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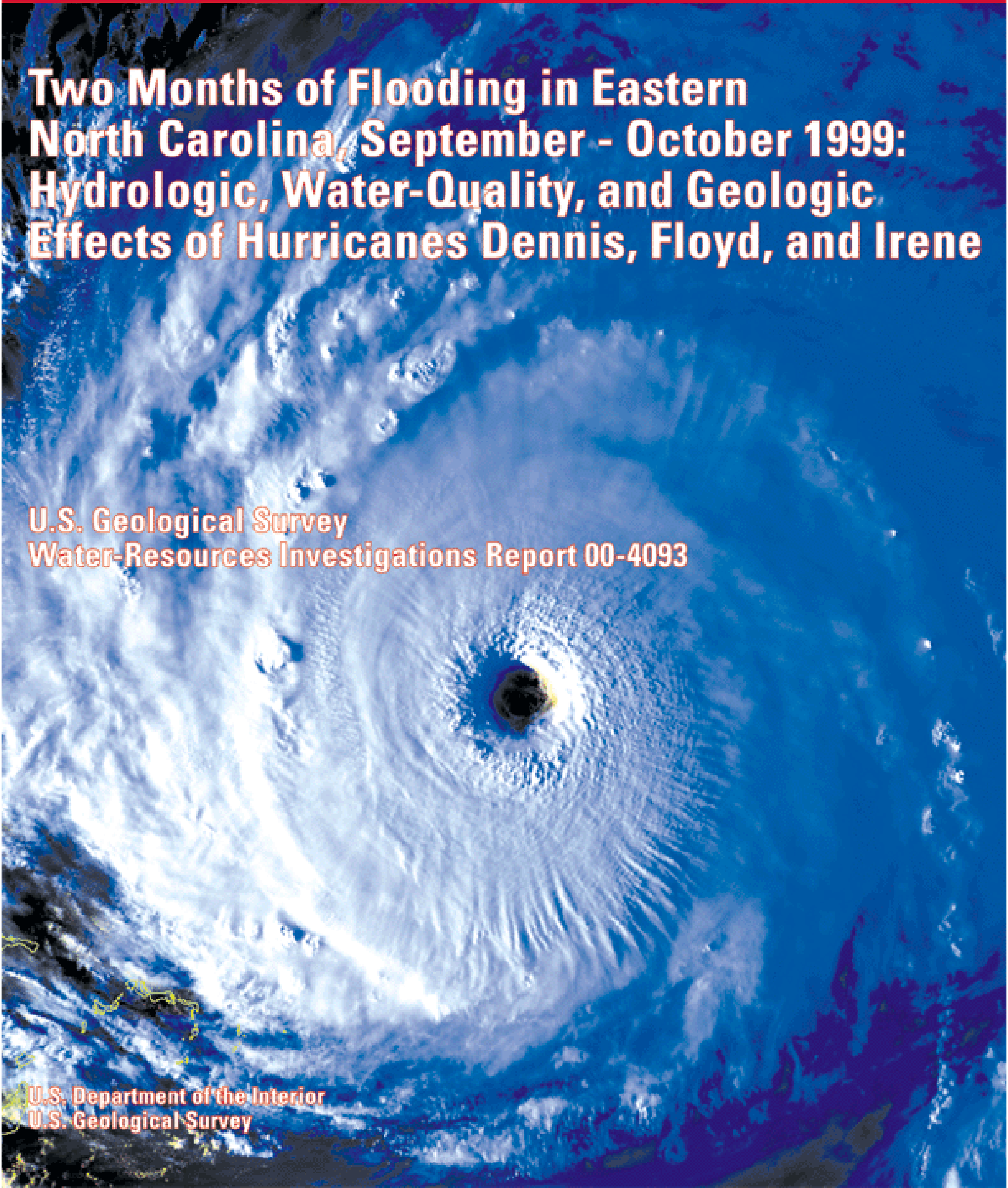
Two Months of Flooding in Eastern North Carolina, September - October 1999: Hydrologic, Water-Quality, and Geologic Effects of Hurricanes Dennis, Floyd, and Irene



U.S. Geological Survey
Water-Resources Investigations Report 00-4093

U.S. Department of the Interior
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Two Months of Flooding in Eastern North Carolina, September–October 1999

Hydrologic, Water Quality, and Geologic Effects of Hurricanes Dennis, Floyd, and Irene

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U.S. DEPARTMENT OF THE INTERIOR
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The combined effects of Hurricanes Dennis, Floyd, and Irene in September and October 1999 resulted in 2 months of flooding throughout most of eastern North Carolina. Hurricane Dennis battered the Outer Banks for almost a week in early September, resulting in severe shoreline erosion in some locations near Buxton and Rodanthe. Upon making landfall less than 2 weeks before Hurricane Floyd, Hurricane Dennis delivered 4 to 8 inches of rain to much of the Tar and Neuse River Basins, breaking a drought and saturating soils. Hurricane Floyd will likely be the second or third most costly hurricane to strike the United States in the 20th century, resulting in more fatalities than any hurricane to strike the United States since 1972. Rainfall amounts recorded during Hurricane Floyd (September 14–17, 1999) and accumulated during the months of September and October were unprecedented for many parts of eastern North Carolina during more than 80 years of precipitation records. Most recording stations in eastern North Carolina received at least half the average annual rainfall during the 2 months. Flooding was at record levels, and 500-year or greater floods occurred in all of the State's river basins east of Raleigh. More than half of the average annual nitrogen and phosphorus loads were transported in the Neuse and Tar Rivers by floodwaters during the 1-month period between mid-September and mid-October. Shoreline erosion from the passage of Hurricane Floyd was particularly severe along Oak and Topsail Islands; the effects of Hurricane Floyd on shoreline erosion and dune retreat were greater than the effects of Hurricane Bonnie in 1998. Fortunately, Hurricane Irene in mid-October did not make landfall in North Carolina, but rainfall from the storm did help ensure that several rivers in eastern North Carolina remained above flood stage for almost 2 months.

USGS

Houses near surf in Rodanthe, N.C.

HURRICANES IN NORTH CAROLINA

Reports of intense summer storms in eastern North Carolina began soon after the first European visits to the region. Sir Francis Drake reported "a great storm" that persisted for 3 days in June 1586 at Roanoke Island (Stevenson, 1989). A 6-day "tempest" in August 1587 again affected Drake and his fleet, who were forced to ride out the storm offshore from Roanoke Island.

Between 1886, when reliable records began, and 1999, a total of 990 tropical cyclones (low-pressure systems that form over warm tropical ocean waters between June and November) have been recorded in the Atlantic Ocean and Gulf of Mexico (State Climate Office of North Carolina, 1999a). During this 114-year period, 33 tropical cyclones (about 3 percent of the total) made direct landfall in North Carolina, or an average of about one every 3.4 years (fig. 1). An average of about 6 hurricanes (tropical cyclones with wind speeds exceeding 74 miles per hour [mph]) form each year in either the Atlantic Ocean or Gulf of Mexico. Of the 33 cyclones that made landfall in North Carolina during 1886–1999, 26 were hurricanes (fig. 1).

Hurricane Hazel (1954) is the only Category 4 storm (wind speeds between 131 and 155 mph) that has made landfall in North Carolina since 1886. Three Category 3 storms (wind speeds between 111 and 130 mph) have entered the State during the last 114 years, but two of these storms occurred in the last 4 years—Hurricane Fran in 1996 and Hurricane Bonnie in 1998. In fact, as many hurricanes and tropical storms have made landfall in North Carolina during the 4-year period 1996–99 as during the 35-year period between 1961 and 1995 (fig. 1).

The remnants of hurricanes that made landfall in other states also have had a significant effect on North Carolina. Winds from Hurricane Hugo caused extensive damage in Charlotte and other parts of the western Piedmont in 1989. Costly flooding occurred in Mecklenburg County in 1995 and again in 1997 as the remnants of Tropical Storm Jerry (1995) and Hurricane Danny (1997) passed through the State. Flood damage in Mecklenburg County exceeded $4 million in 1995 and more than $60 million in 1997 (Robinson and others, 1998). Floods having recurrence intervals of 100 years or greater occurred on some streams in Mecklenburg County during both of these events.

Three of the four most costly hurricanes in U.S. history have made landfall in or passed through North Carolina (National Hurricane Center, 1999a). The most costly hurricane in U.S. history was Hurricane Andrew (1992), which passed through Florida and caused an estimated $26.5 billion in damages (National Hurricane Center, 1999a). Hurricane Hugo (1989), which made landfall in South Carolina but passed through the western Piedmont of North Carolina, caused an estimated $7 billion in damages and was the second most costly hurricane. However, estimates of losses due to Hurricane Floyd in North Carolina alone are nearly $6 billion (Raleigh News and Observer, 1999), so this storm could become the second, or certainly the third, most costly hurricane in U.S. history. In addition, Hurricane Floyd resulted in more fatalities in the United States than any hurricane since Hurricane Agnes in 1972 (National Hurricane Center, 1999b). Prior to Hurricane Floyd, Hurricane Fran (1996) was the third most costly hurricane, resulting in estimated damages of $3.2 billion.


USGS

Damaged house near surf in Rodanthe, N.C.

Figure 1. Number of tropical cyclones, by type, making landfall in North Carolina, 1890–1999.

INTRODUCTION

The combined effects of Hurricanes Dennis, Floyd, and Irene in September and October 1999 resulted in almost 2 months of flooding throughout most of eastern North Carolina. Hurricane Floyd resulted in more fatalities than any hurricane to strike the United States since 1972, including 52 fatalities in North Carolina (Tom Hegele, North Carolina Division of Emergency Management, written commun., January 19, 2000). Rainfall amounts recorded during Hurricane Floyd (September 14–17, 1999) and accumulated during the months of September and October were unprecedented for many parts of eastern North Carolina during more than 80 years of precipitation records. Flooding was at record levels and occurred in all of the State's river basins east of Raleigh.

The U.S. Geological Survey (USGS) is responsible for collecting and interpreting earth-science information, including flood and geologic data, for the Nation. As part of this mission, the USGS, in cooperation with the North Carolina Department of Environment and Natural Resources, the U.S. Army Corps of Engineers, the Federal Emergency Management Agency, and numerous other State and local agencies, is documenting the effects of Hurricanes Dennis, Floyd, and Irene on the water and coastal resources of North Carolina. The purpose of this report is to provide hydrologic and geologic information concerning the effects of Hurricanes Dennis, Floyd, and Irene on eastern North Carolina. Included in this report is information on the rainfall that led to the flooding, flood data, measured water-quality conditions during the flooding, and effects of the hurricanes on shoreline conditions.

USGS

USGS staff making discharge measurement during flooding on the Tar River near Rocky Mount, N.C.

FEMA

Flooded subdivision in Greenville, N.C.

Acknowledgments

R. Boyles with the North Carolina State Climate Office at North Carolina State University, provided maps showing rainfall distributions during Hurricanes Dennis and Floyd. Reviews by T. Brown, U.S. Army Corps of Engineers Wilmington District; S. Harned, National Weather Service Raleigh Forecast Office; and J. Feldt, National Weather Service Southeast River Forecast Center are gratefully acknowledged. Flood data collected under difficult conditions by staff from the U.S. Geological Survey offices in Raleigh, Charlotte, and Asheville, North Carolina; Pearl, Mississippi; and Columbia, South Carolina, made this report possible.


USGS

Flooded shopping center along the Neuse River in Kinston, N.C.

Photograph Credits

Photographs used in this report were contributed by Federal Emergency Management Agency (FEMA) [Dave Gatley and Dave Saville]; Goldsboro News-Argus [Ed Hayden]; National Aeronautics and Space Administration (NASA), Goddard Space Flight Center; National Oceanic and Atmospheric Administration (NOAA), Satellite Services Group, National Climatic Data Center; North Carolina Division of Emergency Management (NCDEM); U.S. Geological Survey, Center for Coastal Geology; U.S. Geological Survey, Earth Resources Observation Satellite (EROS) Data Center; and U.S. Geological Survey, North Carolina District Office.

NCDEM

Flooded shopping center at Princeville, N.C.


FEMA

Electrical substation near the Tar River, Greenville, N.C.

During most of 1999 prior to September, almost the entire State of North Carolina was in a drought condition. The rainfall deficit (based on 1960–90 monthly averages) for the 12 months preceding September 1999 was

9.31 inches at Asheville,
10.41 inches at Charlotte,
5.27 inches at Greensboro,
6.39 inches at Raleigh,
13.0 inches at Kinston, and
2.75 inches at Wilmington

(National Climatic Data Center 1998, 1999; State Climate Office of North Carolina, 1999b). As a result, some restrictions on water use had been implemented at numerous locations around the State.

Hurricanes Dennis, Floyd, and Irene occurred within a 6-week period between September 4 and October 17, 1999. All three storms brought extremely heavy and, in some cases, unprecedented rainfall to eastern North Carolina. Rocky Mount, located in the central part of the Tar-Pamlico Basin, received 37.72 inches of rain during September–October, or about 85 percent of the average annual rainfall for that location (table 1). Kinston, in the Neuse River Basin, received 29.48 inches of rain during the same period, and more than half of the average annual rainfall fell during September alone. Most reporting stations in the central and western Coastal Plain received at least half the average annual rainfall during September–October (table 1).

Table 1. Rainfall amounts, in inches, associated with Hurricanes Dennis, Floyd, and Irene, September–October 1999; Hurricane Fran, September 1996; and annual average (1960–90) rainfall at selected locations in North Carolina

[est., estimated values; —, no data; range of values indicates more than one reporting station; >, greater than. Rainfall data are from the State Climate Office of North Carolina at North Carolina State University (1999b) and National Climatic Data Center (1996a)]

Location (fig. 3)	Hurricane Dennis (Sept. 3–7, 1999)	Hurricane Floyd (Sept. 14–17, 1999)	Hurricane Irene (Oct. 17–18, 1999)	Sept.–Oct. 1999 total	Sept. 4–6, 1996 (Hurricane Fran)	Annual average rainfall
Tar-Pamlico River Basin						
Oxford	6.07	5.67	1.94	20.15	7.30	43 (est.)
Louisburg	5.59	8.88	2.01	24.34	6.36	45.56
Rocky Mount	5.06–7.59	14.07–18.00	5.16	37.72	5.17	44.24
Enfield	7.01	11.84	4.30	32.39	4.38	44.54
Greenville	7.03	12.63	3.29	30.20	6.17	49.00
Washington	7.60	10.73	5.07	31.05	4.61	46.96
Neuse River Basin						
Durham	3.30	5.98	0.91	18.60	8.38	48.10
Raleigh	8.46	6.55	1.50	24.24	8.80	41.43
Clayton	5.35	9.80	2.59	20.98	6.98	45.11
Goldsboro	7.19–7.94	12.06–12.70	4.36	32.10	6.41	49.27
Wilson	7.60	10.73	5.07	31.05	4.27	46.96
Kinston	6.07–6.93	13.35–13.98	5.37	29.48	5.15	51.20
New Bern	4.00	5.51	6.39	19.82	—	53.11
Trenton	7.42	14.98	—	>24.60[a]	8.33	52.22
Cape Fear River Basin						
Chapel Hill	12.52	4.67	0.84	26.55	7.81	46.02
Dunn	4.50	7.65	4.34	23.81	6.59	47.72
Fayetteville	2.12	7.23	4.19	21.83	3.75	46.72
Clinton	2.96	11.50	4.33	27.50	7.86	49 (est.)
Willard	1.30	13.23	—	>21.01[a]	9.38	53.04
Elizabethtown	>1.19[b]	>14.19[b]	>6.69[b]	>28.00[b]	8.01	46.78
Wilmington	0.59	19.06	2.73	27.10	5.23	54.27
Waccamaw and Lumber River Basins						
Lumberton	1.34	9.82	5.48	24.16	5.89	46.54
Whiteville	1.52	16.76	5.97	34.27	7.80	48.73
Other sites						
Lewiston	3.56	9.73	3.47	19.55	3.95	46.82
Williamston	7.20	16.28	5.54	35.55	8.07	48.07
Edenton	5.07	6.18	6.12	23.59	2.15	48.54
Elizabeth City	7.68	2.64	5.06	17.73	1.44	48.48
Plymouth	5.03	7.37	—	>15.15[a]	4.13	51.06
Morehead City	4.29	4.33	—	>11.21[a]	>10.91[b]	55.05
Hoffman Forest	6.49	9.78	—	>19.58[a]	13.27	55.60

[a]October rainfall records are unavailable.
[b]Partial record; some missing values for the period.

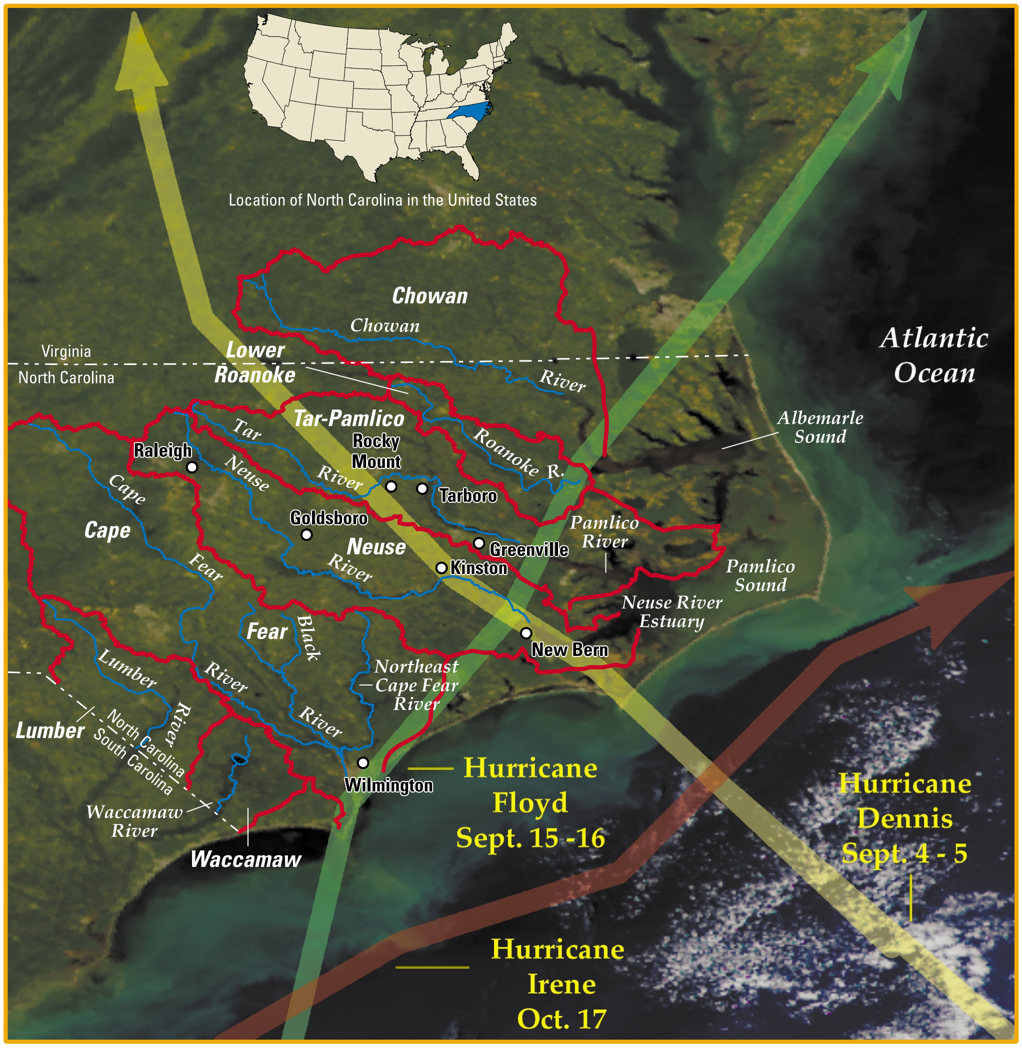


Figure 2. Satellite image of eastern North Carolina with generalized basin outlines and tracks for Hurricanes Dennis, Floyd, and Irene, September–October 1999. (Satellite image from National Aeronautics and Space Administration, 1999.) Flooding along selected rivers, such as the Tar, Neuse, and Waccamaw, can be seen, as well as sediment plumes in Albemarle Sound and the Pamlico River.

Hurricane Dennis followed an unusual path, approaching the coast, retreating to about 150 miles offshore, meandering offshore for several days, approaching the shore again, and eventually moving across North Carolina during September 4–5 in a west-northwesterly direction over the Neuse and Tar-Pamlico River Basins (fig. 2). Rainfall amounts were generally greatest near the coast, but exceeded 7 inches in much of the central Neuse and Tar-Pamlico River Basins (table 1; fig. 3).

Hurricane Floyd made landfall near Cape Fear on September 15 with the center of the storm traveling to the east of Wilmington (fig. 2). The storm moved in a north-northeasterly direction over the lower Cape Fear, Neuse, Tar-Pamlico, lower Roanoke, and Chowan River Basins. The storm delivered 12 to 18 inches of rain to much of the Neuse and Tar-Pamlico River Basins (table 1; fig. 4), triggering regional flooding that continued throughout the remainder of September and most of October.

Hurricane Irene never made landfall in North Carolina, but moved in a northeasterly direction just east of the coastline on October 17 (fig. 2). However, rainfall amounts associated with Hurricane Irene exceeded 5 inches in the eastern part of the Neuse Basin and in the central and eastern Tar-Pamlico Basin (table 1). The additional rainfall from Hurricane Irene coupled with the already-saturated soil and elevated river levels ensured that the Tar and Neuse Rivers remained above National Weather Service (NWS) flood stage throughout most of September and October.

Hurricane Floyd Rainfall Recurrence Intervals

Extremely large rain events are characterized by (1) the duration of the rain event, (2) the magnitude of the rainfall for a selected duration, and (3) the recurrence interval, or the chance that a rain event of a specified duration and magnitude will occur in any particular year. The 100-year, 12-hour rainfall for eastern North Carolina is between 7 and 8 inches (Hershfield, 1961). This means that a rain event that lasts 12 consecutive hours and delivers at least between 7 and 8 inches of rainfall has a 1-percent chance of occurring during any given year in eastern North Carolina. Likewise, the 100-year, 24-hour rainfall for eastern North Carolina is between 8 and 9 inches (Hershfield, 1961). Rainfall amounts associated with more rare events (for example, 500-year storms)

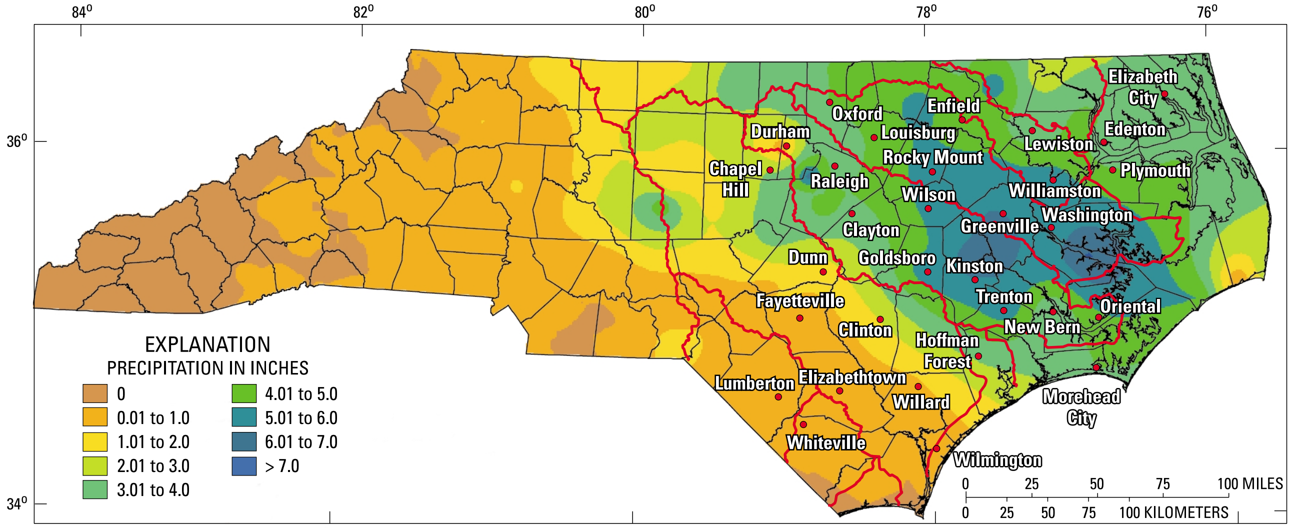


Figure 3. Rainfall in North Carolina, September 4–5, 1999, during the passage of Hurricane Dennis and locations of selected raingages in eastern North Carolina. (Rainfall map from the State Climate Office of North Carolina, 1999c.)

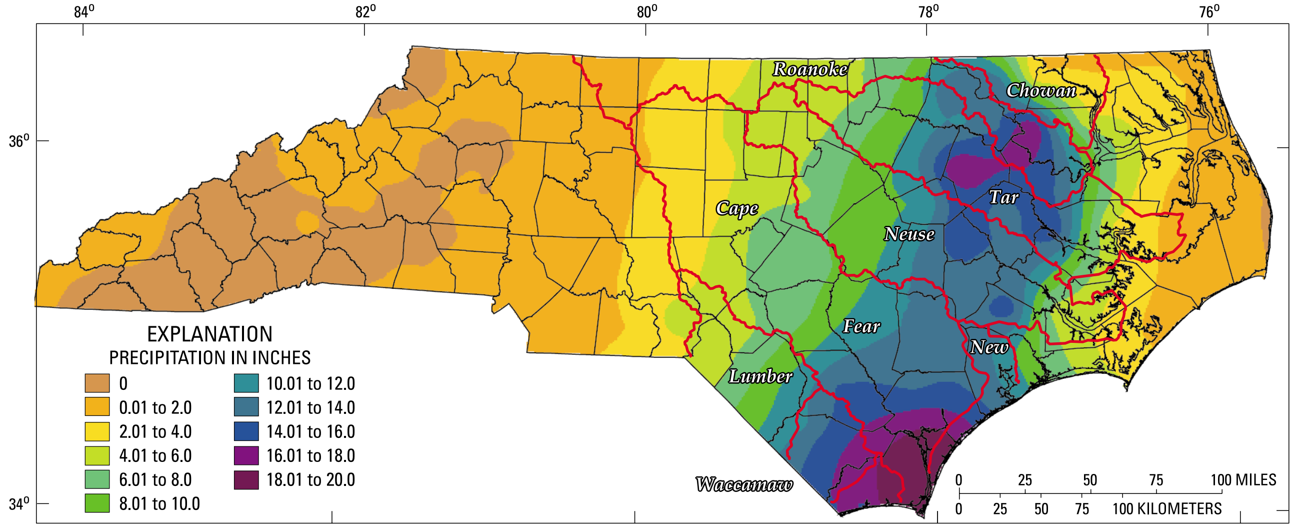


Figure 4. Rainfall in North Carolina, September 14–16, 1999, prior to and during the passage of Hurricane Floyd. (Rainfall map from the State Climate Office of North Carolina, 1999d.)

have not been established for most locations in the United States.

The greatest consecutive 12-hour rainfall at Kinston during Hurricane Floyd was approximately equal to the 100-year rain event, but the greatest 12-hour rainfall at Rocky Mount exceeded the 100-year rainfall (table 2). At both Kinston and Rocky Mount, the greatest 24-hour rainfall during Hurricane Floyd far exceeded the 100-year rainfall (table 2); at Rocky Mount, the measured

Table 2. Maximum observed 12-hour and 24-hour rainfall, in inches, at Rocky Mount and Kinston, N.C., during Hurricane Floyd, September 15–16, 1999, and 100-year rainfall statistics for eastern North Carolina

Location (fig. 3)	Rainfall, in inches			
	Maximum 12-hour (observed)	[a]100-year, 12-hour	Maximum 24-hour (observed)	[a]100-year, 24-hour
Rocky Mount	10.38	7–8	14.73	8–9
Kinston	7.90	7–8	12.54	8–9

[a]Statistics from Hershfield (1961).

24-hour rainfall was almost double the statistically derived 100-year rainfall. Consequently, from a statistical perspective the rainfall associated with Hurricane Floyd was extremely unusual with a very low probability of occurrence.

August–September 1955 Rainfall and September–October 1999 Rainfall

The 1999 hurricane season in North Carolina has been compared with the 1955 season, when three hurricanes made landfall in the State during a 5-week period between August 12 and September 19 (figs. 1, 5). Rainfall amounts during August–September 1955 (National Climatic Data Center, 1955a,b) were, for some locations, greater than rainfall amounts during September–October 1999. For example, Maysville, which is located in Onslow County near the current raingage at Hoffman Forest (fig. 3), received 50.26 inches during August–September 1955. Kinston (fig. 3) received 29.89 inches during the same period, or about the same amount of rainfall as during September–October 1999. Maysville, Morehead City, Oriental, and New Bern all reported monthly rainfall in excess of 20 inches for both August and September 1955.

For most of eastern North Carolina, however, monthly rainfall was generally much greater in September 1999 than in August 1955—both months during which two hurricanes made landfall in North Carolina (fig. 6). Rainfall throughout most of the Tar-Pamlico River Basin was two to three times greater in September 1999 than in August 1955 (fig. 6). Likewise, rainfall in the upper and middle Neuse River Basin was almost two times greater in September 1999 than in August 1955 (fig. 6). Only in the extreme eastern part of the State did August 1955 rainfall exceed September 1999 rainfall. The heaviest rainfall was more widespread in September 1999 than in August 1955, and fell over parts of the river basins that are more susceptible to flooding.

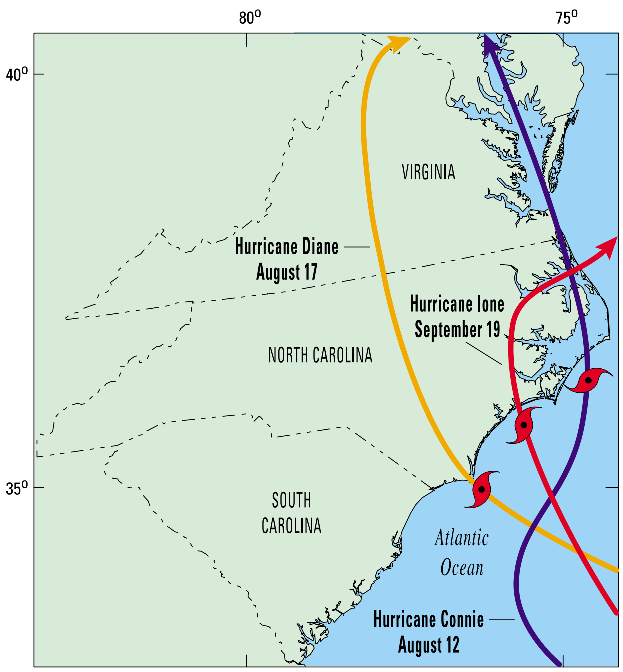


Figure 5. Generalized tracks of Hurricanes Connie, Diane, and Ione, August–September 1955.


FEMA

Road damage from flooding in Greenville, N.C.


NCDEM

Pine Knoll Shores, N.C.

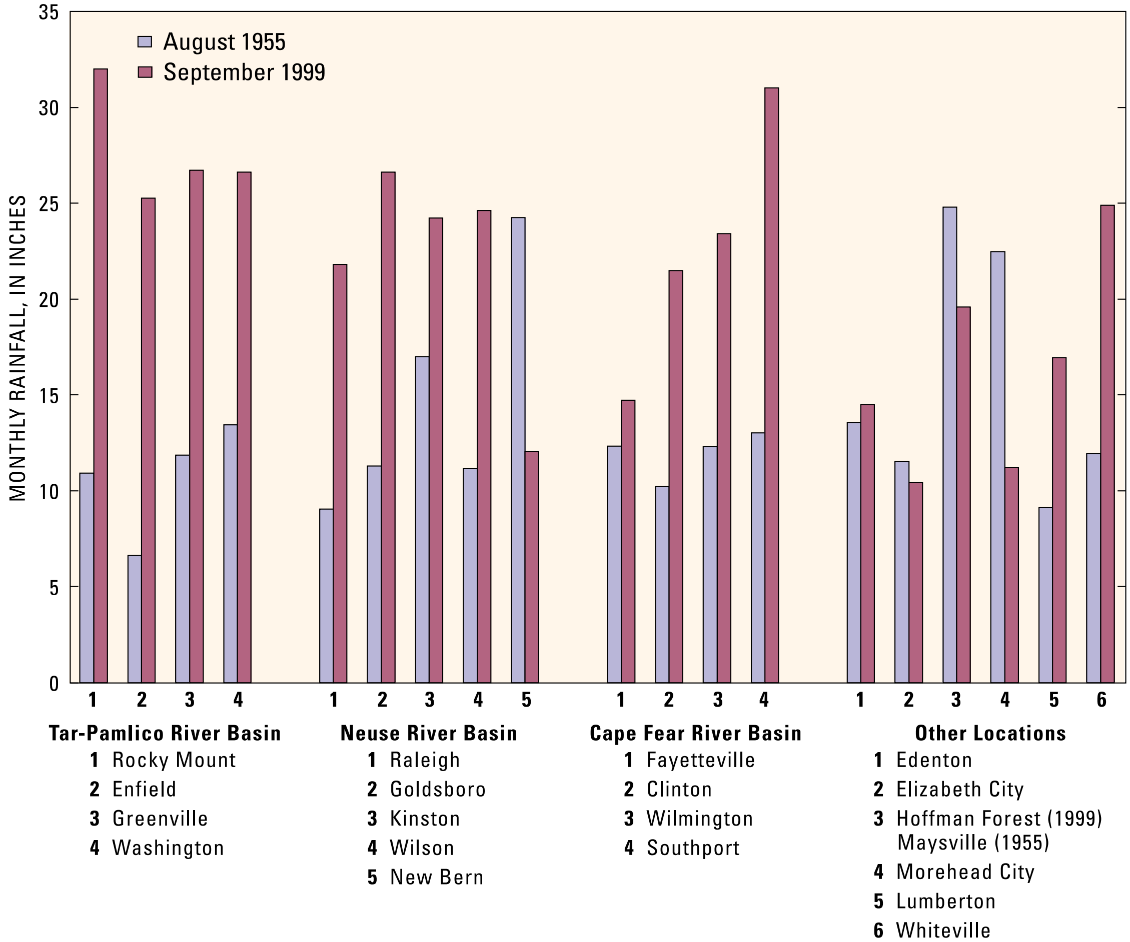


Figure 6. August 1955 and September 1999 monthly rainfall at selected sites in the Tar-Pamlico, Neuse, and Cape Fear River Basins, and at selected other sites.

Hurricane Floyd Rainfall Compared to Hurricane Fran (1996) Rainfall

Hurricane Fran in September 1996 resulted in extensive flooding in many of the same areas affected by Hurricane Floyd (Bales and Childress, 1996). Flood recurrence intervals were in excess of 100 years at a number of locations in the upper Tar-Pamlico Basin, upper Neuse Basin, and throughout much of the Cape Fear River Basin.

Rainfall amounts associated with Hurricane Fran were greater than those of Hurricane Floyd in the upper Tar (Oxford) and upper Neuse (Durham and Raleigh) River Basins (table 1). Hurricane Fran rainfall also was greater than Hurricane Floyd rainfall in the upper Cape Fear River Basin (Chapel Hill, table 1), including the Haw and Deep River Basins, where Hurricane Fran flood recurrence intervals were generally between 100 and 500 years. In addition, Hurricane Fran rainfall exceeded Hurricane Floyd rainfall near the coast at Morehead City and Hoffman Forest (table 1). However, with these few exceptions, Hurricane Floyd rainfall was much greater than rainfall from Hurricane Fran. For example, at Rocky Mount and Kinston, Hurricane Floyd rainfall was almost three times greater than Hurricane Fran rainfall (table 1). The highest reported consecutive 24-hour rainfall associated with Hurricane Fran was 6.70 inches at Franklinton (National Climatic Data Center, 1996b), which is about 10 miles west of Louisburg (fig. 3). This rainfall amount corresponds to approximately a 24-hour 25-year rainfall event, compared to Hurricane Floyd rainfall, which was much greater than a 24-hour 100-year rainfall event (table 2).

The Relation of Rainfall to Flooding

As a general rule, it should not be assumed that a 100-year rain event would result in a 100-year flood. Conditions prior to a particular storm affect the amount of runoff that occurs during the storm. Dry soil allows more infiltration of rainfall and less runoff, whereas wet soil results in more runoff for the same amount of rainfall. The soaking rains from Hurricane Dennis (table 1) that fell over a wide area of eastern North Carolina immediately prior to Hurricane Floyd resulted in wet soils capable of storing little additional water.

Another factor that affects the relation of a particular rain event to the potential for flooding is the spatial extent and duration of the rainfall relative to the watershed size. An intense, localized thunderstorm may result in 100-year rainfall over part of a basin but little rainfall over the remainder of the watershed, resulting in minimal downstream flooding. Moreover, a 100-year, 1-hour storm on a 1-square-mile (mi^2) basin will more likely result in severe flooding in that basin than the same event on a 1,000-mi^2 basin; longer duration storms generally are required to produce flooding in large river basins. Consequently, the wet soils caused by Hurricane Dennis, the broad regional coverage of rainfall from Hurricane Floyd (table 1; fig. 4), and the long duration of the rainfall combined with the large rainfall amounts (table 2) ensured that unprecedented regional flooding would occur in eastern North Carolina in response to these storms.

Grifton, N.C.

Flooded church near the Black River near Tomahawk, N.C.

Flooded car in Greenville, N.C.

Surf at Pine Knoll Shores, N.C., prior to Hurricane Floyd landfall

The record rainfall amounts from Hurricanes Dennis and Floyd led to widespread and prolonged flooding in eastern North Carolina. With the exception of the Lumber River Basin, all of the major river basins in eastern North Carolina experienced flooding at the 500-year recurrence interval (table 3; fig. 7).

NCDEM

Flooded mobile home park along the Tar River

Table 3. Hurricane Floyd flood information for selected streamgaging stations in North Carolina and Virginia

[All sites in North Carolina, unless noted; mi^2, square miles; ft, feet; ft^3/s, cubic feet per second; >, greater than; nd, not determined; <, less than]

Site no. (fig. 7)	USGS station no.	Station name	Drainage area (mi^2)	Period of record	Gage datum (ft above sea level)	1999 floods				Previous peaks of record		
						Date	Peak stage (ft above datum)	Peak flow (ft^3/s)	Recurrence interval (years)	Date	Peak stage (ft above datum)	Peak flow (ft^3/s)
Chowan River Basin												
1	02047000	Nottoway River near Sebrell, Va.	1,421	1941–99	5.94	9/20	27.01	35,700	50–100	7/19/75	24.43	26,000
2	02049500	Blackwater River near Franklin, Va.	617	1941–99	1.56	9/18	26.27	23,000	100–500	9/14/60	17.14	9,420
3	02051500	Meherrin River near Lawrenceville, Va.	552	1928–99	136.56	9/18	29.95	15,590	10–25	8/17/40	42.00	38,000
4	02053200	Potecasi Creek near Union	225	1958–99	3.53	9/16	28.9	17,000	>500	8/19/92	21.77	5,650
5	02053500	Ahoskie Creek at Ahoskie	63.3	1964–99	17.46	9/17	17.32	8,570	>500	6/1/84	12.49	2,580[a]
Roanoke River Basin												
6	0208111310	Cashie River near Windsor	108	1987–99	15	9/16	18.52	15,700	>500	10/18/92	11.51	3,150
Tar-Pamlico River Basin												
7	02081500	Tar River near Tar River	167	1940–99	287.25	9/16	17.59	11,000	10	9/6/96	24.06	19,900
8	02081747	Tar River at Louisburg	427	1964– 99	176.71	9/17	26.05	23,700	50–100	9/7/96	25.34	21,100
9	02082506	Tar River below Tar River Reservoir	777	1973–99	85.9	9/17	32.89	29,300	100–500	3/23/98	23.67	14,700
10	02082585	Tar River at Rocky Mount	925	1977–99	53.88	9/17	31.66	34,100	100–500	9/12/96	25.88	15,100
11	02082770	Swift Creek at Hilliardston	166	1963–99	130.42	9/17	21.30	23,000	>500	6/5/79	14.27	6,030
12	02082950	Little Fishing Creek near White Oak	177	1960–99	116.44	9/16	30.8	31,000	>500	10/7/72	24.80	18,000
13	02083000	Fishing Creek near Enfield	526	1923–99	74.26	9/18	21.65	30,000	500	8/18/40	17.72	12,600[b]
14	02083500	Tar River at Tarboro	2,183	1897–1905; 1931–99	10.37	9/19	41.51	70,600	>500	8/20/40	31.77	37,200
15	02083800	Conetoe Creek near Bethel	78.1	1957–99	30	nd	19.79	nd	nd	8/23/67	15.74	2,580
16	02084000	Tar River at Greenville	2,620	1997–99	-2.36	9/21	29.72	73,000	nd	3/28/98	18.08	25,500
17	02084160	Chicod Creek near Simpson	45	1975–87; 1992–99	0	9/18	21.46	nd	nd	8/27/98	13.45	3,150

Table 3. Hurricane Floyd flood information for selected streamgaging stations in North Carolina and Virginia--Continued

[All sites in North Carolina, unless noted; mi^2, square miles; ft, feet; ft^3/s, cubic feet per second; >, greater than; nd, not determined; <, less than]

Site no. (fig. 7)	USGS station no.	Station name	Drainage area (mi^2)	Period of record	Gage datum (ft above sea level)	1999 floods: Date	1999 floods: Peak stage (ft above datum)	1999 floods: Peak flow (ft^3/s)	1999 floods: Recurrence interval (years)	Previous peaks of record: Date	Previous peaks of record: Peak stage (ft above datum)	Previous peaks of record: Peak flow (ft^3/s)
Tar-Pamlico River Basin (Continued)												
18	02084472	Pamlico River at Washington	3,125	1999[c]	0	9/16	8.14	nd	nd	not applicable		
19	02084557	Van Swamp near Hoke	23	1977–99	20	9/16	7.43	383	25	10/8/96	5.98	409[d]
Neuse River Basin												
20	02087183	Neuse River near Falls	772	1981–99[e]	194.69	10/14	5.95	6,330	5–10	9/16/96	8.05	7,650
21	02087324	Crabtree Creek at U.S. 1 at Raleigh	121	1990–99	183.27	9/16	16.88	8,050	nd	9/6/96	18.23	12,700
22	02087500	Neuse River near Clayton	1,150	1981–99[e]	128.41	9/17	20.67	20,500	25–50	9/7/96	20.12	19,700
23	02087570	Neuse River at Smithfield	1,206	1908–91; 1999	99.26	9/18	26.72	>17,800	>50	4/29/78	nd	15,800
24	0208758850	Swift Creek near McCullars Crossroads	35.8	1989–99	258	9/16	13.06	3,640	10	9/6/96	14.15	6,790
25	02088000	Middle Creek near Clayton	83.5	1940–99	184.53	9/16	13.02	5,270	10–25	9/6/96	14.88	11,900
26	02088500	Little River near Princeton	232	1930–99	107.75	9/17	16.58	20,700	>500	10/6/64	13.94	7,150
27	02089000	Neuse River near Goldsboro	2,399	1981–99[e]	42.95	9/20	28.85	38,500	50	9/12/96	26.21	29,300
28	02089500	Neuse River at Kinston	2,692	1981–99[e]	10.90	9/22 9/23	27.71	36,300	50–100	9/17/96	23.26	27,100
29	02090380	Contentnea Creek near Lucama	161	1977–99[e]	117.43	9/16	25.0	24,000	100	10/6/64	16.28	5,860
30	02091000	Nahunta Swamp near Shine	80.4	1955–99	50.74	9/17	21.00	23,000	>500	10/6/64	14.14	5,470
31	02091500	Contentnea Creek at Hookerton	733	1928–99	14.85	9/18	28.28	31,900	>500	10/8/64	22.11	17,200
32	02091814	Neuse River near Fort Barnwell	3,900	1996–99	0	9/20	22.75	57,200	nd	2/6/98	14.01	24,300
33	02092500	Trent River near Trenton	168	1951–99	19.15	9/17	22.33	15,000	>500	9/21/55	17.84	9,100
New River Basin												
34	02093000	New River near Gum Branch	94.0	1950–73; 1988–99	0	9/16	25.12	15,000	>500	9/20/55	19.99	7,900
Cape Fear River Basin												
35	02096960	Haw River near Bynum	1,275	1973–99	283.31	9/16	13.42	23,100	<2	9/6/96	21.76	76,700
36	02102000	Deep River at Moncure	1,434	1931–99	185.06	9/6	9.15	23,000	2–5	9/18/45	17.20	80,300
37	02102500	Cape Fear River at Lillington	3,464	1981–99[e]	104.62	9/16	14.46	29,800	2	9/7/96	18.97	51,800
38	02102908	Flat Creek near Inverness	7.63	1969–99	191.18	9/16	3.84	173	2–5	4/1/73	7.30	394
39	02105500	Cape Fear River at Lock 3	4,852	1981–99[e]	28.97	9/17	21.59	37,500	10	9/8/96	26.75	nd
40	02105769	Cape Fear River at Lock 1	5,255	1981–99[e]	-2.90	9/20	23.30	40,000	5–10	9/11/96	24.29	48,300
41	02105900	Hood Creek near Leland	21.6	1953–73; 1994–99	12.22	9/16	13.89	4,800	100	8/27/98	11.53	2,650
42	02106500	Black River near Tomahawk	676	1952–99	24.61	9/18	27.14	28,500	100–500	9/17/84	22.08	17,500
43	02108000	Northeast Cape Fear River near Chinquapin	599	1941–99	17.28	9/18	23.51	30,700	>500	7/6/62	20.16	20,400

Table 3. Hurricane Floyd flood information for selected streamgaging stations in North Carolina and Virginia--Continued

[All sites in North Carolina, unless noted; mi^2, square miles; ft, feet; ft^3/s, cubic feet per second; >, greater than; nd, not determined; <, less than]

Site no. (fig. 7)	USGS station no.	Station name	Drainage area (mi^2)	Period of record	Gage datum (ft above sea level)	1999 floods: Date	1999 floods: Peak stage (ft above datum)	1999 floods: Peak flow (ft^3/s)	1999 floods: Recurrence interval (years)	Previous peaks of record: Date	Previous peaks of record: Peak stage (ft above datum)	Previous peaks of record: Peak flow (ft^3/s)
Lumber and Waccamaw River Basins												
44	02109500	Waccamaw River at Freeland	680	1939–99	15.52	9/20	19.30	31,200	>500	9/12/96	17.02	12,400
45	02134500	Lumber River at Boardman	1,228	1929–99	72.05	9/19	10.70	13,400	25	9/24/45	10.64	13,400
Miscellaneous stations												
46	0208453300	Pamlico River at Light 5	not applicable									
47	02092162	Neuse River at Marker 38 at New Bern	not applicable									

[a]Instantaneous peak flow occurred on October 5, 1964.
[b]Instantaneous peak flow occurred on December 2, 1934.
[c]Record began in June 1999.
[d]Instantaneous peak flow occurred on November 6, 1977.
[e]Regulated period of record, used to compute flood recurrence intervals.

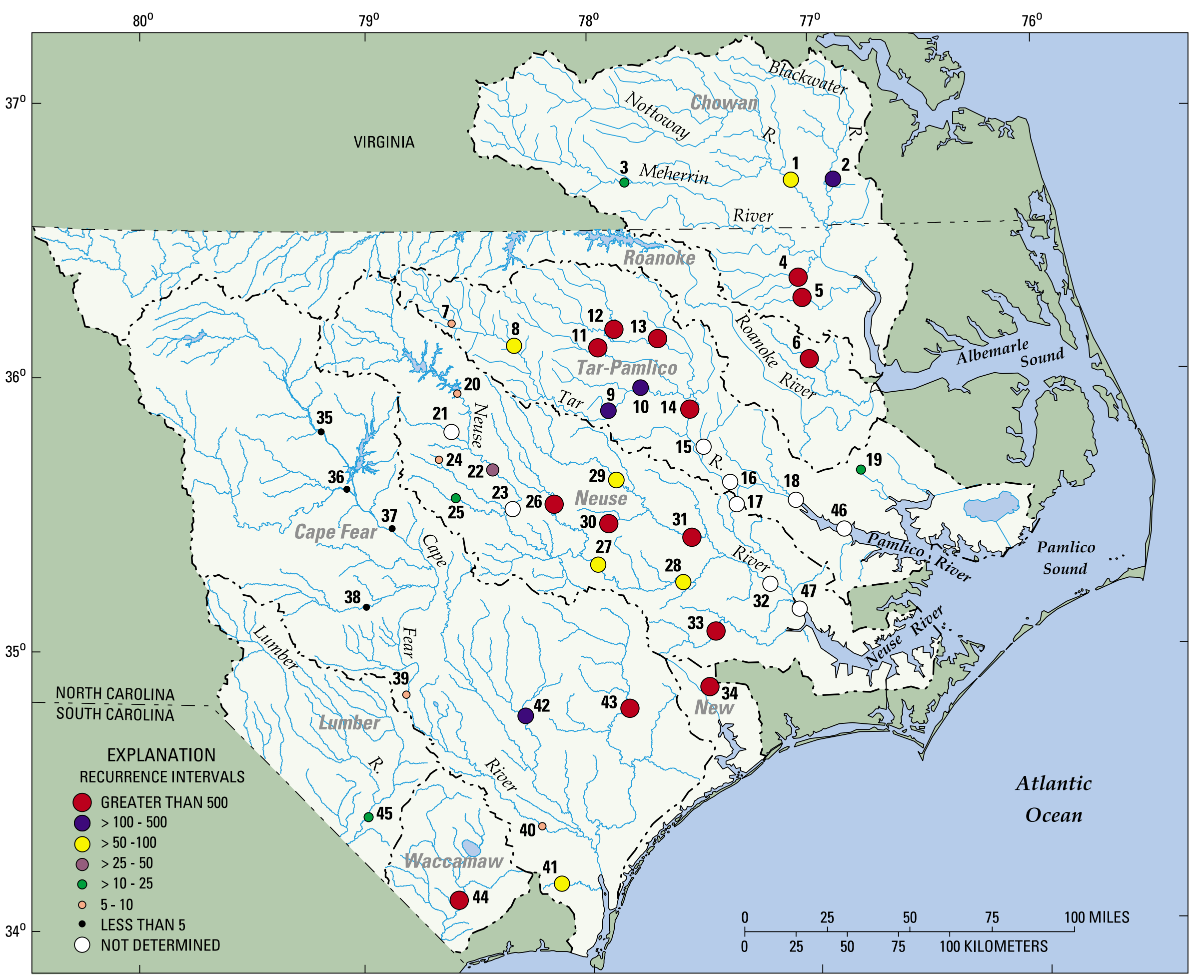
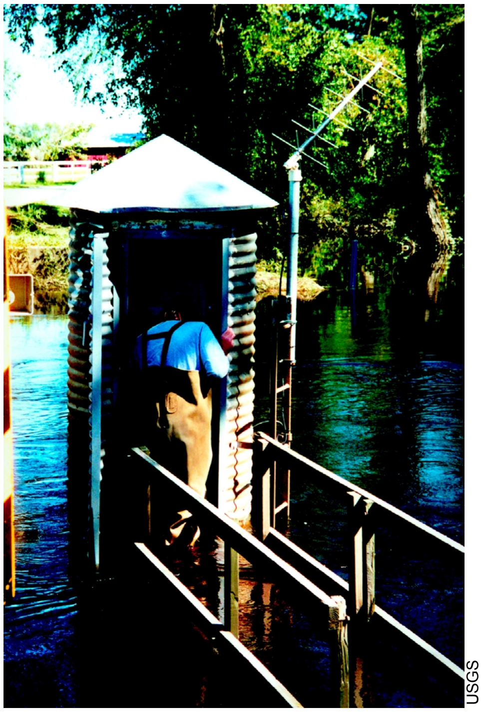


Figure 7. Site locations and flood recurrence intervals for September–October 1999 flooding at selected streamgaging sites in North Carolina and Virginia.

Tar-Pamlico River Basin

Some of the most widespread flooding occurred in the Tar-Pamlico River Basin downstream from Louisburg (site 8, fig. 7). Record water levels were recorded at 11 of the 12 USGS stream-gaging stations in the Tar-Pamlico Basin (excluding site 18 on the Pamlico River, where previous high water levels have been in response to storm surge). Measured flood flows on the Tar River and major tributaries downstream from site 9 at the Tar River Reservoir had recurrence intervals in excess of 100 years, and several sites had recurrence intervals in excess of 500 years (table 3). At Tarboro (site 14, fig. 7), where streamflow records have been collected since 1897, the peak stage during this event was almost 10 feet higher than the previously recorded peak stage, which occurred in August 1940 (table 3; fig. 8). Water levels remained above flood stage at Tarboro for most of September and October (fig. 8). The maximum flood flow at Tarboro in 1999 was almost double previous maximum flow recorded at the site in more than 100 years. Flood recurrence intervals could not be determined at sites 15 (Conetoe Creek) and 17 (Chicod Creek) because flows at these sites were affected by backwater from the Tar River. An insufficient period of record (greater than 10 years is needed) was available at sites 16 (Tar River



Conetoe Creek near Bethel, N.C.

N.C. Highway 33 flooded by the Tar River

U.S. Highway 64 near Princeville, N.C.

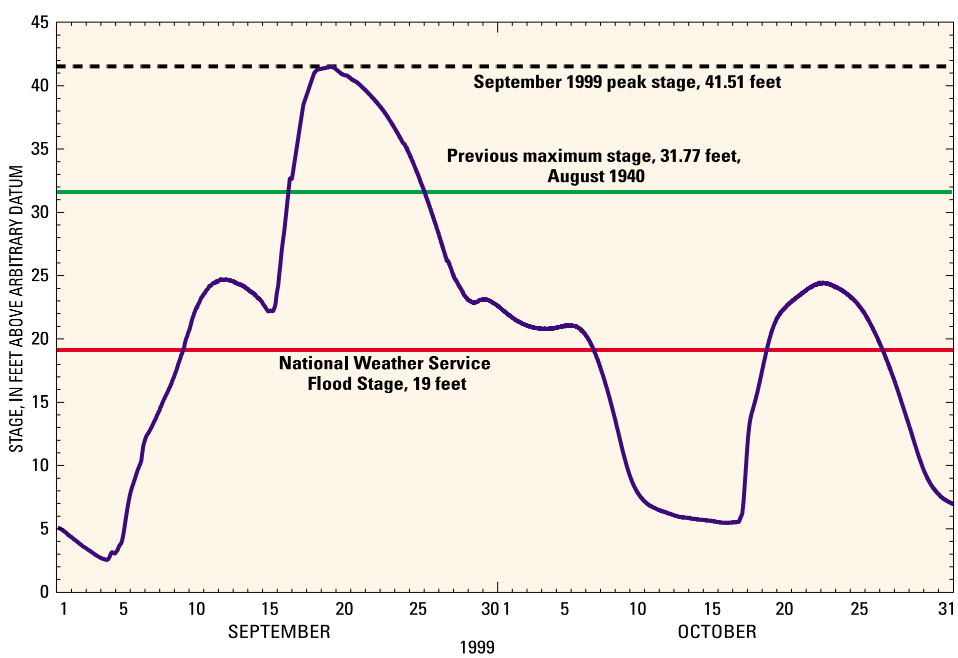


Figure 8. Stage hydrograph for the Tar River at Tarboro (site 14, fig. 7), September–October 1999.

at Greenville) and 18 (Tar River at Washington) to estimate flood recurrence intervals.

Neuse River Basin

The most prolonged flooding of September–October 1999 occurred in the Neuse River Basin (fig. 9). Water levels were above flood stage at Goldsboro (site 27, fig. 7) from September 7 until the end of October, and the water level at Kinston (site 28, fig. 7) was still 1.5 feet above flood stage at the end of October. There are 16 USGS streamgaging stations in the Neuse River Basin downstream from and including Clayton (site 22, fig. 7); not all sites are included in table 3 and figure 7. New records for maximum water levels were established at 14 of the 16 sites, except at Swift Creek (site 24) and Middle Creek (site 25), which are the westernmost of the 16 gages. This means that, with the exception of Swift Creek and Middle Creek, all of the record water levels recently established by Hurricane Fran downstream from Clayton were exceeded as a result of Hurricane Floyd (for example, at Goldsboro, fig. 9). Flood recurrence intervals were greater than 500 years for the Little River (site 26), Nahunta Swamp (site 30), Contentnea Creek at Hookerton (site 31), and the Trent River (site 33); maximum water levels recorded at these sites exceeded previously established maximum values by 2.6 feet (site 26, with 80 years of record) to almost 7.2 feet at site 30, where more than 40 years of streamflow data have been recorded (table 3).

Contributions to streamflow from the upper Neuse Basin (upstream from Falls Dam) were small relative to contributions downstream from Clayton (fig. 10). During September, flow at Falls Dam accounted for about 10 percent of the total flow volume at Goldsboro and about 8 percent of the total monthly flow volume at Kinston. In contrast, the drainage area at Falls Dam represents about 32 percent of the total drainage area at Goldsboro and about 29 percent of the drainage area at Kinston. During October, the volume of water released from Falls Dam was equivalent to about 26 percent of the total flow volume at Goldsboro and about 22 percent of the total flow volume at Kinston. Hence, in both September and October, the volume of flow contributed by Falls

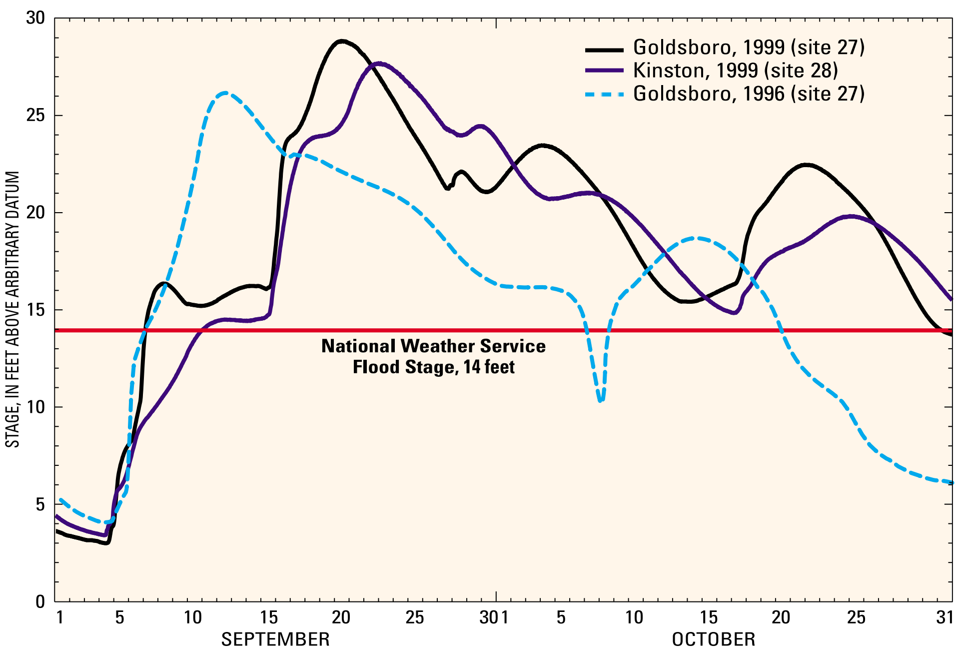


Figure 9. Stage hydrographs for the Neuse River at Kinston, September–October 1999, and near Goldsboro, September–October 1996 and 1999.

Storm surge flooding in Dare County

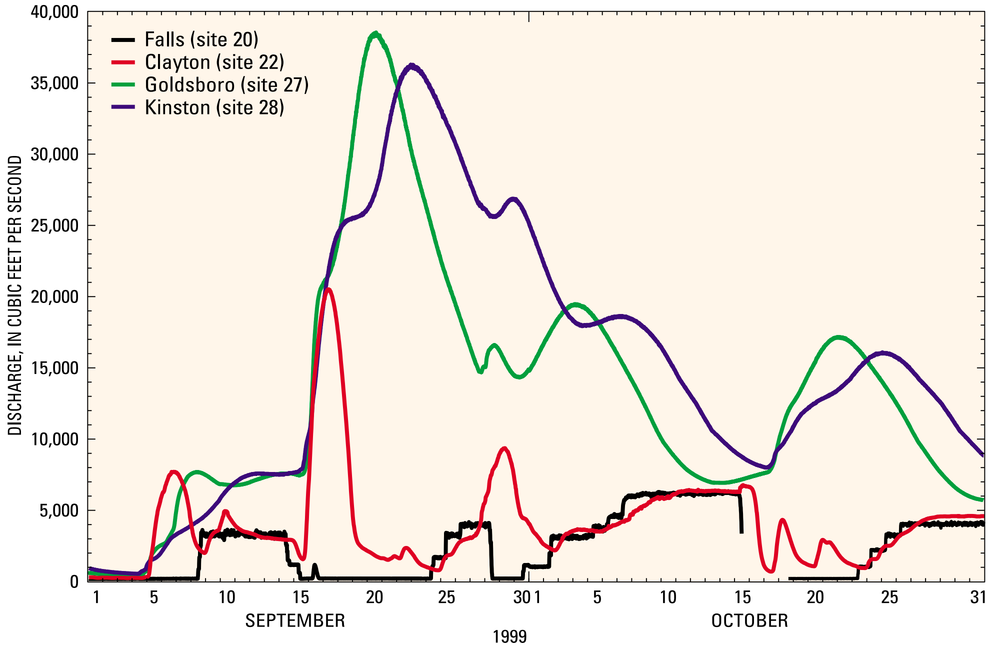


Figure 10. Streamflow in the Neuse River at four locations between Falls Dam and Kinston, September–October 1999.

Dam to the total flow at Goldsboro and Kinston was less than might be expected if the Neuse River were unregulated and if contributions to streamflow were proportional to drainage area. Another way to express the difference between flow contributions from the upper Neuse River Basin and the basin downstream from Falls Dam is in equivalent inches of runoff. The flow from Falls Dam during September was equivalent to 1.9 inches of runoff from the 772-mi^2 drainage basin upstream from the dam. The runoff from the 1,920-mi^2 portion of the Neuse Basin between Falls Dam and Kinston during September was 8.5 inches. In comparison, the average *annual* runoff for the entire Neuse River Basin upstream from Kinston for the period 1983–99 (the period after the completion of Falls Dam) was about 14 inches.

Neuse River flooding in Goldsboro, N.C. Acoustic Doppler current profiler used for discharge measurements shown in the foreground on the boat bow.

Cape Fear River Basin

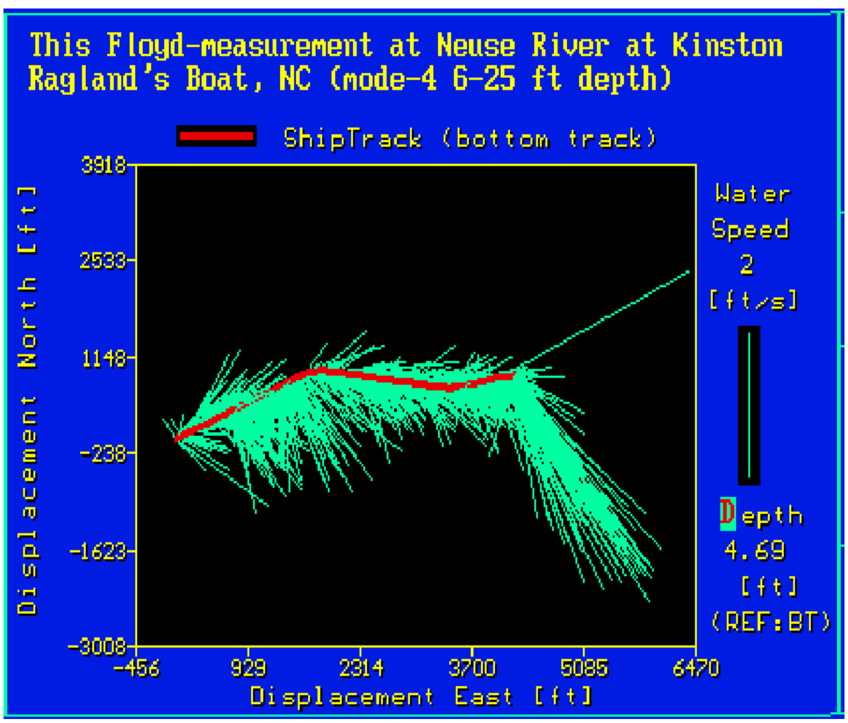
Flooding was much less widespread in the Cape Fear River Basin than in the Tar-Pamlico and Neuse River Basins. The most severe flooding occurred near Wilmington and along the Black and Northeast Cape Fear Rivers, near the location where Hurricane Floyd made landfall. New maximum water-level records were established on Hood Creek (site 41), Black River (site 42), and Northeast Cape Fear River (site 43), and flood recurrence intervals at those sites were between 100 and in excess of 500 years (table 3). On the Northeast Cape Fear River, the September 1999 maximum water level exceeded the previous record by almost 3.4 feet, and the peak flow was 50 percent greater than the previously recorded peak flow, which occurred in 1962 (table 3).

Other River Basins

The number of streamgages in northeastern North Carolina is small relative to those in the Tar-Pamlico and Neuse River Basins, so the extent and magnitude of flooding in that region is not as easily determined.

However, several streams in the Chowan River Basin experienced 50- to greater than 500-year flood flows (table 3; fig. 7). The previously recorded maximum water levels were exceeded at Potecasi Creek (site 4) and Ahoskie Creek (site 5) in North Carolina, as well as on the Nottoway (site 1) and Blackwater (site 2) Rivers in Virginia near the North Carolina–Virginia State line (fig. 7). The previously recorded maximum water level on the Cashie River (site 6) was exceeded by 7 feet during Hurricane Floyd, and the flood recurrence interval was greater than 500 years.

The high rainfall amounts in southeast North Carolina (table 1) had a dramatic effect on the Waccamaw River (site 44; fig. 7), where streamflow has been recorded for 60 years (table 3). The maximum streamflow recorded following Hurricane Floyd was more than 2.5 times greater than the highest streamflow ever recorded at the site (table 3), and the flood-flow recurrence interval was greater than 500 years. The previous highest streamflow occurred as a result of Hurricane Fran in 1996. The maximum streamflow in the Lumber River at Boardman (site 45) was approximately equal to the highest previously recorded flow (in 1945) at the site, which has 70 years of record. The highest previously recorded water level for the New River (site 34) was established in 1955 as a result of Hurricane Ione (fig. 5; table 3). However, the maximum water level for the New River resulting from Hurricane Floyd rainfall exceeded that from Hurricane Ione by more than 5 feet (table 3), and peak flow resulting from Hurricane Floyd was almost double the 1955 peak flow.



Data from ADCP discharge measurement at Neuse River at Kinston, N.C. Blue-green lines show velocity direction and magnitude (scale at left) along the boat path (shiptrack, red line). Total measured discharge was 27,300 ft^3/s, and total length of measurement was 4,310 feet.

FLOOD RECURRENCE INTERVALS

A statistical technique called frequency analysis is used to estimate the probability of occurrence of a flood peak having a given magnitude. The recurrence interval (sometimes called the return period) of a peak flow is the probability that the flow will be equaled or exceeded in any given year. For example, there is a 1 in 100 (or one percent) chance that a streamflow of at least 45,500 ft^3/s will occur during any year on the Tar River at Tarboro (site 14, table 3; fig. 7). Thus, a peak flow of 45,500 ft^3/s at site 14 is said to have a 100-year recurrence interval, or to be the 100-year flood. This is not to say that a flow of 45,500 ft^3/s will occur only once during the next 100 years, but rather that there is a 1 in 100 chance that a flow of 45,500 ft^3/s will be equaled or exceeded during any given year. Moreover, from a statistical point of view, the fact that a 100-year flood occurs one year does not affect the probability of such a flood occurring the following year.

The standard procedures (Hydrology Subcommittee of the Interagency Advisory Committee on Water Data, 1982) used to compute flood recurrence intervals from data collected at a stream-gaging site are based on a number of assumptions, including the following:

- Distribution of the logarithms of the annual peak flows can be approximated by the Pearson Type-III distribution;
- Annual peak flows are independent;

- No trend is present in the record of annual peak flows; and
- No major changes, such as construction of an impoundment, have occurred in the watershed upstream from the site of interest.

The period of record that is used to compute flood recurrence intervals at a gaging station has a substantial effect on the computed recurrence intervals. For example, recurrence intervals for gaging stations in North Carolina were recently computed by using all available data through September 1996 (Pope and Tasker, 1999). For the Tar River at Tarboro (fig. 11), Pope and Tasker (1999) used data for the period 1897–1996. The period of record used by Pope and Tasker (1999) in the analysis for the Neuse River at Kinston (fig. 12) was 1981–1996, although records have been collected at the site since 1928. The reason for using only the record since 1981 is that construction of Falls Dam, and thus, effects on streamflow, began that year (the dam was closed in 1983). Consequently, data prior to 1981 represent a hydrologic condition different from that after closure of the dam. Following Hurricane Floyd, flood recurrence intervals were recomputed for selected gaging stations in eastern North Carolina to provide the best information for mitigation and rebuilding (U.S. Geological Survey, 2000).

At Tarboro, the 100-year flood that was computed by using the 1897–1999 record was about 10 percent greater than the 100-year flood that was computed by using the 1897–1996 record (table 4). However, at Kinston, the effects of the 3 additional years of record resulted in an increase in the computed 100-year flood flow of more than 40 percent (table 4). The change in the computed 100-year flood flow at Kinston was larger than that at Tarboro because (1) the period of record is shorter at Kinston, and the inclusion of three more flood peaks adds a larger percentage to the period of record at Kinston than at Tarboro; and (2) not only did Hurricane Floyd occur during 1997–99, giving the highest flow during the regulated period (1981–present), but also, the fourth highest flood during the regulated flow period occurred in 1998 (fig. 12).

The length of record used to compute recurrence intervals represents a balance between the needs to (1) reduce variance in the computed recurrence intervals and (2) avoid bias in the distribution of annual peak flows (Committee on American River Flood Frequencies, 1999). It is fairly well established that decadal to centennial variations occur in climate

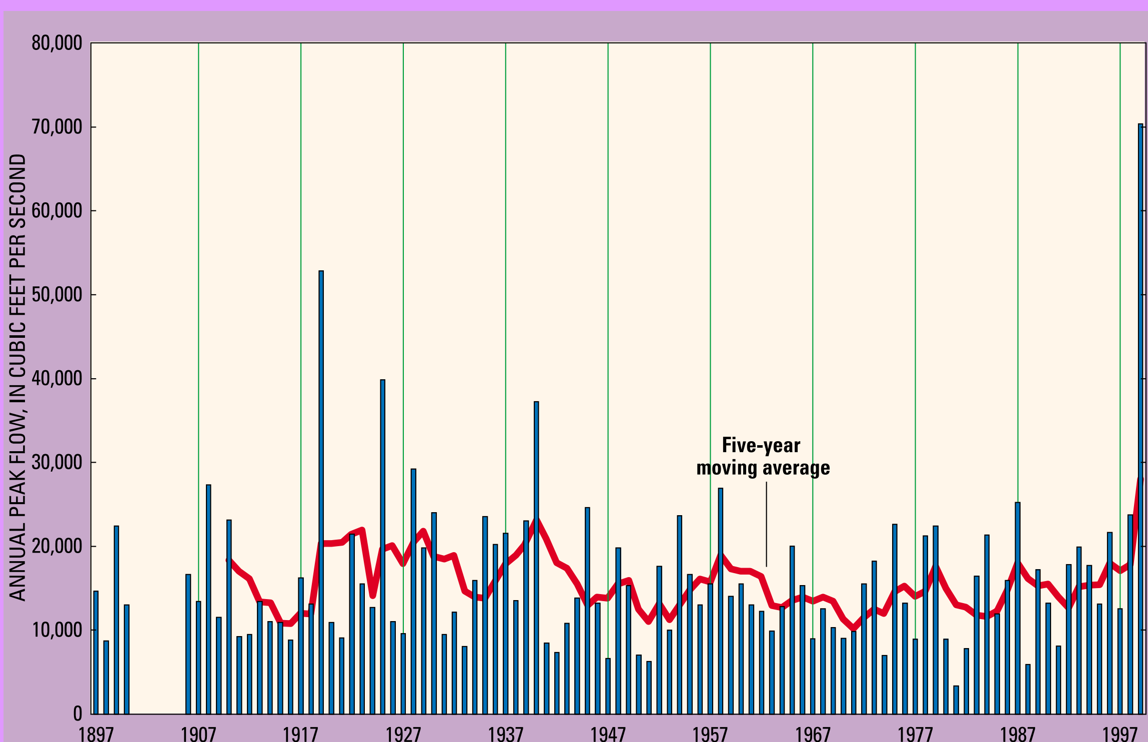


Figure 11. Annual peak flows, Tar River at Tarboro, 1897–1999.

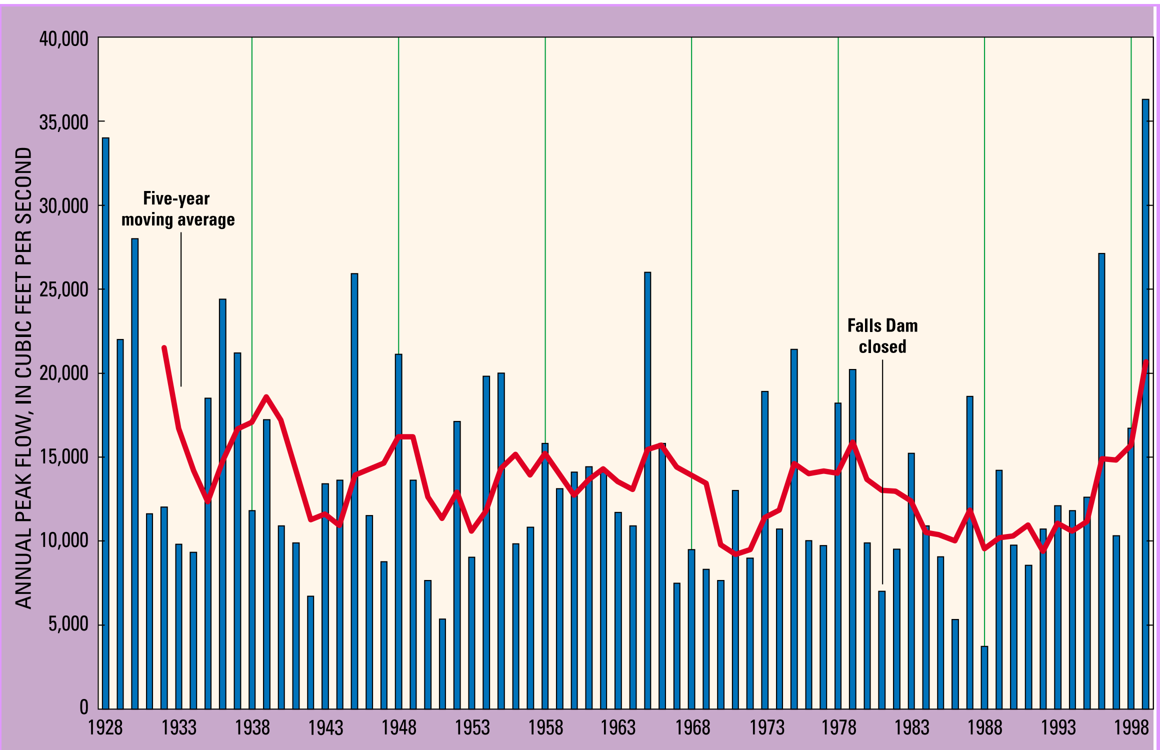


Figure 12. Annual peak flows, Neuse River at Kinston, 1928–1999.

(perhaps now superimposed on long-term human-induced trends) that affect hydrologic conditions (National Research Council, 1998). Consequently, the longer periods of record may include periods during which flood risk is different from the current period or the future design period. For example, four of the five largest floods during the last 102 years at Tarboro occurred during the period 1919–40 (fig. 11). However, there is no indication that a long-term trend in annual peak flows at Tarboro exists (fig. 11). Likewise, at Kinston, 5 of the 11 flood peaks greater than 20,000 ft^3/s occurred during the 10-year period 1928–37 (fig. 12).

On the other hand, a longer period of record reduces the variance in the estimated recurrence intervals. The 90-percent confidence band for the 100-year flood flow estimated for the Tar River at Tarboro is fairly narrow (table 4). However, the 90-percent confidence band for the 100-year flood estimate for the Neuse River at Kinston, where 19 years of record were used in the analysis, is quite large and represents a range in stage of **more than 5 feet**. In the relatively flat topography of the Coastal Plain, this uncertainty in the 100-year flood elevation can translate to a large uncertainty in the delineation of the regulatory 100-year floodplain.

Table 4. Effect of period of record on computed 100-year flood magnitude, Tar River at Tarboro and Neuse River at Kinston, N.C.

[ft^3/s, cubic feet per second; —, not computed]

	Tar River at Tarboro		Neuse River at Kinston	
Period of record	1897–1996	1897–1999	1981–1996	1981–1999
Computed 100-year flood flow, in ft^3/s	41,300	45,500	28,200	40,500
90-percent confidence band, in ft^3/s	—	39,100–53,500	—	29,300–68,700

Freshwater Delivery to Pamlico Sound

Pamlico Sound is a relatively shallow lagoonal estuary with a mean depth of 16 feet and a surface area of 2,060 mi^2 (Giese and others, 1985). The Sound is bounded on the seaward side by the Outer Banks, a barrier island system that restricts water exchange with the Atlantic Ocean through four small inlets. The Chowan River, Roanoke River, and several small rivers drain to Albemarle Sound, which then drains southward to Pamlico Sound or to the Atlantic Ocean through one of the four inlets. Sixty percent of the total Pamlico Sound drainage area is in the basin that drains to Albemarle Sound (table 5).

The ratio of the volume of Pamlico Sound (920 billion cubic feet [ft^3]) to the average annual inflow (32,000 cubic feet per second [ft^3/s]) from the entire basin, including the Albemarle Sound drainage, yields a theoretical freshwater replacement time of about 11 months. Actual residence time is likely longer for many locations in Pamlico Sound because of restricted circulation, the short-circuiting of some inflows, and the position of the tidal inlets relative to the major freshwater inflows. Long water residence times, small tidal amplitude (1.0–1.5 feet), and slow-flowing tributaries make Pamlico Sound an effective trap for dissolved and particulate matter.

Freshwater inflow to Pamlico Sound was estimated for September and October 1999. Flows were determined from data collected at the USGS network of streamgages in North Carolina and Virginia (fig. 7) and from estimates of flow from ungaged areas. Streamflow from 67.7 percent of the land area draining to Pamlico Sound is gaged. Rainfall on the surface of Albemarle Sound and Pamlico Sound was estimated from raingage and Doppler radar measurements, and the rainfall volume was converted to a flow rate for comparison with streamflow. The volume of freshwater inflow as a percentage of Pamlico Sound volume was computed by converting the monthly mean flow rate to a total volume for the month, and then dividing the freshwater inflow volume by the volume of Pamlico Sound. Normal inflow was computed from long-term monthly mean streamflow records. The period of streamflow record at the various streamgages used in the analysis ranged from about 15 years to more than 100 years.

Freshwater inflow volume to the head of the Pamlico River estuary (near site 18, fig. 7) during the month of September was more than 90 percent of the mean annual flow volume (table 5; Bales and Robbins, 1995). Freshwater inflow to the Neuse River estuary (near site 47, fig. 7) was slightly less than inflow to the Pamlico River estuary, with

Table 5. Estimated monthly mean freshwater flow from basins draining to Pamlico Sound, N.C., September and October 1999

[mi^2, square miles; ft^3/s, cubic feet per second]

Basin	Drainage area (mi^2) [percentage of total Pamlico Sound drainage]	September 1999		October 1999	
		Monthly mean flow (ft^3/s)	Inflow volume as a percentage of Pamlico Sound volume: actual [normal]	Monthly mean flow (ft^3/s)	Inflow volume as a percentage of Pamlico Sound volume: actual [normal]
Albemarle Sound subbasin					
Roanoke	9,776 [32]	20,040	5.65 [1.70]	13,410	3.90 [1.87]
Chowan	4,929 [16]	35,750	10.1 [0.57]	9,210	2.68 [0.71]
Other drainage to Albemarle Sound	2,722 [9]	19,720	5.56 [0.31]	5,930	1.73 [0.39]
Rainfall on the surface of Albemarle Sound	933 [3]	12,950	3.65 [0.47]	1,660	0.48 [0.47]
Subtotal for Albemarle Sound subbasin	18,360 [60]	88,460	25.0 [3.05]	16,800	8.79 [3.44]
Neuse	5,598 [17]	45,060	12.7 [1.17]	29,920	8.71 [0.90]
Tar-Pamlico	4,302 [14]	47,280	13.3 [0.61]	15,030	4.38 [0.60]
Other drainage to Pamlico Sound	560 [2]	6,140	1.73 [0.13]	2,220	0.65 [0.10]
Rainfall on the surface of Pamlico Sound	2,060 [7]	22,120	6.23 [1.55]	5,360	1.56 [1.54]
TOTAL	30,880 [100]	209,000	58.9 [6.50]	82,700	24.1 [6.58]

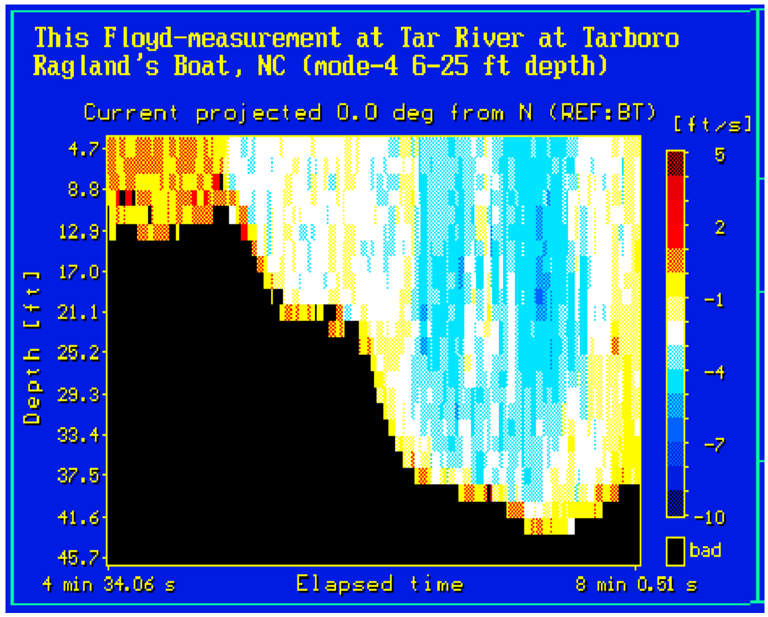
September inflow equivalent to 55–60 percent of annual inflow (table 5; Robbins and Bales, 1995). Estimated mean water residence time was about 7 days for the Pamlico and Neuse River estuaries during September, compared to a long-term annual average of 72 and 68 days for these estuaries, respectively (Bales and Robbins, 1995; Robbins and Bales, 1995).

During September–October 1999, the total freshwater inflow volume to Pamlico Sound was equivalent to about 83 percent of the total volume of the Sound, whereas under normal conditions inflow volume during these 2 months is equivalent to about 13 percent of the volume of the Sound (table 5; Giese and others, 1985). This means that by the end of October much of the water that was in the Sound at the beginning of September could have been displaced by floodwaters.

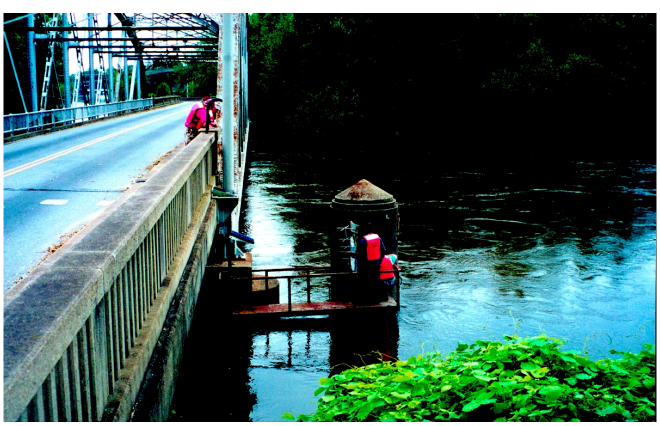
In September alone, the freshwater inflow to Pamlico Sound was about an order of magnitude greater than normal (table 5). Although the Roanoke River Basin comprises almost one-third of the total Pamlico Sound drainage area, freshwater inflow from this basin accounted for only about 10 percent of the total inflow to the Sound because of (1) the presence of a large flood-control reservoir near the downstream end of the basin and (2) the paths of the hurricanes, which avoided much of the basin (fig. 2). On the other hand, the Neuse and Tar-Pamlico River Basins, which together compose about 31 percent of the Pamlico Sound drainage area, contributed about 44 percent of the inflow to the Sound in September, and more than half of the inflow to the Sound in October. This is particularly important because both of these rivers drain directly to Pamlico Sound and because these rivers are known to carry relatively high loads of nutrients and other contaminants (North Carolina Department of Environment, Health, and Natural Resources, 1993, 1994; Harned and others, 1995).


USGS

USGS staff making a discharge measurement using an acoustic Doppler current profiler on the Tar River



Results of ADCP measurement at Tar River at Tarboro, N.C., showing cross-sectional distribution of velocity. Negative velocities in the center of the channel are about 5 feet per second and are oriented downstream. Note upstream eddies along the left edge. Total measured discharge was 33,600 ft^3/s, and the width of the measured cross section was 1,120 feet.


USGS

Tar River at Greenville, N.C.

Floods can transport tremendous quantities of material from the land surface into the stream system, inundate areas that are contaminated with a variety of substances, flood wastewater-treatment facilities that may be located in or near the floodplain, and result in the failure of animal waste lagoons. The large volume of water transported during the Hurricane Floyd flooding demonstrated that even low concentrations of pollutants can result in the transport of extremely high loads (or mass) of these materials through the stream system and ultimately to the estuaries of eastern North Carolina. The somewhat limited water-quality sampling that was conducted following Hurricane Fran (Bales and Childress, 1996) proved to be very informative because little is known about water-quality conditions during extremely large floods. Water-quality samples were collected during the flooding that followed Hurricane Floyd in order to better document and understand the transport of nutrients, metals, pesticides, and other pollutants during extreme floods; to document loadings of pollutants transported to the coastal waters; to compare Hurricane Floyd water-quality conditions with those resulting from Hurricane Fran; and to provide a basis for understanding possible future environmental changes (such as accelerated estuarine eutrophication) that may result from the floods.

Floodwater-quality samples were collected at 15 sites (fig. 13; table 6) beginning on September 16, 1999, following the passage of Hurricane Floyd through the State, and continuing through October 5, 1999. Five sites on the Tar River from Tar River (site 7) to Greenville (site 16) were sampled; five sites were sampled on the mainstem of the Neuse River from Clayton (site 22) to Fort Barnwell (site 32) and two Neuse River tributary sites were sampled; the Cape Fear River at Lock 1 (site 40) was sampled, as were the Northeast Cape Fear River near Chinquapin (site 43) and the Lumber River at Boardman (site 45). Samples were collected on the day of the peak discharge on the Tar River from Louisburg to Greenville (sites 8, 9, and 16), except at Tarboro (site 14), where the first sample was collected 2 days after the peak at 93 percent of the peak discharge. The Tar River

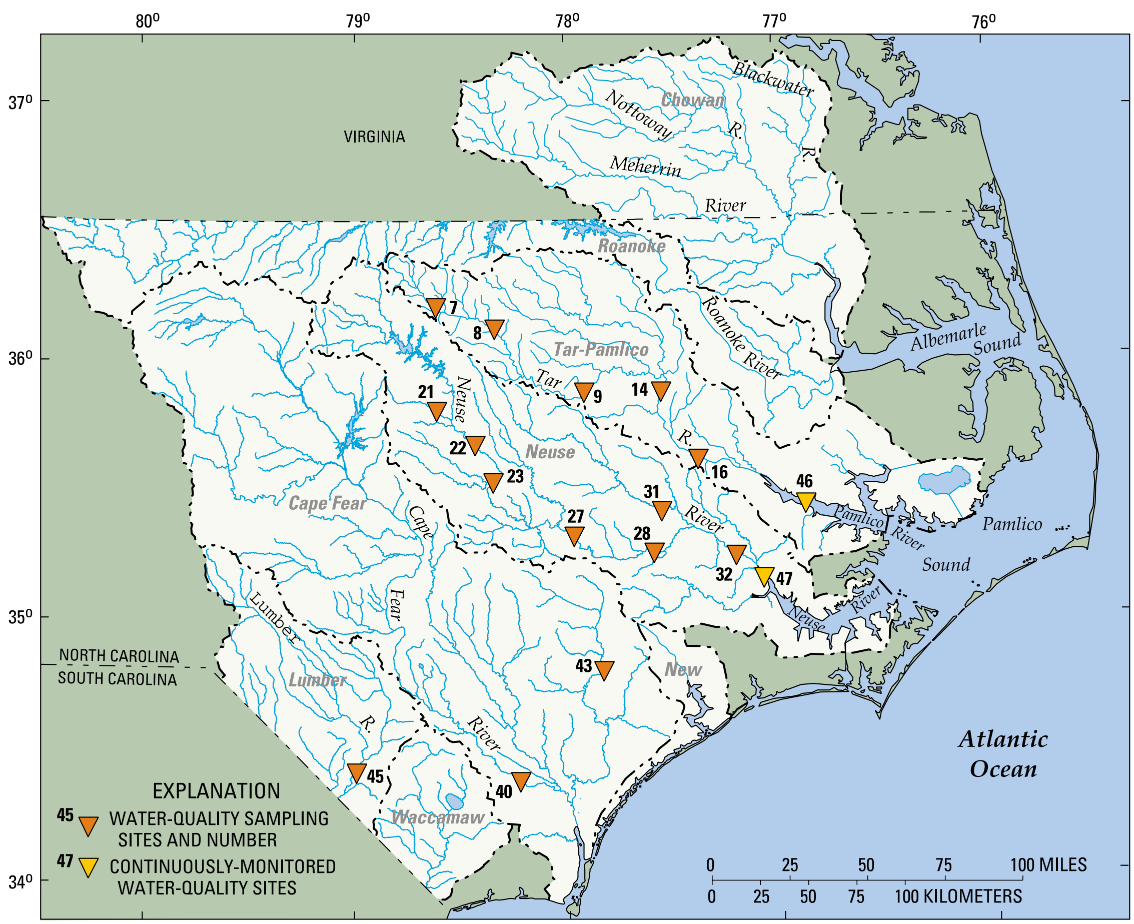


Figure 13. Sites at which water-quality samples were collected by the USGS in September–October 1999, following Hurricane Floyd.

Table 6. Summary of floodwater-quality samples collected in eastern North Carolina, September–October 1999

[ft^3/s, cubic feet per second; VOCs, volatile organic compounds]

Site no. (fig. 13)	Site name	Date	Flow (ft^3/s)	Data collected						
				Physical[a]	Suspended sediment	Nutrients[b] and organic carbon	Bacteria[c]	Metals[d]	VOCs[e]	Pesticides[f]
Tar-Pamlico River Basin										
7	Tar River near Tar River	9/17	4,940	yes	yes	yes	yes	yes	no	yes
		9/19	156	yes	yes	yes	no	yes	no	yes
		10/5	81.3	yes	no	no	no	no	no	no
8	Tar River at Louisburg	9/17	23,400	yes	yes	yes	yes	yes	no	yes
		9/19	5,190	yes	yes	yes	no	yes	no	yes
		10/5	644	yes	no	no	no	no	no	no
9	Tar River below Tar River Reservoir	9/17	24,000	yes	yes	yes	no	yes	no	yes
		9/19	18,800	yes	yes	yes	no	yes	no	yes
		9/23	2,240	yes	yes	yes	yes	no	no	no
		10/5	1,700	yes	no	no	no	no	no	no
14	Tar River at Tarboro	9/21	65,400	yes	yes	yes	yes	yes	no	yes
		9/27	23,200	yes	yes	yes	no	yes	yes	yes
		10/5	13,000	yes	yes	yes	yes	yes	yes	yes
16	Tar River at Greenville	9/20	71,800[g]	no	no	no	yes	no	no	no
		9/21	72,300	yes	yes	yes	yes	yes	no	yes
		9/29	29,600	yes	yes	yes	no	yes	yes	yes
Neuse River Basin										
21	Crabtree Creek at U.S. 1 at Raleigh	9/16	6,010	yes	yes	yes	no	yes	no	yes
22	Neuse River near Clayton	9/17	20,400	yes	yes	yes	yes	yes	no	yes
		9/19	2,620	yes	yes	yes	no	yes	no	yes
		9/20	1,880	yes	yes	yes	yes	yes	no	yes
		9/28	7,260	yes	no	no	no	no	no	no
23	Neuse River at Smithfield	9/17	22,300[h]	yes	yes	yes	no	yes	no	yes
		9/19	15,300[h]	yes	yes	yes	no	yes	no	yes
		9/20	8,020[h]	yes	yes	yes	yes	yes	no	yes
		9/28	6,670[h]	yes	no	no	no	no	no	no
27	Neuse River near Goldsboro	9/17	22,500	yes	yes	yes	yes	yes	no	yes
		9/28	16,400	yes	yes	yes	yes	no	no	yes
28	Neuse River at Kinston	9/20	27,300	yes	yes	yes	yes	yes	no	yes
		9/28	25,600	yes	yes	yes	yes	no	no	yes
31	Contentnea Creek at Hookerton	9/21	26,500[g]	yes	yes	yes	yes	yes	no	yes
32	Neuse River near Fort Barnwell	9/22	55,300[g]	yes	no	yes	yes	yes	no	yes
Cape Fear River Basin										
40	Cape Fear River at Lock 1	9/23	28,600	yes	yes	yes	yes	yes	no	yes
		9/30	17,200	yes	no	yes	yes	yes	yes	yes
43	Northeast Cape Fear River near Chinquapin	9/21	16,800	yes	yes	yes	yes	yes	no	yes
		9/24	8,500	yes	no	yes	no	yes	no	no
		9/30	3,580	yes	no	no	yes	no	no	no
Lumber River Basin										
45	Lumber River at Boardman	9/21	12,500	yes	yes	yes	yes	yes	no	yes
		9/23	11,000	yes	no	no	no	no	no	no

[a]Includes water temperature, specific conductance, dissolved oxygen concentration, and pH.
[b]Includes dissolved ammonia, dissolved nitrite plus nitrate, total Kjeldahl nitrogen, total nitrogen (calculated), total phosphorus, total orthophosphorus, suspended organic carbon, and dissolved organic carbon.
[c]Includes E. coli and C. perfringens.
[d]Includes dissolved manganese, copper, arsenic, lead, selenium, chromium, cadmium, mercury, iron, zinc, nickel, and beryllium.
[e]Samples were analyzed for concentrations of seven volatile organic compounds.
[f]Samples were analyzed for concentrations of 47 pesticides.
[g]Estimated mean daily value.
[h]Discharge values estimated from 1983 stage-discharge rating.

near Tar River (site 7) was sampled the day following the peak when the flow was about 50 percent of the peak discharge. Peak or near peak discharges were sampled on the Neuse River at Clayton (site 22), Smithfield (site 23), and Fort Barnwell (site 32). The Neuse River at Goldsboro (site 27) and Kinston (site 28) were sampled within 3 days in advance of the peak at 63 and 75 percent of the peak discharge, respectively. Two tributaries, Crabtree Creek (site 21) and Contentnea Creek at Hookerton (site 31), were sampled at about 75 percent of the peak flow and after the peak discharge had occurred. In the Cape Fear and Lumber River Basins, samples were collected within 3 days after the peak discharge. The Cape Fear River at Lock 1 (site 40) was sampled at 72 percent of the peak, the Northeast Cape Fear River (site 43) at 60 percent, and the Lumber River at Boardman (site 45) at 92 percent.

Samples were analyzed for nutrients, trace metals, dissolved and suspended organic carbon, suspended sediment, and *Escherichia coli (E. coli)* and *Clostridium perfringens (C. perfringens)* bacteria (table 6). In addition, 28 samples were analyzed for 47 pesticide compounds and 4 samples were analyzed for 7 volatile organic compounds related to fuels. Dissolved oxygen concentrations, pH, specific conductance, and water temperature were measured at all sites. Analyses reported for nitrate plus nitrite are given herein as nitrate concentrations because nitrite concentrations were less than reporting levels. All nitrogen species are reported in milligrams per liter as nitrogen (N). Results are compared to other water-quality samples collected by the USGS since 1990 at the Tar River at Tarboro; the Neuse River near Clayton, at Smithfield, near Goldsboro, at Kinston, and near Fort Barnwell; Contentnea Creek at Hookerton; and the Cape Fear River at Lock 1, including samples collected at most of these sites during flooding from Hurricane Fran in 1996.

USGS

USGS staff collecting water-quality samples on the Tar River

Dissolved Oxygen, pH, and Specific Conductance

Dissolved oxygen concentrations less than the established minimum standard concentration of 4 milligrams per liter (mg/L) by the North Carolina Department of Environment, Health, and Natural Resources (1997) were measured in the Tar River at Tarboro and Greenville; the Neuse River at Kinston and near Goldsboro; Contentnea Creek; the Northeast Cape Fear River; and the Lumber River. Concentrations measured by the USGS during the Hurricane Floyd flooding ranged from 0.99 mg/L on the Tar River at Tarboro (site 14) to 8.7 mg/L on the Tar River at Rocky Mount (site 10), both of which occurred on September 23, or 1 week after the peak discharge at the sites. Dissolved oxygen concentrations were between 2 and 3 mg/L in the Neuse River 5 days after the peak streamflow. In the Northeast Cape Fear River, dissolved oxygen concentrations were at or below 3.5 mg/L 12 days after the peak streamflow.

Staff from the North Carolina Division of Water Quality measured dissolved oxygen concentrations at many sites throughout eastern North Carolina on September 27–28 after the flooding (North Carolina Division of Water Quality, 1999).

USGS

Water-quality samples are processed on-site in specially equipped vehicles

On September 27, the median dissolved oxygen concentration at 10 sites in the Lumber River Basin was 5.2 mg/L with a minimum of 1.3 mg/L; the median concentration in the Waccamaw River Basin was 2.55 mg/L with concentrations at all 6 sites less than or equal to 2.7 mg/L. Also on September 27, the median dissolved oxygen concentration measured at 16 sites in the Tar River Basin was 4.5 mg/L with a minimum concentration of 0.17 mg/L, and a maximum concentration of 8.07 mg/L at Rocky Mount, which is where the USGS measured the maximum dissolved oxygen concentration in the Tar River. On September 28, at 11 sites in the Chowan River Basin, the median dissolved oxygen concentration was 2.5 mg/L and the minimum concentration was 1.2 mg/L.

Although dissolved oxygen concentrations were quite low, the sustained hypoxic conditions that occurred in floodwaters from Hurricane Fran did not occur after Hurricane Floyd (table 7). These somewhat higher dissolved oxygen concentrations that occurred in Hurricane Floyd floodwaters may have been the result of one or a combination of the following factors:

- Air temperatures following Hurricane Floyd were somewhat cooler than after Hurricane Fran.
- Higher and more sustained flows after Hurricane Floyd provided greater dilution of oxygen-consuming materials.
- Slower recession of Hurricane Floyd floodwaters resulted in a more gradual delivery of organic matter from the floodplain to the river than during Hurricane Fran flooding.


NCDEM

Farm surrounded by floodwaters

Table 7. Dissolved oxygen concentrations, in milligrams per liter, at selected sites in the Neuse and Cape Fear River Basins, N.C., approximately 5 days following the passages of Hurricanes Floyd (1999) and Fran (1996)

[—, no data]

Site no. (fig. 13)	Station name	Hurricane Floyd Sept. 16–17, 1999 (sampled Sept. 20–21, 1999)	Hurricane Fran Sept. 5–6, 1996 (sampled Sept. 10, 1996)
22	Neuse River near Clayton	7.5	5.0
23	Neuse River at Smithfield	4.9	3.8
27	Neuse River near Goldsboro	—	0.4
28	Neuse River at Kinston	2.8	0.9
31	Contentnea Creek at Hookerton	2.9	1.0
40	Cape Fear River at Lock 1	4.4	2.5

Specific conductance values were low compared to previous records (table 8) indicating the effects of dilution from the floodwaters of Hurricane Floyd. Likewise, pH values were about 0.5 to 1.0 standard units lower than typical values measured during the previous 9-year record. The lower pH likely was the result of the large volume of rainfall during September and October; rainfall typically has a pH of about 4.5 in eastern North Carolina (National Atmospheric Deposition Program, 1999). Measurements of pH ranged from 4.4 in the Lumber River on September 21 and 23 to about 6.5 at several locations in the Tar River on October 5.

Nitrogen, Phosphorus, and Organic Carbon

For three of the five sites for which comparisons could be made (table 8), maximum ammonia concentrations measured in floodwaters were approximately equal to the median concentrations measured from January 1990 to August 1999, and certainly

Table 8. Summary of water-quality samples collected during 1990–99 at selected sites in eastern North Carolina, and maximum concentrations measured following Hurricane Floyd, September–October 1999

[<, less than]

Site name [site no.] (fig. 13)	January 1990–August 1999				September–October 1999
	No. of samples	Maximum concentration	Minimum concentration	Median concentration	Maximum concentration [date]
Specific conductance (microsiemens per square centimeter)					
Tar River at Tarboro [14]	59	339	49	105	57 [10/5]
Neuse River at Smithfield [23]	70	331	68	184	78 [9/20]
Neuse River at Kinston [28]	84	258	58	120	70 [9/28]
Contentnea Creek at Hookerton [31]	88	221	55	98	35 [9/21]
Cape Fear River at Lock 1 [40]	22	186	54	108	90 [9/30]
Ammonia (milligrams per liter)					
Tar River at Tarboro [14]	60	0.25	<0.015	0.05	0.051 [9/21]
Neuse River at Smithfield [23]	63	.34	<.01	.04	.087 [9/19]
Neuse River at Kinston [28]	80	1.20	<.015	.05	.072 [9/28]
Contentnea Creek at Hookerton [31]	87	2.0	<.015	.076	<.02 [9/21]
Cape Fear River at Lock 1 [40]	21	.15	.03	.08	.155 [9/23]
Organic nitrogen (milligrams per liter)					
Tar River at Tarboro [14]	60	0.90	0.31	0.45	0.79 [10/5]
Neuse River at Smithfield [23]	63	.86	.25	.51	.56 [9/17]
Neuse River at Kinston [28]	79	2.13	<.251	.44	.73 [9/28]
Contentnea Creek at Hookerton [31]	85	1.085	.34	.51	.58 [9/21]
Cape Fear River at Lock 1 [40]	21	.85	.30	.50	.65 [9/30]
Nitrite plus nitrate (milligrams per liter)					
Tar River at Tarboro [14]	60	0.90	<0.05	0.40	0.032 [10/5]
Neuse River at Smithfield [23]	63	3.20	.40	1.5	.23 [9/20]
Neuse River at Kinston [28]	80	2.00	<.05	.80	.14 [9/20]
Contentnea Creek at Hookerton [31]	87	1.029	<.05	.69	<.05 [9/21]
Cape Fear River at Lock 1 [40]	21	1.10	.33	.66	.33 [9/30]
Total phosphorus (milligrams per liter)					
Tar River at Tarboro [14]	60	0.22	<.03	0.09	0.1 [9/21 and 10/5]
Neuse River at Smithfield [23]	68	.49	.02	.15	.12 [9/17]
Neuse River at Kinston [28]	81	.29	<.02	.10	.14 [9/20 and 9/28]
Contentnea Creek at Hookerton [31]	87	.42	<.004	.145	.15 [9/21]
Cape Fear River at Lock 1 [40]	21	.26	.08	.135	.14 [9/30]
Orthophosphorus (milligrams per liter)					
Tar River at Tarboro [14]	60	0.27	<.0.01	0.05	0.049 [9/21]
Neuse River at Smithfield [23]	63	.33	<.01	.08	.045 [9/19]
Neuse River at Kinston [28]	80	.37	<.004	.054	.078 [9/28]
Contentnea Creek at Hookerton [31]	87	1.20	<.01	.08	.07 [9.21]
Cape Fear River at Lock 1 [40]	21	.16	.03	.07	.056 [9/30]
Suspended organic carbon (milligrams per liter)					
Tar River at Tarboro [14]	40	2.8	0.1	0.8	2.1 [9/21]
Neuse River at Kinston [28]	59	2.7	<.2	.7	.6 [9/21 and 9/28]
Contentnea Creek at Hookerton [31]	66	3.2	<.2	.5	1.1 [9/21]
Dissolved organic carbon (milligrams per liter)					
Tar River at Tarboro [14]	42	11	4.9	6.8	16 [9/27]
Neuse River at Kinston [28]	60	9.6	4.2	6.5	15 [9/28]
Contentnea Creek at Hookerton [31]	69	15	4.7	6.7	14 [9/21]

much less than the maximum concentrations measured during that period. However, the ammonia concentration measured on September 23, 1999, at the Cape Fear River at Lock 1 was the highest ammonia concentration measured at the site during 1990–99. Organic nitrogen, total phosphorus, and orthophosphorus concentrations measured in floodwaters were approximately equal to median concentrations measured from January 1990 to August 1999 (table 8). Nitrate concentrations measured in Hurricane Floyd floodwaters were low compared to previous measurements made from January 1990 to August 1999 (table 8).

In the Tar-Pamlico River Basin, concentrations of nitrate ranged from below detection (<0.005 mg/L) to 0.073 mg/L (Tar River at Louisburg) except at Tar River at Tar River, which had a concentration of 0.11 mg/L on the falling side of the peak streamflow. Ammonia concentrations ranged from below detection (<0.002 mg/L) to 0.150 mg/L at site 9 (Tar River below Tar River Reservoir). Most of the nitrogen at the Tar-Pamlico River Basin sites occurred as organic nitrogen. Organic nitrogen concentrations ranged from 0.5 to 1.0 mg/L. These concentrations generally were greater than the 75-percentile concentration determined from previous records (Harned and others, 1995; table 8).


NCDEM
Flooded hog farm

In the Neuse River Basin, nitrite plus nitrate concentrations ranged from below detection (<0.05 mg/L) to 0.31 mg/L. Ammonia concentrations ranged from <0.02 to 0.171 mg/L. Both the maximum ammonia and maximum nitrate concentrations occurred on the falling side of the peak at Clayton (site 22). One of the highest ammonia concentrations was measured during the peak streamflow at Crabtree Creek at Raleigh (0.129 mg/L, site 21)—a small urban tributary to the Neuse River. The ammonia concentration measured near the streamflow peak in Contentnea Creek at Hookerton (site 31), a Neuse River tributary that drains a primarily agricultural basin, was <0.02 mg/L; the nitrate concentration also was quite low (<0.05 mg/L) compared with typical nitrate concentrations there (median is 0.69 mg/L; table 8). As in the Tar-Pamlico Basin, most of the nitrogen at the Neuse River Basin sites occurred as organic nitrogen; concentrations ranged from 0.5 to 1.7 mg/L with the maximum concentration occurring at Fort Barnwell (site 32). This concentration was nearly double the concentrations measured at Kinston (site 28) during the flooding. Higher


FEMA
Wastewater-treatment facility in Greenville, N.C.

NITROGEN AND PHOSPHORUS IN SURFACE WATERS

Eutrophication of freshwater streams generally results from an excessive amount of phosphorus in the system, whereas excessive nitrogen is most often the cause of eutrophication in estuaries. In order to prevent nuisance plant growth in streams, the U.S. Environmental Protection Agency (USEPA) has established a desired goal of 0.1 mg/L of total phosphorus concentrations in freshwaters not flowing directly into reservoirs or lakes (U.S. Environmental Protection Agency, 1986a), but currently there is no national recommendation for total nitrogen concentrations in either freshwater or coastal systems. The USEPA is leading efforts to develop regional criteria for both phosphorus and nitrogen in surface waters across the Nation.

Nitrate is generally the primary form of nitrogen dissolved in water. Ammonia is commonly associated with point sources and is converted to nitrate or nitrogen gas in aerated water. Organic nitrogen, mostly from plant material, can compose a large part of the total (dissolved and particulate) nitrogen concentration in a stream. Total phosphorus in streams consists of phosphates that do not dissolve readily, but are commonly attached to soil particles, and orthophosphates, which are readily dissolved and easily assimilated by aquatic plants.

In general, nitrogen and phosphorus concentrations are most elevated in small streams that drain basins with large proportions of urban or agricultural land use (U.S. Geological Survey, 1999). Point-source discharges are a major source of nitrate to the Tar and Neuse Rivers, but ground water is an important source of phosphorus to many streams in eastern North Carolina (Spruill and others, 1998). Nutrient concentrations in streams that drain to the Albemarle and Pamlico Sounds were high relative to 19 other large drainage basins studied by the USGS during 1992–95 (Spruill and others, 1998).

concentrations at Fort Barnwell may have been the result of greater inundation of land areas downstream from Kinston, resulting in higher organic nitrogen loadings. Previous measurements of organic nitrogen made at Fort Barnwell during less-than-normal flows in April and July 1999 were lower—measuring 0.45 and 0.37 mg/L, respectively; however, nitrate concentrations in April and July were an order of magnitude higher.

Ammonia concentrations in the Cape Fear River (site 40), Northeast Cape Fear River (site 43), and Lumber River (site 45) ranged from 0.025 mg/L at site 45 to 0.246 mg/L at site 43. The highest ammonia concentration (0.246 mg/L) measured among all of the flood samples (table 6) was in the Northeast Cape Fear River and occurred 6 days following the flood peak. Nitrate concentrations at these three southeast North Carolina sites ranged from 0.015 mg/L at site 45 to 0.330 mg/L at site 40. Median organic nitrogen concentrations at sites 40, 43, and 45 were similar to median flood-sample concentrations measured in the Tar and Neuse Rivers—about 0.7 mg/L—although the maximum concentration in the Northeast Cape Fear River was 1.1 mg/L.

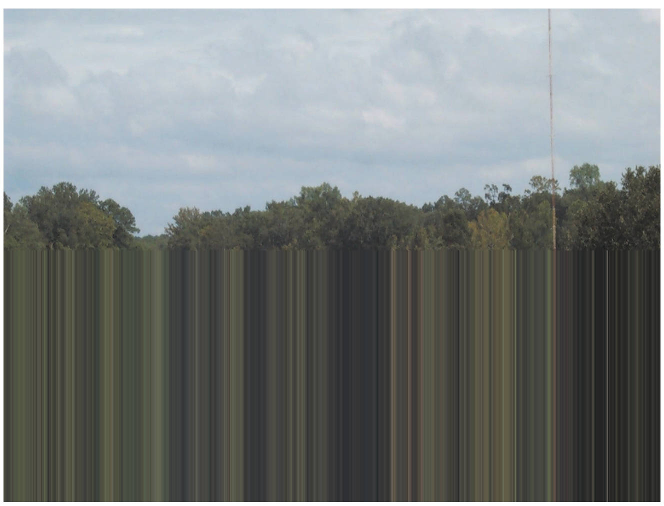
Dissolved organic carbon (DOC) concentrations ranged from 8.4 to 16 mg/L as carbon (C) in the Tar, Neuse, and Cape Fear Rivers, and 17 to 25 mg/L in the carbon-rich, coastal Northeast Cape Fear and Lumber Rivers. These DOC concentrations in floodwaters generally exceeded the highest DOC concentrations previously measured by the USGS in the Tar and Neuse Rivers during the 1990's (table 8).

Floodwaters had two primary effects on nitrogen, phosphorus, and organic carbon. First, floodwaters resulted in tremendous dilution of these constituents. For example, the maximum ammonia concentration at Tarboro (site 14) was 0.051 mg/L on September 21 when the flow was 61,000 ft^3/s. If the same mass of ammonia was present at the long-term September mean flow of 1,220 ft^3/s, then the ammonia concentration would have been 2.55 mg/L, or a concentration about 10 times greater than was measured during 1990–99 at the site (table 8). Despite this dilution, maximum concentrations of ammonia, organic nitrogen, total phosphorus, and orthophosphorus were similar to 1990–99 median concentrations. Only nitrate levels were low compared to 1990–99 concentrations. The second effect of floodwaters was to export large amounts of organic matter from the floodplains to the streams, as indicated by the high organic nitrogen, DOC, and suspended organic carbon concentrations. The long-term effects of these large loads of organic matter on coastal waters remains to be seen.

Bacteria

Floodwaters from Hurricane Floyd inundated animal waste lagoons in eastern North Carolina, killed tens of thousands of livestock, and overwhelmed municipal waste-treatment plants. The risk to public health from floodwaters contaminated by pathogenic bacteria or viruses was a major concern. Twenty-four samples were collected for the analysis of *E. coli* and *C. perfringens* bacteria. These samples were analyzed, using membrane filtration methods, at the USGS laboratory at Columbus, Ohio. E. *coli* and *C. perfringens* are nonpathogenic organisms, but their

Flooded farm



presence indicates contamination from human or animal wastes. The USEPA single-sample ambient water-quality criterion for *E. coli* bacteria density in recreational waters is 235 colonies per 100 milliliters (cols/100 mL) (USEPA, 1986b). Because C. *perfringens* forms an environmentally resistant spore, the bacteria has been proposed as an indicator for the presence of other environmentally resistant microorganisms that are pathogenic. No water-quality criterion has been established for C. *perfringens*.

Densities of E. coli ranged from 57 to 13,000 cols/100 mL and densities of *C. perfringens* from 5 to 170 cols/100 mL (fig. 14). The maximum *E. coli* density occurred in the Neuse River at Fort Barnwell (site 32, fig. 14A). Densities greater than 5,000 cols/100 mL occurred in the Neuse River at Clayton (site 25), Tar River at Louisburg (site 8), and Cape Fear River (site 40). All but the Lumber River and Contentnea Creek had *E. coli* densities that exceeded the USEPA criterion. Generally, *C. perfringens* is much less abundant in natural waters than *E. coli,* and measured densities of *C. perfringens* were, at most sites, two orders of magnitude less than *E. coli.* Neuse River sites had somewhat greater densities of *C. perfringens* than the Tar River sites (fig. 14B), probably reflecting higher point-source dicharges to the Neuse River. Maximum densities of C. perfringens occurred in the Neuse River at Clayton (site 22) and Neuse River at Smithfield (site 23)—both of which are fairly near large municipal wastewater-treatment plant outfalls—and Contentnea Creek (site 31). The lowest densities of *C. perfringens* occurred in the Northeast Cape Fear and Lumber Rivers, neither of which have large municipal point sources.

Samples were collected during two or more different streamflow conditions at sites 14, 16, 21, 22, 27, 28, 40, and 43 (table 6). As floodwaters receded, a decrease in *E. coli* density was observed for Tar River at Tarboro, Neuse River near Clayton and at Smithfield, and Cape Fear River. In the Neuse River near

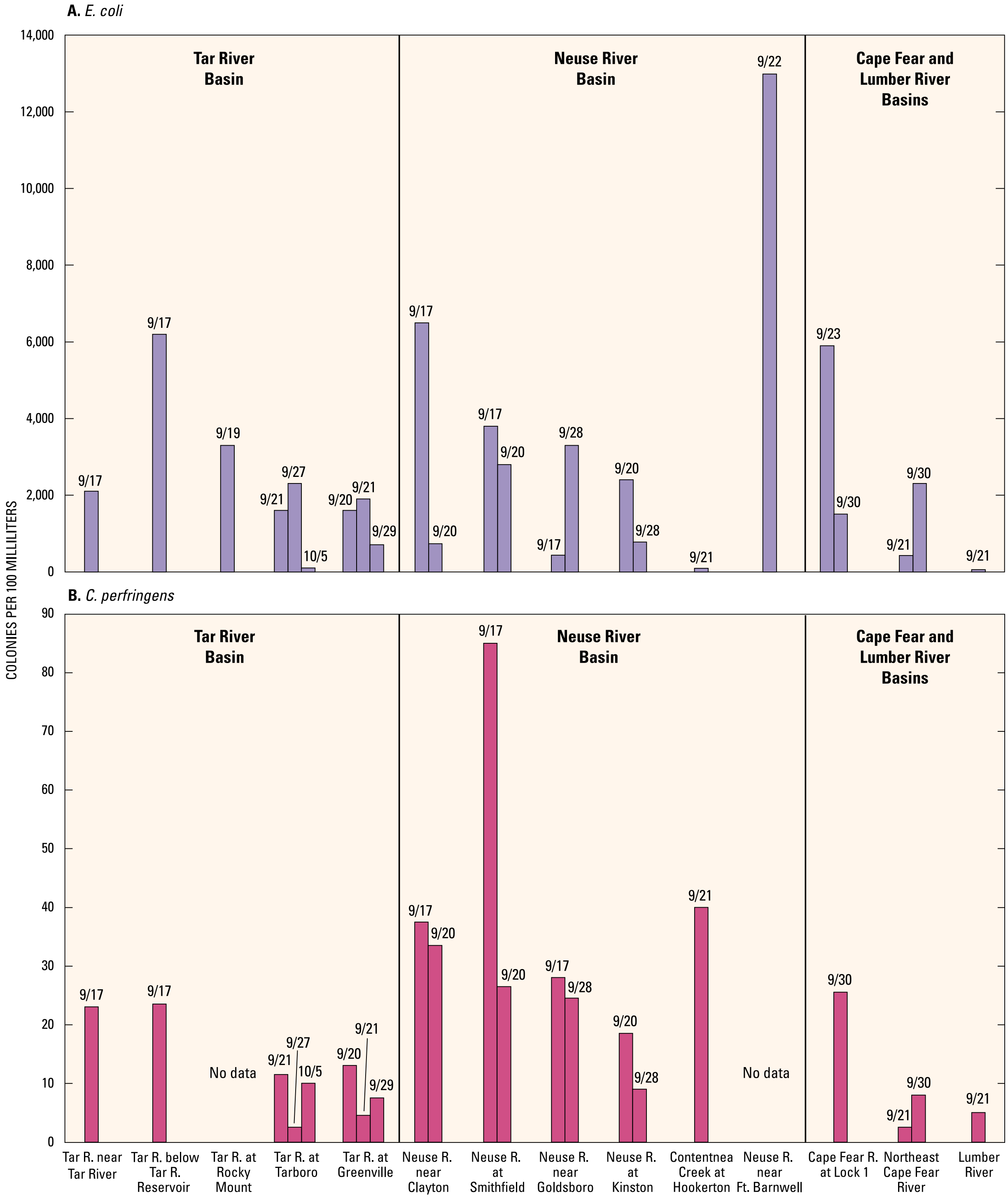


Figure 14. Densities of E. coli and C. perfringens bacteria collected near peak streamflow from Hurricane Floyd flooding, September 17–30, 1999.

Goldsboro and the Northeast Cape Fear River, *E. coli* density was substantially greater in receding floodwaters than near the peak streamflow. Except for the Neuse River at Smithfield, *C. perfringens* densities did not change substantially as floodwaters receded.

These floodwater densities of *E. coli* and *C. perfringens* are some of the first such data collected for either indicator species in North Carolina. As such, these data can be used as a baseline for future results.

Pesticides and Fuels

Twenty-eight floodwater samples were analyzed for 47 different pesticide compounds by using a broad-spectrum, low-level, solid-phase extraction and gas chromatography/mass spectrophotometry analytical method (Zaugg and others, 1995). Minimum detection levels for these compounds vary. Of the 47 pesticide compounds, 17 were found in very low but detectable concentrations ranging from 0.4 to 102 nanograms per liter (ng/L) (table 9). The maximum detected concentration was metolachlor in the Neuse River at Smithfield (site 23). Metolachlor, atrazine, and prometon—all herbicides—were the pesticides most commonly detected. Metolachlor was detected in every sample, atrazine in 25 samples, and prometon in 24 samples. Metolachlor, carbaryl (an insecticide used on lawns, fruit trees, and pets), malathion (an insecticide used to control insects on fruits, vegetables, and animals), and diazinon (a residential insecticide) were detected in the greatest concentrations. The largest number of pesticides were detected in Contentnea Creek (site 31), which is a predominantly agricultural basin; 13 pesticides were detected at site 31. A total of 12 pesticide compounds were detected in the Neuse River near Fort Barnwell (site 32). The fewest pesticide compounds were detected in the Tar River near Tar River, where only metolachlor was detected, and the Lumber River where only metolachlor and atrazine were detected.

The highest concentrations of diazinon (an insecticide used to treat lawns and for pest control) was

WATERBORNE PATHOGENS

Waterborne pathogens are bacteria, viruses, and protozoans that cause diseases in humans and are transmitted by drinking or exposure to contaminated water. Waterborne pathogens are found in nearly all surface-water systems, as well as in many ground-water systems, and generally originate from body fluids and feces of humans and animals. Contamination of surface waters by fecal material is a special concern during floods because of failed wastewater-treatment plants, septic systems, and animal waste lagoons. Additional contamination may result where floodwaters innundate vast areas of land that may be contaminated by fecal material from wildlife, livestock, or wastewater spray irrigation systems.

The presence of certain types of bacteria are used as indicators of fecal contamination. Water-quality regulations regarding fecal contamination of surface waters in North Carolina are based on the presence of fecal coliform bacteria, which may or may not be of fecal origin. The presence of a specific fecal coliform bacterium, *Escherichia coli,* is direct evidence of fecal contamination. Another type of bacterial indicator of fecal contamination is fecal streptococci. Enterococci, which is a type of fecal streptococci, is a more specific indicator of contamination than fecal streptococci.

Clostridium perfringens is an enteric bacterium that forms a spore which is more tolerant to environmental conditions than other traditional indicators of fecal contamination. *C. perfringens* is primarily associated with human waste and is resistant to the chlorination process used to disinfect treated wastewater immediately prior to discharge. Consequently, *C. perfringens* is a useful indicator of fecal contamination from point sources.

There are more than 100 types of human waterborne viruses. Bacteriophages (or phages) are viruses that infect bacteria and are present wherever coliform bacteria are present. A coliphage is a virus that specifically infects and replicates in *E. coli* bacteria; coliphage is considered to be representative of the transport and survival of viruses in the environment. *Bacteriodes fragilis* phage has been found only in human feces, is unable to multiply in the environment, and is a promising indicator of human fecal pollution.

The two most common protozoans implicated in outbreaks of waterborne diseases are *Cryptosporidium* and *Giardia lambia. Cryptosporidium* is a parasite that infects many wild and domestic animals, as well as humans, and is highly resistant to disinfectants used to purify drinking water. *Giardia* is a one-celled, microscopic parasite that lives in the intestines of people and animals. During the past 15 years, *Giardia* has become recognized as one of the most common causes of waterborne disease in humans in the United States. This parasite is found in every region of the United States and throughout the world, and is moderately resistant to disinfectants.

Table 9. Concentrations of selected pesticides detected in samples of Hurricane Floyd floodwaters in eastern North Carolina, September 16–October 5, 1999

[—, not detected]

Site no. (fig. 13)	Site	Date	Pesticide concentration, in nanograms per liter																
			Alachlor	Atrazine	Butylate	Carbaryl	Chlorpyrifos	Cyanazine	Deethyl atrazine	Diazinon	Malathion	Metolachlor	Napropamide	Pendimethalin	Prometon	Simazine	Tebuthiuron fil	Terbacil	Trifluralin
7	Tar River near Tar River	9/17	—	—	—	—	—	—	—	—	—	11.2	—	—	—	—	—	—	—
		9/19	—	6.1	—	—	—	—	—	—	—	8.5	—	—	8.3	—	—	—	—
8	Tar River at Louisburg	9/17	—	7.1	—	—	—	—	—	—	—	9.1	—	—	13.4	—	—	—	—
		9/19	—	7.0	—	—	—	—	—	—	—	10.2	—	—	9.0	7.8	—	—	—
9	Tar River below Tar River Reservoir	9/17	—	6.9	—	14.1	7.9	—	—	—	—	13.4	—	—	11.9	—	—	—	—
		9/19	—	5.6	—	—	5.3	—	—	—	—	12.4	—	—	8.4	8.3	—	—	—
14	Tar River at Tarboro	9/21	—	6.8	—	8.8	8.6	—	—	—	—	23.2	—	—	—	—	—	—	—
		9/27	8.3	6.1	—	4.7	2.7	7.4	—	—	—	26.6	—	—	6.6	5.1	—	—	—
		10/5	—	—	—	—	—	—	—	—	—	11.4	—	—	5.8	—	—	—	—
16	Tar River at Greenville	9/21	10.8	6.0	—	12.7	8.0	5.2	—	5.9	—	31.9	—	—	5.8	6.0	—	—	—
		9/29	8.6	9.5	7.2	6.0	5.4	—	2.3	3.2	—	35.8	—	—	6.4	—	—	—	—
21	Crabtree Creek at U.S. 1 at Raleigh	9/16	—	9.7	—	40.8	—	—	—	48.2	—	35.7	—	—	18.3	12.1	—	—	—
22	Neuse River near Clay-ton	9/17	—	7.1	—	47.6	9.9	—	—	29.1	—	73.8	—	—	16.7	12.7	—	—	—
		9/19	—	4.1	—	50.0	10.2	—	—	26.4	—	22.3	—	5.1	8.9	7.7	—	—	—
		9/20	—	7.4	—	22.4	9.7	—	—	25.8	—	22.2	—	—	11.0	10.4	—	—	—
23	Neuse River at Smith-field	9/17	—	—	—	46.9	6.6	—	—	23.9	—	102	—	—	15.5	—	—	—	—
		9/19	—	3.6	—	19.0	4.4	—	—	11.9	—	26.8	—	—	6.1	6.1	4.5	—	—
		9/20	—	7.0	—	17.0	7.6	—	—	—	—	22.5	—	—	10.7	8.4	—	—	—
27	Neuse River near Goldsboro	9/17	—	16.6	—	—	—	—	—	—	—	25.3	—	—	—	12.6	—	—	—
		9/28	—	6.7	—	18.4	—	—	—	9.9	—	12.4	—	—	11.3	8.7	—	—	—
28	Neuse River at Kinston	9/20	10.4	10.3	—	—	—	8.9	—	—	51.9	22.0	—	—	13.9	8.2	—	—	—
		9/28	7.6	5.6	—	—	—	5.7	—	4.9	—	20.0	—	—	10.6	5.4	—	—	—
31	Contentnea Creek at Hooker-ton	9/21	10.3	8.8	2.5	12.0	4.9	7.9	—	3.5	—	19.1	—	—	8.7	5.7	2.2	12.2	4.7
32	Neuse River near Fort Barnwell	9/22	11.7	11.2	5.2	15.3	1.8	8.1	—	12.2	12.5	23.6	—	—	12.6	6.3	—	—	0.4
40	Cape Fear River at Lock 1	9/23	—	16.5	—	6.0	—	—	4.9	4.4	11.2	37.5	—	—	8.0	16.0	—	—	—
		9/30	—	33.9	—	6.7	—	4.3	6.5	8.1	4.3	28.7	—	—	15.9	4.2	—	—	—
43	Northeast Cape Fear River near Chinqua-pin	9/21	8.9	6.3	—	12.4	—	—	—	4.9	—	30.9	5.1	—	2.4	—	—	—	—
45	Lumber River at Boardman	9/21	—	9.4	—	—	—	—	—	—	—	17.4	—	—	—	—	—	—	—

detected in Crabtree Creek, which drains an urban basin, and the Neuse River near Clayton, located immediately downstream from Raleigh. Concentrations of the insecticide carbaryl also were highest at these two sites, as well as the Neuse River at Smithfield. These results are consistent with national findings, which indicate that insecticide concentrations generally are higher in urban streams than in other settings (U.S. Geological Survey, 1999).

Previously collected pesticide data from the Tar River at Tarboro (site 14) and the Neuse River at Kinston (site 28) indicate that detections of metolachlor and atrazine are not uncommon, and that concentrations in floodwaters were somewhat lower than concentrations previously measured under normal flow conditions. For example, in 20 samples collected from the Tar River at Tarboro (site 14) between 1993 and 1994, the median concentration of metolachlor was 36 ng/L and the maximum concentration was 78 ng/L compared to a maximum floodwater concentration of 27 ng/L (table 9). On the other hand, the peak flow at Tarboro was about 50 times greater than the long-term mean September flow, so pesticide concentrations were highly diluted. In the Neuse River at Kinston (site 28), 35 measurements of atrazine during 1994–99 had a median concentration of 20 ng/L and a maximum of 14 ng/L compared to a maximum floodwater concentration of 10.3 ng/L (table 9).

Because of concerns about fuel spills during the flooding that followed Hurricane Floyd, four water samples were collected and analyzed for fuel and fuel oxygenate compounds benzene, diisopropyl

PESTICIDE CONTAMINATION OF SURFACE WATERS

Total annual pesticide use in the United States is about 1 billion pounds (U.S. Geological Survey, 1999), of which about 70 to 80 percent is for agricultural applications. Pesticides include both herbicides, which account for about 60 percent of agricultural pesticides, and insecticides, which are generally more toxic to aquatic life than herbicides. Pesticides, including agricultural pesticides, are detected in all types of settings, including urban areas (for example, Bales and others, 1999), but insecticides are more likely to be detected in high concentrations in urban streams than in other settings (U.S. Geological Survey, 1999).

In streams that drain to the Albemarle and Pamlico Sounds, the most commonly detected pesticides in 1993–95 were the herbicides metolachlor, atrazine, alachlor, and prometon (Spruill and others, 1998). The highest concentrations generally occurred in late May and early June; concentrations then decreased throughout the summer. Consequently, if flooding had occurred earlier in the summer, the concentrations of pesticides detected in floodwaters may have been greater than were detected in September. The greatest incidence of pesticide detection during 1993–95 occurred in the Tar River Basin (Spruill and others, 1998). During the 1999 flooding, however, the greatest occurrence of pesticides was in the Neuse River and Contentnea Creek, a major tributary to the Neuse River. Atrazine, carbaryl, metolachlor, diazinon, and malathion were the most commonly detected pesticides in small streams that drain developed areas of Charlotte, which is probably typical of urban areas in eastern North Carolina (Bales and others, 1999). Small streams draining residential areas had the greatest incidence of detection of pesticides in Charlotte.

USGS

USGS isokinetic water-quality sampler

ether, ethyl tert-butyl ether (ETBE), ethyl benzene, toluene, xylene, methyl tert-butyl ether (MTBE), and methyl tert-pentyl ether. Three samples were collected from the Tar River at sites 14 (two samples) and 16. A sample also was collected at site 40 on the Cape Fear River. The only compound detected was MTBE at sites 16 (57.8 ng/L) and 40 (36.3 ng/L). However, such limited sampling, in terms of frequency and areal coverage, cannot provide an accurate assessment of the impact of fuel spills on floodwater quality.

Nitrogen and Phosphorus Loads

A load is an estimate of the total mass of a constituent passing a selected stream location during a given period of time. For example, a nitrogen load calculated for the Pamlico River at Washington prvides an estimate of the total pounds of nitrogen entering the Pamlico River estuary during the period of interest. Loads from different size basins can be normalized by dividing the load by the basin area, providing a yield (in, for example, pounds per square mile per year), so that export from different basins can be compared. There is some uncertainty in the calculation of floodwater loads because of the small number of water-quality samples used in the calculation. However, as a result of the relatively small variation at a site in constituent concentrations during flooding, the calculated loads seem to provide reasonable estimates of basin export.

Nitrogen and phosphorus loads were determined at selected locations for September 15–October 20, 1999, by using calculations of mean daily discharge and periodic measurements of concentration. The 36-day period used for the load calculations includes the rise, peak, and fall of floodwaters from Hurricane Floyd. At most sites, subsequent rainfall from Hurricane Irene (October 17–18) caused secondary flooding (for example, figs. 8 and 10) that was not included in these load calculations because concentration data were not collected during this secondary rise. For the Pamlico River at Washington where daily mean discharge data were not available, an estimate of monthly mean discharge for September and October and the median of water-quality data from samples collected by the North Carolina Division of Water Quality during September and October (Larry Ausley, Division of Water Quality, written commun., January 2000) were used to calculate the nitrogen and phosphorus yield for September and October.

USGS

Black River near Tomahawk, N.C.

The cumulative load of nitrogen in Hurricane Floyd floodwaters ranged from 450 tons in the Lumber River (site 45) to 4,200 tons in the Neuse River near Fort Barnwell (site 32, fig. 15). At Kinston (site 28), a nitrogen load of about 1,700 tons, equivalent to half of the mean annual nitrogen (3,400 tons; Harned and others, 1995), was carried by

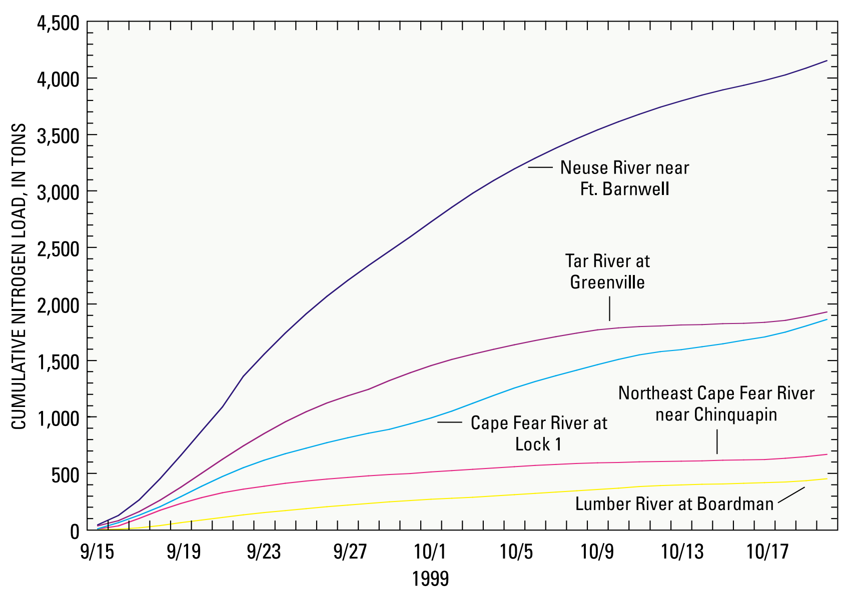


Figure 15. Cumulative total nitrogen load at sites near the mouths of the Tar, Neuse, Cape Fear, Northeast Cape Fear, and Lumber Rivers.

Hurricane Floyd floodwaters during this 36-day period (fig. 16). At Tarboro (site 14) almost 80 percent of the mean annual load (2,200 tons; Harned and others, 1995) was transported in Hurricane Floyd floodwaters (fig. 17).

One flood sample (table 6) was collected in the Neuse River near Fort Barnwell (site 32), where the highest nitrogen load was estimated to have occurred during flooding (fig. 15). The sample, collected in advance of the peak streamflow on September 22, had a total nitrogen concentration of 1.77 mg/L as N. Two previous measurements of total nitrogen at this site in April and July 1999 under low-flow conditions had concentrations that were similar to the concentration measured in September 1999. The median (1.23 mg/L as N) of these three analyses (April, July, and September) was used as an estimate of concentrations before and after the peak streamflow. This resulted in an estimate of 3,900 tons for the floodwater nitrogen load and a total nitrogen yield of 1.0 tons per square mile (tons/mi^2). To determine a maximum load and yield, the concentration measured during the flooding (1.77 mg/L) was used as an estimate of concentration for the entire period, and resulted in an estimated load of 5,400 tons and a yield of 1.4 tons/mi^2. A conservative estimate of nitrogen concentration is based on the minimum concentration (1.11 mg/L as N on April 21, 1999) previously measured at Fort Barnwell, and results in a load of about 3,500 tons and a yield of 0.9 tons/mi^2.

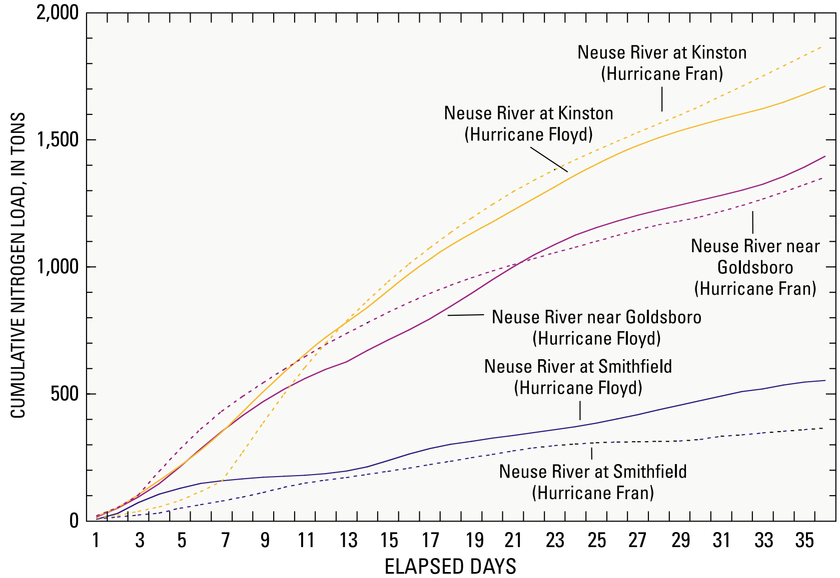


Figure 16. Cumulative total nitrogen load at selected Neuse River sites in floodwaters from Hurricanes Floyd (1999) and Fran (1996).

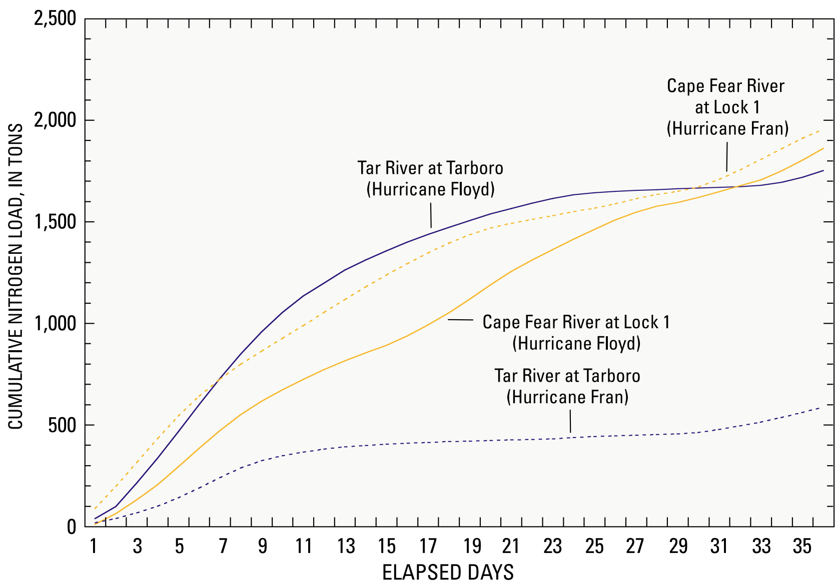


Figure 17. Cumulative total nitrogen load at selected Tar and Cape Fear River sites in floodwaters from Hurricanes Floyd (1999) and Fran (1996).

The total load of nitrogen carried in Hurricane Floyd floodwaters was quite similar to the total load carried by Hurricane Fran floodwaters in the Neuse River (fig. 16) and the Tar and Cape Fear Rivers (fig. 17)—despite the greater total streamflow resulting from Hurricane Floyd. Nitrogen concentrations generally were less in Hurricane Floyd floodwaters than following Hurricane Fran (Bales and Childress, 1996). In the Tar River Basin, where the Hurricane Floyd peak discharge was more than three times that from Hurricane Fran, nitrogen load at site 14 was 1,800 tons in Hurricane Floyd floodwaters compared to 590 tons in Hurricane Fran floodwaters.

For the period September 15 to October 20, total nitrogen yield in basins upstream from the sampled sites ranged from 0.34 to 1.1 tons/mi^2 (fig. 18A). Although the total nitrogen load was much smaller for the Northeast Cape Fear River (site 43) than for the Neuse River

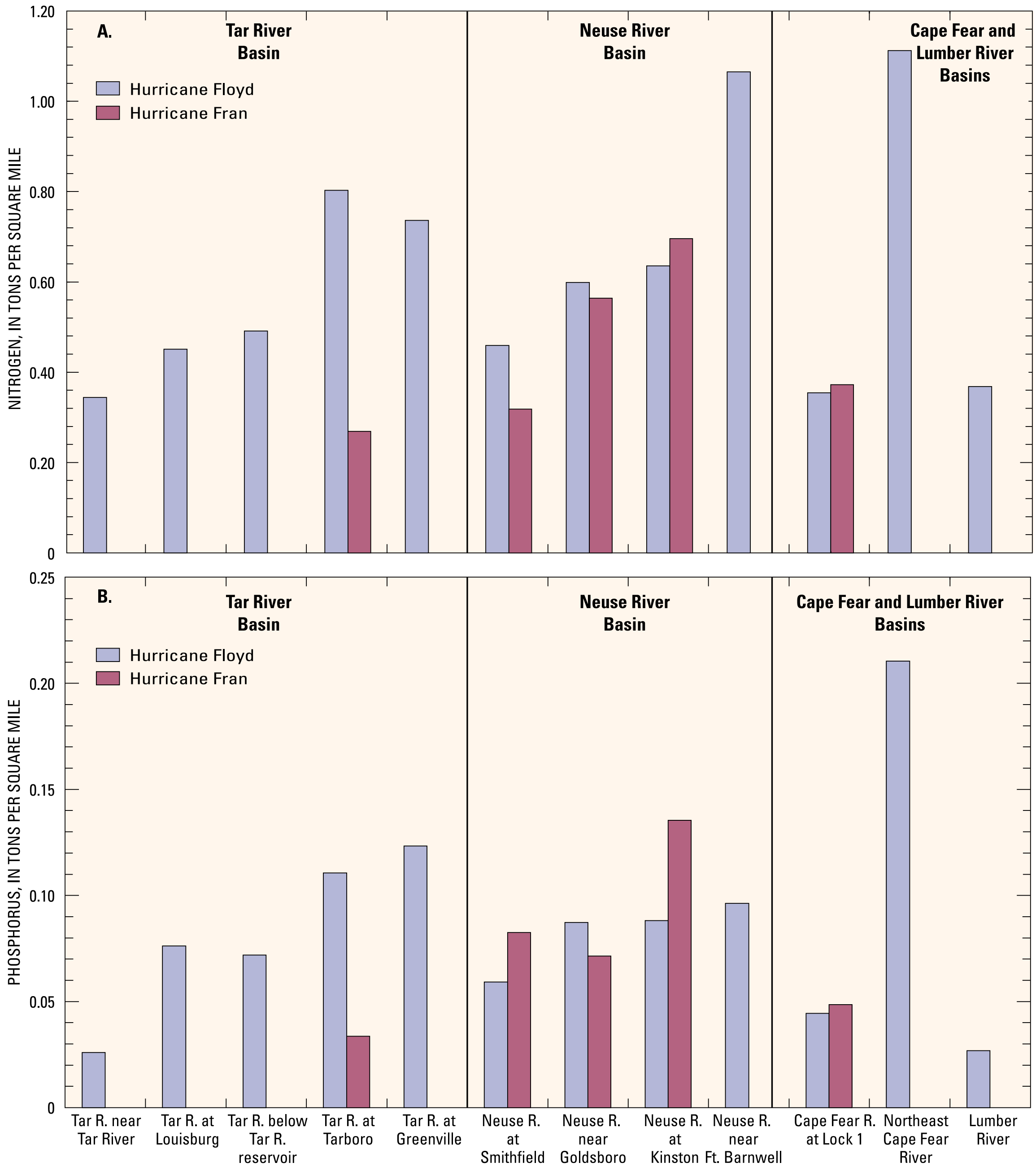


Figure 18. (A) Nitrogen and (B) phosphorus yields at selected sites in floodwaters from Hurricanes Floyd (1999) and Fran (1996).

near Fort Barnwell (site 32—the site with the greatest total nitrogen load; fig. 15), the yield for the two basins was approximately the same (fig. 18A). The yield for the Pamlico River at Washington (site 18) was calculated, based on monthly data, at 0.81 tons/mi^2 in September and 0.28 tons/mi^2 in October. Nitrogen yields resulting from Hurricane Floyd were similar to those resulting from Hurricane Fran in the Neuse and Cape Fear Basins (fig. 18A). However, the nitrogen yield for the Tar River at Tarboro (site 14) was 0.80 tons/mi^2 in Hurricane Floyd floodwaters compared to 0.27 tons/mi^2 in floodwaters from Hurricane Fran, which is a result of much more widespread flooding in the Tar River Basin after Hurricane Floyd than after Hurricane Fran.

Phosphorus loads for September 15 to October 20 ranged from 30 tons in the Lumber River (site 45) to 370 tons in the Neuse River near Fort Barnwell (site 32; fig. 19). The estimated phosphorus load at Kinston (site 28) was 66 percent of the mean annual phosphorus load of 350 tons (Harned and others, 1995). The estimated load during flooding at Tarboro (site 14) was 89 percent of the mean annual load of 270 tons (Harned and others, 1995). Phosphorus yields ranged from 0.03 to 0.21 tons/mi^2 (fig. 18B). The lowest yield was in the Lumber River Basin (site 45), and the highest yield was in the Northeast Cape Fear River (site 43). The yield was 0.19 tons/mi^2 for the Tar-Pamlico River Basin above Washington (site 18; this estimate was for September based on the monthly average discharge and the median concentration). Although the Neuse River near Fort Barnwell (site 32) carried a greater total phosphorus load (fig. 19), the Northeast Cape Fear had a greater yield (fig. 18B). In the Neuse and Cape Fear River Basins, total phosphorus yields resulting from Hurricane Floyd were generally slightly less than those resulting from Hurricane Fran. In the Tar River Basin, however, the phosphorus yield resulting from Hurricane Floyd was nearly triple that from Hurricane Fran. The concentration of phosphorus was similar, but the quantity of streamflow that resulted from Hurricane Floyd was much greater.

Streamflow measurement using acoustic Doppler current profiler and radio transmitter, Potecasi Creek

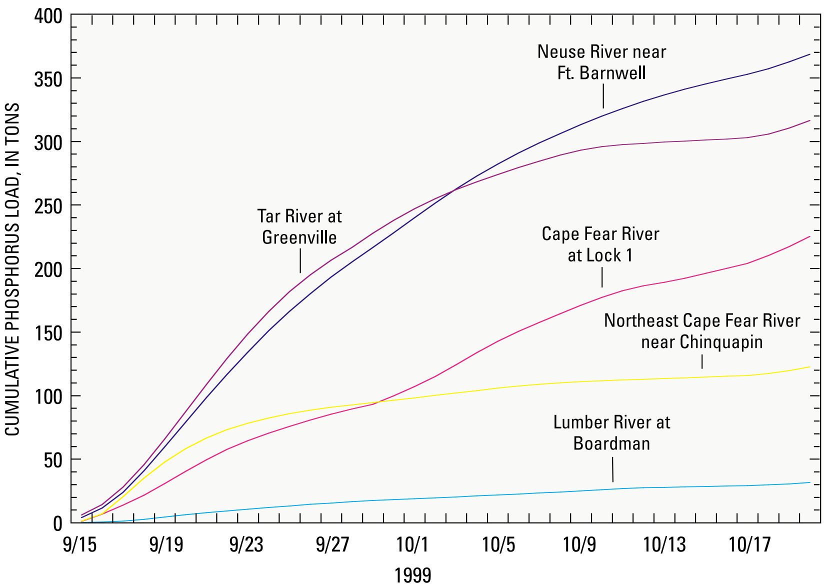


Figure 19. Cumulative total phosphorus load at sites near the mouths of the Tar, Neuse, Cape Fear, Northeast Cape Fear, and Lumber Rivers.

As previously discussed, residence time in the Pamlico River and Neuse River estuaries was greatly reduced during the flooding. Consequently, nutrients and organic matter that are typically biochemically transformed or settle in these systems likely passed directly through the estuaries to Pamlico Sound. The effects of this massive pulse of nitrogen, phosphorus, and organic carbon on the Pamlico Sound ecosystem remains to be seen.

U.S. Highway 17 in Brunswick County

Salinity and Dissolved Oxygen in the Pamlico and Neuse River Estuaries

Floodwaters entering the Pamlico and Neuse River estuaries flushed brackish water out of the estuaries. High flows associated with Hurricane Dennis resulted in increased stratification and decreased salinity in the

Pamlico River estuary (fig. 20). Following Hurricane Floyd, there was little salt in much of the Pamlico River (fig. 21). Near-surface salinity remained less than 2 parts per thousand (ppt) in December 1999, whereas salinity at this location typically ranges from 7 to 11 ppt during October to November (Bales and Robbins, 1995). As late as January 2000, near-surface salinity at site 46 remained about 1 ppt, and near-bottom salinity was about 5–7 ppt, demonstrating the continued effect of the high volume of freshwater discharged to the estuary. The effects of the flooding on salinity seem to be more extreme in the Neuse River estuary. Both near-surface and near-bottom salinity in the Neuse River remained less than 2 ppt in January 2000 as far downstream as Cherry Point, where the estuary makes a 90-degree bend from the southeast to the northeast (fig. 7).

Hurricane floodwaters also affected dissolved oxygen concentrations in the estuaries, although persistent and extremely low dissolved oxygen conditions were not observed. Prior to Hurricane Dennis, dissolved oxygen in the Neuse River at New Bern (site 47, fig. 7) was near zero at the bottom, but was between 8 and 10 mg/L near the water surface. Following Hurricane Floyd, the water column was mixed, with only a small difference between near-surface and near-bottom dissolved oxygen (fig. 22). Dissolved oxygen gradually recovered during October, but was generally between 4 and 6 mg/L, which is somewhat low for fall conditions. Dissolved oxygen concentrations increased with distance downstream from New Bern during September and October. Dissolved oxygen concentrations generally were greater than 6 mg/L in the Pamlico River estuary during September and October, except near Washington, where dissolved oxygen increased from about 2 mg/L in late September to 6 mg/L by about mid-October.

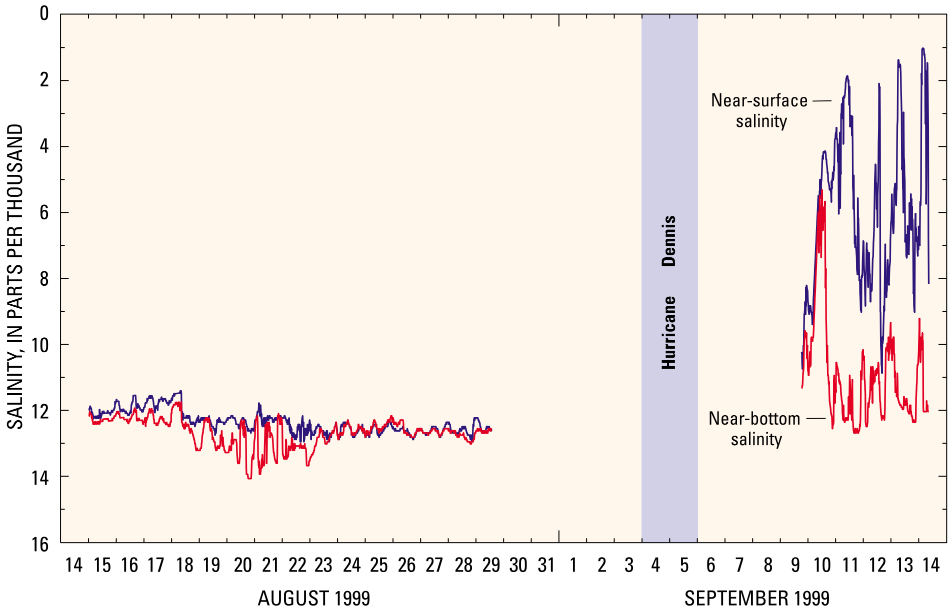


Figure 20. Near-surface and near-bottom salinity measured at Pamlico River at Light 5 (site 46, fig. 7) during August–September 1999.

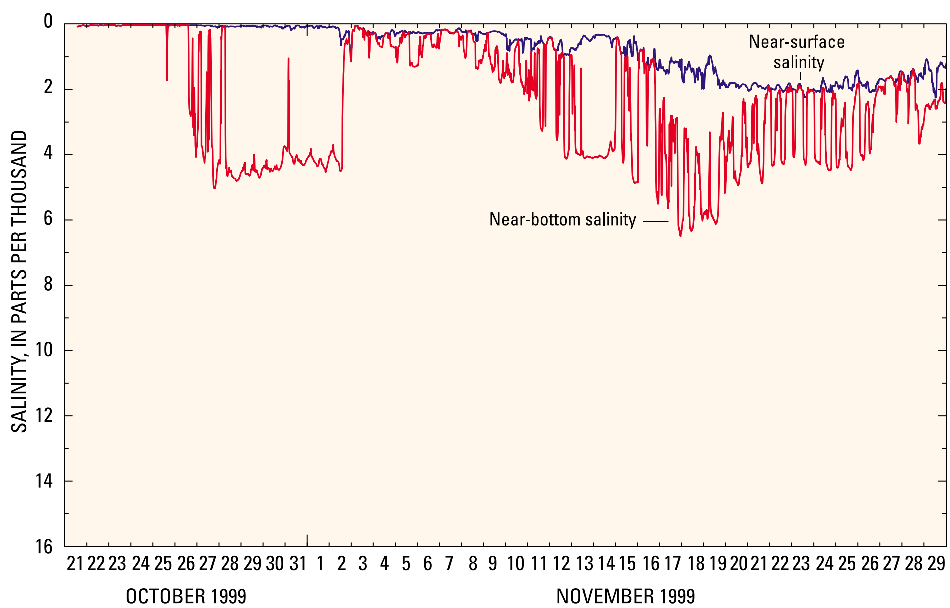


Figure 21. Near-surface and near-bottom salinity measured at Pamlico River at Light 5 (site 46, fig. 7) during October–November 1999.

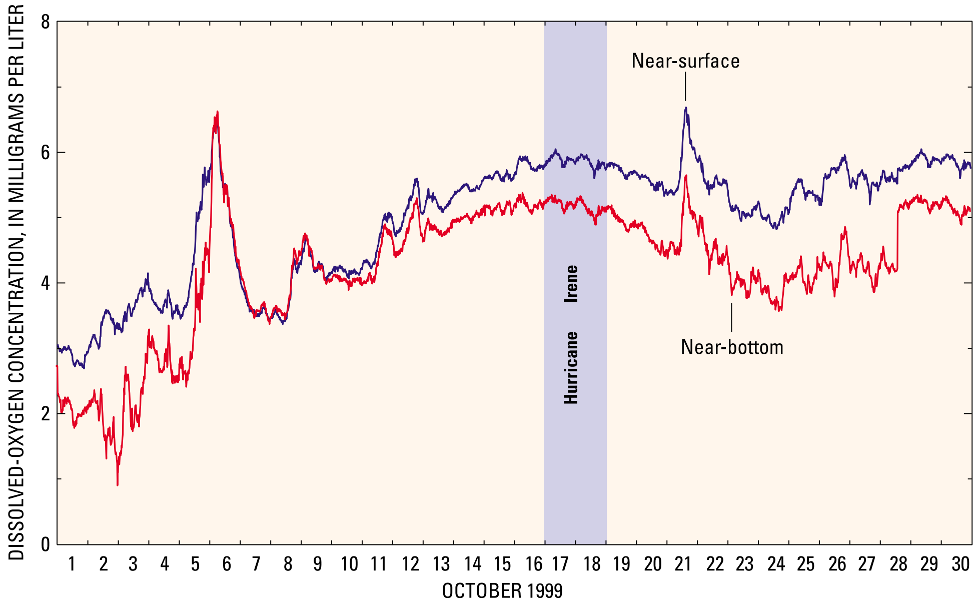


Figure 22. Near-surface and near-bottom dissolved oxygen concentration at Neuse River at Marker 38 at New Bern (site 47, fig. 7), October 1999.

FEMA

Flooded church at U.S. Highway 70, Kinston, N.C.

USGS

Salinity, dissolved oxygen, water temperature, and pH monitoring station, Pamlico River at Light 5

NCDEM

Checking the mail

Hurricane Dennis approached the North Carolina coast on August 29 as a Category 2 hurricane, and eventually made landfall south of Cape Hatteras on September 4 as a tropical storm. Although winds from Hurricane Dennis were not particularly strong, the duration of the effects of the storm on North Carolina's shoreline was remarkable. Hurricane Dennis meandered about 150 miles off the coast of the northern Outer Banks for nearly a week, generating large waves that pounded the coast. In fact, at a buoy located in 65 feet of water near the U.S. Army Corps of Engineers Research Pier at Duck (fig. 23), the maximum wave height during Hurricane Dennis was 20.5 feet, which was the third highest wave height documented at the site in more than 20 years of record. Sea level, which includes the effects of both astronomical tides and storm surge, was also near record heights at the Research Pier during the prolonged storm. Storm tides were 3 to 5 feet above normal along much of the North Carolina coast on both August 30 and again on September 4 (Beven, 2000). According to preliminary calculations, the elevation of wave runup on the beach at Duck (that is, the highest reach of the waves) was among the highest on record. These kinds of calculations are being used to understand the distribution and magnitude of dune retreat, a major effect of the storm on the Outer Banks. Along the northern Outer Banks, from near the Virginia–North Carolina State line to south of Cape Hatteras at Ocracoke Inlet, dunes are prominent geologic features and afford the first line of defense against storm erosion and wave overwash.

In order to measure the amount of shoreline change resulting from Hurricane Dennis, the USGS, in cooperation with National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA), conducted an airborne laser altimetry survey of the northern Outer Banks using NASA's Airborne Topographic Mapper (ATM) on September 8, immediately following the storm. These data were compared to a survey completed 1 year prior to the storm. Initial analyses indicate that erosion of dunes between Cape Hatteras and Oregon Inlet was highly variable along the coast. In some areas, dunes retreated more than 100 feet, whereas in other areas the dunes were stable.

Overtopping and overwash occurred at some locations along the Outer Banks, seriously affecting N.C. Highway 12 (figs. 24, 25, and 26). Before Hurricane Dennis, the dunes at a location north of Buxton (fig. 23) were nearly 20 feet high (fig. 26). Replacement dunes were constructed by using bulldozers

Figure 23. Locations at which shoreline change and overwash were documented.

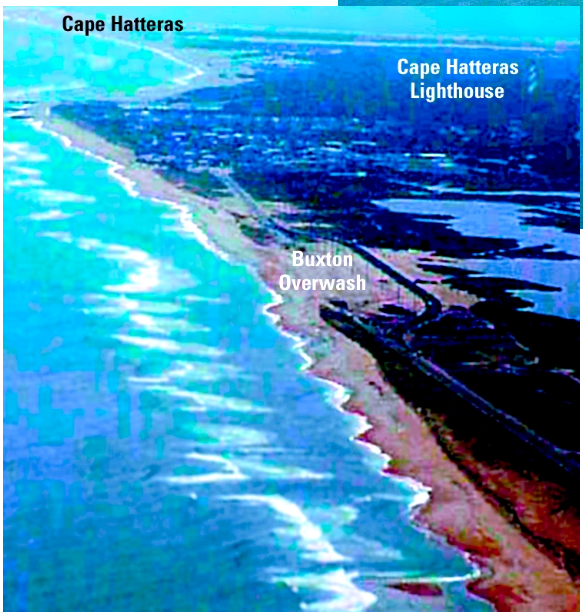


Figure 24. Storm wave overwash along N.C. Highway 12 north of Buxton, N.C., September 8, 1999.

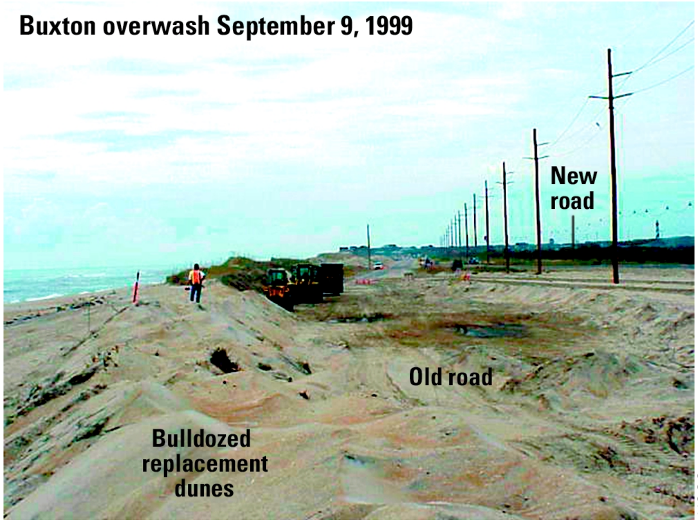


Figure 25. Former location of N.C. Highway 12 near Buxton and replacement dunes.

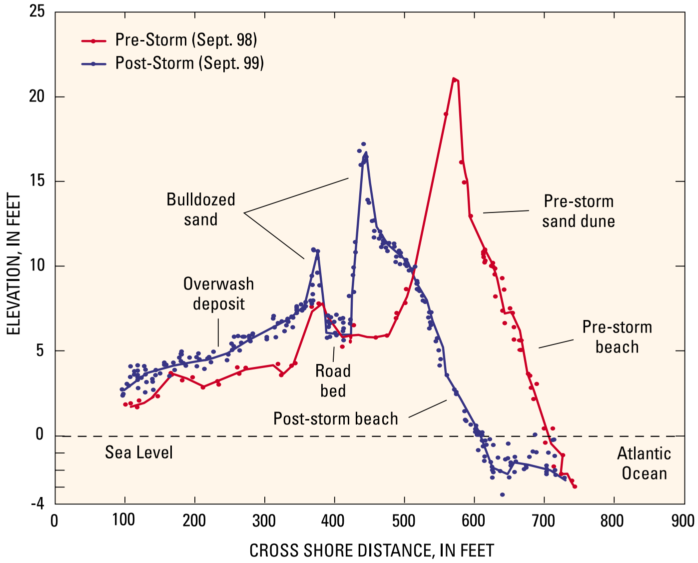


Figure 26. Cross-shore profiles of the area north of Buxton where N.C. Highway 12 was destroyed. Profiles were obtained after Hurricane Dennis by using laser altimetry. The pre-storm dune was completely eroded, and the area was overwashed. After the storm, a new dune was created using bulldozers.

following the storm, and were located landward of the original dune line. The replacement dunes were approximately 5 feet lower than the dunes destroyed during the storm.

Another heavily eroded area at Rodanthe (fig. 23) led to the condemnation (fig. 27) and loss of several ocean-front houses. The laser altimetry data clearly reveal the lost houses (fig. 28). This spatial variability of high erosional rates and lower erosional rates was repeated along the coast over scales of miles, and may be related to varying nearshore geology. Identification of the causes of the variability in erosional rates is a major research objective of the USGS Coastal and Marine Geology Program.

Whereas Hurricane Dennis was notable because of duration, Hurricane Floyd at one time was one of the strongest storms to threaten the eastern coast of the United States this century. Hurricane Floyd made landfall with sustained winds of 110 mph and a storm surge of about 10 feet (Pasch and others, 2000). The maximum surge occurred near high tide contributing substantially to extensive overwash, dune retreat, and damage to homes on barrier islands such as Oak and Topsail Islands (fig. 23). As was done following Hurricane Dennis on the northern Outer Banks, shoreline topography was measured using airborne laser altimetry immediately following Hurricane Floyd. Initial results indicate that the effects of Hurricane Floyd on shoreline erosion and dune retreat were greater than the effects of Hurricane Bonnie, a Category 3 storm that made landfall in the same area in 1998.


USGS

Figure 27. Houses standing in the surf at Rodanthe, N.C. With no protective dunes remaining to protect the houses, the balcony supports were destroyed during the storm. These houses have been condemned.


USGS

Ocean overwash resulting from Hurricane Floyd


NCDEM

Houses near the surf with little or no protective dunes, Oak Island, N.C.

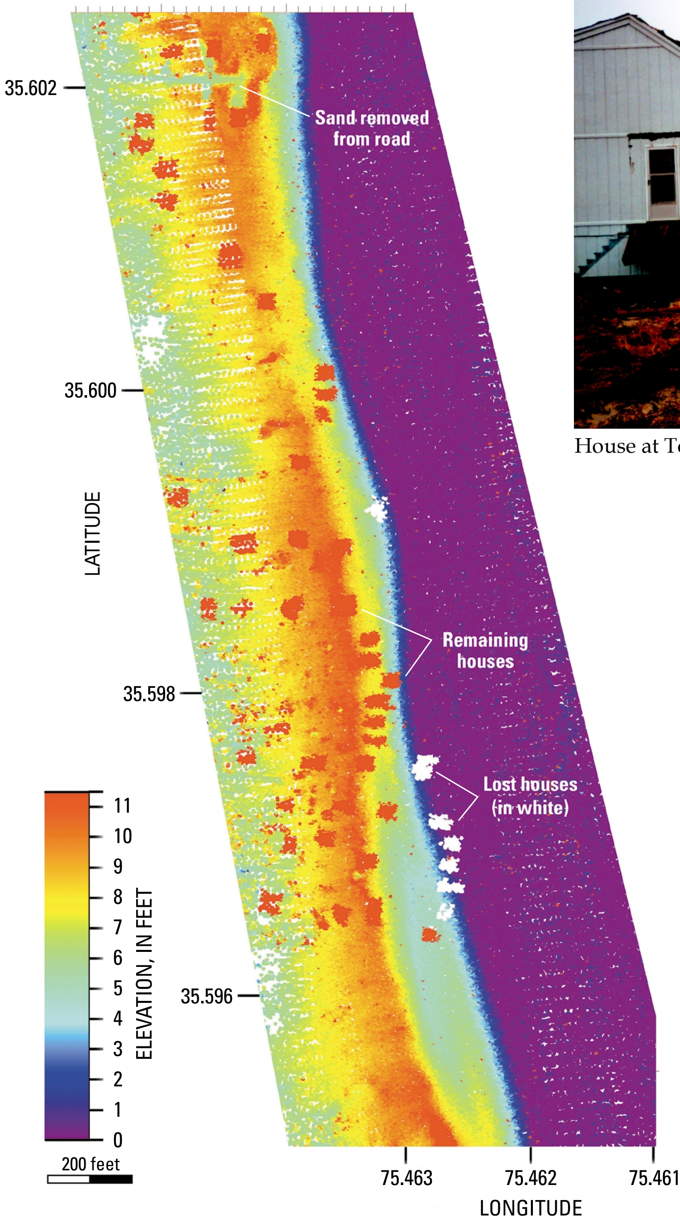


Figure 28. Post Hurricane Dennis topography generated from laser altimeter data of an area near Rodanthe, N.C. The dark blue/purple colors are water. Note the red "rectangles" which indicate houses that survived the storm. The white "rectangles" are houses observed in the pre-storm topography that were destroyed during the storm.

House at Topsail Beach now located seaward of dunes after Hurricane Floyd

Extensive dune erosion resulting from Hurricane Dennis, northern Outer Banks

Events in 1999 continued a pattern that began in 1996 with greater-than-normal tropical cyclone activity in North Carolina. Between 1886 and 1999, one tropical cyclone made landfall in North Carolina on average once every 3.4 years, and between 1961 and 1995, only six tropical cyclones made landfall in the State. However, between 1996 and 1999, six additional tropical cyclones made landfall in North Carolina, and several others (for example Jerry in 1997 and Irene in 1999) substantially affected the State.

The combined effects of Hurricanes Dennis, Floyd, and Irene in September and October 1999 resulted in almost 2 months of flooding throughout most of eastern North Carolina. Hurricane Floyd will likely be the second or third most costly hurricane to strike the United States in the 20th century and resulted in more fatalities than any hurricane to strike the United States since 1972, including 52 fatalities in North Carolina. Rainfall amounts recorded during Hurricane Floyd (September 14–17, 1999) and accumulated during the months of September and October were unprecedented for many parts of eastern North Carolina during more than 80 years of precipitation records. Flooding was at record levels, and 500-year or greater floods occurred in all of the State's river basins east of Raleigh, with the exception of the Lumber River Basin.

Surf at Pine Knoll Shores, N.C., prior to Hurricane Floyd landfall

Some of the most widespread flooding occurred in the Tar-Pamlico River Basin downstream from Louisburg. Measured flood flows on the Tar River and major tributaries downstream from the Tar River Reservoir near Rocky Mount had recurrence intervals in excess of 100 years, and several sites had recurrence intervals in excess of 500 years. At Tarboro, where streamflow records have been collected since 1897, the peak stage during this event was almost 10 feet higher than the previously recorded peak stage. Flood recurrence intervals in many of the tributaries to the Neuse River downstream from Clayton were in excess of 500 years, but flood recurrence intervals along the main-stem of the Neuse were between 25 and 50 years, although the Neuse River at Kinston was above flood stage all of October. Floods having recurrence intervals near or in excess of 500 years also occurred on the Cashie River and Ahoskie and Potecasi Creeks in northeast North Carolina; and on the New, Northeast Cape Fear, Black, and Waccamaw Rivers in southeast North Carolina.

Damaged property at Pine Knoll Shores, N.C., after Hurricane Floyd

As a result of the flooding, the total freshwater inflow volume to Pamlico Sound during September–

October was equivalent to about 83 percent of the total volume of the Sound, whereas under normal conditions, inflow volume during these 2 months is equivalent to about 13 percent of the volume of the Sound. This means that by the end of October, much of the water that was in the Sound at the beginning of September could have been displaced by floodwaters. Estimated mean water residence time was about 7 days for the Pamlico River and Neuse River estuaries during September compared to a long-term annual average of 72 and 68 days, respectively, for these estuaries. Consequently, material that might normally be deposited or biochemically transformed in the estuaries was transported into Pamlico Sound.

The cumulative load of nitrogen in Hurricane Floyd floodwaters during September 15–October 20 ranged from 450 tons in the Lumber River to 4,200 tons in the Neuse River near Fort Barnwell. The mean annual nitrogen in the Neuse River at Kinston is about 3,400 tons; about half of this load was carried by Hurricane Floyd floodwaters during this 36-day period. In the Tar River at Tarboro, almost 80 percent of the mean annual nitrogen load of 2,200 tons was transported in Hurricane Floyd floodwaters. The total load of nitrogen carried in Hurricane Floyd floodwaters was quite similar to the total load carried by Hurricane Fran floodwaters in the Neuse, Tar, and Cape Fear Rivers, despite the generally greater total streamflow resulting from Hurricane Floyd. During the same period, phosphorus loads ranged from 30 tons in the Cape Fear River to 370 tons in the Neuse River near Fort Barnwell. The estimated phosphorus load in the Neuse River at Kinston was 66 percent of the mean annual phosphorus load of 350 tons, and the estimated phosphorus load during flooding in the Tar River at Tarboro was 89 percent of the mean annual load of 270 tons.

FEMA

Flooded home near Greenville, N.C.

Of the 47 different pesticide compounds analyzed, 17 were detected in floodwaters at concentrations ranging from 0.4 to 102 nanograms per liter. The highest pesticide concentration detected was metolachlor in the Neuse River at Smithfield. Metolachlor, prometon, atrazine, and carbaryl were the compounds most commonly detected, and metolachlor and carbaryl were detected in the greatest concentrations. The greatest number of pesticide compounds were detected in the Neuse River near Fort Barnwell.

Although winds from Hurricane Dennis were not particularly strong, the storm meandered about 150 miles off the coast of the northern Outer Banks for nearly a week, generating large waves that pounded the coast. As a result, erosion of dunes between Cape Hatteras and Oregon Inlet was highly variable; in some areas, dunes retreated more than 100 feet, whereas in other areas the dunes were stable. The effects of Hurricane Floyd on shoreline erosion and dune retreat seem to have been greater than the effects of Hurricane Bonnie, a 1998 Category 3 storm that made landfall in the same area as Hurricane Floyd.

Hurricanes and floods are complex natural events that occur with some regularity in North Carolina, as well as in many locations around the world. These *natural events* become *natural disasters* when people and property are located in positions vulnerable to the destructive effects of these events. As the population increases in eastern North Carolina, there is an increasing possibility that natural events will result in more costly and more deadly natural disasters (Barton and Nishenko, 1994). The lessons learned as a result of the hurricanes and floods of 1999 can be used to guide rebuilding and mitigation of the effects of future hurricanes and floods in North Carolina.

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Wastewater-treatment plant in Goldsboro, N.C.