Climatology and Hydrology of Eastern North Carolina and Their Effects on Creating the Flood of the Century

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Hurricane Floyd crossed eastern North Carolina on September 15 and 16, 1999, causing the largest disaster in the State's history. The majority of the damage was caused by flooding associated with heavy rainfall rather than by high winds or coastal erosion. The rainfall produced a flood that exceeded the predictions for the 100 year event, catching most of the residents of the region by surprise. The general perception was that the region had seen hurricanes of that magnitude before and that they had not produced such extreme floods. This particular flood occurred because hurricane Floyd arrived less than two weeks after hurricane Dennis, which dropped up to 10 inches of rain on the region, saturating the soil and raising river levels to the bankfull stage. When hurricane Floyd dropped an additional 8-16 inches, the likelihood of a severe flood was enhanced. There are a number of physical features of eastern North Carolina that contributed to making this flood so severe. These include: the shape of the drainage systems; the topography of the coastal plain; the characteristics of the soils; and the land-use on the coastal plain. These factors combine with precipitation to produce hydrologic conditions that are highly variable, as these factors vary in time and space. When these factors come together in certain unique ways, extreme events, such as the flood associated with hurricane Floyd, occur.

Introduction

On September 16, 1999, hurricane Floyd made landfall on the coast of North Carolina in the vicinity of Wrightsville Beach. Residents of coastal areas along the southeast coast of the United States had been following the progress of this hurricane for several days as it moved through the Caribbean, across the Bahamas and along the Florida coast. As with all hurricanes, the National Weather Service predicted landfall over a rather broad section of coast, this time ranging from Charleston, South Carolina to Morehead City, North Carolina. Of great concern early on was the speed of the winds, which were reaching 150 mph, making Floyd a category 5 storm. As Floyd moved north, however, the wind speeds diminished, so that by the time it crossed the coast maximum winds were around 100 mph. To the residents of eastern North Carolina, the storm had become more of a nuisance, not even measuring up to the force of hurricanes Bertha and Fran which had followed nearly the same path in 1996. What people did not realize was that this storm was going to create widespread havoc throughout the region.

By the morning of September 17, 1999, hurricane Floyd had already moved far enough north that rainfall had ceased in the southern part of the state. The sun appeared during the early afternoon across all but the northern-most part of the region. The heavy rains overnight had caused localized flooding along small creeks, but these waters quickly passed through the system. Residents began hearing warnings of possible flooding along the major rivers that afternoon, and indeed water levels began to rise that evening. When people awoke on Saturday, September 18th, residents of the floodplains of the Tar, Neuse and Cape Fear Rivers found water lapping at their doors. Widespread evacuations began, and people looked on incredulously as water rose in their living rooms destroying treasured possessions. There was a general sense of amazement that such a disaster had developed from this rather innocuous storm. Yes, rainfall had been significant, but people recalled other storms that produced as much rainfall and no flooding. It turns out that a rather unique set of circumstances combined to create this flood.

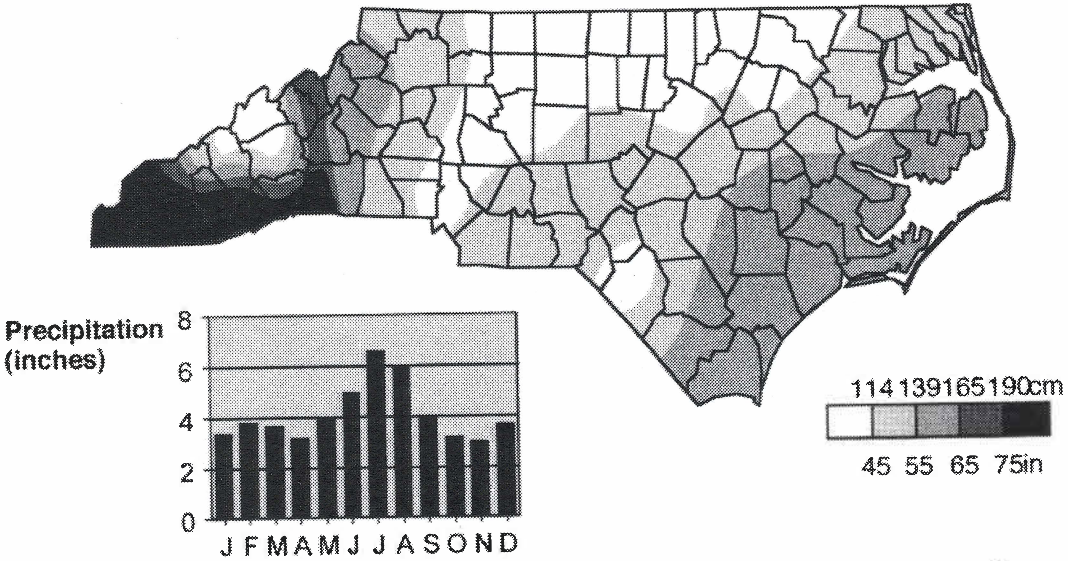

Figure 1. North Carolina annual rainfall and monthly distribution of rainfall for the Coastal Plain.

The purpose of this paper is to examine the climatic and hydrologic conditions of Eastern North Carolina with the purpose of explaining how this flood occurred. In order to accomplish this, a review of factors that affect flooding in this region will be undertaken and then rainfall and river stage data will be provided to characterize the magnitude of the event. There are five factors that affect river flow in general and flooding in particular:

1. The amount of precipitation and its intensity;

2. The shape of the drainage basin;

3. The topographic characteristics of the drainage basin;

4. The characteristics of the soils within the drainage basin; and

5. The land use characteristics of the region.
Each of these factors will be discussed within the context of eastern North Carolina.

Eastern North Carolina

Eastern North Carolina coincides with the region called the coastal plain. It consists of a flat, relatively featureless plain that slopes gently from the Piedmont to the ocean, losing about 200 feet in elevation over its 75-100 mile width. The flat appearance of the plain would suggest that runoff and surface erosion are minimal, but recent research by Phillips *et al.* (1993; 1999) and Slattery *et al.* (1997) suggests that this is not true.

Rainfall across Eastern North Carolina ranges from 45-65 inches per year (Figure 1), with the higher amounts concentrated along the coast, mainly in the southern two-thirds of the region. Rainfall is highly seasonal, with maximum amounts of 5-7 inches during June, July, August and September. There are four precipitation mechanisms responsible for the rain: 1. Cold fronts that cross the state from west to east and that dominate from fall to spring; 2. Thunderstorms produced by convective systems that develop during the hot, muggy summer months; 3. Coastal rain associated with northeaster storms that develop off the Cape Hatteras coastline; and 4. Tropical storm systems that track north from the Caribbean, often developing into hurricanes. Hurricanes are most likely to affect the region in late summer and early fall. This is a period of the year when monthly rainfall drops from about 4.5 inches in September to about 3 inches in November.

Four large river systems flow across the coastal plain (Figure 2). The drainage basins are elongated in a northwest-southeast direction, with the main trunks of the rivers running mainly along the southern margins of the watersheds. The location of the rivers with respect to their floodplains is significant because higher ground is generally located on the southern side of the rivers whereas broad, flat floodplains lie to the north. This configuration explains the fact that the most extensive flooding occurred north of the rivers, with sections of Tarboro, Greenville, Goldsboro and Kinston among other local communities being completely inundated.

There is a general perception that the soils of the coastal plain are predominantly sandy with silt/clay soils located in marshy or low-lying areas. The particle size characteristics of soils are an important component of the hydrologic system because they determine to a certain extent the amount of precipitation that can infiltrate into the soil, and therefore the amount of water that runs off across the surface. The infiltration/run-off relationship determines the rate at which the river discharge increases following the beginning of rainfall, and the length of time over which increased discharge occurs. A soil survey of Pitt County (Soil Conservation Service, 1974), located approximately in the middle of the coastal plain, reveals that about 63% of the land has soils characterized as poorly- or extremely poorly-drained, and the remaining 37% are equally divided between moderately well- and well-drained. Infiltration experiments conducted on two fields in southern Pitt County reveal the degree to which the particle size characteristics affect infiltration. The first field consisted primarily of soils of the Wagram series, characterized as well-drained loamy sand soils with an A horizon approximately two feet in depth. The second field consisted of Lenoir Series soils described as poorly drained loams with

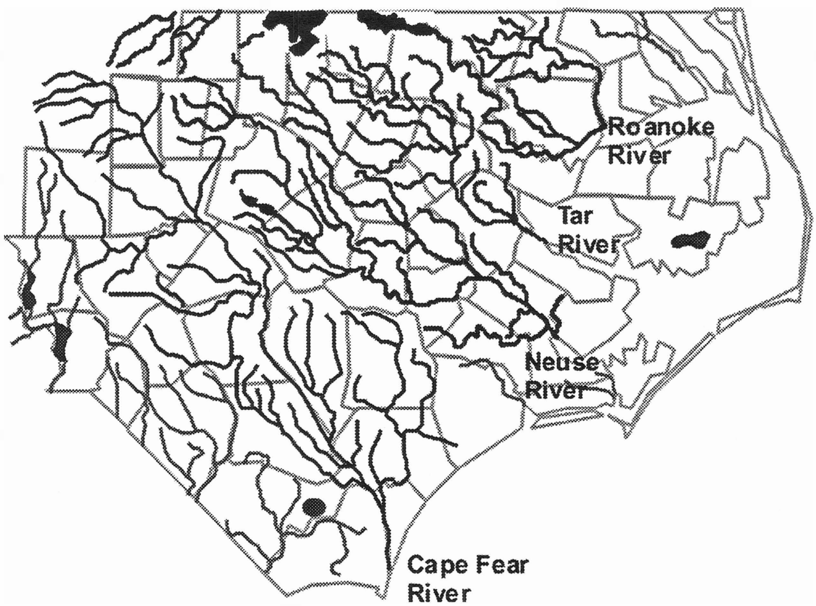

Figure 2. Drainage systems of the Coastal Plain of North Carolina.

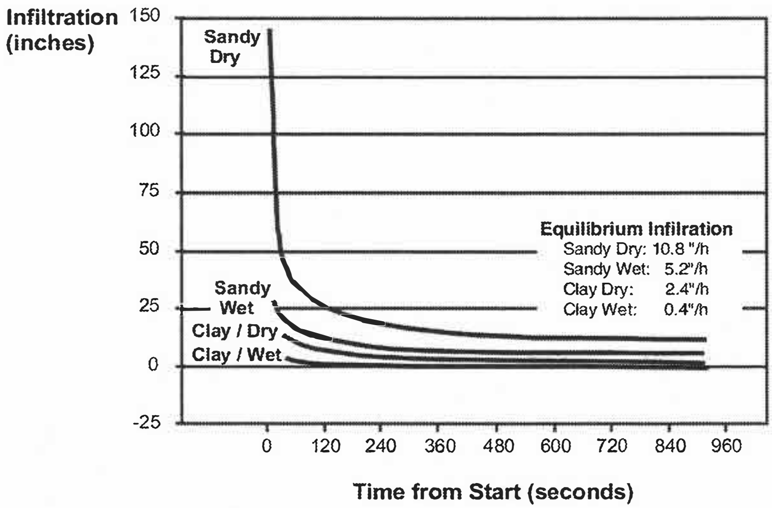

Figure 3. Infiltration on two Coastal Plain agricultural fields.

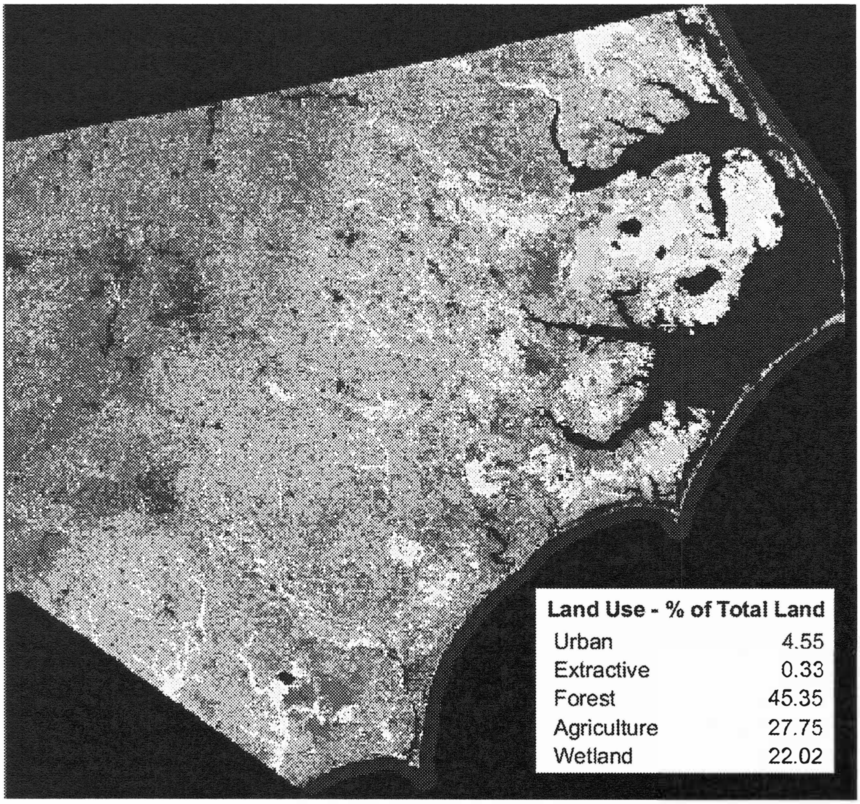

Figure 4. Land use in Eastern North Carolina. White represents agricultural land; light grey is wetland; medium grey is forest; dark grey is urban; nearly black is water.

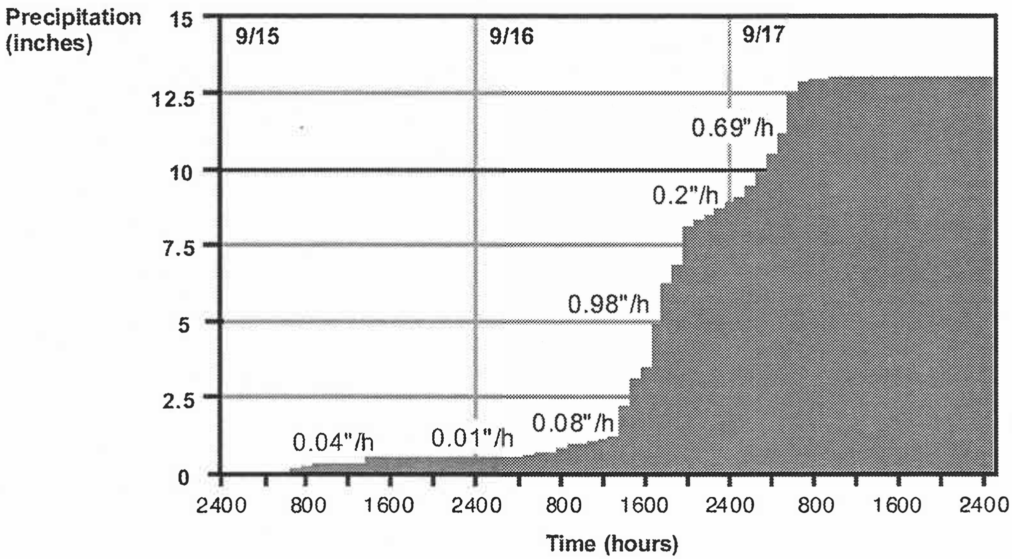

Figure 5. Precipitation recorded at Kinston, NC, September 14-16, 1999. Also shown are rainfall intensities for selected periods during the storm.

a shallow A horizon at about 8 inches depth. The infiltration data (Figure 3) reveal sharp differences between the soils. The first set of infiltration runs took place in late April, 1996 after a long period without rain. Gravimetirc soil moisture on the Wagram field was 0.7% and on the Lenoir field 6.4%. The second infiltration run was done in September, 1996, after hurricane Fran. Gravimetric soil moisture was 31% on the Wagram field, but not measured on the Lenoir field. On the dry fields, the initial infiltration rate is very high on the Wagram field, but it falls off to an equilibrium value of 10.8 inches/hour after 15 minutes of running time. Infiltration is lower on the Lenoir field, starting at 25 in/hr and achieving equilibrium at 2.4 in/hr. Under wet conditions, the infiltration rates are very low - 5.2 in/hr on the Wagram field and 0.4 in/hr on the Lenoir field. Given these observations, we could expect infiltration rates of 5-10 in/hr on about 18% of Pitt County, and rates of 0.5-2.5 on about 63% of the County. It seems safe to conclude that the 18% defined as moderately well-drained would have infiltration rates in the 2.5-5 in/hr range.

Land use in Eastern North Carolina is dominated by agriculture (Figure 4). Land classified as agricultural makes up about 28% of the image shown in Figure 4. The primary crops grown in the region are tobacco, cotton, corn and soy. The planting schedule can be important to hydrological processes as fields are left bare for certain parts of the year. Tobacco is generally planted in early spring and harvested by mid-summer, whereas cotton and soy are planted in late spring or early summer and harvested in mid to late fall. Fields are generally left bare over the winter, although in recent years there has been an increase in the number of fields planted with a cover crop such as rye.

Hurricane Floyd

On September 7th, 1999, a tropical depression was identified by the National Weather Service, located some 950 miles east of the Leeward Islands. By early on September 8th, the storm had gained sufficient strength to be classified as a tropical storm, and it became hurricane Floyd on September 10th, when the eye of the storm was located some

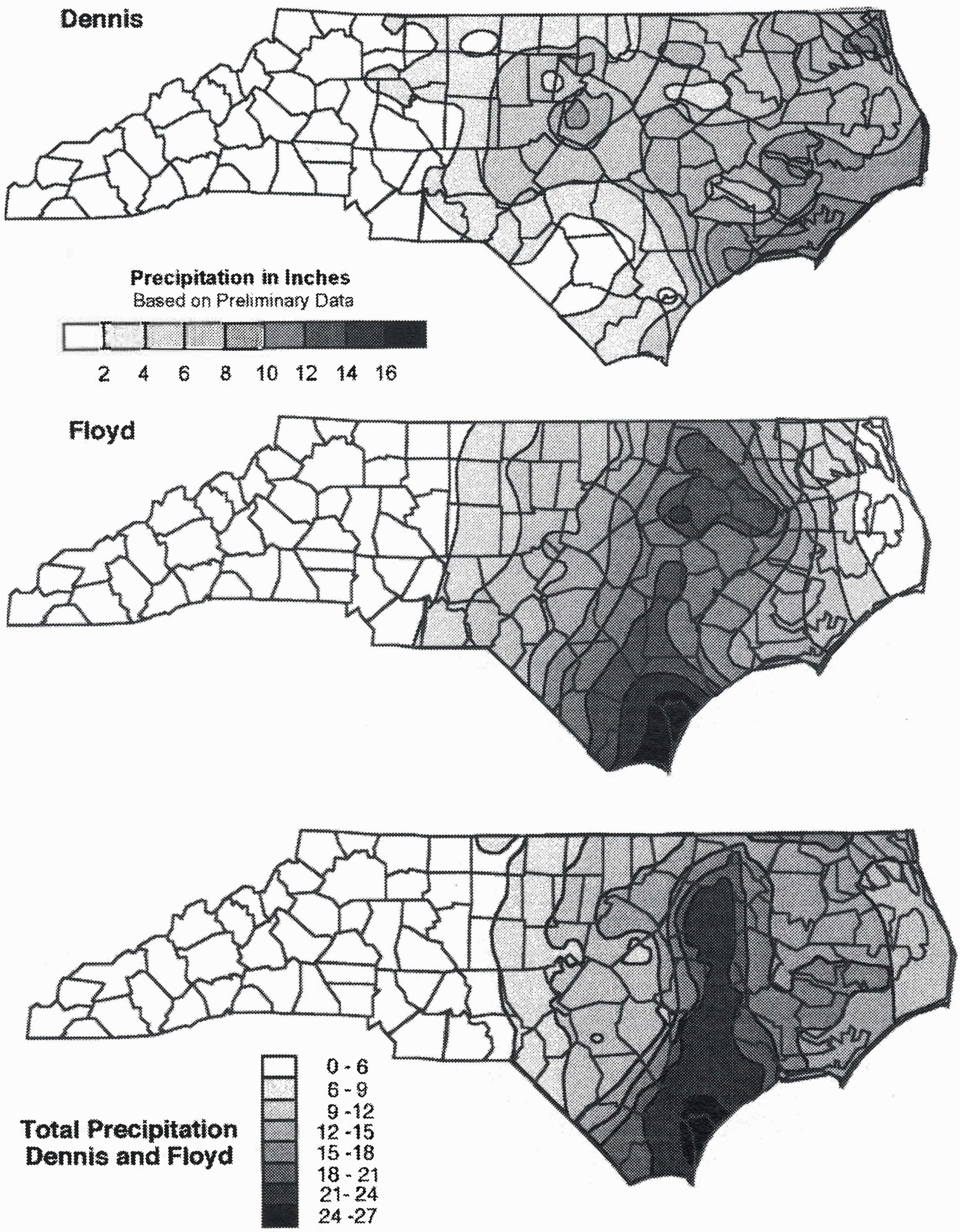

Figure 6. Distribution of rainfall during Hurricanes Dennis and Floyd. Also shown is total precipitation from the two events. (Note: Data for Dennis and Floyd are preliminary data, obtained from the State Climatic Office of North Carolina; precipitation total data are from the National Climate Data Center)

190 miles east of Barbuda. At that point, Floyd was moving in an east-northeast direction at 10 mph. On September 14th, Floyd crossed the Bahamas, moving at a speed of 14 mph toward the coast of Florida. Maximum sustained winds were 150 mph, making it a very strong category 4 storm on the Saffir-Simpson scale. Experts observed that Floyd had developed into a very large storm in which hurricane force winds (>74 mph) extended 125 miles out from the eye. The cloud cover associated with Floyd extended about 750 miles in a north-south direction, and 650 in an east-west direction. By contrast, comparable measurements made for hurricane Andrew when it was in approximately the same location, some 350 miles east of Miami, reveals a more compact storm, some 250-280 miles wide.

As Floyd progressed through the eastern Caribbean, forecasters believed that the storm would turn to the north. However, Floyd confounded the experts by continuing on a westward course, and evacuations were carried out along the entire coast of Florida. Late in the evening of September 14th, Floyd finally began the long-awaited turn to the north. At this time, the outer bands of the hurricane began to cross the North Carolina coastline, coming into contact with a strong cold front that was moving across the southeast. The stalled cold front produced 0.5 to 1.0 inches of rain across eastern North Carolina on September 14th, and into the early morning of September 15th (Figure 5). At 5 am on September 15th, the eye of the storm was centered 100 miles east of Cape Canaveral, moving forward at 14 mph, with maximum sustained winds of 140 mph. By 1pm, the eye was located about 150 miles east of Jacksonville. Maximum sustained wind speed had diminished to 125 mph, hurricane force winds (>74mph) still extended out to 140 miles from the eye, and tropical storm force winds (>39mph) extended out 230 miles. At this time, Floyd was about 250 miles south of Wilmington, NC. The heavier rain bands were beginning to move across the North Carolina coastal plain, producing heavy precipitation during the afternoon of September 15th (Figure 5). Tropical storm winds began to be felt along the NC shoreline from Wilmington to Morehead City.

By 5pm on September 15th, the storm center had moved to within 215 miles of Wilmington. The storm's forward speed had increased to 17 mph, while the maximums sustained winds had dropped to 115 mph. The hurricane force winds still extended 140 miles out from the eye. By 11 pm that night, the storm center was 100 miles south of Wilmington. Hurricane Floyd finally made landfall at 3 am on September 16th, at Cape Fear. Maximum sustained winds at that time were 110 mph. The National Weather Service continued to call for 6 to 12 inches of rain along the hurricane path, as it had been doing for the previous 24 hours. The hurricane was moving faster as it passed over the coast, advancing northward at 20 mph. At 7 am, the center was approximately over New Bern, moving at 24 mph. Maximum sustained winds had dropped to 100 mph. By 11 am, the storm was passing over Virginia Beach, moving offshore again. Maximum winds speeds were 80 mph.

The primary impact of Floyd was the rainfall associated with the storm. Whereas the National Weather Service had been predicting 6 to 12 inches of rain, preliminary data indicate that 10 to 18 inches of rain actually fell over much of eastern North Carolina (Figure 6). This amount of rainfall is unusual for this region, representing 15-25% of the annual total, and exceeding the average monthly rainfall for September by 6-12 inches. However, the region has experienced heavy rain before, having had recent experiences with hurricanes Bertha, Fran, and Gloria. Inhabitants of eastern North Carolina were, therefore, surprised when many small creeks in the region suddenly grew, overflowing their banks and flooding extensive areas adjacent to the streams. Residents woke up on Friday September 17th to find that the main stems of the region's rivers were predicted to reach flood stage during the course of the day and that the rivers would continue to rise for several days. Stage data for the Tar River at Greenville typify the rivers' conditions throughout the region (Figure 7). At this point, discharge data are not yet available from the USGS, but the agency estimates that the discharge will rank the flood in the 200 year recurrence interval range. This is significantly different from the 500 year level that many have cited, but this estimate is based on the stage data which have inherent inaccuracies.

The Hurricane Floyd Flood

All information about Hurricane Floyd suggests that this storm should have produced moderate flooding. Instead, Floyd created the worst disaster in the history of the state of North Carolina. Indeed, some estimates indicate that 50,000 homes were affected by the flood waters and that total losses will exceed $6 billion. The question on many people's mind is: what made Floyd such a devastating storm?

The answer to the question is found in the topics reviewed above. The primary factor was the fact that not two weeks prior to Floyd's arrival, hurricane Dennis moved over the Outer Banks and then stalled offshore. The result was several days of rain throughout the region, with rainfall totals reaching 8-12 inches (Figure 5). In fact, this amount of rain was sufficient to raise the rivers to bankfull stage. The rivers had only just begun to recede when Floyd arrived. The precipitation totals for the two storms are depicted in Figure 5. The map shows that much of eastern North Carolina received at least 13 inches of rain, with some places receiving over 20 inches. It is useful to consider the rainfall in terms of the infiltration data presented in Figure 3 and in terms of the nature of the soils that predominate in eastern North Carolina. Given that poorly drained soils make up the majority of the soils of the region, and given the infiltration rates of these soils, we can assume that rainfall intensities greater than about 0.5 inches per hour will result in nearly all the rain running off the land. These intensities occurred several times during the passage of Floyd. Using Pitt County as an example, about 270,000 acres are poorly drained. If we assume no infiltration on this land, and we estimate that 12 inches of rain fell during Floyd, there would be 11.8 billion cubic feet of water to dispose of. Given that the Tar River drainage system comprises about seven counties, if we assume that comparable amounts of water were

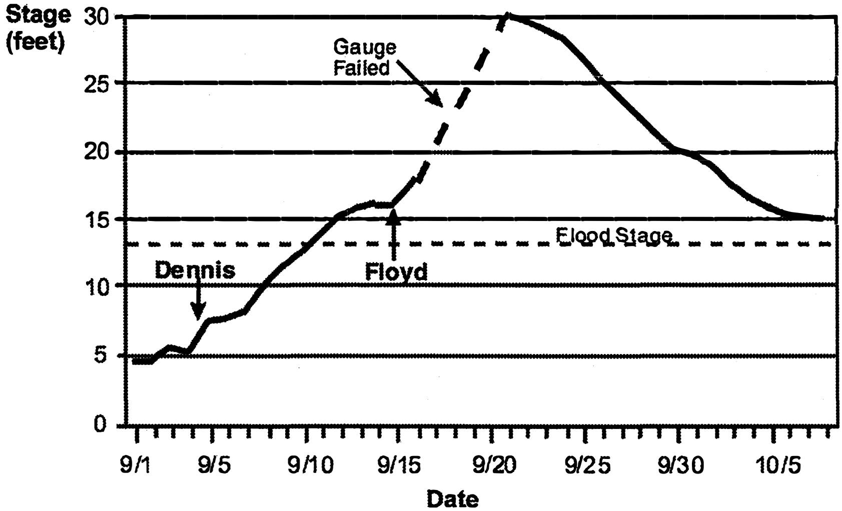

Figure 7. River stage data for the Tar River at Greenville, September, 1999 (data from USGS Regional Office, Raleigh, NC).

generated in each county, there would be nearly 100 billion cubic feet of water to move through the system.

The runoff situation in Eastern North Carolina is modified by the land use characteristics of the region. The heavy agricultural usage means that the vegetation cover is modified at certain periods of the year when the harvest occurs. The tobacco harvest typically occurs in late July through August. The result was that when Dennis and Floyd moved through eastern North Carolina many fields were covered only with crop residues. The absence of this vegetation can be expected to increase the intensity of rainfall impact on the surface and to increase run off.

From a hydrological standpoint, it could be argued that the flood associated with Floyd could have been worse had the storm track and river basin orientations not been perpendicular to each other. There is evidence that discharge is intensified when a storm tracks along the axis of a drainage basin, but it is attenuated when the storm passes across the basin perpendicular to its axis. This was the case during Floyd. Although there was considerable rain at the upper ends of the coastal plain drainage basins, it took several days for the peak flow to move downstream. This at least allowed evacuations to occur with some time to spare.

Conclusions

We have learned many lessons from this particular storm. It is clear that we do not completely understand all the interactions involved in environmental events - at least while they are occurring. If we did, we would have seen that the environmental factors that existed in eastern North Carolina prior to the storm were likely to lead to a catastrophic situation. The flood associated with Floyd was the product of a set of conditions that were relatively unique. The most important of these factors was the heavy rainfall that occurred just 10 days earlier when hurricane Dennis passed across the region. The rainfall associated with Dennis was spread across several days and increased soil moisture. The wet soils then inhibited infiltration when the rainfall from Floyd fell. The high percentage of poorly-draining soils in the region combined with pre-existing moisture conditions to limit infiltration. This and the intense rainfall that occurred during the storm led to high run off. The relatively rapid rise of the Tar River suggests that surface or sub-surface run-off was quite significant in this storm. All these conditions are also influenced by the absence of vegetation on the tobacco fields. The biggest problem for inhabitants of the coastal plain, and for the managers of the occupied areas, is that it is virtually impossible to quantify the combinations of these factors to produce reliable probability-of-occurrence data. Thus, the link between the operation of the physical system and the management of human systems will be very difficult to establish with a high degree of certainty.

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