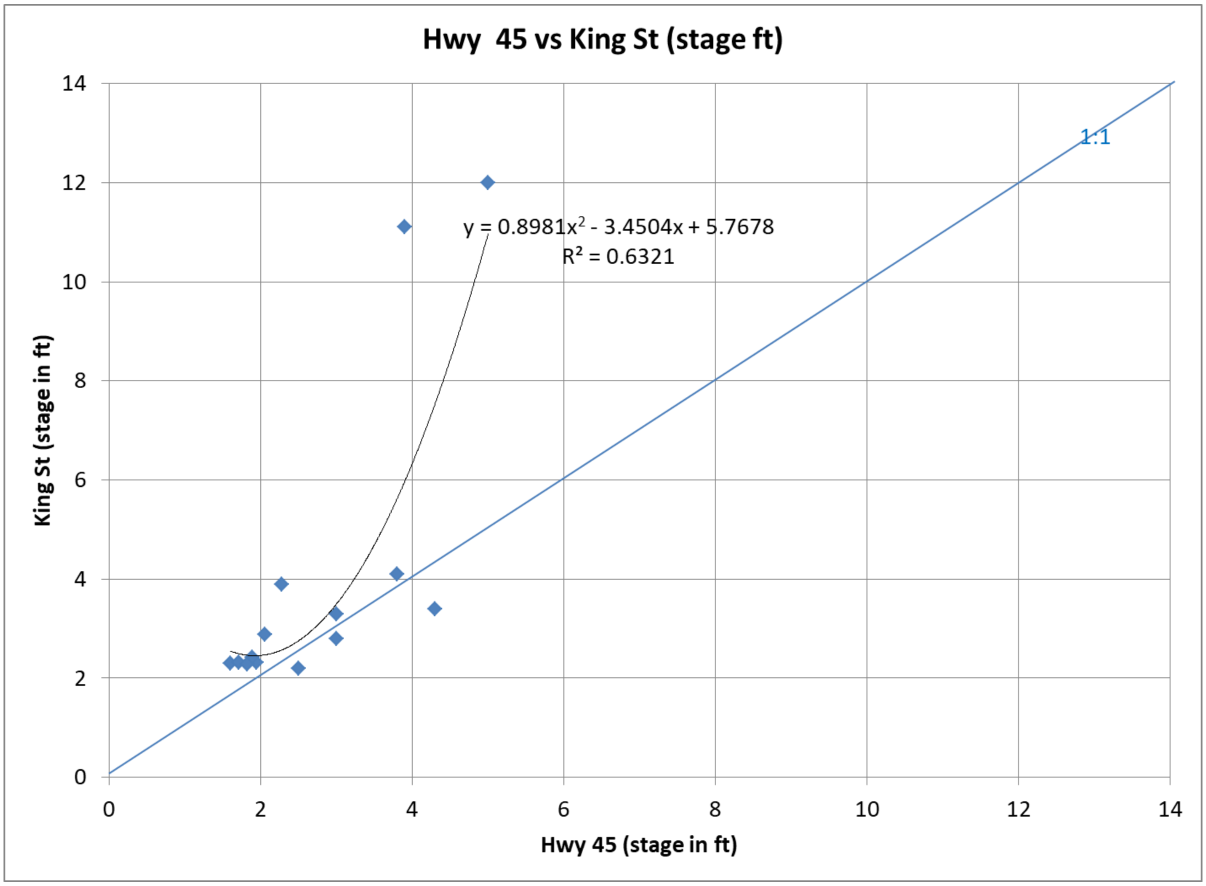


FIGURE 3-23. Water level stages at King Street and Hwy 45 Bridge are plotted for 15 high crest conditions. The blue line represents the 1:1 relationship between the two sites. Two regressions are shown. A 3rd order polynomial regression is used to predict the relationship between sites for all samples (black line). A simple linear regression running through zero is used to predict results for all but the 3 highest crests at School Rd.

In conclusion, the comparison of high crests between sites confirms and extends our findings for the 2018-19 study. School Road is not always a good predictor of Windsor water levels. At low, normal and less than extreme high flow conditions, water levels at Windsor are more similar to downstream than upstream signals. Hwy 45 is well correlated with Bowling Farm and King Street water levels. At the two highest crests at both School Rd. and two of the three highest crests at Hwy. 45, King Street stages were also high. Obviously, the number of examples at extreme conditions is minimal. Results do indicate that downstream processes can impact flooding at Windsor, even under extreme conditions upstream, and transition in dominance of control is complex and unresolved. This is certainly an area requiring more understanding. **It is recommended that further evaluation take place concerning the predictability of downstream and upstream conditions, particularly if a major event should occur during the next year, utilizing the three Cashie River gages (School Rd., King St., Bowling Farm), two Albemarle (Salmon Creek, Colerain), and lowermost Roanoke River (Hwy 45) gages.**

Prediction of Floods in Windsor

The previous analysis compared similarities in water levels between King Street and other sites. All of these were done for pairs of levels at the same time. Determining that water-level patterns at King St. were more similar to all downstream sites than to the one upstream site is informative, but not predictive in time. Decision making at Windsor would be enhanced if patterns at another site preceded expected patterns at Windsor. For example, the Roanoke River Hwy. 45 site, controlled primarily by Albemarle-Chowan storm surges and tides, is similar to the Cashie River water level patterns. Could the changing water level pattern from an oncoming storm in the Sound, presage later patterns at Windsor? Decision making is improved the farther in advance such similarity occurred.

To determine the predictability potential, the patterns at the four sites were analyzed as follows. Windsor King St. water levels were compared to preceding water levels at Hwy. 45 Bridge, Bowling Farm, and School Rd. by progressively lagging measurements by 1 hour for each correlation up to 24 hours. For example, King St. was correlated with the Bowling Farm at a specific time, and then with 1 hour prior to that time, 2 hours prior, etc. through a 24-hour day prior. This was done for each of the 4 periods under consideration. Thus, it was assumed that small-scale weather events that have occurred since NC LOW's water-level gages were installed (mid-2018, see Appendix A) that wind effects are predictably linked to downstream sites and rain-generated discharges are linked to upstream input.

The "coefficient of determination" was used as the index of importance of similarity. The lag in hours of measurements to reach the maximum coefficient was then identified. The coefficient of determination is an estimate of how much variation in one variable is explained by its correlation with the other. The value ranges from 0 to 1 with the amount of explained variation increasing as the value increases. A value of 1 equals 100% explained variation. Separate analyses were conducted for each site pair and each of the four periods described in previous sections. For example, during the Hurricane Florence period water levels at Bowling Farm explained 92% of the variation at King Street 3 hours later (Figure 3-24).

Predictability success was mixed (Figure 3-24). Overall, the preceding water levels at Bowling Farm did best predict those at Windsor King St. under all conditions. Roanoke River Hwy 45 Bridge provided the next best prediction, and the lag time was longer. Correlations between King Street and School Road were weak by this analysis with no predictive power. The patterns were generally of decreasing correlation with increased lag time. Encouragingly, the maximum similarities with other sites tended to be highest during the periods of the two Hurricanes. Bowling Farm and Hwy 45 Bridge showed the strongest predictability at these times and that predictability for Windsor occurred at least several hours in advance. As might be expected Bowling Farm was more like King St. than was Hwy. 45 Bridge, but the lag was generally longer at the bridge.

MAXIMUM SIMILARITY (MAXIMUM COEFFICIENT OF DETERMINATION)				
SITES	LOW FLOW	HURRICANE FLORENCE	TROP. STORM MICHAEL	HIGH FLOW & FRONTAL SYS.
KING ST. vs BOWLING FARM	0.45	0.92	0.69	0.22
KING ST. vs HWY 45 BRIDGE	0.37	0.91	0.53	0.11
KING ST. vs SCHOOL RD.	0.01	0.28	0.07	0.001
HOURS LAGGED FOR MAXIMUM SIMILARITY				
KING ST. vs BOWLING FARM	1	3	24	12
KING ST. vs HWY 45 BRIDGE	2	13	16	24
KING ST. vs SCHOOL RD.	0	0	0	0

FIGURE 3-24. Predictability of previous high water levels measured at three downstream sites relative to the Windsor King St. site. Indexes of "maximum coefficient of determination" (or similarity) explain the variation in water levels at Windsor King St. by those at the paired site. Hours of lag to "maximum coefficient of determination" indicates how far in advance best predictions might be made.

The take away message is that downstream site water-level information can provide some advanced warnings for Bertie County coastal systems as storms approach. Further analysis is necessary to determine if a more accurate index of flooding can be developed. The recommendations are to **1) lengthen the prediction time through analyses and measurements of storm water dynamics farther into the Albemarle Sound and Chowan River estuaries; and 2) establish permanent water level stations at Sans Souci, Salmon Creek, Albemarle Sound Bridge, and Chowan River estuary at Colerain to provide additional information to complement the existing School Rd., King St., and Hwy 45 sites.**

ALBEMARLE SOUND AND CHOWAN RIVER ESTUARINE SYSTEMS

Comparison to the Lower Roanoke River

The Chowan River estuary forms the entire eastern boundary of Bertie County and is an intimate arm of Albemarle Sound estuary. Together, these two large water estuarine bodies form the mixing basin for riverine input of fresh water and oceanic input of salt water. The Chowan-Albemarle system has its own day to day hydrodynamics driven by the local and regional weather processes. However, this system becomes a complex energy machine when the riverine and/or oceanic systems move into storm mode. Unfortunately, little quantitative information exists on the dynamic water-level responses within the Chowan-Albemarle system when major storm events occur. The new information in this report is only a beginning, but it may help in predicting not only flooding conditions but also shoreline erosion associated with high storm surges.

NC LOW established two HOBO water-level recorders within the Chowan River and western Albemarle Sound (see Figure 4-1 and Appendix A). One was at Colerain along the western shore of the Chowan River and situated between the Wicomoco Bluffs to the south and the Cow Island Swamp to the north. The second gage was installed on a heavy dock within the mouth of Salmon Creek, 14.7 miles south of Colerain and at the western end of Albemarle Sound (Figure 4-1).

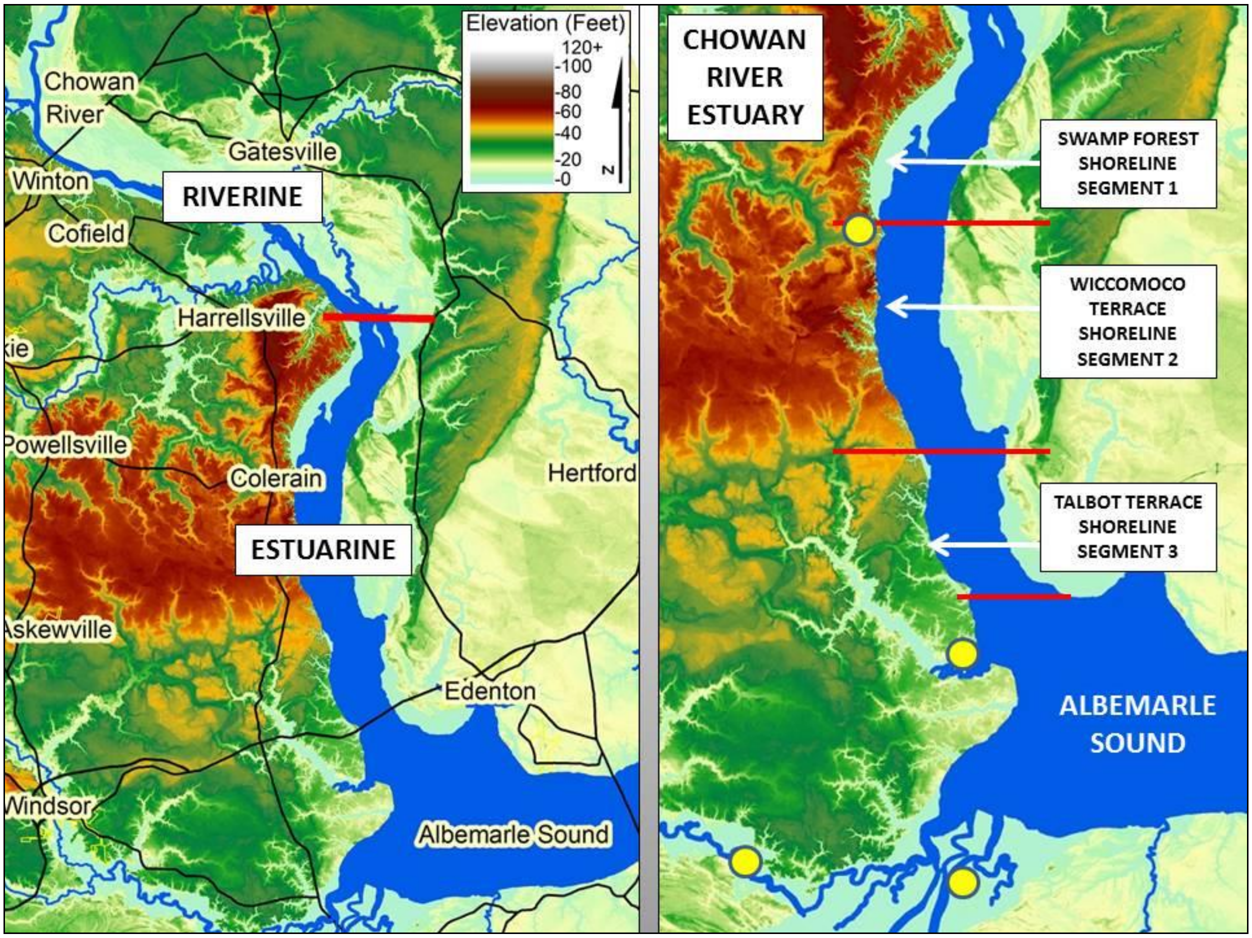


FIGURE 4-1. Two color topography maps of the Albemarle and Chowan estuarine systems that border Bertie County. The left panel shows the narrow Chowan River channel and wide floodplain to the north that gradually changes at the red line to a wide channel with only local floodplains to the south. This drowning of the riverine system is due to the ongoing rise of global sea level. The right panel is a closer view of the three shoreline segments of the western side of the Chowan River estuary. Yellow dots in the right panel show locations of water level recorders utilized in this section of the report; from N to S they are Colerain and Salmon Creek, Hwy 45 in the lower Roanoke River, and Bowling Farm in the lower Cashie River (location information is in Appendix A). Topographic data are from the NC 2015 LiDAR program. Map prepared by D. Ames.

Water-level patterns at the three western Chowan River-Albemarle Sound sites are compared during three different time periods: 8-8 to 9-25-2018 Hurricane Florence (Figure 4-2); 9-25 to 10-23-2018 Tropical Storm Michael (Figure 4-3); and 2-26 to 4-15-2019 winter to spring transition (Figure 4-4). Atmospheric pressure at each location is shown to help track weather conditions that sometimes reflect wind changes and resulting water level fluctuations. The Chowan-Albemarle water levels are also compared to those at the Westover Hwy. 45 gage on the lowermost Roanoke River, which is also dominated primarily by signals from estuaries, and to a lesser extent, water levels from the upstream Roanoke River dam discharge.

The similarities in water levels across the three sites during each of the three periods are striking (Figures 4-1, 4-2, and 4-3). As with the lower Cashie River, a small semi-diurnal tidal signal is evident at all sites. Numerous short-term, upper and/or downward spikes in water level are driven by the passage of frontal systems and the associated wind/storm tides. A good example of this is seen in Figure 4-2 from 10-11to 10-12-2018 with a significant rise and fall in water level coincided with Tropical Storm Michael, as well as a drop in atmospheric pressure. Figure 4-3 demonstrates a series of frontal systems that occurred between March 20 and April 15, 2019. This figure also demonstrates a longer-term pattern of wind setup that raised water levels about 0.5 to 1 foot throughout the western estuarine system including the lowermost Roanoke River (Hwy 45) from March 2 and March 20, 2019. Thus, this wind setup is probably not due to the Roanoke River dam discharge that was also high during this same period as similarly demonstrated in Figures 3-20 and 3-21.

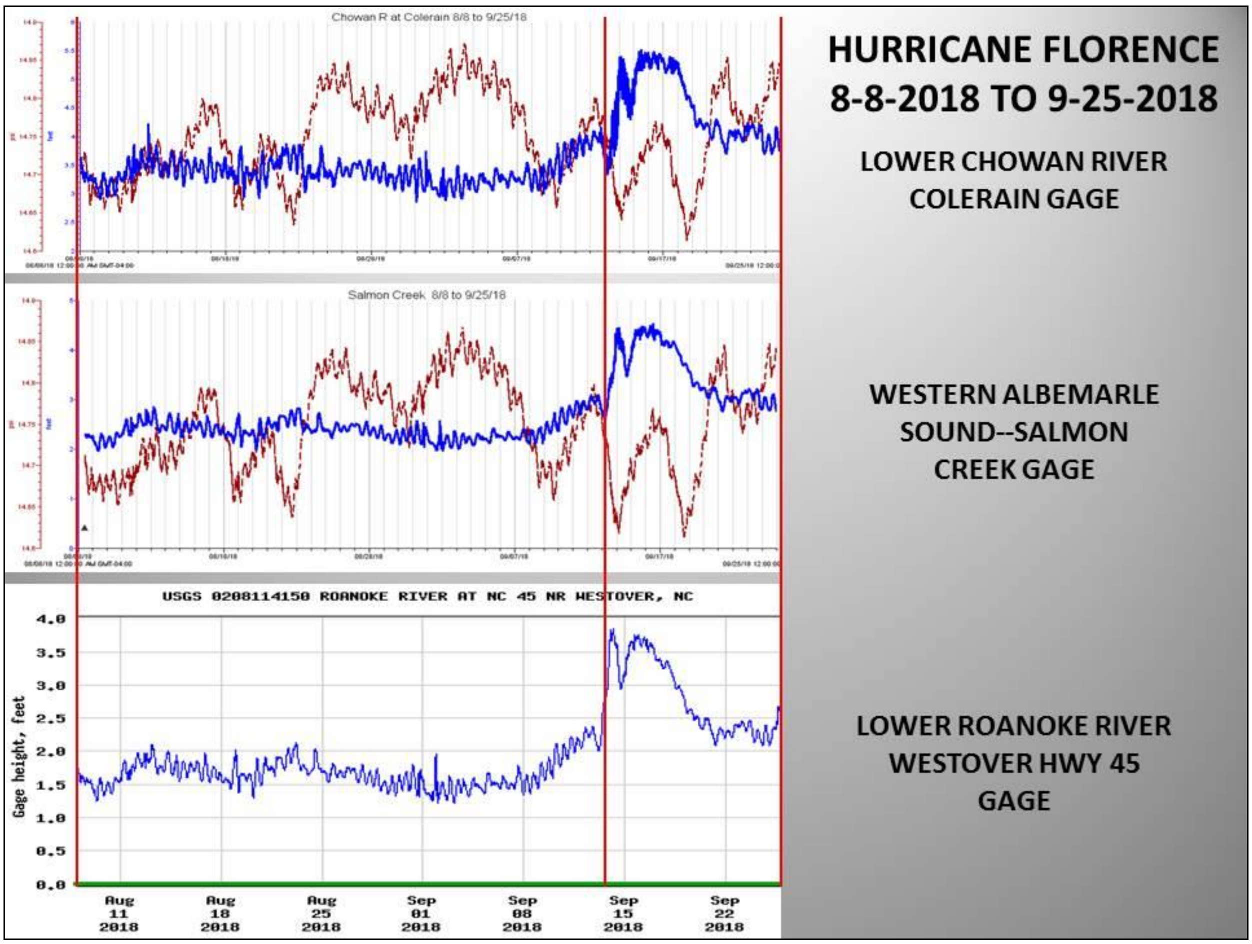


FIGURE 4-2. Water levels are shown for the period 8-8 to 9-25-2018 in blue and atmospheric pressure in red. Top panel is the Chowan River at Colerain, middle panel is west Albemarle Sound (in mouth of Salmon Creek), and bottom panel is the lowermost Roanoke River (Westover Hwy 45 Bridge). Notice the different types of wind setups, small frontal systems, hurricane Florence (middle red line) and astronomical tides that are superimposed on the background. Also, notice how all three systems are intimately connected. The water-level plots in this report are not corrected for absolute elevation.

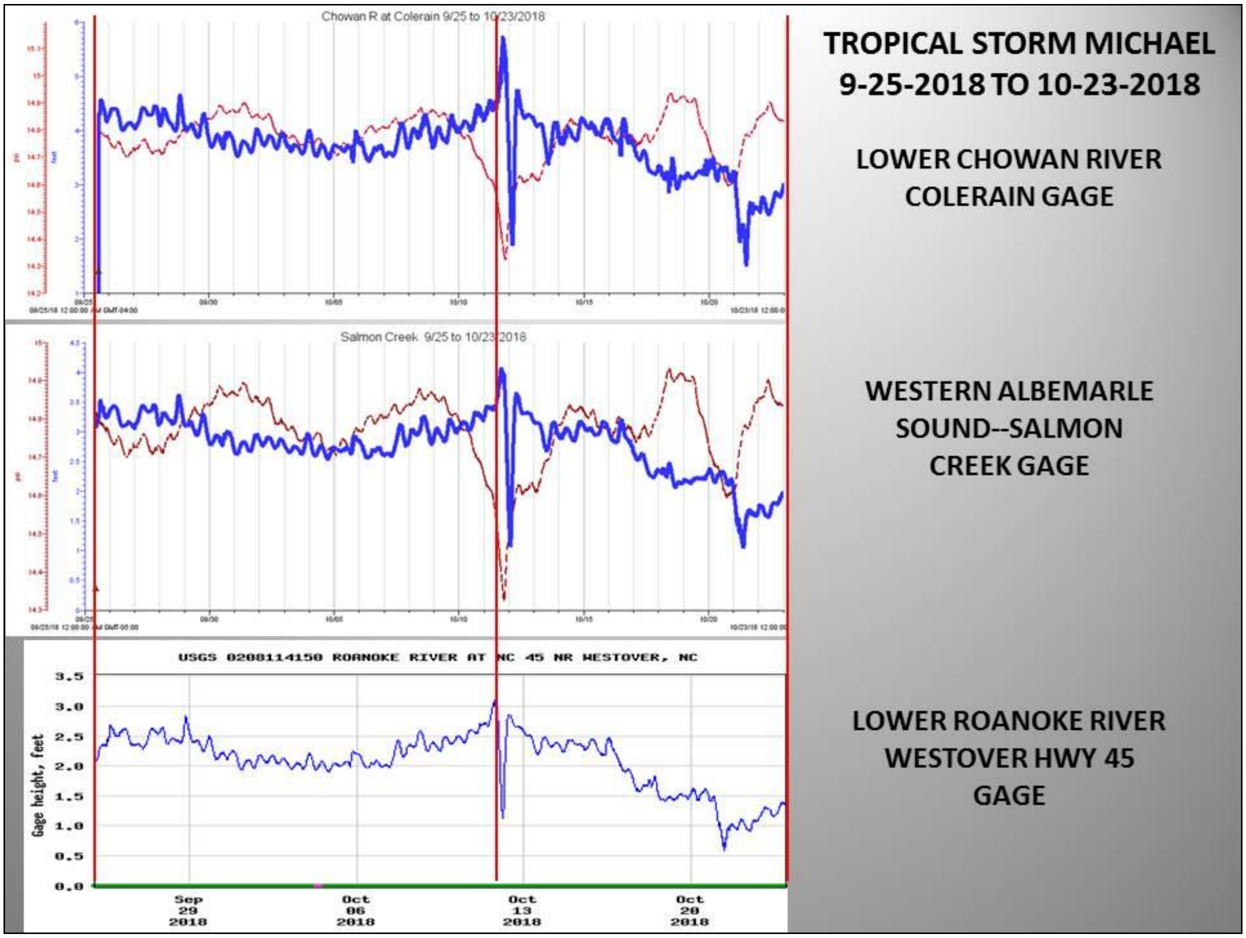


FIGURE 4-3. Water levels are shown for the period 9-25 to 10-23-2018 in blue and atmospheric pressure in red. Top panel is the Chowan River at Colerain, middle panel is west Albemarle Sound (in mouth of Salmon Creek), and bottom panel is the lowermost Roanoke River (Westover Hwy 45 Bridge). Notice the different types of wind setups, small frontal systems, tropical storm Michael (middle red line) and astronomical tides that are superimposed on the background. Also, notice how all three systems are intimately connected. The water-level plots in this report are not corrected for absolute elevation.

Much of the water level record during the first two periods showed relatively stable levels (Figures 4-2 and 4-3). Levels at all three sites varied less than 1 foot from 8-8 to 9-8-2018 (Figure 4-2). Then levels rose and fell after a few days. Water levels remained stable until about 10/10 when the aforementioned spike occurred (Figure 4-3). After this spike the water levels began to fall. There is no clear increase or decrease in water level consistently linked to changes in atmospheric pressure. This is not surprising since wind direction and speed are important to directing water levels in the wide and open Chowan. Wind is affected by atmospheric pressure but not in a way that predicts direction.

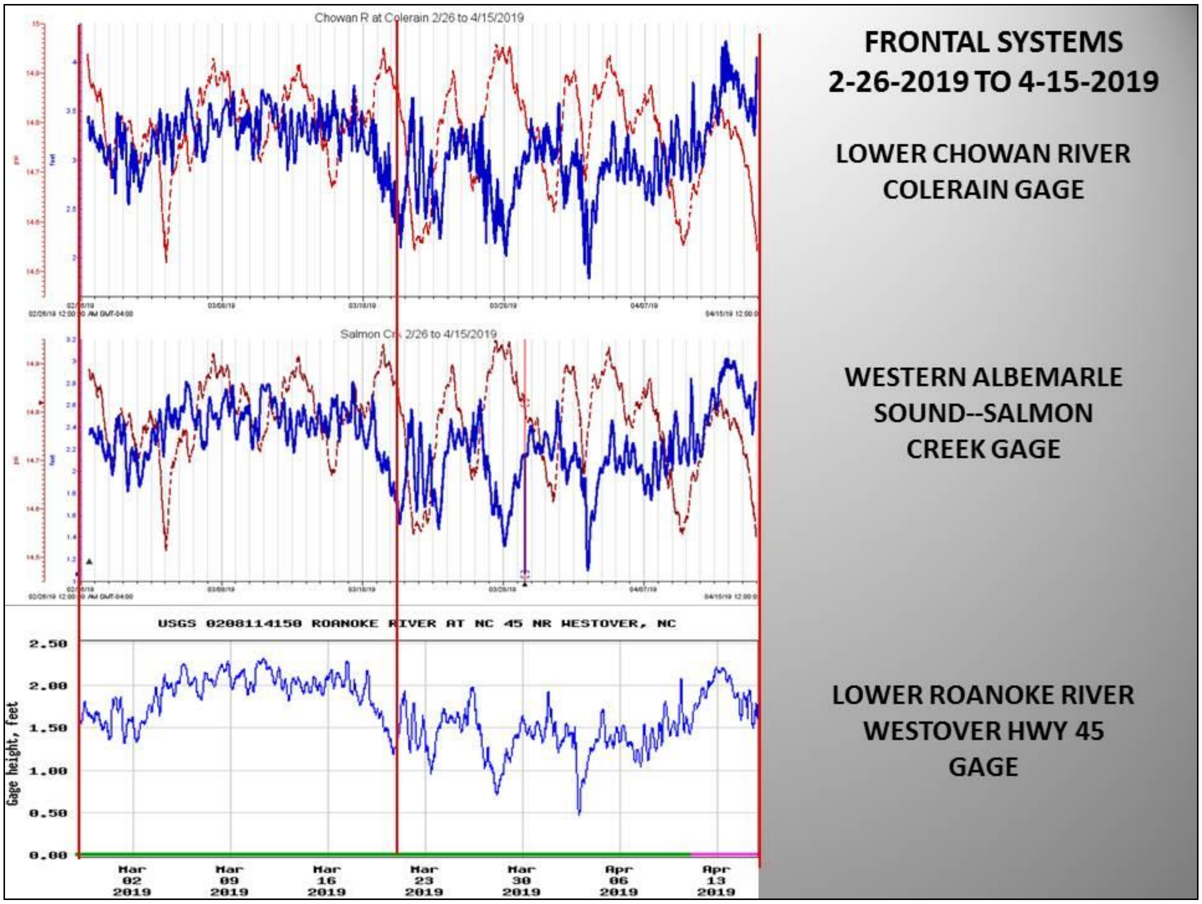


FIGURE 4-4. Water levels are shown for the period 2-26 to 4-15-2019 in blue and atmospheric pressure in red. Top panel is the Chowan River at Colerain, middle panel is west Albemarle Sound (in mouth of Salmon Creek), and bottom panel is the lowermost Roanoke River (Westover Hwy 45 Bridge). Notice the different types of wind setups, frontal systems, and astronomical tides that are superimposed on the background. Also, notice how all three systems are intimately connected. The water-level plots in this report are not corrected for absolute elevation.

In summary, the water-level patterns in the lower Chowan River and the western end of Albemarle Sound (Salmon Creek site) are very similar to one another, as well as the lower Roanoke (Hwy 45 site). Patterns appear to be highly dependent on local wind dynamics of the Sound as perceived by local knowledge. However, development of mathematical cause and effect relationships are beyond the scope of the present project. Such relationships would be needed for predicting conditions of flooding and bluff erosion. Also, the observation period for this project did not include any extreme conditions that would cause severe floods and significant erosion. Thus, any equations based on existing data would have to be extrapolated. Appropriate wind and weather information is available for the lower Chowan and western Albemarle (e.g., Edenton KEDE Northeastern Regional Airport). Together with a larger dataset of water levels these equations could be developed. Therefore, a recommendation is that one permanent gaging station be established on the Chowan River and one in western Albemarle Sound to develop predictive capability and monitoring for future storm events.

Drowned River Estuaries

Estuaries form in response to rising sea level causing the sea to systematically flood up the paleo-valley developed by the historic drainage system. Drowned-river estuaries form in the valley bottoms of the drainage system as sea level rises. The higher ridge crests or inter-stream divides between stream valleys form the upland regions of the Carteret, Pamlico, Albemarle, Bertie, and Dismal Swamp Peninsulas. Due to the low sloping land surface within the northeastern North Carolina Coastal Plain (Figure 3-3), coastal flooding occurs far upstream producing the deeply embayed estuarine system.

Estuaries are great mixing basins of fresh and oceanic waters that occur at sea level. The downstream portion of the Roanoke River is a drowned, trunk river estuary known as Albemarle Sound. Albemarle Sound receives water input from millions of acres in upland NC and VA. The eastern boundary of Albemarle Sound is the barrier island chain of the Outer Banks. As the fresh water in the riverine portions of this drainage approach sea level, the flow decreases and begins to mix and interact with estuarine waters of Albemarle Sound. The estuarine waters flow slowly eastward towards the Outer Banks, where they increasingly mix with ocean water, are discharged through Croatan Sound into Pamlico Sound and finally into the Atlantic Ocean through inlet-outlet systems in the barrier islands. The lower portions of all tributary streams flowing into Albemarle Sound, including the Chowan River, become estuaries where the stream's channel bottom drops below sea level and begins interacting with the oceans water and dynamics.

Albemarle Sound is dominantly a fresh to slightly brackish water estuary because of the large size of the Roanoke River drainage basin, the resulting high volumes of fresh water discharge, and the lack of inlets-outlets in the northern segment of NC's barrier islands. The Roanoke River and Albemarle Sound are brown-water drainage systems due to the large sediment load due to upstream bank erosion in the short-term and upland erosion off the Appalachian and Piedmont Provinces in the long term. However, the tributary estuaries to the Albemarle primarily consist of fresh water that is darkly stained by dissolved organic matter derived from the floodplain swamp forests and pocosins that they drain.

Albemarle Sound System

Thus, the Albemarle Sound estuary is the Roanoke River drainage basin that has been drowned in its lower reaches by the ongoing post-glacial rise in sea level. Sediment from the sediment-laden Roanoke River settles out in Albemarle Sound and accumulates through time. Much of the Roanoke River sediment load is deposited at the head of Albemarle Sound where the bottom of the Roanoke River channel rises from 20 to 40 feet below modern sea level to the shallow waters within the Bachelor Bay "bay-head delta" that is only about 5 to 10 feet deep (Figures 4-5 and 4-6). Albemarle Sound widens eastward to about 12 miles and deepens with a gentle slope to about 20 foot water depth before it rises up onto the Colington Shoals sand flats (less than 5 feet) behind the Outer Banks barrier islands. A thick sequence of shallow-water, coastal marine sediment deposits have filled the Roanoke River valley during the past 9,000 years of rising sea level. This sediment sequence contains a detailed record of the evolutionary history of post-glacial climate and sea level change.

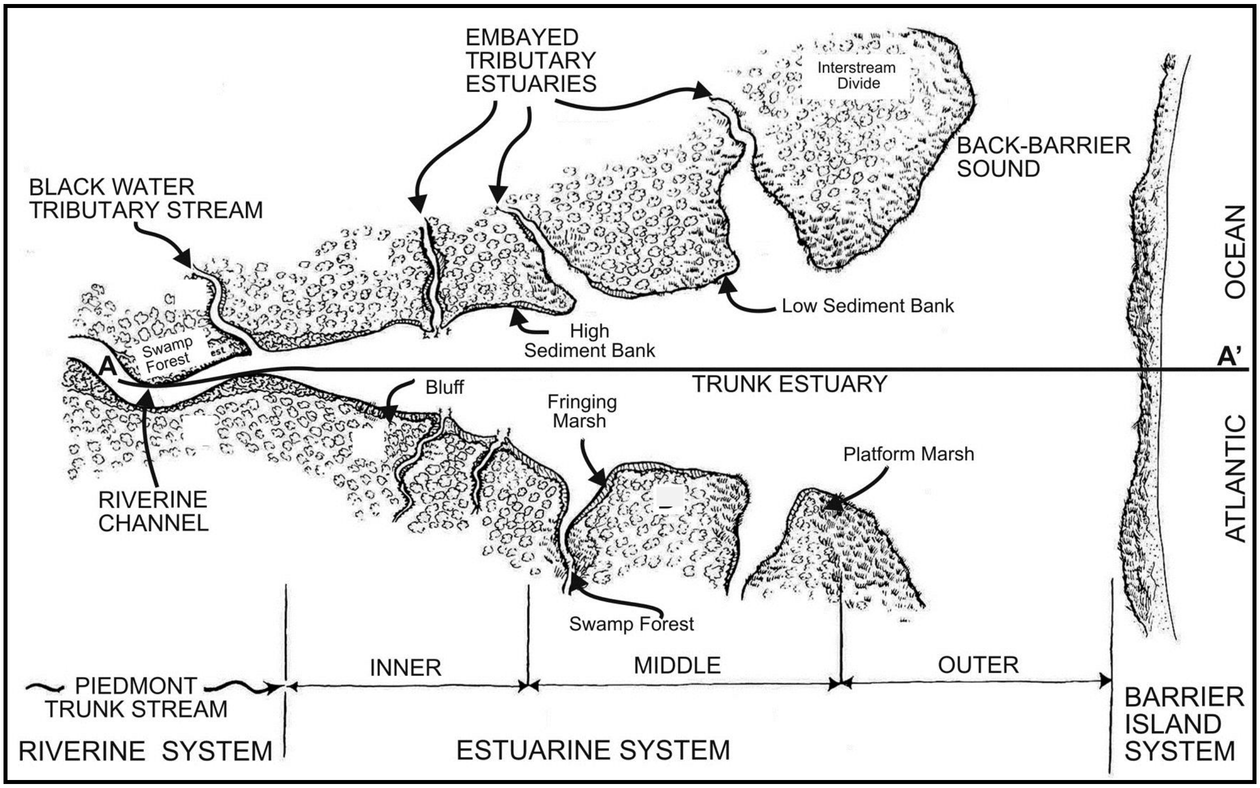


FIGURE 4-5. A schematic map shows the Roanoke River, Albemarle Sound, and Outer Banks coastal systems and the different coastal environments that result from drowning a river drainage system by rising sea level. Cross section A-A' is the location of the bathymetric profile in Figure 4-6. Figure is not drawn to scale.

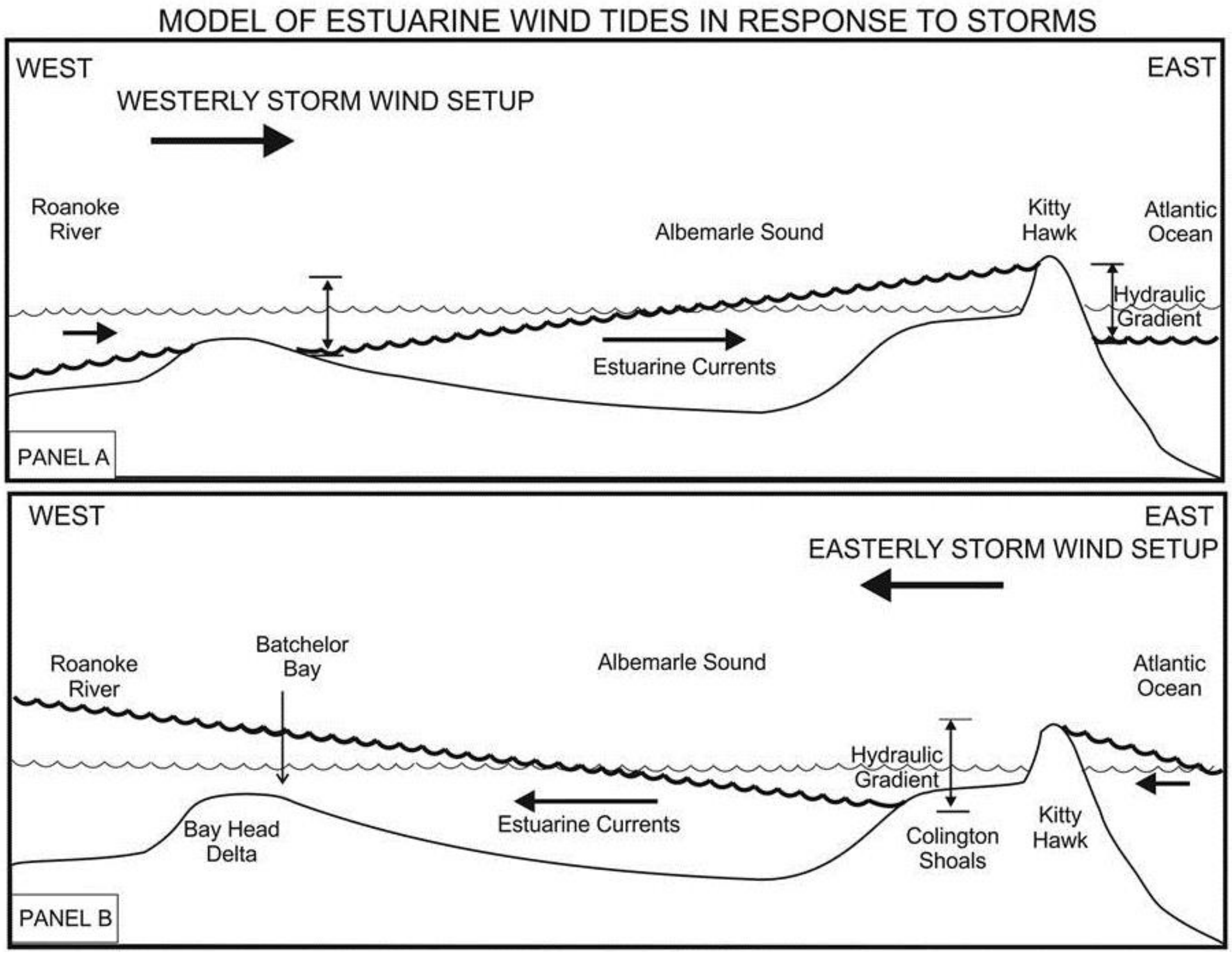


FIGURE 4-6. Schematic model shows two west to east cross-sections of A-A' in Figure 4-5. The profile in panel A and B show two important concepts. First is the generalized bathymetric profile from the mouth of the Roanoke River, across the bay head delta in Bachelor Bay, to the Outer Banks barrier island. Second is the exaggerated effect of the "teeter-totter" resulting from the westerly storm winds (Panel A") and easterly storm winds (Panel B) of a major hurricane moving across the waters of Albemarle Sound. The profiles are not drawn to scale.

Wind readily pushes water around on any large water body, such as Albemarle Sound, producing small, irregular wind tides. But if the wind is strong enough it can produce a storm surge that piles a substantial amount of water up against the shoreline. This effect is illustrated in Figure 4-6. With no wind, the water surface on Albemarle Sound tends to be a flat, smooth surface without waves or slope. As the wind begins to blow, waves form that increase in size through time. As the wind continues to build, water currents begin to move in the direction of the wind, lowering the water surface in the upwind direction and raising the water surface in the downwind direction causing the adjacent lowlands to flood. These pulses of wind setup generally result in 1 to 2 feet of persistently low and high water levels that can last for days, weeks and rarely even months. This regional sloped water ramp will be maintained as long as there is a consistent wind pattern that holds the ramped wind setup in place.

Larger water-level fluctuations (2 to 4 feet) occur as frontal systems pass rapidly over Albemarle Sound with strong, short-term winds (hours to a day or two) that shift dramatically as the storm system moves through. A common frontal pattern starts with warm, moist S or SW winds, then shifting to strong NE winds that blow water out of eastern portions of the sound and raise water levels in western portions. As the front passes through, the wind shifts to strong NW and blows water out of the west and floods the backside of the Outer Banks. The actual orientation, intensity, and duration of the storm winds will determine the magnitude and duration of the resulting storm surges.

The largest storm surges (from 4 to 10 feet or more) are generally related to either tropical storm systems (primarily during summer and fall) or non-tropical storm systems (nor-easters primarily during winter and spring). These water level rise events erode the shoreline and cause severe flooding and property damage to piers, roads, and land structures. When the winds diminish, the water flows back down the ramp to its original flat surface. Figure 4-6 is a model that shows how the wind tides and storm surges work on the east-west oriented Albemarle Sound. The wind tides on the north-south Chowan River estuary generally responds synchronously with Albemarle Sound (Figures 4-2, 4-3, and 4-4) but with slight variations in magnitude depending on the N-S wind component.

Winds causing high tides at the W end of Albemarle Sound can cause backflow up both the Roanoke and Cashie Rivers. Whereas, winds blowing high water against the sound-side of the Outer Banks can lower water levels in both the lower Roanoke and Cashie Rivers increasing the hydraulic flow and river discharge. Superimposed on top of the wind tides are the very small astronomical tides that reach into the mouth of the lower Roanoke River to Williamston (only if there is low dam discharge) and up the Cashie River to Windsor as demonstrated in Figures 2-9, 2-10, and 3-11, respectively. However, the wind or astronomical tides do not reach the School Road gage upstream of Windsor (Figure 3-11) unless there is a major storm surge. When the Roanoke Rapids dam is discharging large volumes of water as shown in Figures 2-9 and 2-10, the downstream flow is continuous and is the only signature all the way downstream to the road-dam at Williamston (and occasionally to Jamesville), where the water level is too high to carry any signature from Albemarle Sound wind tides or astronomical tides.

A quick moving tropical storm or nor'easter will blow the water in and out or vice versa quickly with minimal effect on the Roanoke and other tributary systems such as the Cashie River. However, slow moving storms have time and energy to cause substantial outflow or backflow of water in the adjacent river systems. Most storms that move directly across the NC coastal system will have both a high and low water component to the storm surge. However, if the storm is further east or further west it may only result in half of the cycle at any one location with either a high or low water event.

Storm events with substantial winds, waves, and rainfall, produce storm surges of four feet or more up against the bluffs on the west side of the Chowan River. The area will experience severe bluff erosion and damage to coastal communities. The impact of these storm surges to the Cashie River and other upstream tributaries is more subtle. The vast area of vegetated floodplain swamp forest slows the upstream rate of storm surge flow and rapidly buffers out the impact of wind and waves. If the event is of a longer duration (like a multiday nor'easter), water levels in the lower Cashie could rise slowly and then impede the outflow of Cashie River flood waters. Most tropical storms are often more rapidly moving events which would result in decreased storm surge impact upstream. This might even decrease the impact of upstream flooding as the backside of the storm blows the Albemarle Sound surge back up against the Outer Banks increasing the hydraulic head in the upstream portion of the tributary streams. **In summary, the Albemarle and Chowan estuaries have minimal astronomical tidal fluctuations, but they have tremendous surface areas or fetch (large distances that wind can blow over open water). These northeastern North Carolina estuaries are dominated by storm-tide and wind wave processes that can lead to serious coastal flooding and erosion problems.**

Chowan River Drainage System

The Chowan River forms in VA just N of the NC border with the confluence of the Nottoway and Blackwater Rivers. The largest part (76%) of the Chowan Basin is in VA with about 1,378 square miles of woodlands and agricultural fields and over 800 miles of streams within NC. The Chowan River main stem in NC flows S for nine miles and then SE for sixteen miles as a riverine system with a primary channel and broad floodplain swamp forests that fill the valley bottom. Just N of Holiday Island (red horizontal line in Figure 4-7) the primary river channel drops below sea level where the Chowan transitions from riverine to estuarine conditions. From the Holiday Island area the drowned river valley of the Chowan Estuary trends S for about twenty three miles where it joins Albemarle Sound, the drowned valley of the lower Roanoke River. Major tributaries flowing into the NC portion of the Chowan basin includes the Meherrin and Wiccocon Rivers, and the Potecasi, Ahoskie, and Salmon Creeks. Due to the generally N-S orientation and distance inland from the Atlantic Ocean, the Chowan River is generally a totally fresh, black-water drainage that is influenced by both strong storm tides and minor astronomical tides from the E-W oriented Albemarle Sound.

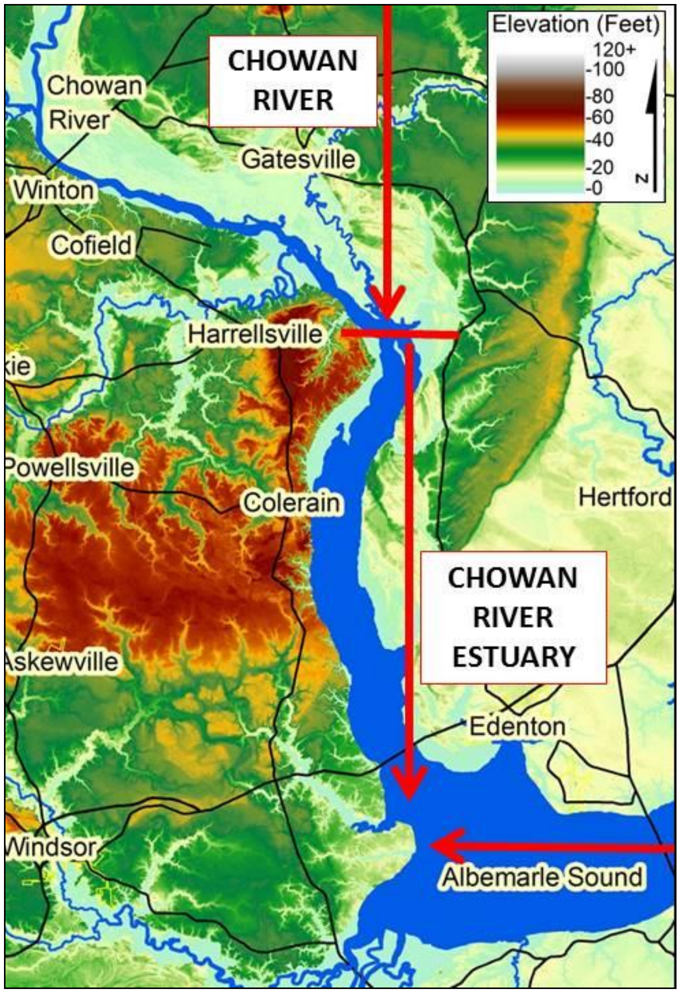


FIGURE 4-7. This color topography map shows the transition from the Chowan River embayed zone N of the red horizontal line to the drowned-river estuarine zone S of the line. The line occurs just N of Holiday Island, where the riverine and estuarine processes are just beginning to interact and the river is still dominated by primary floodplain swamp forest. South of Holiday Island is the Chowan River estuary where the primary floodplain swamp forest and associated peat deposits have been drowned and largely eroded away as a result of rising sea level and storm dynamics. LiDAR map was prepared by D. Ames.

During lower stages of sea level, the Chowan River was a tributary to the Roanoke River as the Roanoke flowed E across the outer Coastal Plain. However, rising sea level has flooded the eastern portion of the Roanoke River valley and the southernmost portion of the Chowan River valley to form the Albemarle Sound and Chowan River estuaries, respectively (Figure 4-7). The river valleys within the two trunk drainage systems are similar with similar histories. South of Holiday Island, the Chowan River is dominated by estuarine characteristics with a major loss of riverine floodplain as the swamp forest flats are drowned by rising sea level and eroded by the increasing energy of an expanding water body. Two large remnants of the riverine floodplain swamp forest still exist within the Chowan River Estuary: one on the W side and N of Colerain (Cow Island Swamp) and the other on the E side and on both sides of the highway 17 bridge (Rocky Hock Swamp Figure 4-8).

FIGURE 4-8. Photograph of the Rocky Hock remnant floodplain swamp forest that occurs on the eastern side of the Chowan River estuary and on both sides of the Highway 17 Bridge. Notice the effects of ongoing process of drowning due rising sea level: 1) bald cypress trees survive with permanent flooding, 2) whereas the other swamp forest trees can't and stand as dead soldiers, broken logs, and stumps in permanently flooded conditions. Photograph is by S. Riggs.

The outer edge of the remnant floodplain swamp forest is drowning by the ongoing rise of sea level. All tree species in the swamp forest that are adapted only to irregular flooding will drown. Bald cypress can tolerate permanent flooding which leads to an outer fringe of living cypress trees (Figure 4-8). Storms blow over the dead trees while the waves erode peat from around the stumps causing the shoreline to recede. These remnant swamp forests will keep up vertically with sea-level rise within their interiors, but are receding laterally. In the long-term these remnant swamp forests are doomed to be completely eroded as the estuary expands in response to rising sea level. As swamp forest is eroded away, the shoreline intersects the adjacent upland resulting in an eroding sediment-bank shoreline and leaving vast areas of shallow water filled with dead stumps and logs.

The NC Natural Heritage Program has designated over 100 miles of the Chowan River as "significant aquatic habitat" due to its rich population of important game fish species. Also, the Cow Island Swamp Forest and its slopes and ravines are classified as a "Significant Natural Area". Much of the riverine swamp forest N of Holiday Island (over 32,570 acres) is public property and constitutes the Chowan Swamp State Natural Area and the Chowan River Game Lands managed by the NC Div. of Parks and Recreation and NC Wildlife Resources Commission, respectively.

Bertie County Eastern Shorelines

The eastern estuarine shoreline of Bertie County consists of four major segments that have the following characteristics and resulting patterns of shoreline erosion (Figure 4-9). The shoreline along the eastern side of the Chowan River estuary is dominated by a major sediment bank shoreline where the Wicomoco and Talbot terraces are truncated by the Chowan River valley. The bluffs rise to 80 feet above sea level at the terminus of the Wicomoco Terrace and up to 45 feet above sea level where the Talbot terrace is intersected (Figure 1-4). Within the Chowan River estuary the remnant floodplain swamp forests continue to vertically accrete organic matter through time in response to their effort to keep up with ongoing rise of sea level. Some areas with old tributary channels will have swamp forest peat fill that can be up to 30 feet thick. However, with the ongoing rise of sea level, the estuary is migrating laterally upstream causing the floodplain swamp forest to systematically recede on the downstream side and migrate up valley on the upstream side.

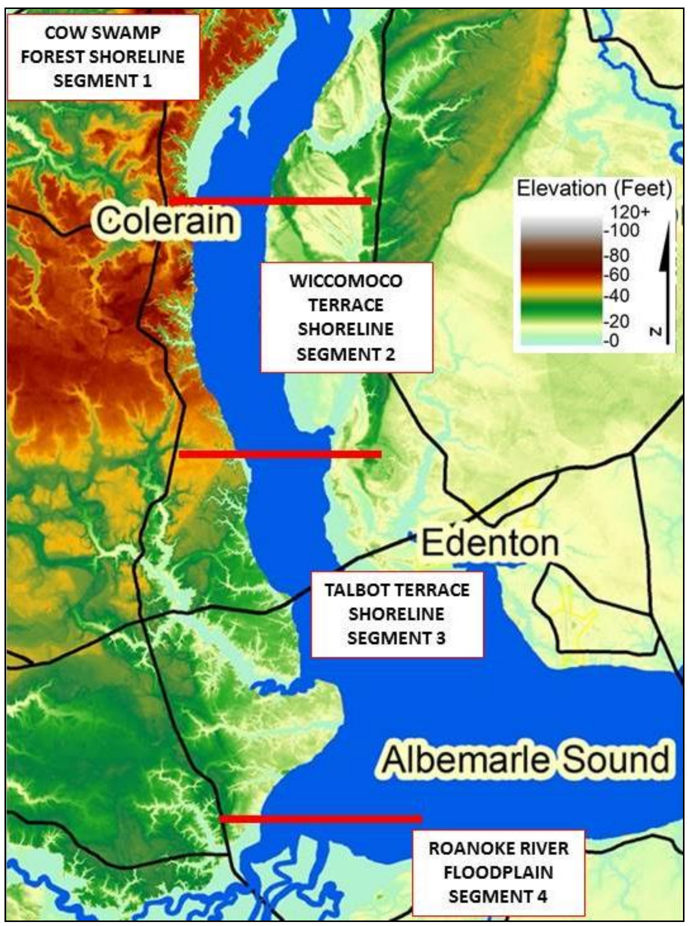


FIGURE 4-9. This color topography map shows the Bertie County eastern shoreline of the Chowan River estuar, from Cow Island Swamp in the N to the S side of the Roanoke River floodplain. There are four dramatically different types of shorelines that have different flooding and erosion problems, as well as associated ecosystems and potential uses. LiDAR map was prepared by D. Ames.

All the bluffs are eroding, except W of Cow Island segment 1, since rising sea level has drowned all other natural floodplain swamp forests that used to occur on the shallow flats adjacent to the Chowan River channel. The frequent stumps throughout the shallow waters are the only remnants of these former floodplain swamp forests. The remaining bluffs have been actively receding since. The abundant ravines are still active with small delta plains deposited off the mouth of each ravine; each delta usually has an outer rim of cypress trees that act as a natural cypress headland that minimizes the erosion and protects the delta and associated houses that occur on the delta flats.

Chowan River Shoreline: Segment 1

Segment 1 extends from the northern border with Hertford County to Colerain (Figure 4-10). The shoreline consists of a ½ to 1 mile wide swamp forest occurring E of the high bluff of the Wicomoco Terrace and its associated ravine drainages (Figure 4-11). The swamp forest is basically at sea level and composed of wetland vegetation, much of which can only tolerate irregular and short-term flooding in response to tidal fluctuations and storm surge by water that is totally fresh. The inner portion of the swamp forest has slightly higher elevations than the perimeter with the annual accretion of organic matter that can keep up with a slow rise in sea level.

Since sea-level is slowly rising, the swamp forest is drowning from the outside inward. As permanent flooding occurs, all tree and shrub species die along the eastern edge except for the bald cypress which can tolerate permanent flooding. This results in an outer several hundred-foot cypress fringe (Figure 4-12) in which the rest of the swamp forest vegetation has died and is ultimately blown over by storm winds. The Wicomoco Bluff and associated ravines occur along the W side of the swamp forest occur along the E side of the Wicomoco Terrace with all of its agricultural fields. The ravines are filled with upland hardwood forests. The swamp forest is riddled by old creek valleys that were associated with each of the ravines during prior times when sea level was lower than present. The Cow Island Swamp Forest should be protected as a "significant natural area". It acts as a natural storm buffer for the Wicomoco Bluff and associated uplands to the west, and along with the cypress fringe and associated creeks, could be utilized as part of a sustainable eco-tourism business for recreation and education.

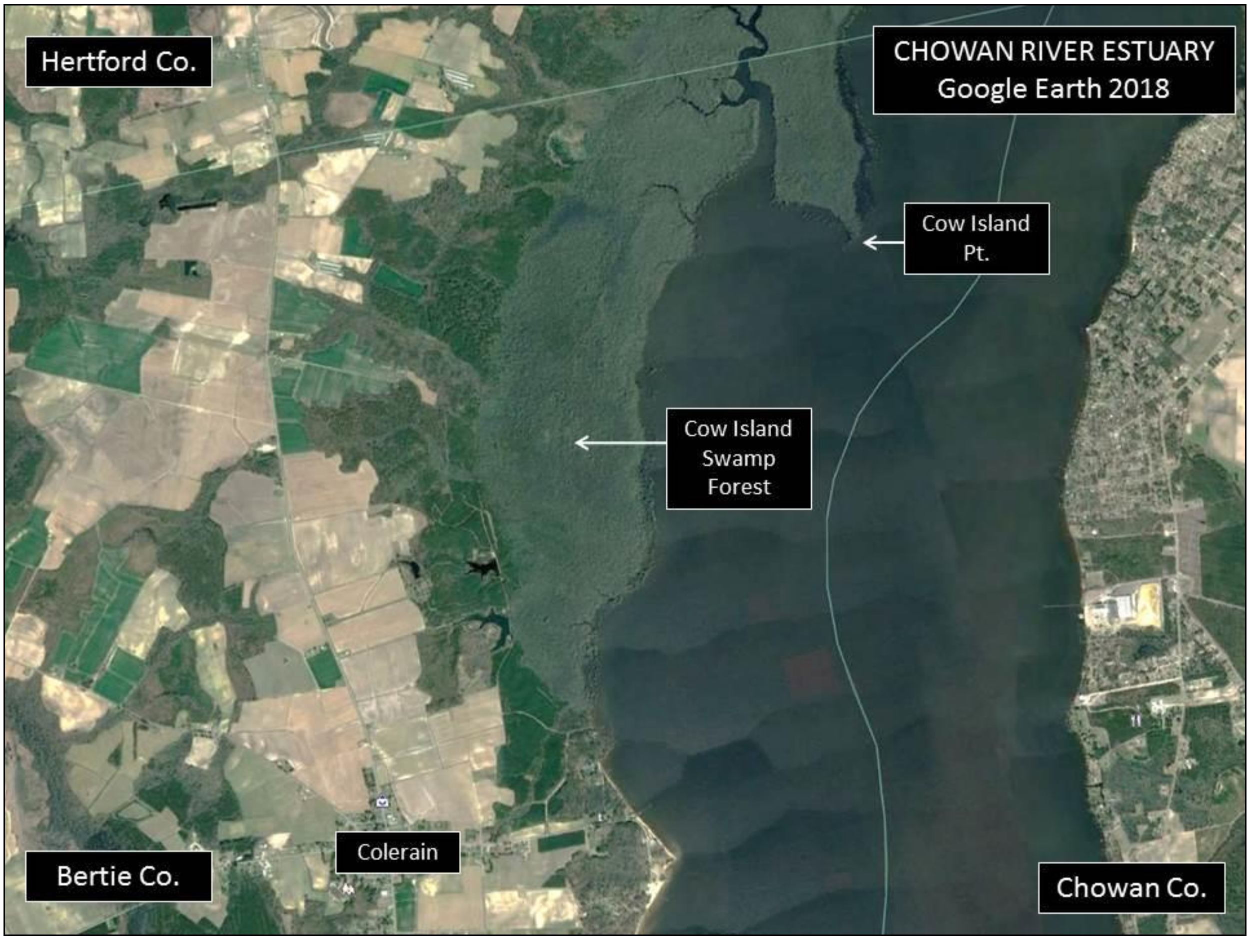


FIGURE 4-11. This Google Earth aerial photograph of shoreline segment 1 extends from the Hertford County line in the N to Cape Colerain in the S. Notice the abrupt change along the western side of the Cow Island Swamp from swamp-forest vegetation (gray green) to the Wicomoco Bluff with its ravines filled with old hardwood forests (bright green) and the upland agricultural fields. Also, notice the cypress fringe that occurs along the E side of the Cow Island Swamp (Figure 4-12).

FIGURE 4-12. Photograph of the cypress fringe along the east side of the Cow Island Swamp Forest. This cypress swamp acts as a natural storm buffer for the Wicomoco Bluff and associated uplands to the W and the cypress fringe and associated creeks form natural tracks for kayakers and canoers. Photograph is by S. Riggs.

Chowan River Shoreline: Segment 2

From Colerain south to Heritage Wharf, the shoreline consists of 45 to 80 foot high Wicomoco Bluffs that are eroded into the E side of the Wicomoco Terrace. The bluffs are highest in the N and slope gently southward (Figure 4-9).

Erosion of the bluffs responds to rain, wind, and storm surge in different ways. First is a heavy or repeated series of rainfalls on the terrace surface that results in the water seeping downward into and saturating the porous quartz sand bed. With time the water flows down to the impermeable clay layer and then flows laterally and weeps out of the bluff, depositing a bed of iron oxide (ironstone) at the clay-sand interface. But, if a strong wind blows along with the heavy rainfall, the wind-blown trees along the upper edge of the saturated bluff will cause massive landslides of sand and trees down to the beach (Figure 4-13). Subsequent wind tides and waves will erode the slumped sediments, redistributing the slumped sand and vegetation throughout the strand-plain beach. If the slumped sand does not get eroded, it will begin to revegetate, and along with the tree debris, will provide short-term, natural protection from further erosion. The second part of the bluff erosion results from severe storm surges (4 to 10 feet) that cause the water level and associated waves to overstep the beach and directly erode the lower clay bed. In many places along the bluff, the clay bed tends to be a very sandy mud which readily fails under the pounding attack of large waves.

FIGURE 4-13. The Wicomoco Bluff shows a partially vegetated bank on the left grading to a recently eroded segment on the right with a new slump block in the middle. Notice the new young pines starting to revegetate an older slump block on the lower right. Not only do these slump blocks supply new and sole source of sand to the narrow strand-plain beach, but if allowed to revegetate, will provide short-term buffer protection for the eroding cliff. Photograph is by S. Riggs.

The bluff is generally composed of the following marine strata (Figure 4-14). A basal layer of tight and slick, highly burrowed, blue to gray clay. The clay bed in certain areas grades upward into an extremely fossiliferous muddy sand containing abundant marine finger corals, scallops, oysters, and clams. Above the clay is a very thick layer of clean quartz sand that is often cross-bedded and full of crab burrows. The contact between the overlying sand and underlying clay contains many small springs that continuously weep water and precipitate orange iron oxide that can form a bed up to two to three feet thick. As the bluff erodes it supplies the sand that forms a thin strand-plain beach along with fragment to boulder size pieces of ironstone, mudstone, and fossils.

FIGURE 4-14. Upper left panel is a view looking south from the Wicomoco Terrace on top of the eroding bluff with the Chowan River estuary. Upper right panel is a water level view looking north at the Wicomoco Bluff. Notice the large delta flat and cypress that form a resistant headland sticking out into the Chowan River estuary. Lower left panel is a view looking north along a different section of Wicomoco Bluff in which the upper sand bed is highly vegetated with water seeping out of the bank on top of the very thick lower clay bed. Notice the very tough and pure clay bed at the base that grades upward into a very fossiliferous sandy mud bed in the upper 2/3. Also, notice the very narrow strand-plain beach and the natural vegetation jetties trapping sand in the distance. Lower right panel is a close-up of the fossil bed in the lower left panel. The elongate and rounded fossils are all finger corals, the arcuate fossils are clams, and minor amounts of scallops and oysters; all organisms that live in warm, shallow, and calm ocean waters deposited during a former time when sea level was at least 20-25 feet higher than it is today. Photographs are by S. Riggs.

Chowan River Shoreline: Segment 3

The shoreline from Heritage Wharf south to Salmon Creek, Scotch Hall, and Black Walnut Point consists of the smaller 20 to 40 foot high cliffs of the Talbot Terrace. The cliffs are also highest in the north and slope gently southward. South of the Hwy 17 Chowan River Bridge, increased wave energy and storm surge resulting from the direct influence of the 75 mile long east-west fetch of Albemarle Sound, increases the erosional impact on the southeastern shorelines of Bertie County.

FIGURE 4-15. Photograph is a view looking south at the erosional bluff associated with the Talbot Terrace with elevations between 30 to 40 feet in shoreline segment 3. The eroding bluff has a recent landslide that has not been rained on yet. Notice the different kind of sediments as compared to the Wicomoco bluffs in Figure 4-14 and 4-13. Also, notice the importance of the collapsed vegetation in protecting a small headland and in trapping the small amount of beach sand in the foreground. The water body is the western end of Albemarle Sound. Photograph is by S. Riggs.

Roanoke River Floodplain Shoreline Segment 4

Shoreline segment 4 is the eastern end of the Roanoke River valley which is at sea level and filled with a vast floodplain swamp forest (Figure A9). This shoreline is also eroding, but by the process of drowning along the eastern edge in response to rising sea level (Figure 4-16). The long 75 mile east-west fetch of Albemarle Sound means that severe storm surges pound the leading edge of the swamp forest and its soft peat deposits. Once the storm surge gets beyond the leading edge, the energy is largely dissipated by the vast vegetative buffering within the floodplain.

FIGURE 4-16. An oblique aerial photograph of the eastern edge of the Roanoke River floodplain the faces the long fetch of the east-west oriented Albemarle Sound. Notice the drowning process that kills most of the trees and leaving a narrow cypress rim growing in Albemarle Sound. Photograph is by S. Riggs.

<u>Incised Ravines, Deltas, and Cypress Headlands</u>

The drainage system off the eastern side of the Talbot Terrace (east of Hwy. 45) is dominated by a dozen or more short (less than 1 to 2 miles) steep ravines that are deeply incised into the bluffs (Figure 4-17). Where each ravine flows into the Chowan River estuary, there is a shallow delta flat that is generally surrounded by a cypress fringe. This is where all of the older shoreline communities occur. The delta flat is semi-protected from shoreline erosion by the cypress fringe. Consequently, each ravine and its delta flat forms a cypress headland. The bluffs between the cypress headlands are much more vulnerable to erosion and results in a series of cuspate-shaped embayments between cypress headlands.

Today, most of these ravines no longer have permanent water flows, but are driven by storm runoff or intermittently fed by springs. The ravines generally contain a unique forest habitat and ecosystem that the NC Natural Heritage Program classifies as "regional significant natural communities" of mixed hardwoods (dominated by oak, hickory, beech, tulip, and holly trees). Most large ravines have multiple tributaries that have deposited small sediment deltas where they enter the main stem. These flatter areas are perfect locations for ephemeral ponds or even more permanent ponds behind beaver dams or man-made mill dams used for grinding grain and/or providing irrigation waters. The flat delta lobes that extend into the downstream water bodies are large enough to support small communities and/or former herring fishery businesses. Because these delta lobes are low lying, the communities or businesses are heavily bulk-headed and tend to get slammed by storm surge flooding during major tropical storm events.

FIGURE 4-17. Google Earth 2018 images show two different short, steep, incised ravine systems with their significant hardwood ecosystems draining into the Chowan River Estuary and surrounded by agricultural fields. The left panel is an entire ravine drainage system incised into the high Wiccomoco Terrace in the vicinity of Ashland. The right panel is a partial ravine drainage system incised into the lower Talbot Terrace in Bertie County's "Tall Glass of Water". Notice the ephemeral ponds and the small delta and cypress fringe in the left panel and the dammed ponds on a tributary to the trunk ravine and its smaller delta and cypress fringe in the right panel.

Since the ravines are incised into either the Wiccomoco Terrace (45-80 foot elevations) or the Talbot Terrace (20-45 foot elevations), the adjacent areas between ravines form spectacular coastal bluffs along the Chowan River, Albemarle Sound, and Roanoke River. These bluffs are continuously sculpted by the dynamics of the adjacent water bodies and are generally areas of severe erosion. Consequently, as more and more people move to the edge of water bodies with spectacular view-scapes, they also, tend to clear the natural forests for manicured lawn-scapes and bulldoze down the steep and eroding bluffs for water access and erosion control structures (Figure 4-18). An end result is that the significant fauna and flora expose a critical component of North Carolina's history of past climate change and sea-level fluctuations within the natural bluffs and associated ravine habitats, which are both rapidly becoming endangered ecosystems.


FIGURE 4-18. Left panel shows a Google Earth 2018 image of an incised ravine with its delta and cypress headland at the top and a housing development on the top of the adjacent Talbot Terrace overlooking Albemarle Sound. Since the Talbot bluff was severely eroding, the development bulldozed the bluff and put in several levels of wood and rock bulkheads, along with an array of jetties as shown in the right panel. Now that the sand supply from the eroding bluff is no longer available, the beaches are disappearing. Major storm surges will continue to destroy the bulkheads and take away the remaining sand (see Hurricane Isabel section). Right panel photograph is by S. Riggs.

STORM AND HISTORIC FLOODS

Storms and Coastal System Dynamics

Storms are the drivers of coastal system change—they deliver the upland waters in the form of rainfall that weathers and erodes the uplands, builds the drainage systems, transports the resulting sediments downstream where they are deposited within the coastal marine system to build the continental margin. Storms are the great modifiers of the coastal system, eroding land here and building beaches there as sea level responds to major climatic changes through time. Thus, shorelines are high-energy, dynamic portions of the coastal system that are generally event-driven by individual storms or sets of storms and can result in massive changes within time frames of hours to years. The cumulative impact of energy from multiple storms and numerous winter storm seasons can radically change the shoreline—eroding some, building others, but always moving sediment about like chess pieces on a game board.

"Since the days of the first European explorers, North Carolina has had a long and brutal hurricane history. Countless big storms have over-washed our coast and battered our state, and many North Carolinians have lost their lives in the desperate struggle against water and wind" (Barnes, 2013). During these 435 years since, all portions of North Carolina have been victimized by multiple tropical storms at one time or another. And there are more devastating hurricanes to come with severe physical, social, and economic impacts, just as they have been in the past. But today we can learn from the historical record and do a better job of living with these global events.

The NOAA map is a summary of 250 "Billion-Dollar Weather and Climate Disasters" within the United States that have occurred during the period between 1980-July 9, 2019 (Figure 5-1). North Carolina was ranked by NOAA in the second tier of states with a total of 79 billion dollar disasters during the 39 year time frame that included 19 tropical cyclones, 43 severe and winter storms (nor'easter frontal systems), and 12 droughts. Most disaster events are regional in nature and thus involved multiple states; NC has been on the receiving end of about 32% of the total 250 events at the average rate of about two events per year. The total estimated cost of the 250 events to the US has been over 1.7 trillion dollars. Figure 5-2 is a plot of the 250 events and clearly demonstrates the increasing frequency of disaster events during the 21st century (NOAA, 2019).

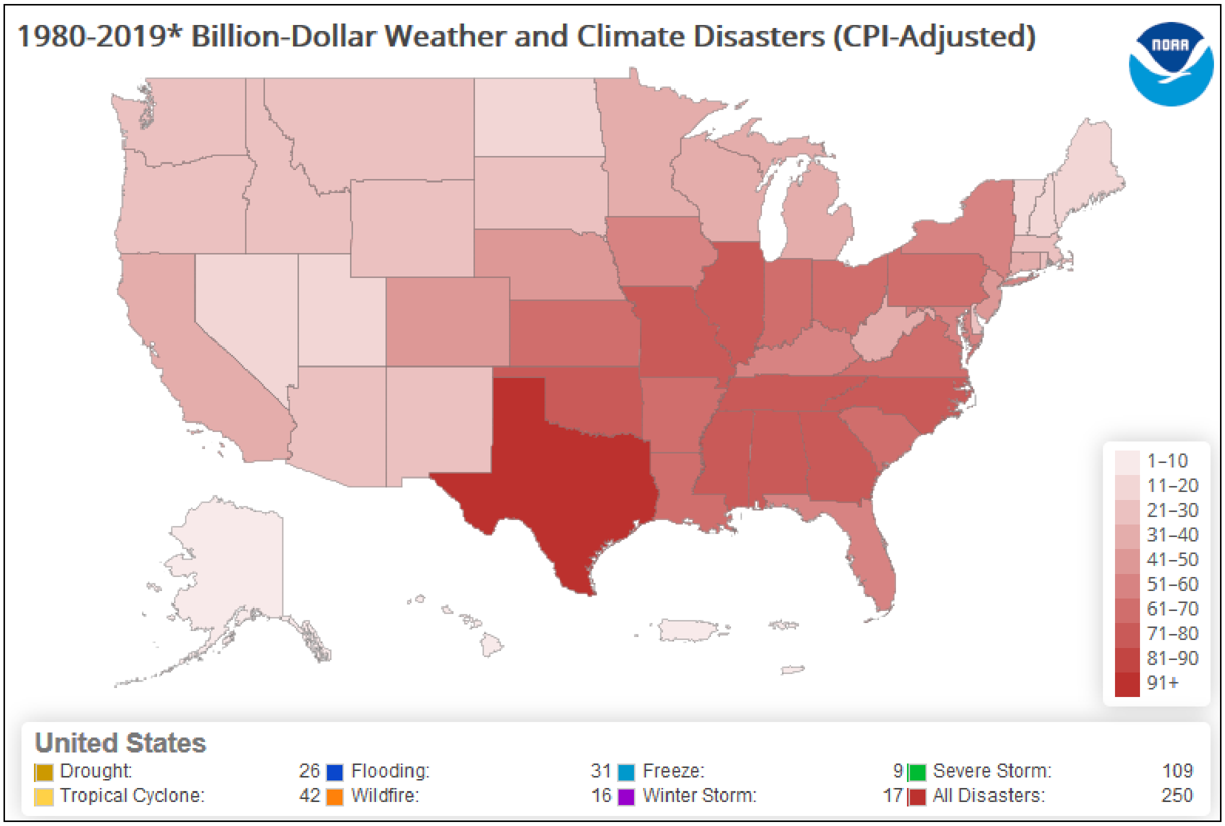


FIGURE 5-1. The 1980 to July 9, 2019 NOAA map of number and types of Billion-Dollar weather and climate disaster events in each state of the US (NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters, 2019 https://www.ncdc.noaa.gov/billions/).

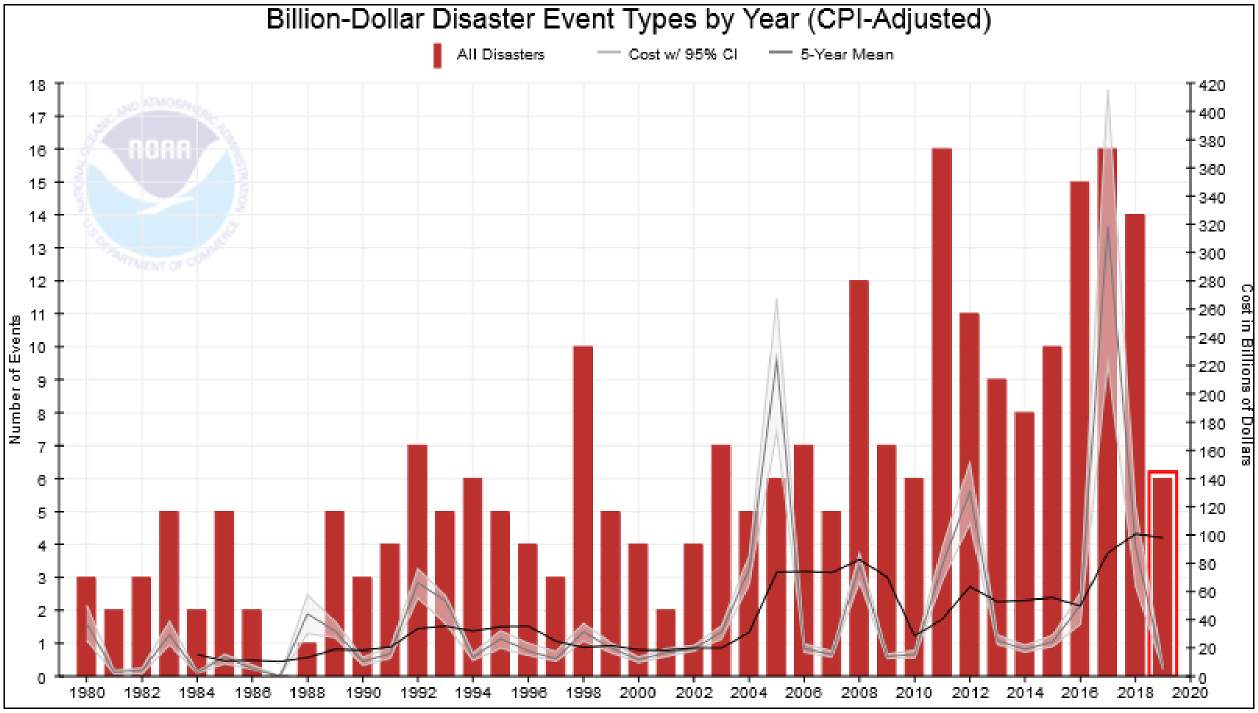


FIGURE 5-2. The 1980 to July 9, 2019 NOAA plot of number and cost of billion-dollar weather and climate disaster events per year (NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters, 2019 https://www.ncdc.noaa.gov/billions/).

In coastal North Carolina the major disaster events are generally weather driven tropical storms or the extra-tropical nor'easters or frontal systems. The resulting impact of any given event is extremely variable and dependent on numerous processes and climatic conditions such as the following.

1. Seasonal and prior set up conditions
2. Frequency and pattern of storms
3. Storm type
4. Storm path and speed of travel
5. Storm intensity and duration
6. Resulting rainfall amount, rates, and aerial extent
7. Size and duration of storm surges, currents, and waves
8. Human modifications within the drainage and shoreline systems
9. Pattern, type, and density of growth and development in adjacent upland areas

Tropical Storms

Two general types of storms dominate the North Carolina coastal system and directly affect the hydrology of the associated surface water drainage systems. During the summer and fall seasons tropical storms and hurricanes are the dominate storm type impacting the coastal zone. The Atlantic Basin has averaged 10.6 named tropical storms per year, 5.9 hurricanes per year, and 2.2 major (category 3 to 5) hurricanes per year (NOAA, 2005). The North Carolina Climate Office (2019) reported that between 1851 and 2018, North Carolina experienced 83 land-falling hurricanes during the past 167 years for an average of 1 tropical storm every 2 years

(Figure 5-3). An additional 299 tropical storms occur within 150 miles of North Carolina and indirectly affect the state for a net average of about 2.3 tropical storms per year (Figure 5-3). Those storms that move up the east coast along the Gulf Stream have their greatest impact directly upon the coastal plain rivers, estuaries, and barrier islands. Whereas, those storms that come ashore along the Gulf Coast often move northeast along the Appalachian Mountains discharging large volumes of rain water affecting the flow dynamics of the larger drainage basins, such as the Roanoke River.

Statistic	**Direct Land-falling Storms in NC**	**Non-land-falling Storms Affecting NC Within 150 Miles**	**Total Storms Affecting NC**
Number of Storms	83	299	382
Percentage of Storms	4.43%	15.97%	20.41%
Average Years Between Storms	2.02	0.56	0.44
Average Storms Per Year	0.49	1.78	2.27

FIGURE 5-3. North Carolina Tropical Storm Statistics (1851 - 2018). North Carolina Climate Office (https://climate.ncsu.edu/climate/hurricanes/statistics?state=NC).

Recently, Windsor has received a visitation from a series of significant tropical storms including Dennis and Floyd in 1999; Isabel in 2003; Irene in 2011; Hermine, Julia, and Matthew in 2016, and most recently Florence and Michael in 2018. The latter two in 2018 were only glancing blows to Bertie County, but represent an important lesson in the far reaching consequences that indirectly impact many that are not in the direct path of these high energy events (Figure 5-4).

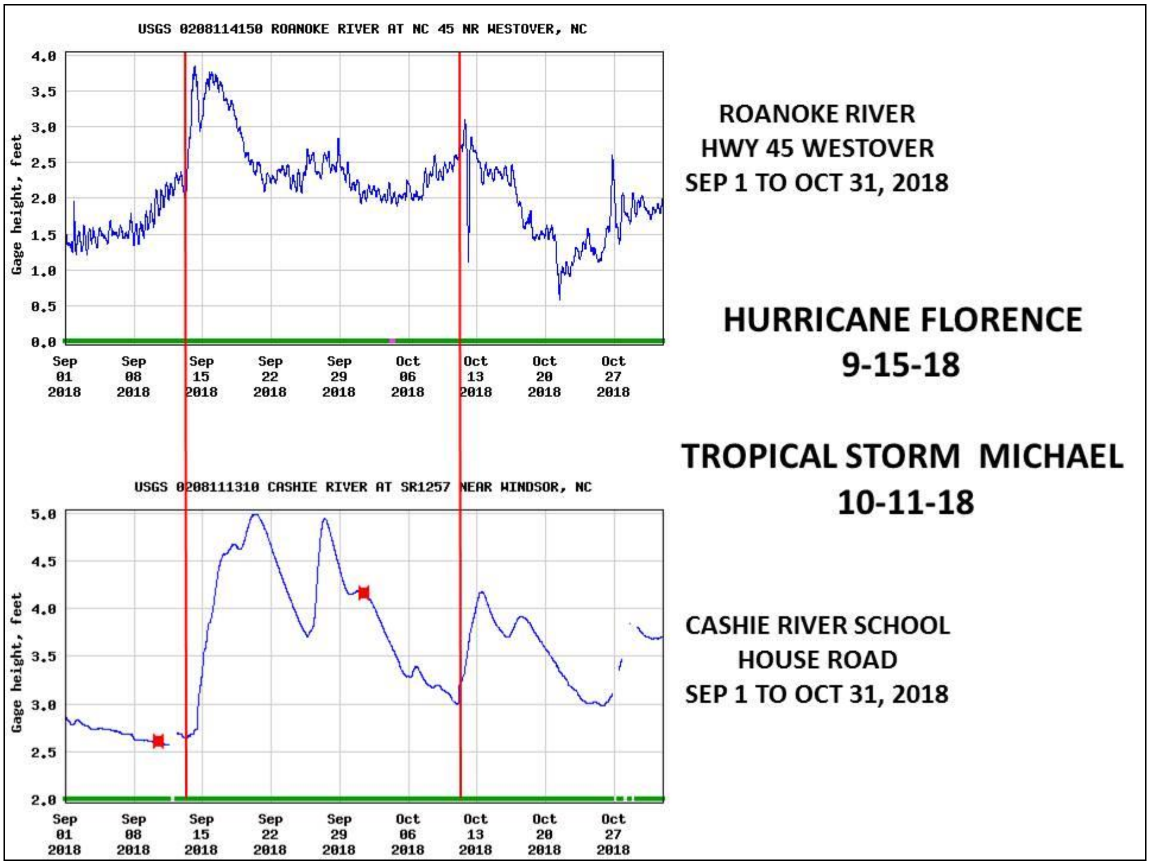


FIGURE 5-4. Neither Hurricane Florence nor Tropical Storm Michael directly impacted Bertie County with substantial wind or rain, but they did leave a major signal on the water-level plots of the gages at Hwy 45 in lowermost Roanoke River and at School Rd. in the upper Cashie River. The upper panel shows two minor and different types of storm surge records from Albemarle Sound. The lower panel displays a series of rainfall runoff signals. Figures 3-14 and 3-15 show that both of these signals occurred simultaneously on the lower Cashie River gages at Windsor King St. and Bowling Farm). Had either or both of these events been a more direct hit on Bertie County, the cumulative impact would have resulted in a catastrophic flooding event as a consequence of the intimate communication between the water bodies. Since it is the downstream pattern of flow that is important, none of these plots are corrected for absolute elevation.

Extra-Tropical Storms (Frontal Systems) and Role of Storm Surge

The second storm type that dominates the North Carolina hydrologic regime is the extra-tropical event or nor'easters that come through NC as frontal systems. During late fall through early spring, North Carolina will experience up to 35 frontal systems moving eastward off the continent with up to 5 major storms per year. These low pressure systems generally cover much broader areas and have longer durations, but also generally have lower wind speeds and amounts of precipitation. Never-the-less, the net energy and water input to the drainage and coastal systems is cumulative and can be catastrophic, particularly if there are two or three storms that come in quick succession.

Unusually high and low water levels in the Bertie Water Crescent and generally caused by the passage of frontal weather systems through the region. These frontal systems are frequent, but quit irregular, depending largely on the season of the year and the activity of the upper atmosphere jet streams. As they pass through North Carolina, the W to SW winds blow the waters eastward in Albemarle Sound. The frontal system winds then shift to E and NE driving the Albemarle waters westward and putting a fraction to several inches of rain on the ground. As the front moves offshore the winds shift strong to NW and W and blow the sound waters back to the E. The resulting wind-tide pumping cycle in the Albemarle dominates the water-level record in the lowermost Roanoke River, the Cashie River to Windsor King St. and the Chowan River. Consequently, the frequency, pattern, and intensity of these frontal system tides will determine the status of the groundwater table. During 2018-2019 this regular pattern of frontal systems has kept the floodplains full, the Cashie River high and kept the Roanoke River lakes (behind the dams) full requiring the USACE to continue discharging floodwaters for much of the year (Figure 5-5).

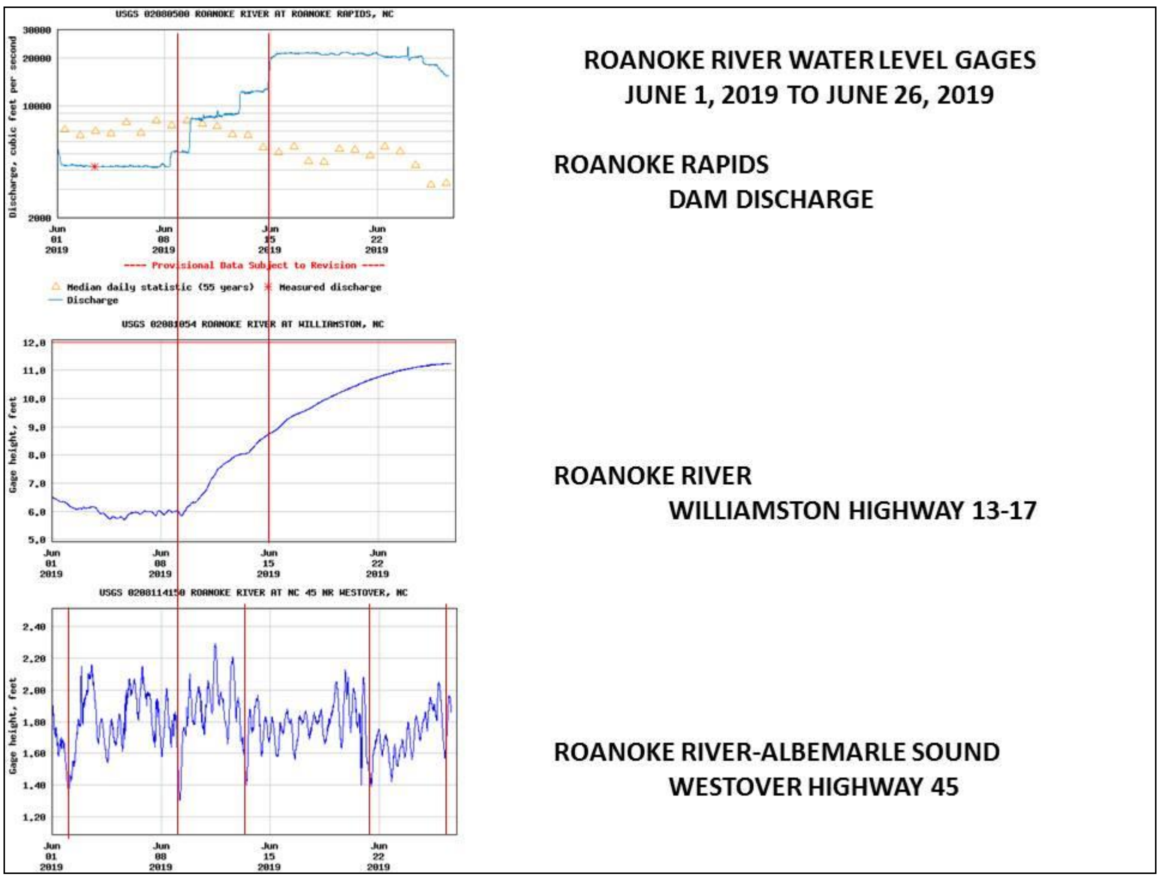


FIGURE 5-5. The three simultaneous water-level plots for June 1-26, 2019 in the lower Roanoke River show the dominant influence of dam discharge downstream to the Williamston Hwy 13-17 road dam. The lower panel (Westover Hwy 45) shows no record of dam discharge. Rather it is dominated by the wind tides and small storm surges resulting from a series of frontal systems (red lines) passing through the region. Since it is the downstream pattern of flow that is important, none of these plots are corrected for absolute elevation.

In addition, spring and summer represents the major growth period when trees are growing new biomass and reproducing and evapotranspiration is at its maximum. This biologic pumping system lowers the groundwater table and decreases the general flow into adjacent stream systems, except during major rain events. In late fall and winter evapotranspiration by trees and plants is at its minimum since most plants are dormant. Thus, the floodplain swamp forests and associated streams tend to be drier and generally lower in the spring-summer growth season than during the fall-winter dormant season. With the excessive rains of 2018-2019, the importance of this dynamic was minimized with respect to changing water levels.

The three simultaneous water-level plots for July 1-24, 2019 (Figure 5-6) show three different types of signals. The lower Roanoke River panel at Westover Hwy 45 is dominated by Albemarle wind tides, astronomical tides, and frontal systems. Whereas the lower Roanoke River panel at Jamesville, just upstream of the Hwy 45 panel, records the dam discharge during the first week with a minimal Albemarle signal on top. With declining dam discharge, the water level record becomes dominated by the Albemarle signals. The bottom panel is the School Rd. gage in the upper Cashie River (Figure 5-6) that shows no evidence of either dam discharge or the different Albemarle tides, rather it is totally dominated by both local and regional rainfall events.

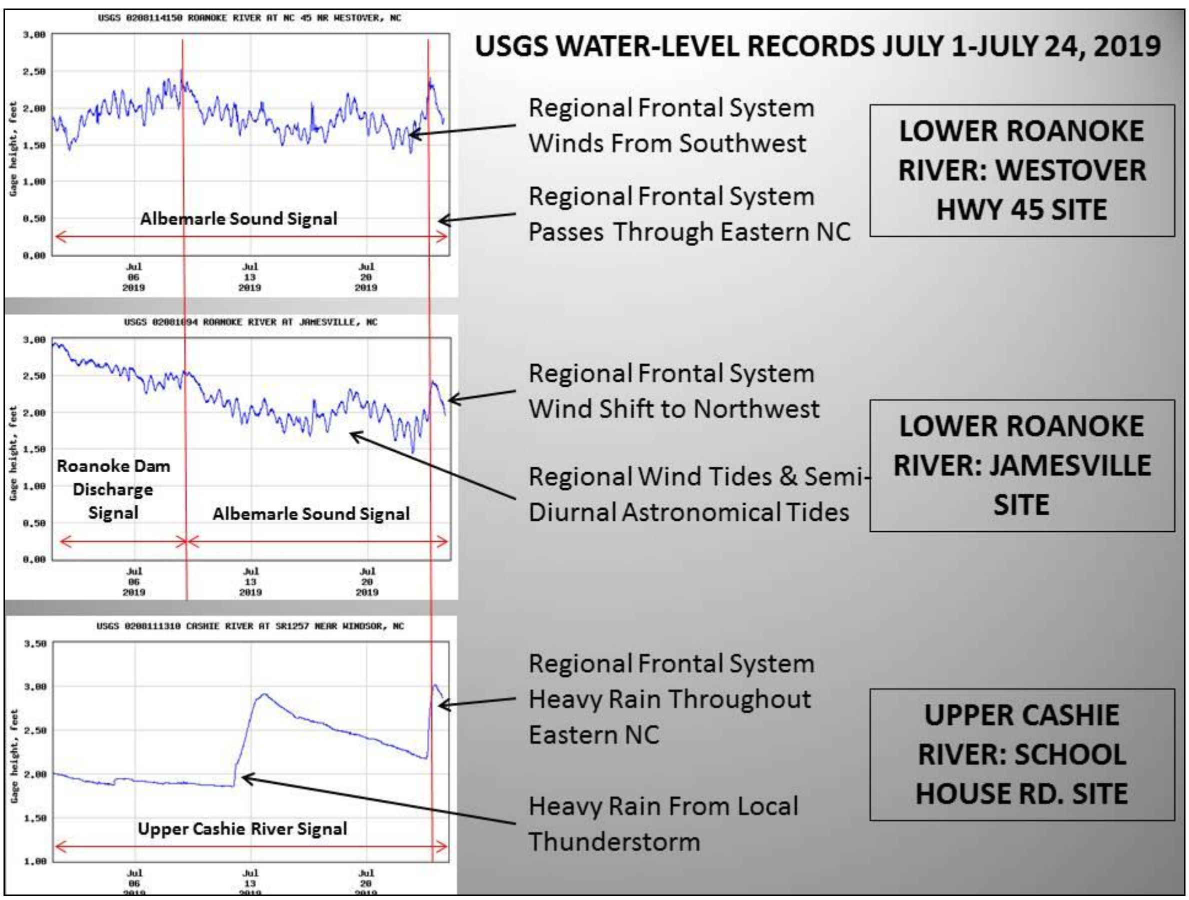


FIGURE 5-6. The three simultaneous water-level plots for July 1-24, 2019 show three different types of signals. The upper panel is dominated by Albemarle wind tides, astronomical tides, and frontal systems. The middle panel, just upstream of the top panel, records the dam discharge of

the first week with a minimal Albemarle signal on top. With declining dam discharge, the middle panel becomes dominated by the Albemarle signals. The bottom panel shows no evidence of either dam discharge or the different Albemarle tides, rather it is totally dominated by both local and regional rainfall events. Since it is the downstream pattern of flow that is important, none of these plots are corrected for absolute elevation.

What is the role of wind tides and storm surge on the Albemarle-Chowan estuaries to possible flooding in Bertie County. The data on the extreme Roanoke River flooding suggests that there has been little to no communication with the Cashie River during this year's water-flow conditions. When the Roanoke River is in flood stage due to high rates of dam discharge, the lower Roanoke River flow below the Williamston Hwy 13/17 road dam spreads out across the entire broad floodplain. The increased dam discharge causes slight rises (inches to 1 foot) to the entire Roanoke River elevation from Jamesville east to the Hwy 45 bridge. If Albemarle Sound water level is low due to westerly wind tides, then the flow rate from upstream increases and the lowermost Roanoke River elevation decreases. However, if the Albemarle Sound water level is high due to easterly wind tides, then the Roanoke flow rate from upstream decreases causing the elevation of the lowermost Roanoke River to rise slightly with the Albemarle Sound overprint on top, as well as causing the lower Cashie River water level to rise. The only time that Roanoke River floodwaters are able to backflow up the lower Cashie River, is when a substantial storm surge occurs at the western end of Albemarle Sound. This situation causes a major water-level rise throughout the lower Cashie River, and with a major rainfall in the upper Cashie River basin at the same time, would result in the potential for serious flood conditions in Windsor.

Role of Sea-Level Rise

Another factor in degree of flooding is the slower and longer term impact of rising sea-level. Almost all coastal towns in NC are now experiencing significantly more frequent "nuisance flooding events" (small-scale events, particularly associated with the spring tides and frontal weather events). Many of NC's towns now have "frequent flooding" or "no wake zone" signs. For example, the low areas in Wilmington, Main Street in Beaufort and Manteo now flood numerous times a year without storms. Many small communities and farms on the Outer Albemarle, Pamlico, and Carteret peninsulas are under a few inches of water for weeks to months a year. Some lowland farms are experiencing increasing amount of salt-water encroachment and there are large areas of expanding ghost forests that are slowly being drowned. This is all real and is add a few more inches to the mean elevation of the Cashie River.

Figure 5-7 is a calculation of the recent rate of sea-level rise based on the Oregon Inlet tide gauge data for the past 25 years. These data demonstrate a 4.6 inch rise since 1995 which is a rate that is comparable to the projected rate of the NC Science Panel for 2019 (Figure 5-8). The NC Science Panel in 2015 projected a mean sea level rise for the years 2045 and 2100 to be about 9 inches and 39 inches, respectively. The lower end of the Cashie River (Bowling Farm) has an in situ early 18th century dock that is now below 1 to 2 feet of water (the red dashed line in Figure 5-9). The dock was built and utilized when it was above sea level about 1 to 2 feet. This suggests that there has probably been a 2 to 4 foot rise in sea level since the early 1700s which supports both Figures 5-7 and 5-8 and helps to explain why Windsor has begun to flood more frequently. Figure 5-10 is from NOAA's "sea level rise viewer" program that shows the increased permanent flooding that will occur in the lowlands around the four water-front villages by 2100 if the NC Science Panels projection is realized. Plymouth and Jamesville will be on the Albemarle Sound, not the Roanoke River.

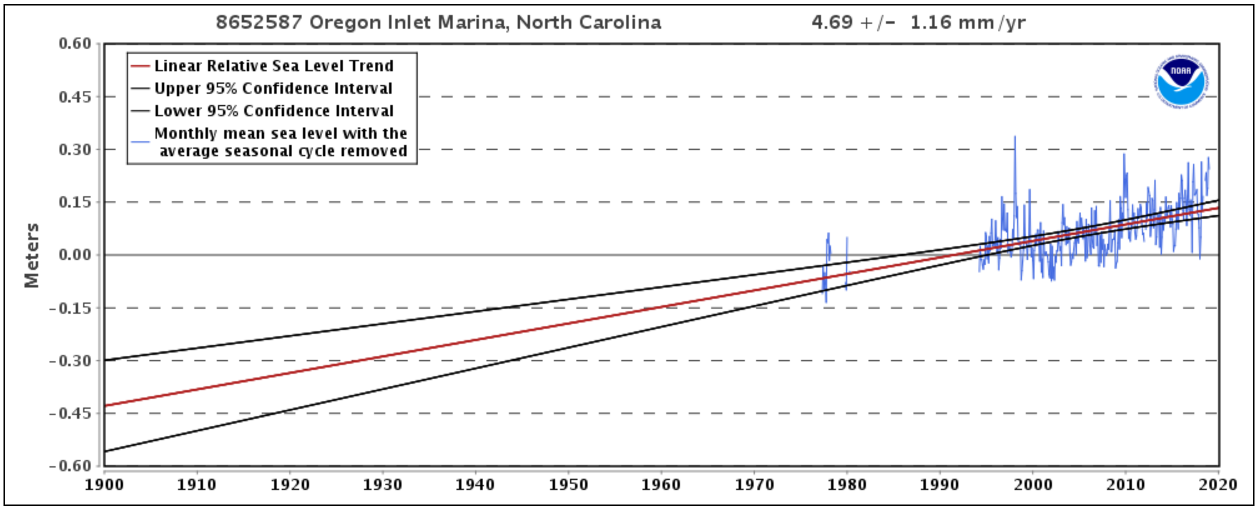


FIGURE 5-7. Recent rate of sea-level rise based on the Oregon Inlet tide gauge data for the past 25 years demonstrates about a 4.6 inch rise since 1995.

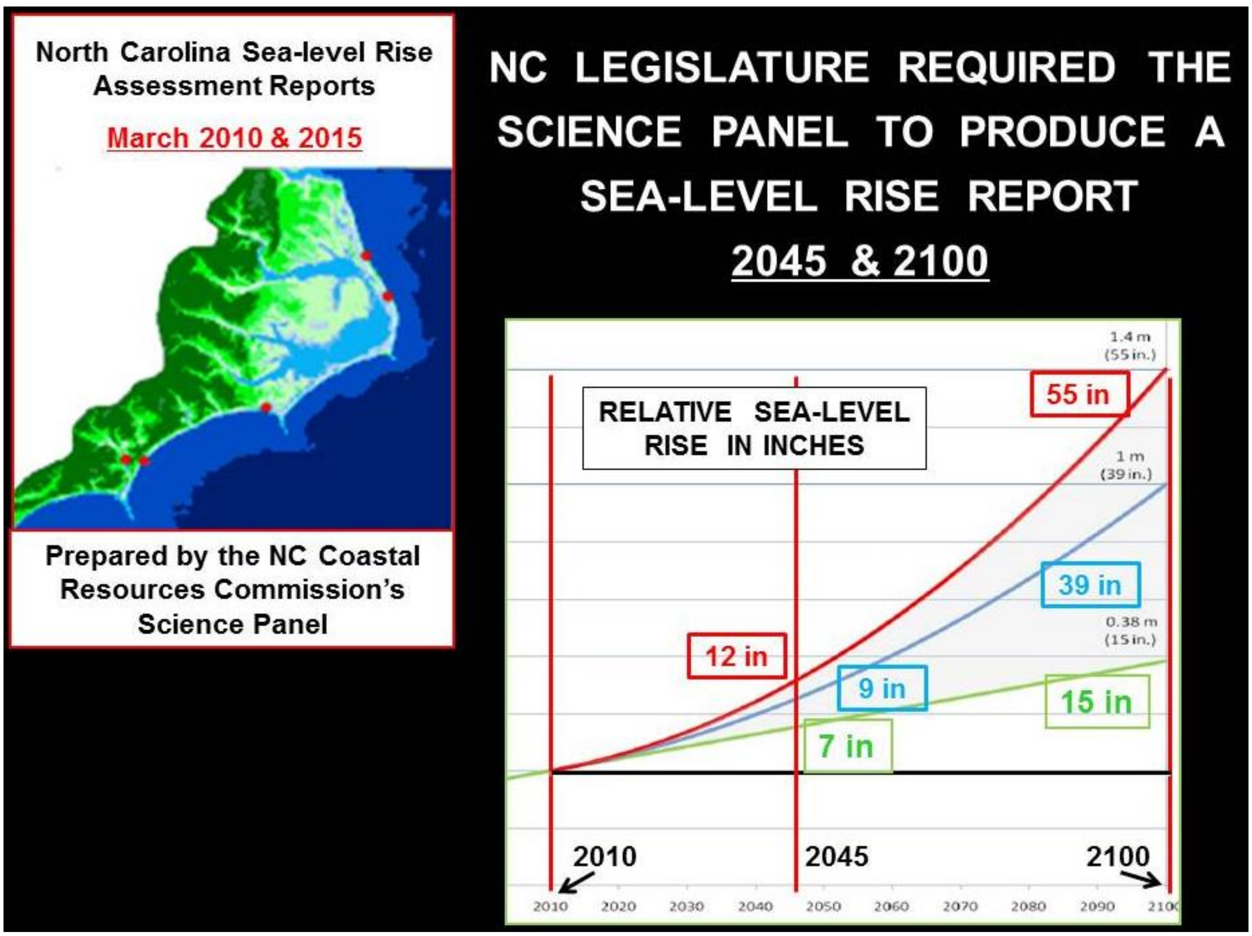


FIGURE 5-8. Projected rates of sea-level rise published in the 2010 and 2015 NC legislative reports by the NC Science Panel. The projections of sea level rise in NC were for the years 2045 and 2100, respectively (blue line). The error bars are in red and green. These projections are based on tide gage data going back to the early 20th century.

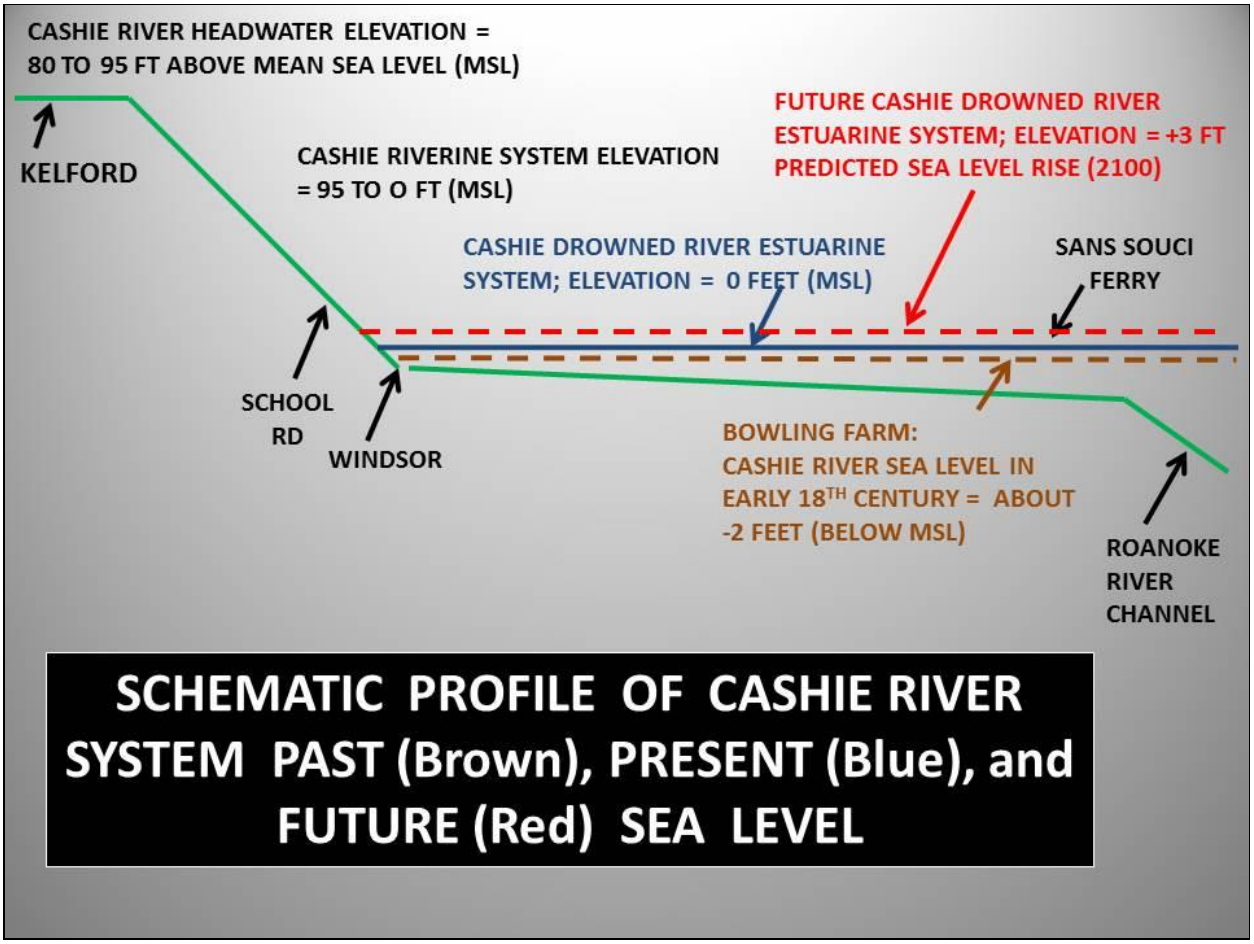


FIGURE 5-9. A schematic cross section shows the upper Cashie River gradients from the top of the Wicomoco Terrace at Kelford, across the Talbot Terrace to sea level at Windsor. The lower Cashie River from Windsor to Albemarle Sound is today at sea level and carries all of the wind tide and astronomical tide signals of Albemarle Sound, as well as evidence of past (brown) and future (red) sea level rise since the early 18th century and projected to 2100. MSL is the present mean sea level.

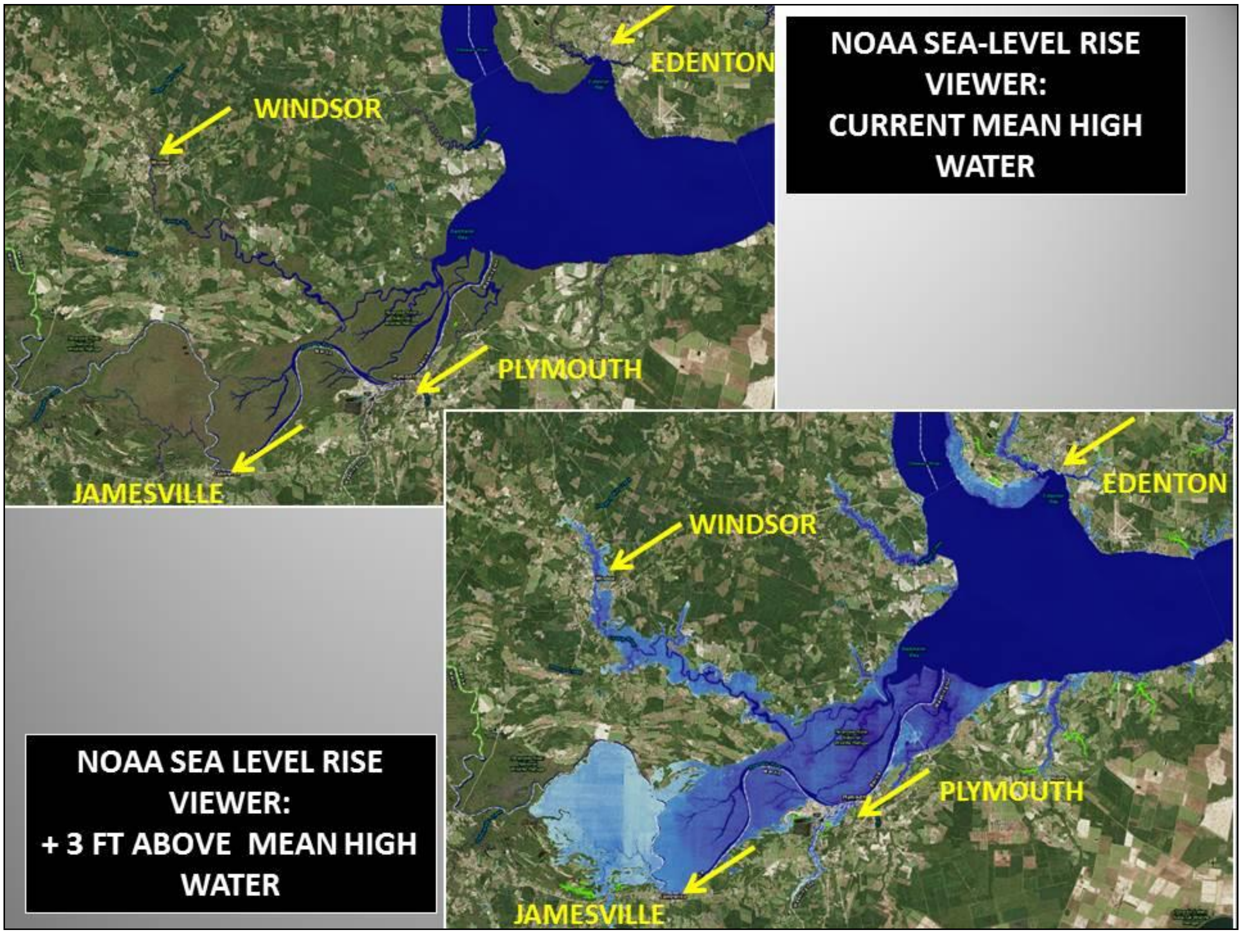


FIGURE 5-10. Aerial photographs from NOAA's "Sea Level Rise Viewer" shows 4 villages located at the water's edge under present sea level conditions. The lower panel raises sea level by 3 feet above today's mean water level. The medium to lite blue colors represent the present wetland and low upland that will be permanently flooded. The real problem for the four villages comes when there is a storm tide or rainfall flood on top of this higher water level.

HISTORIC FLOODS RELEVANT TO THE BERTIE REGION

Hurricane Florence (9-15-2018) and Tropical Storm Michael (10-11-2018)

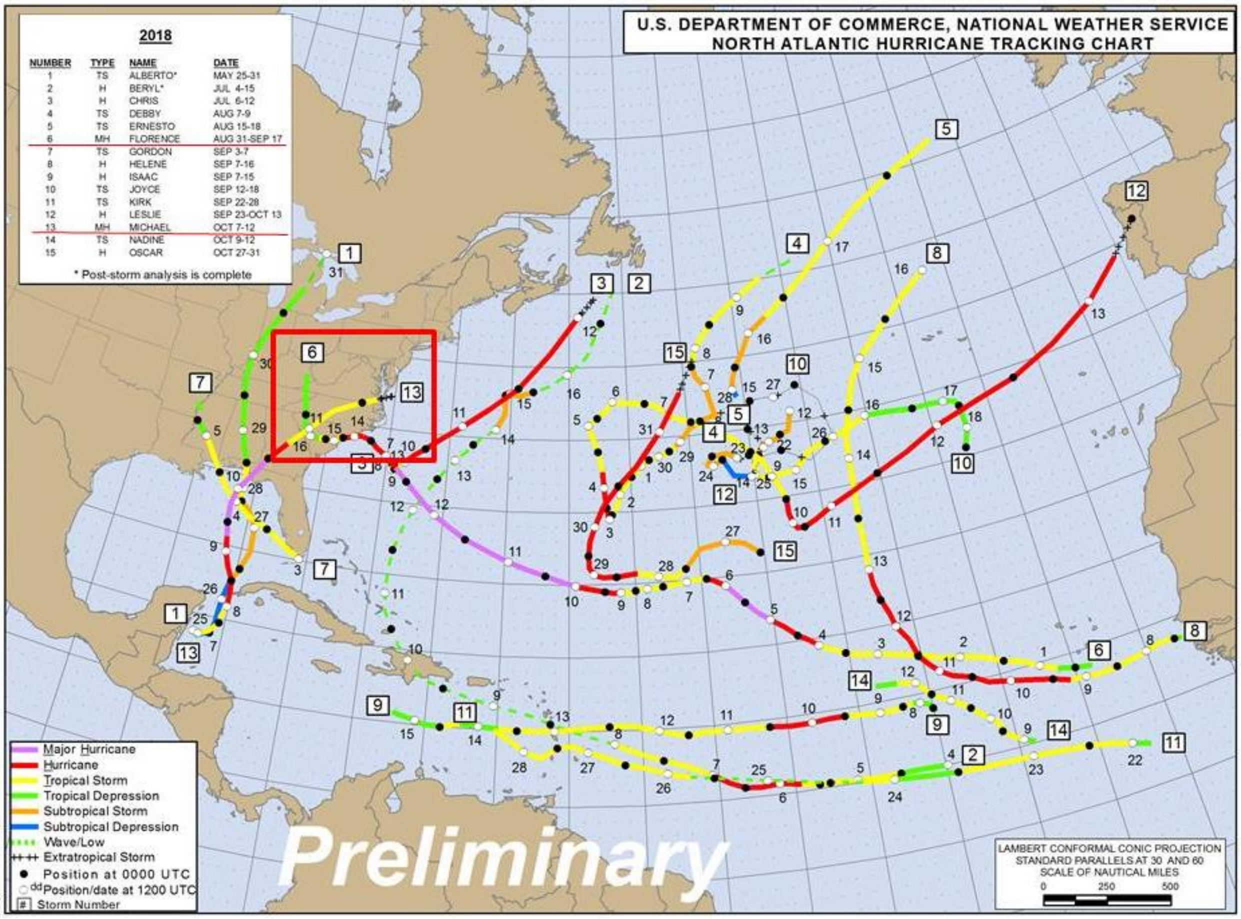


FIGURE 6-1. The NOAA storm track map for 2018 hurricane season shows the tracks of Hurricane Florence (no. 6) and Tropical Storm Michael (no. 13) through North Carolina.

On September 7 to 17, 2018 Hurricane Florence made landfall about a mile south of Wrightsville Beach, NC with winds of 90 mph. The storm began a slight turn from NW to the W and finally turning N across the western most portion of NC. This major change in the storms track took it off the path for a direct hit on Bertie County and resulted in a backdoor impact from heavy rains throughout the Roanoke River drainage basin. On October 11, 2018 a severely downgraded Tropical Storm Michael moved NE through the central portion of NC, dropping a large volume of water in the Roanoke River drainage basin. Together these two back-door storms filled the lakes and upper Roanoke River forcing the US ACE to flood the lower Roanoke River with high dam discharges for most of the next six months.

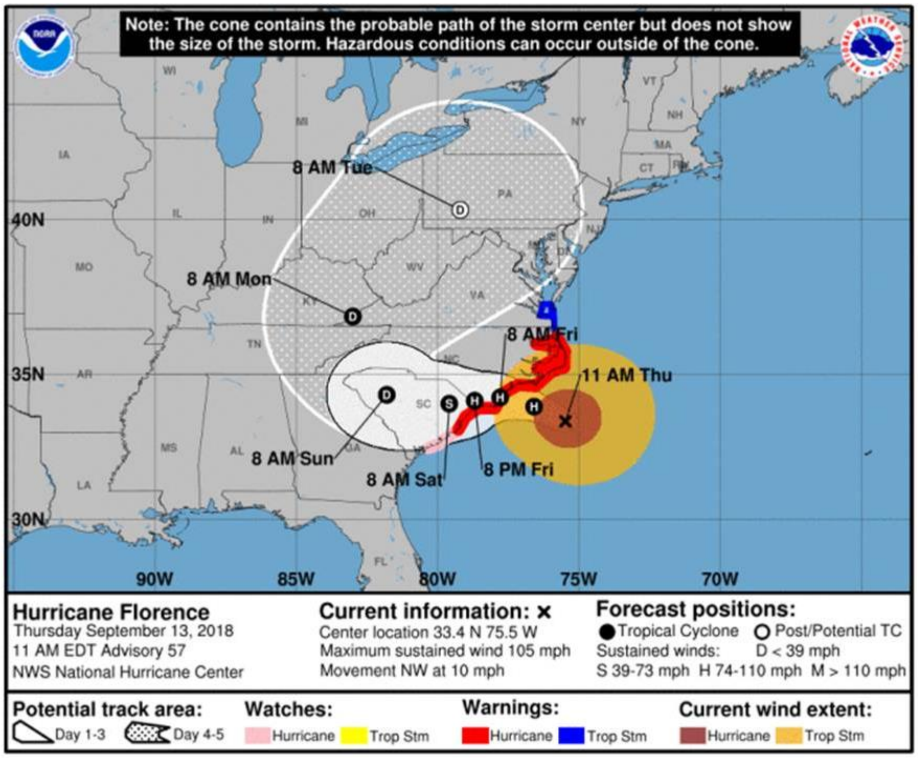


FIGURE 6-2. The NOAA map shows the landfall of Hurricane Florence and projected track through western North Carolina with small storm surge on Albemarle Sound and major rainfall throughout the Roanoke River watershed.

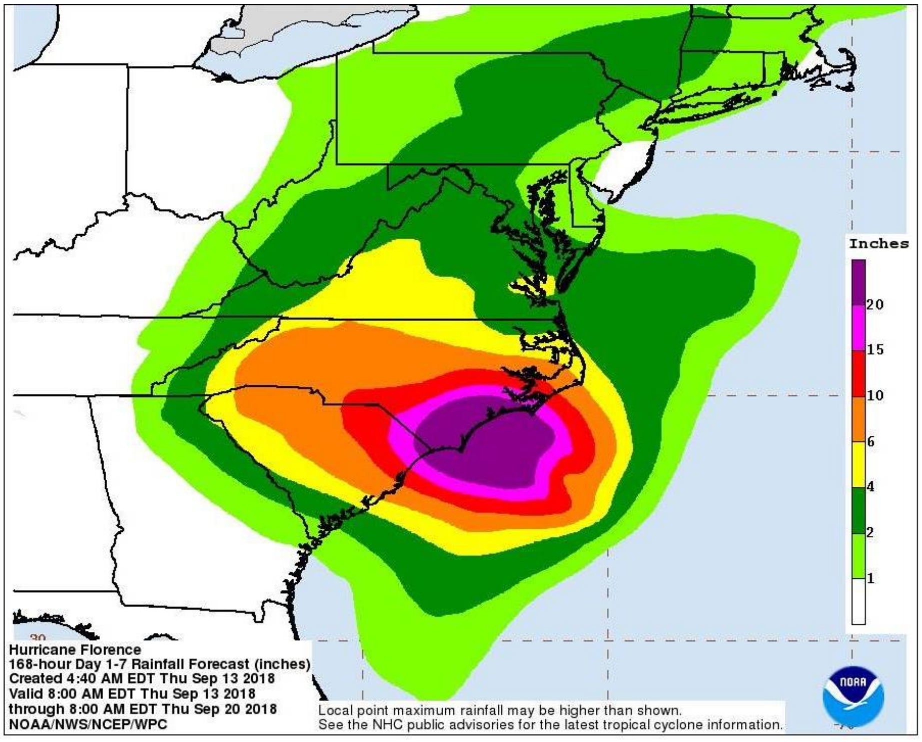


FIGURE 6-3. The NOAA map of precipitation resulting from Hurricane Florence as it moved across North Carolina.

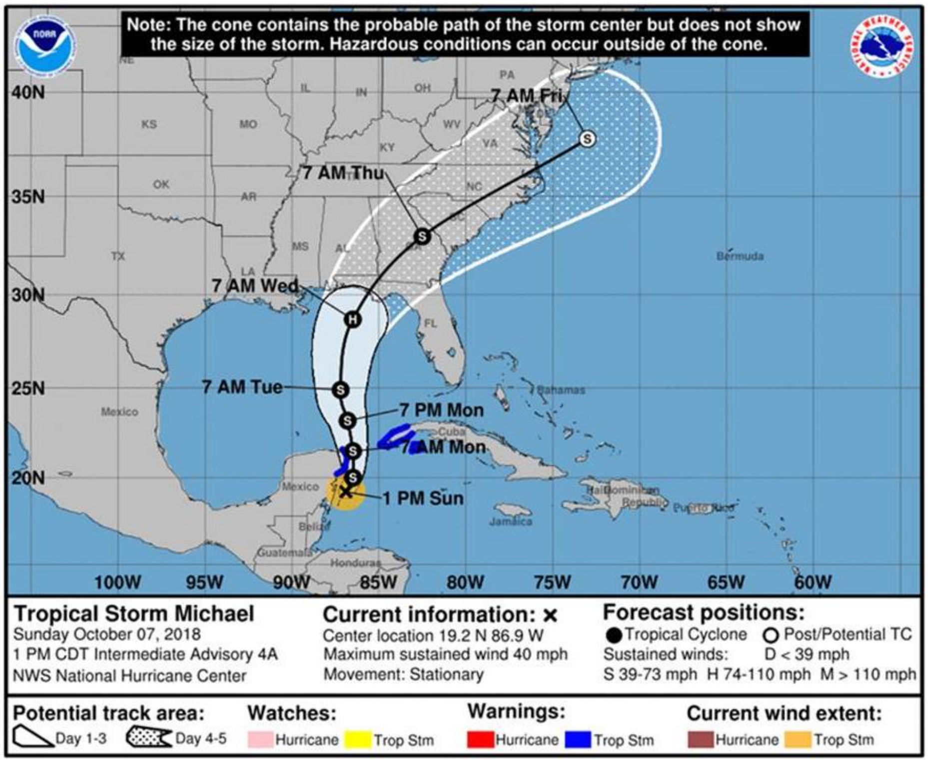


FIGURE 6-4. The NOAA map shows the landfall of Hurricane Michael and projected track as a tropical storm through central North Carolina producing a very small storm surge on Albemarle Sound and major rainfall throughout the Roanoke River watershed.

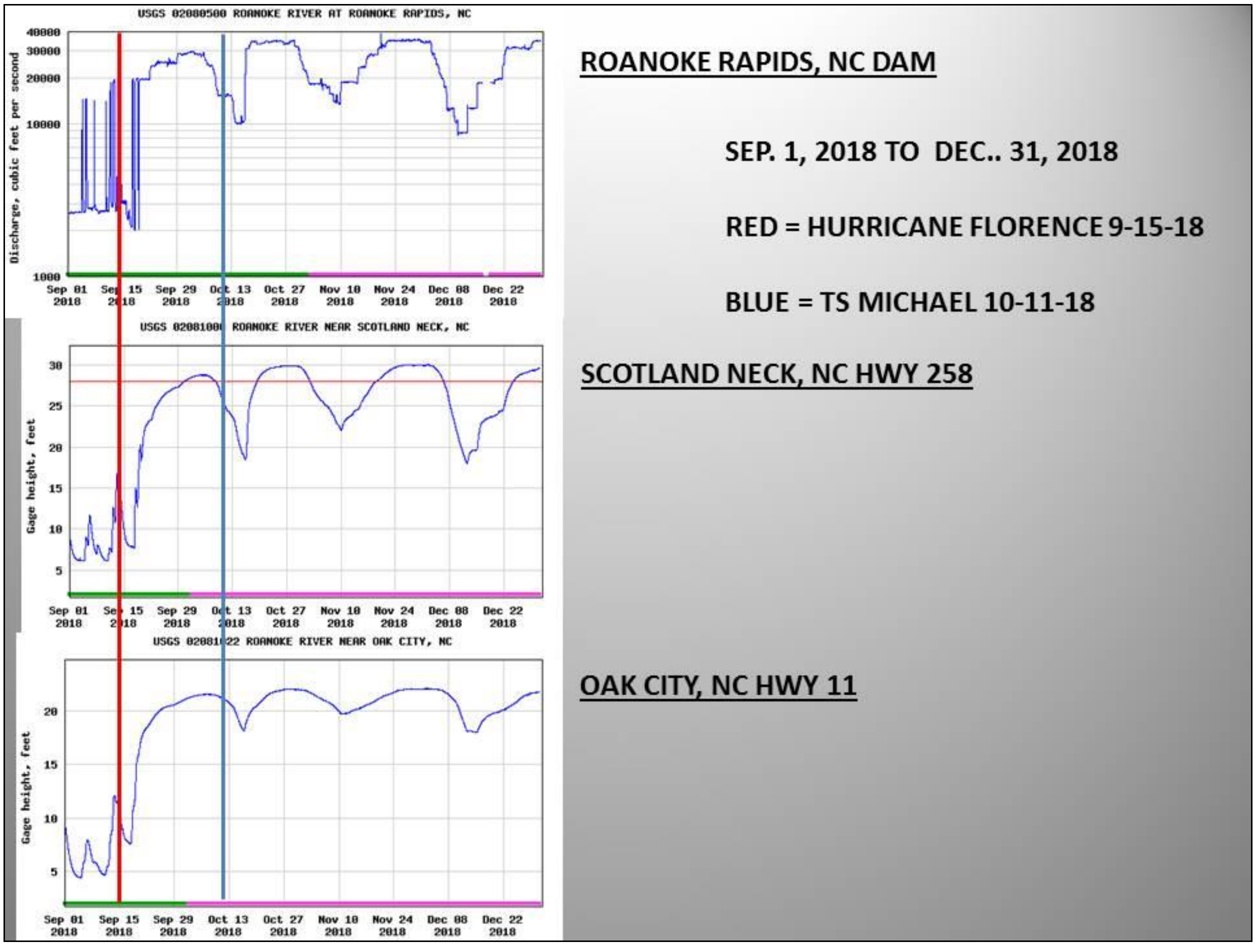


FIGURE 6-5. Figure shows the USGS water-level gages at Roanoke Rapids dam (top panel), Halifax-Scotland Neck at Hwy 258 middle panel, and Oak City at Hwy 11 (bottom panel) from Sep. 1, 2018 to Dec. 31, 2018. Changing water levels are totally due to fluctuations in dam discharge as demonstrated in the pattern of discharge measured by flow in cubic feet per second (cfs) on the top and downstream gages height in feet (ft). The change in volume of discharge is the response to the upstream rainfall from the remnants of Hurricane Florence and Tropical Storm Michael as they moved north over the vast Roanoke River watershed. Notice how the waves of discharged flow decrease in amplitude downstream. Since it is the downstream pattern of flow that is important, none of these plots are corrected for absolute elevation.

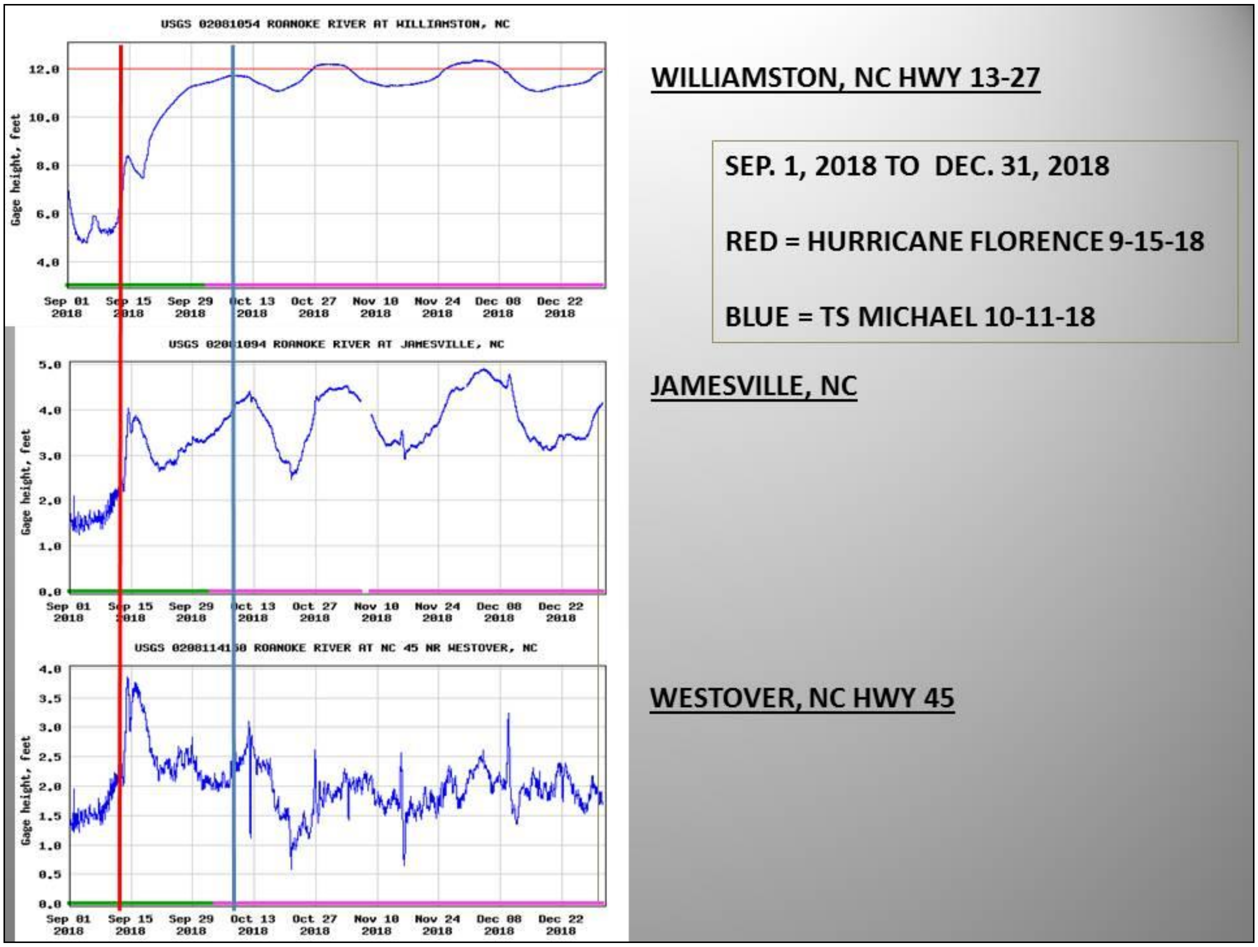


FIGURE 6-6. Figure shows the USGS water-level gages at Williamston Hwy 13-17 (top panel), Jamesville (middle panel), and Westover Hwy 45 (bottom panel) from Sep. 1, 2018 to Dec. 31, 2018. The change in volume of discharge is the response to the upstream rainfall from the remnants of Hurricane Florence and Tropical Storm Michael as they moved north over the vast Roanoke River watershed. Notice how the waves of discharged flow decrease in amplitude downstream to Williamston, then shifts to a mixed dam and Albemarle signal at Jamesville, and the Albemarle dominated signal at Hwy 45. Since it is the downstream pattern of flow that is important, none of these plots are corrected for absolute elevation.

The change in volume of discharge (top panel in Figure 6-5) is the response to the upstream rainfall from the remnants of Hurricane Florence and Tropical Storm Michael as they moved north over the vast Roanoke River watershed. Water levels in the downstream panels of Figure 6-5 are totally a product of dam discharge and carry a similar signature to the Williamston Hwy 13-17 gage in Figure 6-6. The panels in Figure 6-6 demonstrate a rapidly changing water level pattern from dam discharge to the pattern at Jamesville that represents a mixed signal of upstream and downstream influences. At Hwy 45 the signal is dominated by Albemarle Sound dynamics. The latter pattern is comparable to those with no dam discharge signal including Salmon Creek and Colerain on the Chowan River, and Bowling Farm and Windsor King Street on the lower Cashie River.

In Figure 6-7 the upstream School Rd. (top panel) is driven totally by rainfall, while the downstream Hwy 45 (bottom panel) is driven primarily by Albemarle Sound wind and storm tides. Neither of these gages interacts with each other, but they both interact directly with the Windsor King St. gage. Consequently there is an important response that represents the cumulative impact from both sets of dynamics in the Windsor region. This cumulative impact can lead to catastrophic flood responses when both processes are somewhat larger than the response from the fringe influences of Florence and Michael. This response is very clear in the catastrophic floods of Hurricanes Julia and Matthew in 2016 and Hurricane Irene in 2011.

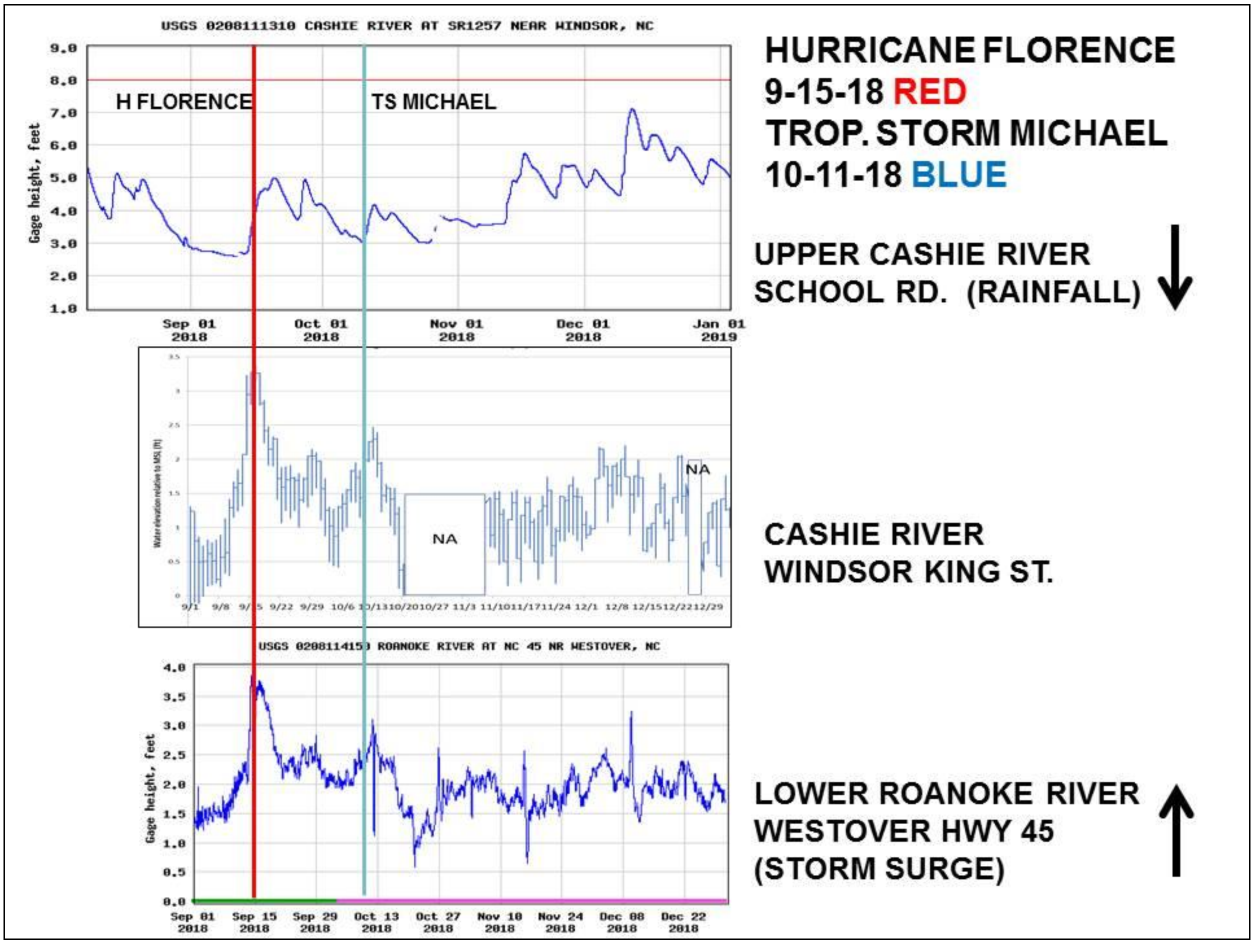


FIGURE 6-7. Figures show the USGS water-level gages from the lower Roanoke River at Westover Hwy 45 (bottom panel), to the lower Cashie River at Windsor King St. (middle panel), and the upper Cashie River at School Rd. (top panel) from Sep. 1, 2018 to Dec. 31, 2018. Since it is the downstream pattern of flow that is important, none of these plots are corrected for absolute elevation.

Tropical Storms Hermini and Julia, and Hurricane Matthew (8 to 10, 2016)

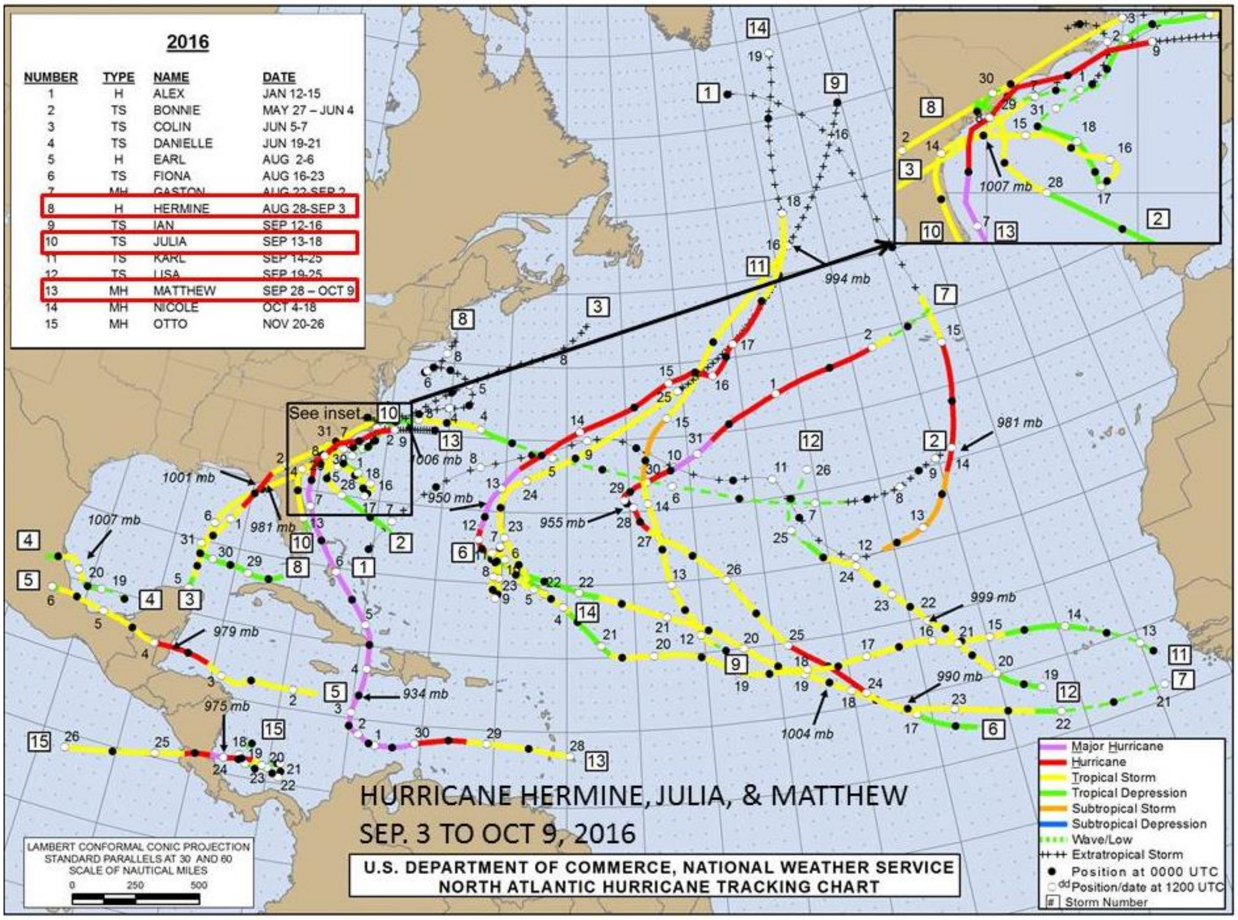


FIGURE 6-8. The NOAA storm track map for 2016 hurricane season shows the tracks of Tropical Storm Hermine (no. 8), Tropical Storm Julia (no. 10), and Hurricane Matthew (no. 13) as they passed through North Carolina. The cumulative impact of these three storms created catastrophic flooding events out of the second two storms.

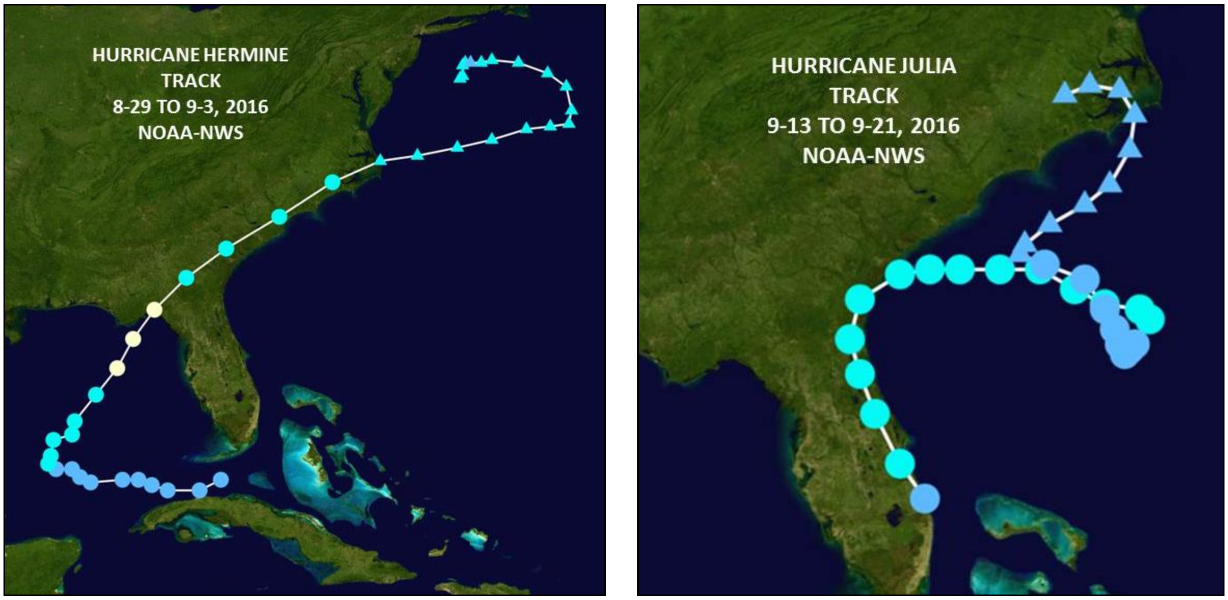


FIGURE 6-9. Storm tracks show the first two tropical storms, Hermine (left panel) and Julia (right panel), to impact Bertie County flooding in the fall of 2016. The circles represent the hurricane designation categories 1-5 and the triangles represent tropical storm designation. The maps are from NOAA's Nation Weather Service.

FIGURE 6-10. Storm track for the third tropical storm, Matthew, to impact the Bertie County flooding in October 2016. The map is from NOAA's Nation Weather Service.

On September 2, 2016, Hurricane Hermine was downgraded to a tropical storm as it traveled NE through coastal NC (Figures 6-8 and 6-9). It was a fast moving storm as it passed over the Albemarle Peninsula and the Outer Banks north of Cape Hatteras with sustained tropical storm-force winds and heavy rainfalls, 6 inches of rain was recorded in the Jamesville area. This storm produced a 2.5 ft. storm surge in western Albemarle Sound, but because of its track and rate of travel, there was no following storm surge on the backside of the Outer Banks (Figure 6-11). But the rains did fill the river systems of eastern NC.

Hermine was followed on September 15, 2016 by Hurricane Julia which passed east offshore of Georgia, drifted erratically offshore and finally turned back the NW towards Charleston (Figures 6-8 and 6-9). As it approached the coast the hurricane was downgraded to a tropical storm, turned NE and slowly curved to the west and came ashore in the vicinity of Ocracoke Inlet as a slow moving tropical storm. Its western track along the Albemarle Peninsula resulted in a 2 foot storm surge in western Albemarle Sound along with severe rainfalls of up to 12 inches or more throughout Bertie region. The combination of Albemarle wind set up, heavy rains, and an already full river system, led to a catastrophic flood in Windsor with over 14 ft crest at School Rd. (Figure 6-11). The Windsor King St. gage was not functioning during either Hermine or Julia. Because of the westerly track along the Albemarle Peninsula, there was no following storm surge on the back side of the Outer Banks.

The Bertie County region had already received up to a 1.5 feet of rain when the third storm came along. On October 8, 2016 Hurricane Matthew after making landfall in South Carolina as a category 2 storm, moved offshore and tracked NE hugging the NC coast as a category 1 storm (Figures 6-8 and 6-10). The storm track was shore parallel towards Cape Lookout where it turned more easterly leaving the Outer Banks. The large size of Matthew caused a 3.5 foot storm tide in western Albemarle Sound (Figure 6-11) and torrential rains that were up to 15.65 inches in the Cape Fear River and up to 10 inches in the Bertie County region. Wilmington set a new storm tide record at 3.53 feet beating the previous record of 3.47 feet set during Hurricane Hazel on October 15, 1954. The consequence of the third major event in 1.5 months was another catastrophic flood in Windsor with the flood crest at School Rd. of 16.63 feet and a crest at King St. of 12 feet on the Cashie River gages (Figure 6-11).

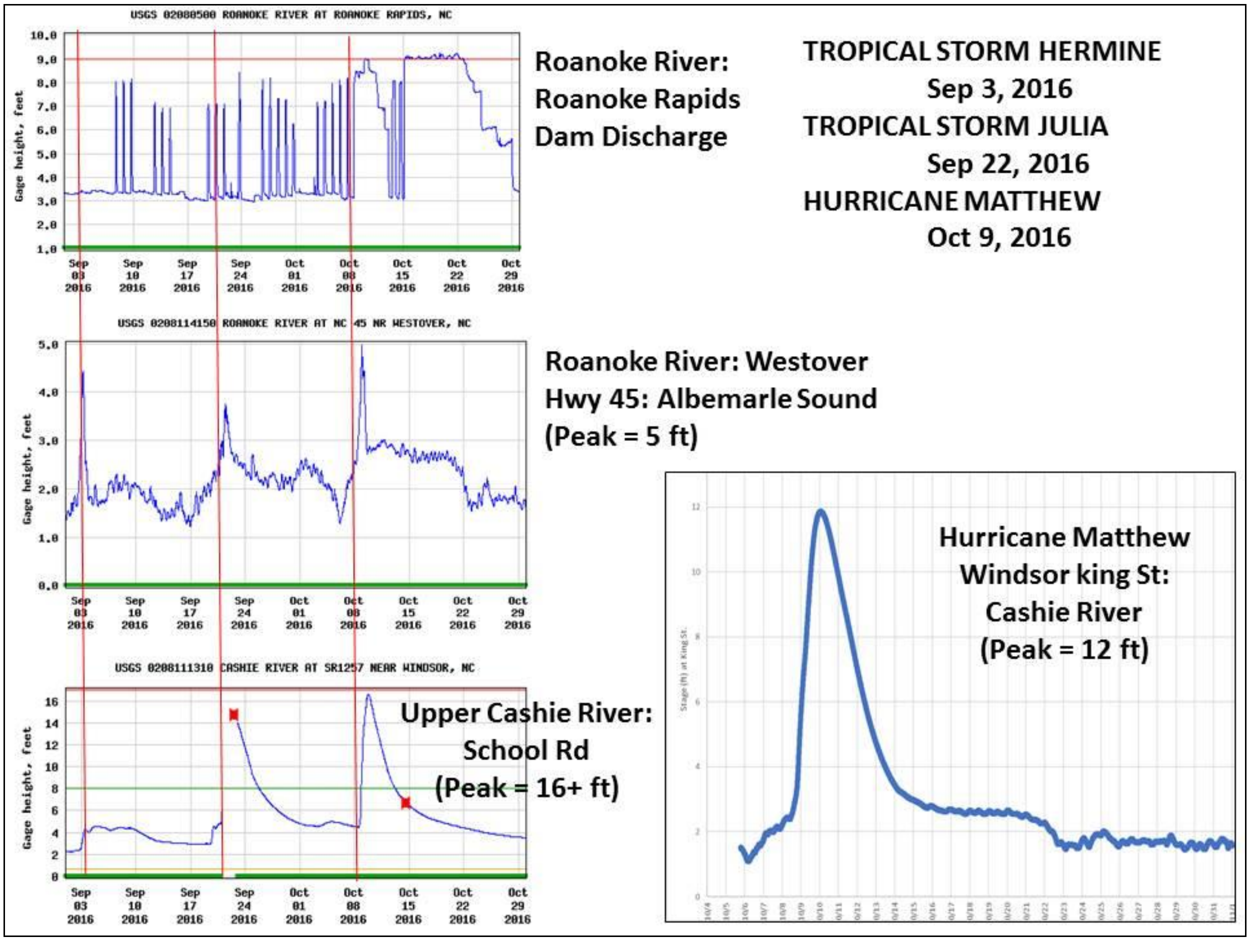
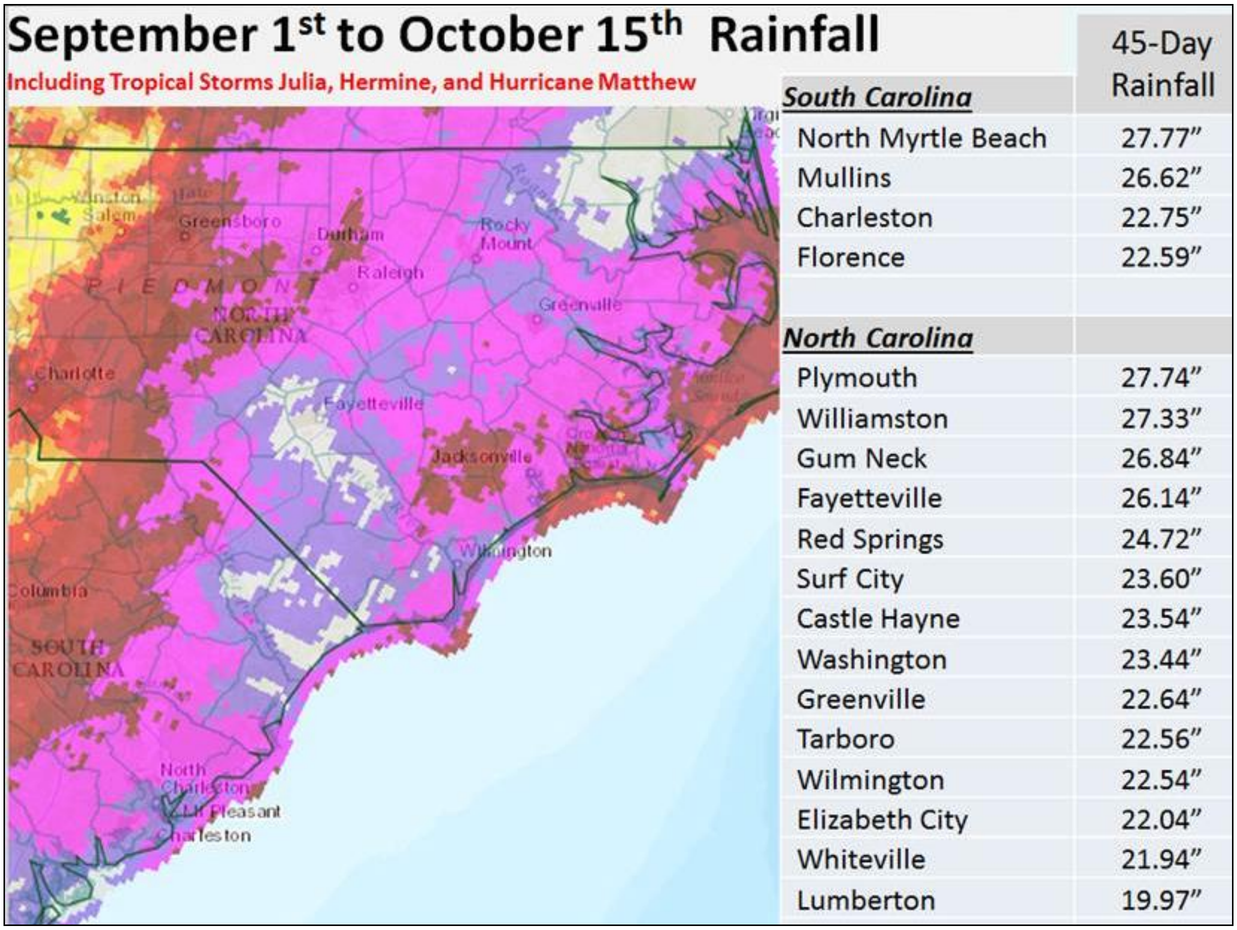


FIGURE 6-11. Water-level gages show the sequential impact of three major tropical events that directly impacted the Bertie County region in the time period of September 1 through October 30, 2016. The Windsor King St. gage unfortunately was not in service during Hermine and Julia, but was working during Hurricane Matthew. Notice that all three storms had major storm surges on Albemarle Sound, but only the latter two had substantial rain components in the upper Cashie River. Since it is the downstream pattern of flow that is important, none of these plots are corrected for absolute elevation.

The net rainfall for the period from Sept. 1 through Oct. 15 was overwhelming for the region with Williamston recording 27.33 inches (Figure 12). The total rainfall for the entire Bertie region for all of 2016 ranged between 12 to 24 inches above normal. The amount of rain from three storms alone would have caused flooding of the Cashie River, but it would not have been as severe without the cumulative impact of full river/groundwater systems, major storm surges and wind setup on Albemarle Sound, and changing land use buffer zones. The catastrophic impact of these three tropical storms defined the lowest portions of downtown Windsor, which are essentially in the Cashie River floodplain (Figures 6-13 and 6-14).



	45-Day Rainfall
South Carolina	
North Myrtle Beach	27.77″
Mullins	26.62″
Charleston	22.75″
Florence	22.59″
North Carolina	
Plymouth	27.74″
Williamston	27.33″
Gum Neck	26.84″
Fayetteville	26.14″
Red Springs	24.72″
Surf City	23.60″
Castle Hayne	23.54″
Washington	23.44″
Greenville	22.64″
Tarboro	22.56″
Wilmington	22.54″
Elizabeth City	22.04″
Whiteville	21.94″
Lumberton	19.97″

FIGURE 6-12. Total rainfall amounts from the three tropical storms, Hermine, Julia, and Matthew, to impact the Bertie County flooding during the period of September 1 through October 15, 2016. Notice the highest amount of rain occurred in the white areas including most of Bertie County; yellow and red indicate the lowest amounts of net rainfall. The map and data are from NOAA's Nation Weather Service.

FIGURE 6-13. Photograph of the Cashie River flood waters on the King Street Bridge in the Town of Windsor as a result of Hurricane Matthew on October 10, 2016. The water level gage on this bridge crested at 12 feet. Photograph is by S. Sauer.

FIGURE 6-14. Photograph of the Cashie River flood waters on King Street in the lowest portion of King Street in downtown Windsor as a result of Hurricane Matthew on October 10, 2016. Photograph is by S. Sauer.

Hurricane Irene: August 27, 2011

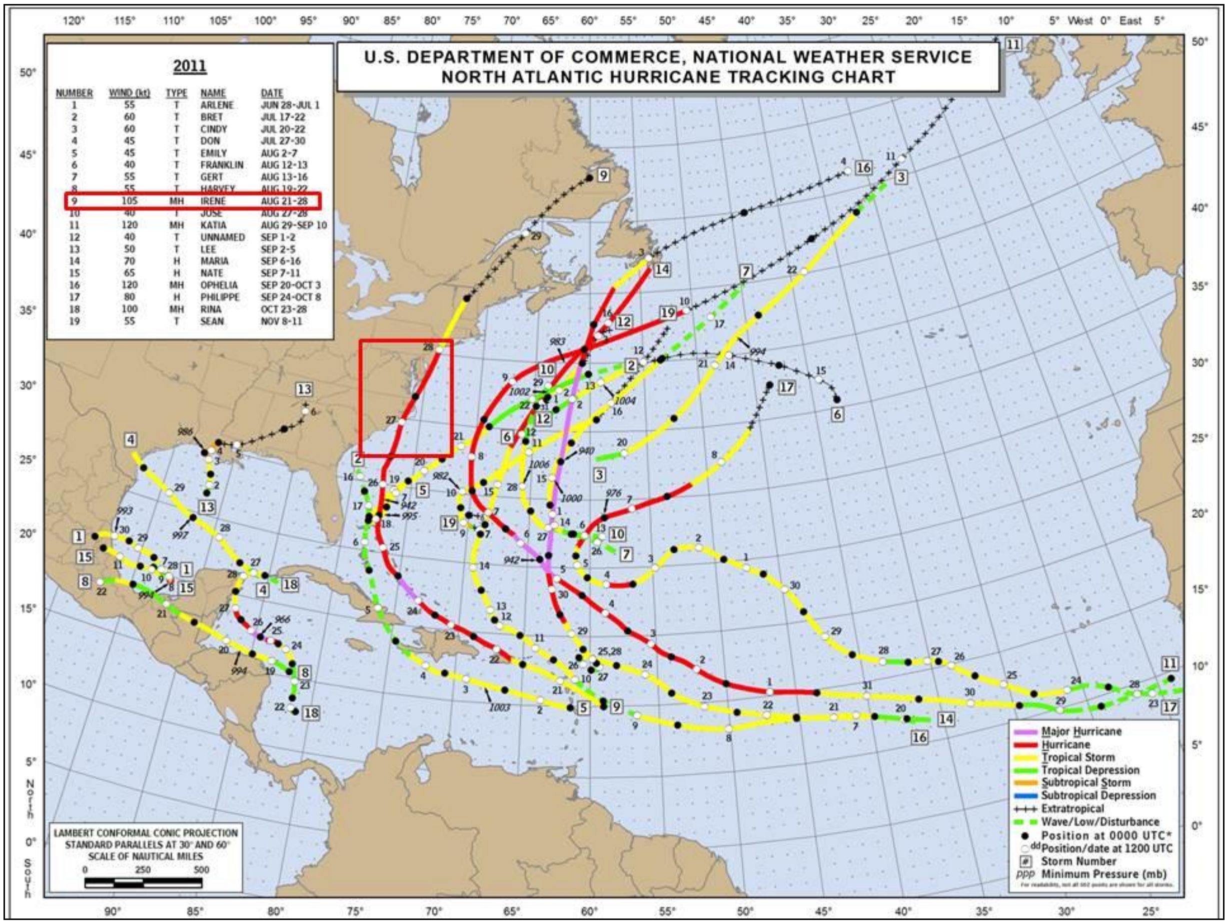


FIGURE 6-15. Storm track for Hurricane Irene that impacted Bertie County with severe flooding in August 2011. The map is from NOAA's Nation Weather Service.

Irene was a category 1 hurricane as it made landfall near Cape Lookout on the morning of August 27 with 85 mph winds (Figure 6-15). The storm tracked due north across Pamlico Sound, Albemarle Peninsula and Albemarle Sound, and then veered NNE as it entered Virginia and moved back offshore, all as a category 1 hurricane. Persistent winds were a dominant component producing storm surges reported from 7.62 feet at Oregon Inlet and up to 11 feet on different portions of NC's Inner Banks (Figure 6-16). Rainfall amounts of 5 to 15 inches were recorded along the track of the storm in NC (Figure 6-17). As this broad storm tracked north, the counter-clockwise winds first blew the waters in Pamlico and Albemarle Sounds westward producing major storm surges along the western side of the Inner Banks including the lower Roanoke, Chowan, and Cashie Rivers (Figure 6-18). As the eye of the storm moved into southeastern Virginia, the westerly winds produced destructive storm surges along the sound-side of the Outer Banks. This storm produced a broad range of destruction within the NC coastal system exceeding $1.2 billion of damage (Associated Press) and led to the official retirement of the name "Irene" (World Meteorological Organization).

FIGURE 6-16. Satellite image of Hurricane Irene on August 27, 2011 as it traveled north over the Albemarle Peninsula and Albemarle Sound. The red arrows show how the leading winds blew a major storm surge to the western side of Albemarle Sound and the following winds blew the storm surge eastward to impact the backside of the Outer Banks. NASA satellite image.

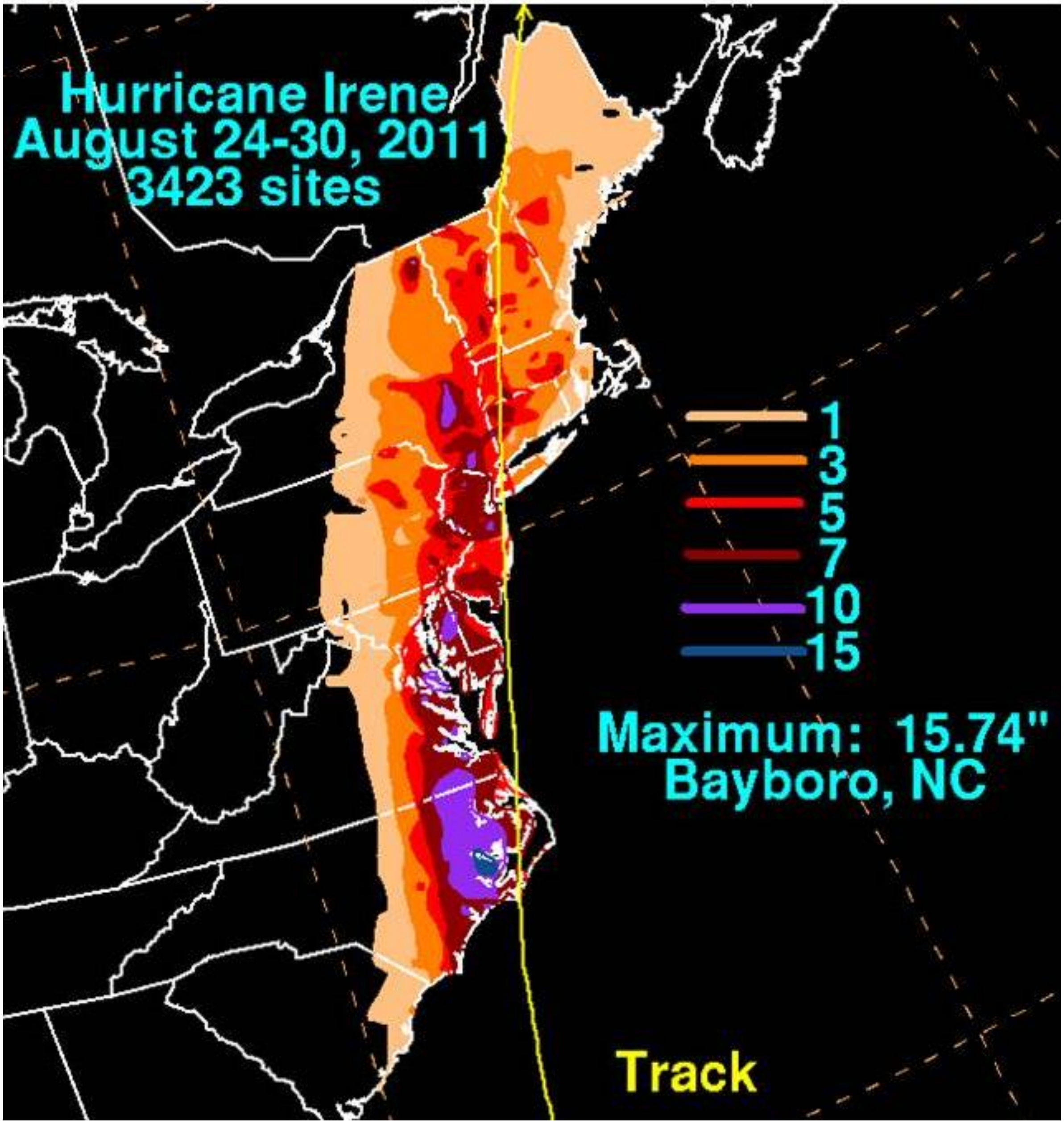


FIGURE 6-17. Map of the net rainfall associated with Hurricane Irene as the storm tracked due north across Pamlico Sound, the Albemarle Peninsula, and Albemarle Sound. The Bertie County region received up to 10 inches of rain. Data are from NOAA's National Weather Service.

According to the USGS water-level gage at Westover Hwy 45 in the lowermost Roanoke River, the western storm surge was about +5 feet above normal as the storm approached the Albemarle Sound (Figure 6-18). As the storm passed into Virgina, the backflow storm surge dropped the water level back to normal. Then the rising flood waters from upstream rainfall raised the water level about 2 feet and slowly declined over the next few days. No apparent storm surge reached the School House Road gauge; the water level rise was due totally to the approximate 5 to 7 inch rainfall in the Upper Cashie River.

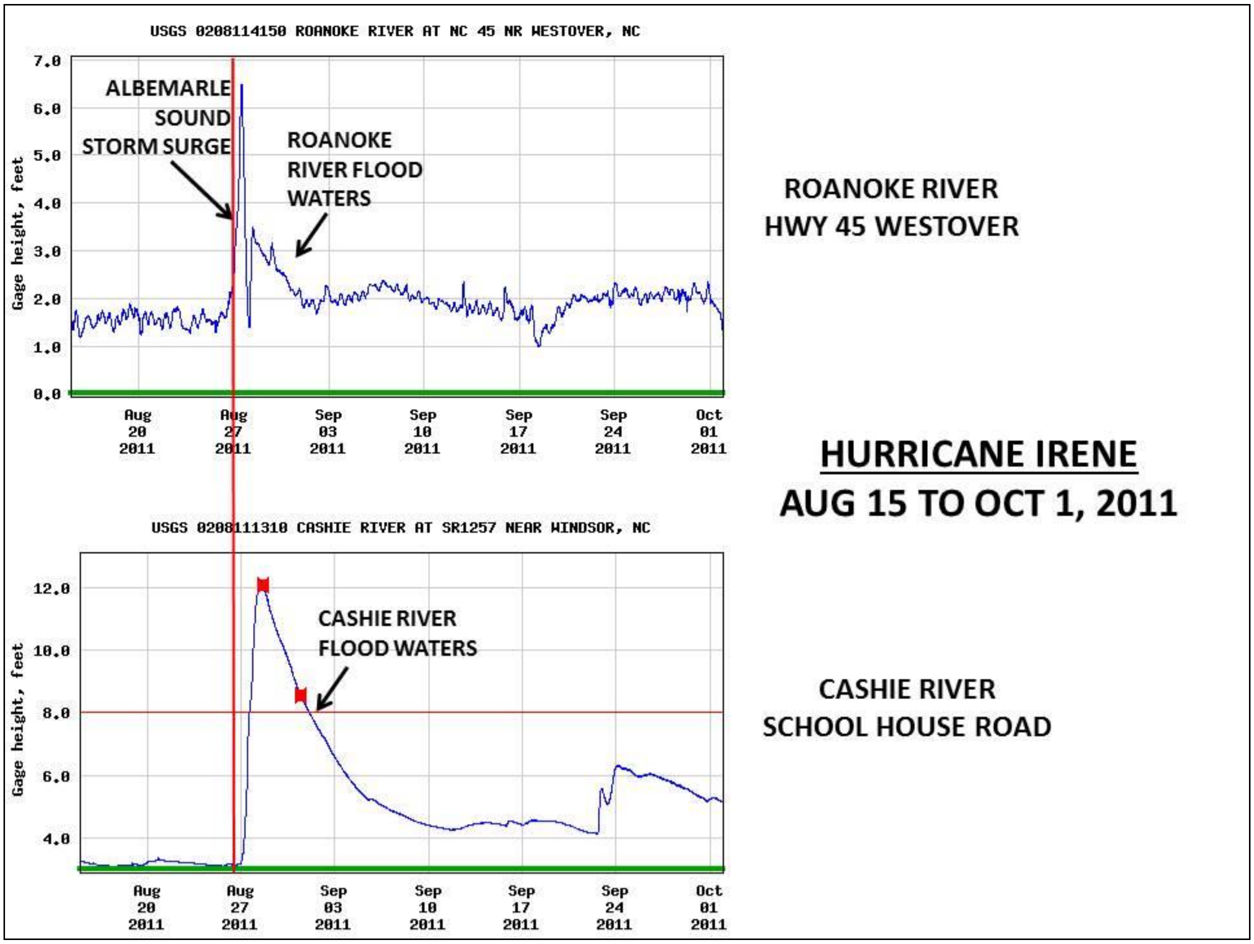


FIGURE 6-18. Water-level records from Westover Hwy 45 in the lowermost Roanoke River (upper panel) and School Rd. in the upper Cashie River (lower panel) as Hurricane Irene passed over eastern NC. Since it is the downstream pattern of flow that is important, none of these plots are corrected for absolute elevation.

What was the level of flood waters in Windsor from Hurricane Irene? Since the Lower Cashie River at the King Street gage in Windsor mimics the Hwy 45 gage and records the daily tidal cycles, it would have responded to some extent with the Albemarle storm surge. Even if only by a few inches to a few feet, it would have increased the consequences of the flood waters coming down from the upper Cashie River. If there was any increase in the elevation of the Cashie River in Windsor due to the backflow of storm surge waters that preceded the upstream discharge from the heavy rains it would have resulted in a severe flood rather than a moderate flood—inches matter when dealing with catastrophic flooding.

Hurricane Isabel, September 18, 2003

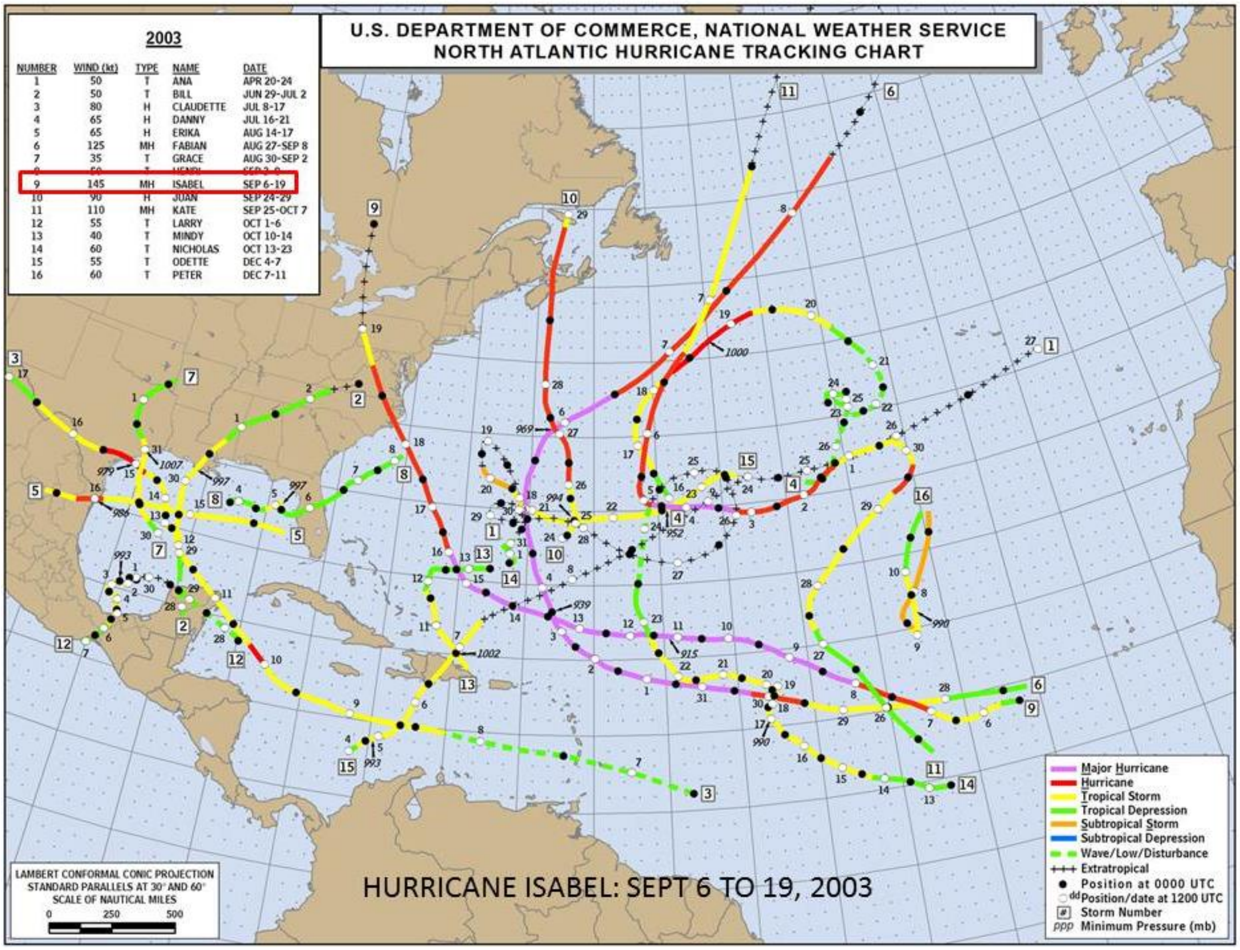


FIGURE 6-19. Storm track for Hurricane Isabel that impacted Bertie County with severe flooding on September 18, 2003. The map is from NOAA's Nation Weather Service.

Hurricane Isabel made landfall on Core Banks of the Cape Lookout National Seashore as a category 2 storm at noon on September 18, 2003 (Figure 6-19). The eye of the storm tracked NW rapidly across southern Pamlico Sound, inner portion of the Albemarle Peninsula, and then traveled through Bertie County with the eye generally following NC Hwy 45. The fast moving storm dropped 4 to 7 inches of rain, but it wasn't the rain that caused the problems in NC. Rather the strong storm surges on Pamlico and Albemarle Sounds in response to 75 to 100 mph winds caused the major damage. As the storm moved across the Inner Banks, the counter-clockwise rotation was predicted by NOAA to produce storm surges of 4 to 10 feet up the Neuse and Pamlico Rivers, and only 4 to 6 feet up the western Albemarle Sound (Figure 6-20). However, based on visual observations by Bertie County citizens, the 75 mph winds and 100 mph gusts actually produced up to 10 to 12 foot storm surges along the western shores of Albemarle Sound and the Chowan River Estuary resulting in severe shoreline erosion and flooding of low-lying structures (Figures 6-21, 6-22, and 6-23).

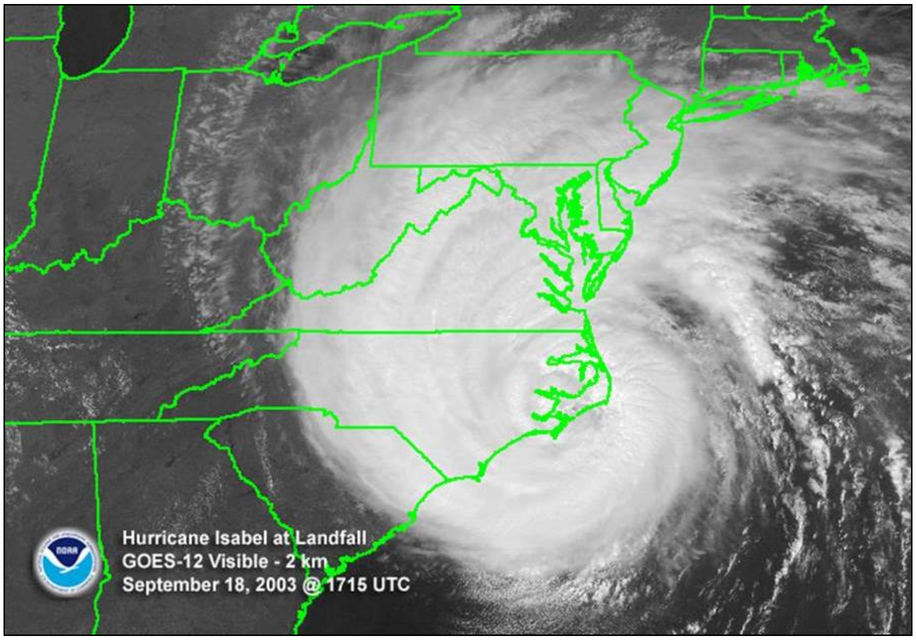


FIGURE 6-20. Satellite image of Hurricane Isabel at landfall on September 18, 2003 as it traveled northwest over the Albemarle Peninsula and Albemarle Sound, and moved across Bertie County along Hwy 45. NASA satellite image.

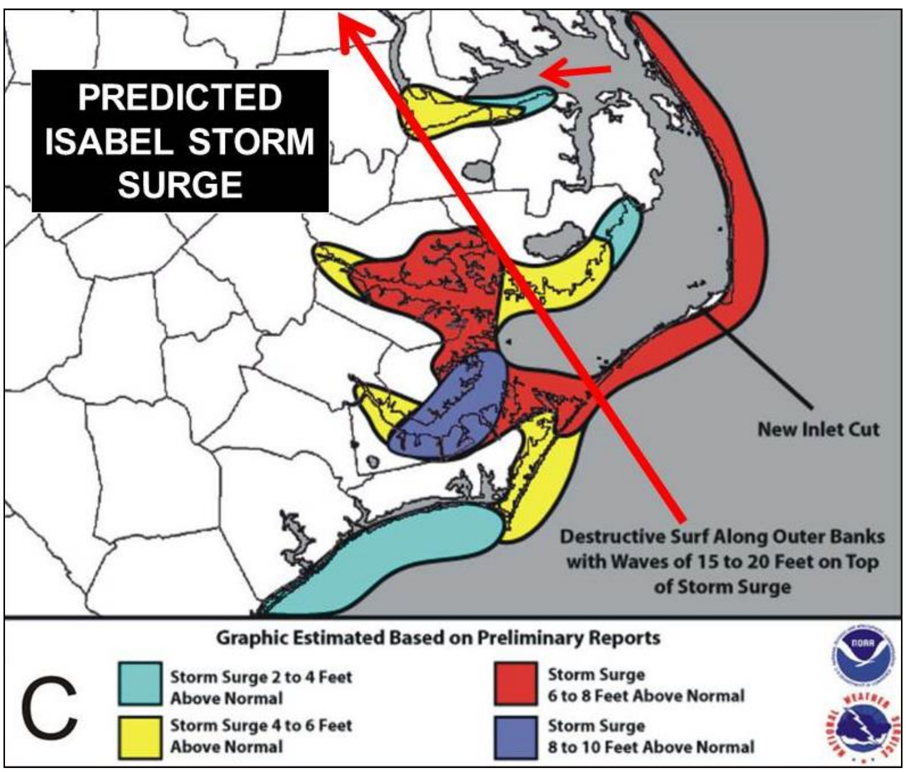


FIGURE 6-21. Map shows the predicted track and storm surge prior to the landfall of Hurricane Isabel (category 2 hurricane at landfall on September 18, 2003). The storm made landfall in the Core Banks area of Cape Lookout National Seashore. The map is from NOAA's NWS.

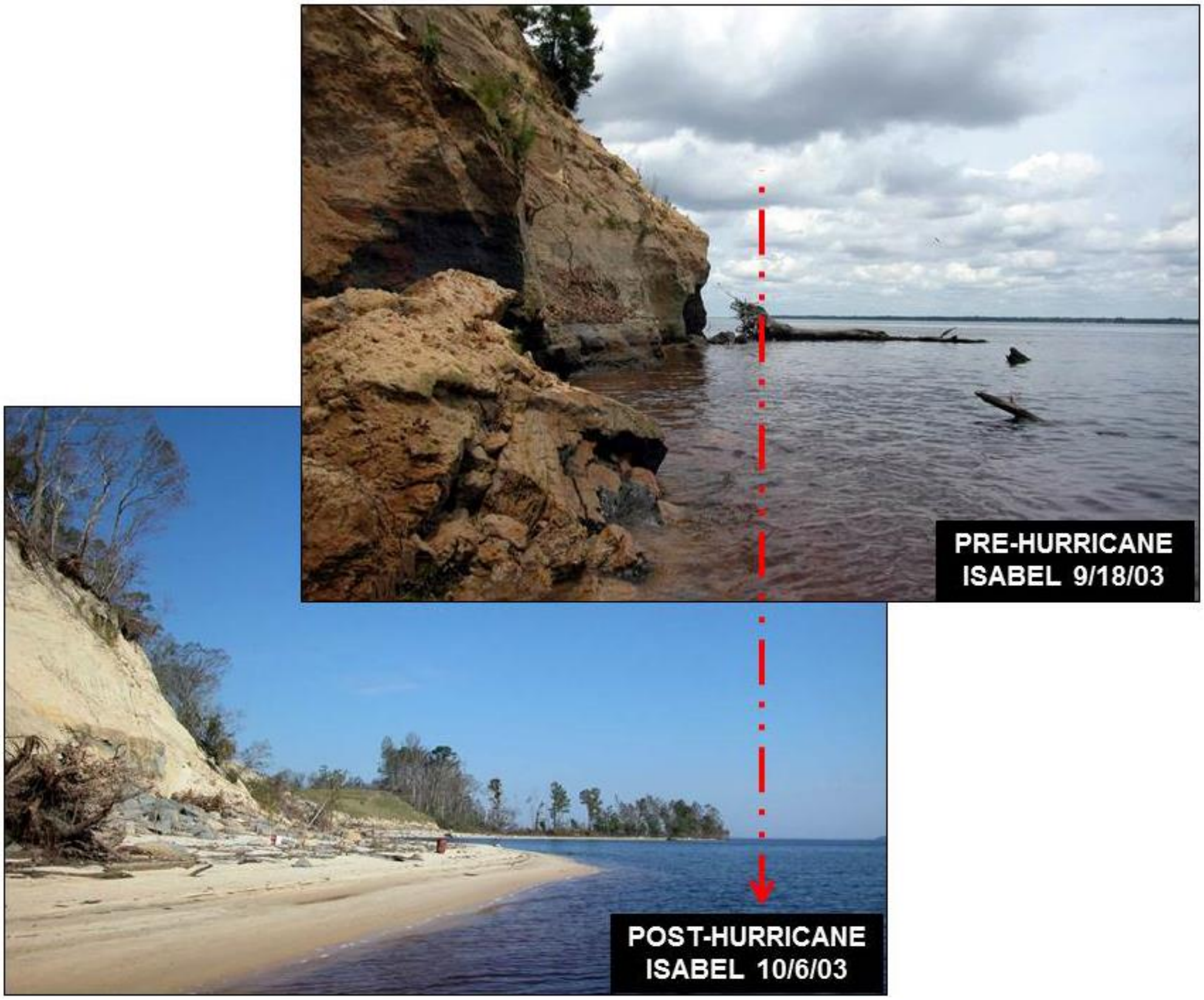


FIGURE 6-22. A pair of photographs of the Chowan River Bluff at Bull Pond before (top) and after (bottom) Hurricane Isabel passed just a few miles west of this location. In a few hours the fast moving storm produced a storm surge up to about 10 to 12 feet against the Chowan River bluffs. With wind gusts up to 100 mph, the waves caused up to 50 feet or more of shoreline erosion of the high sediment bluff shorelines and flooded the low-lying houses. Notice most of the tight gray clay layer has been eroded away leaving large clay boulders on a broad sandy beach. The red line shows the approximate pre-storm location of the shoreline. Photographs are from Riggs and Ames (2003).

FIGURE 6-23. This house, located on the Chowan River in Colerain, was severely impacted by Hurricane Isabel on September 18, 2003. The red line shows the level of Hurricane Isabel storm surge that was between 9 to 11 feet above mean water level at the base of a wooden bulkhead (blue line). The garage on the left was floated away, windows were broken out, wave driven water flooded the first floor, and the dock floated up against and scared the large pine tree on the right. Photograph is by S. Riggs.

FIGURE 6-24. Photograph of the severely modified Talbot Terrace shoreline (about 30 feet high) at the west end of Albemarle Sound where frequent storm surges up to 5 feet and occasional surges up to about 12 feet above sea level impact the shoreline (e.g., yellow line = approximate level of Hurricane Isabel). After Hurricane Isabel the eroded vertical bluff shoreline was located approximately where the red line occurs. Following the hurricane, a large volume of infill dirt was dumped, the shoreline was bulldozed back into Albemarle Sound, and bulk-headed. The bulk-head frequently fails in response to common smaller storm surges. Also, notice that there is no sandy beach due to the elimination of the eroding bluff, which was the source of the beach sand. Notice the natural cypress headland at the northern edge of the bulk-head. Photograph is by S. Riggs.

The fast moving Isabel decreased to a tropical storm as in entered Virginia that evening with the backflow of the counter-clockwise circulation blowing the water out of the Chowan and western Albermarle. This 180 degree shift in wind resulted in severe storm-surge flooding and destruction on the sound-side of Kitty Hawk on the Outer Banks. This rapid wind change probably caused the southerly and easterly winds on the back side of the storm to blow out the Cashie River allowing the rain runoff that followed to cause minimal flooding. Satellite imagery on the following, clear-sky day (September 19, 2003) shows the incredible amount of eroded sediment suspended in the waters of Albemarle Sound and associated tributary estuaries (Figure 6-25).

FIGURE 6-25. A post-Hurricane Isabel (September 19, 2003) satellite image of northeastern North Carolina shows the incredible load of suspended sediment in the waters of Albemarle Sound and its tributaries. The severe storm surge caused massive erosion of sediment bank shorelines along the western Albemarle Sound and Chowan River as a direct result of the counter-clockwise wind flow that produced a 9 to 11 foot storm surge as the storm approached Bertie County. As the storm moved into Virginia the west winds blew the sediment-laden, storm surge waters eastward flooding the sound-side of the Outer Banks. Satellite image is from MODIS Image Gallery, Space Science and Engineering Center, University of Wisconsin, Madison, WI.

<u>Hurricanes Dennis (8-24 to 9-7, 1999) and Floyd (9-7 to 9-17-1999)</u>

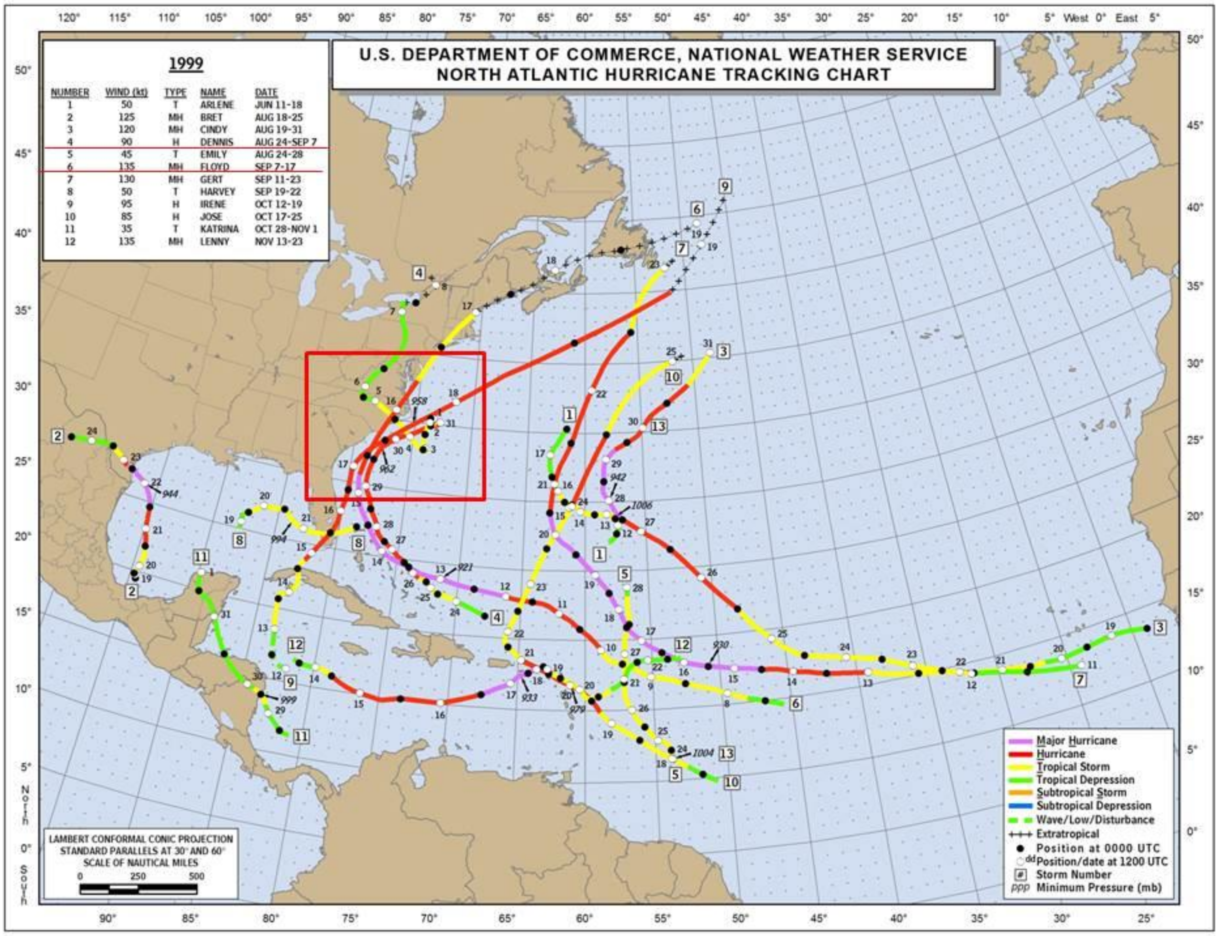
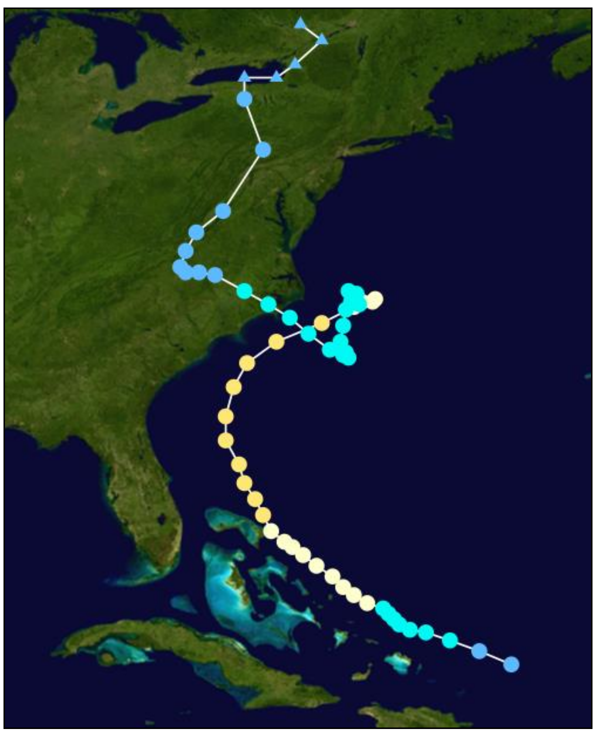


FIGURE 6-26. Storm tracks for Hurricane Dennis and Hurricane Floyd whose cumulative impact caused severe flooding in Bertie County from early September well into October of 1999. The map is from NOAA's Nation Weather Service.

North Carolina's "flood of the century" occurred primarily within the riverine sections of the coastal plain drainage system from early September through the middle of October in 1999. The magnitude of this flood was first and foremost the product of two months of severe rainfall in the North Carolina Coastal Plain (Riggs, 2001). Five different rain events (Hurricane Dennis circled by twice, Hurricane Floyd, one tropical depression, and one frontal system) produced rainfall that ranged from 20 to 40 inches during that period depending upon the location within the flood region.

These five storm events produced different kinds of flooding and damage depending on where you were within the drainage basin. For example, there were three different flash floods that sent the tributary streams quickly out of their banks and severely impacted the upland areas adjacent to the upper tributary streams. These floods dissipated just as quickly as they formed, but with a severe price tag. As the flash flood waters were discharged into the trunk streams, the main rivers began to rise and water filled the primary and secondary floodplains, as well as the lower tributary streams. With each new rain, the already saturated ground caused the tributaries to discharge more water faster into the trunk stream. Longevity of the flood was due to multiple rain events, high downstream water levels caused by back-flow from storm surges and net water discharge in the downstream estuaries, and restrictions to flow that occur within the floodplains themselves (i.e., natural riverine geometry, road dams, hydroelectric power dams, etc.).

Hurricane Dennis, a category two storm moved northeast, parallel to the NC coast on August 30 when it was degraded into a tropical storm on September 1 with an erratic track offshore of Cape Hatteras NC. By September 4 Dennis strengthened, turned NW, and made landfall at Cape Lookout as a strong tropical storm (Figure 6-27). The track of this unusually wide, slow moving storm would have caused a major storm surge in the western Albemarle and on the lower Cashie River. Dennis was also a major rain maker for northeastern NC with from 5 to 7 plus inches in the Bertie County region (Figure 6-27). On September 16 the School Rd. water-level gage recorded the highest river crest of 18.52 feet with catastrophic floods on the Cashie River in Windsor. More importantly this storm filled the rivers, floodplains, and groundwater within the adjacent uplands that set the stage for the catastrophic Hurricane Floyd.



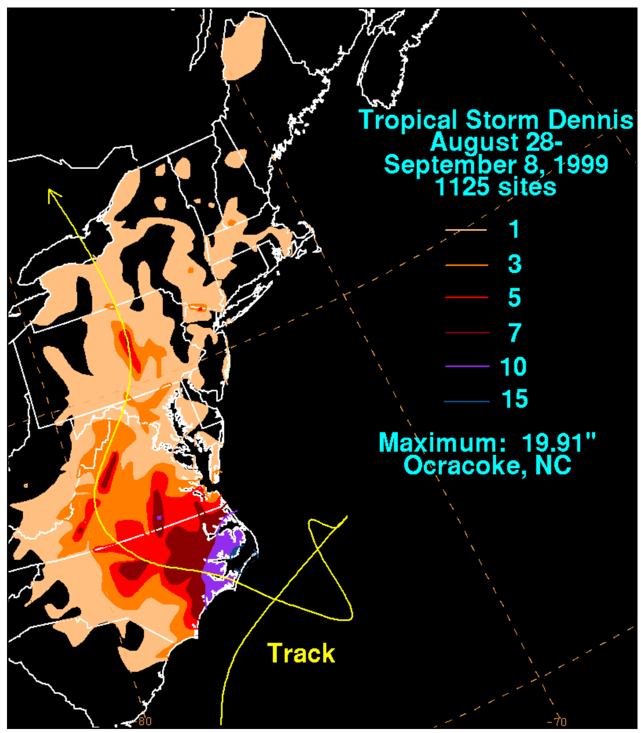


FIGURE 6-27. Map on the left shows the track of Hurricane Dennis to its location off Cape Hatteras when it became erratic and was downgraded to a tropical storm. The storm finally turned NW and made landfall at Cape Lookout. Map on the right shows the rainfall amounts in eastern NC resulting from the storm. Maps are from the NOAA's National Weather Service.

Hurricane Floyd, a powerful category 4 Cape Verde storm formed on September 7 and came ashore on September 16 as a category 2 hurricane in the Cape Fear region of southeastern

NC (Figures 6-28 and 6-29). This storm event occurred just 12 days after Tropical Storm Dennis saturated eastern NC. Floyd produced torrential rainfall in eastern NC (Figure 6-30), adding more rain to an area already flooded by Hurricane Dennis. Floyd's rain caused much widespread flooding over a period of several weeks with nearly every river basin in the eastern part of the state exceeding a 500-year flood levels. As the broad storm passed over northeast NC its track was just west of Pamlico and Albemarle Sounds resulting in storm surges of 5 to10 feet above normal along the inner portions of the Neuse River, Pamlico River, and Albemarle Sound with rain totals ranging from 4 to 18 inches (Figure 6-30).

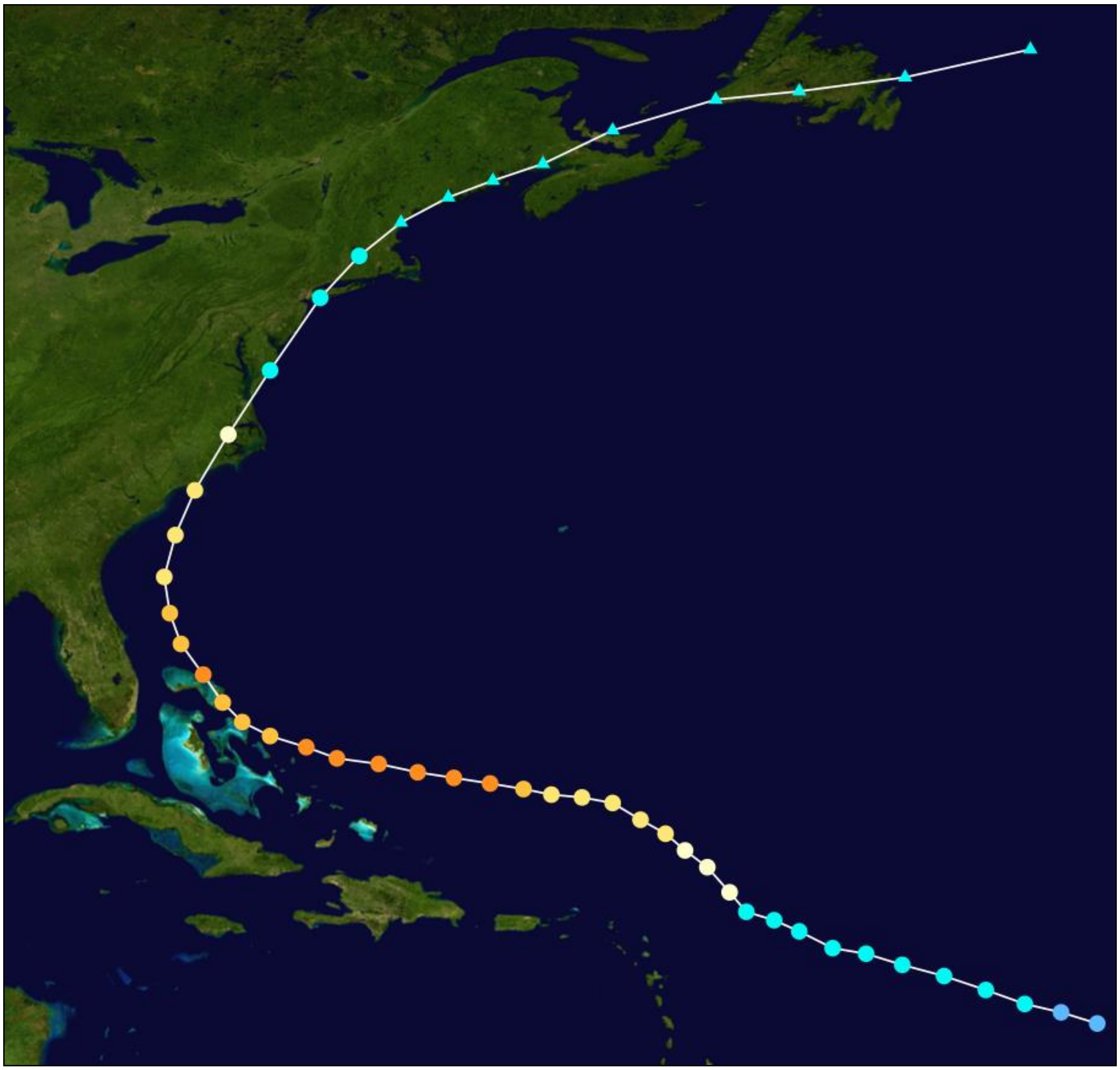


FIGURE 6-28. Map shows the track of Hurricane Floyd initially as a category 4 storm (orange dots) in the Atlantic and downgraded to a category 2 storm (cream dots) by the time it made landfall at Cape Fear, NC and traveled northeast across the Coastal Plain as one of history's major storm events. Triangles indicate tropical storm conditions. Map is from the NOAA's National Weather Service.

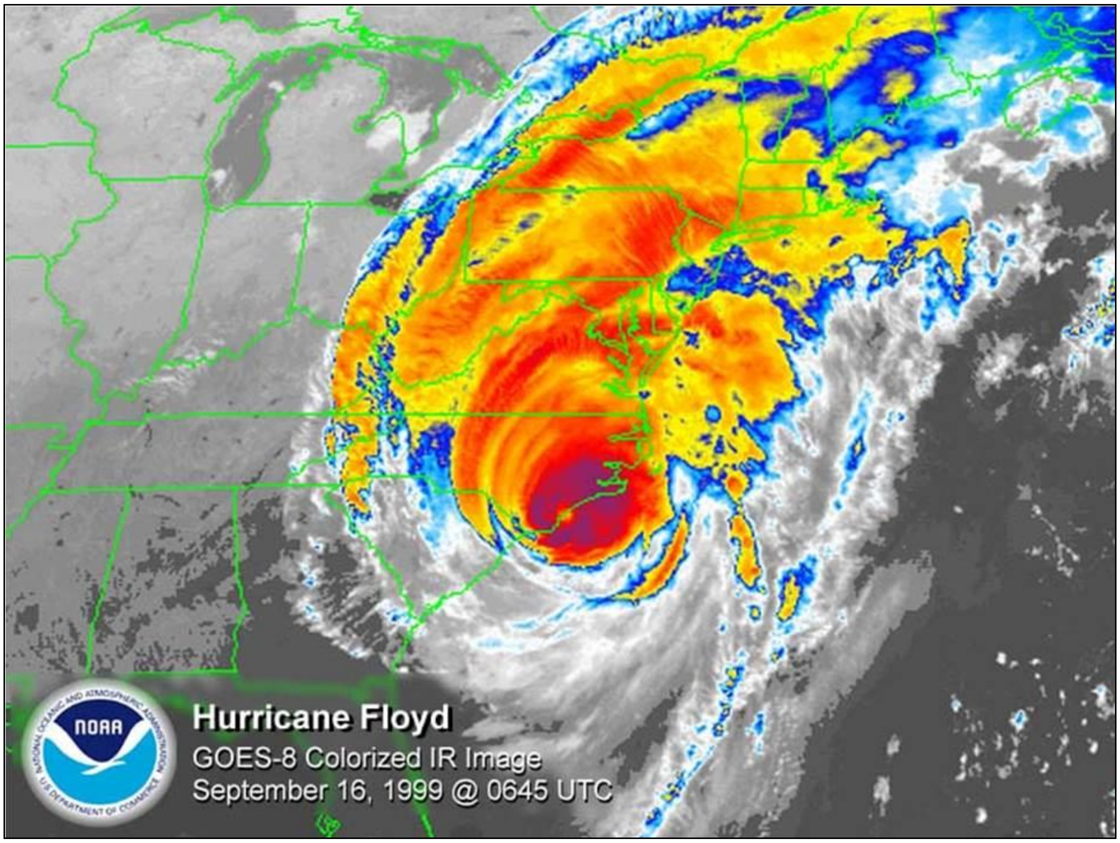


FIGURE 6-29. Satellite image of an extremely large and strong Hurricane Floyd with a well-defined eye made landfall as a category 2 storm at Cape Fear in southeastern North Carolina on September 16, 1999.

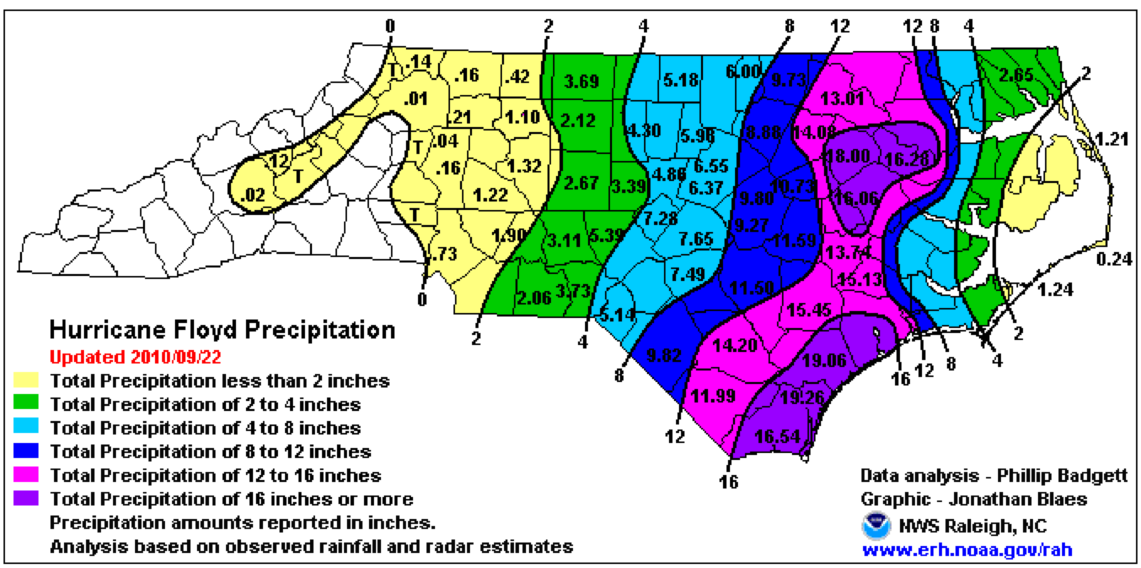


FIGURE 6-30. Map of the total Hurricane Floyd precipitation as the storm made landfall at Cape Fear on September 16, 1999 and traveled slightly NE across the central NC Coastal Plain. Map is from the NOAA NWS in Raleigh, NC.

The Questions:

Why should a smaller storm with lower precipitation total (TS Dennis) event on a generally dry landscape create an 18.52 foot water-level crest at School Road, when a much larger storm event with greater precipitation total (H Floyd) on a wet landscape resulted in only a 12.52 foot water-level crest at School Rd.?

What were the flood levels in the Town of Windsor?

Possible Scenario:

1. All of the historic data to answer these questions are not readily available, partly due to a lack of recorders in appropriate locations and partly is the lack of historical preservation of pre-existing data; but this is a possible scenario of what happened to cause this overall catastrophic flooding event in Bertie County.
2. The Dennis-Floyd catastrophic flooding event was the cumulative impact of two large events and a series of smaller and local rain events.
3. Each of the major events had extremely different tracks, rates of movement, and impacts on conditions within existing landscapes and waterscapes.
4. The precipitation levels from TS Dennis in Bertie County ranged from 5 to 7+ inches in the Bertie region that produced a water-level crest of 18.52 feet, whereas the precipitation levels from H Floyd in the Bertie region ranged from 8 to 16+ inches and produced a water-level crest of only 12.52 feet on the upper Cashie River at the School Road gage.
5. This difference in flooding response is likely due to the different track of each storm and the different effect of the wind directions and resulting storm surges.
6. TS Dennis had a NW track on the S side of Albemarle Sound resulting in strong counter-clockwise easterly winds producing a strong storm surge on the western end of Albemarle Sound. This storm surge caused a backflow up the Cashie River prior to the rainfall runoff that took several days to fill the upper Cashie River on top of a falling storm surge (Figure 6-31). The result was two crests, the first due to storm surge from about Sep. 4th to 7th and the second exceedingly high water-level crest of 18.52 feet from about Sep. 16th to 20th at the School Rd. gage. This later record crest was the result of the cumulative impact of TS Dennis rainfall on top of an already high river level resulting from the initial storm surge and resulted in almost a month-long flood.
7. In contrast, the fast moving H Floyd was east of the Bertie region and moving NE into Virginia, but did not produce a western storm surge in front of the storm. Rather, it was the storm’s back side as it moved over the Albemarle that produced westerly winds from the strong counter-clockwise flow. These westerly winds blew the water out of western Albemarle Sound creating a storm surge behind the Outer Banks. This increased the hydraulic gradient on the Cashie River, increasing the flow down the Cashie River and decreasing the catastrophic impact as compared to Tropical Storm Dennis and indicated at the School Rd. river gage (Figure 6-31).
8. Consequently, the record rainfall of 8 to 16+ inches from H Floyd caused the upper Cashie River School Rd. gage to crest at only 12.52 feet. However, this was enough to cause a second 500-year flood in Windsor with high water lasting less than two weeks.

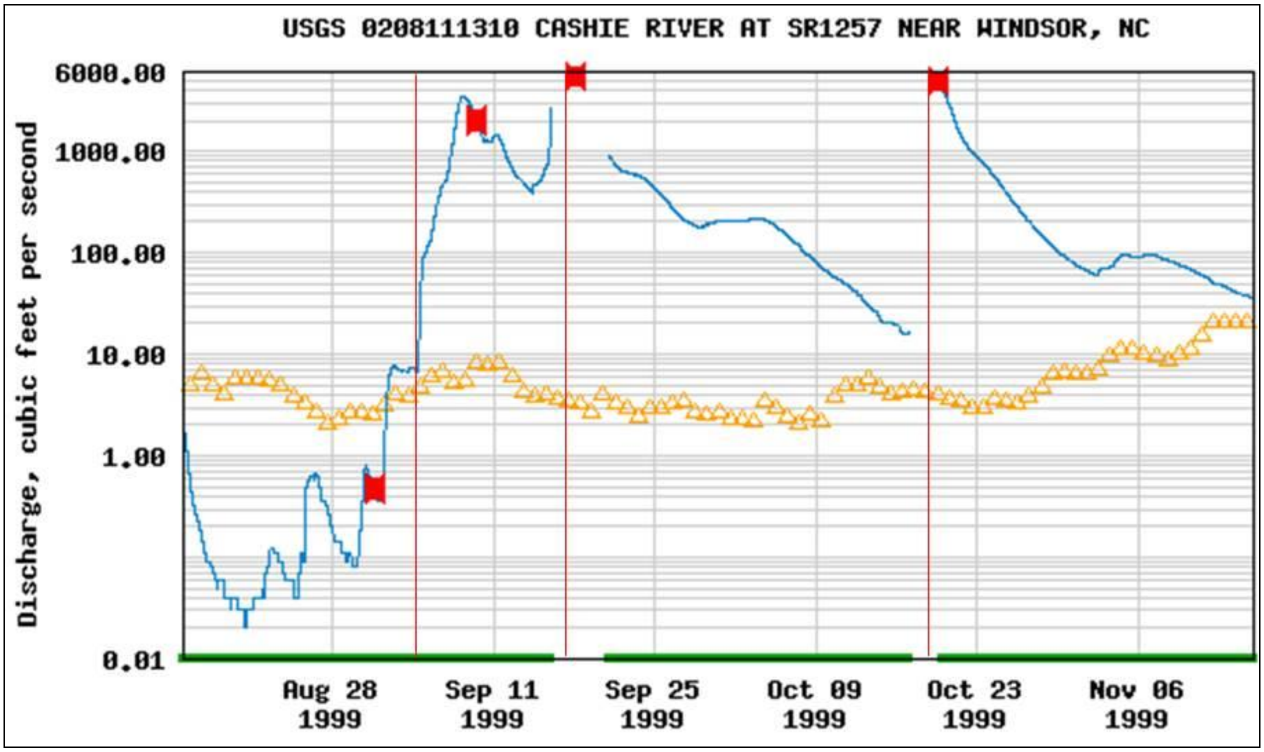


FIGURE 6-31. Plot shows the water-level discharge rate for the upper Cashie River at the USGS School Road water-level gage during Hurricane Dennis 9-4-1999 and Hurricane Floyd 10-19-1999. The first two red vertical lines show the beginning of storm surge backflow from Albemarle Sound that crested between 9-4 to 9-7, 1999 followed by the rainfall runoff crest between 9-16 to 9-20, 1999. The second crest resulted in a 18.52 foot record flood crest and catastrophic flooding in downstream Windsor. Dennis was soon followed by Hurricane Floyd, which dumped 8 to 16+ inches of rain, but without a storm surge. The now saturated Cashie River valley flooded again, but at a lower level and for a shorter time period.

APPENDIX A

BERTIE WATER SYSTEM DATA SOURCES

USGS Streamflow Data for North Carolina

Roanoke River Gages	Gage Number
Roanoke Rapids	(02080500)
Halifax	(0208062765)
Scotland Neck-Hwy 258	(02081000)
Oak City-Hwy 11	(02081022)
Hamilton	(02081028)
Williamston-Hwy 13-17	(02081054)
Jamesville	(02081094)
Westover-Hwy 45	(0208114150)

Upper Cashie River Gages

SR 1257 Windsor (School Rd) (0208111310) data go back to 1987

NC FIMAN Water-Level Recorder

Cashie River: Windsor King St. Gage–Data go back to 1/10/2013

NC LOW HOBO Water-Level Recorders

Chowan River Estuary, Colerain: N. Perry (6/26/2018 to 4/15/2019)
Pier: 36°12'20.12"N; 76°45'4.60"W

W Albemarle Sound, Bal Gra: D. Hall (6/19/2018 to 8/8/2018; lost in H. Florence)
Pier: 36° 1'0.39"N; 76°42'13.80"W

W Albemarle Sound, Salmon Creek State Natural Area: (7/12/2018 to 4/15/2019)
Dock: 36° 0'27.54"N; 76°42'20.89"W

Lower Cashie River, R. Bowling Farm: (Pier, 6/19/2018 to 4/15/2019)
Pier: 35°55'31.83"N; 76°50'3.75"W

E Roquist Creek, B. Copeland Farm: (10/23/2018 to 4/15/2019)
Piling: 35°56'45.94"N; 76°54'53.59"W

NC LOW Acknowledgements

NC Low wants to specifically thank the following individuals whose help and interest in acquiring water-level information within the various water bodies of the Bertie Water Crescent where HOBOS were installed. Their willingness to let us use their property and docks, as well as their enthusiasm for the project is greatly appreciated.

Jaquelin and Norman Perry at Colerain on the Chowan River Estuary
Dick Hall at Bal Gra on the western end of Albemarle Sound
North Carolina Coastal Land Trust and North Carolina State Parks at the mouth of Salmon Creek
Becky and Bob Bowling on the lower Cashie River

Brad Copeland on the lower Roquist Creek
Jean Richter at the Roanoke River National Wildlife Refuge
Tom Stroud at the North Carolina Partnership for the Sounds

USGS and NC Climate Data for North Carolina

Tar River Gauge, Greenville, NC (Green St) (02084000)
Lewiston and Edenton: Precipitation Gages

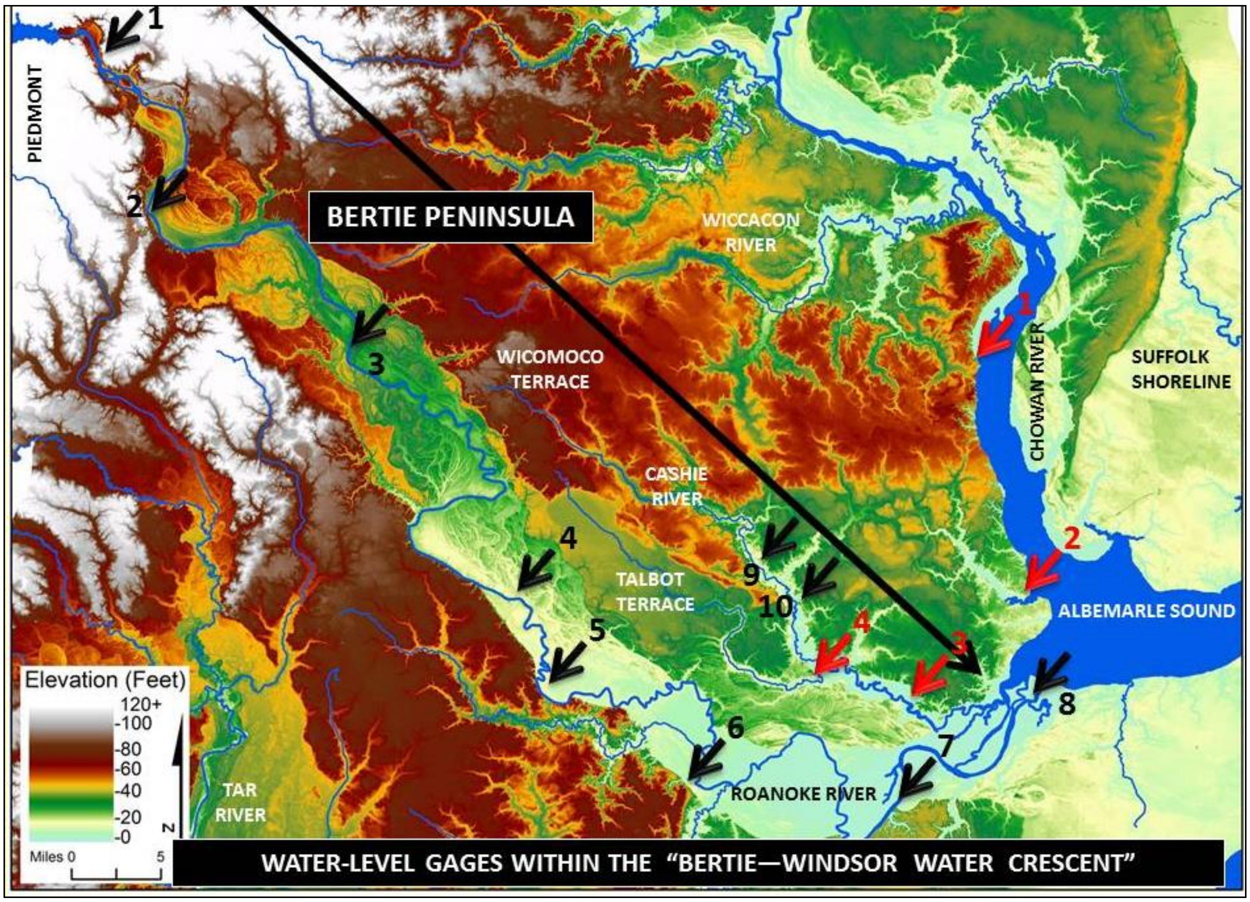


FIGURE 7-1. Color topography map of the Bertie Peninsula shows the location of 10 USGS and NC FIMAN gages (black) and 4 NC LOW HOBO (red) gages utilized for this report. Map prepared by D. Ames.

Procedures for HOBO Installation

FIGURE 7-2. Picture of the HOBO Water-Level Logger utilized at four sites in this report.

HOBO data loggers measure pressure and use the measurements to convert to depth of water. The under-water HOBO component measures the combination of atmospheric pressure, hydrostatic pressure, and water temperature. A separate HOBO component placed at the top of the PVC pipe or somewhere in the air in a nearby location to measure only atmospheric pressure. Software subtracts the atmospheric pressure from the combined pressure to derive hydrostatic pressure. Hydrostatic pressure is calibrated to water depth measured at the time of downloading data. The five underwater HOBOs were mounted within a 2 inch PVC pipe that was attached to a pier piling or driven into the creek bottom. The HOBO's were set at a measurement interval of 5 minutes with a field data download time of about six weeks. One water level recorder mounted on a pier at Bal Gra at the west end of Albemarle Sound was lost during Hurricane Florence. The other four recorders listed above worked perfectly through the time of this final report and provided data utilized in combination with the other pre-existing water level gauges (listed above) for this report.

FIGURE 7-3. Bob Christian and Bo Dame install HOBO water level recorders at Salmon Creek State Natural Area (upper left), Colerain on the Lower Chowan River estuary (upper right), Bowling Farm on the Lower Cashie River, and east end of Roquist Creek. Photographs are by S. Riggs.

APPENDIX B

INTERNET DATA SOURCES FOR THE BERTIE PENINSULA

1. COCO-RAHS Volunteer Precipitation Data
https://www.cocorahs.org/state.aspx?state=nc

2. NCSU State Climate Office (Aaron Sims-Interim Director; 919-515-3056)
https://climate.ncsu.edu/cronos
Information about the network is located at http://climate.ncsu.edu/econet
Interactive map of the stations and parameters are at the address:
http://climate.ncsu.edu/map
Historical data, please fill out an online request form at
http://climate.ncsu.edu/services/request.php or call main line at 919-515-3056 .

3. Rick Leuttich at UNC-CH-IMS Storm Surge Data and Coastal Emergency Risks Assessment
https://adcirc.org/at UNC-CH or http://nc-cera.renci.org/ or https://cera.coastalrisk.live/

4. National Weather Service
Advanced Hydrologic Prediction (NWS AHPS) at Williamston, NC
https://water.weather.gov/ahps2/hydrograph.php?wfo=mhx&gage=wlln7
North Atlantic Hurricane Tracking Charts https://www.nhc.noaa.gov/data/
National Hurricane Center https://www.nhc.noaa.gov/data/
National Weather Service, Raleigh, NC www.erh.noaa.gov/rah5

5. NOAA U.S. Monthly Climate Report Summary for June 2019:
https://www.ncdc.noaa.gov/sotc/national/201906
NOAA.gov Highlights: https://www.noaa.gov/news/
NOAA Climate.gov: https://www.climate.gov
U.S. Drought Portal: https://www.drought.gov
NOAA Sea-Level Rise Viewer: https://coast.noaa.gov/slr/#/layer/slr/1/-8484661.880896213/4298647.601442325/12/satellite/3655/0.8/2050/interHigh/midAccretion

6. North Carolina Climate site measures water levels: https://fiman.nc.gov/fiman/#
https://climate.ncsu.edu/cronos

7. US GEOLOGICAL SURVEY Current and historic hydrologic river conditions
https://waterdata.usgs.gov/nc/nwis/uv/?site_no=0208114150&PARAmeter_cd=00065,00060
https://waterdata.usgs.gov/nc/nwis/water

8. USGS Current Water Data for the Nation

Streamflow: https://waterfata.usgs.gov/nc/nwis/rt
Precipitation: https://waterfata.usgs.gov/nc/nwis/rt
Flood Event Viewer: https://stn.wim.usgs.gov/FEV/

9. Roanoke River Partners (maps with property ownership, camping platforms, & boat access)

http://roanokeriverpartners.com/resources-water-flow.aspx

10. Roanoke River National Wildlife Refuge-US Fish & Wildlife Service

http://roanokeriver.fws.gov
https://www.fws.gov/gis/data/CadastralDB/index_cadastral.html

11. US Army Corps of Engineers USACE

Water Management Status of John H. Kerr Dam
Duck Field Research Facility www.frf.usace.army.mil/149_EHAT.gif

12. Weather Underground

https://www.wunderground.com/

13. National Aeronautical and Space Agency NASA Earth Observatory

https://earthobservatory.nasa.gov/

14. S. Riggs at ECU Geology for 2008 Roanoke River report:

www.ecu.edu/cs-cas/geology/facultystaff.cfm
https://core.ecu.edu/core.ecu.edu/geology/riggs/coastal-processes-september-2008.pdf

15.North Carolina Sea Grant: https://ncseagrant.ncsu.edu/search
https://ncseagrant.ncsu.edu/ncseagrant_docs/products/2000s/coastal_processes_conflicts.pdf

17. Peanut Belt Research Station, Lewiston, NC: Weather information web site:

https://climate.ncsu.edu/cronos/?station=LEWS&temporal=daily

18. Elizabeth City, NC, US Coast Guard Station: Weather information web site:

https://climate.ncsu.edu/cronos/?station=KECG&temporal=daily

APPENDIX C

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APPENDIX D

CASHIE RIVER WATER QUALITY IN VICINITY OF WINDSOR, NC

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Final Report to North Carolina Land of Water
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Disclaimer: *This study was conducted as a student project to provide an educational experience and general overview of water quality of the Cashie River. No certified laboratory was used, techniques did not rigorously meet standard methods and no claim is made of quantitative accuracy of results. They should only be interpreted with these issues in mind.*

7 August 2019

Background

The town of Windsor, North Carolina is located in Bertie County and lies along the Cashie River. Windsor's population is approximately 3,769,[1,2] and Bertie County is designated as a Tier 1 County (most economically distressed) by the North Carolina Department of Commerce.[3] Immediately downstream of Windsor the Cashie River widens and meanders for approximately 13 miles until it coalesces with floodplains of the Roanoke and Middle Rivers before empting into Albemarle Sound. The region of the Lower Cashie is characterized by low elevation and broad cypress-gum swamps bisected by slow black water streams.

The Cashie River Basin generally, and the Windsor area in particular, undergoes annual flooding. In the past 20 years Windsor has experienced four major flood events associated with tropical cyclones occurring in the last 10 years: Hurricane Floyd (1999), Tropical Storm Nicole (2010), Tropical Storm Julia and Hurricane Mathew (2016). It should be noted that the 2016 events occurred within a 13 day period, and during the events of Hurricane Matthew the town of Windsor received upwards of 12 inches of rain, and the Cashie River at School Road crested 8 feet above flood stage. Each flood event resulted in severely damaged homes and local businesses, specifically Hurricane Matthew, totaling over $2.8 million in damages. In a news statement[4] after Hurricane Matthew, Mayor Jim Hoggard stated, "There's nothing we can do to stop the Cashie from running over its banks."

In the aftermath of the 2016 storms, there was strong desire to plan for the sustainability of Windsor due to its historic and economic significance to Bertie County. Grant funding became available to support two flood studies of the Cashie River Basin. One study, undertaken by NC State University and NC Sea Grant, examines upstream processes to identify engineering options for reducing the direct flow of flood water into the town of Windsor.[1] A second study, referred to as the Bertie Water Crescent Project, is being conducted by North Carolina Land of Water (NCLOW - http://www.nclandofwater.org/). The focus of this investigation is more on downstream processes contributing to the chronic flooding problem, as well as examining long-term sustainability options with respect to eco-tourism. The water quality component for the Bertie Water Crescent Project was conducted by the Biology Department at Chowan University.

Study Objectives

The study by the Biology Department at Chowan University, led by Drs. Brian Duffy and Bo Dame with the assistance of two undergraduate students (K. Alexis Bolam and Skadi Kylander), evaluated water quality dynamics of the Cashie River. Study objectives were to identify variation in water quality variables and assess any relationship between the variables and water level. The study examined if there are specific times, locations, or conditions that challenge water quality in the area, and assessed if water quality in the Cashie River can be considered of high quality and be an additional regional asset for encouraging eco-tourism and sustainable development. Specific water quality variables that were measured include standard physical parameters (Tables B4-7), bacterial analyses (Table B8), and nutrients (Tables B9-B11). Local weather conditions and water level data were recorded during each sampling event.

Methods

Water samples were collected monthly and when possible after major precipitation events beginning in August 2018. Four sampling sites were used and including two sites located upstream of Windsor, one in Windsor and one downstream (Figure 1). Site codes and GPS coordinates of the sampling locations are found below in Table 1.

Table 1: GPS coordinates and description of water sampling sites.

Sampling Site	Code	Latitude	Longitude	Description
Francis Mill Road	FM	N 36.12417°	W 77.12112°	Bridge on Francis Mill Road.
School Road	SR	N 36.04764°	W 76.98508°	Bridge on School Road.
Nature Center	NC	N 35.99112°	W 76.94344°	Dock at Roanoke River National Wildlife Refuge Administration Building & Visitor Contact Station.
Sans Souci	SS	N 35.91130°	W 76.81709°	Pier adjacent to boat ramp at the Sans Souci Ferry.

Variables that were measured during each sampling event include the following:

- Nitrogen as ammonia (NH_3-N) and nitrate (NO_3^-), and soluble reactive phosphorus (PO_4^{3-})
- Physical parameters (ratio of water depth to Secchi depth, water temperature, pH, dissolved oxygen, and conductivity*)
- *E. coli* and coliform bacteria**

**Conductivity technique and equipment was found to be inconsistent and unreliable, and therefore is not reported within this document.*
***Bacteria parameter was added during the November 2018 sampling event*

Nutrient analyses were performed using a Hach Water Testing Kit (#25598-33), and physical parameters were measured using a YSI 30 conductivity meter, YSI 60 pH meter, and a YSI Pro 20 meter with DO sensor. Water transparency and water depth were estimated using a standard 20 cm diameter Secchi disk. *E. coli* and coliform bacteria were estimated using Micrology Labs' Coliscan Easygel procedure (https://www.micrologylabs.com/page/93/Coliscan-Easygel). A SPER Scientific Mini Environmental Meter was used for measuring air temperature and relative humidity, and local weather conditions just prior to, and during, sampling events were recorded from the Weather Underground station (https://www.wunderground.com/) nearest to the study area. Stream flow characteristics (including gauge height and discharge) were obtained from the United States Geological Survey's Water Resources webpage for USGS Gauge 0208111310 Cashie River at SR1257 near Windsor, NC. (https://nwis.waterdata.usgs.gov/nc/nwis/uv?cb_00060=on&cb_00065=on&format=html&site_no=0208111310&period=&begin_date=2018-11-08&end_date=2018-11-09)

Results

Significant precipitation events occurred during or immediately before the December 2018, January 2019, February 2019, March 2019 and April 2019 sampling events. It was also noted that the May 2019 event was significantly higher in air temperature than previous samplings. Data from the USGS Stream Gauge at SR 1257, which corresponds to the School Road sampling station, is shown in Table 2 below.

Table 2: Data from the USGS Stream Gauge at SR 1257.

Sample Date	**8/31**	**10/12**	**11/8**	**12/13**	**1/15**	**2/19**	**3/25**	**4/16**	**5/9**
Time	15:00	15:30	15:45	10:00	15:00	17:15	17:15	16:15	12:15
Water Level (ft)	2.87	3.89	3.56	6.72	6.03	6.07	4.57	6.14	2.87
Discharge (ft^3/s)	6.78	51.6	33.7	488	315	324	100	339	7.30

Only one weather station was found through Weather Underground within the study area. It is located approximately 5 miles due east of Windsor (36.005^o N, 76.782^{o}W; Station Name = Karo White; Station ID = KNCWINDS12). Total precipitation amounts recorded at this station for each sampling date plus two days prior are shown in Table 3 below.

Table 3: Total Precipitation Amounts at Karo White Station.

Sample Date	**8/31**	**10/12**	**11/8**	**12/13**	**1/15**	**2/19**	**3/25**	**4/16**	**5/9**
Total Precipitation (inches) for 2 Days Prior to Sample Date	No Data	No Data	0.17 (Sample Date Only)	0.21	1.12	0.56	0.94	0.03	0.00

Water transparency was estimated using a Secchi disk, a common instrument that may be interpreted in different ways. Results may allow one to make conclusions about the trophic state of a water body (Oligotrophic – very clear water, Mesotrophy – water moderately clear, Eutrophic – high density of plants and phytoplankton that could be unpleasant for swimming, or Hypereutrophy – water is not suitable for recreation). In contrast turbid and blackwater streams, transparency may depend more on non-living and naturally occurring material dissolved or mixed into the water. The ratio of the Secchi depth to water depth is a metric of water transparency, where the larger the ratio value, the more transparent the water or at least how much of the water column is lit. Values closer to 1 are indicative of light penetrating to the bottom. Generally, Secchi depth was less than half the water column depth at most sites and times (Table 4). Light penetrates farther into the water column than this but with decreasing amounts. Note that this ratio depends both on the attenuation or decrease in light and the depth of water.

Table 4: Ratio of Secchi Depth to Water Depth in meters (m).

Site	**8/31**	**10/12**	**11/8**	**12/13**	**1/15**	**2/19**	**3/25**	**4/16**	**5/9**
FM	0.41	0.26	0.42	0.76	0.54	0.43	0.53	0.33	0.39
SR	0.21	0.31	0.36	0.27	0.38	0.16	0.33	0.36	0.21
NC	0.16	0.15	0.19	0.23	0.19	0.25	0.27	0.19	0.21
SS	0.51	0.47	0.54	0.48	0.38	0.54	0.41	0.48	0.40

Table 5 shows the pH values obtained during the study. pH is the measure of how acidic or basic the water is on a scale of 0 – 14; a common pH for river water is around 7.4[5,6], but blackwater streams would be normally expected to be more acidic. pH values that are too acidic within a blackwater stream (<4) can be harmful to fish, plants, or for recreational water use. The pH of the Cashie River is near neutral and reasonable for recreational purposes.

Table 5: pH values for each site during the study period.

Site	**8/31**	**10/12**	**11/8**	**12/13**	**1/15**	**2/19**	**3/25**	**4/16**	**5/9**
FM	7.34	6.31	6.40	7.12	7.78	7.73	7.85	7.49	6.91
SR	7.36	6.54	6.50	7.30	7.66	7.60	7.60	7.02	6.92
NC	7.44	7.33	6.32	7.89	8.20	8.28	7.98	7.41	7.04
SS	7.90	6.90	6.89	7.19	7.70	7.91	7.91	7.21	7.32

Aquatic organisms require an adequate supply of dissolved oxygen (DO) gas. Optimal DO concentrations for most fish species range between 7-12 mg/L.[5,6] Oxygen levels that remain below 5 mg/L can be damaging to fish growth and 1-2 mg/L (called hypoxia) can result in fish kills. A deficiency of oxygen can be the result of bacteria or animal waste or too much algal growth and decay. Or low DO may simply be the result of natural organic matter from leaf-fall into the stream. Conversely, too much DO (or percent saturation) is not ideal as high levels usually result from photosynthesis by large amounts of uncontrolled plant growth and algal blooms, potentially from fertilizer runoff. DO values recorded during the study period are displayed in Table 6, and include the percent saturation where 100 percent saturation is most desirable (the values were converted using the following site: http://www.waterontheweb.org/under/waterquality/dosatcalc.html).

All sites demonstrated DO concentrations ≤5 mg/L during warm months, but no one site consistently had the lowest concentrations. The greatest number of hypoxic samples was FM, most upstream; and SS, most downstream, had no concentrations ≤2.0 mg/L. As indicated, blackwater streams have large amounts of naturally occurring organic matter. Its decomposition may be responsible for the low DO, or it might result from decomposition of imported organic matter from human sources. The cause remains to be identified. During cooler months, DO is close to saturation for all sites.

Table 6: Dissolved Oxygen in mg/L (Percent Saturation).

Site	**8/31**	**10/12**	**11/8**	**12/13**	**1/15**	**2/19**	**3/25**	**4/16**	**5/9**
FM	1.10 (13.3)	2.06 (24.9)	1.80 (21.8)	11.35 (137.37)	11.86 (143.5)	10.09 (122.12)	9.86 (119.3)	7.61 (92.1)	2.57 (31.1)
SR	2.01 (24.3)	3.43 (41.5)	2.82 (34.1)	11.22 (135.8)	11.01 (133.3)	9.17 (110.9)	8.44 (102.2)	5.77 (69.8)	2.39 (28.9)
NC	5.47 (66.2)	1.63 (19.7)	3.20 (38.7)	10.91 (132.1)	10.72 (129.8)	8.99 (108.8)	8.06 (97.6)	4.34 (52.5)	2.03 (24.6)
SS	2.10 (25.4)	3.14 (38)	6.63 (80.2)	7.31 (88.5)	7.19 (87.0)	9.04 (109.4)	9.67 (117.0)	4.83 (58.5)	5.27 (63.8)

Temperature is a major control on biological growth and metabolic rates and can govern the types of organisms found. Most aquatic organisms can survive with a temperature range of 5-25 degree Celsius. Generally sites were found to be maintained between these temperatures (Table 7). August 13, 2018 had the highest temperatures and exceeded 25 degrees. It should be noted that water temperature and DO are inversely related – as water temperature rises, the oxygen solubility decreases and respiration increases. Colder water conditions should be able to hold more oxygen and respiration is less.[7] This relationship is consistent within that found in the Cashie River.

Table 7: Water Temperature in degree Celsius (^oC).

Site	8/31	10/12	11/8	12/13	1/15	2/19	3/25	4/16	5/9
FM	27.2	21.6	17.0	4.6	5.1	8.7	16.2	17.8	22.7
SR	27.1	22.7	17.4	4.6	5.1	9.0	14.9	18.3	21.7
NC	29.7	27.0	16.9	5.3	4.7	9.8	15.2	18.8	23.5
SS	30.2	25.5	18.1	6.9	8.9	9.4	14.7	20.9	23.5

Although bacteria are present in lakes, rivers, and streams, most are considered not harmful. Certain bacteria like *Escherichia coli* or *E. coli* are found in the intestines of warm blooded animals, such as humans. It is a member of a group called fecal coliform and is a strong indicator of sewage or animal waste contamination. A more general group is the total coliforms (or just coliforms), which may include species not associated with feces. In North Carolina surface waters that are designated for primary recreation should have fecal coliform levels that do not exceed 200 colonies per 100 milliliter (mL).[8] This regulatory bacterial density is called the maximum contaminant level (MCL) for recreational waters. It should be noted, however, that occasional higher numbers are common after storm events or where agricultural runoff occurs. High densities after storms are more common for coliforms more than fecal coliforms. The values reported are calculated *E. coli* and coliform colonies per 100 mL (Table 8). Note that fecal coliforms were not measured, and therefore our results do not directly address legal requirements. We will not address the general coliform densities, as these may not be good indicators of fecal contamination when compared to *E. coli* in natural surface waters. Six of 28 samples equaled or exceeded 200 colonies per 100mL with *E. coli* levels, and all but one were all less than 500 colonies per 100 mL. No one site had more than 2 high levels. More assessment of bacterial water quality may be warranted using a certified laboratory and appropriate methodology.

Table 8: Calculated *E. coli* / Coliform (colonies per 100 mL).

<u>Site</u>	8/31	10/12	11/8	12/13	1/15	2/19	3/25	4/16	5/9
FM	-	-	0 / 50	0 / 350	50 / 900	200 / 2450	200 / 500	50 / 2200	0 / 800
SR	-	-	100 / 400	0 / 3700	50 / 2500	300 / 5750	450 / 400	0 / 2150	50 / 750
NC	-	-	50 / 350	50 / 3150	150 / 5700	300 / 5050	100 / 5050	0 / 3250	100 / 1950
SS	-	-	0 / 400	500 / 1200	0 / 200	0 / 350	0 / 100	0 / 350	0 / 1500

Nitrate (NO_3^-) is one of the most common contaminants in rural areas as it originates from fertilizers, septic systems, and manure storage. Nitrogen from fertilizer not taken up by plants or crops can be carried away by surface runoff and can leach into groundwater. Natural levels of nitrate are usually less than 1 mg/L; however, concentrations over 10 mg/L can be detrimental to health and will have an effect on the aquatic environment.[5-8] As apparent from Table 9, measureable concentrations of nitrate were rare. Only 7 of 36 samples had measureable concentrations. No sampling event yielded alarming levels of nitrate. Only December 13, 2018 demonstrated detectable concentrations at all 4 sites. It should be noted that positive and negative controls were used in conjunction with each nutrient analysis due to the frequency of near-non-detectable (ND) values obtained.

Table 9: Nitrate (NO_3^-) Nutrient Analysis Results in mg/L.

<u>Site</u>	8/31	10/12	11/8	12/13	1/15	2/19	3/25	4/16	5/9
FM	ND	ND	ND	1.0	ND	ND	ND	ND	ND
SR	0.2	ND	1.0	0.5	ND	ND	ND	ND	ND
NC	1.5	ND	ND	2.0	ND	ND	ND	ND	ND
SS	ND	ND	ND	2.0	ND	ND	ND	ND	ND

Two forms of Nitrogen exist within the Total Ammonia Nitrogen analysis: ammonia (NH_3) and ammonium (NH_4^+). Ammonium is generally dominant in most natural waters. NH_3 is reported as toxic to freshwater organisms at concentrations from 0.53 – 22.8 mg/L. There are numerous potential sources: accidental agricultural release, residential disposal (of ammonia containing products), waste water, atmospheric depositions, and point sources, like mining and industrial operations.[9]

In order to determine specific ammonia forms from the obtained total Ammonia Nitrogen analysis, NH_3 or NH_4^+, a mathematical equation (shown below) utilizing the table provided from the Hach Kit[10] was used. The representative calculated ammonium values are presented (mg/L NH_4^+):

Calculated NH_3= ((Hach Kit NH_3-N test result (mg/L) x percent NH_3 from table provided in Hach Kit) / 100) x 1.2

Calculated NH_4^+= *(Hach Kit NH_3-N test result (mg/L) x (100 - percent NH_3 from table provided in Hach Kit) / 100) x 1.3*

Ammonium concentrations (and hence ammonia concentrations) were undetectable most times. This is partly related to the insensitivity of the Hach method (Table 10). Detectable concentrations occurred only in warmer months. Highest concentrations occurred on May 2019 (Table B10). These higher concentrations may result from greater respiration of organic matter in the river or run-off. The source can not be determined here.

Table 10: Calculated Ammonium (NH_4^+) Nutrient Analysis in mg /L.

Site	**8/31**	**10/12**	**11/8**	**12/13**	**1/15**	**2/19**	**3/25**	**4/16**	**5/9**
FM	0.26	ND	ND	ND	ND	ND	ND	ND	0.52
SR	0.19	ND	ND	ND	ND	ND	ND	ND	0.39
NC	ND	ND	ND	ND	ND	ND	ND	0.13	0.13
SS	ND	ND	ND	ND	ND	ND	ND	ND	ND

Phosphorus is one of the key elements necessary for plant growth. The most common form of phosphorus in rural areas and surface waters is orthophosphate (i.e., soluble reactive phosphorus (SRP)), which is produced by natural processes during decomposition. It is found in fertilizers and sewage and can be released into waters from both sources. Measuring SRP can also be useful in predicting algal and plant growth. Phosphate ions, like PO_4^{3-}, are rarely toxic to humans or aquatic life unless found in high concentrations; however, it could stimulate the growth of phytoplankton and aquatic plants, which would decrease the amount of DO available in the water system and could lead to eutrophication.

Concentrations of phosphate greater than 0.1 mg/L could impact on riverine algal growth.[5-7] Detectable concentrations of SRP were commonly found at all sites beginning with the November 8, 2018 sampling (Table 11). Concentrations at Francis Mill Road were often the highest, while those at Sans Souci were the lowest. Concentrations tended to be either low throughout the river or trended to decreasing concentrations from upstream downward.

Table 11: Soluble Reactive Phosphorus (PO_4^{3-}) Nutrient Analysis in mg/L.

Site	**8/31**	**10/12**	**11/8**	**12/13**	**1/15**	**2/19**	**3/25**	**4/16**	**5/9**
FM	ND	ND	0.80	0.04	0.02	0.10	0.04	0.50	0.68
SR	ND	ND	0.27	0.06	0.02	0.16	0.04	0.18	0.56
NC	ND	ND	0.21	0.04	0.04	0.02	ND	ND	0.24
SS	ND	ND	0.04	0.06	0.02	0.02	ND	ND	0.02

Conclusions

Data from this study suggest generally good water quality conditions at our study sites in the Cashie River during the fall and winter months sampled. Although at times some contaminants (nutrients or *E. coli*) had elevated values, no sustained, alarming trends were detected at any site during the study period. The May 2019 sampling event did have elevated values for total nitrogen ammonia and soluble reactive phosphorus. Low dissolved oxygen events were typically more common during the warner months. These results indicate the need for additional monitoring during summer months to document conditions at the time of year when many local water quality issues may emerge. Continued monitoring beyond the summer is also recommended to establish long-term trends and to capture impacts of future storm events. Additional recommendations include:

- Incorporate standard laboratory methods for nutrient analyses to allow for more precise data and determination of small concentrations that are not within the capabilities of a Hach Kit.
- Expand the number of sampling sites that likely involve increased storm runoff from more developed areas within and around the town of Windsor.
- Increase the number of parameters measured including chlorophyll concentration, benthic invertebrates, plankton, and fish. For the latter three parameters suggested, presence-absence of key indicator taxa and diversity indices are often used as standard biological indicators of water quality.

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