FLOODPLAIN SEDIMENTATION DURING AN EXTREME FLOOD: THE 1999 FLOOD ON THE TAR RIVER, EASTERN NORTH CAROLINA

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Abstract: This study examines floodplain sedimentation following the largest flood in the 98-yr. record on the Tar River, North Carolina. Hurricane Floyd made landfall just 10 days after Hurricane Dennis in September 1999, bringing unprecedented rainfall (30–46 cm) and flooding to eastern North Carolina. A field survey of the lower 350 km of the river showed that this >500 yr. flood deposited very little overbank sediment (<1 mm) on most of the floodplain. We used suspended sediment concentrations measured on the Tar River from 1958–1967 to suggest that the seasonal timing and sequencing of flood events in 1999 are the most probable explanations for the minimal geomorphic impact of this extreme flood. The early autumn timing of the flood coincided with crops that were mature but not yet harvested, and when natural vegetation was very dense and effective at stabilizing channel banks, hillslopes, and floodplain soils. Hurricane Dennis may have exhausted the available sediment supply and transported this sediment to the Pamlico Sound before reaching flood stage, thereby reducing the sediment available to be transported and deposited by the flood that followed Hurricane Floyd. [Key words: floods, floodplain sedimentation, Hurricane Floyd.]

INTRODUCTION

The geomorphic impact of floods with varying magnitudes and frequencies has been the focus of considerable research (reviewed by Kochel, 1988). Although Wolman and Miller (1960) concluded that the most geomorphic work (defined by the amount of suspended sediment transport) was accomplished by flow events of moderate magnitude and frequency (recurrence intervals of 1–2 yrs.), they also recognized that large floods can produce significant changes in floodplain and channel morphology. Wolman and Gerson (1978) later defined the broader concept of geomorphic effectiveness—the ability of an event to modify landforms in a way that persists over long periods of time. Such modifications require that critical thresholds for the entrainment of sediment are exceeded. Because low-frequency, high-magnitude events exert the largest forces on the landscape and have the greatest capacities to transport sediment, it is reasonable to assume that they have the

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potential to produce the most significant geomorphic changes and the most lasting imprint in the stratigraphic record.

Although many studies have demonstrated a strong relationship between moderate-flow events and sediment transport and channel morphology (e.g., Andrews, 1980), it has been difficult to achieve a consensus on the role that large floods play in landscape modification and floodplain evolution. In some cases large floods have produced catastrophic impacts by scouring channel and floodplain surfaces and/or depositing large amounts of sediment (Schumm and Lichty, 1963; Baker, 1977; Wolman and Gerson, 1978; Nanson, 1986; Osterkamp and Costa, 1987; Schalk and Jacobson, 1997). In other cases only minor geomorphic changes occur (Wolman and Eiler, 1958; Costa, 1974; Moss and Kochel, 1978; Kochel, 1988; Costa and O'Connor, 1995; Gomez et al., 1995; Magilligan et al., 1998).

Explanations for these varied geomorphic responses to large floods are as varied as the responses themselves. The timing and sequencing of events and the availability of sediment may be as significant as flood magnitude in determining the effects of flooding (Wolman and Gerson, 1978; Beven, 1981; Gomez et al., 1995; Magilligan et al., 1998). Modification of landforms only occurs when erosional thresholds are exceeded (Baker, 1977; Wolman and Gerson, 1978), which, on many rivers, may only take place during large infrequent floods and tends to persist longer in arid and semiarid environments than in humid-region environments. Thus, the focus on the magnitude and frequency of channel-forming discharges has shifted to an interest in the shear stress or stream power of large flood flows and the balance between erosional forces and the resistance of sediments to entrainment (Baker, 1977; Baker and Costa, 1987; Magilligan, 1992; Lecce, 1997a, 1997b). The general consensus is that landform-modifying floods capable of producing channel and floodplain scour are more likely in steep, narrow valleys, while sedimentation is favored in wide, low-gradient valleys (Baker, 1977; Nanson, 1986; Baker and Costa, 1987; Magilligan, 1992). Moreover, while shear stress and stream power may aid in determining the effectiveness of flood flows in depositing sediment and modifying channels and floodplains, the duration and volume of flow may be more important than the amount of energy available for geomorphic work at the peak discharge (Costa and O'Connor, 1995).

Because sediment is the most important carrier of many trace elements in fluvial systems (Horowitz, 1991), understanding contaminant transport and storage in such systems requires information on the amount and spatial distribution of overbank sedimentation, as well as the magnitude-frequency characteristics of sediment-transporting events. It is widely understood that the magnitude of overbank sedimentation on floodplains can vary spatially during individual floods (Middlekoop and Asselman, 1998) and over longtime intervals (Knox, 1987; Lecce, 1997a; Lecce and Pavlowsky, 1997, 2001; Trimble, 1999). Studies designed to examine spatial variations in sedimentation rates (using a variety of different methods) have provided substantial spatial detail, but are usually averaged over relatively long time periods (tens to hundreds of years). As such, they show the combined effects of floods of different magnitudes (Asselman and Middlekoop, 1998). In contrast, investigations of discrete flood events are often limited to small areas (Gomez et al., 1997). Relatively few studies have examined overbank sedimentation produced by large, individual floods because their occurrence is inherently infrequent and the depositional evidence of these events in floodplain stratigraphy is short-lived and difficult to recognize as discrete units (e.g., Gomez et al., 1995).

The Coastal Plain of North Carolina has long been considered a slowly eroding landscape, however, recent research suggests that soil erosion may be more significant than previously believed (Phillips, 1992a, 1992b, 1995; Phillips et al., 1993; Slattery et al., 2002). Nevertheless, little is known about the transport and storage of the eroded soil (Phillips et al., 1993). Phillips (1992a, 1992b, 1995) has shown that upland soil erosion and sediment yields of many streams confined to the Coastal Plain may equal or exceed those of Piedmont rivers. Much of the soil eroded from uplands, however, may be stored in the headwater portions of small watersheds (often redistributed within individual agricultural fields) rather than being transported downstream (Phillips et al., 1999a, 1999b; Slattery et al., 2002). Phillips (1992a, 1992b) also suggested that the sediment dynamics in the upper portion of Piedmont-draining rivers are effectively decoupled from the lower basin so that little Piedmont-derived sediment reaches the lower Coastal Plain. Because rivers in wide, low-gradient valleys tend to be associated with hydraulic characteristics favorable to deposition (Magilligan, 1992; Lecce, 1997a, 1997b), and because many studies have found extensive sediment storage and very low sediment delivery ratios throughout the region (e.g., Trimble, 1977; Simmons, 1988; Phillips, 1995), it is reasonable to expect that the 1999 flood had the capacity to remobilize sediment from storage and deliver it to the lower Tar River to produce a relatively large amount of floodplain sedimentation.

Extraordinary floods provide an unusual opportunity to assess the effectiveness of extreme events in producing persistent geomorphic change and lasting evidence in sedimentary deposits. This paper examines floodplain sedimentation following the 1999 "flood of the century" on the Tar River in eastern North Carolina (Fig. 1). We used measurements from a post-flood reconnaissance survey of the lower Tar River floodplain to provide the first documentation of overbank sedimentation following an extreme flood on a large Coastal Plain river. This knowledge is critical for improving our understanding of basic sediment transport/deposition dynamics during rare floods, the delivery, distribution, and environmental fate of contaminants in fluvial systems, and the importance of large events in the stratigraphic record.

Flood Characteristics and Data Collection

During the late summer of 1999 rainfall amounts were far below normal in eastern North Carolina (Bales et al., 2000). After stalling off the Outer Banks of North Carolina for several days, Hurricane Dennis moved inland and delivered 10–20 cm of rain over most of the Tar River basin (Sept. 5–6), saturating soils and increasing stages in the Tar River to near or slightly above bankfull stage. Hurricane Floyd made landfall 10 days later (Sept. 14) and delivered 30–46 cm of rain over much of the basin, causing unprecedented flooding. The rainfall during Hurricane Floyd far exceeded the 100-yr., 24-hr. rainfall amount, and at Rocky Mount the measured 24-hr rainfall was almost double the 100-yr. rainfall (Bales et al., 2000). At many stations, rainfall from these two hurricanes equaled 40–60% of the average annual

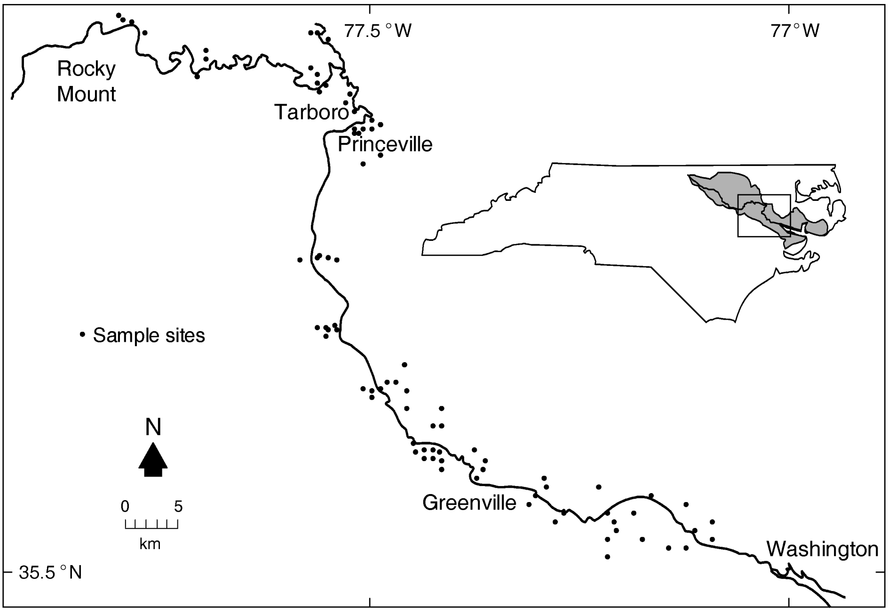

Fig. 1. Sampling sites along the study reach and its location in the Tar River basin, North Carolina (inset).

total. Bales et al. (2000) estimated the recurrence interval for the 1999 flood at >500 yrs. for all of the major river basins in eastern North Carolina. At Tarboro (drainage area = 5654 km^2), the river crested at 12.5 m, 2.3 m above the previous record peak in 1919, producing a peak discharge (1999 m^3/s) that was 34% larger than the previous record flow of 1495 m^3/s (Fig. 2). The Tar River at Greenville (drainage area = 6786 km^2) crested at 9.1 m (1.6 m higher than the previous peak in 1919), and remained above flood stage for 30 consecutive days. The peak discharge of 2067 m^3/s was 57% larger than the previous record in 1919 (1317 m^3/s). USGS collected a total of only 11 samples of suspended sediment concentrations in the entire Tar River basin during this flood. Concentrations were very low in the lower portion of the watershed, but because the sampling occurred at the peak discharge or on the receding limb of the flood hydrograph, it is likely that they do not represent peak concentrations.

We conducted a field survey of sedimentation (Jan.–Feb. 2000) as soon as possible after the flood receded and a rare winter snow had melted in order to minimize modification of the sediment by organisms or human activities and to accurately distinguish the flood sediment from the pre-flood soil surface. Sampling sites were selected on the floodplain of the lower Tar River between Rocky Mount and Washington, North Carolina (Fig. 1). Samples were also collected at varying distances from the channel to account for systematic changes across the floodplain. The selection of sampling locations was controlled to some extent by access to the

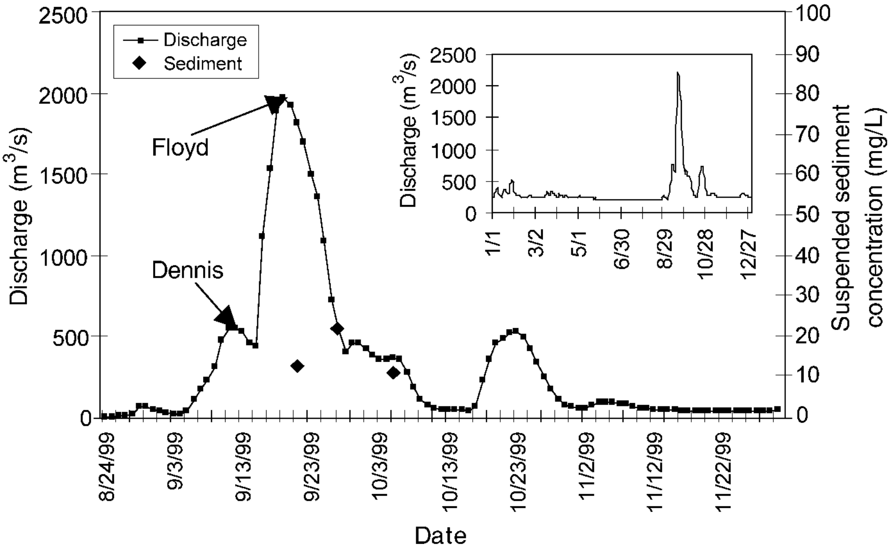

Fig. 2. Daily mean discharge and suspended sediment concentrations during the flood of 1999 for the Tar River at Tarboro. Arrows indicate peak discharges associated with hurricanes Dennis and Floyd. The inset graph show discharge for the entire year. *Source*: USGS (2002).

river and private property. Nevertheless, we sampled 84 sites that provided reasonably complete coverage of the study reach.

The intermingling of small amounts of sediment with organic debris made simple depth measurements impossible in most cases, therefore, we collected all flood sediment and organic debris above the pre-flood soil surface within a 25-cm diameter ring. The flood sediment generally was easily distinguishable from the pre-flood surface, which contained well-decomposed plant litter over a mineral soil. The high winds of hurricanes Dennis and Floyd led to the accumulation of a layer of undecomposed leaves on top of the pre-flood surface (Fig. 3). Sediment transported by the flood was deposited in thin layers on top of the leaf layer or between individual leaves and other organic debris that settled from the flood water. The top of the sequence contained another layer of leaves related to leaf-fall in autumn. After separating the sediment from the large volume of organic litter by wet sieving, the mineral fraction was dried, weighed, and converted to depth of sedimentation assuming a bulk density of 1.5 g/cm^3 (Lecce and Pavlowsky, 1997).

Floodplain Sedimentation

Our observations in the field were fairly obvious and confirmed by analysis of the samples: the 1999 flood deposited little fine sediment on most of the Tar River floodplain (Table 1). In most cases, we observed only a "dusting" of sediment within the plant litter, in abandoned homes, and on other human structures. In many instances, the amount of sediment was below our ability to measure it even in areas

Table 1. Fine Sediment Deposition

Sampling location	Thickness (mm)					
	Mean	Median	*SD*	Minimum	Maximum	*n*
Rocky Mount to Tarboro	2.0	1.0	2.2	0.1	10.1	27
Tarboro to Greenville	2.9	2.2	3.1	0.0	9.9	36
Greenville to Washington	0.8	0.2	1.2	0.0	3.7	21
Entire reach (Rocky Mount to Washington)	2.0	0.9	2.5	0.0	10.1	84

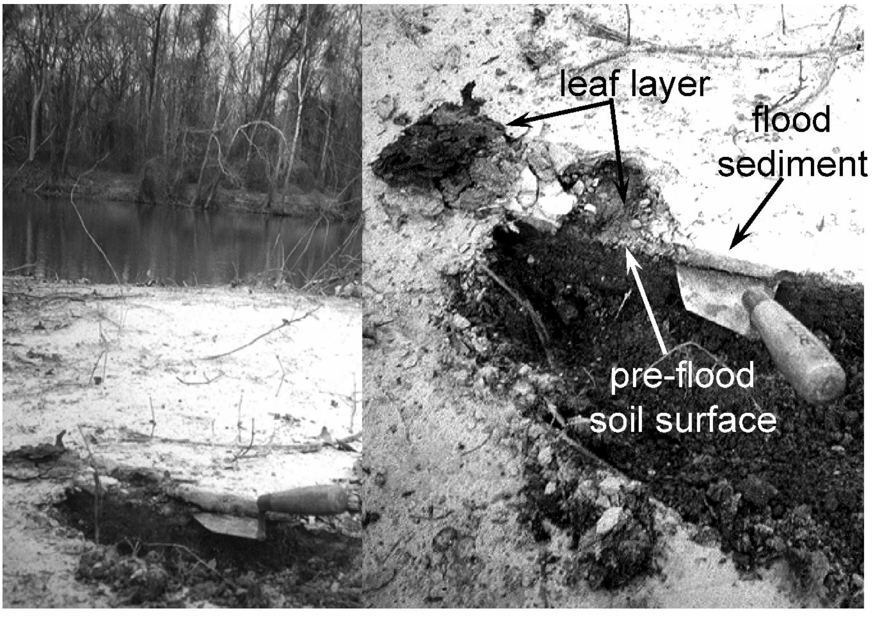

Fig. 3. A 2-cm thick veneer of sand deposited on the south bank of the Tar River northwest of Greenville near Ironwood. A layer of undecomposed leaves associated with the high winds of hurricanes Dennis and Floyd separate the pre-flood soil surface from the flood sediment. Note that this is not representative of the amount of sediment deposited at most of the sampling sites, which in many cases was not even measurable.

that clearly had been inundated by water depths exceeding 3.0 m. The median thickness of fine sediment deposition was 0.9 mm. Variations in thickness were influenced to some extent by the subtle topography on the floodplain, particularly in areas where ponding allowed sediment to continue settling from suspension after most of the floodwater had receded. The time available for most of the sediment to settle from suspension was controlled by the flood hydrograph (<30 days) because there are few levees along the Tar River. Despite the lengthy period of time available for sediment to settle from suspension, the maximum thickness of fine-sediment deposition (10 mm) was surprisingly small for a flood of this magnitude.

We observed larger accumulations of coarser sediment in three relatively isolated situations. First, overbank flow deposited a minimal amount of sandy

Fig. 4. Sand deposited downstream from where a tributary (lower left) entered the Tar River near the Ironwood site. No sand was observed upstream from the tributary.

sediment on natural levees. These deposits were generally not very thick or spatially extensive, ranging from <5 mm to 20 cm. Second, in locations where the bankfull channel of the Tar River meandered sharply across the floodplain, flood flows transported sand onto the floodplain. The thickness of these deposits varied substantially, but deposition was limited to a small section of floodplain immediately downstream from the source. Third, several tributaries draining the steeper southern part of the watershed provided a local source of sediment (in some cases, derived from residential developments) that was deposited on the floodplain immediately downstream from the confluence with the Tar River (Fig. 4).

Unlike the 1993 flood that produced localized scour from levee breaks along the Mississippi River (Gomez et al., 1995) and extensive scour along the Missouri River (Jacobson and Oberg, 1997; Shalk and Jacobson, 1997), we observed no evidence of scour on the floodplain. We attribute this to the lack of levee breaks to concentrate flow, low stream-power values on the floodplain (~10–15 W/m^2), and floodplain soils stabilized by dense vegetation cover.

DISCUSSION

Although the 1999 flood on the Tar River was the largest event on record (>500-yr. recurrence interval), our field observations and measurements indicate that little fine sediment was deposited from suspension on most of the Tar River floodplain. The lack of suspended sediment measurements during Hurricane Dennis and on the rising limb of the flood that followed Hurricane Floyd make it difficult to provide conclusive explanations of the small amount of deposition. We believe, however, that our results support the seasonal timing and sequencing of flood events in 1999 as the most probable explanation (Beven, 1981; Nash, 1994; Gomez et al., 1995; Magilligan et al., 1998). This interpretation is supported by suspended sediment sampling on the Tar River at Tarboro from 1958–1967. These data indicate that long periods of low flow followed by even modest discharges produced sediment concentrations much higher than measurements taken during the 1999 flood. Sediment concentrations frequently exceeded 150–200 mg/L during 1958–1967, with a maximum concentration of 465 mg/L for a discharge of 93 m^3/s on June 22, 1967. Although much smaller than the 1999 flood, the largest discharge during this period was 756 m^3/s and produced a peak suspended sediment concentration of 140 mg/L (May 12, 1958). It is unlikely that the availability of sediment for the 1999 flood would have been reduced by the exhaustion of sediment sources during the dry summer of 1999 when the last modest peak discharge occurred on May 18 (36 m^3/s), and the last flow to reach flood stage was on January 29 (300 m^3/s). There was sufficient time after January 29, therefore, for low flows to deposit sediment in the channel of the Tar River and its tributaries. The data from 1958–1967 also show that most floods demonstrate clockwise hysteresis (~70–75%), frequently with very low concentrations following the peak discharge. The prevalence of clockwise hysteresis suggests that the source of suspended sediment is usually local, probably fine sediment deposited within the channel during the waning stages of earlier floods (Asselman and Middlekoop, 1998). Thus, it appears likely that sediment concentrations were higher prior to the flood peak produced by Hurricane Floyd, and may have been highest during the flows associated with Hurricane Dennis. Assuming this was the case, and because Hurricane Dennis generally did not produce discharges that exceeded the bankfull stage, much of the sediment transported during the 1999 flood may have been routed toward the Pamlico Sound before the extensive inundation of the floodplain occurred after the runoff from Hurricane Floyd. The extremely low concentrations measured on the waning stages of the 1999 flood may reflect both sediment exhaustion and dilution by the extraordinary flood volume.

The seasonal timing of floods on the Tar River coincided with land cover conditions that were most conducive to erosion and sediment transport. This may also help explain the lack of sedimentation during the 1999 flood. Most annual floods (53%) occur in January, February, and March (Fig. 5) when natural vegetation is dormant and agricultural fields are barren. Almost 40% of the annual sediment discharge measured at Tarboro during 1958–1967 occurred during these three months (Fig. 6). Autumn is not normally associated with high suspended sediment concentrations because densely vegetated hillslopes, agricultural fields, and channel banks limit sediment production. By early summer, first order drainage ditches and stream channels become choked with vegetation, discouraging sediment transport and disrupting the linkage between headwater sediment sources and lower portions of the drainage network. Thus, it may be that the timing of the 1999 flood in September when most crops had not been harvested and natural vegetation was dense played

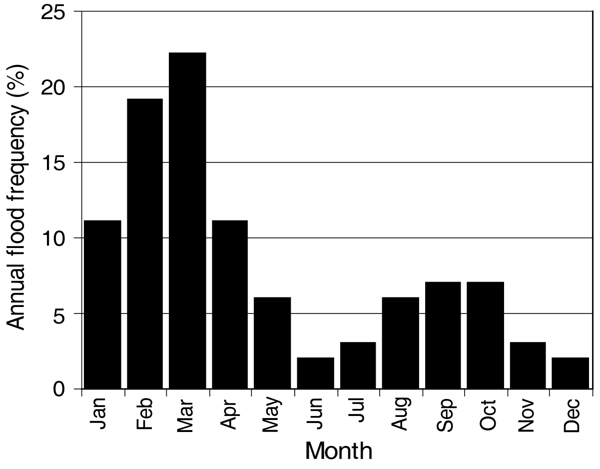

Fig. 5. Annual flood frequency for the Tar River at Tarboro, 1897–1900 and 1906–2001.

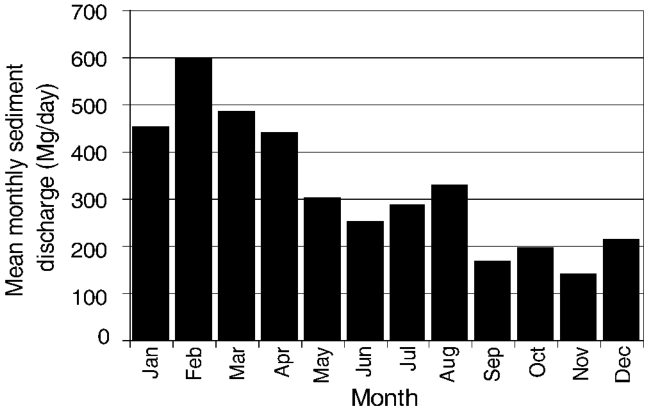

Fig. 6. Sediment discharge for the Tar River at Tarboro, 1958–1967.

an important role in reducing sediment concentrations for what otherwise may have been a more significant depositional event.

We do not necessarily intend to imply that excessive sedimentation would have occurred if sediment concentrations had approached historical maximums recorded on the Tar River. Many researchers have shown that sediment concentrations and sediment discharges tend to be low on the large, low-gradient rivers that characterize the Atlantic Coastal Plain (e.g., Simmons, 1988). Assuming that all the sediment settled out from a 3-m water column with a concentration of 465 mg/L (the maximum concentration measured during 1958–1967), only ~1.2 mm of sediment would have been deposited. Dense vegetation stabilizes this low-gradient channel and floodplain during the growing season so that even high discharges are not likely to produce the extensive scour that would lead to high sediment concentrations and substantial overbank sedimentation.

Magilligan et al. (1998) argued that a large flood may leave little lasting evidence of its occurrence where (1) erosion is minimized by energy dissipation on wide floodplains with cohesive soils, (2) event timing or sequencing limits sediment supply, and (3) the linkage between the hillslope supply of sediment and the channel is weak. The first two conditions existed in the Tar River basin during the 1999 flood. The floodplain is wide and densely vegetated to dissipate energy and further resist the erosion of cohesive soils. The timing of the 1999 flood coincided with the season when the natural vegetation is most dense and when most crops were mature and largely unharvested. Furthermore, the flood occurred only 10 days after Hurricane Dennis, which may have mobilized most of the sediment available for transport before flood stages were reached. Although evaluating the linkage between the hillslope supply of sediment and the channel was beyond the scope of this study, several recent studies at least suggest that slopes and channels in similar basins may be decoupled to some extent. Fryirs and Brierley (1999) showed that while soil erosion has been relatively high in large parts of the tectonically stable, low-relief landscapes of southeastern Australia, this sediment has not been efficiently transported to the drainage network. In a small, headwater basin on the Coastal Plain, Slattery et al. (2002) found that, despite significant soil erosion, the coupling between hillslopes and stream channels is weak because of extensive colluvial and alluvial storage within individual fields. The predominantly gentle topography of the lower portion of the Tar River watershed suggests that the destabilization of hillslopes was probably minimal during the 1999 flood, and in any case, during our field survey downstream from Rocky Mount we observed no evidence of slope failures that would provide a significant source of sediment. Although the upper Tar basin is within the eastern Piedmont, and would be more susceptible to slope instability, the upper basin received much less rainfall during Hurricane Floyd than farther downstream. Phillips (1992a, 1992b) has also shown that sediment dynamics in the Piedmont and Coastal Plain portions of the watershed are decoupled. Thus, this extreme flood left little or no sedimentological or morphological evidence in proportion to its magnitude. Even where relatively thick deposits of sand occurred, the localized nature of these deposits makes it unlikely that they would be recognized in the stratigraphic record as indicative of a major flood.

CONCLUSION

A field survey of floodplain sedimentation following the >500-yr. flood on the Tar River in 1999 revealed that very little sediment was deposited. The average thickness of fine sediment deposition was 0.9 mm, and in many cases the amount of sediment could not even be measured. Thicker deposits of sand were observed, but were not spatially extensive. Most of these localized deposits were related to inputs from tributaries along the steeper south side of the Tar River. We conclude that the seasonal timing and sequencing of flood events in 1999 are the most probable explanations for the lack of significant sedimentation from this extreme event.

The flood occurred in early autumn when crops were mature but not yet harvested, and when natural vegetation is very effective at stabilizing channel banks, hillslopes, and floodplain soils. Hurricane Dennis, which occurred just 10 days before Hurricane Floyd, may have exhausted the available sediment supply and transported this sediment to the Pamlico Sound before the Tar River reached flood stage.

In so far as the role of large floods in landscape modification and floodplain evolution is uncertain (Magilligan et al., 1998), event-based field assessments are important to help improve our understanding of basic sediment transport/deposition dynamics during large, rare floods and to facilitate comparisons with the dynamics of large floods on other river systems. Such studies also provide additional evidence necessary to understand the significance of large events in the sedimentary record.

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