HYDROLOGIC AND WATER-QUALITY RESPONSE OF FORESTED AND AGRICULTURAL LANDS DURING THE 1999 EXTREME WEATHER CONDITIONS IN EASTERN NORTH CAROLINA

J. D. Shelby, G. M. Chescheir, R. W. Skaggs, D. M. Amatya

ABSTRACT. *This study evaluated hydrologic and water-quality data collected on a coastal-plain research watershed during a series of hurricanes and tropical storms that hit coastal North Carolina in 1999, including hurricanes Dennis, Floyd, and Irene. During September and October 1999, the research watershed received approximately 555 mm of rainfall associated with hurricanes. This was the wettest such period in a 49-year historical weather record (1951-1999). Prior to the hurricanes, the watershed experienced a dry late winter, spring, and summer (565 cm for Feb.-Aug.). This was the third driest such period in the 49-year record. Maximum daily flow rates measured across the research watershed were greater during hurricane Floyd than for any other time in a four-year (1996-1999) study of the watershed. Daily flows observed for an agricultural subwatershed were generally greater than for a forested subwatershed throughout the study, and during the hurricanes of 1999. Daily nutrient loads measured across the research watershed were greater during hurricane Floyd than for any other time in the study. In general, the two-month period of hurricanes produced total nitrogen and total phosphorus loads nearly equal to average loads for an entire year. Total annual nitrogen export from an agricultural subwatershed was 18 kg/ha in 1999, with 11 kg/ha (61%) lost during September and October. Total annual nitrogen export from a forested subwatershed was 15 kg/ha in 1999, with 10 kg/ha (67%) lost during September and October. The nitrogen export observed in the forested subwatershed was high compared to other forested areas, likely due to the highly permeable organic soils in the watershed. Total annual phosphorus export from an agricultural subwatershed was 0.9 kg/ha in 1999, with 0.7 kg/ha (78%) lost during the hurricanes/tropical storms. Total annual phosphorus load from a forested subwatershed was 0.1 kg/ha in 1999, with 74% of the load exported during the months of September and October. Hurricanes and floods occur with some regularity in North Carolina, but the effects are infrequently documented. This study provides information that will contribute to greater understanding of how watersheds respond to these events.*

Keywords. *Coastal plain, Hurricane, Hurricane Floyd, Hydrology, Nutrient export, Water quality, Watershed scale.*

Large storms can have acute effects on water quality; large nutrient and sediment exports can occur during a short time frame (Bales et al., 2000; Bales, 2003). Hurricane-related events have produced large nutrient loads to rivers and estuaries of North Carolina. In the Tar River at Tarboro, North Carolina, the floodwaters associated with hurricane Floyd (15 Sept. to 20 Oct. 1999) transported nearly 80% of the long-term-mean annual nitrogen load and 89% of the long-term-mean annual phosphorus load (Bales, 2003). Another study (Gentry et al., 1998) noted that nitrate-nitrogen export from agricultural fields with tile drainage (Illinois) was associated with high flow events. Gentry et al. (1998) reported that 75% of the annual nitrogen exported from one tile drain (17 ha effective drainage area in corn) occurred in only nine days of flow associated with a record rainfall event. Borah et al. (2003) reported that most nitrate-nitrogen transported from an east central Illinois watershed occurred during single-event storms. These studies describe how patterns of nutrient and sediment loss vary under different conditions and indicate that intense storms can be responsible for most of the nutrient and sediment export from a watershed.

This study compiled and analyzed data from a large, multi-use watershed in the lower coastal plain of North Carolina. Hydrology and water quality were monitored from 1996 through 1999. During the study period, data for a series of large, hurricane-related events were gathered. The data from this study provide insight into how a coastal plain watershed behaves under "normal" as well as extreme conditions. The study measured continuous rainfall, drainage, and nutrient and total suspended solids export in the research watershed.

OBJECTIVES

The overall objective of this study was to determine the impacts of the hurricanes and related storms during 1999 on the hydrology and water quality of a coastal plain watershed. Specific objectives were to:

Article was submitted for review in April 2005; approved for publication by the Soil & Water Division of ASABE in November 2005. Presented at the 2004 ASAE Annual Meeting as Paper No. 042221.

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- Compare the watershed hydrology observed during the hurricanes and storms of 1999 to watershed hydrology observed in other years (1996-1998).
- Compare water quality (nitrogen, phosphorus, and total suspended solids loads) observed during the hurricanes and storms of 1999 to water quality observed in other years (1996-1998) on the same watershed.
- Assess hydrology and water quality differences in two subwatersheds of different land uses (forested vs. agricultural) and soil types.

Study Area

The research watershed is located in the lower coastal plain of North Carolina, near the town of Plymouth. The primary land uses (fig. 1) in the watershed are typical for the region and include managed forest (52%), unmanaged forested wetlands (11%), agriculture (36%), and housing and commercial development (1%).

The research watershed is within HUC-03010205130010 and is divided into subwatersheds and fields with outlet stations instrumented to measure flow rates and nutrient concentrations (fig. 2). The watershed is approximately 10,000 ha and ultimately drains to Kendrick's Creek, 6 km upstream of the Albemarle Sound. An extensive artificial drainage network covers the flat terrain of the research watershed, making the otherwise poorly drained soils usable for agricultural or silvicultural production.

Forested Subwatershed S4

Subwatershed S4 (fig. 2), approximately 2950 ha, is primarily loblolly pine (*Pinus taeda*) plantation with stands ranging from one to 30 years old. A 95 ha section of natural wetland is also present in the S4 subwatershed. The dominant soil (60%) in the forested S4 subwatershed is Belhaven muck (loamy, mixed, dysic, thermic Terric Haplosaprists) (SCS, 1981). Other soils present in this subwatershed are Portsmouth fine sandy loam (fine-loamy over sandy or sandy-skeletal, mixed, semiactive, thermic Typic Umbraquults),

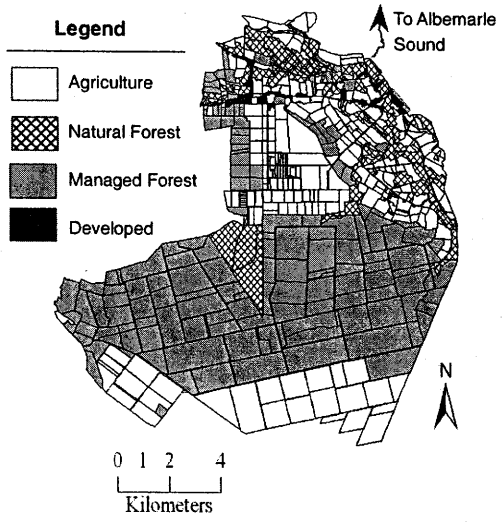

Figure 1. Boundaries of 10,000 ha research watershed with land uses indicated by color.

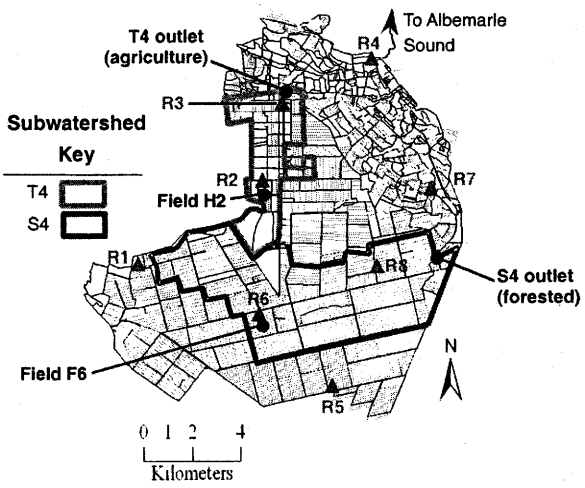

Figure 2. Diagram of research watershed with indicators for subwatershed areas and outlets, monitored fields, and rainfall gauges (R1 through R8).

Cape Fear loam (fine, mixed, semiactive, thermic Typic Umbraquults), and Pungo muck (dysic, thermic Typic Haplosaprists) (SCS, 1981). In this subwatershed, the organic soils (Belhaven muck and Pungo muck) have "cured out" or "ripened" over many years, changing the chemical and water-holding properties. During dry periods, this cured organic layer provides a suitable environment for mineralization and subsequent nitrification of organic nitrogen. The drying or curing of the organic material created macropores that increased the drainable porosity and hydraulic conductivity of the soil. In another study on this subwatershed, Diggs (2004) noted that these soils had low bulk density and very high porosity, especially in the upper layers. The study reported drainable porosity values from 0.15 to 0.21 cm/cm at depths of 20 to 50 cm below the soil surface for field F6 on Belhaven muck within the S4 subwatershed (Diggs, 2004). Diggs (2004) reported saturated lateral conductivities from field F6 of 700 cm/h in the upper 40 cm of the soil profile, 350 cm/h between depths of 30 to 45 cm, and 10 cm/h between depths of 45 to 60 cm below the soil surface.

The S4 subwatershed contains an extensive open-ditch drainage network that includes lateral field ditches, generally 0.8 to 1.2 m deep and spaced 80 to 100 m apart, which drain to collector canals and ultimately to the subwatershed outlet. Within the Results and Discussion section of this article, detailed data are presented for one field (field F6) located on Belhaven muck within the S4 subwatershed. Field F6 contains loblolly pine planted in 1992. More detailed descriptions of the soils, vegetation, and drainage systems on the S4 subwatershed can be found in Diggs (2004).

Agricultural Subwatershed T4

Subwatershed T4 (fig. 2), 710 ha, is mixed land use catchment. The predominant land use in T4 is agricultural (390 ha). Most of the cropland was planted in a rotation of three crops in two years (corn, winter wheat, and soybeans) and utilized a system of tile and ditch drainage. Fertilizer application rates were typically 150 to 200 kg/ha of N and 50 to 70 kg/ha of P for the corn crop, and 100 to 160 kg/ha of N and 50 to 70 kg/ha of P for the winter wheat crop. No

applications were made on the soybean crop. Seventy hectares of the agricultural area is pasture land that was irrigated with swine lagoon wastewater from a 200-sow swine unit. The pasture land was grazed by a herd of 175 breeding age cows. The remaining area within this subwatershed is forest or natural wetland.

The primary soils found in the T4 subwatershed are Portsmouth fine sandy loam, Roanoke silt loam (fine, mixed, semiactive, thermic Typic Endoaquults), and Cape Fear loam (SCS, 1981). Soil hydraulic conductivities and drainable porosities were much lower for these mineral soils than for the cured organic soils on subwatershed S4. Burchell (2003) reported soil saturated lateral conductivities for Cape Fear loam within the agricultural area of T4 (pasture) of 20 cm/h in the upper 40 cm of the soil profile and 6 cm/h at depths of 40 to 65 cm below the soil surface. Burchell (2003) reported soil drainable porosity of 0.03 to 0.05 cm/cm from zero to 100 cm below the surface for the same soil. In this study, data are presented from field H2 (fig. 2) on Portsmouth fine sandy loam within the T4 subwatershed. This Portsmouth soil had saturated lateral conductivities ranging from 3 to 4 cm/h in the top 30 cm and from 0.4 to 2 cm/h at depths of 30 to 100 cm below the soil surface (Arnold, 2004). Drainable porosity of this Portsmouth soil was from 0.03 to 0.04 cm/cm from zero to 100 cm below the soil surface (Arnold, 2004). Field H2 was drained by 1.2 m deep subsurface drain tubes spaced 22.9 m apart (Mohammed, 1997; Arnold, 2004).

Weather Conditions of 1999

The year 1999 was one of extremes; dry conditions were followed by storms. This study compiled and examined an array of hydrology and water quality data from components of the 10,000 ha research watershed during this unique period and compared the results to prior years on record (1996-1998).

Prior to the hurricane season, the entire state experienced a dry spring and summer. According to the Palmer Drought Severity Index (based on precipitation, temperature, soil moisture), by 28 August 1999 all of eastern North Carolina was suffering from moderate to severe drought conditions (NOAA, 1999).

Following the dry period, three hurricanes, Dennis (29 Aug. to 7 Sept.), Floyd (14-17 Sept.), and Irene (17-18 Oct.), brought tremendous amounts of rainfall to North Carolina in a short, 6-week period (National Hurricane Center, 1999). Parts of the coastal plain received rainfall exceeding 760 mm for September and October. At both Kinston and Rocky Mount, North Carolina, the 24 h rainfall recorded during hurricane Floyd far exceeded the 100-year rainfall recurrence interval (Bales et al., 2000). All of the North Carolina river basins east of Raleigh, except the Lumber River basin, experienced unprecedented, 500-year exceedance-level flooding following this series of hurricanes (Bales, 2003).

Hurricane Dennis reached the coast of North Carolina by 29 August, producing heavy rainfall. Dennis was downgraded to a tropical storm on 1 September but continued to linger near North Carolina's coast through 3 September. Finally, Dennis made landfall in North Carolina on 4 September and ultimately dissipated (Beven, 2000). Hurricane/tropical storm Dennis brought 102 to 230 mm of rainfall to eastern North Carolina, saturating dry soils (Bales et al., 2000). The average rainfall recorded in the research watershed was 60 mm for 29 August to 1 September and 162 mm for 3 to 7 September.

On 15 September 1999, hurricane Floyd made landfall near Wilmington, North Carolina (Pasch et al., 1999). This large hurricane added additional rainfall to already saturated soils, generating a large volume of surface runoff and creating flooding throughout much of eastern North Carolina. The U.S. Geological Survey reported 305 to 457 mm of rainfall on much of the Neuse and Tar-Pamlico River basins during 14 to 17 September attributable to hurricane Floyd (Bales et al., 2000). The average rainfall recorded in the research watershed, located east of the most impacted areas, was 185 mm for the same period.

During 17 and 18 October 1999, North Carolina received additional rainfall from yet another hurricane, Irene (Avila, 1999). This hurricane did not make landfall in North Carolina but passed east of the research watershed, adding rainfall to already inundated areas. The average rainfall recorded in the research watershed due to hurricane Irene was 109 mm.

Methods

Weather, hydrology, and water quality were intensively measured and recorded in the research watershed from 1996 through 1999.

Hydrology Measurements

Rainfall amounts within the research watershed were collected at seven locations, R1, R2, R3, R5, R6, R7, and R8 (fig. 2), using automatic tipping-bucket rainfall gauges. Onset Hobo event loggers recorded rainfall at R1, R3, R5, R7, and R8. Rainfall amounts at R2 and R6 were recorded by a Campbell Scientific CR10X weather station, which also continuously measured and recorded air temperature, wind speed and direction, relative humidity, net radiation, and solar radiation.

Water table fluctuations were continuously measured in fields across the research watershed. Water table monitoring wells used pulley/float water level monitoring devices linked to Blue Earth Research ST485 loggers. For forested subwatershed S4, water table fluctuation is presented for field F6. Measured water table fluctuation in field H2 represents typical water table behavior in agricultural subwatershed T4.

Flow in drainage canals/streams was determined at field and subwatershed outlets on a continuous basis. This was accomplished at the outlet of subwatershed S4 and field outlet F6 using v-notch weir structures. Each weir structure was equipped with two pulley/float water level recorders and a Blue Earth Research ST485 data logger. Flow over each weir structure was calculated using stage data measured upstream and downstream of the weir.

In agricultural subwatershed T4, continuous outflow was determined by measuring water depth and velocity with a Unidata Starflow ultrasonic Doppler flowmeter in a concrete, double box culvert that serves as the subwatershed outlet. Outflow from field H2 was determined using a Signet MK515 Industrial Paddlewheel flowmeter, water level recorders, and Blue Earth Research ST485 data loggers to measure flow volumes pumped from sumps that received drainage from 1.2 m deep subsurface drain tubes (Arnold,

2004). Surface drainage was determined by measuring the flow volume pumped from sumps receiving drainage from 4.6 × 30.5 m surface runoff plots on the H2 field (Mohammed, 1997).

Water Quality Measurements

Water quality monitoring was performed using a combination of automatic and grab sampling. At each subwatershed outlet, a Sigma 900 automatic sampler (Hach USA, Loveland, Colo.) collected timed discrete samples (during selected storm events) or flow-proportioned composite samples (during most of the study period). Samples were recovered from the field every two weeks and transported to the laboratory on ice. The samples were subsequently frozen until analyzed. The sampling frequency was such that suspended solids and nutrient concentration values were used to calculate daily loads for each outlet. Grab samples were taken nominally at two-week intervals. The grab samples were used to verify the automatic samples and to fill in data if the automatic samplers malfunctioned. Each sample was analyzed in a university laboratory for total phosphorus (TP), ortho-phosphate-phosphorus (OP-P), ammonium-nitrogen (NH_4-N), nitrate-nitrogen (NO_3-N), total Kjeldahl nitrogen (TKN), and total suspended solids (TSS) using a LACHAT Quickchem 8000 instrumentand standard methods (APHA, 1995). More detailed descriptions of the analysis methods used in this laboratory can be found in Burchell (2003).

Data Analysis

Contaminant loadings during the study period were calculated using measured daily flow volume (m^3/day) and daily contaminant concentrations (mg/L). Daily concentrations used in the calculations were equal to the concentrations of the flow-proportioned composite sample collected over the sampling period. For discrete samples, daily concentrations were calculated assuming that nutrient and TSS concentrations varied linearly between consecutive samples.

Subwatershed outflow and contaminant loads associated with the 1999 events were compared to other events on record in the research watershed, including hurricanes and tropical storms and large storms in February 1998. The February 1998 storms were associated with an El Niño event (Ross et al., 1998) caused by sea surface temperature increases in the equatorial Pacific Ocean (McCabe and Dettinger, 1999). In the southeastern U.S., El Niño events are associated with increased rainfall (Beckage et al., 2003; Hansen et al., 1998).

Probability distribution plots were produced for daily flow and daily load values for both subwatersheds. The flow probability plot was produced by ranking daily flow values (cm/day) for the entire study (1996-1999). The load probability plots were produced by ranking daily values of TN and TP load per unit area (kg/ha) for the entire study. Some significant flow and load events are highlighted on the figures with unique markers and labeled for a specific named event.

To evaluate water quality data collected in each subwatershed, flow-weighted concentrations for each nutrient and TSS were calculated. The flow-weighted concentrations

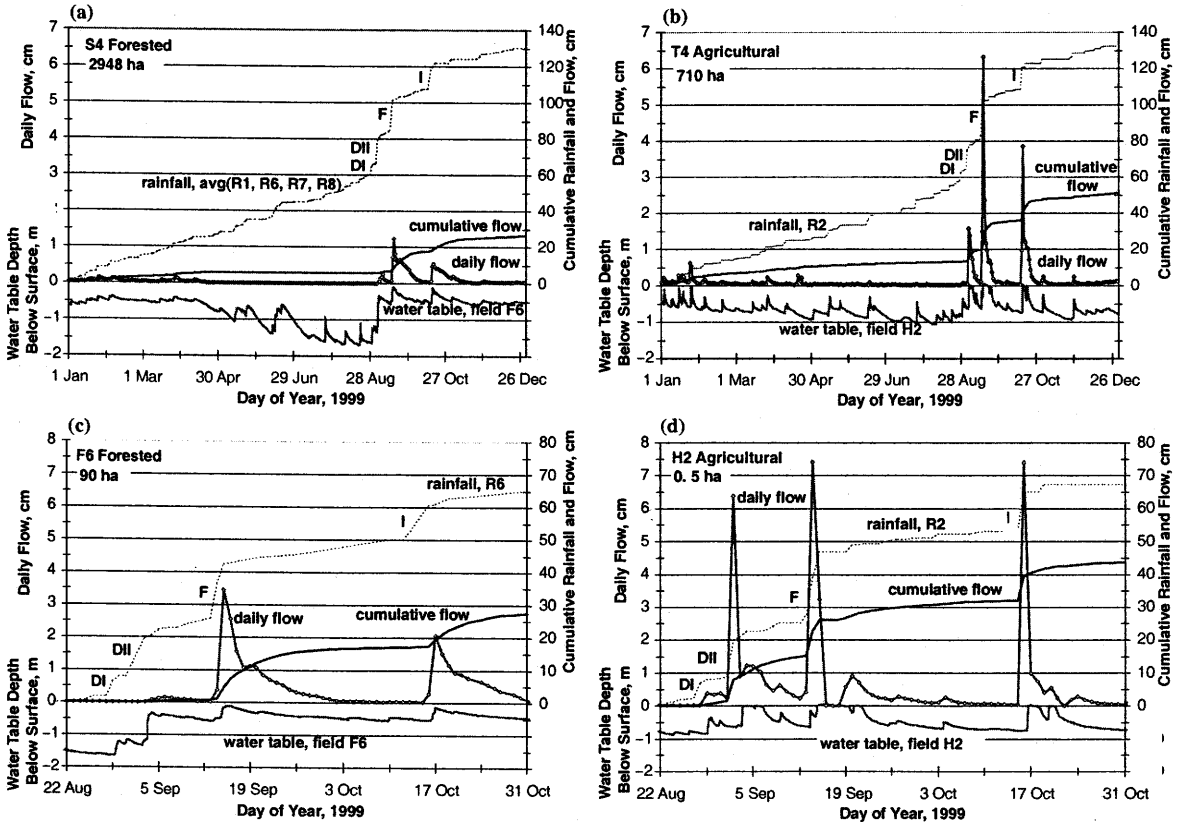

Figure 3. Daily flow, cumulative flow, cumulative rainfall, and water table response for subwatersheds (a) S4 and (b) T4 for 1999, and (c) F6 and (d) H2 for the storm period of 1999. DI = hurricane Dennis (first pass), DII = hurricane/tropical storm Dennis (second pass), F = hurricane Floyd, and I = hurricane Irene.

were derived by dividing the total nutrient or TSS load for a selected time period by the total volume of flow for that time period. For instance, a flow-weighted concentration of TP was determined for 1999 by dividing the total TP load for the year by the total flow volume for the year.

Paired two-sample Student's t-test was used to determine whether mean monthly flow or mean monthly load values were distinct for S4 and T4 over the study period. The paired t-test was also used to determine if peak daily flow values were distinct for the 56 events where peaks occurred at both subwatershed outlets. This t-test does not assume that the variances of both populations are equal.

Results and Discussion

Rainfall

The measured annual rainfall averaged over the research watershed was 1303 mm for 1999. This annual rainfall amount was nearly the same as the long-term-mean annual rainfall of 1296 mm for Plymouth, North Carolina (1951-1999). The 4-year-mean annual rainfall (1996-1999) measured in the research watershed was approximately 1228 mm.

The distribution of rainfall in 1999 was exceptional even though the total rainfall for 1999 was near the long-term-mean annual rainfall (fig. 3). The beginning of 1999 was dry. Total rainfall measured throughout the research watershed for February through August 1999 was 565 mm. This was the third lowest amount observed for this time period in the 49-year weather record (1951-1999) for Plymouth, North Carolina, following 1985 (509 mm) and 1993 (511 mm).

The dry period was followed by several large rainfall events. The first pass of hurricane Dennis produced 60 mm of rainfall in the research watershed (29 Aug. to 1 Sept.), the second pass of hurricane Dennis contributed 162 mm of rainfall (3-7 Sept.), hurricane Floyd produced 185 mm of rainfall (14-16 Sept.), and hurricane Irene added 109 mm of rainfall (17-18 Oct.). Together, the three hurricanes of 1999 contributed 516 mm of the 596 mm total rainfall in the research watershed from August 28 through October 18. The "wet period" (here defined as Sept. and Oct.) of 1999 was the wettest in the 49-year weather record for Plymouth, North Carolina (555 mm). The long-term-mean rainfall (1951-1998) for September and October is only 207 mm. The second greatest "wet period" was in 1996 (472 mm), which included hurricanes Bertha, Fran, and Josephine.

Water Table and Flow

Measured water table response, cumulative flow depth, daily flow depth, and cumulative rainfall are presented for stations S4, F6, T4, and H2. For the subwatershed stations (S4 and T4), data are presented for the entire year 1999, while for the respective fields (F6 and H2), data are for the hurricane period only (fig. 3). Flow values were computed on a per unit area basis. Rainfall data presented are from either the nearest gauge (fields) or an average of gauges (subwatersheds).

On 1 January 1999, the water table was 0.5 m or more below the surface in both the forested and agricultural areas. The water table dropped through the dry summer months at both locations. For example, the water table reached a maximum depth of 1.7 m below the surface in forested field F6 and 1.1 m below the surface in agricultural field H2 by the end of August. Rainfall from hurricane Dennis, starting 29 August, began to reduce the soil water deficit and raise the water table. The first pass of Dennis raised the water table in field H2 to within 0.3 m of the soil surface, but only to 1.2 m below the surface in field F6 (fig. 3). The water table reached the soil surface with the second pass of Dennis in field H2 and was raised to 0.3 m below the surface in field F6. Generally, flow was not measured from each field/subwatershed until the water table was within approximately 50 cm of the soil surface. Hurricanes Floyd and Irene brought the water table to the surface again in the agricultural field and near the surface in the forested field.

The agricultural subwatershed responded differently to the hurricane events compared to the forested subwatershed. Field F6 and the other fields within S4 have oxidized organic soils with a higher drainable porosity compared to field H2 and the other agricultural fields (Diggs, 2004; Burchell,

Table 1. Maximum daily flow rate and total flow for each storm period compared to average rainfall in the research watershed (average of R1, R2, R5, R6, R7, and R8).

		Station			
Storm Event and Rainfall	Storm-Related Flow	S4, Forest (2948 ha)	Field F6, Forest (90 ha)	T4, Agriculture (710 ha)	Field H2, Agriculture (0.5 ha)
Hurricane Dennis	Day of maximum flow:	No flow	No flow	31 Aug.	30 Aug.
Rain days: 29 Aug. - 1 Sept.	Max. daily flow (mm/day):	--	--	1	4
Rain: 60 mm	Flow period:	29 Aug. - 2 Sept.	29 Aug. - 2 Sept.	29 Aug. - 2 Sept.	29 Aug. - 2 Sept.
	Total flow in period (mm):	0	0	3	14
Hurricane/tropical storm Dennis	Day of maximum flow:	8 Sept.	7 Sept.	4 Sept.	3 Sept.
Rain days: 3-7 Sept.	Max. daily flow (mm/day):	3	2	16	64
Rain: 162 mm	Flow period:	3-13 Sept.	3-13 Sept.	3-13 Sept.	3-13 Sept.
	Total flow in period (mm):	11	8	59	135
Hurricane Floyd	Day of maximum flow:	17 Sept.	16 Sept.	16 Sept.	15 Sept.
Rain days: 14-16 Sept.	Max. daily flow (mm/day):	12	35	63	74
Rain: 185 mm	Flow period:	14 Sept. - 16 Oct.	14 Sept. - 16 Oct.	14 Sept. - 16 Oct.	14 Sept. - 16 Oct.
	Total flow in period (mm):	109	164	164	171
Hurricane Irene	Day of maximum flow:	19 Oct.	18 Oct.	18 Oct.	17 Oct.
Rain days: 17-18 Oct.	Max. daily flow (mm/day):	5	21	39	74
Rain: 109 mm	Flow period:	17 Oct. - 3 Nov	17 Oct. - 3 Nov	17 Oct. - 1 Nov	17 Oct. - 1 Nov
	Total flow in period (mm):	57	102	113	115

2003). Due to higher drainable porosity, the organic soils require a greater amount of rainfall to fill soil pores, resulting in a smaller water table response to a given amount of rain (fig. 3). The water table in the forested area is also affected by the deeper rooting depths and higher evapotranspiration (ET) of the trees compared to agricultural row crops (Holmes and Wronski, 1981). This is reflected in the deeper maximum water table depth observed in 1999 in S4 (1.7 m) compared to T4 (1.1 m). The deeper water table and higher drainable porosity of soils in the forested subwatershed resulted in the water table remaining below the surface during both passes of hurricane Dennis, and consequently much less flow occurred from the forested subwatershed than from the predominantly agricultural subwatershed due to this storm (table 1).

The rainfall brought by hurricane Floyd raised the water table to the surface in T4 and very near the soil surface in S4 (fig. 3), causing flow from both sites. Fields in the agricultural subwatershed have little surface storage (5 to 10 mm) compared to the forested fields (100 to 150 mm). Thus, continued rainfall associated with Floyd produced mostly surface runoff in the agricultural areas, while most of the flow from the forested site was subsurface drainage. Consequently, maximum daily flows from each of the three hurricanes were greatest in the agricultural subwatershed (table 1). For hurricane Floyd, maximum daily flow measured from the agricultural field (H2) was 74 mm; the agricultural subwatershed (T4) had a maximum daily flow of 63 mm. For the same storm, maximum daily flows measured were 35 mm from the forested field (F6) and 12 mm from the forested subwatershed (S4).

Daily flow rates measured in subwatersheds S4 (forest) and T4 (agriculture) resulting from the hurricanes and tropical storms of 1999 were compared to other noteworthy events measured in the research watershed (fig. 4). The daily flow rates associated with hurricane Floyd precipitation were greater from both S4 and T4 than for other major events measured during the 4-year study. This maximum daily flow value measured from the forested subwatershed (S4) was only about 20% of that occurring from the agricultural subwatershed (T4).

The peak daily flow rate from Floyd was measured at S4 on 17 September, while the peak daily flow rate from T4 was measured a day earlier on 16 September (table 1). The flow hydrograph for a given storm event is attenuated at S4, since the S4 drainage area is large and surface storage is high compared to T4. High flow rates at S4, however, are maintained for a longer duration than at T4. Lower soil drainable porosity, or volume for water storage, causes the water table to fluctuate more rapidly in the T4 subwatershed than in the S4 subwatershed. This low storage volume in the soil coupled with low storage on the soil surface contributes to the quick response seen in measured flows from T4 for a given rainfall event. Flow peaks measured at T4 (agricultural) were significantly higher (T4 mean = 8.6 mm/day, S4 mean = 2.7 mm/day, $t = 4.7$, $p < 0.0001$, $df = 55$) than those measured at S4 (forested) for the 56 flow events where flow peaks occurred at both subwatershed outlets during the 4-year study.

Another way to view the magnitude of various events measured during the study is through a probability distribution of the daily flows measured in each subwatershed from 1996 through 1999 (fig. 5). The largest daily flow value measured from each subwatershed resulted from precipitation associated with hurricane Floyd; however, rankings of the daily flow rates from different storms were not the same for the two subwatersheds. Daily flow rates from S4 were ranked with the highest values for hurricane Floyd, followed by Josephine, El Niño, Irene, and Dennis, while daily flow rates from T4 were ranked with the highest values for hurricane Floyd, followed by Irene, El Niño, Josephine, and Dennis.

The differences between the storm rankings of the two subwatersheds is likely due to differences in storage in the soil profiles and on the soil surface. The greater storage potential on the S4 subwatershed causes outflow from storm events to be affected by dry antecedent conditions. For example, peak daily flow from hurricane Dennis was just barely in the top 10% of daily flow rates at S4, while the peak flow from Dennis was nearly in the top 1% of daily flow rates at T4. Recall that hurricane Dennis was preceded by a long dry period that caused a greater soil water deficit in the cured organic soils on S4 than in the mineral soils on T4.

To compare subwatersheds S4 (forest) and T4 (agriculture), a cumulative plot for 1999 flow depth was produced (fig. 6). Each subwatershed received approximately 130 cm of rainfall in 1999. Additionally, some fields in T4 received an unknown amount of irrigation. Measured drainage for

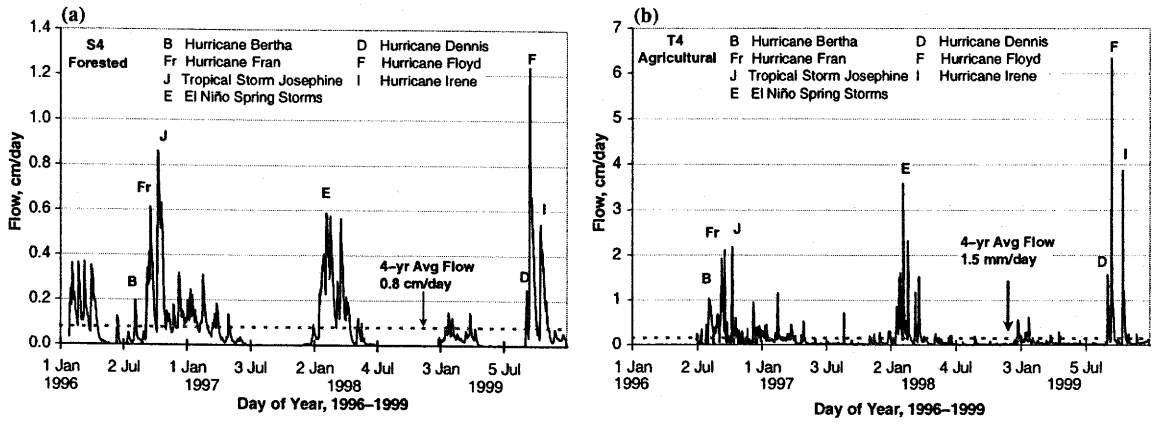

Figure 4. Daily flow at stations (a) S4 and (b) T4 for 1996-1999. Peaks of large events are labeled, and average daily flow is included (T4 data were not measured from 1 Jan. to 28 June 1996).

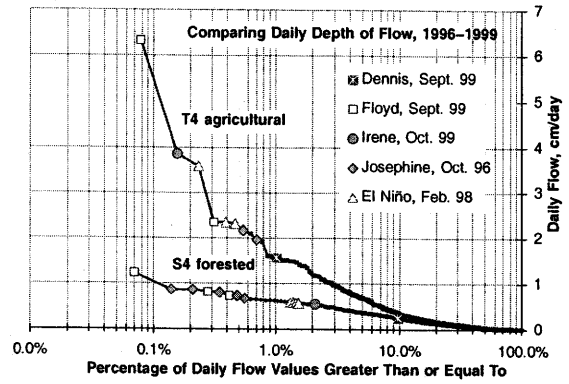

Figure 5. Comparison of probability distribution of daily flows measured at T4 and S4 for the study period, 1996-1999.

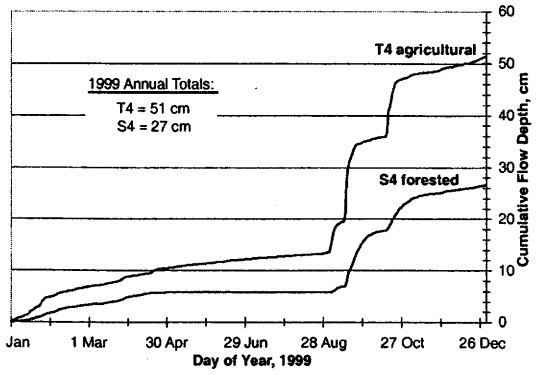

Figure 6. Comparison of cumulative daily flow from subwatersheds T4 and S4 for 1999.

1999 from T4 was nearly twice that of S4 (51.3 cm vs. 26.6 cm). Over the 1996-1999 study period, monthly flow values were significantly higher for the T4 subwatershed than for the S4 subwatershed (T4 mean = 4.68 cm, S4 mean = 2.36 cm, $t = 4.4$, $p < 0.0001$, $df = 41$). The difference in outflow volumes is likely due to higher ET rates from the forested subwatershed. Forest vegetation is continuous through the year and has deeper rooting depths compared to annual agricultural crops (Holmes and Wronski, 1981). In addition, the soils on the forested subwatershed have higher drainable porosity; therefore, the water storage volume that is available for ET is greater in the forested area.

Nutrient and Total Suspended Solids Transport

A comparison of nutrient loads indicates that the magnitude of nutrient export for 1999 was similar to average annual losses measured in the study, but most of the exports for 1999 occurred in a short, 2-month period (table 2). Measured data are presented (tables 2 and 3) for TP, OP-P, TKN, NH_4-N, NO_3-N, and total suspended solids (TSS). Data for organic nitrogen (ON = TKN – NH_4), total nitrogen (TN = TKN + NO_3), and dissolved inorganic nitrogen (DIN = NO_3 + NH_4) were calculated and are included in the tables.

Total annual nitrogen (N) load from T4 was 18 kg/ha in 1999, compared to the 4-year-mean annual load of 15 kg/ha. An 11 kg/ha export was measured during September and October 1999 from T4. Total annual N load from S4 was 15 kg/ha in 1999, compared to the 4-year-mean annual load of 16 kg/ha. A 10 kg/ha export was measured during September and October 1999 from S4. Over the 1996-1999 study period, monthly TN loads were not significantly higher for the T4 subwatershed than for the S4 subwatershed (T4 mean = 1.45 kg/ha, S4 mean = 1.24 kg/ha, $t = 0.9$, $p < 0.1737$, $df = 41$)

Nitrogen export from subwatershed S4 is consistently higher than loads from other forested sites in North Carolina (Chescheir et al., 2003). This high N export is presumably due to oxidation of the organic soils on the site (Diggs, 2004). Chescheir et al. (2003) reported that annual TN exports from 75% of 13 forested study sites on the North Carolina coastal plain were less than 6.5 kg/ha, with annual DIN exports less than 2.9 kg/ha and ON exports less than 4.0 kg/ha.

Total annual phosphorus load from T4 was 0.9 kg/ha in 1999, the same as the 4-year-mean annual load. Total annual phosphorus load from S4 was 0.08 kg/ha in 1999, the same as the 4-year-mean annual load. Exports of 0.7 and 0.06 kg/ha

Table 2. Average annual nutrient and total suspended solids export per unit area (kg/ha) for subwatersheds S4 and T4 compared to 1999 exports.

	TP	OP	TKN	NH_4	NO_3	TSS	TN	ON	DIN
Forested subwatershed S4 (2948 ha)									
4-year annual mean	0.08	0.02	7.5	1.0	8.2	68.3	15.7	6.5	9.2
1999	0.08	0.02	7.5	0.8	7.3	53.6	14.8	6.7	8.1
Sept. - Oct. 1999	0.06	0.01	5.2	0.6	5.2	27.3	10.4	4.6	5.8
Agricultural subwatershed T4 (710 ha)									
4-year annual mean	0.9	0.3	5.6	0.3	9.5	252.0	15.1	5.3	9.8
1999	0.9	0.5	5.6	0.1	12.1	152.5	17.7	5.5	12.2
Sept. - Oct. 1999	0.7	0.4	3.4	0.02	7.5	79.2	10.9	3.4	7.5

Table 3. Study nutrient and total suspended solids export as flow-weighted concentrations (mg/L) for subwatersheds S4 and T4, compared to 1999 export concentrations.

	TP	OP	TKN	NH_4	NO_3	TSS	TN	ON	DIN
Forested subwatershed S4 (2948 ha)									
Total study (1996-1999)	0.03	0.01	2.6	0.3	2.8	23.7	5.4	2.3	3.2
1999	0.03	0.01	2.8	0.3	2.7	20.2	5.6	2.5	3.1
Sept. - Oct. 1999	0.04	0.01	3.0	0.4	3.0	15.9	6.1	2.7	3.4
Agricultural subwatershed T4 (710 ha)									
Total study (1996-1999)	0.2	0.1	1.1	0.1	2.0	51.4	3.1	1.1	2.0
1999	0.2	0.1	1.1	0.01	2.4	29.7	3.4	1.1	2.4
Sept. - Oct. 1999	0.2	0.1	1.0	0.01	2.2	23.5	3.2	1.0	2.2

were measured during September and October 1999 from T4 and S4, respectively. Over the 1996-1999 study period, monthly TP loads were significantly higher for the T4 subwatershed than for the S4 subwatershed (T4 mean = 0.094 kg/ha, S4 mean = 0.019 kg/ha, $t = 4.7$, $p < 0.0001$, $df = 55$). Higher levels of TP and OP measured in the T4 subwatershed were attributed to fertilizer use and the land-application of swine lagoon effluent, as well as higher surface runoff from agricultural land with good surface drainage.

Total annual TSS load from T4 was 153 kg/ha in 1999, compared to the 4-year-mean annual load of 252 kg/ha. A 79 kg/ha export was measured during September and October 1999 from T4. Total annual TSS exported from S4 was 54 kg/ha in 1999, compared to the 4-year-mean annual load of 68 kg/ha. A 27 kg/ha export was measured during September and October 1999 from S4. The 1999 TSS load was lower than the 4-year-mean annual TSS load for both subwatersheds. In both subwatersheds, the 4-year-mean annual TSS load was elevated by the 1996 load. Total annual TSS loads in 1996 from T4 and S4 were 427 and 113 kg/ha, respectively. The hurricanes that occurred in 1996 (Bertha, Fran, Josephine) occurred somewhat earlier in the growing season than the hurricanes of 1999. However, in 1999, drought conditions were present during the early and middle parts of the growing season, the time when the majority of sediment losses typically occur from agricultural land. Over the 1996-1999 study period, monthly TSS loads were significantly higher for the T4 subwatershed than for the S4 subwatershed (T4 mean = 24.0 kg/ha, S4 mean = 5.8 kg/ha, $t = 3.6$, $p < 0.0004$, $df = 41$).

On an annual basis and over a large land area, the year of the hurricanes (1999) did not produce larger than average nutrient and TSS losses. This is not to suggest, however, that on a shorter time scale hurricane-size storms have no greater impact than smaller storm events. The amount of nutrients lost during the hurricanes of 1999 was nearly as high as total losses for an average year. Half of the TSS lost during 1999 was during the 2-month hurricane period.

Table 3 presents the overall flow-weighted concentration of nutrient or TSS for each subwatershed for 1999, September and October 1999 (hurricanes Dennis, Floyd, and Irene), and for the overall study. This value gives a convenient estimate of the average nutrient loss per flow volume for these forested and agricultural subwatersheds.

Overall flow-weighted concentrations of N observed from subwatershed T4 during the study were 3.1 mg/L for TN, 1.1 mg/L for ON, 2.0 mg/L for NO_3-N, and 0.1 mg/L for NH_4-N. Overall flow-weighted concentrations of N observed from subwatershed S4 during the study were 5.4 mg/L for TN, 2.3 mg/L for ON, 2.8 mg/L for NO_3-N, and 0.3 mg/L for NH_4-N. Nitrogen concentrations observed in drainage water from subwatershed S4 and field F6 were abnormally high compared to those observed in other water quality studies of forested lands in North Carolina, where TN concentrations were typically less than 1.8 mg/L (Chescheir et al., 2003). The high concentrations of N in waters from S4 and field F6 are likely due to the organic soils present and the high hydraulic conductivities of those soils. Organic nitrogen is likely converted to soluble NO_3 by mineralization and nitrification during dry conditions and is subsequently flushed from the soil in subsurface drainage resulting from rainfall events (Diggs, 2004).

To illustrate the magnitude of the daily loads produced by the storms of 1999 compared to other events on record, TN and TP load probability distributions were produced (fig. 7) for subwatersheds S4 and T4. Some significant events are highlighted on the figures with unique markers, as indicated in the legend. Recall the daily flow probability plot for these two stations (fig. 5). For S4, the highest daily flow was noted for hurricane Floyd, followed by tropical storm Josephine. For T4, the highest daily flow was noted for hurricane Floyd, followed by hurricane Irene, and then for the El Niño storms.

Differences in daily loading rates between the two subwatersheds increased as the loading events became greater. That is, the daily loading rates from the agricultural subwatershed (T4) became proportionally greater than the loading rates from the forested subwatershed (S4) as the event size increased. Values for daily TN loading rates were very similar between the two subwatersheds for the lower 98% of the daily TN loads. For the top 1% of the daily TN loads, values for daily TN loading rates were greater from the T4 subwatershed than from the S4 subwatershed until the daily TN load at T4 was more than 2 times greater than at S4 for hurricane Floyd. Differences between the TP daily loading rate values for the two subwatersheds were evident for the top 30% of the daily TP loads. Daily TP loading from the T4 subwatershed became proportionally greater than daily loading from the S4 subwatershed until the TP load at T4 was more than 30 times greater than the TP load at S4 for hurricane Floyd.

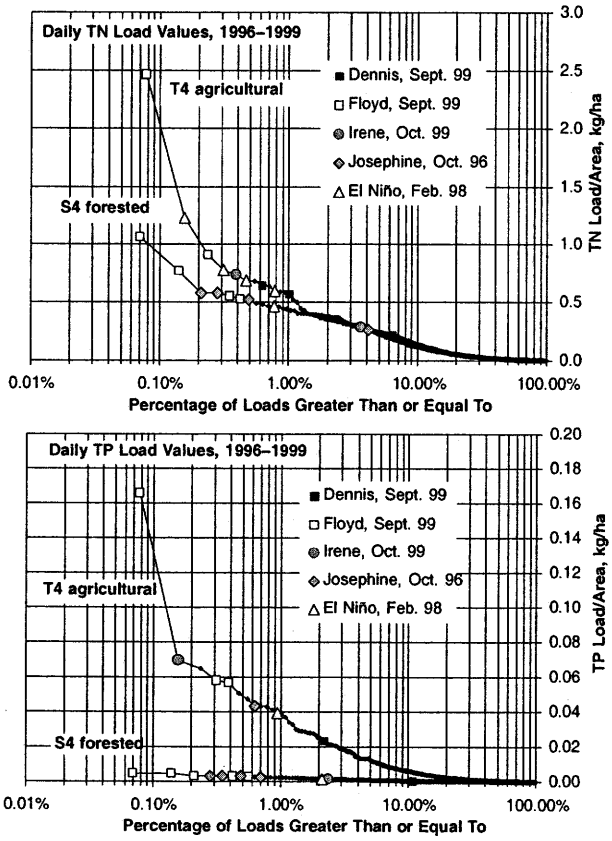

Figure 7. (a) Total nitrogen and (b) total phosphorus probability of load exceedance over years 1996-1999 for subwatersheds T4 and S4.

Comparing daily flow and daily load probability data, it is evident that not all peak loads occurred during the greatest storm events. For S4, TN and TP load rates followed the same ranking as observed for daily flow rates, with the highest values for hurricane Floyd, followed by Josephine, El Niño, Irene, and Dennis. For T4, the highest daily TN load was attributed to hurricane Floyd, followed by the El Niño storms, but daily flow associated with hurricane Irene was greater than daily flow associated with the El Niño storms (figs. 5 and 7). The El Niño storms ranked lower for daily TP load from T4, with the highest daily TP load occurring in response to hurricane Floyd, followed by Irene, Josephine, El Niño, and Dennis.

Hurricane Floyd produced the greatest daily TSS load in both T4 and S4 (fig. not included; see Shelby, 2002). Although hurricanes Floyd and Josephine produced the highest measured daily flows in S4, the two highest TSS daily loads were associated with hurricane Floyd and the El Niño storms (Shelby, 2002). Likewise, hurricanes Floyd and Irene produced the highest measured daily flows in T4, but the highest TSS daily loads were associated with hurricanes Floyd and Josephine (Shelby, 2002). This illustrates the importance of a storm's timing with regard to the nutrient and TSS loads it will produce. Each watershed, and even each contaminant, appears to be sensitive to different types of storm events.

Summary and Conclusions

A variety of data, including precipitation, water table fluctuation, outflow, and nutrient and TSS export, were collected from a research watershed from 1996 through 1999. A case study presentation was utilized to note the differences in hydrologic and water quality response of two subwatersheds in 1996-1998 compared to 1999, when hurricanes Dennis, Floyd, and Irene affected the area.

The year 1999 was one of extremes: a very dry late winter, spring, and summer followed by an unprecedented series of hurricanes/tropical storms that produced record amounts of rainfall. The period from February through August 1999 was the third driest such period in 49 years of record. Then, the research watershed received approximately 555 mm of rainfall during September and October 1999, the wettest such period in 49 years of record.

The hurricanes and related storms of 1999 produced record flow and nutrient loads throughout the research watershed. Daily flow rates measured across the research watershed were greater during hurricane Floyd than for any other time in the four-year study period. Total annual flows from the agricultural and forested subwatersheds in 1999 were similar to average annual flows for the three previous years, but flows in 1999 were concentrated in the months of September and October. Of the 1999 annual flow, 64% and 66% occurred in the months of September and October for the forested and agricultural subwatersheds, respectively.

Each subwatershed had a unique hydrologic response to the hurricanes of 1999. Daily flows observed for the agricultural subwatershed were generally greater than for the forested subwatershed throughout the study and during the hurricanes of 1999. The forested subwatershed (S4) has mostly organic soils with a large amount of drainable pore space and deeper rooting depths that resulted in greater storage in the profile at the end of the dry period, compared to the mineral soils of the agricultural subwatershed (T4). The forested subwatershed has a larger reservoir (soil pores) to fill before outflow occurs, compared to the agricultural subwatershed.

The magnitude of nutrient export for 1999 was similar to average annual losses measured in the study, but again most of the exports for 1999 occurred in a short, 2-month period. Approximately 60% to 70% of annual TN and TP load for 1999 was lost in September and October during large storm events. Total annual nitrogen export from the predominately agricultural subwatershed (T4) was 18 kg/ha in 1999, with 11 kg/ha lost during September and October. Total annual nitrogen export from the forested subwatershed (S4) was 15 kg/ha in 1999, with 10 kg/ha lost during September and October.

The forested subwatershed in this study exported nearly as much nitrogen as the predominately agricultural subwatershed. The nitrogen export observed from the mostly organic soils on the forested subwatershed was high compared to other studies of drained forest soils in the region. The high export of N from the forested subwatershed (S4) is likely due to the organic soils present and the high hydraulic conductivities of those soils. Organic nitrogen is likely converted to soluble NO_3 by mineralization and nitrification during dry conditions and is subsequently flushed from the soil in subsurface drainage resulting from rainfall events.

Hurricanes and floods occur with some regularity in North Carolina, but the effects are infrequently documented. The data presented here will contribute to greater understanding of how watersheds respond to these events. This study confirms that the majority of flow and nutrient/TSS export from a watershed can occur primarily through storm events. But each watershed has a unique response to storm events due to the characteristic of the watershed, such as land use, size, and soil properties.

Acknowledgement Section

The work reported herein is a product of the North Carolina Agricultural Research Service, North Carolina State University, Raleigh, N.C. This study was supported by grants from USDA CSREES NRI program (Projects # 94–34214–1137 and 98–35102–6493), the U.S. EPA 319 Grant Program. The authors would like to acknowledge in kind support of Weyerhaeuser Company and the efforts of Joe Hughes, Martin Lebo, Sandra McCandless, Joe Bergman, and Cliff Tyson. Also acknowledged are the contributions of Wilson Huntley and Jay Frick of the Department of Biological and Agricultural Engineering, and J. Wendell Gilliam and Bertha Crabtree of the Department of Soil Science at North Carolina State University.

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