Abstract

Shelby, Jennifer Duvall. Evaluation of Hydrology and Water Quality in a Large Watershed in North Carolina's Lower Coastal Plain Following the Hurricanes and Related Storms of 1999. (under the direction of Dr. R. W. Skaggs and Dr. G. M. Chescheir)

Quantifying and recording the impacts of large storm events is important to watershed management. Large concentrations of nutrients and pollutants may be lost from a watershed in runoff during these events.

This project documents the hydrologic and water quality response of a lower coastal plain watershed to the weather events of 1999 compared to 1996 through 1998. The watershed, which includes agriculture, natural forest, and managed forest, was instrumented to measure water quantity, water quality, and weather. Data was collected from 3 subwatersheds.

In 1999 the watershed received approximately 555 mm of rainfall during September and October associated with hurricanes, the wettest such period in 49 years. Prior to the hurricanes, the watershed experienced a dry spring and summer (565 cm for Feb.-Aug.). The period from February through August of 1999 was the third driest such period in 49 years.

The forested subwatershed (S4) has mostly organic soils with a large amount of drainable pore space, compared to the mineral soils of the agricultural subwatershed (T4). These pores were filled by the first hurricane (Dennis), which effectively made two passes over the watershed. During the first occurrence of hurricane Dennis, the forested subwatershed produced no flow, the agricultural watershed produced 2.9 mm of flow, and the mixed-use watershed (C2) produced 2.4 mm of flow. With the second pass of

Dennis, the pores of forested soils were filled and 10.8 mm of flow occurred. In the agricultural subwatershed and the mixed-use subwatershed five to six times more flow occurred (59.1 mm and 64.5 mm, respectively). For hurricane Floyd, the flow response was similar for all subwatersheds since the soils were saturated (108.9 mm from S4, 164.2 mm from T4, and 163.3 from C2).

Daily flow rates measured across the research watershed were greater during hurricane Floyd than for any other time in the four-year study. Daily flows observed for the agricultural subwatershed were generally greater than for the forested subwatershed or for the mixed-use subwatershed throughout the study, and during the hurricanes of 1999. Total annual flow from the agricultural and forested subwatersheds in 1999 was similar to average annual flow for the three previous years, but that flow was concentrated in the months of September and October. Sixty-four and 66 percent of the 1999 annual flow occurred in the months of September and October for the forested and agricultural subwatersheds respectively.

Daily sediment and nutrient loads measured across the research watershed were greater during hurricane Floyd than for any other time in the four-year. In general, the two month period of hurricanes (1999) produced TN and TP loads comparable to loads for an entire year.

Total annual nitrogen load from an agricultural subwatershed was 18 kg/ha in 1999, compared to the 4-year annual average load of 15 kg/ha. Total annual nitrogen load from a forested subwatershed was 15 kg/ha in 1999, compared to the 4-year annual average load of 16 kg/ha. The nitrogen export observed in the forested subwatershed was high compared to other studies, likely due to the organic soils. Total annual phosphorus load from an agricultural subwatershed was 0.9 kg/ha in 1999, the same as the 4-year annual average load. Total annual phosphorus load from a forested subwatershed was 0.1 kg/ha in 1999, the same as the 4-year annual average load.

An agricultural area receiving swine lagoon effluent produced on average 44 kg/ha of TN, 30 kg/ha NO_3, and 2 kg/ha TP. In 1999 the annual export was 106 kg/ha of TN, 73 kg/ha NO_3, and 3 kg/ha TP.

Evaluation of Hydrology and Water Quality in a Large Watershed in North Carolina's Lower Coastal Plain Following the Hurricanes and Related Storms of 1999

By

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Biography

Jennifer Lynn Duvall Shelby was born August 12, 1976 in Greenville, Kentucky to James and Wanda Duvall. She has one brother, Craig Duvall. She grew up in Greenville and graduated from Muhlenberg South High School in 1994. After high school, Jennifer attended the University of Kentucky in Lexington, Kentucky. She graduated cum laude in December of 1998 with a Bachelor of Science degree in Agricultural Engineering. Her BS degree was completed with emphasis on hydrology and environmental sciences- she was awarded an Environmental Certificate by the UK College of Engineering.

In January of 1999, immediately following graduation from UK, Jennifer began pursuing a Master of Science degree in Biological and Agricultural Engineering at North Carolina State University, in Raleigh, North Carolina. In June 1999 she married her husband Brad Shelby, also of Greenville, Kentucky. After fulfilling coursework, teaching, and research requirements, Jennifer completed her MS degree under the supervision of Dr. Wayne Skaggs and Dr. George "Chip" Chescheir in May 2002.

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Background

In North Carolina and other humid regions, annual precipitation is greater than annual evapotranspiration; therefore, runoff can be expected from land surfaces for at least some storm events. The quantity of surface runoff depends on many factors, including landuse, storm size and intensity, soil type, and slope. Likewise, the quality of runoff water depends on many factors, but inevitably runoff carries sediment, nutrients, and other chemicals with it into surface waters. Sediment and sediment-bound phosphorus are common polluters of surface water.

Another pathway for excess water to leave the landscape is via subsurface drainage, or seepage of excess water through the soil profile. Depending on site and soil conditions, subsurface drainage can be the lateral flow of water through soil or drain tubes to ditches or streams (return to surface water). Subsurface drainage can also be the downward movement of water into groundwater supplies. Either way, any soluble chemicals in the soil could move with the seepage and contaminant important water resources. For example, the nitrate (NO_3-N) form of nitrogen (N) is highly soluble and can move easily with subsurface flow. In the relatively flat, poorly drained topography of North Carolina's coastal plains, subsurface drainage is often the primary path of NO_3-N outflow to surface water.

Excess water will ultimately move through the landscape into surface or groundwater supplies, thus it is important to minimize negative impacts on our water resources caused by chemicals/pollutants in runoff or seepage (nonpoint source pollution). Otherwise, our water resources will become impaired: eutrophication may occur, plants and animals may lose habitat, drinking water may be unsafe and require extra treatment, or recreational limitations may be imposed.

Also important in North Carolina and other coastal states is the preservation of estuarine water quality, which in part can be obtained by the continued effort to preserve stream water quality. North Carolina has enacted legislation to protect waterways, particularly with regard to nitrogen reduction. The Neuse and Tar-Pamlico river basins both drain to estuaries; these two basins have experienced increasing water quality problems due to development and agriculture. Of particular concern, is excess N transported to sensitive N-limited estuarine waters. To counteract degrading water quality associated with excess N in the Neuse and Pamlico rivers, total maximum daily load (TMDL) values are being used to regulate nutrient loads. The TMDL is allocated to sources throughout each river basin. As part of the TMDL scheme, the North Carolina Department of Environment and Natural Resources has mandated a 30 percent reduction of the nitrogen load to the Neuse and Pamlico Rivers (NCDENR, 2002). Current strategies to reduce nitrogen transport to waterways in these basins, and ultimately to the estuaries, include efforts by wastewater dischargers, developers, farmers, and fertilizer applicators. Some land is being taken out of agricultural production through conservation easements, and other farmers are utilizing treatment mechanisms, including controlled drainage, riparian buffers, and nutrient management. Further study is needed to determine what TMDL values should be, and how they should be allocated across a watershed in order to reduce nonpoint source pollution.

Pollutants

Healthy, productive waterways contain a balance of nutrients, but when drainage carries excess nutrients into waterways, the delicate balance may be disrupted. Thus, excessive amounts of common nutrients are considered aquatic pollutants.

Some nutrients move into waterways in dissolved form, while others are commonly soil-bound, transported with eroded sediment. Nitrate-nitrogen (NO_3-N) is a highly soluble nutrient transported by surface or sub-surface water flow to our waterways. Sources of such nitrogen include fertilized agricultural land, lawns, gardens, and golf courses; farm land where animal waste is applied; municipal water and waste water treatment facilities; and home septic systems. Most pollutants impacting our water resources originate from nonpoint sources, with agriculture being the largest contributor (Gilliam et al., 1997). In the North Carolina coastal plain, the transport of nitrate to streams via sub-surface drainage outlets is a concern; drained agricultural land has been noted as a significant source of nitrogen to surface waters (Gilliam et al., 1997).

High nitrogen concentrations can adversely impact aquatic systems. One problem associated with high nitrogen concentrations in marine waters (e.g. estuaries) is accelerated eutrophication, or excessive algal/vegetative growth. When the overgrowth of vegetation dies and begins to decompose, much of the aquatic system's dissolved oxygen (DO) is depleted, resulting in further degradation of the water quality and habitat. Eutrophication also diminishes the water’s aesthetic and recreational value, increases the cost of water treatment, and interferes with stream navigation (Thomann and Mueller, 1987).

Phosphorus, commonly transported along with sediment, is also an undesirable aquatic nutrient at high concentrations. Fine soil particles have the greatest potential for transporting nutrients. Clay particles transport a large proportion of the nutrients in runoff (Baker and Johnson, 1983). Clay particles naturally carry a negative charge and bind positively charged ions (NH_4^+, Ca^{+2}, K^+, Na^+). Ortho-Phosphate (e.g. $H_2PO_4^-$) is readily bound to iron and aluminum oxides (FeOOH or AlOH) in soils (Sparks, 1995). Though the greatest source of phosphorus in surface waters is soil-bound phosphorus associated with erosion, phosphorus can be transported in subsurface drainage. Deep sandy soils or soils with high organic matter can export phosphorus through leaching (Sims et al., 1998). Phosphorus is the limiting nutrient in freshwater bodies; excess phosphorus leads to eutrophication in these systems (Correll, 1998). Total phosphorus concentrations greater than 0.01 to 0.02 mg/L are considered levels at which eutrophication will occur in P-limited surface waters (Daniel et al., 1998)

Sediment in runoff from agriculture, mining, forestry, and construction is a threat to water quality. Some tillage practices utilized by farmers result in loose, disturbed, readily erodible soil. In the coastal plain of North Carolina, the land slope is small (< 2%), therefore erosion is not as great as in steeper terrain. In developing areas, construction sites, highway building, and other disturbed areas provide large sources for sediment. Though regulations requiring erosion control (e.g. sediment detention ponds, silt fences, ground cover) on construction sites are in place, developers often apply inadequate erosion control or the structures/efforts are ineffectively applied. Ultimately, where there is disturbed soil, some sediment can be expected to travel via runoff to surface waters, especially in sloping topography.

Sediment and sediment-bound pollutants (e.g. nutrients, pesticides) cause both physical and biological changes in surface waters. In fact, sediment is considered the greatest pollutant of rivers, streams, and lakes by volume in the United States (Knight et al., 1998; Schwab et al., 1996). Sediment accumulation affects streambed characteristics and water quality. Sedimentation can reduce the waterway trafficability, and eventually reduce the stream storage capacity (Schwab et al., 1996). Sedimentation negatively impacts fish and other aquatic organisms by limiting sunlight penetration, reducing visibility, and filling in pools where fish prefer to spawn and organisms live and/or breed (Knight et al., 1998).

To protect water resources, pollutants in addition to sediment and nutrients must also be considered. Land-applied animal waste, animal waste storage facilities (e.g. lagoons), or septic systems can be a source of unhealthy pathogens. Agricultural land can also be a source of pesticides. Commercial areas can be sources of heavy metals, oil, gasoline, and other inorganic pollutants. Each of these pollutants behaves uniquely in an environmental system and must be treated specifically. Attempts must be made to prevent nutrients, sediment, pesticides, pathogens, or other chemicals from being transported into aquatic ecosystems, and treatment mechanism must be utilized to protect water quality

Prevention and Treatment

Current pollution prevention and treatment mechanisms focus both on reducing polluted runoff and on treating polluted runoff. Proactive measures can be taken to minimize the amount of runoff produced on a site, the amount of pollutants contained in the runoff, or the amount of polluted runoff leaving the site. Also, measures can be taken to treat runoff or seepage as it moves through the landscape, before it reaches a water supply. The effectiveness of management practices and treatment mechanisms is highly dependent on the particular site conditions, so there is not a single solution that can be widely applied across the state or country to protect or enhance water quality. But, a variety of management practices and conservation techniques have been tested and proven to effectively improve water quality or prevent water pollution if utilized in the appropriate settings.

In the coastal plains of North Carolina, nutrient management, water table management (controlled drainage), and riparian buffers have been shown to reduce nitrogen and phosphorus concentrations in drainage outflow (Evans et al. 2000), Gilliam et al, 1997). No-till cropping is used successfully to reduce erosion. Government-imposed regulations aimed at maintaining clean water will continue to expand, thus implementation of tested, effective technologies for protecting and improving water resources is imperative.

Obviously, the protection of our water resources from nonpoint source pollution is a varied and important goal. The significance of this study lies in the need and ability to estimate pollutant sources and loads on a large watershed scale. Often, land uses in close proximity to sensitive water bodies have the greatest impact on the quality of those water bodies. Watershed-scale management of nutrient and sediment pollution requires the determination of the cumulative impacts of all land use regions and management practices within a large area. It is often difficult to determine the relative impact of each area on downstream water quality. This study focuses on the hydraulic and nutrient load passing through a large coastal plain watershed of varied land use. This study also investigates the impacts in the watershed due to a series of hurricanes/tropical storms. In order to maintain water quality in North Carolina and beyond, it is crucial to gather information that will lead to enhanced management and treatment of nonpoint source pollution.

Introduction

As population grows and development continues, planning will only become more critical to development and other land use activities on a watershed scale. By 1997 nearly half of all states had adopted watershed-level management schemes for addressing water quality problems (Pelley, 1997). A watershed scale program is a more effective and equitable approach to addressing water quality problems. By involving many stakeholders and considering a watershed's unique issues and impairments, a broader range of desired improvements can be achieved (Wagner et al., 1997, Galya et al., 1998). For water quality improvement practices to be effective, they must be implemented in appropriate positions throughout the watershed. For example, a constructed wetland can more effectively improve water quality if placed in close proximity to a riparian area. Ideally, best management practices (BMPs) would be placed in locations where they will result in the most water quality improvement for the least cost.

If a watershed is intensively monitored for several years and for a range of storm events (small vs. hurricanes), the data can be used to validate watershed scale hydrology and water quality models. These models can allow land planners to predict the cause and effect relationships between BMPs and their placement in the watershed. This research study compiles and analyzes data from a large, multi-use watershed in the lower coastal plain of North Carolina, near the town of Plymouth. Hydrology and water quality were monitored from 1996 through 1999. During the study period, data for a series of large, hurricane-related events was gathered. Large storms can have a significant effect on water quality; the largest nutrient and sediment loads can be lost from the watershed during a short time frame. This extensive data set provides insight into how a coastal plain watershed behaves under 'normal', as well as extreme conditions, and can serve as a tool for making watershed-scale management decisions.

Weather Conditions of 1999

The hurricanes of 1999, Dennis (Sept. 3-7), Floyd (Sept. 14-17), and Irene (Oct. 17-18) brought tremendous amounts of rainfall to North Carolina in a short, 6-week time period. Parts of the coastal plain saw rainfall in excess of 76 cm for September and October. Some North Carolina river basins east of Raleigh experienced unprecedented flooding following hurricane Floyd.

Hurricane Dennis began as a tropical storm in the Caribbean August 24, 1999. As Dennis moved toward the United States it gained hurricane status, and by August 30 Dennis neared the coast of North Carolina accompanied by heavy rainfall. Dennis was downgraded to a tropical storm September 1, but continued to linger near North Carolina's coast through September 3. Finally, Dennis made landfall in North Carolina on September 4 and ultimately dissipated (WRAL, 2000). Hurricane/tropical storm Dennis brought 10.2 to 23.0 cm of rainfall to eastern North Carolina, saturating very dry soils (Bales et al., 2000). Plymouth, North Carolina received 12.8 cm of rainfall from Hurricane Dennis (Sept. 3-7, 1999), as reported by the USGS (Bales et al., 2000). The average rainfall recorded in the research watershed (average from all rainfall stations) for the same period was 16.2 cm.

Before the damage from Hurricane Dennis could be fully tallied, Hurricane Floyd threatened North Carolina. On September 15, 1999 Hurricane Floyd made landfall near Wilmington, North Carolina (WRAL, 2000). This hurricane added additional rainfall to already saturated soils, generating a large volume of surface runoff and creating fatal flooding throughout much of eastern North Carolina. The USGS (Bales et al., 2000) measured 30.5 to 40.6 cm of rainfall during September 14-17, 1999 attributable to Hurricane Floyd in many locations. Near the research site, in Plymouth, the USGS (Bales et al., 2000) recorded 18.7 cm during this time. The average rainfall recorded in the research watershed for the same period was 18.5 cm.

During October 17-18, 1999, North Carolina received additional rainfall from yet another hurricane, Irene. This hurricane did not make landfall in North Carolina, but added rainfall (12.7 cm in many eastern areas of the state) to already indundated areas. The average rainfall recorded in the research watershed due to hurricane Irene was 10.9 cm. The combined effects of hurricanes Dennis, Floyd, and Irene produced elevated river levels (above flood stage) in two of the state's river basins (Tar, Neuse) for nearly 2 months.

Prior to the hurricane season, the entire state experienced a very dry spring and summer. According to the Palmer Drought Severity Index (based on precipitation, temperature, and available soil moisture), by August 28, 1999 all of eastern North Carolina was suffering from a moderate drought (NOAA, 1999). The year 1999 was one of extremes- very dry conditions were followed by large fall storms. This study compiles and examines an array of hydrology and water quality data from the10,000 ha research watershed throughout this unique period and compares the results to prior years on record (1996-1999). Analyzing this collection of data yields a special opportunity to examine the response of a large, multi-use watershed to extreme weather events.

Study Objectives

1. Compile a hydrologic and water quality record for several locations throughout a large coastal plain watershed for 1996-1999, with special emphasis on 1999.

2. Evaluate hydrologic response of the watershed to the hurricanes and related storms of 1999, compared to other years on record.

3. Evaluate hydrology differences due to land use.

4. Evaluate the water quality throughout the watershed related to the hurricanes and storms of 1999, compared to other years on record.

5. Evaluate water quality differences due to land use.

Research Site Description

The research watershed is located in the northeastern lower coastal plain of North Carolina (Figure 1). The site is in Washington county, near the town of Plymouth.

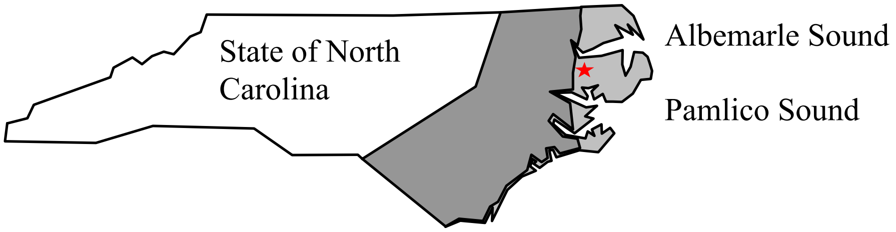

Figure 1. General location of research watershed, denoted by star; dark gray region indicates upper coastal plain and light gray region indicates lower coastal plain.

The primary land uses (Figure 2) in the watershed are typical for the region and include managed forest (52%, pine and mixed hardwood stands), unmanaged forested wetlands and riparian areas (11%), agriculture (36%), and development (~ 1%). Historically, agriculture and silvaculture have been the dominating economic enterprises in Washington County (SCS, 1981). But, the county also produces hogs, cattle, and broilers. Major crops grown in the area utilize artificial drainage and include corn, soybeans, cotton, peanuts, small grains, and some specialty crops (sage). Dominant pasture grasses include tall fescue, white clover, and rye. The commercial woodlands found in Washington County also incorporate enhanced drainage. Most commercial stands consist mainly of loblolly pine, a fast growing timber that is well adapted to the soils and climate of this area. Hardwoods native to this area include red and white oak, gum, hickory, yellow poplar, tupelo, and cypress, depending on the wetness of the soil.

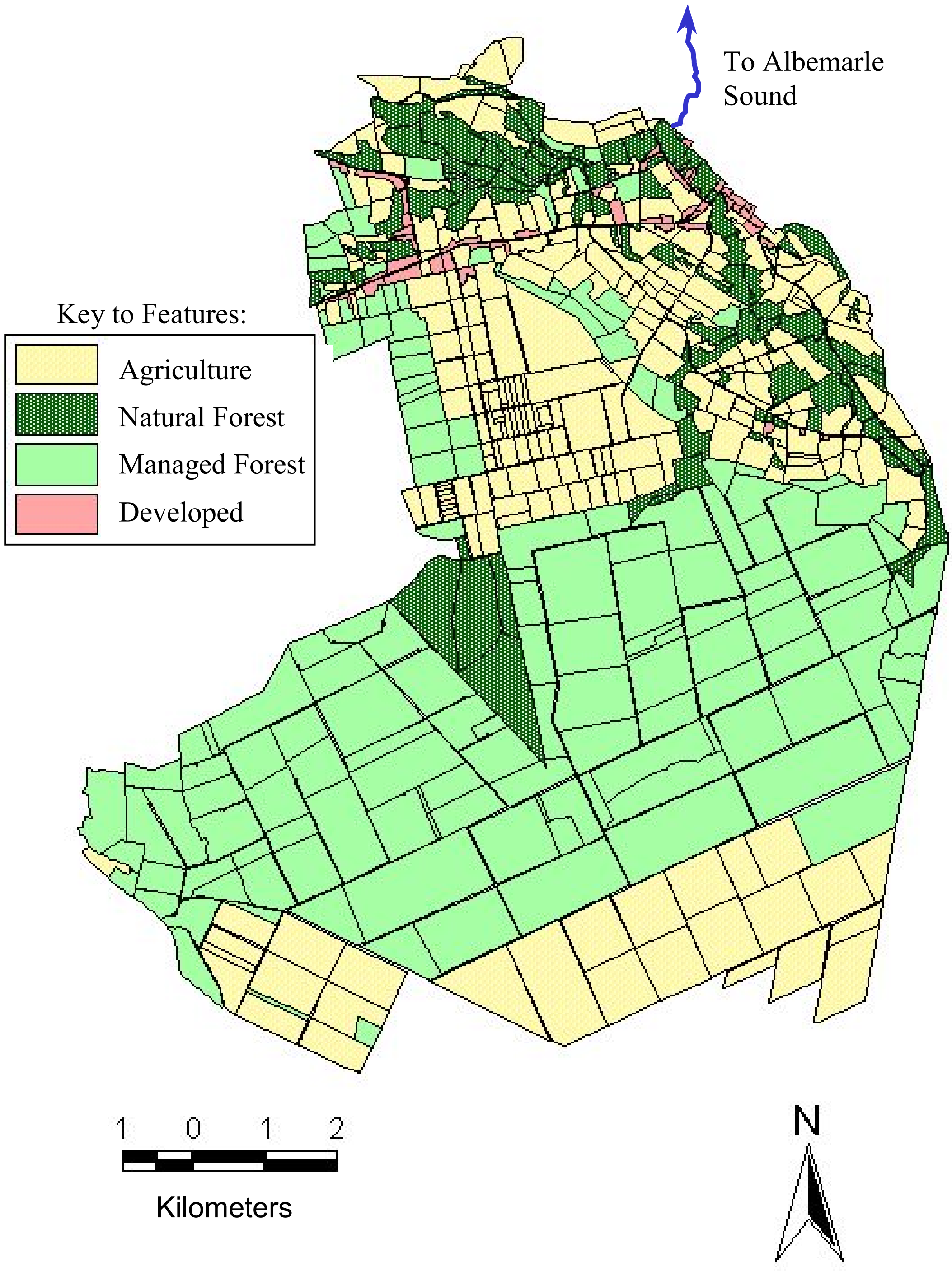

Figure 2. Boundaries of 10,000 ha research watershed; land uses indicated by color.

The research watershed is representative of the agricultural and silvacultural enterprises throughout Washington county. It is divided into subwatershed and field stations, and is heavily instrumented throughout (Figure 3). The watershed is approximately 10,000 ha and ultimately drains to Kendrick's Creek, 6 km upstream of the Albemarle Sound (Birgand, 1996a). The terrain is flat and the soils are generally very poorly drained. If left undrained, the seasonal high water table is at or near the soil surface; but when drained and properly managed these soils are suitable for cultivation. Drainage networks lower the water table to improve field trafficability and reduce stresses on crops caused by excessive soil water. Controlled drainage is used in some areas to hold water back in the drainage canals during drier summer months, providing moisture to growing crops. Controlled drainage can be used during winter months to reduce field nitrogen losses by creating a larger saturated soil zone and increasing the potential for denitrification. An extensive artificial drainage network of drain tubes (tiles), field ditches, and canals covers the research watershed, making it usable for agriculture crops, such as corn or soybeans, and tree plantations. Drainage ditches collect both surface and subsurface runoff, while drain tubes only collect subsurface drainage. Enhanced agricultural drainage channels water from fields into ditches and canals that lead to creeks and streams, and ultimately flow to the Albemarle Sound. Enhanced drainage can result in increased sediment and nutrient loads to the streams and sounds (Skaggs and Gilliam, 1981).

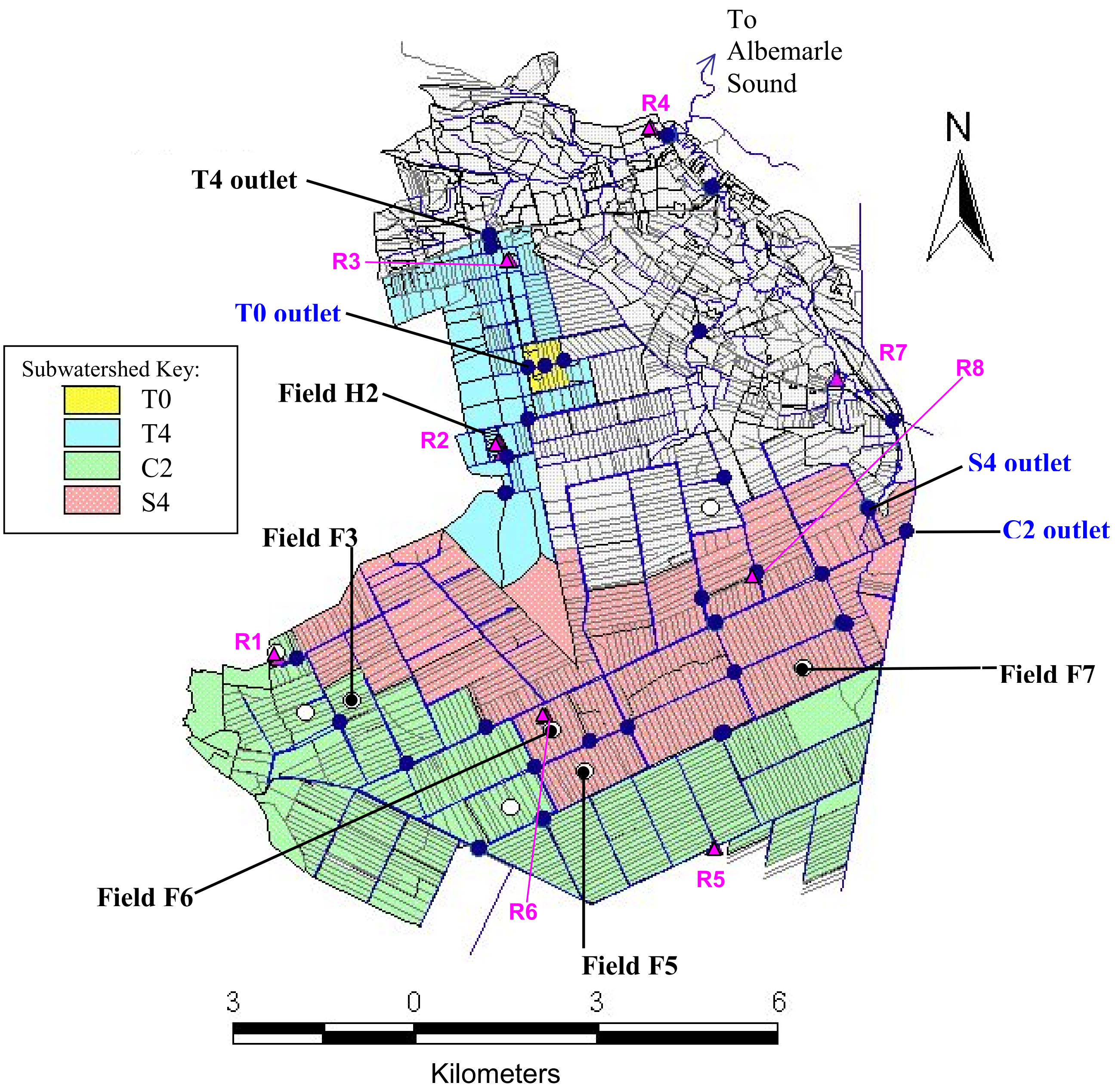

Figure 3. Diagram of research watershed with indicators for: subwatershed areas and outlets, monitored fields, and rainfall gauges.

The hydrology and water quality of three main subwatersheds within the research area, S4, T4, and C2 are analyzed and compared in this study.

Subwatershed S4

Subwatershed S4, approximately 2950 ha, is in the southern region of the research watershed (Figure 3). The primary land use in this subwatershed is loblolly pine (Pinus taeda) plantation, but unharvested, second growth, mixed hardwood stands are present as well. Stands range in age from 1 to 99 years (Weyerhaeuser, 1997). A 95 ha section of natural wetland is also present in the S4 subwatershed.

The dominant soil (approximately 60%) in the forested S4 subwatershed is Belhaven muck (loamy, mixed, dysic, thermic Terric Haplosaprists). The organic surface layer of this soil is typically black muck comprised of highly decomposed sapric material (~ 41 – 130 cm thick). This soil is very poorly drained under natural conditions. The underlying parent material is comprised of loamy marine and fluvial sediments, producing clay loam and loamy sand C horizons (Soil Survey Division, 2002). In this subwatershed, the plantation pine trees have “cured out” or “ripened” the soil and changed its chemical and water-holding properties. During dry periods this cured organic layer is oxidized and is a suitable environment for mineralization and subsequent nitrification of organic nitrogen. The drying of the organic material creates macropores that increase the drainable porosity and hydraulic conductivity of the soil.

Other soil series present in the S4 subwatershed are Cape Fear loam (Fine, mixed, semiactive, thermic Typic Umbraquults), Portsmouth fine sandy loam (Fine-loamy over sandy or sandy-skeletal, mixed, semiactive, thermic Typic Umbraquults), Wasda muck (Fine-loamy, mixed, semiactive, acid, thermic Histic Humaquepts), and Arapaho fine sandy loam(Coarse-loamy, mixed, semiactive, nonacid, thermic Typic Humaquepts) (SCS, 1981, Soil Survey Division, 2002). Generally, the mineral soils (Cape Fear, Portsmouth, Arapaho) dominate the western side of the S4 subwatershed and the organic soils (Belhaven, Wasda) dominate the eastern side.

The S4 subwatershed contains an extensive open-ditch drainage network. Nearly the entire subwatershed is artificially drained using a series of lateral field ditches, which drain to main or collector canals, and ultimately flow to the watershed outlet. Most field ditches are 60 to 120 cm deep and are spaced approximately 80 to 100 m apart. The depth of the collector canals ranges from 180 to 250 cm and the main canals are generally 180 to 300 cm deep (Birgand, 1996b). The S4 watershed outlet consists of a 2.1 m (diameter) corrugated metal pipe (CMP) culvert with a riser structure. The riser structure is equipped with two, V-notch weirs, which were instrumented to continuously measure flow rates and sample for water quality.

Data was also collected for three fields within the S4 subwatershed in this study, field stations F5, F6, and F7 (Figure 3).

Subwatershed T4

Subwatershed T4, 710 ha, is dominated by agriculture (Figure 3). Approximately 390 ha within this subwatershed are intensively farmed; crops such as corn and soybeans are grown utilizing an extensive system of tile and ditch drainage. The remaining area within this subwatershed is forested, natural wetland, or harvested forest. Generally, in this thesis the T4 watershed will be referred to as an "agricultural subwatershed". There is also an operating swine unit within this subwatershed, as well as a region of pasture land upon which liquid swine lagoon waste is surface applied. The area that includes this pasture comprises a station known as T0, which is also analyzed in this study.

The T4 watershed utilizes tile drainage. Tiles are placed 0.8 to 1 m deep and spaced 25 m apart. Tile drains empty to collector canals, which flow to main canals. Weir structures exist through the watershed, allowing drainage to be controlled or managed throughout the year. The ultimate outlet of the T4 subwatershed is a concrete, double box culvert structure (2 X 3m width X 3m height).

The primary soils found in the T4 subwatershed are Portsmouth fine sandy loam (Fine-loamy over sandy or sandy-skeletal, mixed, semiactive, thermic Typic Umbraquults), Roanoke loam (Fine, mixed, semiactive, thermic Typic Endoaquults), and Cape Fear loam (Fine, mixed, semiactive, thermic Typic Umbraquults) (SCS,1981, Soil Survey Division). These three soils make up a general map unit identified by the Soil Conservation Service, which makes up approximately 40 percent of Washington County (SCS, 1981). These mineral soils are flat and very poorly to poorly drained, with a loamy surface layer and a loamy or clayey subsoil.

As mentioned above, a drainage area within T4 was also monitored. This area, called T0, is approximately 50 ha and contains an operating swine unit along with a waste lagoon (Figure 3). The liquid effluent from the lagoon is applied to pasture land within the T0 area. A portion of the T0 subwatershed contains open drainage ditches.

Data was also collected from one field within the T4 subwatershed in this study, field station H2 (Figure 3).

Subwatershed C2

Subwatershed C2, 2700 ha, forms the southern boundary of the research watershed (Figure 3). This is a mixed use subwatershed, with agriculture (row crops, such as corn) dominating the southern fields and managed pine stands in the western part. The landscape in C2 is flat (< 0.2 % slope). The subwatershed is approximately 50 percent agricultural and 50 percent forested. The soils include Belhaven muck (Loamy, mixed, dysic, thermic Terric Haplosaprists), Wasda muck (Fine-loamy, mixed, semiactive, acid, thermic Histic Humaquepts), and Roper muck (fine-silty, mixed, semiactive, acid, thermic Histic Humaquepts). These very poorly drained, organic soils consist of thick, highly decomposed organic surface horizons (sapric material) underlain by silty or loamy marine sediments (parent material). In the western portion of C2, Cape Fear loam (Fine, mixed, semiactive, thermic Typic Umbraquults) is predominant. This very poorly drained mineral soil has an organic surface layer; parent material consists of clayey marine and fluvial sediments.

The C2 subwatershed is artificially drained using approximately 120 cm deep field ditches, spaced 80 to 200 m apart. Typically, field ditches drain to collector canals, which ultimately flow to the C2 outlet. The agricultural fields are more intensively drained than the managed forest area due to better surface drainage.

Within the C2 subwatershed, flow is presented for one field station, a managed forest field, F3 (Figure 3). Field F3 is in the western portion of subwatershed C2, and thus the predominant soil type is Cape Fear loam (Fine, mixed, semiactive, thermic Typic Umbraquults).

Methods

Weather, hydrology, and water quality have been intensively measured and recorded in the research watershed since 1996. The following sections describe the measurements.

Hydrology Measurements

Weather

Rainfall amounts within the watershed are collected at seven locations, R1, R2, R3, R5, R6, R7, and R8 (Figure 3). The gauges are distributed across the research area to quantify spatial variation of rainfall throughout the watershed. Additionally, missing or bad data from one station can be estimated using data from the remaining stations. Automatic tipping bucket rainfall gauges were utilized; the number of tips was collected continuously by an electronic datalogger (Onset Hobo ® Event Logger). Data files were downloaded every two weeks. Manual gauges are in place alongside the tipping bucket gauges to provide backup measurements and as a means of calibrating the automatic gauges.

Two of the rainfall collection sites, R2 and R6, are also sites for full weather stations. Here, air temperature, wind speed, relative humidity, net radiation, and solar radiation are continuously measured and recorded on a Campbell Scientific CR10X ® datalogger. The station R2 is located on a 3 m tower in a mowed grass area within the agricultural subwatershed, T4. Some of the instruments at the R6 weather station are mounted on a tower approximately 2 m above the canopy of plantation pine trees. These instruments can be raised as the trees grow taller. The parameters being measured are sufficient for the calculation of potential evapotranspiration (PET) by the Penman-Monteith method (Monteith, 1965).

Average rainfall from gauges R1, R6, R7, and R8 was used to represent the rainfall in subwatershed S4 and C2. Rainfall from station R2 (and sometimes an average of R2 and R3) was used to represent the precipitation in subwatershed T4.

Water Table

Water table fluctuations are continuously measured in fields across the research watershed; typically measurements were taken from one well per field (Figure 4). For the forested watershed S4, water table fluctuation is measured for the fields F5, F6, and F7. Water table fluctuation was measured for Field H2, which represents typical water table behavior observed in the agricultural watershed T4. Likewise, water table measurements were made in a managed forest field (F3) within subwatershed C2.

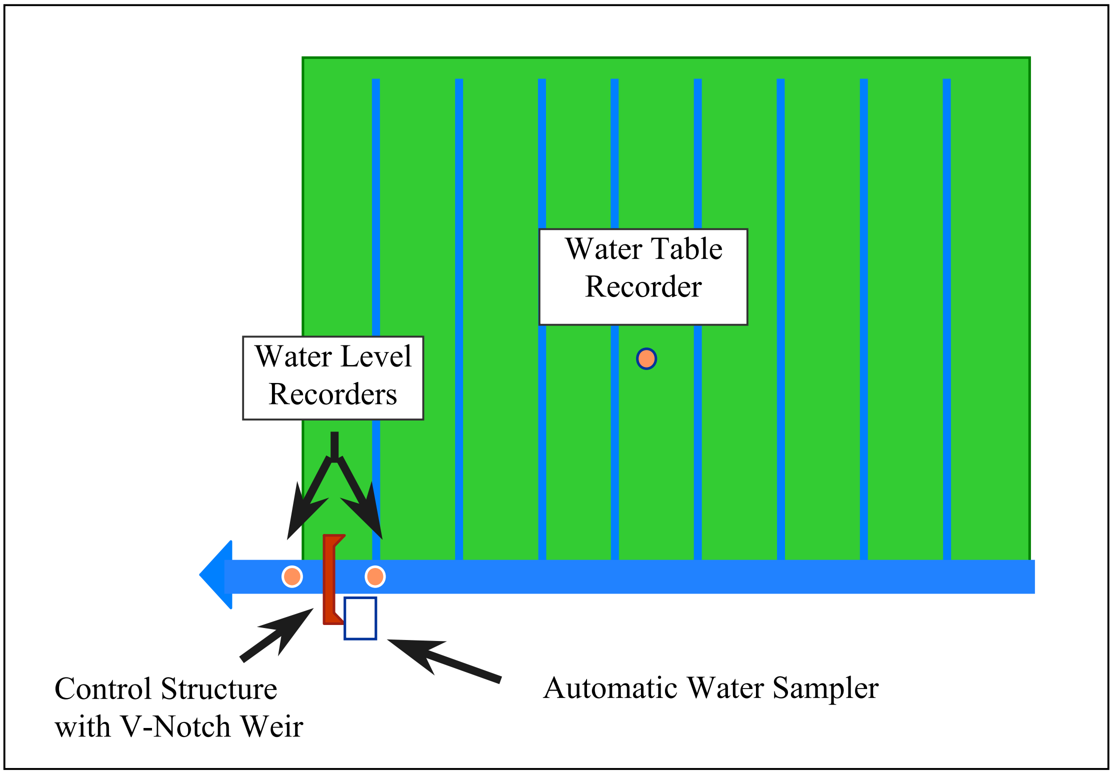

Figure 4. Typical field scale gauging and sampling station.

Water table monitoring wells are installed in selected fields (screened at various depths) and contain pulley/float water level recording devices. The well is constructed of 4-inch PVC pipe and contains the weighted float. The float moves freely with fluctuations in the water table; as the float moves, it turns the pulley. As the pulley turns, a calibrated water table depth is recorded graphically (trace on paper). Turning the pulley also results in changes in voltage of a potentiometer device connected to the recorder. These voltage changes represent water table fluctuations and are recorded by a data logger (Blue Earth Research ST485 ®). Thus, the water table measurements were made in duplicate (on a paper chart and in electronic form). The electronic data were considered the primary source of data, and the paper charts were used as backup when the data loggers failed, or to confirm the electronic data. Typically, the microprocessor was used to record an electronic water table measurement once each hour. The recording devices are housed in a watertight PVC box adjoining the well. The data was downloaded using a portable computer every two weeks; calibrations of the well data were made at this time based on manual readings when necessary. Subsequently, the electronic data were converted to elevation using referenced equations. The elevation of each well structure was surveyed; therefore adjustments were made in each data set to present water table depth from the soil surface.

Flow

The large research watershed contains an extensive drainage network (open ditches and sub-surface tiles). A large portion of the watershed is artificially drained using a series of lateral field ditches, which drain to main collector canals, and ultimately flow to the watershed outlet. Lateral field ditches collect both surface and subsurface drainage. Tile drainage is primarily utilized in the agricultural areas of the watershed. Tile drains collect only subsurface drainage, then drain along with surface drainage to collector canals.

Flow in the drainage canals/streams was measured at several field outlets and at subwatershed outlets on a continuous basis. This was accomplished at the outlet of subwatershed S4 and at the field outlets F5, F6, and F7 (all fields within S4) by using V-notch weir structures made of an aluminum plate (Table 1). The existence of these weirs within the subwatershed S4 may have somewhat restricted and controlled the flow of water through this subwatershed.

Table 1. Description of weir control structures present at outlet of S4 subwatershed and each forested field station within the S4 subwatershed.

Weir Name	No. of Weirs	Weir Angle	Weir Width, m
S4	2	120°	1.18
F7	1	120°	1.6
F6	1	120°	1.3
F5	1	120°	1.51

Each weir structure is equipped with a pulley/float water level recorder both up and downstream of the structure (refer to Figure 4). Each recorder is located in a 4-inch PVC stilling well, similar to the setup described for the water table recorders. The upstream and downstream water levels are measured using the pulley system, but the upstream stage is also logged using a chart recorder (Stevens). Both upstream and downstream stage measured by the simple pulley system were recorded by an electronic data logger (Blue Earth Research ST485 ®). The data were downloaded every two weeks and any necessary calibrations were made at that time. Alongside each recording gauge was a manually examined staff gauge used to confirm and calibrate the recording devices.

By measuring upstream and downstream stages, flow over a weir structure can be calculated even during submergence or backflow. The following relationship was used to calculate flow over a free-flowing (downstream water level below the bottom of the weir V-notch), sharp-crested, 120° V-notch weir (Brater, 1996).

$$Q = 4.36\, H^{2.5} \qquad (1)$$

Where Q is flow rate (cfs) and H is the upstream height of water above the bottom of the V-notch (ft).

Equation 2 is the relationship used to calculate flow when the weir is submerged.

$$Q_{submerged} = \left(4.36\ H_1^{\ 2.5}\right) \cdot \left[1 - \left(\frac{H_1}{H_2}\right)^{0.5}\right]^{0.385} \qquad (2)$$

Where Q is flow rate (cfs), H_1 is the upstream height of water above the bottom of the V-notch (ft), and H_2 is the downstream height of water above the bottom of the V-notch (ft). Flow values were compiled as daily flow amounts (m^3/day).

In the agricultural subwatershed T4, flow at the outlet was determined differently. The outlet of this subwatershed is a concrete, double box culvert. A Starflow ® ultrasonic Doppler flowmeter (by Unidata) was installed in the bottom of one culvert (Figure 5). The device measures and records water velocity, depth, and temperature using an integrated datalogger. The instrument works by sending out a continuous signal from a transmitter and measuring the return signals with a receiver, then resolving the data to a measure of mean water velocity and depth.

Figure 5 . Starflow ultrasonic Doppler flowmeter used to measure water velocity and depth at the outlet of subwatershed T4.

The velocity measurements obtained using the Doppler flowmeter were rather 'noisy'. The velocity trend was obvious, but there is significant scatter in the data points. From field observation, it was known that the spikes in the Doppler data were anomalies, and these spikes had to be dealt with in order to further interpret the velocity data. A FORTRAN computer program was used to smooth the velocity data by detecting high gradients between data points. Low flow periods (or no flow) were at the lower limit of this measuring device, causing data to be particularly 'noisy' at low water levels.

After smoothing the measured velocity data, discharge from the T4 watershed was calculated. Using the measured and smoothed outlet velocity, measured depth of water in the culvert, and the culvert dimensions discharge from the outlet was calculated as simply the product of the velocity and cross-sectional flow area (equation 3).

$$Q = V\ A \qquad (3)$$

b

Where Q is discharge (flow), V is velocity, and A is the cross-sectional area of the flow path (culvert). For convenience, the discharge calculations were performed using a FORTRAN program. The program used the smoothed velocity data and measured water depths as input, and created an output data file of daily flow values.

Within subwatershed T4, outflow was also measured for T0. Flow from T0 was determined by measuring stage upstream and downstream of a weir control structure (Table 2). The monitoring setup and flow calculations for T0 are the same as those described for S4 and its component fields.

Table 2. Description of weir control structure at outlet of station T0, within T4 subwatershed.

Weir Name	No. of Weirs	Weir Angle	Weir Width, m
T0	1	120^{o}	1.03

Flow from the C2 subwatershed was measured similarly to that in T4. A flume was constructed in the outflow channel; water velocity and depth were measured in the flume using a Doppler flow meter, as described above for T4. The flume was constructed of plywood, in a trapezoidal shape (Figure 6, Table 3).

Figure 6. Trapezoidal shape of the C2 flume built into the drainage channel.

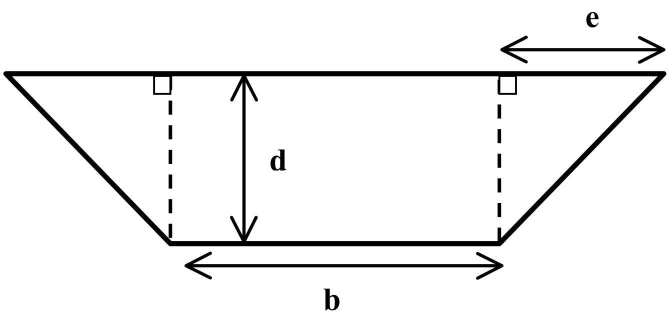

Table 3. C2 average flume dimensions used to calculate flow.

Dimension	**Length**
b	0.88 m
e	1.11 m
d	0.75 m

The velocity measurements obtained for C2 were smoothed, as described for station T4. Flow was calculated using equation 3 with measured/smoothed velocity, measured depth of flow, and the cross-sectional area of the flow path. Measurements were compiled as daily flow values.

Flow from the F3 field station within C2 was determined by collecting stage data (as preciously described) at a weir control structure in the F3 outflow canal (Table 4).

Table 4. Description of weir control structures present at outlet of forested field station within C2 subwatershed.

Weir Name	No. of Weirs	Weir Angle	Weir Width, m
F3	1	120°	1.05

Modeling with DRAINMOD

During the storm events of 1999, measured downstream stage data from station F3 (within C2) was missing (Figure 7). During these large events the F3 weir was significantly submerged or backflow occurred, thus downstream stage data is required to estimate flow. During this period of uncertainty, the hydrology model DRAINMOD (Skaggs, 1980) was used to predict the flow at F3 field outlet, given measured rainfall data and measured conditions (water table) at the time flow data were lost.

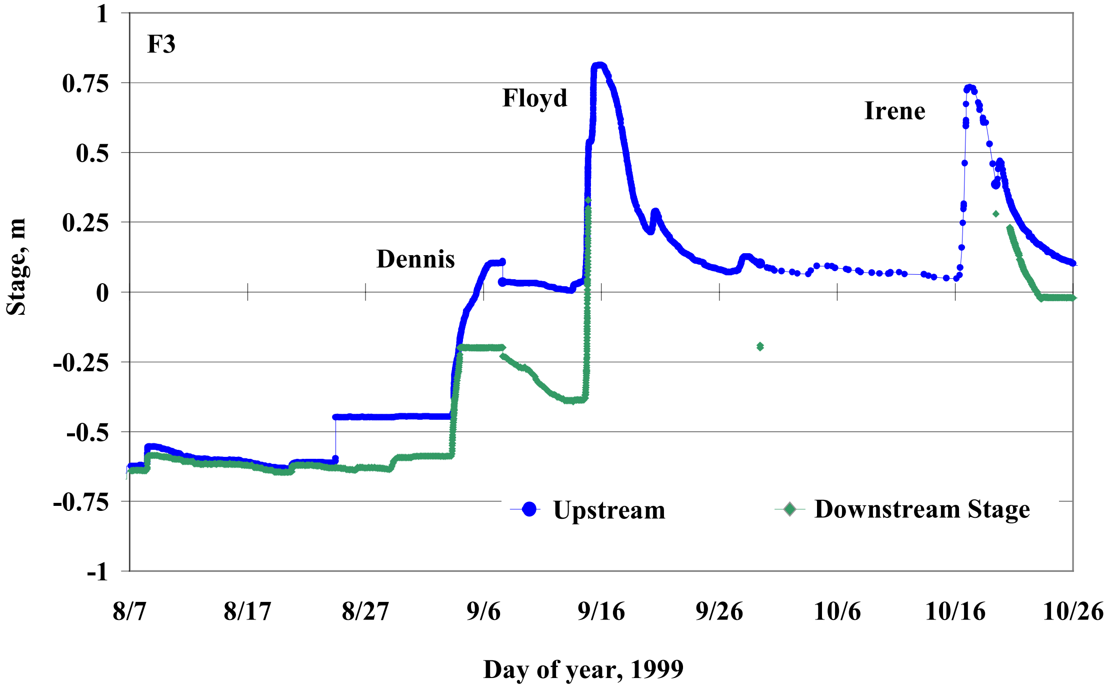

Figure 7. Measured water level (stage) in F3 outlet canal during hurricanes of 1999.

DRAINMOD is a water management simulation model that can be used to predict field-scale water loss (surface and subsurface). DRAINMOD is most applicable to poorly drained soils, which characteristically have little slope (< 2 %), shallow water tables, and are often artificially drained using ditches or sub-surface tile. DRAINMOD was designed to predict field hydrology of poorly drained agricultural land (such as that found in North Carolina's coastal plain) on a continuous time-basis by simulating the processes of infiltration, evaporation, surface runoff, subsurface drainage, water table response, and soil water storage. DRAINMOD calculates drainage rates using Hooghoudt's equation, based on water table depth midway between two parallel drains (Skaggs, 1980). DRAINMOD has been extensively tested with much success and considered reliable for predicting agricultural field hydrology (Chescheir, 1994; Konyha, 1992, Amatya et al., 1993).

DRAINMOD simulations for 1996-1999 were performed on the forested field F3 (within C2 subwatershed) in order to better estimate the flow from F3 during the hurricanes and associated storms during the fall of 1999. First, DRAINMOD simulations were performed to calibrate selected inputs. Inputs (drainable porosity and hydraulic conductivity) were adjusted until the predicted water table matched measured water table fluctuations (Figure 8). DRAINMOD inputs including 50 cm drain depth, 10,000 cm drain spacing, maximum surface storage of 4 cm, Kirkham's depth of 2 cm, and hydraulic conductivity of 18 cm/hr in all layers achieved the best match between measured and predicted water table values. See Appendix A for other DRAINMOD soil inputs (from .sin file). Using these inputs, flow was predicted to fill in the missing field data for F3 (Figure 9).

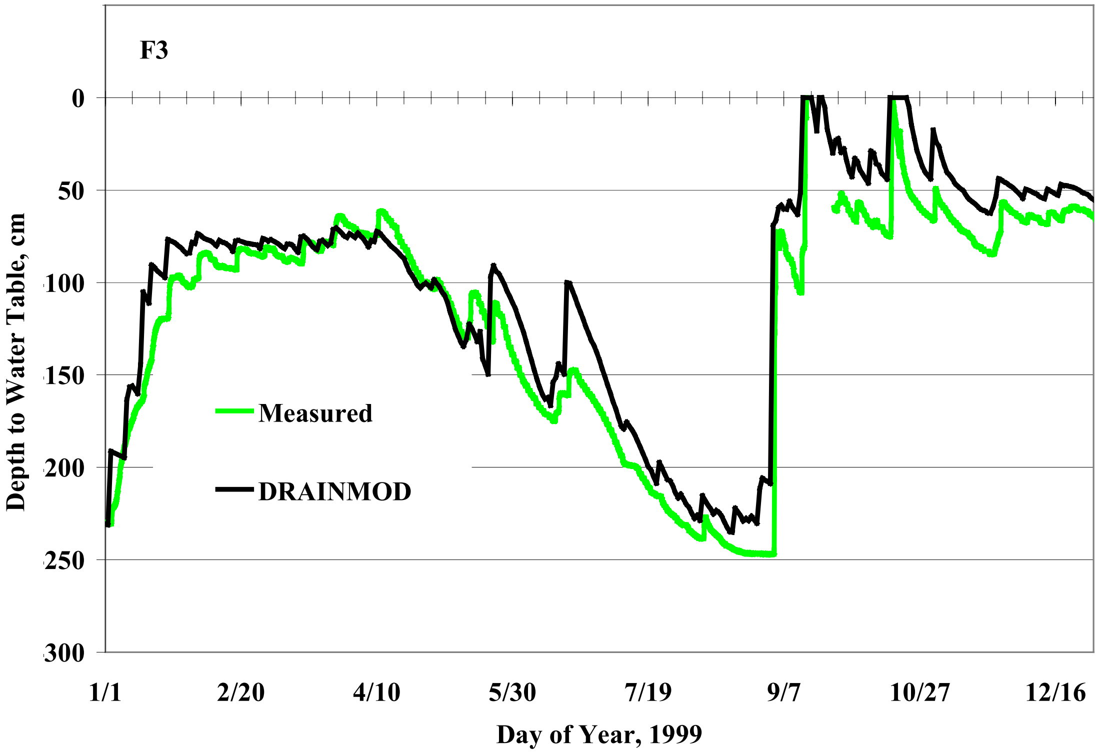

Figure 8. Comparison of F3 measured and DRAINMOD-predicted water table fluctuation for 1999.

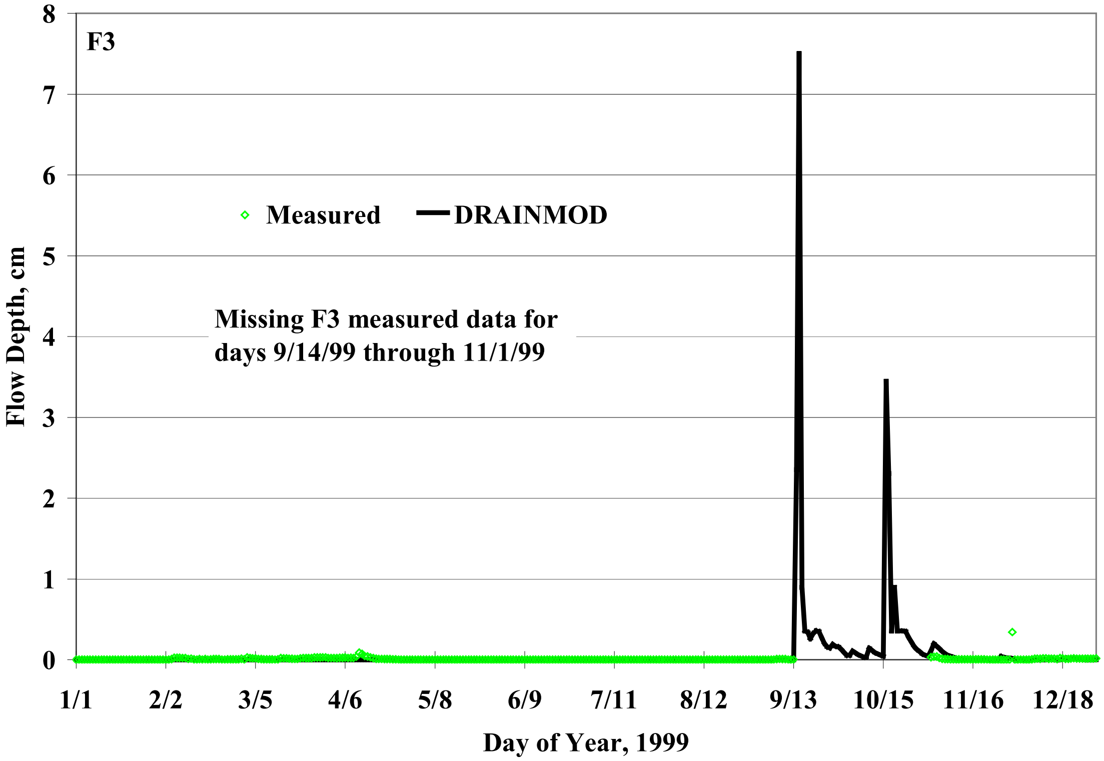

Figure 9. Comparison of F3 measured and DRAINMOD-predicted flow depth for 1999.

The DRAINMOD-predicted flow values were used for field F3 during the high flow period associated with hurricanes Dennis, Floyd and Irene to replace missing data. For the days September 14 through November 1, 1999 DRAINMOD-predicted drainage (flow) values were used for station F3 for all subsequent calculations (water balance, flow, nutrient and sediment loads).

Water Quality Measurements

Water quality monitoring was performed using a combination of automatic and grab sampling. At each monitoring station, an automatic sampler was installed upstream of the water control structure (Figure 4). The samplers take a combination of discrete event samples and flow-proportioned composite samples. Discrete samples were concentrated during the rising limb of a storm hydrograph, to capture the typical 'first flush' of nutrients moving through the station. Discrete sample collection was triggered by rising or falling water level, while composite sample collection was triggered by a specified flow volume passing the weir. The microprocessor connected to the upstream continuous water level recorder signaled the automatic sampler based on prescribed water level or flow volume changes. Grab samples (500 ml) were taken during routine station maintenance and data retrieval visits (nominally at two-week intervals).

The sampling frequency was such that linear interpolation between consecutive nutrient concentration values could be used. This was necessary in order to assign a concentration value to each daily flow value, such that calculation of daily nutrient loads at each station could be performed.

Automatically retrieved samples remained in the field up to 2 weeks. All samples were kept on ice during transport from the field, then subsequently refrigerated until analyzed in the laboratory. Ortho-phosphate phosphorus (OP-P), ammonium nitrogen (NH_4-N), and nitrate-nitrogen (NO_3-N) concentrations were determined colormetrically with a Lachat Quickchem 8000 Instrument, using 4500 Standard Methods (APHA, 1992). Total phosphorus (TP) and total Kjeldahl nitrogen (TKN) concentrations were also determined using standard procedures (APHA, 1992). Sediment concentration for each sample was estimated as total suspended solids (TSS), which was determined using a standard filtering method (APHA, 1992).

Hydrology Results

Rainfall

Measured rainfall amounts varied spatially across the research watershed (Figure 10). For 1999, the greatest cumulative rainfall was measured at station R1 (~ 1370 mm) and the lowest cumulative rainfall amount was measured at station R7 (~ 1210 mm).

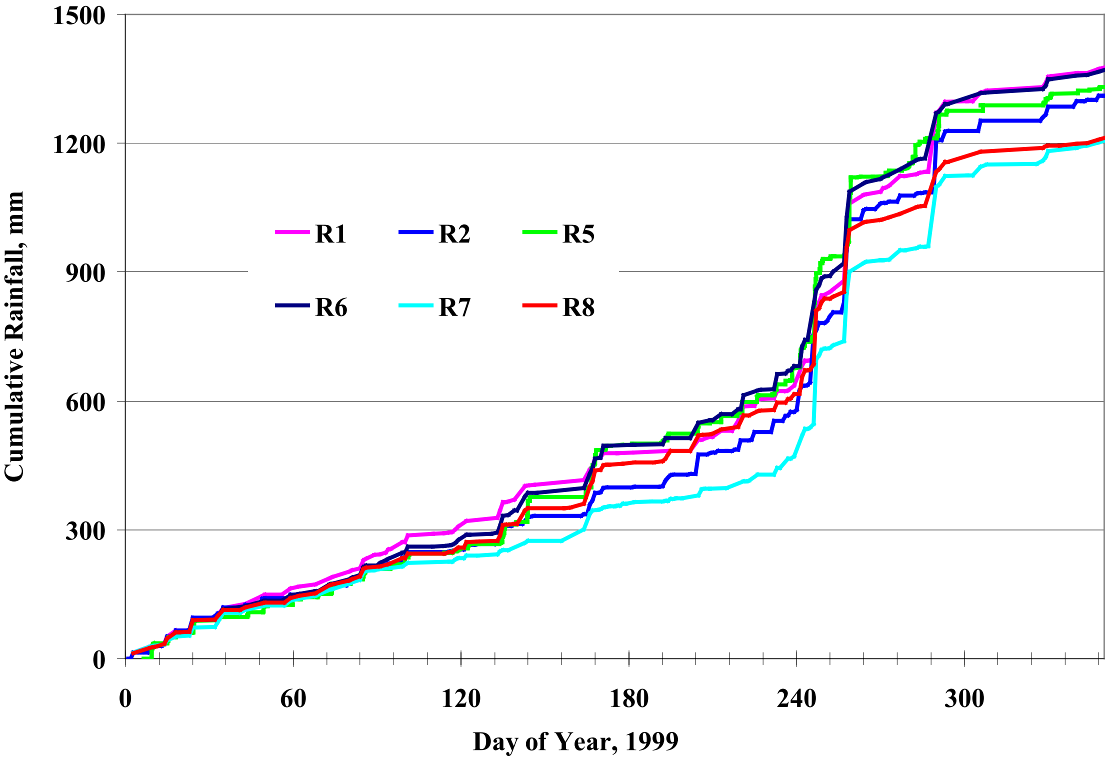

Figure 10. Cumulative annual (1999) rainfall for each station; indicates spatial variability of rainfall across the large watershed.

The average measured annual rainfall (using all 6 stations) in the research watershed was approximately 1302 mm for 1999. The 4-year average (1996-99) annual rainfall measured in the watershed is approximately 1228 mm. This study average corresponds with the longterm annual average rainfall of 1296 mm for Plymouth, North Carolina (1951-99).

The average rainfall from stations R1, R6, R7, and R8 is presented as the average rainfall in the forested subwatershed S4 and the agricultural/forested subwatershed C2, as well as for the field stations within S4 and C2. The station R2 is used as the rainfall corresponding to the agricultural areas, T4 and T0. Figure 11 displays the monthly rainfall totals representing rainfall in the research watershed for the year 1999, compared to the longterm average monthly rainfall (1951-1999).

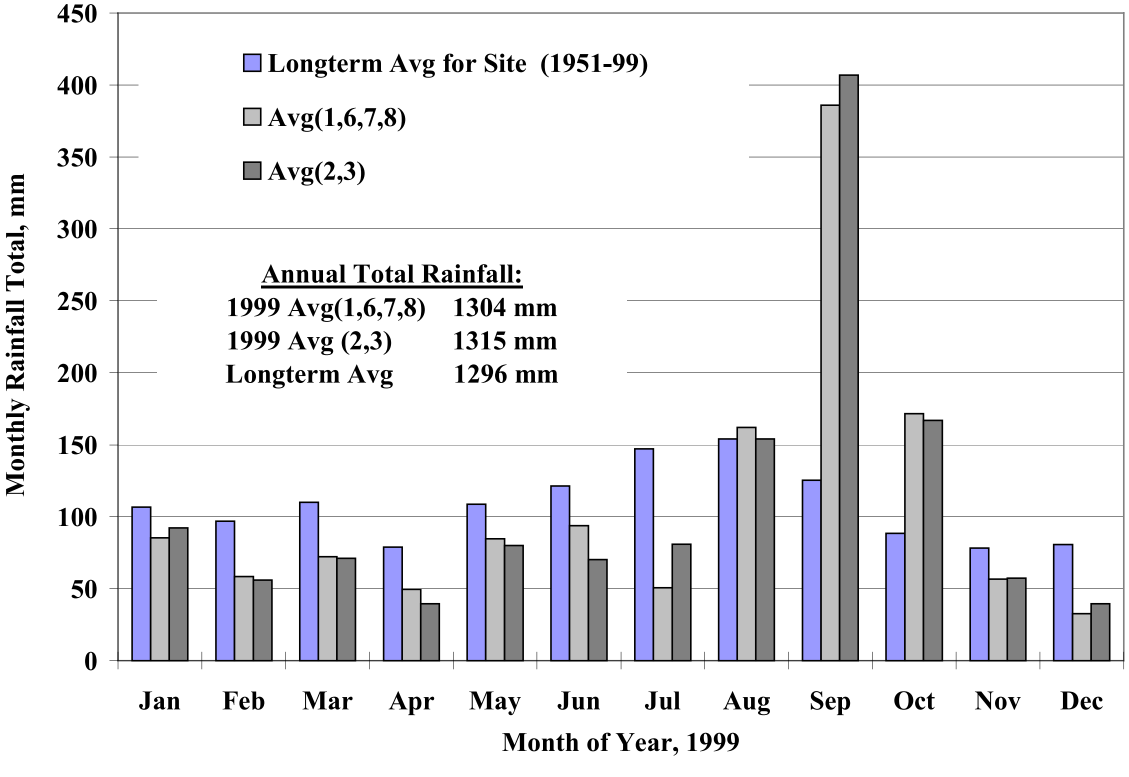

Figure 11. Monthly distribution of rainfall in the research watershed during 1999 compared to longterm average monthly rainfall for Plymouth.

The first part of the year 1999 was very dry. Total rainfall measured throughout the research watershed was less for February through August of 1999 (565 mm), than for the previous years on record, except 1985 (509 mm) and 1993 (511 mm, Figure 12). If the days August 29 and 30 of 1999 are removed from the 'dry period' total, 1999 is the driest ranking year on record (501 mm, Figure 12). Rainfall associated with Hurricane Dennis began on August 29, 1999. The longterm average total rainfall (years 1951 through 1998) at the site for February through the entire month of August is 822 mm. The 'dry period' probability of exceedance plot (Figure 12) demonstrates the magnitude of the 1999 dry season compared to years 1951 through 1998. The 'dry period' of 1999 was indeed one of the driest on record, followed closely by 1985 and 1993.

The long dry period was followed by several very large rainfall events. In 1999, September and October have very high rainfall amounts associated with hurricanes and tropical storms; the average total rainfall for September and October was 555 mm in the research watershed. The longterm average total rainfall (years 1951 through 1998) for these months is only 208 mm. A probability of exceedance plot was constructed for this 'wet period' for years 1951 through 1999. The sum of rainfall from months September and October is considered the 'wet period' for each year. The 'wet period' of 1999 was definitely the wettest on record (555 mm) for this watershed. The second wettest year was 1996 (472 mm), which included hurricanes Bertha, Fran, and Josephine. Indeed 1999 was a unique year- a very dry summer followed by a very wet hurricane season.

The rainfall amount attributed to each hurricane or tropical storm of 1999 was calculated using the average rainfall amount from all 6 rainfall gauging stations (R1, R2, R5, R6, R7, R8; Table 5).

For reference and comparison, the measured monthly rainfall totals for each gauge, potential evapotranspiration (PET), and potential water excess (rain – PET) are summarized for years 1996 through 1999 in Tables 6 through 8.

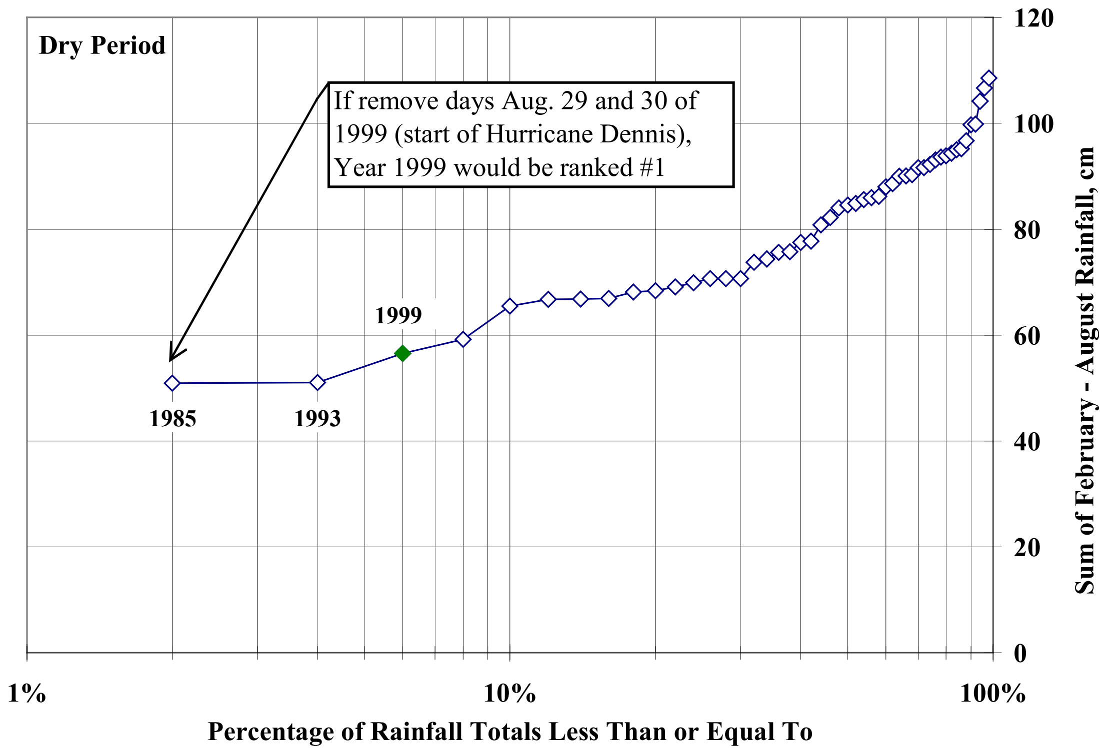

Figure 12. Probability of exceedance for 1999 Dry Period compared to that period for years 1951 –1998.

Figure 13. Probability of exceedance for the 1999 Wet Period compared to that period for years 1951 –1998.

Table 5. Large storm events measured in the research watershed during 1999.

Month of Year, 1999	Storm Event	Average Measured Rainfall (6 stations)
Aug. 29 - Sept. 1, 1999	Hurricane Dennis (I)	60 mm
Sept. 3 - 7, 1999	Hurricane/Tropical Storm Dennis (II)	162 mm
Sept. 14 -16, 1999	Hurricane Floyd	185 mm
Oct. 17 - 18, 1999	Hurricane Irene	109 mm

Table 6. Summary of measured monthly rainfall amounts for each station in the research watershed, years 1996-99.

1996	***Rainfall, mm***						
	R1	**R2**	**R4**	**R5**	**R6**	**R7**	**R8**
Jan	95	121			108		158
Feb	73	65			87		96
Mar	133	132			124		134
Apr	63	59			54		62
May	46	90			57		60
Jun	66	135			97		121
Jul	198	210			185		180
Aug	133	184			133		161
Sep	230	245			223		234
Oct	155	166			168		176
Nov	60	83			46		71
Dec	70	83			128		85
total	1322	1573			1410		1538

1997	***Rainfall, mm***						
	R1	**R2**	**R4**	**R5**	**R6**	**R7**	**R8**
Jan	65	80		67	75	87	75
Feb	49	73		69	66	70	67
Mar	89	92		78	80	90	68
Apr	60	103		84	61	79	76
May	71	80		74	86	75	71
Jun	51	52		40	61	76	51
Jul	113	102		164	85	140	130
Aug	99	123		82	96	99	99
Sep	96	106		85	99	101	92
Oct	60	73		68	72	74	90
Nov	99	90		91	99	96	80
Dec	79	58		88	79	81	82
total	931	1032		990	959	1068	981

Table 6 (continued).

1998 Rainfall, mm

	R1	R2	R4	R5	R6	R7	R8
Jan	170	157		151	151	139	146
Feb	97	152		154	154	140	140
Mar	120	114		120	120	100	107
Apr	69	59		68	73	59	67
May	160	166		112	160	117	116
Jun	116	116		120	121	80	110
Jul	63	60		60	49	54	52
Aug	158	122		183	136	98	130
Sep	47	40		56	33	40	48
Oct	52	53		63	58	49	50
Nov	75	53		73	73	39	67
Dec	152	139		148	148	144	138
total	1279	1231		1308	1276	1059	1171

1999 Rainfall, mm

	R1	R2	R4	R5	R6	R7	R8	Avg(1,6,7,8)
Jan	92	96	88	89	89	72	89	86
Feb	71	53	77	50	58	53	52	59
Mar	79	66	74	70	69	70	71	72
Apr	64	39	45	49	59	28	47	50
May	98	79	72	119	110	40	91	85
Jun	74	66	85	124	111	87	103	94
Jul	38	84	64	64	59	35	71	51
Aug	176	152	126	173	186	139	147	162
Sep	409	429	369	399	385	394	356	386
Oct	196	164	135	140	166	196	129	172
Nov	58	58	49	42	57	57	55	57
Dec	32	40	36	34	32	35	32	33
total	1387	1326	1220	1353	1381	1206	1243	1304

Table 7. Summary of estimated monthly potential evapotranspiration (PET) amounts for two major land uses found within the research watershed, years 1996-99.

Potential Evapotranspiration (PET), mm

Loblolly Pine (Pinus taeda L.)- for managed forest site

	1996	**1997**	**1998**	**1999**
Jan	37	26	29	40
Feb	57	37	30	48
Mar	68	70	54	74
Apr	121	90	90	111
May	104	121	111	129
Jun	117	123	130	120
Jul	125	133	147	158
Aug	108	145	135	138
Sep	79	97	120	80
Oct	81	76	93	77
Nov	41	44	62	60
Dec	30	37	41	40
total	968	999	1042	1075

Potential Evapotranspiration (PET), mm

Short Grass- for agricultural site

	1996	**1997**	**1998**	**1999**
Jan	36	26	37	38
Feb	56	37	44	52
Mar	64	81	82	86
Apr	111	101	105	115
May	104	143	104	122
Jun	113	129	122	114
Jul	111	130	122	141
Aug	91	136	102	121
Sep	74	96	90	72
Oct	73	70	68	51
Nov	42	39	44	32
Dec	38	29	38	39
total	913	1017	958	983

Table 8. Examples of potential water excess (rainfall - PET) for pine stands vs. agricultural fields (grass).

Rainfall Excess, mm				
Excess = Rain (R1,6,7,8) - PET for Loblolly Pine (Pinus taeda L.)				
	1996	**1997**	**1998**	**1999**
Jan	83	50	123	46
Feb	28	26	103	11
Mar	62	12	58	-2
Apr	-61	-21	-23	-62
May	-50	-45	27	-44
Jun	-22	-63	-23	-26
Jul	63	-16	-93	-107
Aug	34	-47	-5	24
Sep	150	0	-78	306
Oct	85	-2	-41	95
Nov	18	50	2	-3
Dec	64	43	105	-7
total	455	-14	154	229

Rainfall Excess, mm				
Excess = Rain (R2) - PET for Short Grass (agricultural)				
	1996	**1997**	**1998**	**1999**
Jan	85	54	120	58
Feb	9	36	108	1
Mar	68	11	32	-20
Apr	-52	2	-46	-76
May	-14	-63	62	-43
Jun	22	-77	-6	-48
Jul	99	-28	-62	-57
Aug	93	-13	20	31
Sep	171	10	-50	357
Oct	93	3	-15	113
Nov	41	51	9	26
Dec	45	29	101	1
total	660	15	273	343

Water Table

Measured water table response, cumulative flow depth, daily flow depth, and cumulative rainfall are presented for each station for the entire year of 1999 as well as for the hurricanes of 1999 (Figures 14 through 31). Water table was measured continuously in the forested fields F3, F5, F6, and F7 and in the agricultural field H2. Rainfall data from the nearest gauge are presented, as indicated on each plot. For comparison, plots are also presented for the larger, subwatersheds C2, S4, T0, and T4 (Figures 24-31) using selected water table data along with flow and rainfall measured on the subwatershed scale. The station name of field-scale water table data is reported on the figures for the larger, subwatersheds. For example in agricultural subwatersheds T4 and T0, data from a well in field H2 is presented.

Initial water table depths in 1999 varied among fields. On January 1, the water table in fields F3 and F5 was deep (~ 2.3 m and 1.6 m, respectively) compared to fields F6 and F7, where the water table depth was about 0.6 m. The water table dropped through the dry summer months at all locations. The water table in field F3 (within C2) was deep at the beginning of 1999 and reached a depth of 2.5 m from the soil surface immediately prior to hurricane Dennis. The large amount of rainfall from hurricane Dennis began to fill the soil water deficit in field F3 (Figures 14 and 15) and raised the water table to approximately 70 cm from the soil surface. For forested fields F5, F6, and F7 the rainfall from hurricane Dennis was sufficient to bring the water table to within 50 cm (or less) of the soil surface (Figures 16 through 21).

The forested fields within S4 are mostly organic soils with a higher drainable porosity compared to the agricultural soils such as in field H2 (Figure 32). 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. For field station F6 the volume drained versus water table depth data (Figure 32) indicate a zone of higher porosity from approximately 0.8 to 1.2 m deep, compared to the zone below (1.4 to 2.2 m). This is reflected by the more rapid water table response seen in the subsurface soil layer (approximately days 200 through 250, Figures 18 and 19). When the water table is drawn down into the deeper, lower porosity zone the water table fluctuation is greater for a given rainfall event.

The water table on agricultural sites, represented by field H2, was only 50 cm deep at the beginning of 1999 (Figures 22 and 23). In general, the water table deepened as the summer progressed, but fluctuated more throughout the season than the water table in the forested fields. Due to the intensive network of tile drains and lower drainable porosity of soils in T4 and T0, a more rapid water table response per a given rainfall event was observed. The maximum water table depth in the agricultural field was approximately 1.1 m from the surface, but the forested water table falls deeper (as deep as 2.5 m). This is due to the deeper rooting zone of the trees, compared to agricultural crops.

The arrival of hurricane Floyd and the rainfall associated with it brought the water table to the surface in most stations (Figures 14 through 31). Thus, additional rainfall associated with Floyd produced surface runoff in the agricultural areas, and to a lesser degree in the forested areas. Negligible flow was measured from each field/subwatershed until the water table was less than 50 cm below the soil surface.

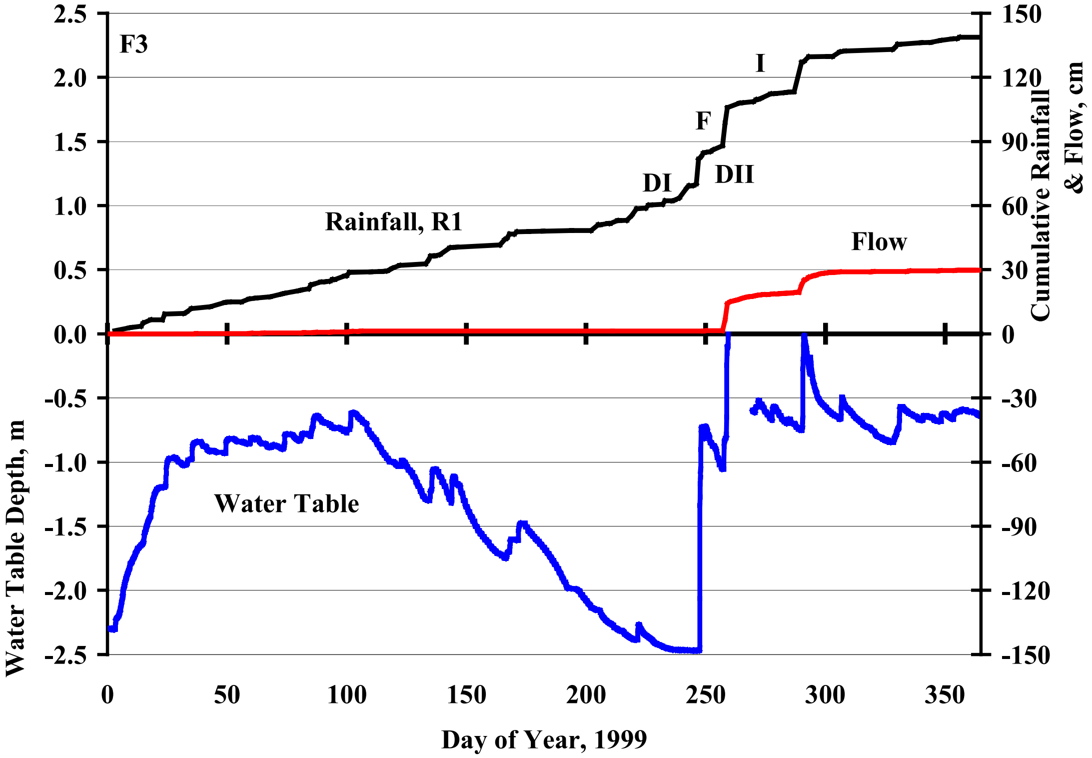

Figure 14. Cumulative rainfall, flow, and water table response for station F3 during 1999.

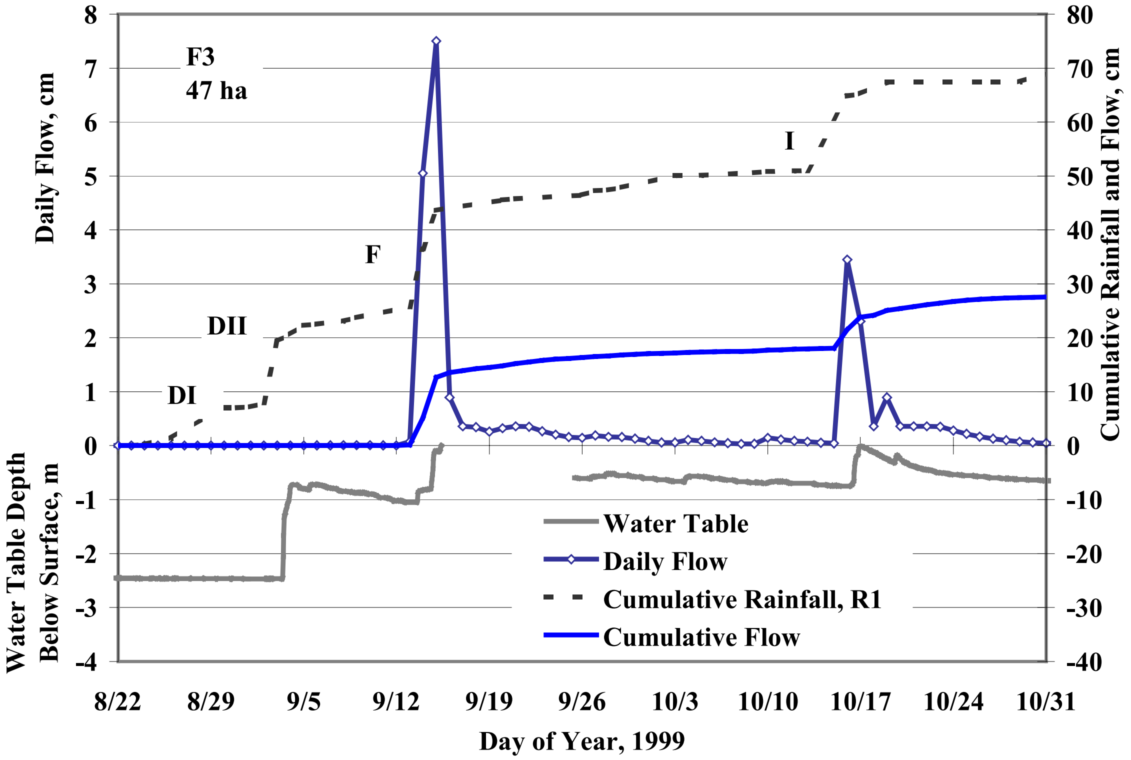

Figure 15. Daily flow, cumulative flow, cumulative rainfall, and water table response for station F3, for the storms of 1999.

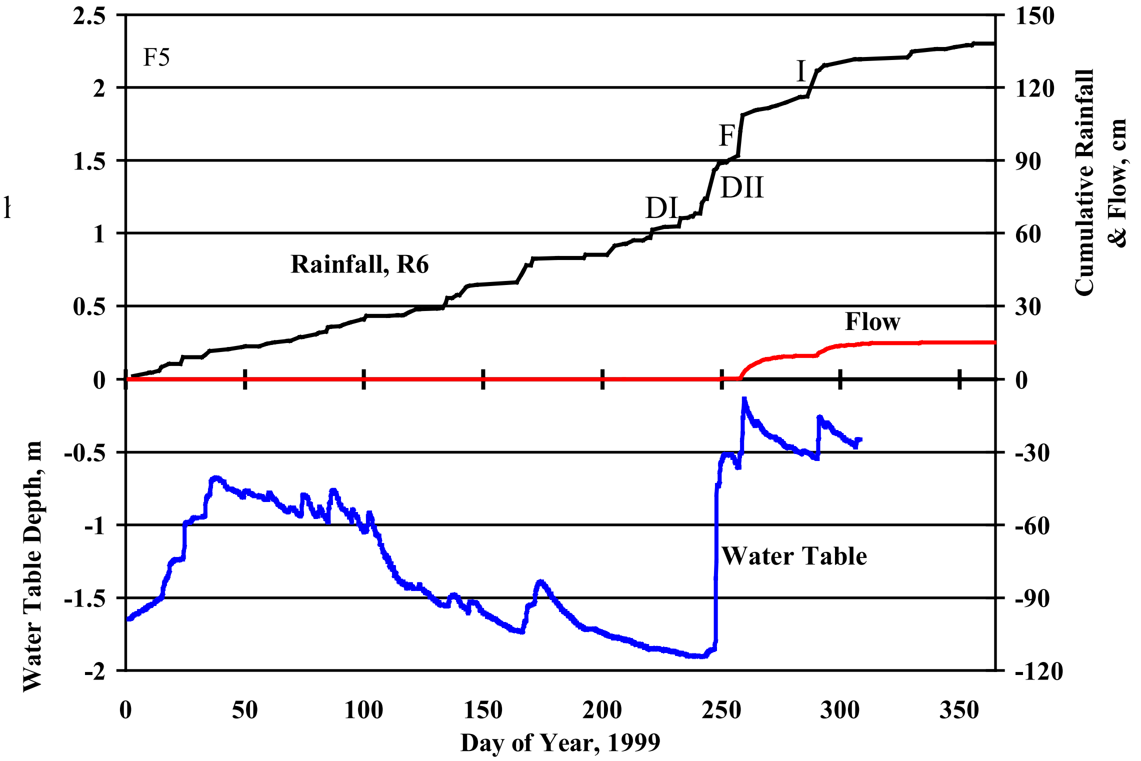

Figure 16. Cumulative rainfall, flow, and water table response for station F5 during 1999.

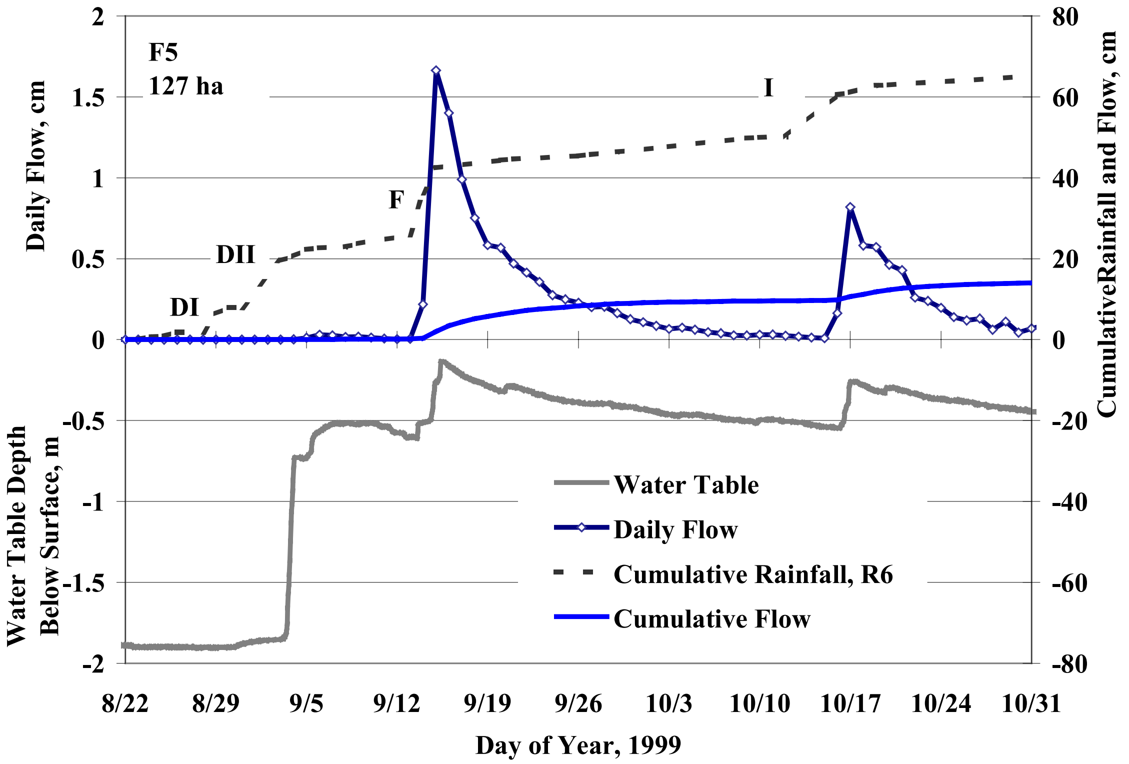

Figure 17. Daily flow, cumulative flow, cumulative rainfall, and water table response for station F5, for the storms of 1999.

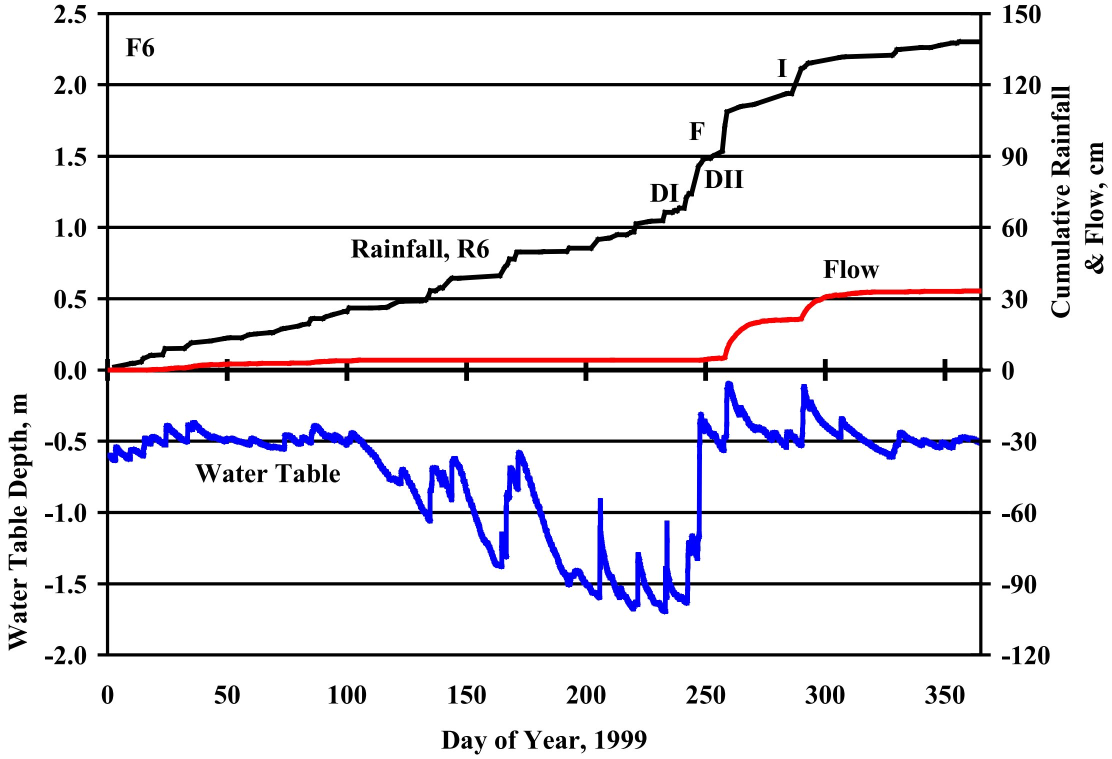

Figure 18. Cumulative rainfall, flow, and water table response for station F6 during 1999.

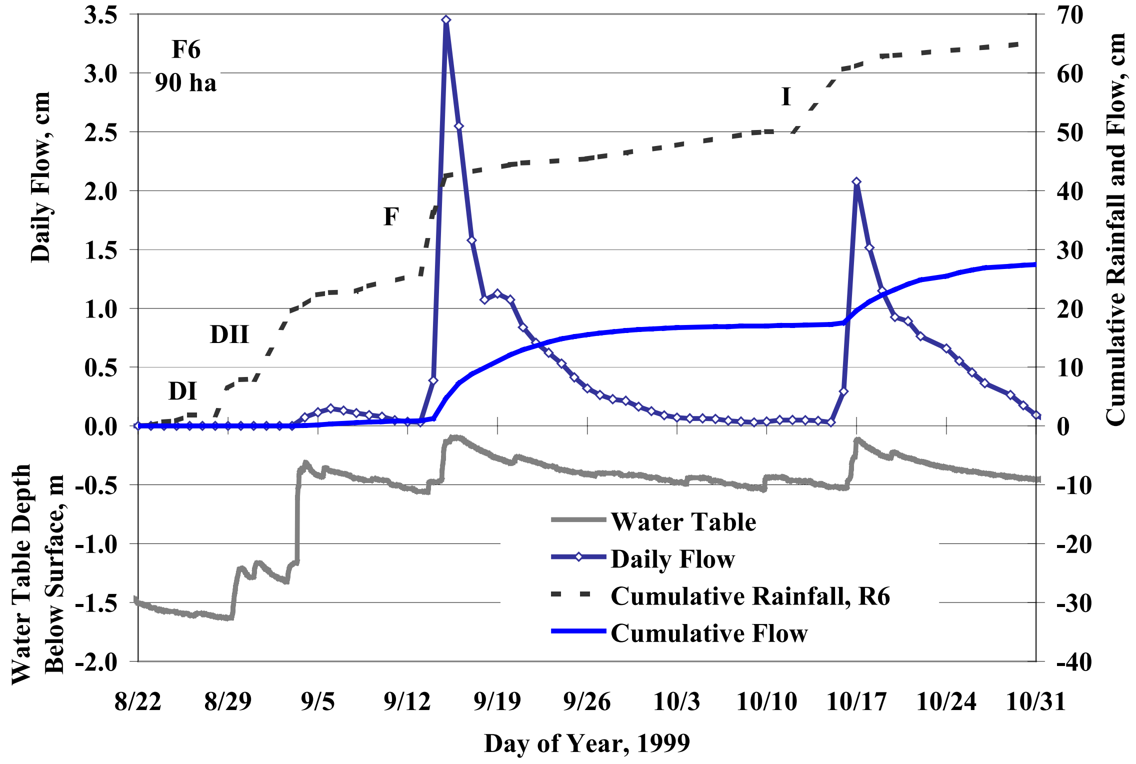

Figure 19. Daily flow, cumulative flow, cumulative rainfall, and water table response for station F6, for the storms of 1999.

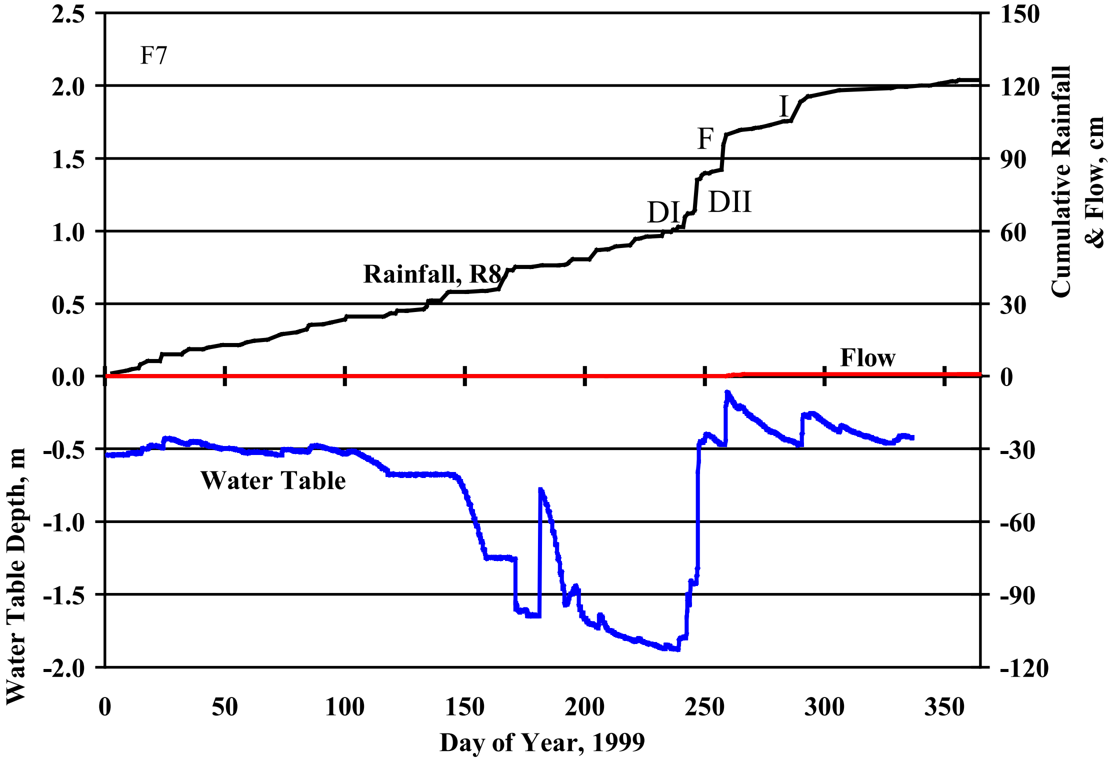

Figure 20. Cumulative rainfall, flow, and water table response for station F7 during 1999.

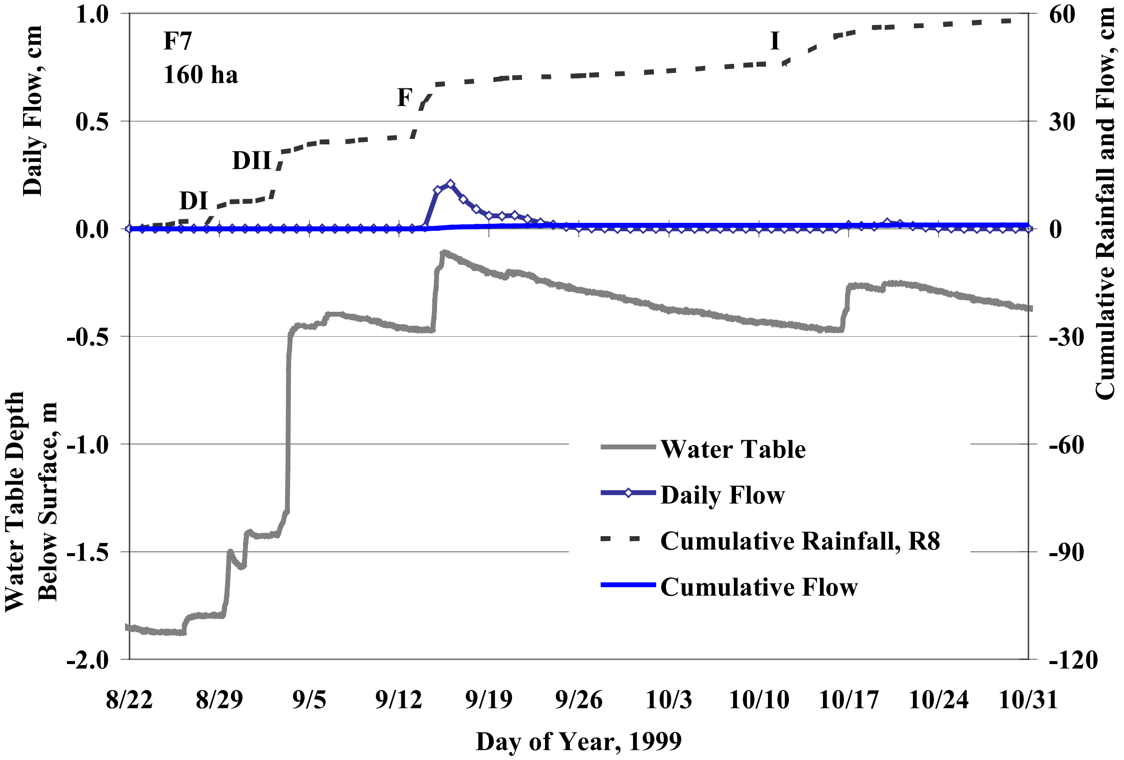

Figure 21. Daily flow, cumulative flow, cumulative rainfall, and water table response for station F7, for the storms of 1999.

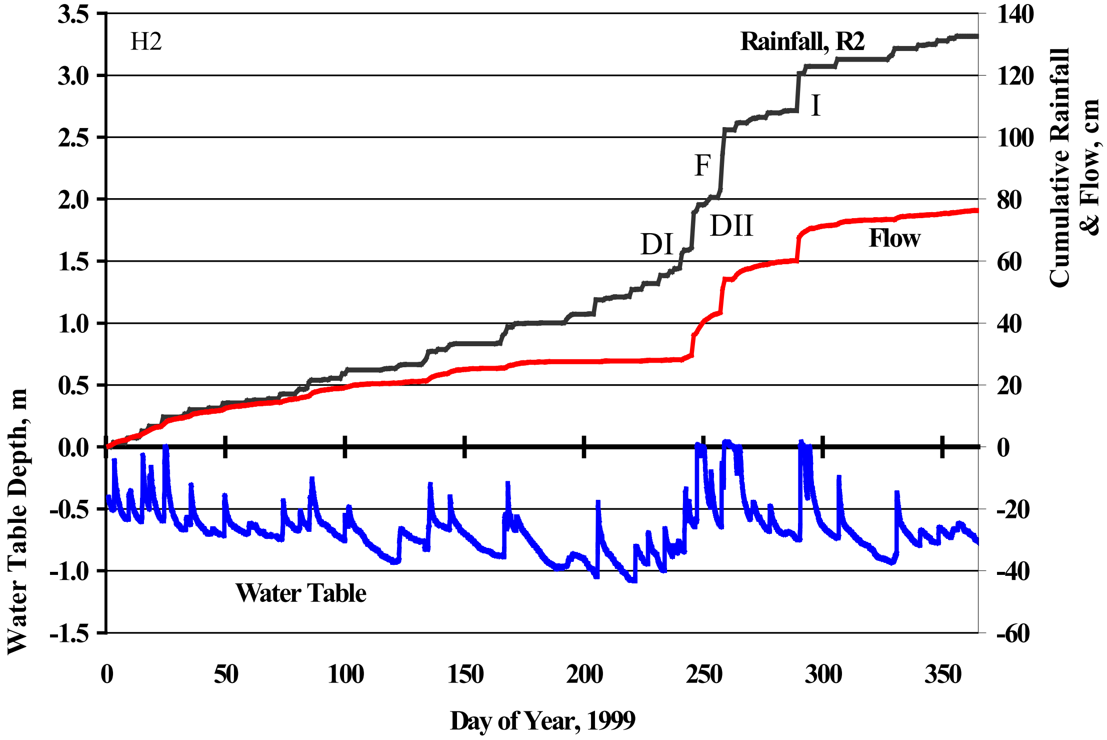

Figure 22. Cumulative rainfall, flow, and water table response for station H2 during 1999.

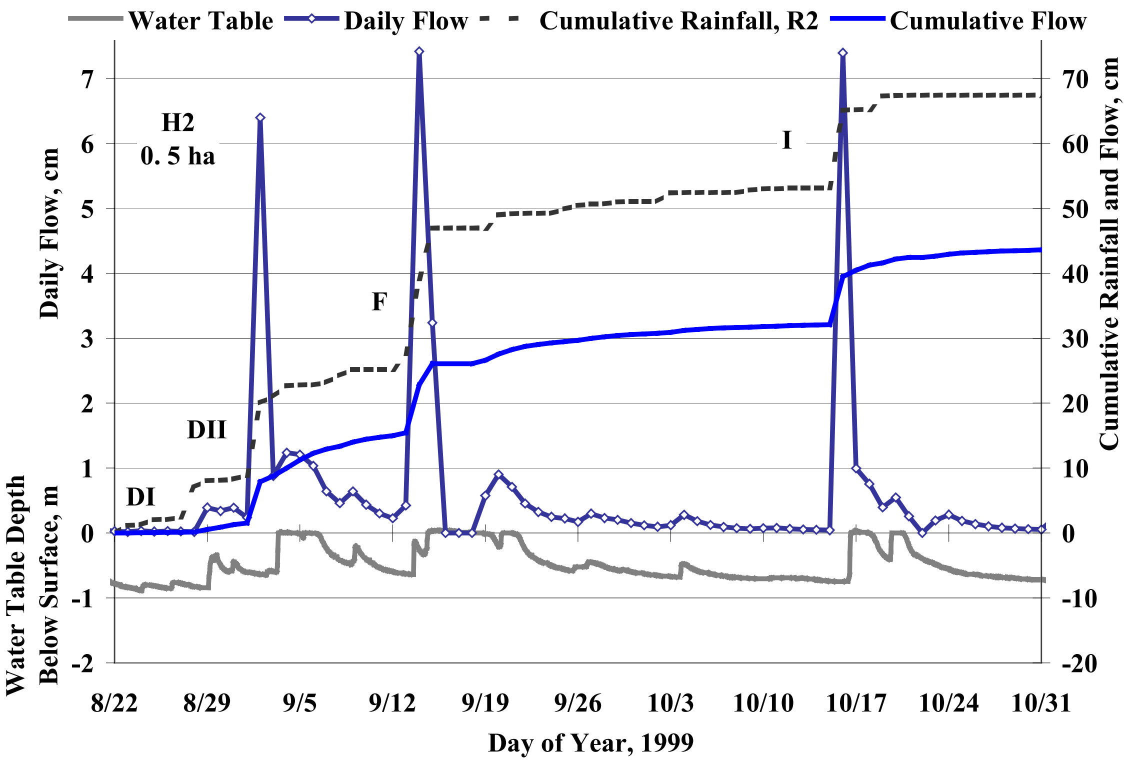

Figure 23. Daily flow, cumulative flow, cumulative rainfall, and water table response for station H2, for the year of 1999.

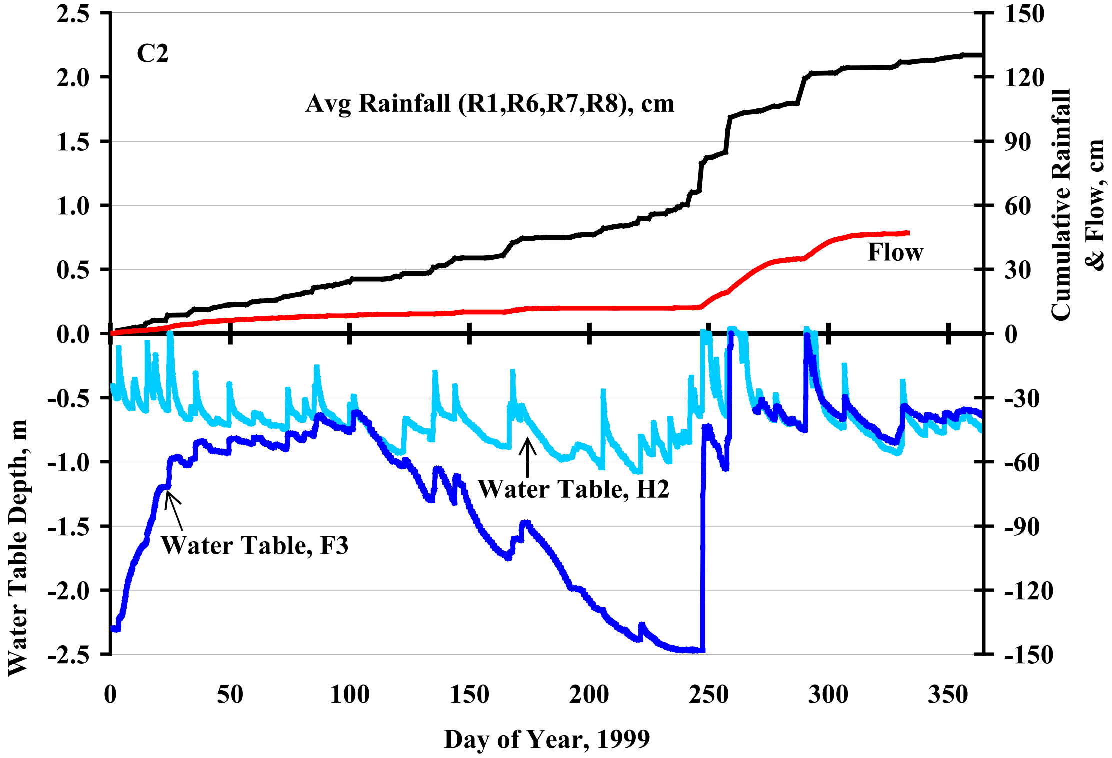

Figure 24. Cumulative rainfall, flow, and water table response for station C2 during 1999.

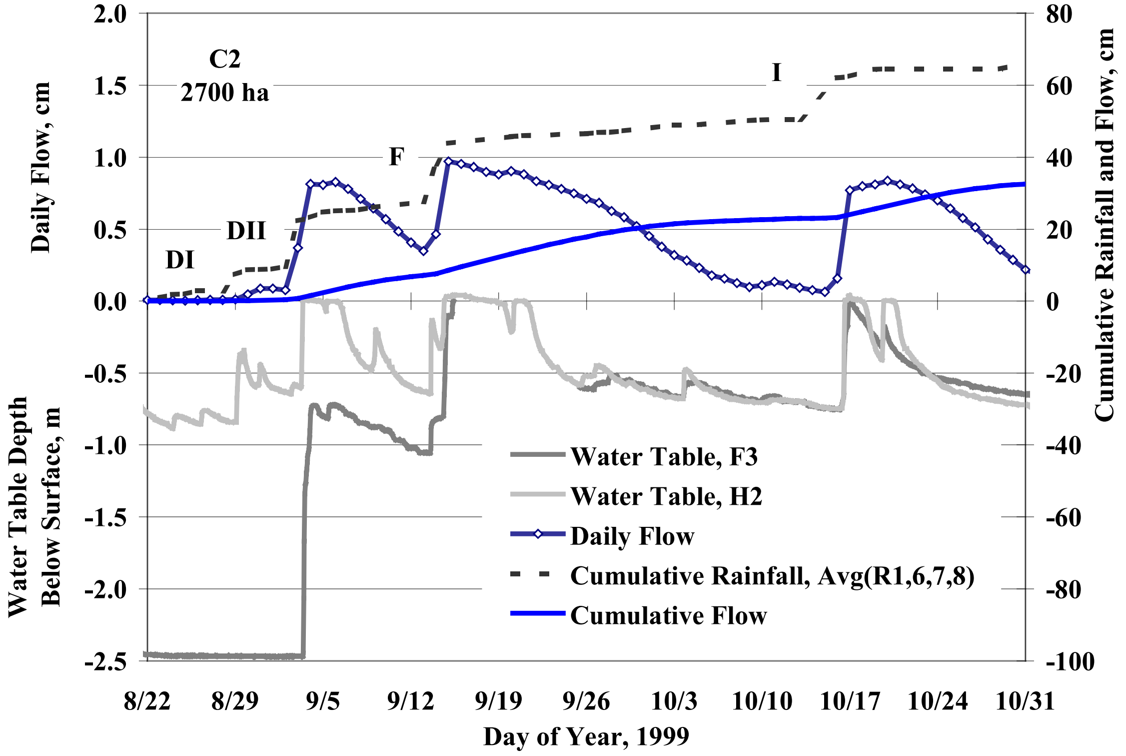

Figure 25. Daily flow, cumulative flow, cumulative rainfall, and water table response for station C2, for the storms of 1999.

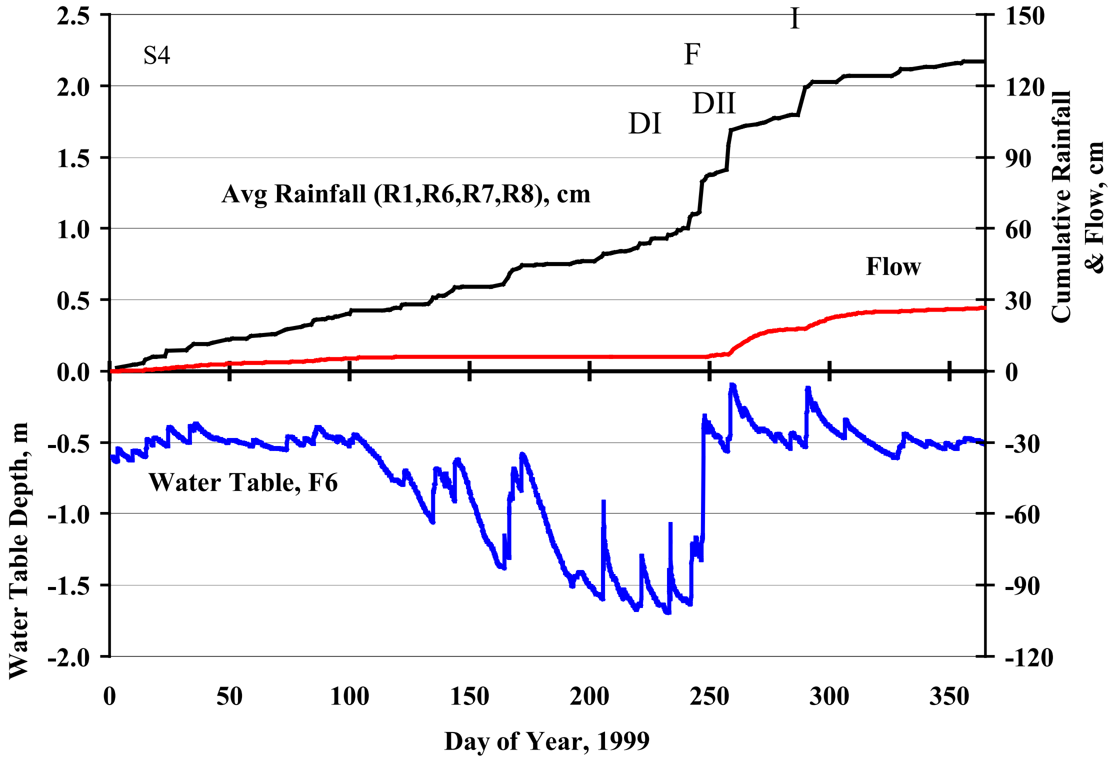

Figure 26. Cumulative rainfall, flow, and water table response for station S4 during 1999.

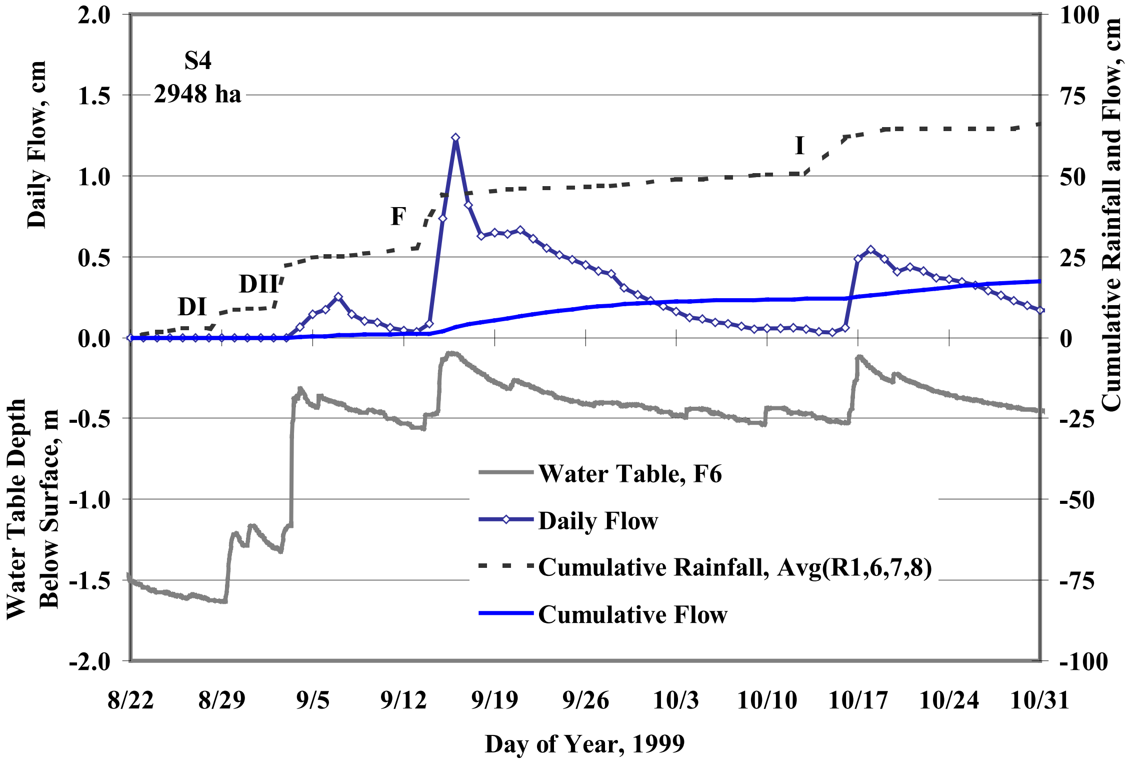

Figure 27. Daily flow, cumulative flow, cumulative rainfall, and water table response for station S4, for the storms of 1999.

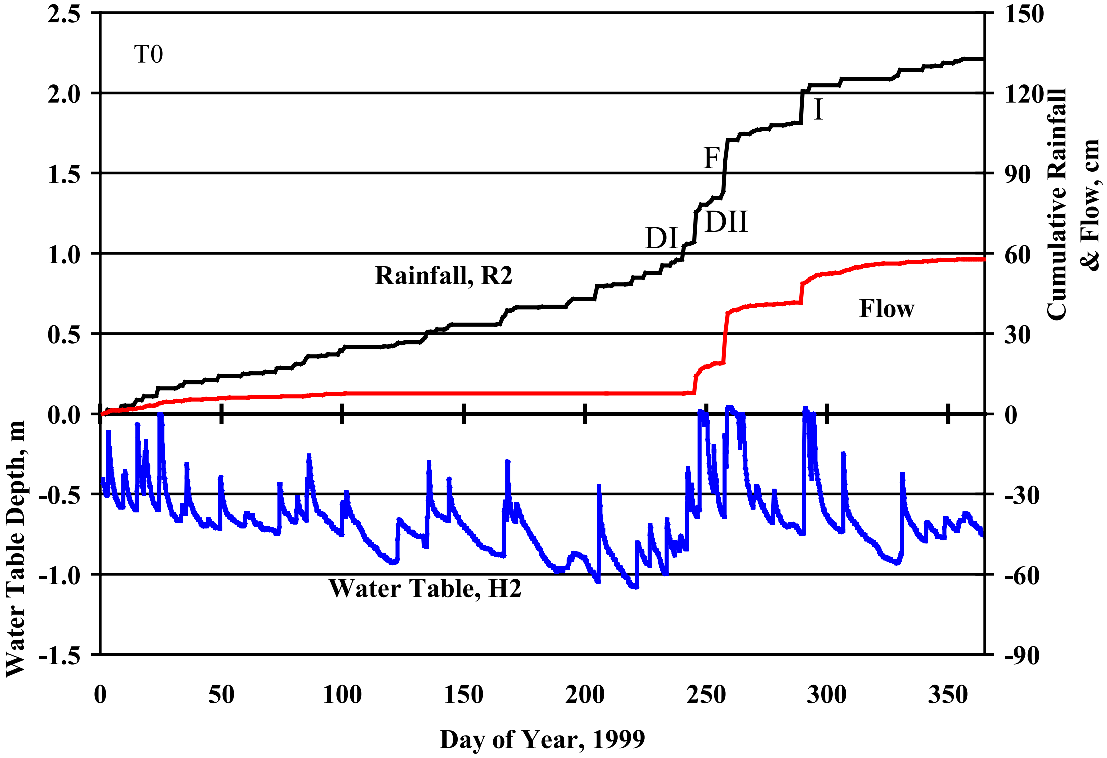

Figure 28. Cumulative rainfall, flow, and water table response for station T0 during 1999.

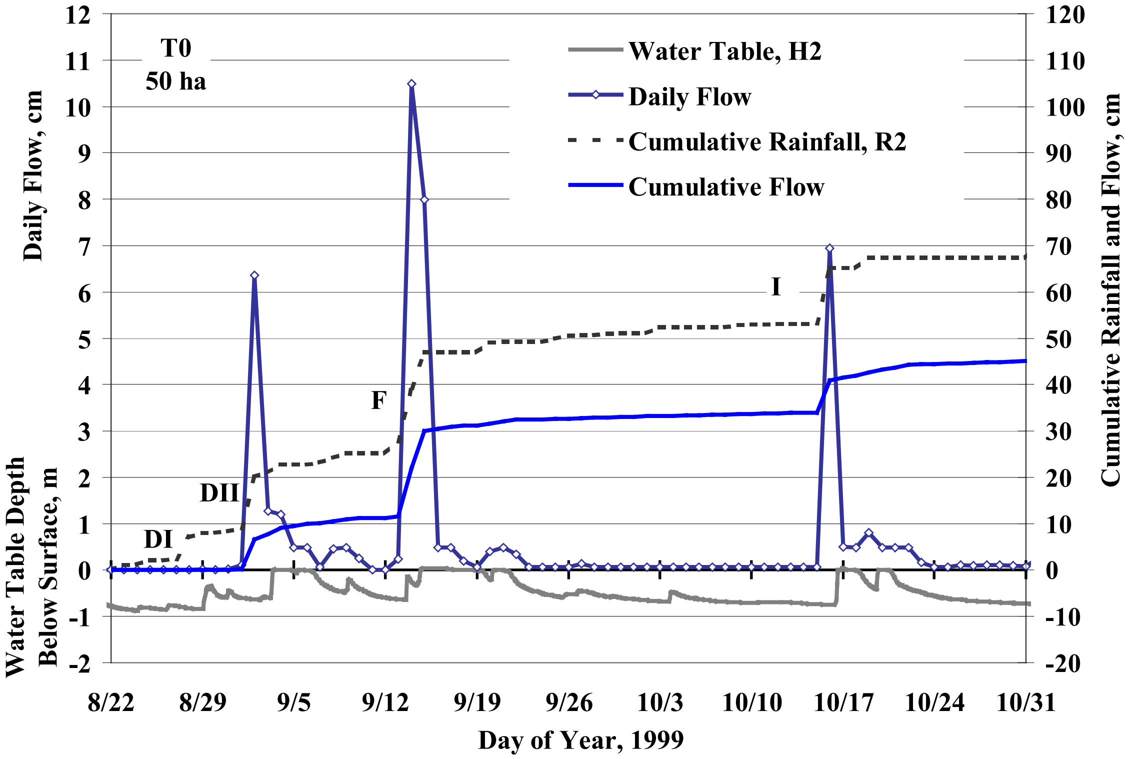

Figure 29. Daily flow, cumulative flow, cumulative rainfall, and water table response for station T0, for the storms of 1999.

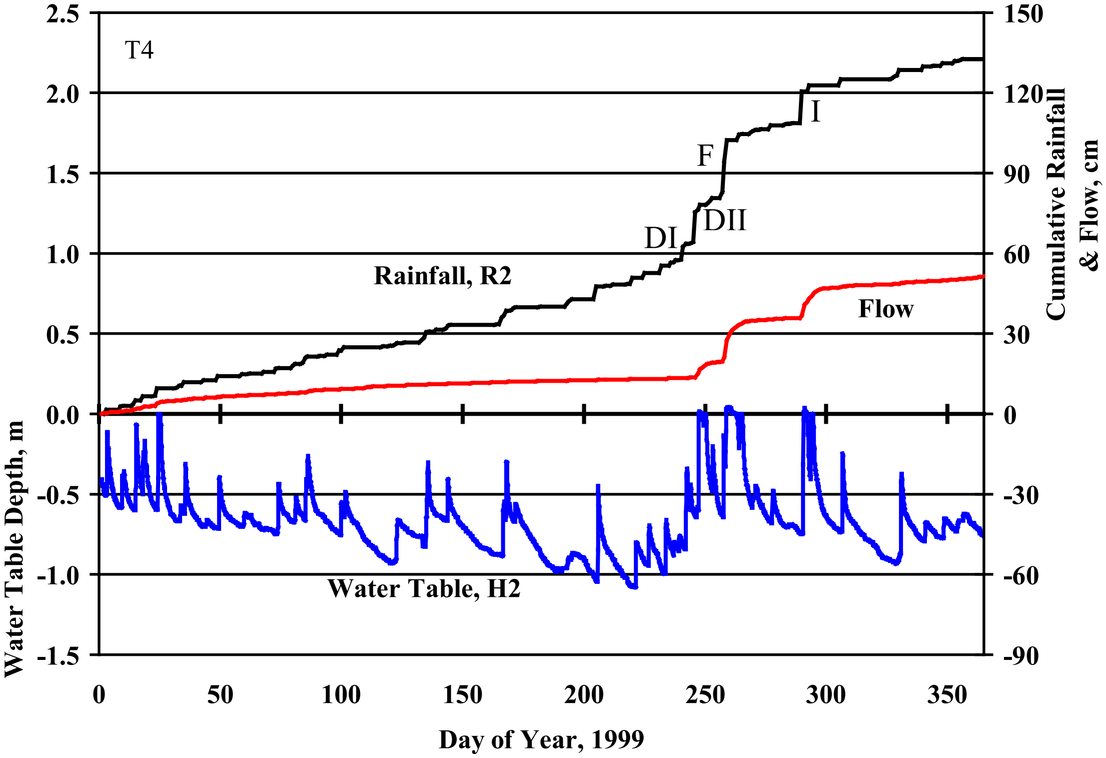

Figure 30. Cumulative rainfall, flow, and water table response for station T4 during 1999.

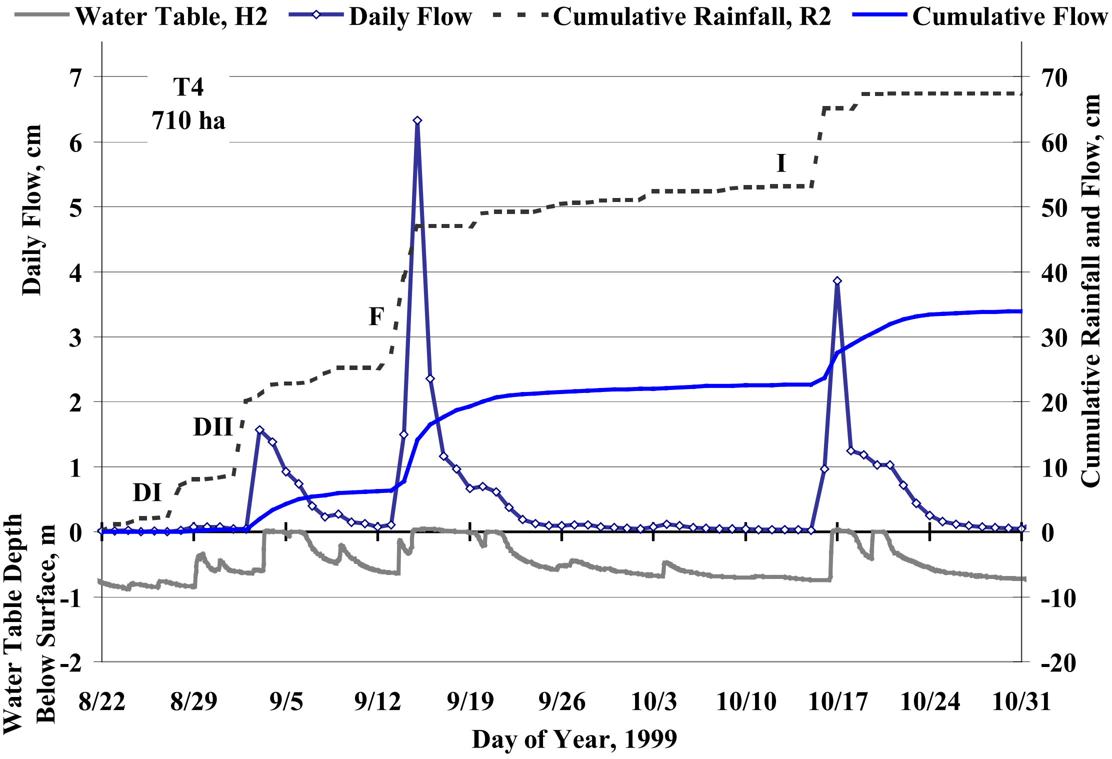

Figure 31. Daily flow, cumulative flow, cumulative rainfall, and water table response for station T4, for the storms of 1999.

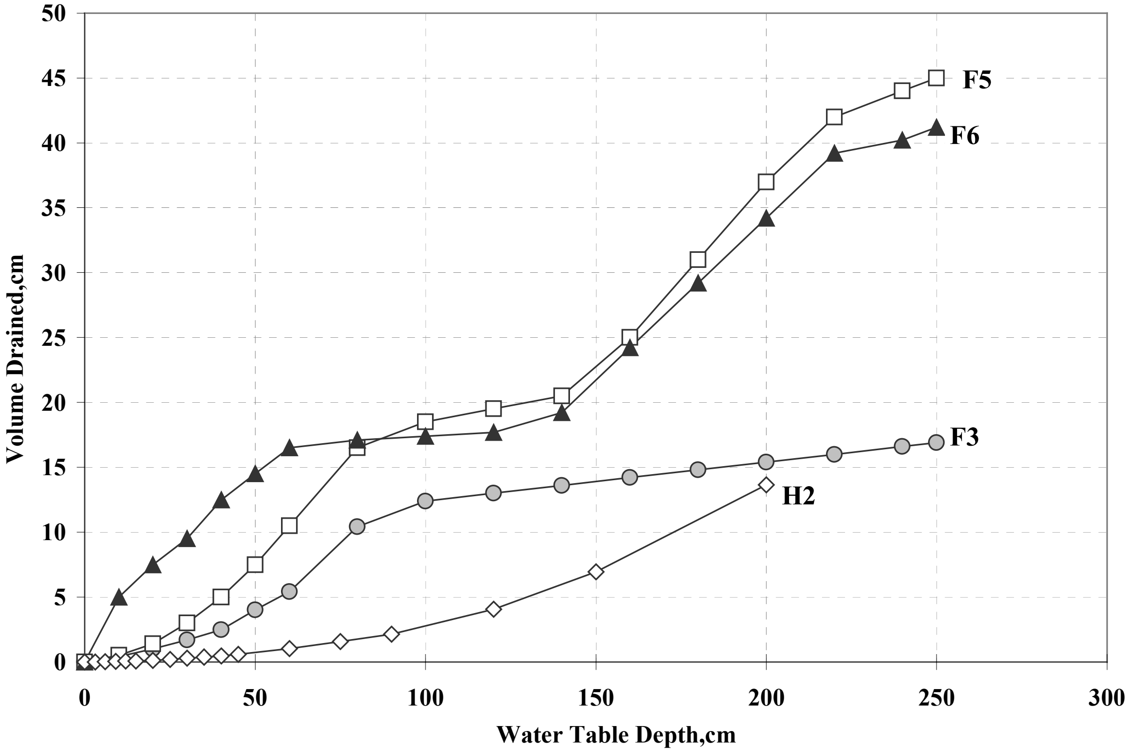

Figure 32. Volume of water drained from soil pores vs. water table depth for four study fields.

Water Balances

In order to further analyze measured rainfall and daily flow data, monthly water balances were produced for each station for 1999. Each water balance is presented as a bar chart and contains monthly totals for rainfall, potential evapotranspiration (PET), and "excess" water, or rainfall less PET (Figure 33). Additionally, monthly flow totals and annual totals of rainfall, PET, excess water, and flow are included on each figure. The monthly water balances are an initial attempt to describe the water balance for each station (Figures 34, 36, 38, 40, 41, 42, 43, 45, and 46). The balances presented do not account for the monthly change in soil water storage (Figure 33). These balances also assume that actual monthly evapotranspiration (AET) was equal to monthly PET, which is not always likely. For fields F3, F5, F6, and H2 the soil water storage was considered on a monthly basis (Figures 35, 37, 39, and 44). For each month the change in soil water storage was calculated based on volume drained versus water table depth data for the field (Figure 32) assuming drained to equilibrium conditions. The cumulative change in soil water is indicated on Figures 35, 37, 39, and 44 by the 'soil water' line. When the water balance is accurate, the 'soil water' line should be consistent with the 'rainfall-PET-flow' line. The data and calculations used to construct Figures 35, 37, 39, and 44 are included in Appendix B.

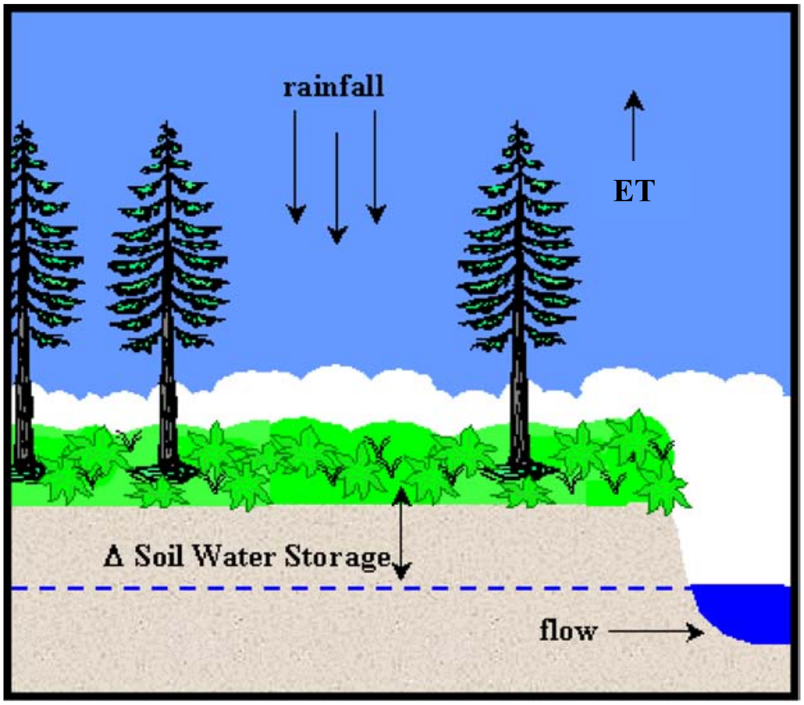

Figure 33. Components of the water balance considered by this study.

For each station, the rainfall amounts from the nearest gauge(s) are presented in the water balances. For S4 and C2, average rainfall from four nearby stations is presented. PET values correspond to estimates for loblolly pine for the forested subwatershed and a short grass reference for the primarily agricultural subwatershed. Though C2 contains both forestry (~ 50 %) and agriculture (~50%) is presented with PET for short grass only. All PET values were estimated using the Penman Monteith method (Monteith, 1965) with measured meteorological data.

The water balance for station F3, a field within C2, shows a close balance at the beginning of the year (Jan., Feb.; Figures 34 and 35, Appendix B.1). As the soil becomes very dry in July, the balance is not as close. It is likely that a dry zone formed in the root zone of the profile even though the water table did not continue to drop. Thus the soil is possibly drier than the 'soil water' quantity (Figure 35) would indicate, that is the drained to equilibrium condition did not exist. Alternatively, it is possible the discrepancy is because actual evapotranspiration (AET) did not reach PET, however the trees in field F3 are mature and AET could reach PET. For the high flow period associated with hurricanes Dennis, Floyd and Irene the F3 weir was very submerged and downstream stage data was missing. Thus, for this time period (9/14/99 - 11/1/99) DRAINMOD field predicted outflow was used, providing an estimate of flow at F3 for that time period. With modeled flow values and the consideration of change in soil water storage, there is a 4 cm discrepancy in the water balance for the month of September (rainfall-PET-flow > volume drained difference).

For station F5 (Figure 36) there was less total flow measured than expected by the water balance. Annual excess water was 31 cm, but measured flow was only 15 cm. The water balance was closer when soil water storage was considered (Figure36, Appendix B.2). Considering change in soil water the annual water budget balances within 3 cm. However, the ‘rainfall-PET-flow’ line indicates the soil is dryer than the 'soil water' line indicates throughout the year (Figure 37). Through the winter, spring, and summer of 1999 some seepage loss was observed from this field to a nearby canal. This problem was rectified during June or July (1999). It is also possible that AET did not reach PET for the very dry month of July.

A very similar pattern is seen in the F6 water balance (Figures 38 and 39, Appendix B.3). The ‘rainfall-PET-flow’ values indicate that the soil is drier than the 'soil water' line. The trees in field F6 were approximately 6 years old (in 1999), and it is possible that AET did not reach PET during the dry summer period. This would account for the discrepancy in the water balance. As in Fields F3 and F5, a dry soil zone likely formed in July that did not result in a corresponding water table drop.

Figure 40 indicates that there is an unaccounted for avenue of water loss in station F7. The weir outlet of field F7 is held high, resulting in a large hydraulic gradient between the outlet and surrounding canals. It is suspected that water is leaving this field through seepage to nearby drainage canals and that the measured flow data are not an accurate representation of the water leaving this field.

The water balance (not accounting for soil water storage) for subwatershed S4 is realistic on an annual basis; it balances within 5 cm (Figure 42). But, the estimated water balance is not as exact on a monthly basis. For the months of April through July, the

AET did not reach PET (not enough water available), but AET was indeed high enough that little or no flow occurred during these months.

The water balance for the mixed use (forestry and agriculture) subwatershed C2 is presented in Figure 41 (without consideration of soil water storage). In the months March through July, there was insufficient rainfall to meet PET; thus PET is an overestimate for AET for these months. If AET is less than PET in March through July, the annual water balance for this station would be very close without accounting for change in soil water.

For the agricultural stations T0 and T4 and the agricultural field H2 (Figures 43, 44, 45, and 46), the water balance does not include any irrigated water in the rainfall totals. Unknown amounts of irrigation were applied within T4 during the summer growing season. Liquid swine effluent was applied at various, unknown times throughout the year in subwatershed T0. The PET values for these areas were estimated for short grass cover. During January through July, the water balance for H2 considering soil water storage (Figure 44, Appendix B.4) indicates that either rainfall is underrepresented (due to unknown irrigation schedule) or that AET did not reach PET.

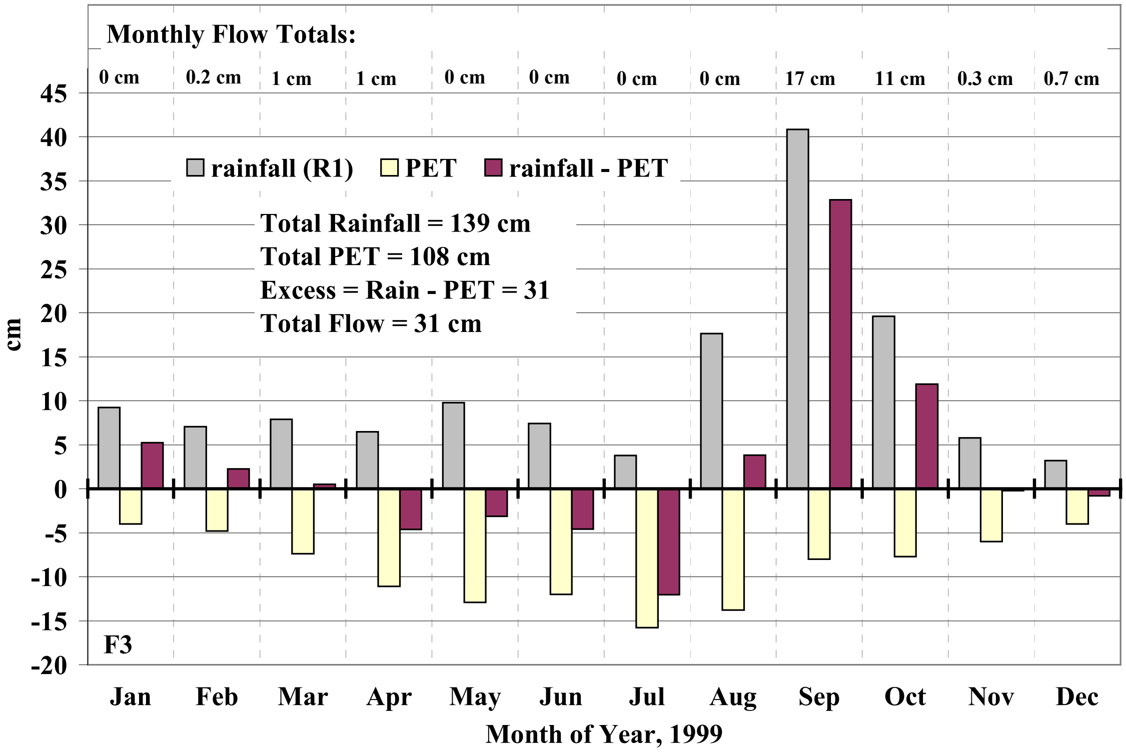

Figure 34. Monthly rainfall, PET, excess water, and flow totals for station F3 for 1999.

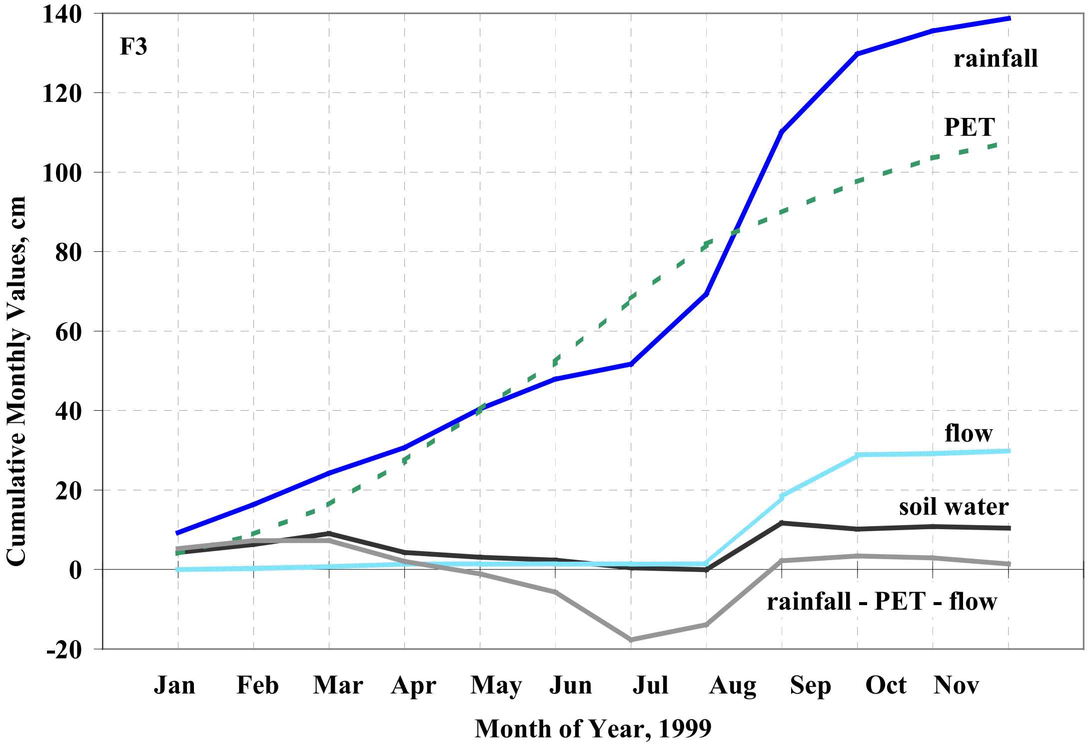

Figure 35. Cumulative water balance for station F3 for 1999.

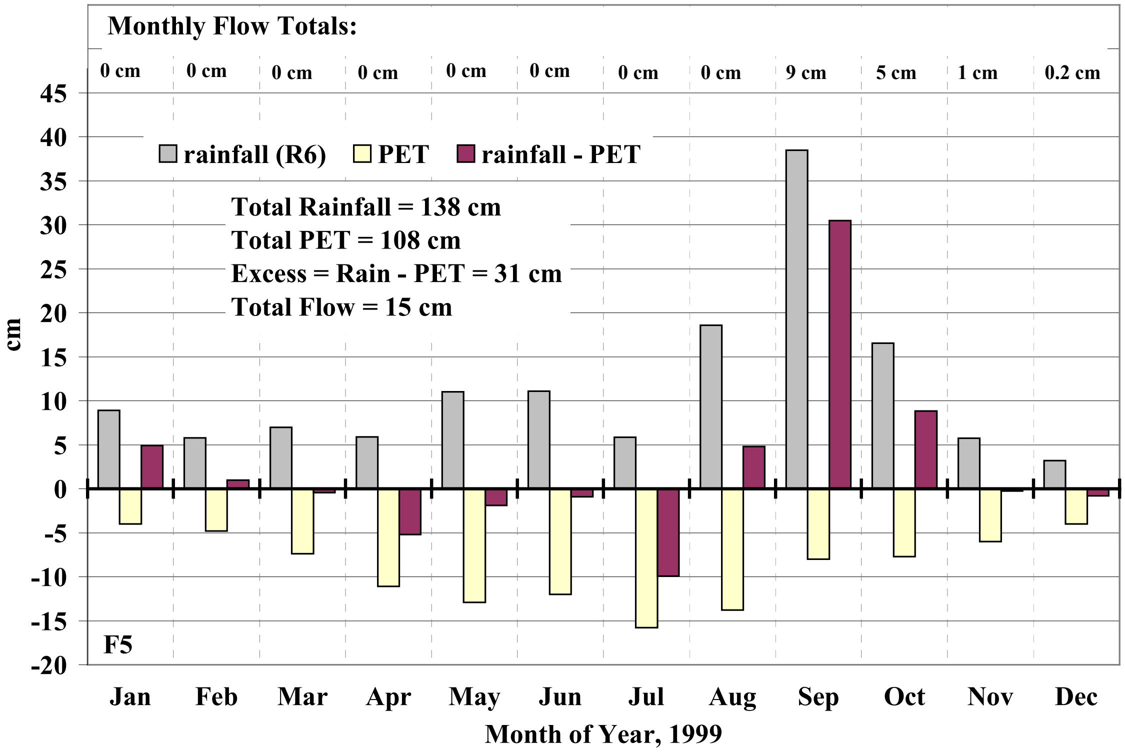

Figure 36. Monthly rainfall, PET, excess water, and flow totals for station F5 for 1999.

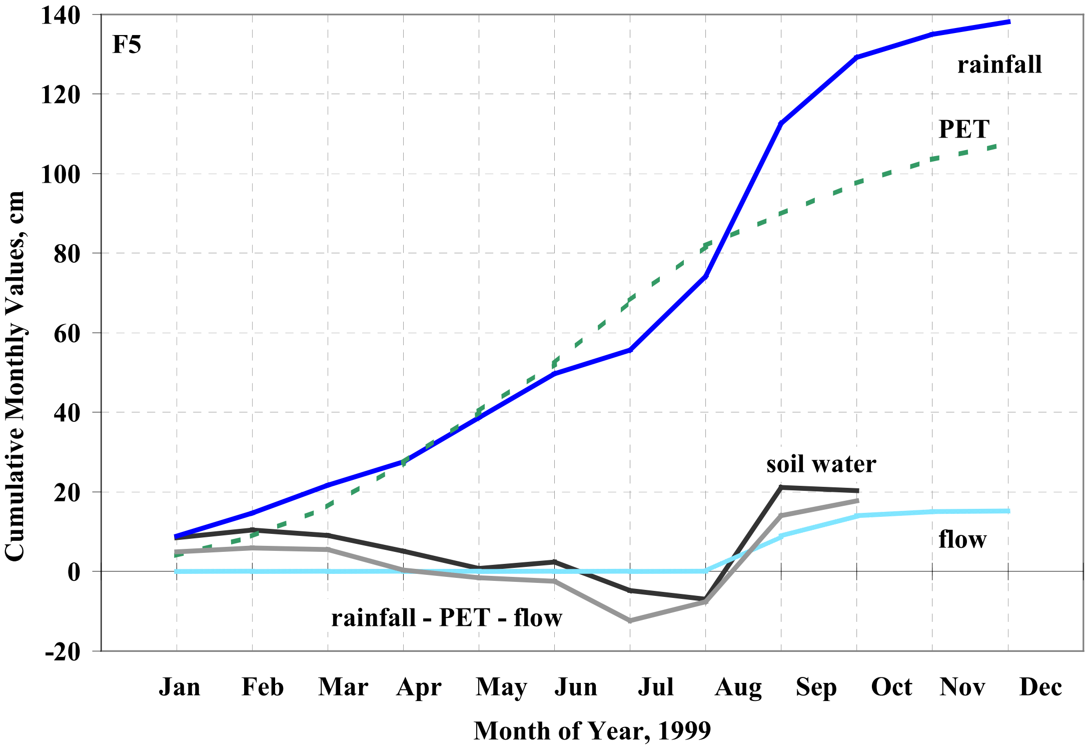

Figure 37. Cumulative water balance for station F5 for 1999.

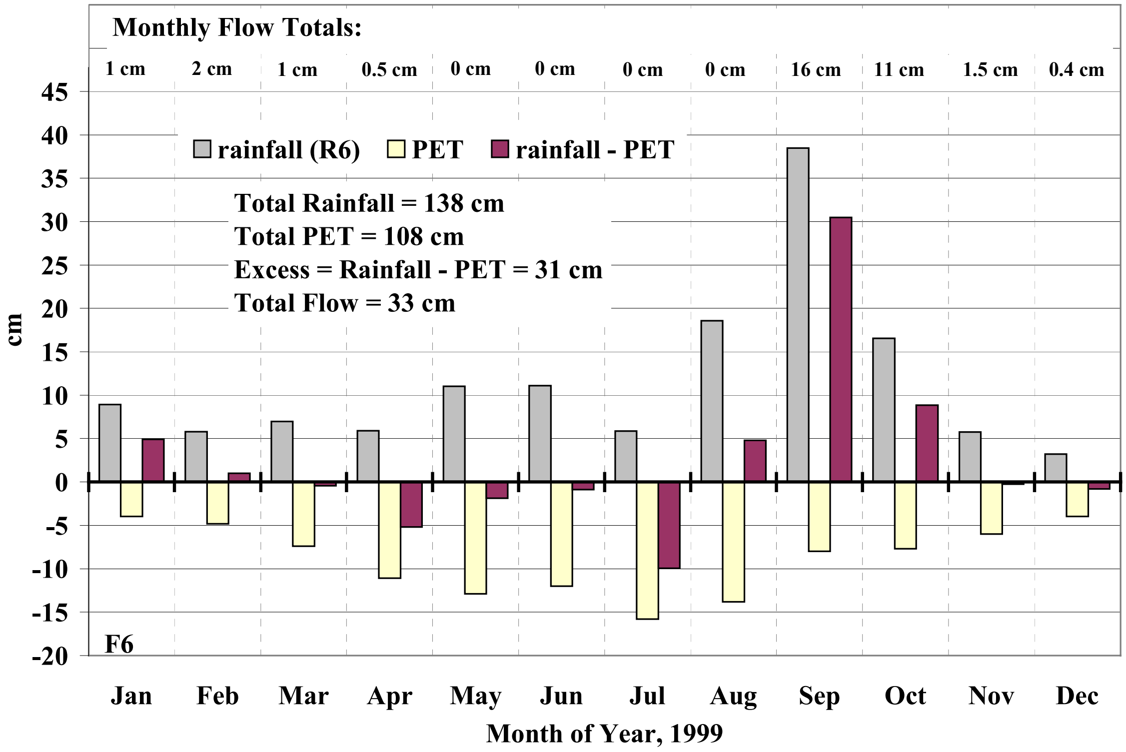

Figure 38. Monthly rainfall, PET, excess water, and flow totals for station F6 for 1999.

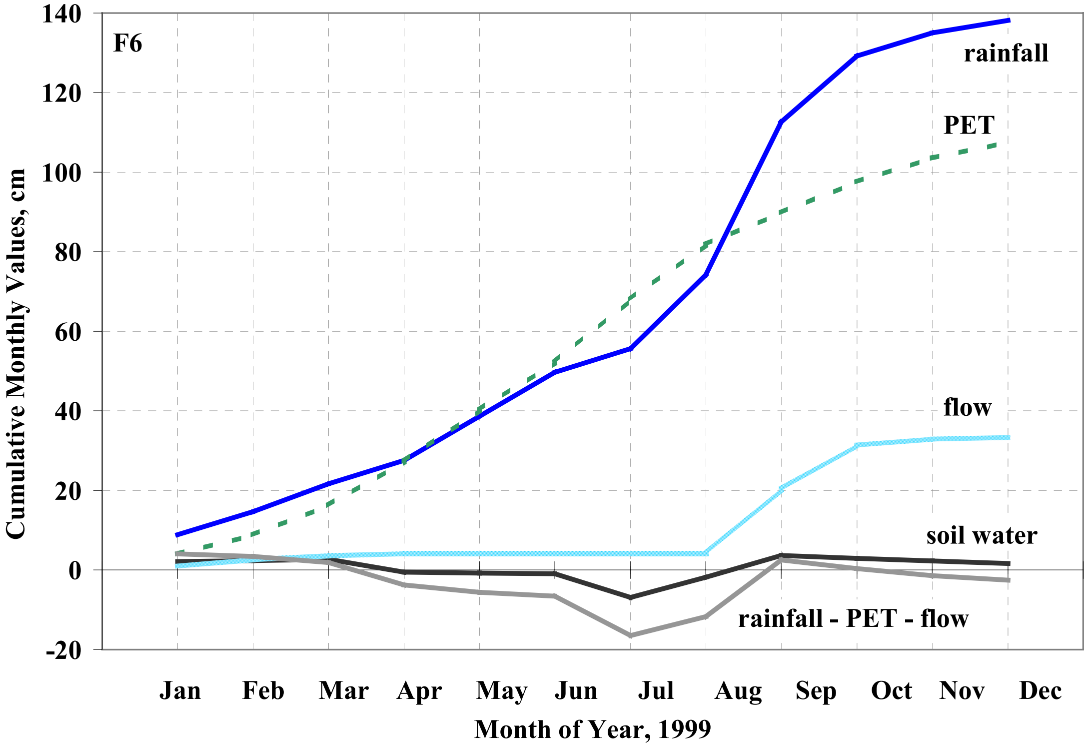

Figure 39. Cumulative water balance for station F6 for 1999.

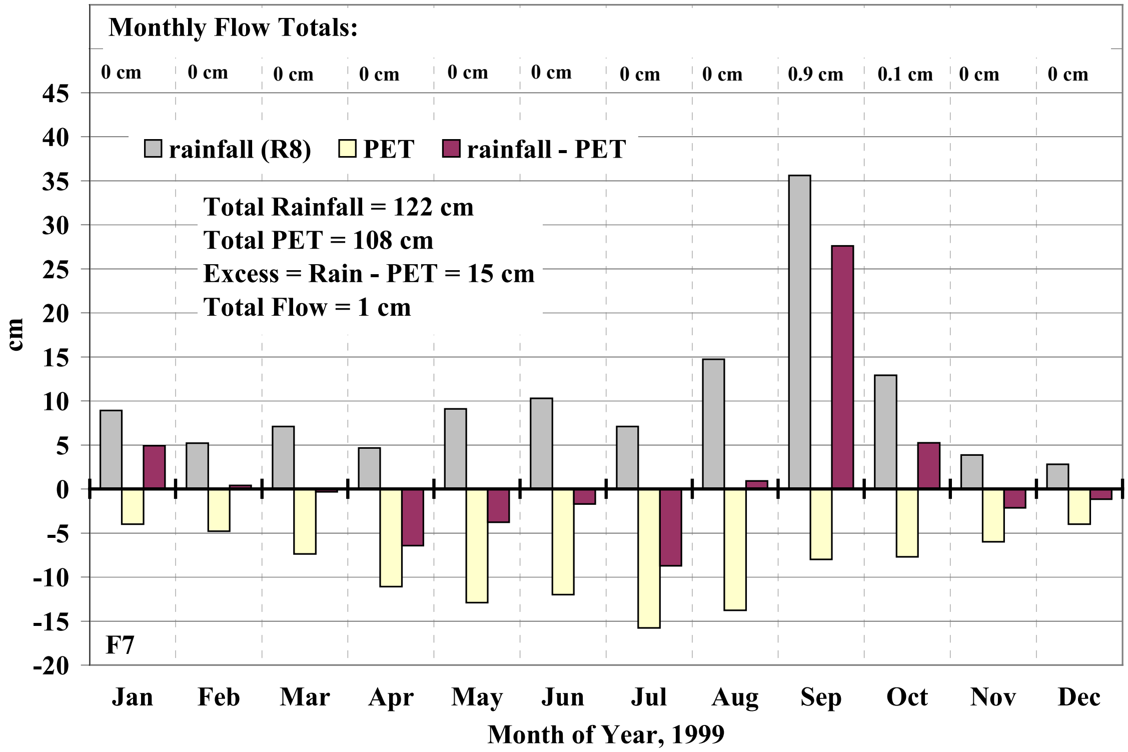

Figure 40. Monthly rainfall, PET, excess water, and flow totals for station F7 for 1999.

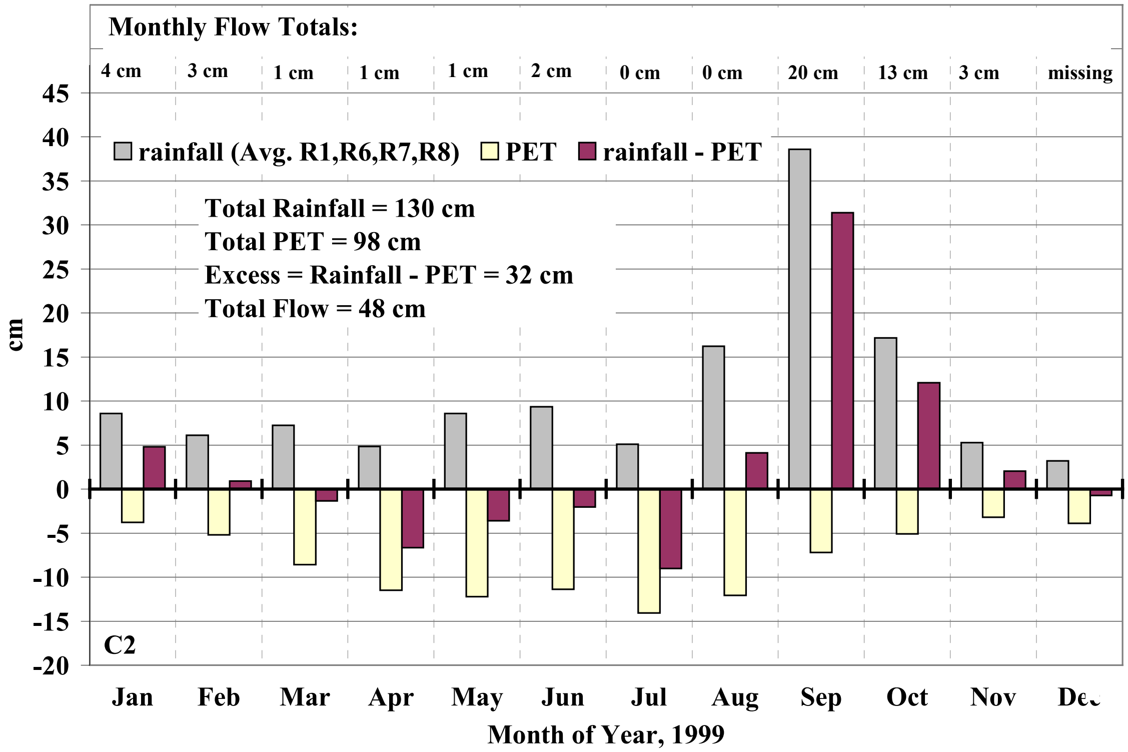

Figure 41. Monthly rainfall, PET, excess water, and flow totals for station C2 for 1999.

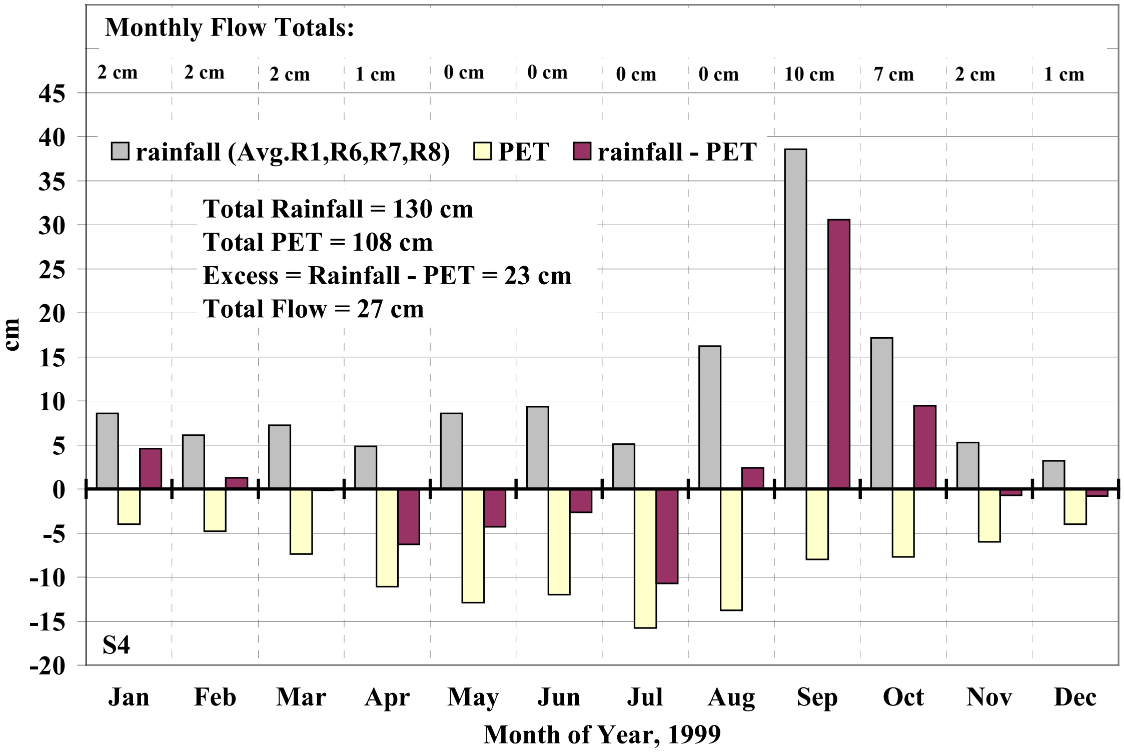

Figure 42. Monthly rainfall, PET, excess water, and flow totals for station S4 for 1999.

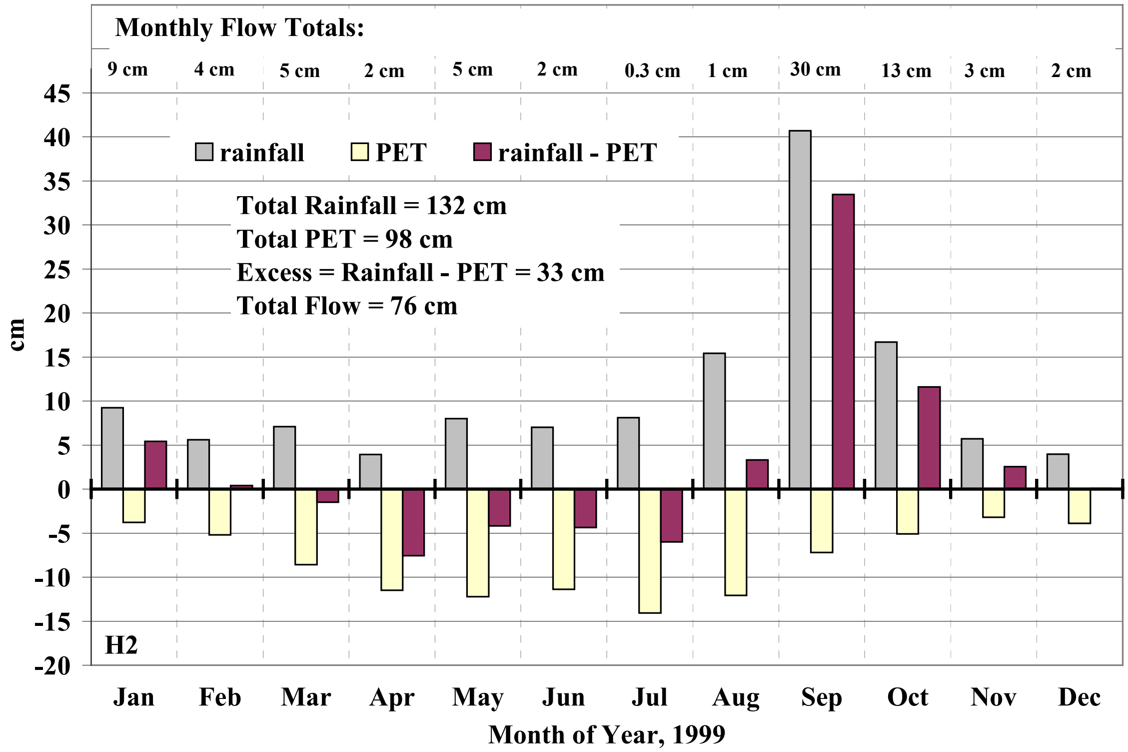

Figure 43. Monthly rainfall, PET, excess water, and flow totals for station H2 for 1999.

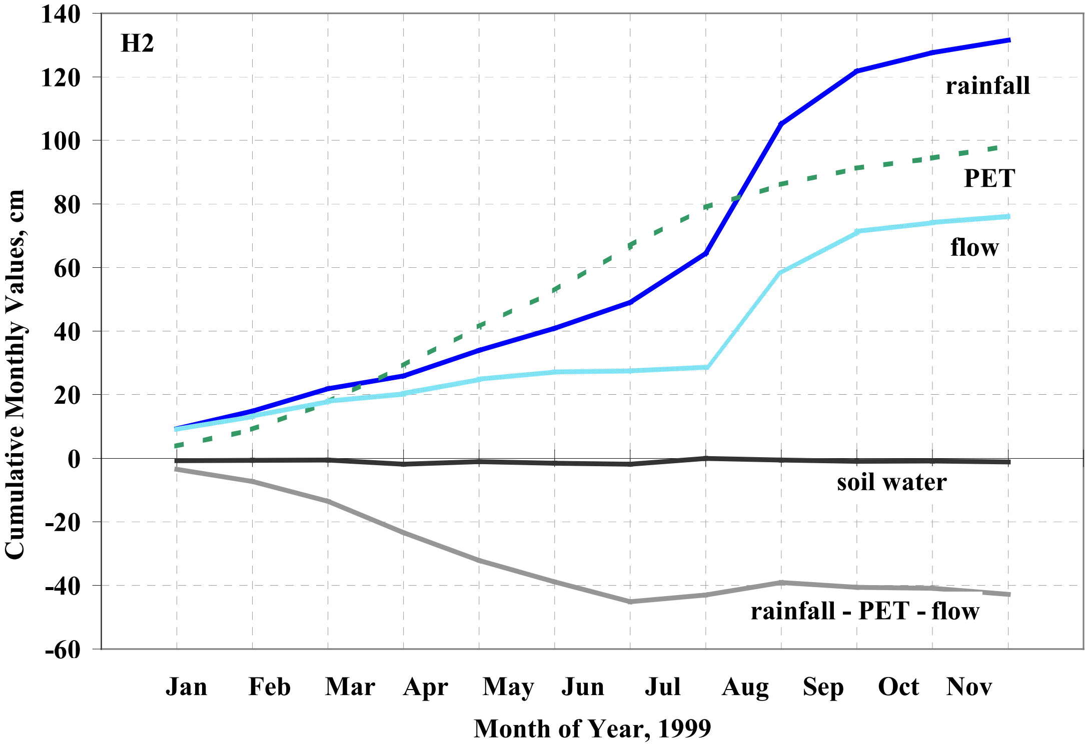

Figure 44. Cumulative water balance for station H2 for 1999.

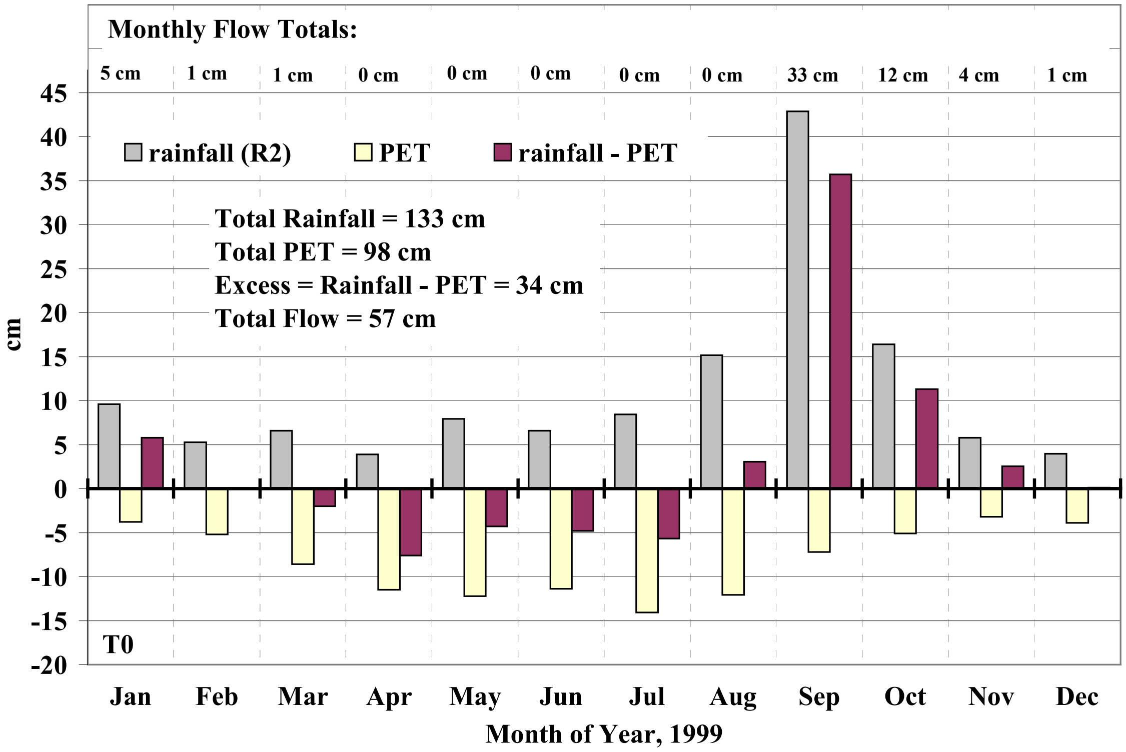

Figure 45. Monthly rainfall, PET, excess water, and flow totals for station T0 for 1999.

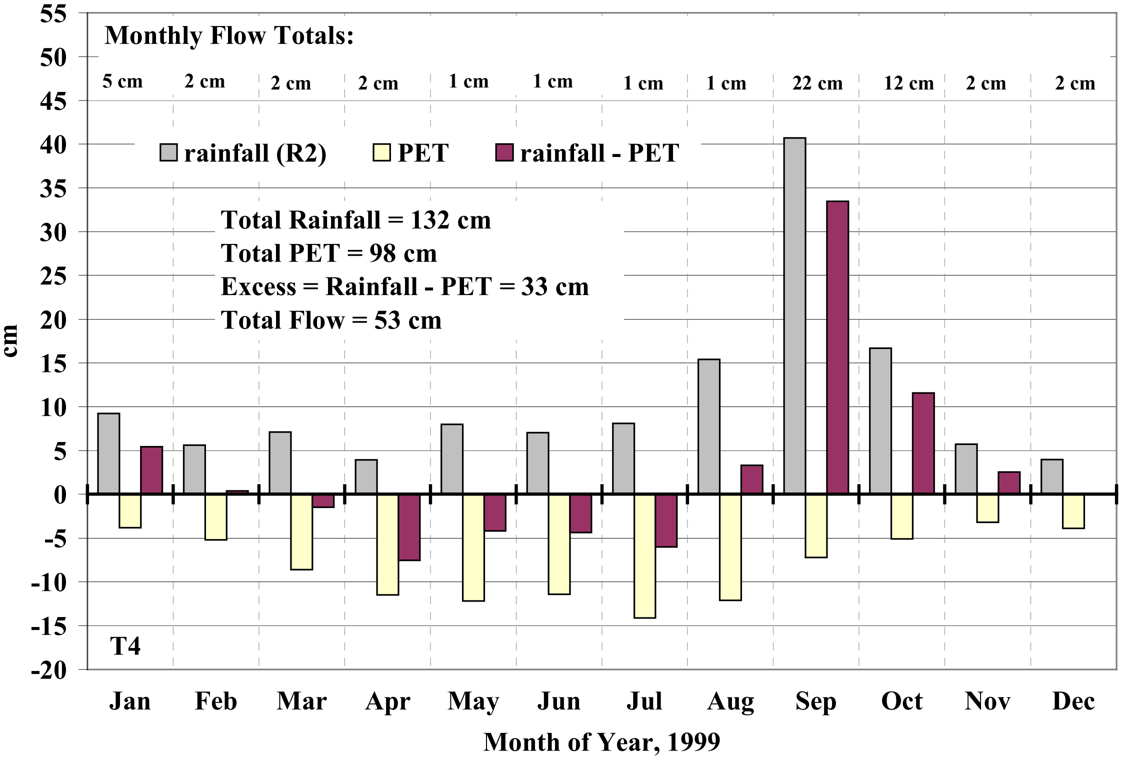

Figure 46. Monthly rainfall, PET, excess water, and flow totals for station T4 for 1999.

Flow

Daily flow values were computed on a per area basis for each station for the entire 4-year study period (Figures 47 through 54). These plots allow the magnitude of flows resulting from the hurricanes and tropical storms of 1999 to be viewed relative to other noteworthy events measured in the research watershed (see also Figures 16, 18, 20, 22, 24, 26, 28, 30, and 32 for closer look at data during hurricanes).

For subwatershed C2, the flow record was obtained for January 1 through November 29 of 1999 only (Figure 47). This is a mixed use subwatershed containing managed pine stands as in S4 (~ 50 %) and cropping similar that in T4 subwatershed (~ 50 %). Many of the soils in C2 are organic and porous, like the soils of subwatershed S4. Additionally, it is much larger than T4. Based on the available C2 data from 1999, it appears that the peak flows for this subwatershed are of longer duration for a given rainfall event than the peak flows observed in T4. Similarly, in the large forested subwatershed S4, peak flows associated with a given rainfall event were prolonged. For large flow events, peak rates are limited by the canal capacity due to very low canal slope and insufficient depth, particularly in subwatershed C2. The canals simply can not convey large flow volumes more quickly.

For the field station F3 (within C2), flow is commonly very low, or zero during the dryer summer months (Figure 49). The peak associated with hurricane Floyd (~35,300 m^3/day) dominates the four-year record and occurred on September 16, 1999; this flow volume is equivalent to 7.5 cm of runoff over the watershed area (47 ha; Figure 16). This is a small field-scale station which results in brief peak flow periods exhibited for each storm event.

For the large S4 subwatershed, flow associated with hurricanes Bertha and Fran (1996), tropical storm Josephine (1996), and El Nino related storms (1998) are indicated in the plot along with flow peaks associated with the storms of 1999 (Figures 48 and 28). Interestingly, Hurricane Bonnie made landfall in North Carolina producing approximately 10 cm rainfall on August 26, 1998, but produced no flow at this site due to dry antecedent conditions. Hurricane Floyd of 1999 undoubtedly produced the largest flow peak compared to the other large events on record, for station S4 as well as for field-scale stations within S4 (F5, F6, F7, Figures 48, 50 through 52). The highest flow rate from Floyd was measured at S4 on September 17, 1999 (Table 9). This flow rate was approximately 364,200 m^3/day, which corresponds to a 1.24 cm depth of runoff over the entire watershed area (2948 ha). The large peak flows resulting from Hurricane Floyd are partially due to the rainfall from Hurricane Dennis, which saturated the profile and raised the water table prior to Hurricane Floyd. As a result, most of the rainfall from Hurricane Floyd was removed by surface runoff and shallow subsurface drainage.

The flow data presented for each station, with the exception of F7, are a good representation of the actual flow occurring for each storm event. During the large hurricane or tropical storm related events, the weirs typically were submerged and backflow occurred in some locations. These conditions were accounted for as much as possible, but studies have indicated that the weir equations used to estimate flow during highly submerged conditions may underestimate true flow. Consequently, the flow associated with hurricane Floyd may be underestimated. This phenomenon does not apply to F3, where flow during the hurricanes was predicted by DRAINMOD.

In Figure 48 it is clear that the large S4 watershed produces flow at the outlet throughout most of the year, which is partly attributable to the deeper depth of the main drainage canal (compared to field ditches). Because the S4 drainage area is large, the flow hydrograph due to a given storm event is somewhat attenuated. The peaks are moderated by the large time of concentration and low hydraulic gradient, and high flow rates are often maintained for a long duration. Another reason this outlet station has sustained high flows after an event is due to the controlled nature of the watershed. The weir structures placed in the upper portions of the watershed contribute somewhat to the attenuation of storm hydrographs. Because this subwatershed has a thick cover of vegetation (forest) and the high drainable porosity of the organic soil, there is very little (if any) surface runoff in this site. The S4 soils store a great deal of water (compared to the mineral soils of T4); the water leaves the system as shallow subsurface drainage.

Very similar daily flow patterns were observed for the forested field stations, within S4 (Figures 50-52). With the exception of station F7, peak flows associated with hurricane Floyd were the largest on record for these stations:

21,100 m^3/day (1.7 cm over 127 ha) for F5;
30,600 m^3/day (3.4 cm over 90 ha) for F6;
3,300 m^3/day (0.21 cm over 160 ha) for F7.

Peak flow due to Floyd was measured on September 17, 1999 for station F7, and on September 16 for the remaining forested field stations (Table 9). The flow data presented for station F7 underestimates the actual drainage amount from this field. Much of the drainage bypassed the measuring station via seepage from the collector canal to the main drainage canal; the F7 water balance collaborates this presumption.

Table 9. Comparison of peak flow dates per station for each storm event relative to days rainfall occurred and flow amounts from each storm event.

Storm Event	**Days, 1999**	**Day of Peak Measured Flow Associated with the Storm Followed by Total Flow For Each Storm Period**							
		T4	**T0**	**S4**	**F3**	**F5**	**F6**	**F7**	**C2**
Hurricane Dennis (I)	Day of Peak Flow	8/31	8/30	no flow	no flow	no flow	no flow	no flow	9/1
Rainfall Days 8/29–9/1	Flow Period:	8/29–9/2	8/29–9/2	8/29–9/2	8/29–9/2	8/29–9/2	8/29–9/2	8/29–9/2	8/29–9/2
	mm of Flow:	2.9	1.7	0	0	0	0	0	2.4
Hurricane/ Tropical Storm Dennis (II)	Day of Peak Flow	9/4	9/3	9/ 8	9/9	9/7	9/7	no flow	9/7
Rainfall Days 9/3-9/7	Flow Period:	9/3–9/13	9/3–9/13	9/3–9/13	9/3–9/13	9/3–9/13	9/3–9/13	9/3–9/13	9/3–9/13
	mm of Flow:	59.1	110.7	10.8	0.4	1.2	8.3	0	64.9
Hurricane Floyd	Day of Peak Flow	9/16	9/15	9/17	9/16	9/16	9/16	9/17	9/16
Rainfall Days 9/14–9/16	Flow Period:	9/14-10/16	9/14-10/16	9/14-10/16	9/14-10/16	9/14-10/16	9/14-10/16	9/14-10/16	9/14-10/16
	mm of Flow:	164.2	227.5	108.9	180.1	95.2	164.0	9.1	163.3
Hurricane Irene	Day of Peak Flow	10/18	10/17	10/19	10/17	10/18	10/18	10/21	10/21
Rainfall Days 10/17–10/18	Flow Period:	10/17-11/1	10/17-10/25	10/17-11/25	10/17-11/1	10/17-11/17	10/17-11/3	10/17-11/27	10/17-11/24
	mm of Flow:	113.2	104.4	72.3	94.9	52.4	102.1	1.1	115.9

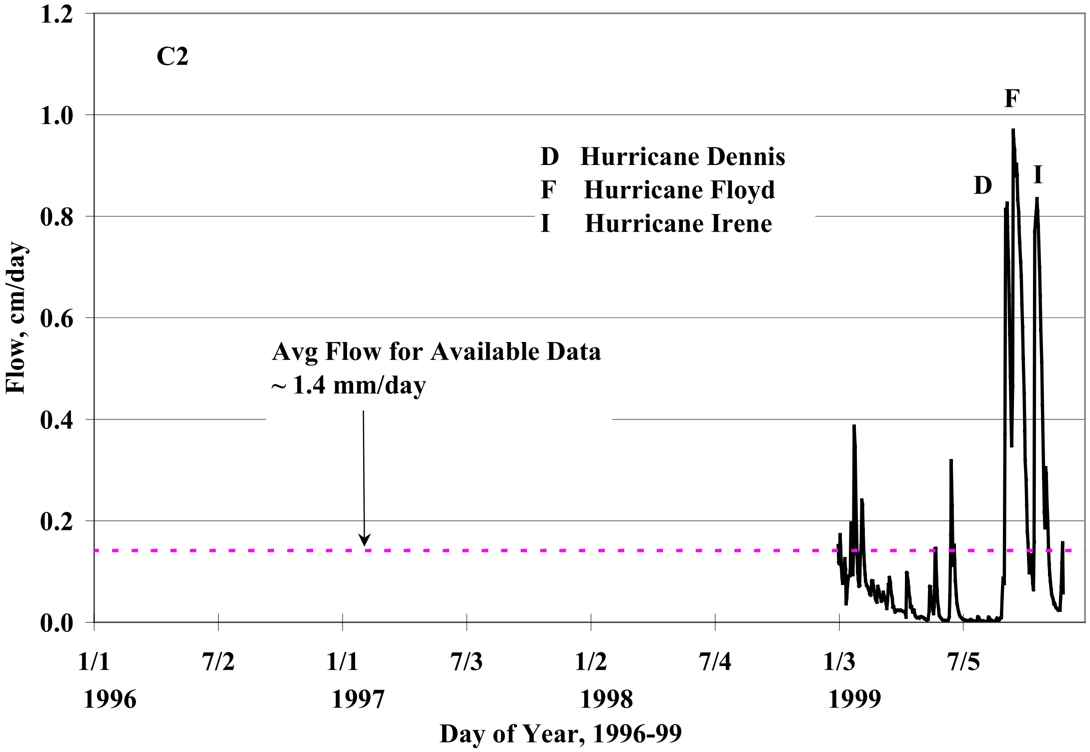

Figure 47. Daily flow at station C2 (drainage area 2700 ha); peaks of large events are labeled and average daily flow is included; only 1999 data available.

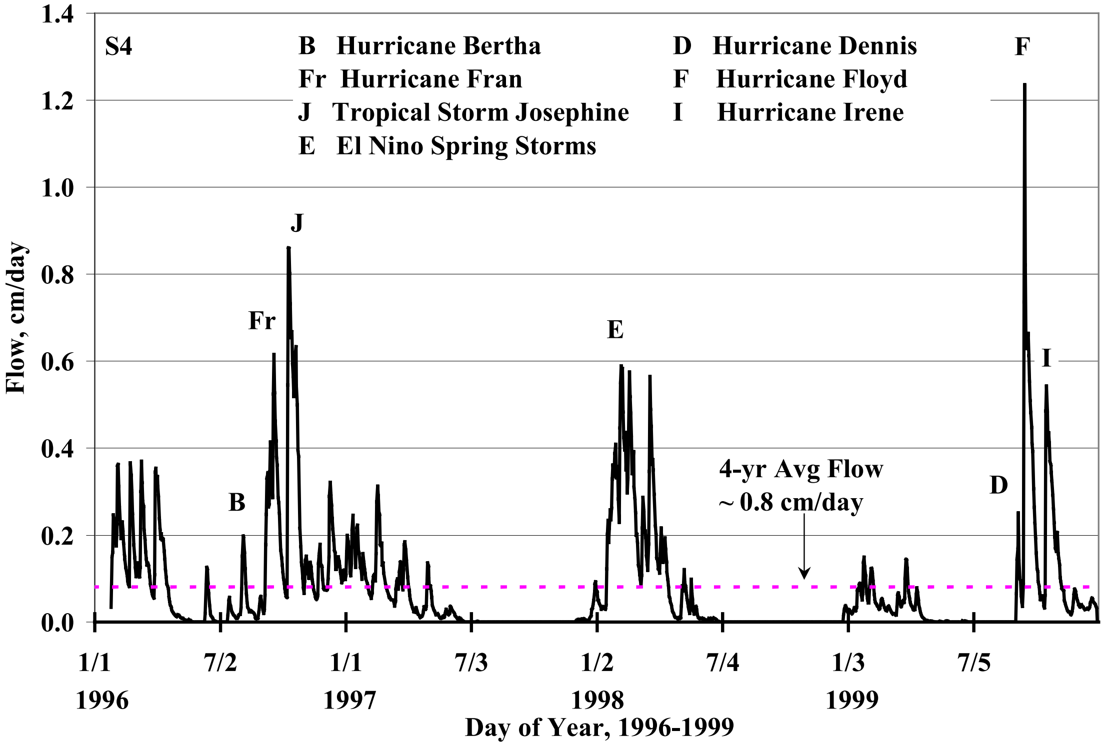

Figure 48. Daily flow at station S4 (drainage area 2948 ha) for years 1996-99; peaks of large events are labeled and average daily flow is included.

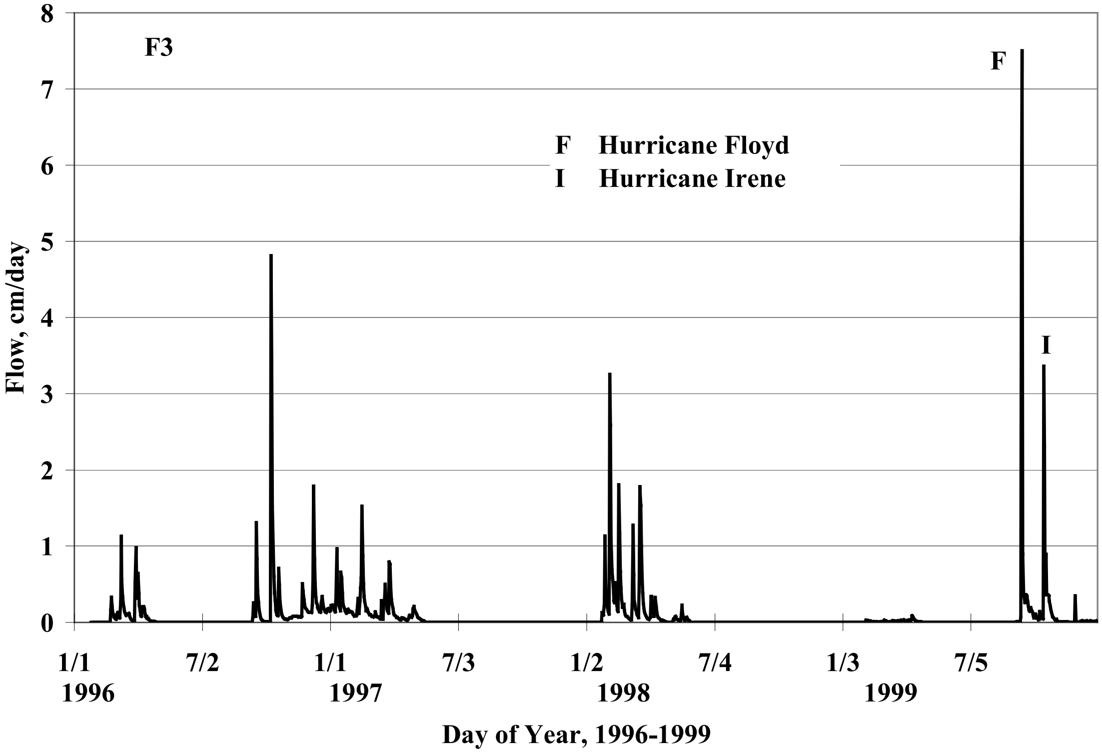

Figure 49. Daily flow at station F3 (drainage area 47 ha) for years 1996-99.

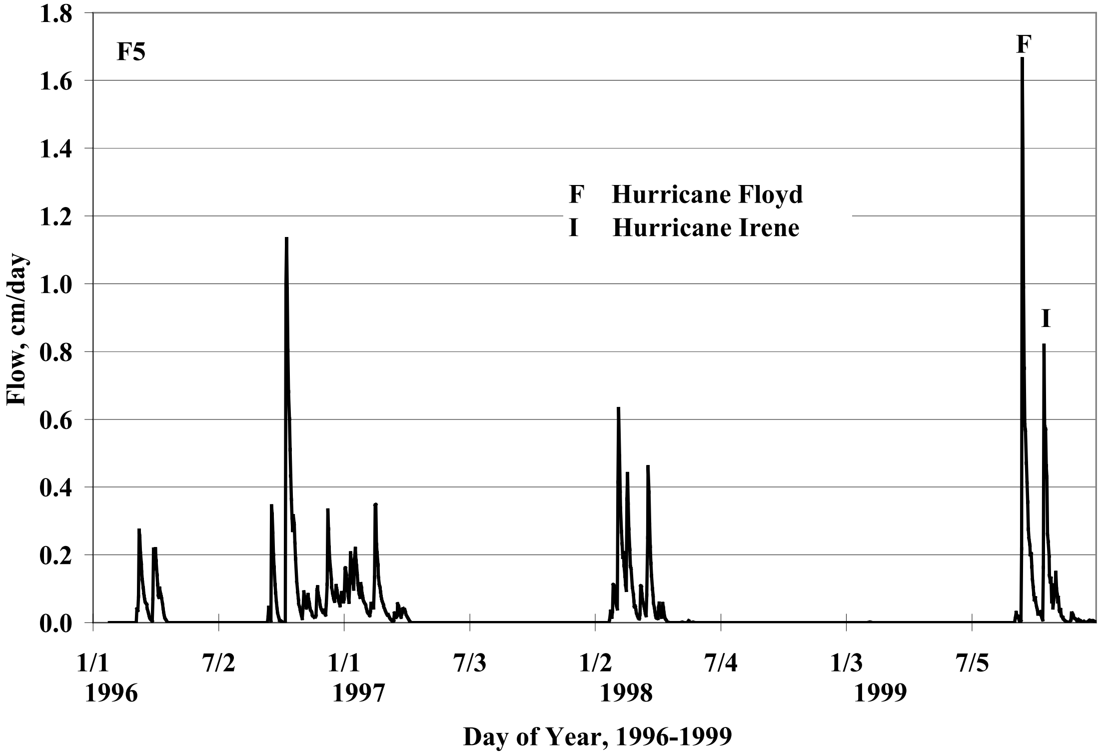

Figure 50. Daily flow at station F5 (drainage area 127 ha) for years 1996-99.

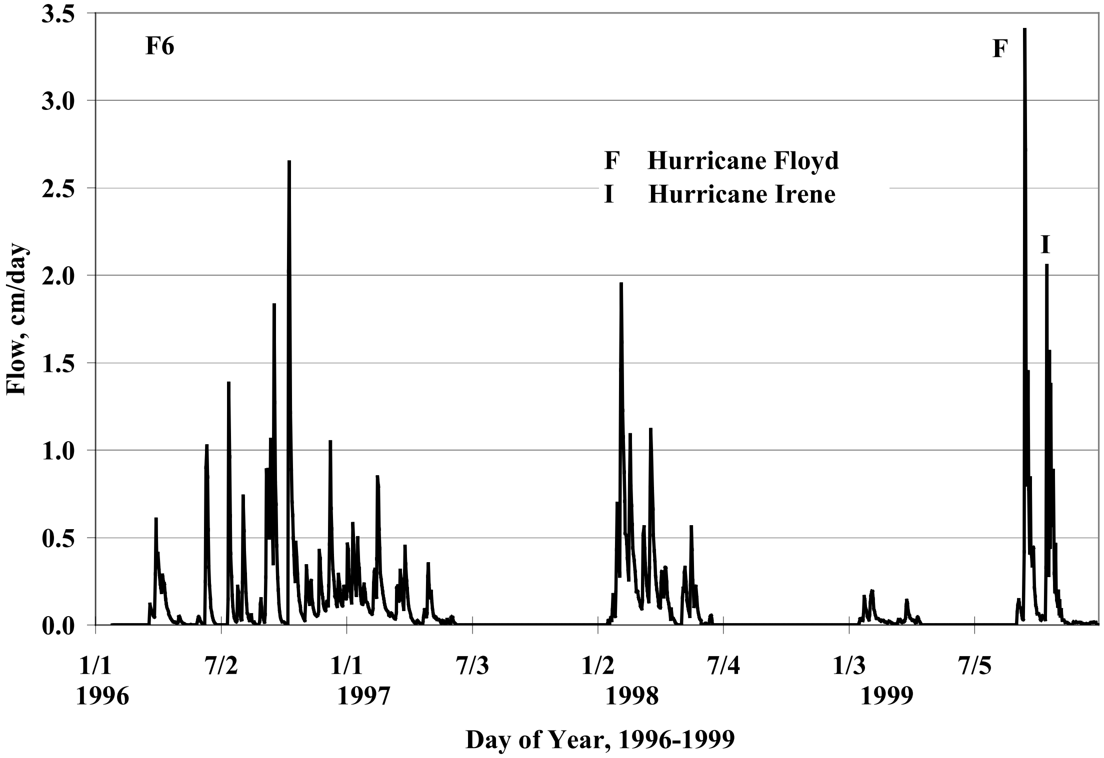

Figure 51. Daily flow at station F6 (drainage area 90 ha) for years 1996-99.

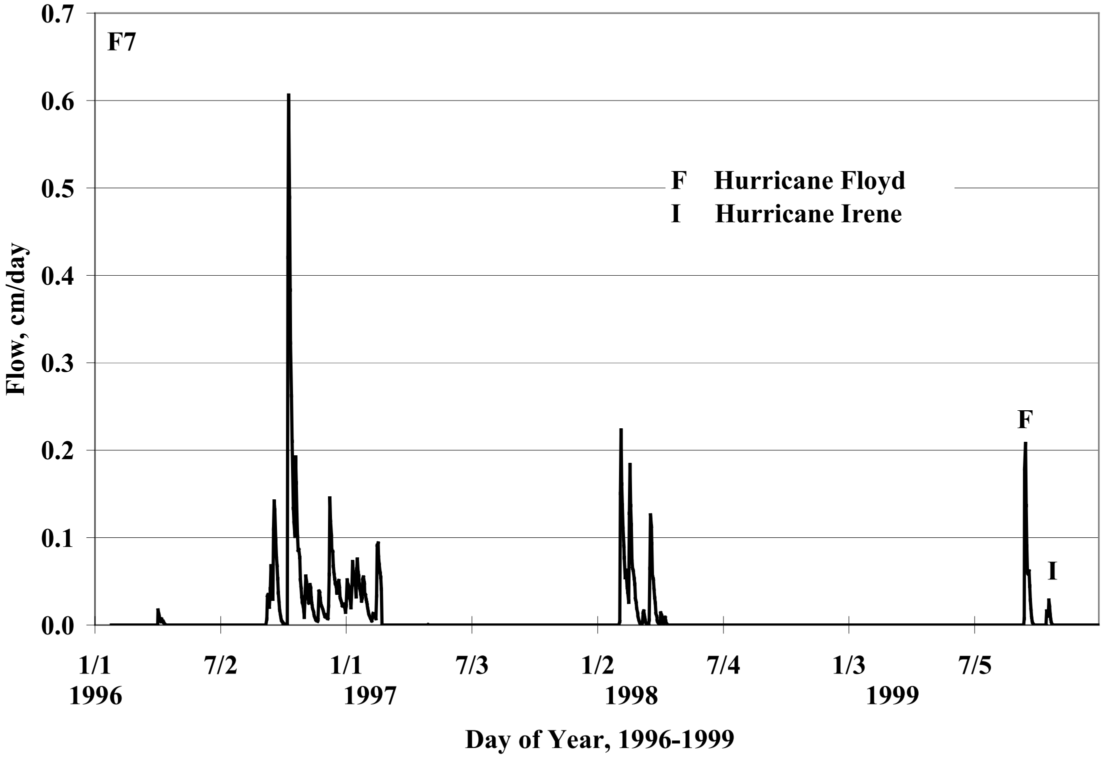

Figure 52. Daily flow at station F7 (drainage area 160 ha) for years 1996-99.

The agricultural subwatershed, T4, also produced flow at the outlet throughout most of the year (Figures 53, 32). Flow peaks for given storm events were shorter in duration, and a greater range of flow rates occurred throughout the year than in S4. The T4 subwatershed is smaller than the S4 subwatershed, 710 ha compared to nearly 3000 ha. This subwatershed (T4) consisted of both pasture and cropped fields (with some forest/wetland), lands which have low surface storage. The majority of the soils in the T4 subwatershed are very poorly drained mineral soils with a low drainable porosity and relatively low hydraulic conductivity. The low drainable porosity, or volume for water storage, causes water table to fluctuate more rapidly in the agricultural watershed than in the forested subwatershed. This subsequently contributes to the quick response seen in measured flows for a given rainfall event. The T4 subwatershed, with low surface storage and poorly drained, low drainable porosity soils tends to produce runoff quicker (and thus less subsurface drainage), resulting in a more 'flashy' runoff response than the forested areas. Another difference between T4 and S4 is that irrigation water was added to some of the fields within T4 during dry periods of summer. The exact date or amounts of irrigation within the T4 watershed are unknown. Nevertheless, any unexplained increases in measured canal flow that are not attributable to a measured rainfall event are likely the result of an irrigation event.

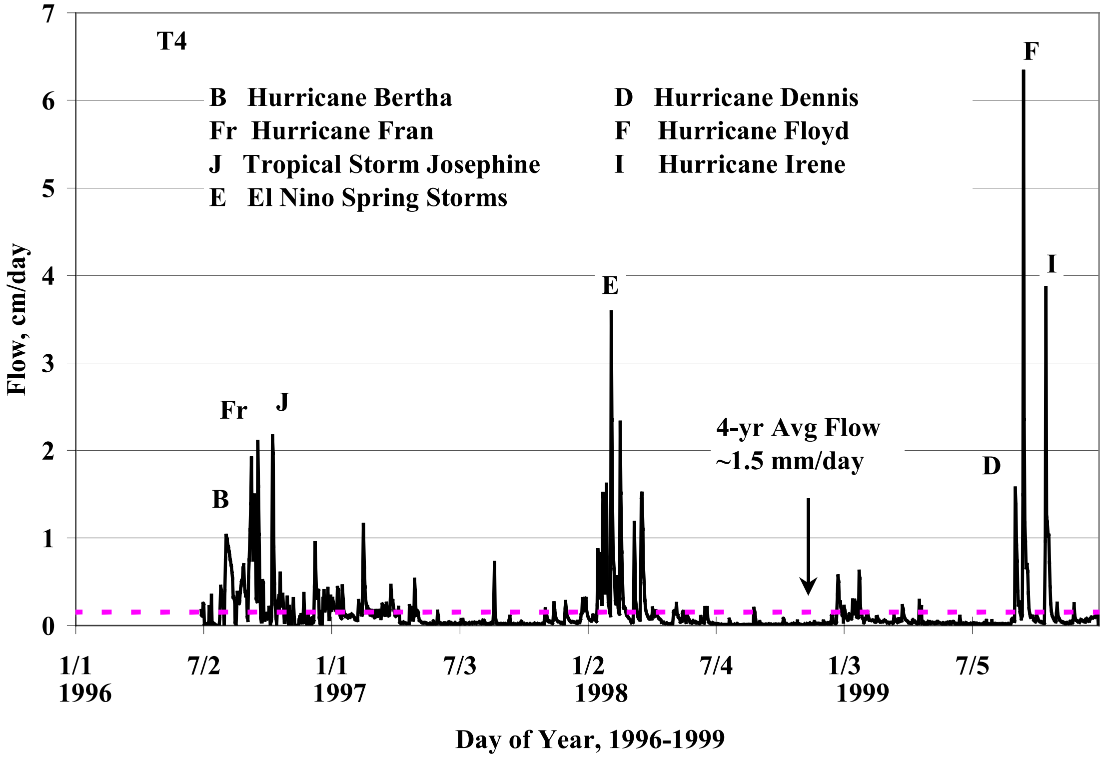

Figure 53. Daily flow at station T4 (drainage area 710 ha) for years 1996-99; peaks of large events are labeled and average daily flow is included.

The daily flow record for station T0 (a component of T4) is presented in Figure 54 (see also Figure 30). The subwatershed T0 contains a swine waste lagoon and pasture areas where lagoon effluent is land applied. As expected T0 (50 ha), behaves much like T4, with regard to the sharp, short duration flow peaks observed. The largest flows on record were observed following hurricane Floyd. Interestingly, for T0 the largest event after Dennis, Floyd, and Irene was associated with hurricane Fran (fall of 1996). But, the largest flow peak observed in the larger T4 watershed after Floyd and Irene was due to the winter El Nino storms in 1998 (due to wet antecedent conditions).

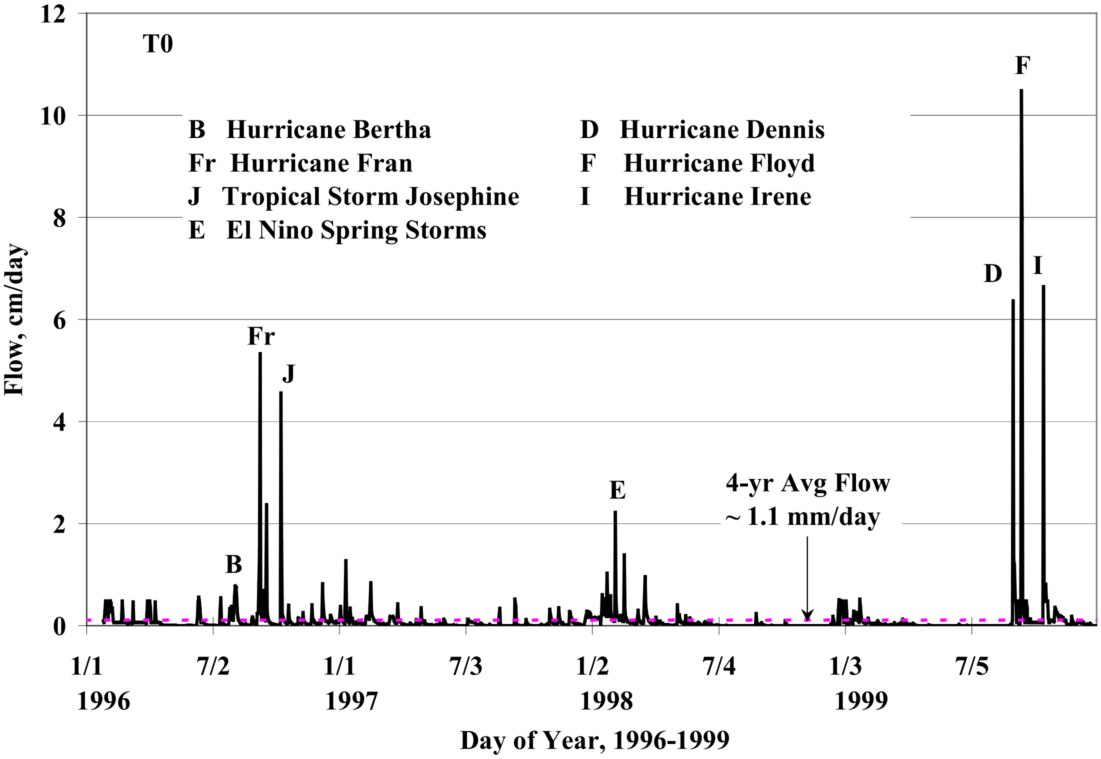

Figure 54. Daily flow at station T0 (drainage area 50 ha) for years 1996-99; peaks of large events are labeled and average daily flow is included.

The daily flow depth measured for subwatersheds T4, S4, and C2 are compared for the hurricanes of 1999 in Figure 55. To make a more definitive comparison based on the land use for the subwatersheds S4 (forest), T4 (agriculture), and C2 (agriculture), a cumulative plot for 1999 (Figure 56) of flow depth over watershed area was also produced for each station. Each subwatershed received approximately 130 cm of rainfall in 1999. Additionally, T4 received an unknown amount of irrigation. Measured drainage for T4 and C2 was nearly twice that of S4 (51.3 cm and 48.1 cm, respectively vs. 26.6 cm). The drainage total was lower for S4 that for T4 or C2 because the forested areas have greater ET than the agricultural areas

The forested area (S4) has continuous vegetation with a deeper rooting depth compared to the agricultural areas (T4 and C2). Also, 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, as is the ET demand. This becomes very evident during the dry period preceding the storms of 1999 and in the response of each subwatershed to those storms.

At the end of the dry period the water table in the S4 subwatershed was approximately 1.7to 1.8 meters deep (Figures 16, 18, 20, and 26). Assuming drained to equilibrium conditions, this depth would correspond to approximately 30 cm of pore space in the forested soils (Figure 32, F5 and F6). On the agricultural lands (C2 ag. water table, T4) the water table was approximately 1.0 m deep at the end of the dry period (Figures 24, 30), which corresponds to approximately 3 cm of dry pore space (Figure 32, H2). The actual soil pore space was presumably greater for all subwatersheds since a surface dry zone had most likely formed, thus making the drained to equilibrium assumption an underestimation of pore space. Regardless of this underestimation, it is evident that more actual ET occurred from the forested subwatershed (S4) than from the agricultural subwatersheds (T4 and C2).

When the hurricanes of 1999 occurred, the pore space on the agricultural subwatersheds filled faster than on the forested subwatershed. A small amount of flow occurred from T4 and C2`, and no flow occurred at S4 in response to the first passage of hurricane Dennis. Much greater amounts of flow occurred from T4 (5.9 cm) and C2 (6.5 cm) than from S4 (1.1 cm) after the return of Dennis as a tropical storm. The pore space in the T4 and C2 soils apparently filled up during the first passage of Dennis, while the pre space in the S4 soils filled up during the second passage of Dennis. The flow volumes in response to hurricane Floyd where high from all of the subwatersheds since the soil pore space in each subwatershed was filled prior to this storm.

While the flow volume in response to the storms are similar for T4 and C2, the peak flow rates are much lower for C2. This is due to the limited capacity of the canal draining C2. From Figure 55, the apparent capacity of the C2 outlet canal is approximately 0.8 cm/day.

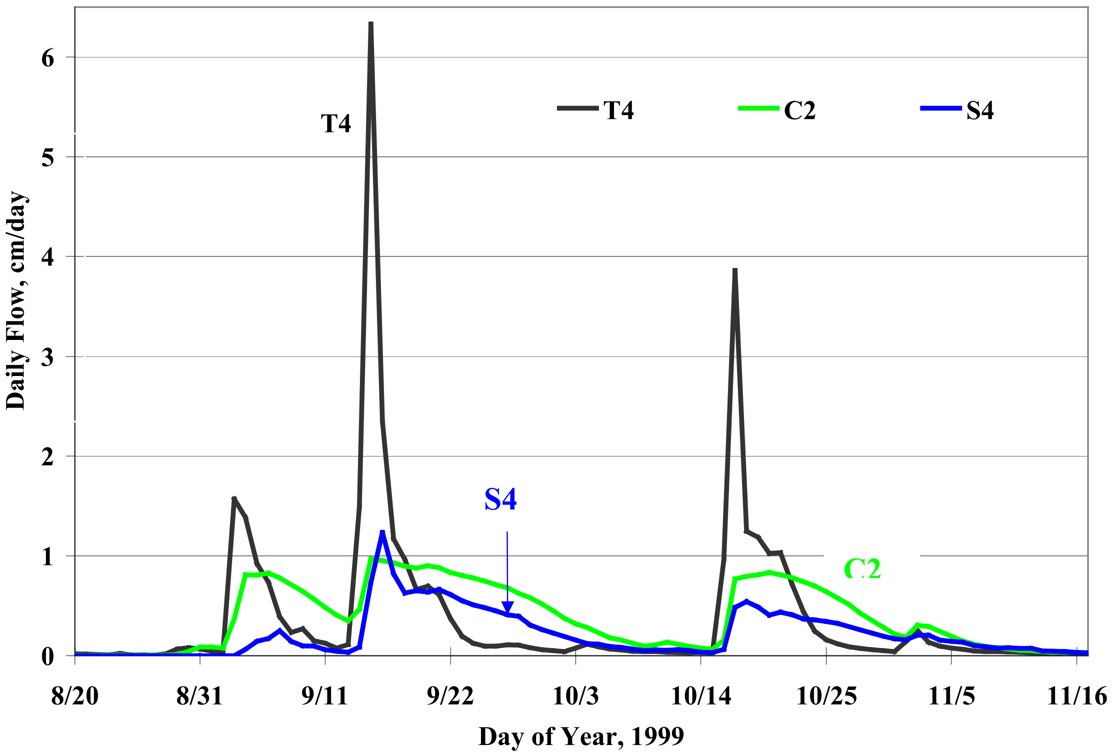

Figure 55. Comparison of daily flow from subwatersheds T4, S4, and C2 during the hurricanes of 1999.

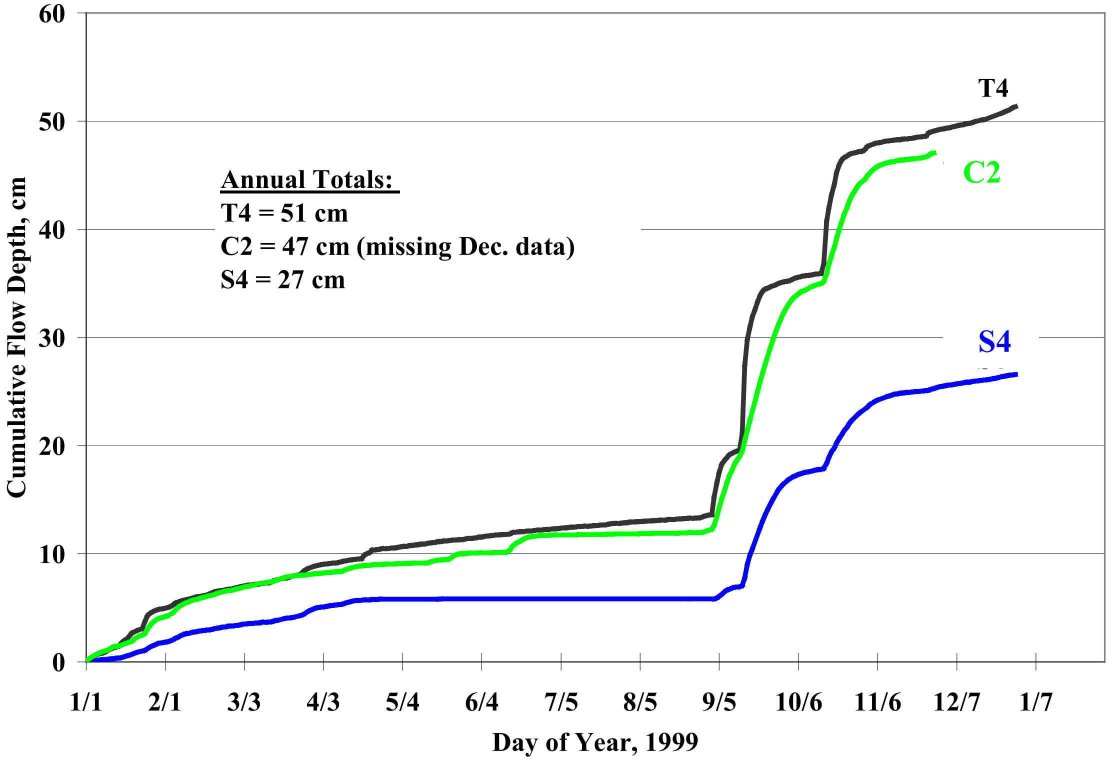

Figure 56. Comparison of cumulative flow from subwatersheds T4, S4, and C2 for 1999.

Flow Probability

Hurricane Floyd of 1999 produced unprecedented flows in the research watershed. Probability plots were produced using the entire flow data set (1996-1999) to illustrate the magnitude of the hurricanes of 1999 relative to previous large events on record. This was done for the two subwatersheds S4 and T4, where complete data records were available (Figures 57 and 58). The largest daily flow on record from the S4 subwatershed was measured during hurricane Floyd, followed by tropical storm Josephine in 1996 (Figure 57).

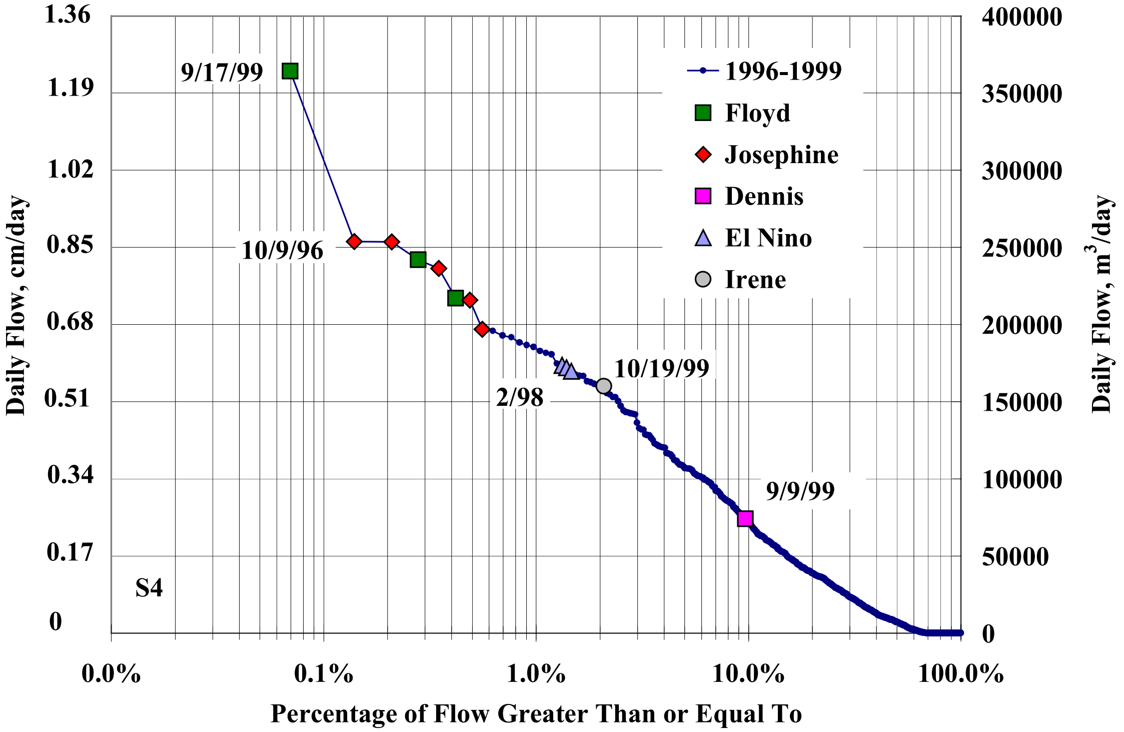

Figure 57. S4 daily flow probability of exceedance for years 1996-99.

A very similar plot was produced for the primarily agricultural subwatershed, T4 (Figure 58). Again, hurricane Floyd produced the largest flow on record, but the second largest flow measured for this subwatershed was associated with hurricane Irene. Larger flow rates were measured from this subwatershed than for S4, as was previously noted. The T4 subwatershed is smaller, less vegetated, more drained by surface drainage, and responds more quickly to short duration, high intensity rainfall events than the forested subwatershed. Both of these plots indicate that hurricane Floyd was indeed a major event in the research watershed. In T4, the February El Nino storms of 1998 produced high flows due partly to the storms timing. The El Nino storms occurred during the non-growing season when ET is lower and antecedent moisture conditions are higher.

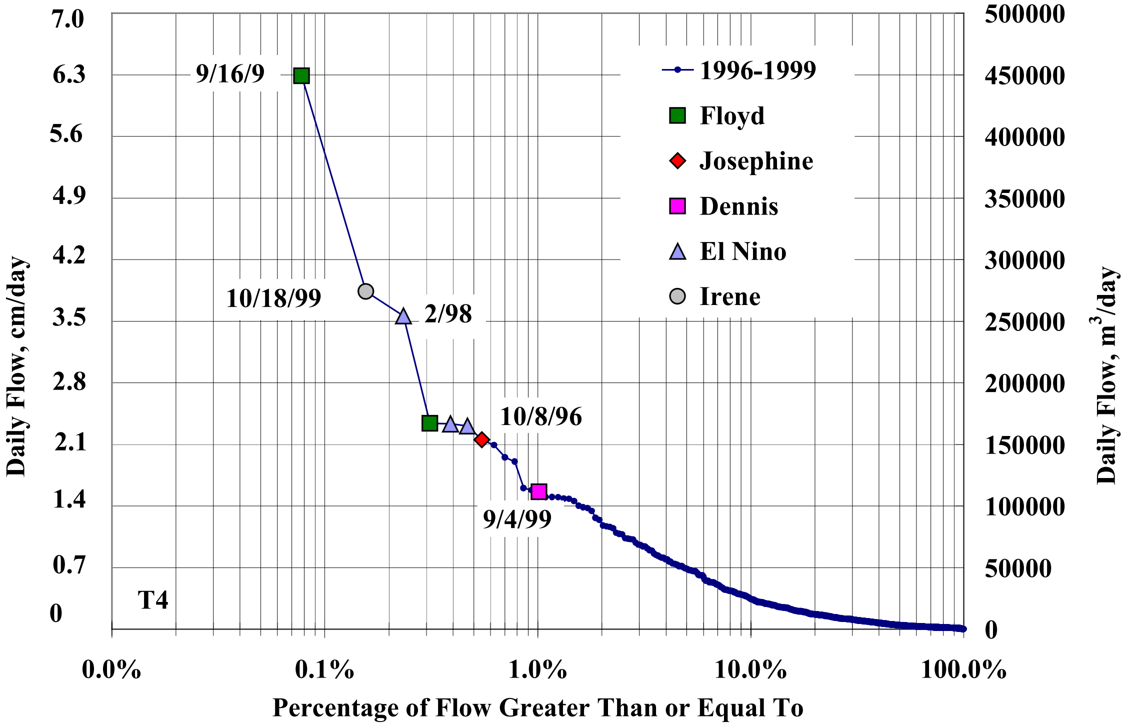

Figure 58. T4 daily flow probability of exceedance distribution for years 1996-99.

Table 10 presents a summary of basic statistics performed on the longterm daily flow measurements for the subwatersheds T4 and S4. On average, larger flows were recorded at T4, and the percentage of daily flows exceeding the longterm mean flow is greater in S4 subwatershed. This relates to the fact that high flows associated with a given event in S4 watershed continue for a longer duration than in subwatershed T4.

Table 10. Summary of statistics on daily flow (mm/day) measurements for stations S4 and T4.

Subwatershed T4:

Flow Statistics	Study (96-99)	1996 (starts 6/28/96)	1997	1998	1999
AVG	1.5	3.2	0.9	1.5	1.4
STD	3.6	4.1	1.2	3.5	4.5
MAX	63.3	21.7	11.5	35.8	63.3
MIN	0	0	0	0	0
PER90	3.4	8.1	2.1	3.0	2.1
PER75	1.3	4.0	1.2	1.1	0.9
MED	0.4	1.7	0.4	0.3	0.4
N	1282	187	365	365	365
SUM		593.7 mm	328.4 mm	536.5 mm	513.4 mm

Percent of daily flows that exceeded the study mean flow for a given time period:

Longterm	1996	1997	1998	1999
22.2%	34.2%	34.8%	19.7%	13.2%

Subwatershed S4:

Flow Statistics	Study (96-99)	1996	1997	1998	1999
AVG	0.8	1.4	0.4	0.8	0.7
STD	1.3	1.6	0.6	1.4	1.4
MAX	12.4	8.6	3.1	5.9	12.4
MIN	0	0	0	0	0
PER90	2.5	3.4	1.3	3.1	1.7
PER75	1.0	1.9	0.6	0.9	0.6
MED	0.2	1.0	0.1	0.0	0.3
N	1437	342	365	365	365
SUM		470.1 mm	143.9 mm	280.9 mm	265.8 mm

Percent of daily flows that exceeded the study mean flow for a given time period:

Longterm	1996	1997	1998	1999
29.6%	34.5%	29.6%	26.6%	22.2%

The statistics for the available C2 flow data (Jan.1 – Nov. 19, 1999) are summarized in Table 11. The average flow depth (1.4 cm) in 1999 at C2 was greater than the average 1999 flow depth observed for S4 but equivalent to the average 1999 flow per area for T4; furthermore the standard deviation of 1999 flows was greater for C2 than for S4. The maximum 1999 flow depth for C2 (9.7 cm) is lower than the corresponding flow depth for T4 (63.3 cm) or S4 (102.4 cm).

Table 11. Summary of statistics on daily flow (mm/day) measurements for station C2.

Subwatershed C2:	
Flow Statistics	**1999 (missing Dec)**
AVG	1.4
STD	2.3
MAX	9.7
MIN	0
PER90	5.1
PER75	1.3
MED	0.5
N	333
SUM	470.4 mm

Water Quality Results

Nutrient Concentrations

For each station, water quality samples were collected and analyzed for total phosphorus (TP), ortho-phosphate phosphorus (OP-P), ammonium nitrogen (NH_4-N), total Kjeldahl nitrogen (TKN) nitrate-nitrogen (NO_3-N), and sediment/total suspended solids (TSS) concentrations. These data were primarily used for calculating mass nutrient loads (concentration X flow = load) for each station. But, it is of interest to view selected concentration data. The patterns of each nutrient were observed along with canal discharge for each station, but only a portion of the data is presented. Over the course of the study, NO_3-N concentration appears to be highly correlated with flow for some of the fields and subwatersheds. High concentrations of NO_3-N can be seen after larger storm events. This is particularly noticeable after storm events following dry periods, and most evident for the large forested subwatershed, S4 (Figure 59). The same pattern can be seen for the forested fields within S4. During dry periods, the organic soils of S4 are aerobic and mineralization occurs, accumulating NO_3-N in the soil system. Organic forms of N mineralize to NH_3/ NH_4, which subsequently can nitrify to NO_3. This NO_3-N readily flushes out of the soil when rainfall events occur. This is especially true for the hurricanes Dennis and Floyd. Nitrate-N accumulated in the soil during the dry summer was flushed out with these storms. From the fall of 1996 through early summer of 1997, there was a consistent series of rainfall events; hurricane Fran and tropical storm Josephine resulted in a "first flush" of NO_3-N and subsequent events resulted in lower NO_3-N concentrations.

Unlike in the forested portions of the watershed, the fields within the agricultural region of the watershed receive nitrogen fertilizer that influences the NO_3-N concentrations measured at T4 (Figure 60). Subwatershed T0 receives animal waste applications during spring and summer months, which results in spikes of NO_3-N (Figure 61). This results in a more scattered plot of NO_3-N concentration over time, which can be observed below in the plots for T4 and T0. This also results in higher maximum NO_3-N concentrations observed in the agricultural area. The majority of the NO_3-N concentrations for stations T4 and T0 fall below 10 mg/L, but a number of very high NO_3-N concentrations were measured from the station T0. The high values measured at T0, from 70 to 115 mg/L, can be attributed to the increased nitrogen load produced by the land application of swine waste within this area. Also, these areas have mineral soils that generally do not have as much mineralizable organic N and thus do not accumulate NO_3-N in the same manner as some forested organic soils (i.e. S4).

Subwatershed C2 contains both organic and mineral soils, and forested and agricultural areas. Though flow data was only available for 1999, nutrient concentration data were available for this station for the entire study period (1996-99). The NO_3-N concentration data are presented with C2 flow for 1999, and S4 flow is included in the plot for previous years (Figure 62). Though S4 flow is not an exact prediction of C2 flow, it does appear that in general, NO_3-N concentrations at C2 are similarly related to flow as at S4.

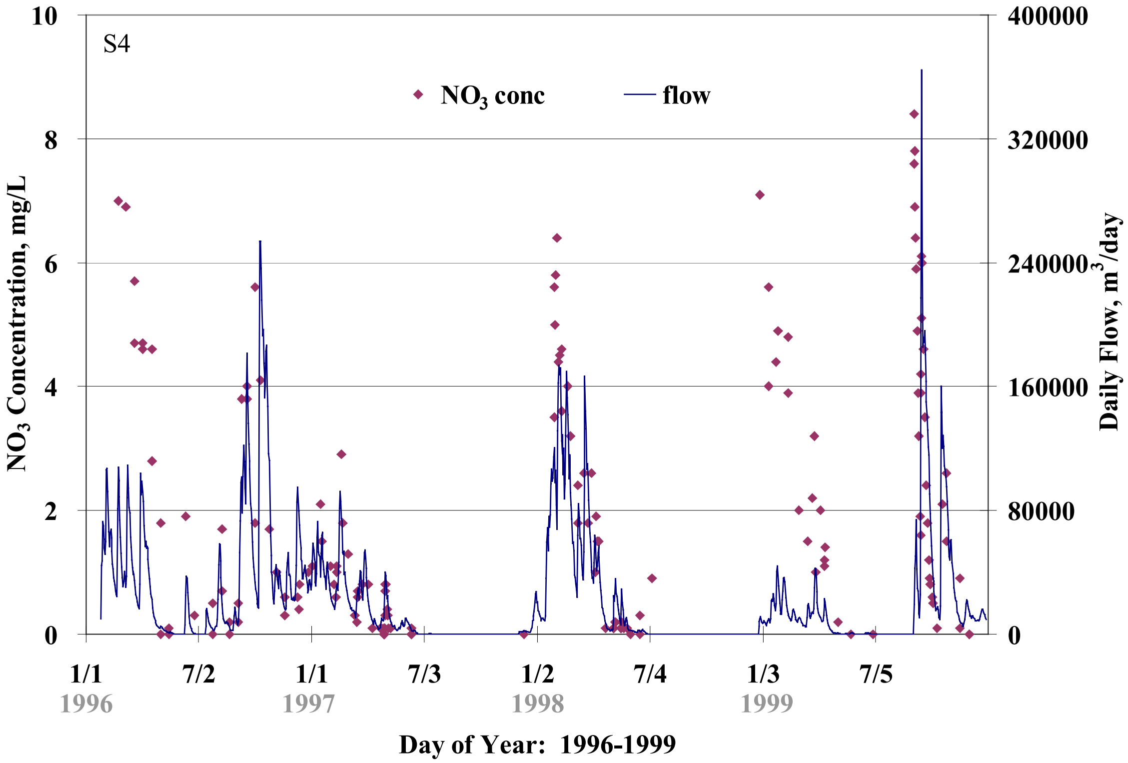

Figure 59. Station S4 daily flow and nitrate-nitrogen concentration for years 1996-99.

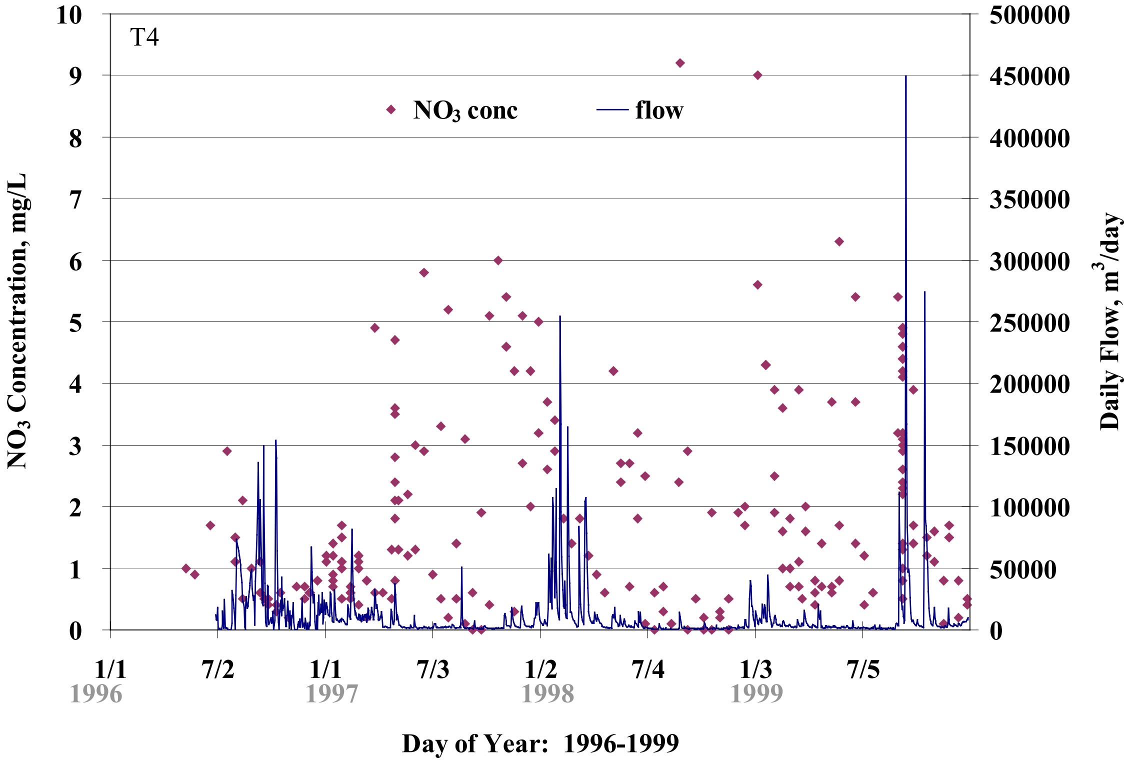

Figure 60. Station T4 daily flow and nitrate-nitrogen concentration for years 1996-99.

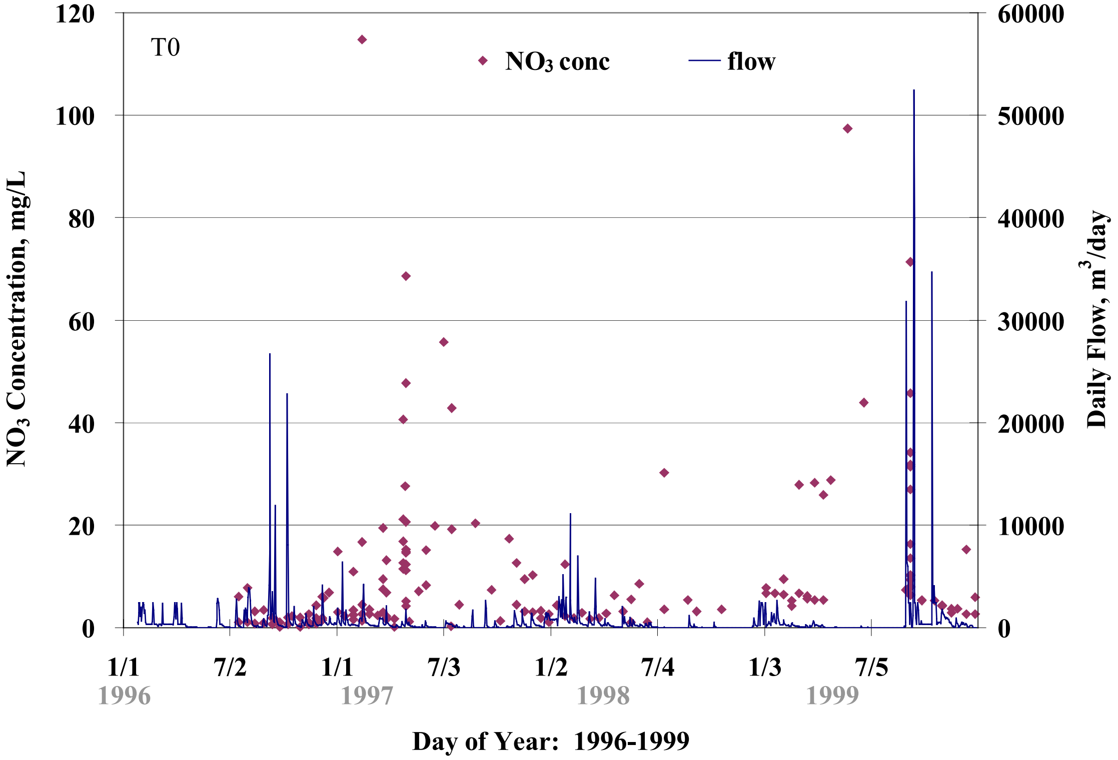

Figure 61. Station T0 daily flow and nitrate-nitrogen concentration for years 1996-99.

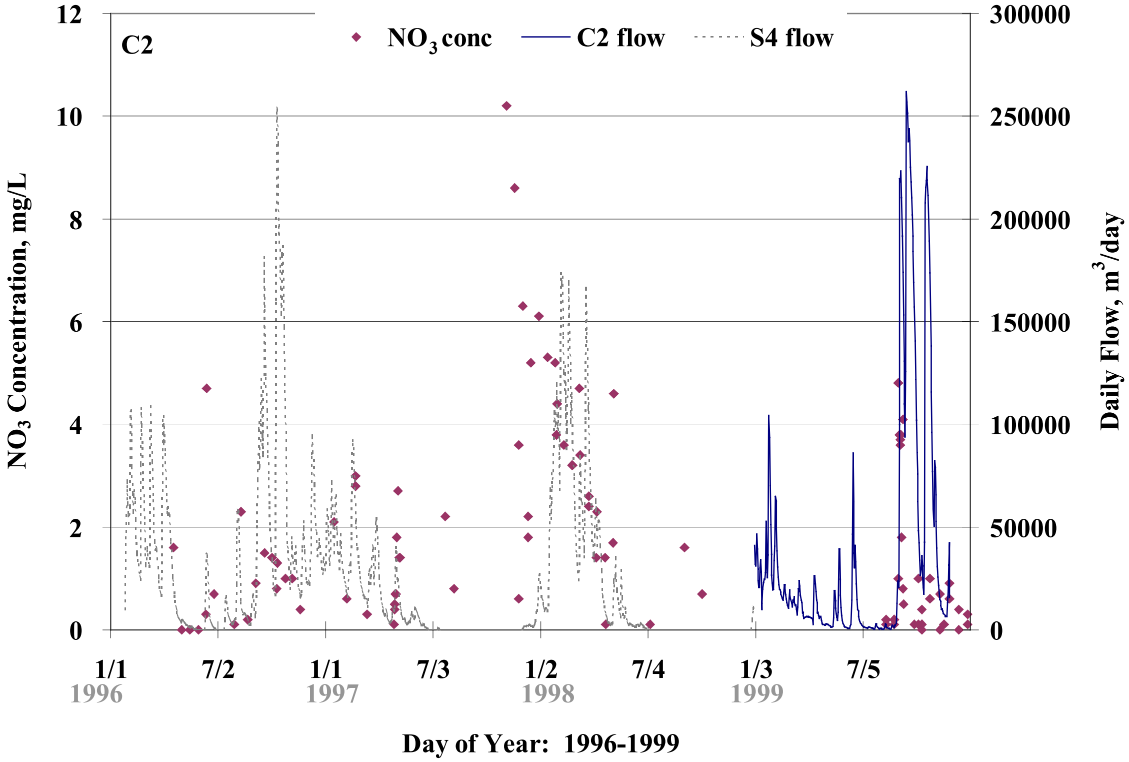

Figure 62. Station S4 daily flow (1996-98) and C2 daily flow (1999) presented with C2 nitrate-nitrogen concentration (1996-99).

Contrarily, organic nitrogen (ON = TKN - NH_4) concentration appears to be rather constant over time, regardless of spikes in discharge. For example, the ON concentrations for station S4 during the 4-year study period fall mostly between 1 and 3 mg/L (Figure 63). The ON concentrations ranged from approximately 2 to 5 mg/L from each of the forested field stations. For comparison, ON concentration data was included from station F6, within S4 (Figure 64). Organic N concentrations observed for the agricultural subwatersheds (T4, T0) and the mixed use subwatershed (C2), were more variable (Figures 65, 66) than for the forested sites. In the spring of 1997 and 1999 high ON concentrations are observed for stations T4 and T0 (Figures 65, 66); this is likely due to application of swine waste within T0. But unlike at the forested stations, ON concentration less than 1 mg/L were frequently observed at T0 and T4. The mineral soils (i.e. T4, T0) have less resident ON than the organic soils (i.e. S4 and component fields), resulting in generally lower baseline concentrations of ON observed at T4 than for S4 and F6 (Figures 63 and 64 vs. Figures 65 and 66). The ON concentration observed at C2, which drained mostly organic soils, had a distribution to that observed at S4 (Figures 67 and 63).

The amount of On mineralized and lost by the process described for the forested subwatershed S4 was unusually high for forested lands in eastern North Carolina. The concentrations of NO_3-N (up to 9 mg/L, Figure 59) and ON (up to 4 mg/L, Figure 63) were much higher than those observed in other studies. In a review of natural and managed forested study sites in eastern North Carolina, Chescheir et al. (2002) reported that mean concentrations in drainage water from the 75% of forested sites were less than 1.8 mg/L for TN, less than 1.5 mg/L for ON, less than 0.6 mg/L for NO_3-N, and less than

0.2 mg/L for NH_4-N. The mean N concentrations (4.6 mg/L TN, 2.4 mg/L DIN, and 2.2 mg/L ON; Figure 68) for the 4-year study period observed at S4 are not typical for eastern North Carolina forests.

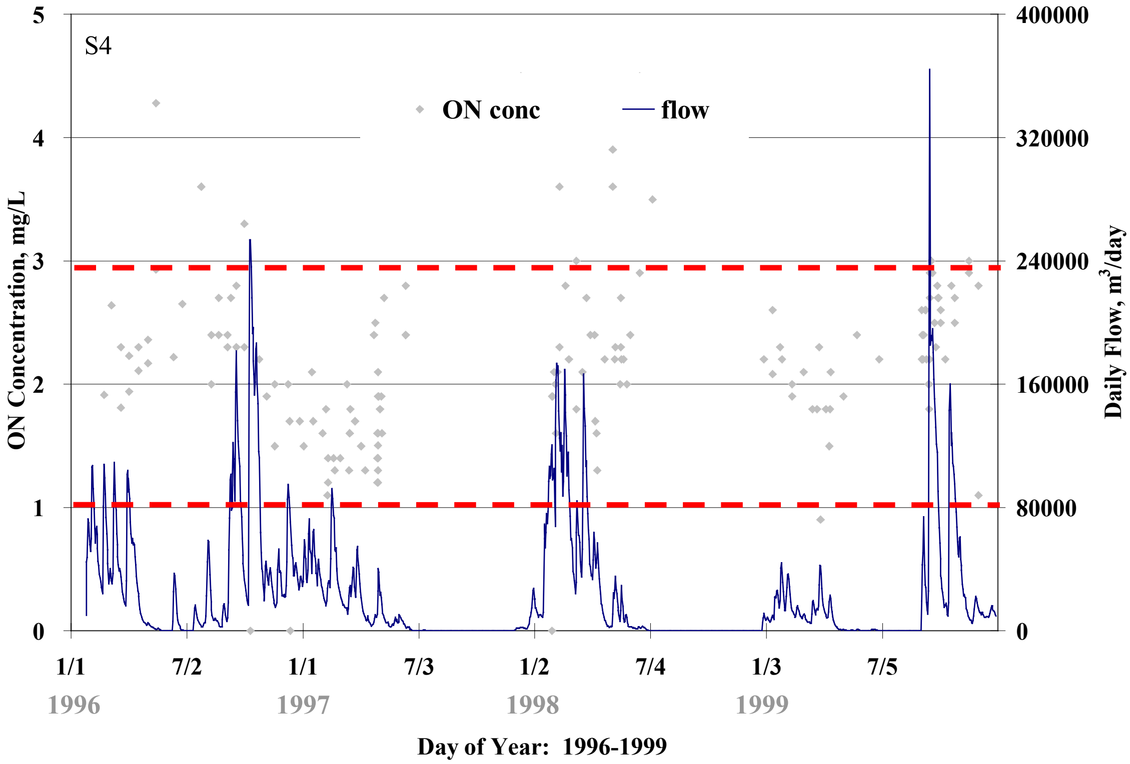

Figure 63. Station S4 daily flow and organic nitrogen concentration for years 1996-99

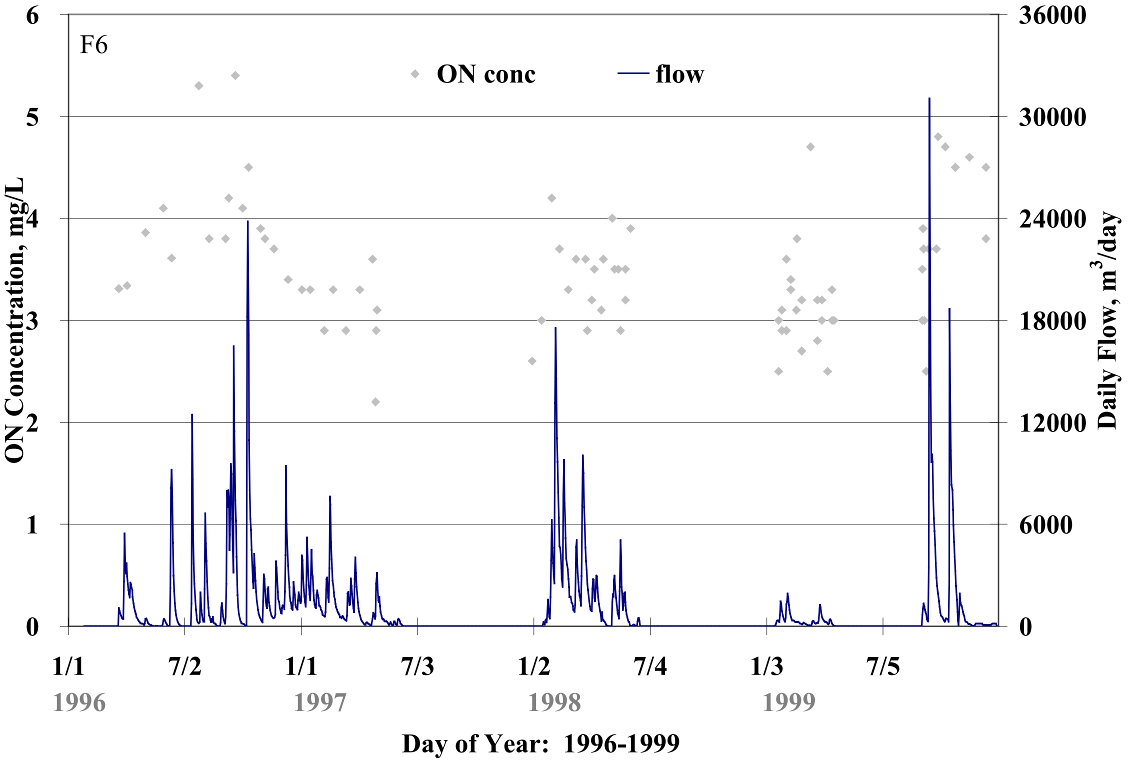

Figure 64. Station F6 daily flow and organic nitrogen concentration for years 1996-99

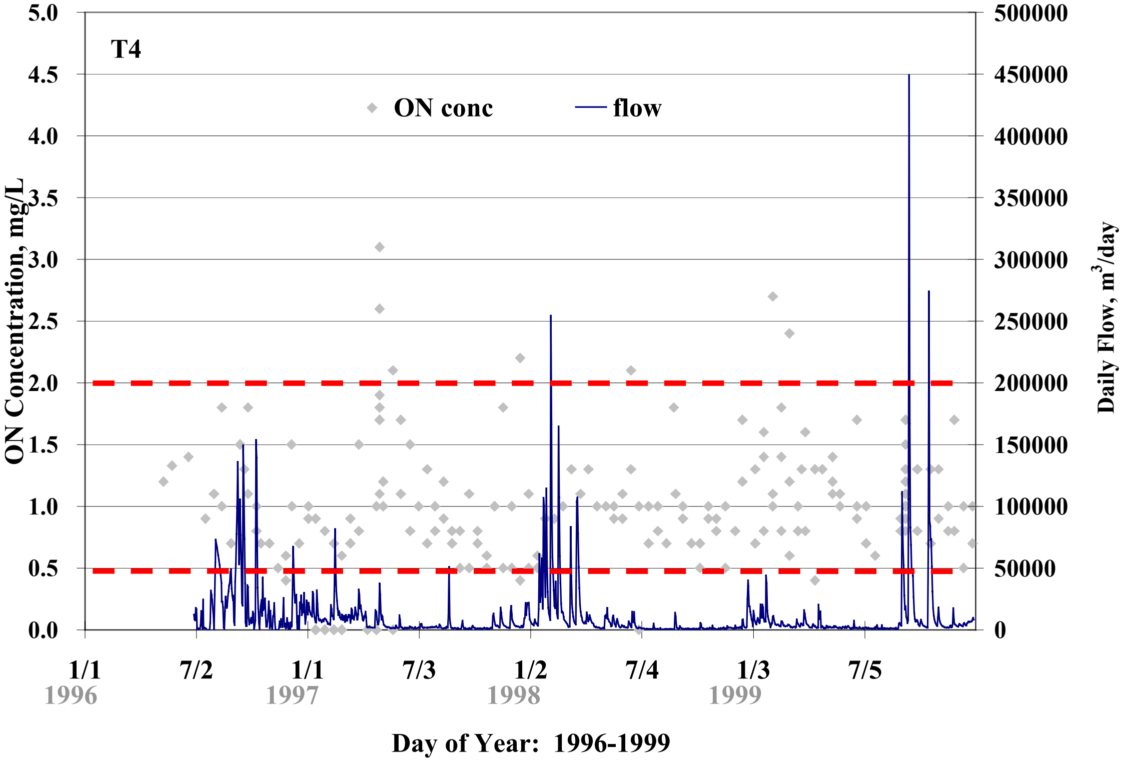

Figure 65. Station T4 daily flow and organic nitrogen concentration for years 1996-99

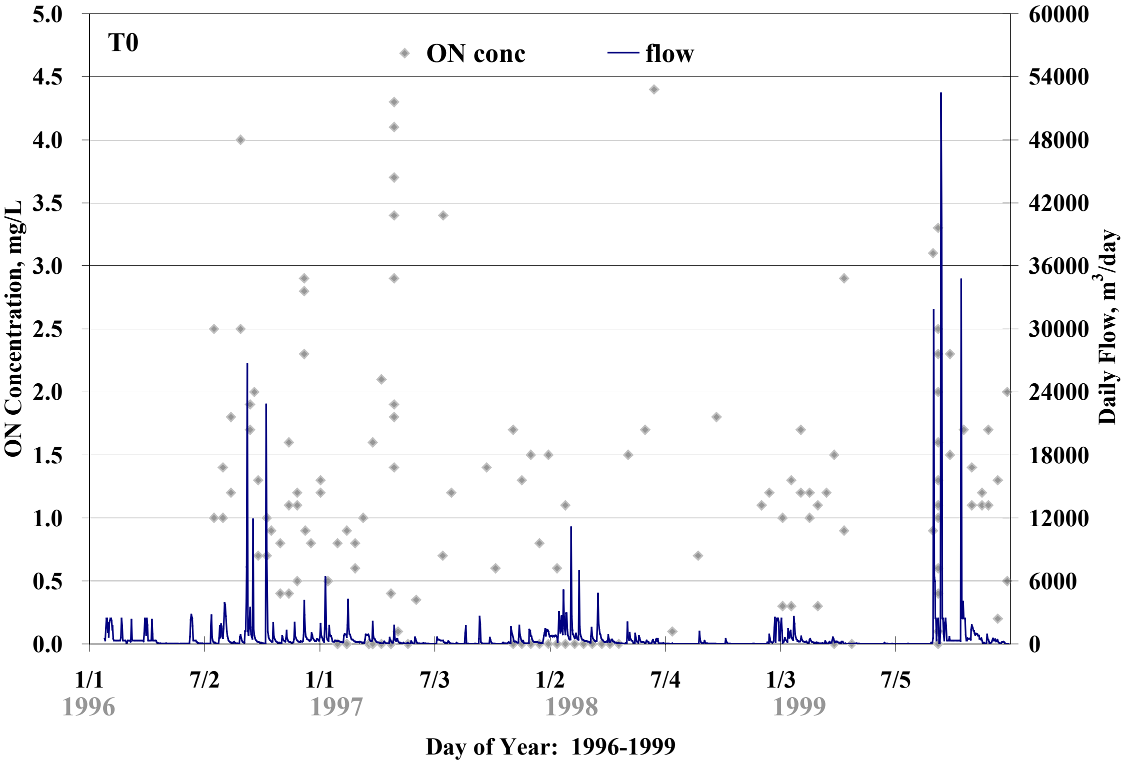

Figure 66. Station T0 daily flow and organic nitrogen concentration for years 1996-99

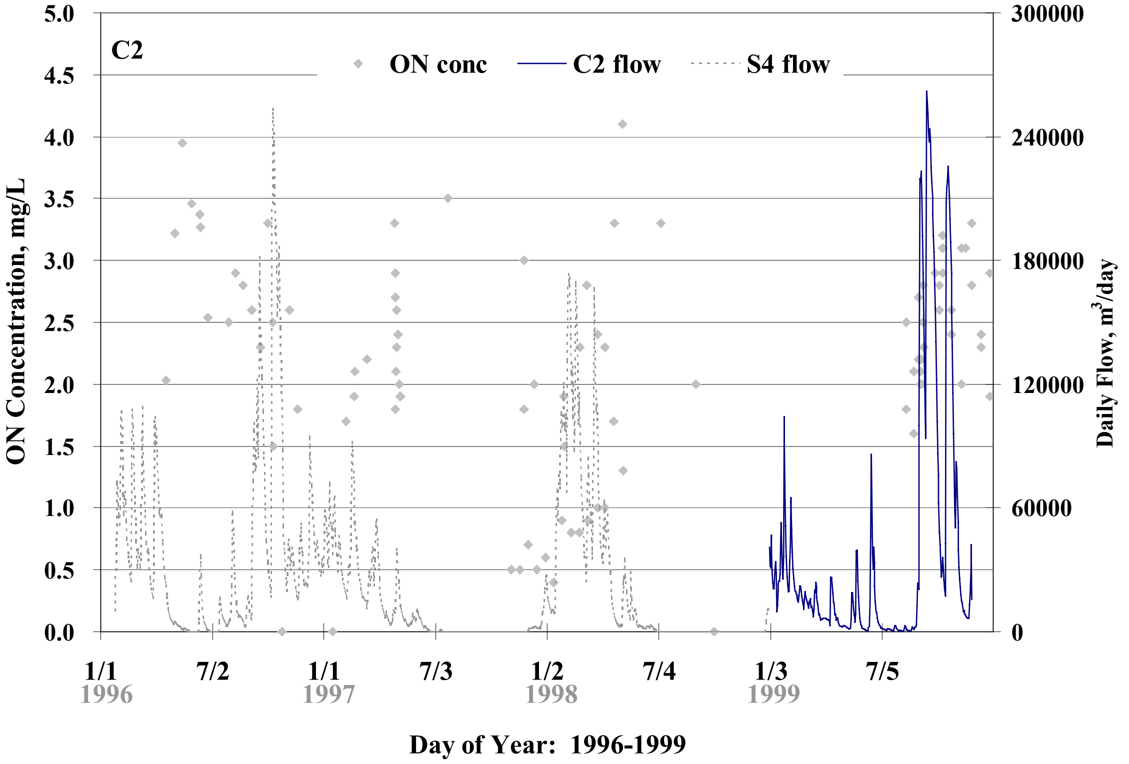

Figure 67. Station S4 daily flow (1996-98) and C2 daily flow (1999) presented with C2 organic nitrogen concentration (1996-99).

The bar charts below (Figures 68 through 71) present the average TN, DIN, and ON concentrations (mg/L) on a seasonal basis compared to the overall study average and the hurricane-related periods of 1999 (for subwatersheds S4, T4, T0, and C2). The y-axis is of the same scale in all figures for easy comparison, except for station T0 where concentrations were much higher. Spring was defined as the months April, May, and June; summer includes months July, August, and September; fall includes months October, November, and December; and winter includes months January, February, and March. For example, the average concentration of TN for spring included all data points from years 1996-99 for the months indicated above; averages for other time periods were computed this way as well. As can be seen in Figures 59 through 67 a large amount of variation was observed in the sample concentration values. Consequently, although differences between seasonal averages were observed, these differences were not statistically significant.

In general, when total nitrogen (TN = TKN + NO_3-N) was analyzed on a seasonal basis, it appears that the greatest TN concentrations are generally observed in the summer months for the forested station S4 (~ 6.5 mg/L) and in the spring months for the agricultural stations T4 and T0 (~ 3.5 mg/L and ~ 28 mg/L respectively). The lowest TN concentrations were generally noted in the spring months for S4. Subwatershed T0 exhibits high TN, DIN, and ON concentrations in the spring and summer, attributable to field waste application (Figure 70). The difference in average TN concentration was not as great among the seasons for the T4 and T0 as for S4. Similarly, the highest seasonal average concentrations of DIN were measured in the summer for the forested subwatershed, and in the spring months for the agricultural watershed. Organic N concentrations appear to vary little seasonally for all stations monitored. The mixed use, agricultural and forested, subwatershed C2 exhibited little seasonal variation of TN, DIN, and ON (Figure 71). The bar charts indicate that TN, DIN, and ON concentrations were somewhat elevated during the hurricanes and related storms of 1999 for each station monitored, excluding station C2. In general, nutrients were flushed into the drainage canals during these events.

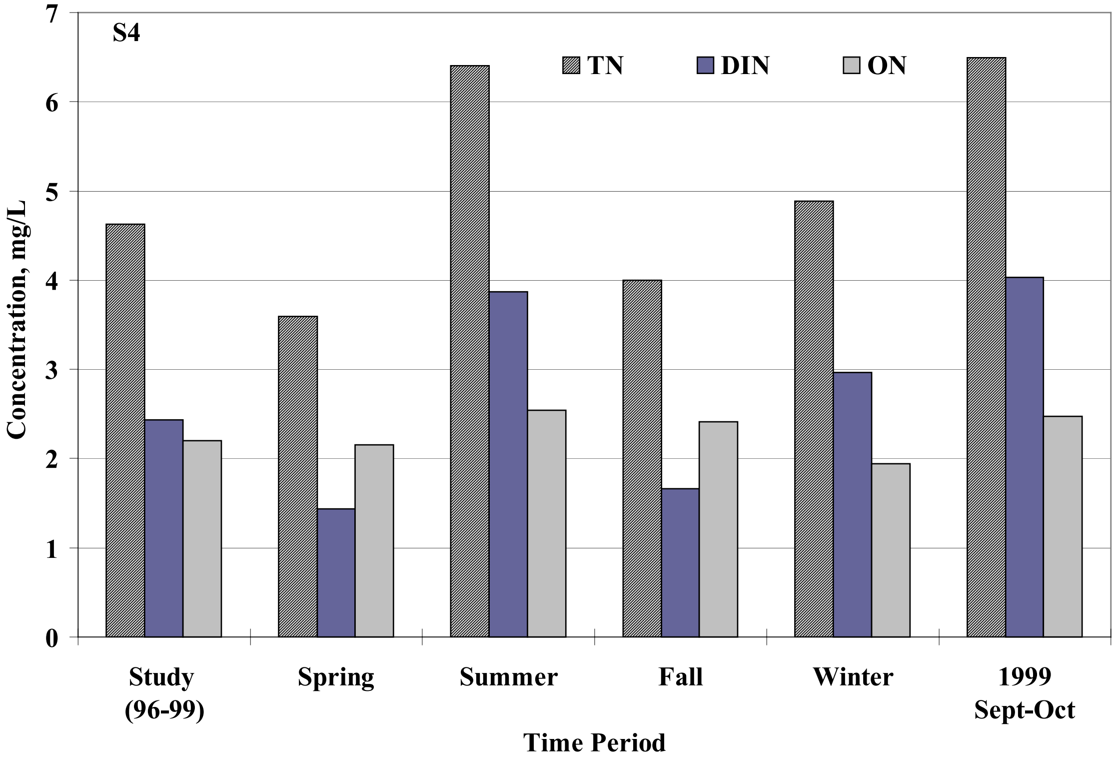

Figure 68. Average seasonal total nitrogen, dissolved inorganic nitrogen, and organic nitrogen concentrations compared to Sept. - Oct. 1999 nitrogen concentrations for station S4.

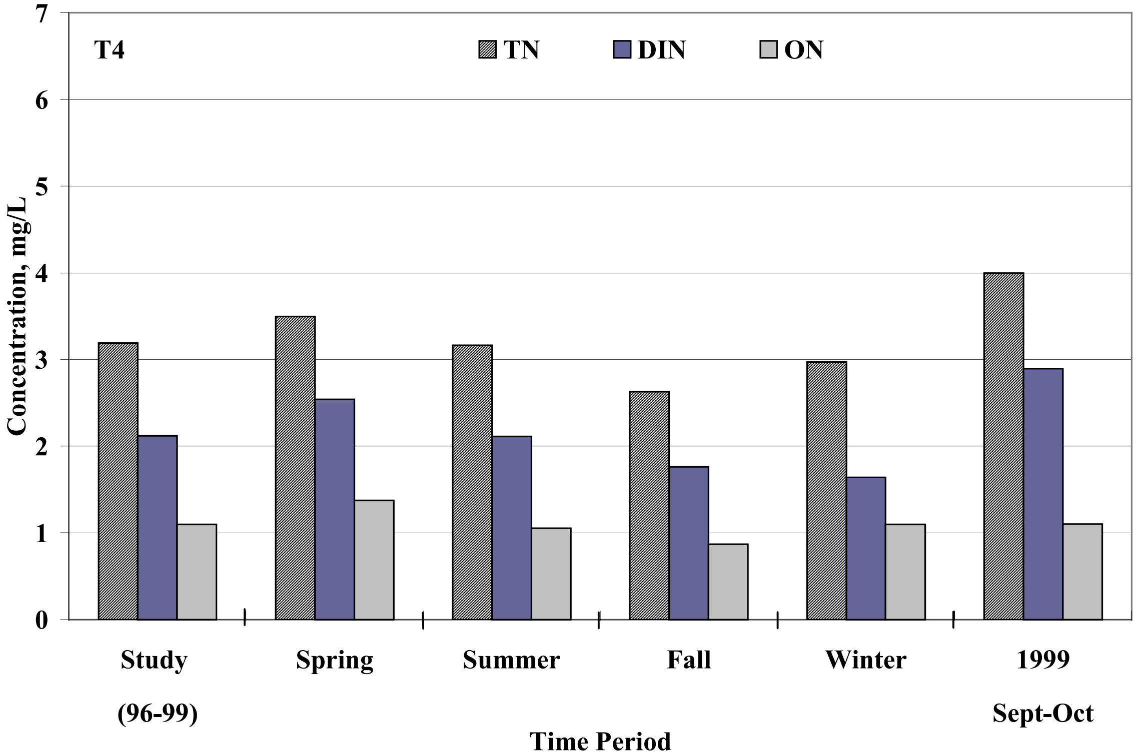

Figure 69. Average seasonal total nitrogen, dissolved inorganic nitrogen, and organic nitrogen concentrations compared to Sept. - Oct. 1999 nitrogen concentrations for station T4.

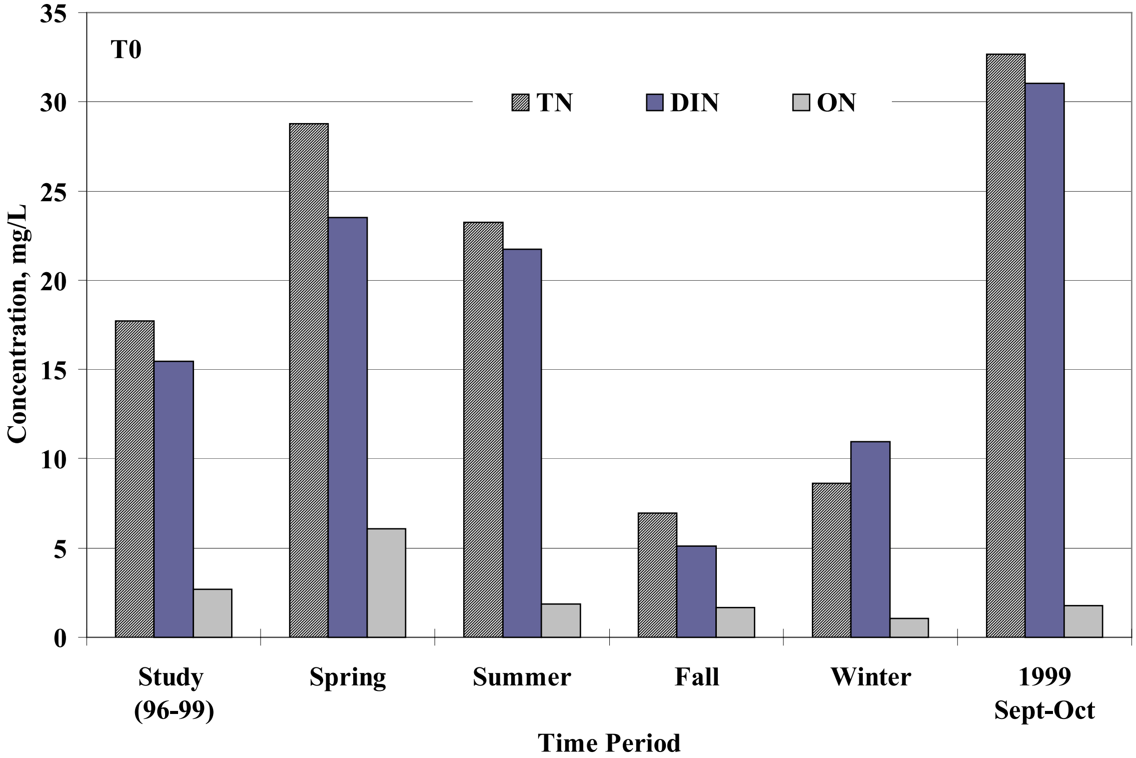

Figure 70. Average seasonal total nitrogen, dissolved inorganic nitrogen, and organic nitrogen concentrations compared to Sept. - Oct. 1999 nitrogen concentrations for station T0.

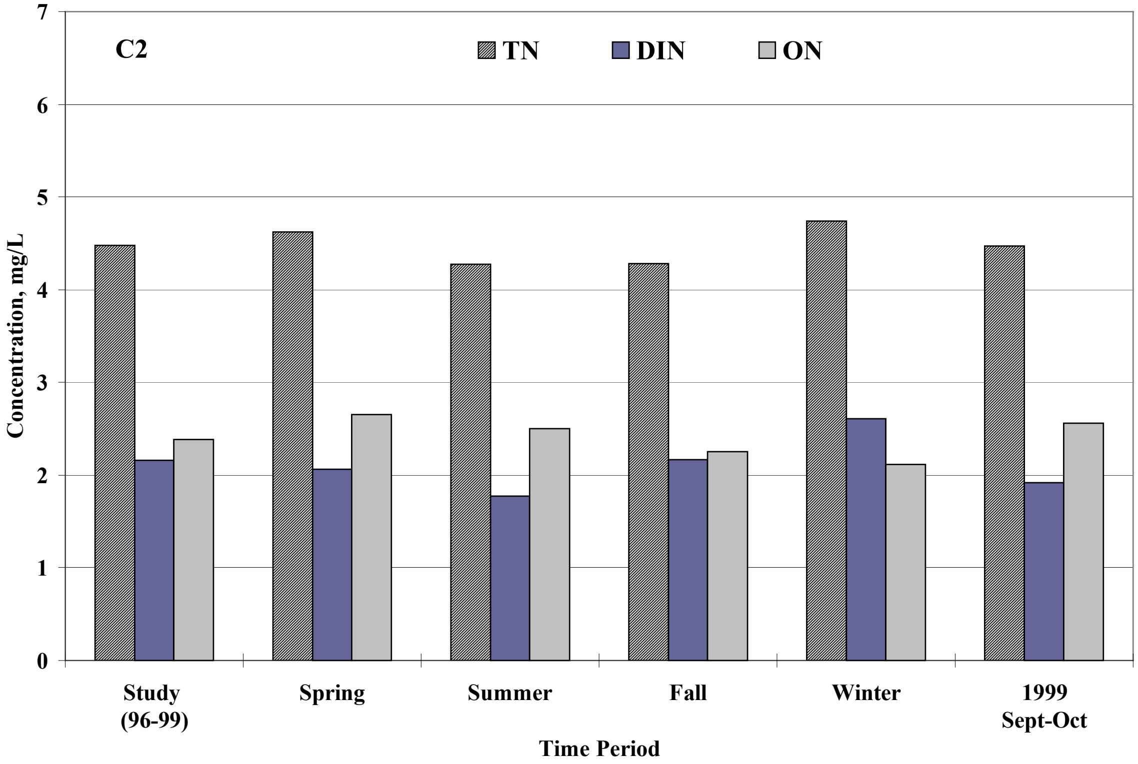

Figure 71. Average seasonal total nitrogen, dissolved inorganic nitrogen, and organic nitrogen concentrations compared to Sept. - Oct. 1999 nitrogen concentrations for station C2.

Seasonal concentrations of NO_3-N, NH_4-N, and DIN (DIN = NO_3 + NH_4) were also analyzed for subwatersheds S4, T4, T0, and C2 (Figures 72 through 75). Again, the y-axis is of the same scale in the figures for S4, T4, and C2, for straightforward comparison. These plots show the relative amounts of NO_3 and NH_4 comprising total DIN.

Overall, when NO_3-N was analyzed on a seasonal basis, it appears that the greatest concentrations were observed in the summer months for the forested S4 (Figure 72). For S4, NO_3-N exceeded NH_4 seasonally, except during the spring. For the agricultural site T4, higher NO_3-N concentrations were noted in the spring months, likely due to fertilizer application (Figure 73). Because swine lagoon effluent is applied in subwatershed T0, elevated concentrations of NO_3-N and NH_4-N were observed in spring and summer months when waste is applied (Figure 74).

For both stations S4 and T4, NH_4-N concentrations were generally low, particularly for station T4 (Figures 72 and 73). It is likely that NH_4-N is being oxidized to nitrate in these systems. In station T0, as expected NH_4-N, is elevated due to the swine waste (Figure 74).

For the entire 4-year study, average DIN concentration in S4 exceeds that of T4, and 4-year average DIN concentrations in C2 are slightly greater than in T4. The bar charts also indicate that average NO_3-N concentrations were elevated during the hurricanes and related storms of 1999 for stations S4, T4, and T0, but that NH_4-N measured during these storms was possibly lower than average.

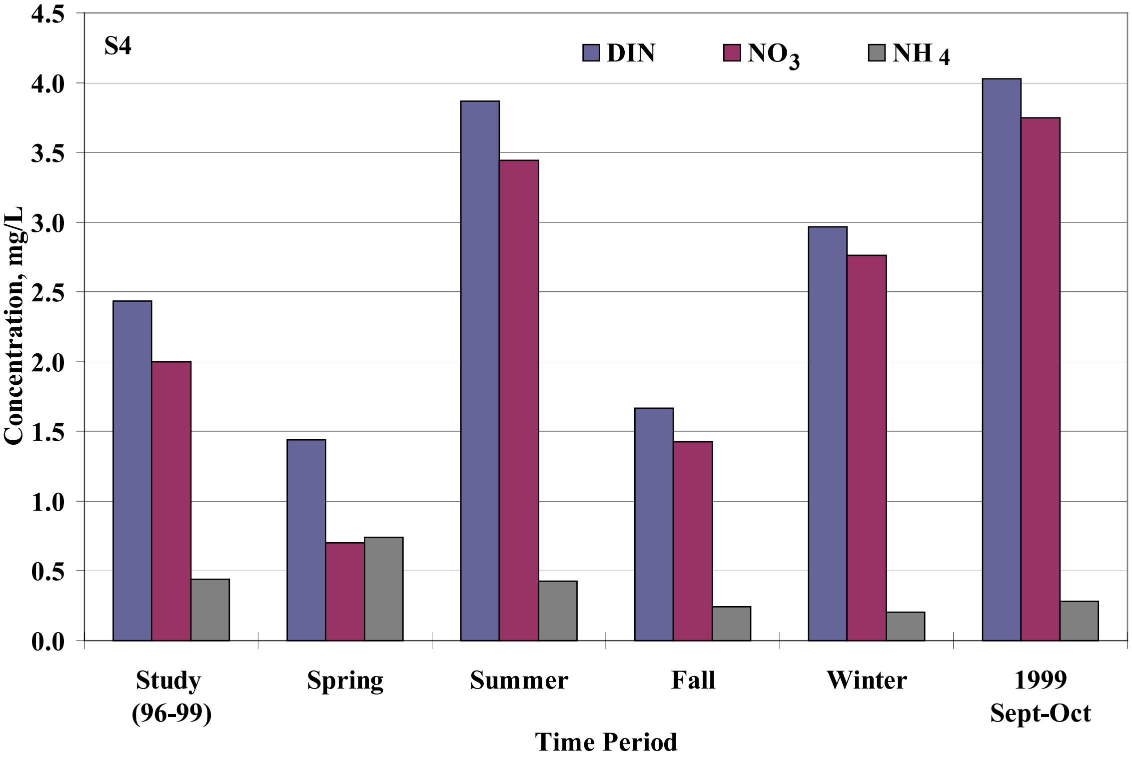

Figure 72. Average seasonal proportions of nitrate and ammonium concentrations (components of dissolved inorganic nitrogen), compared to Sept. - Oct. 1999 concentrations for station S4.

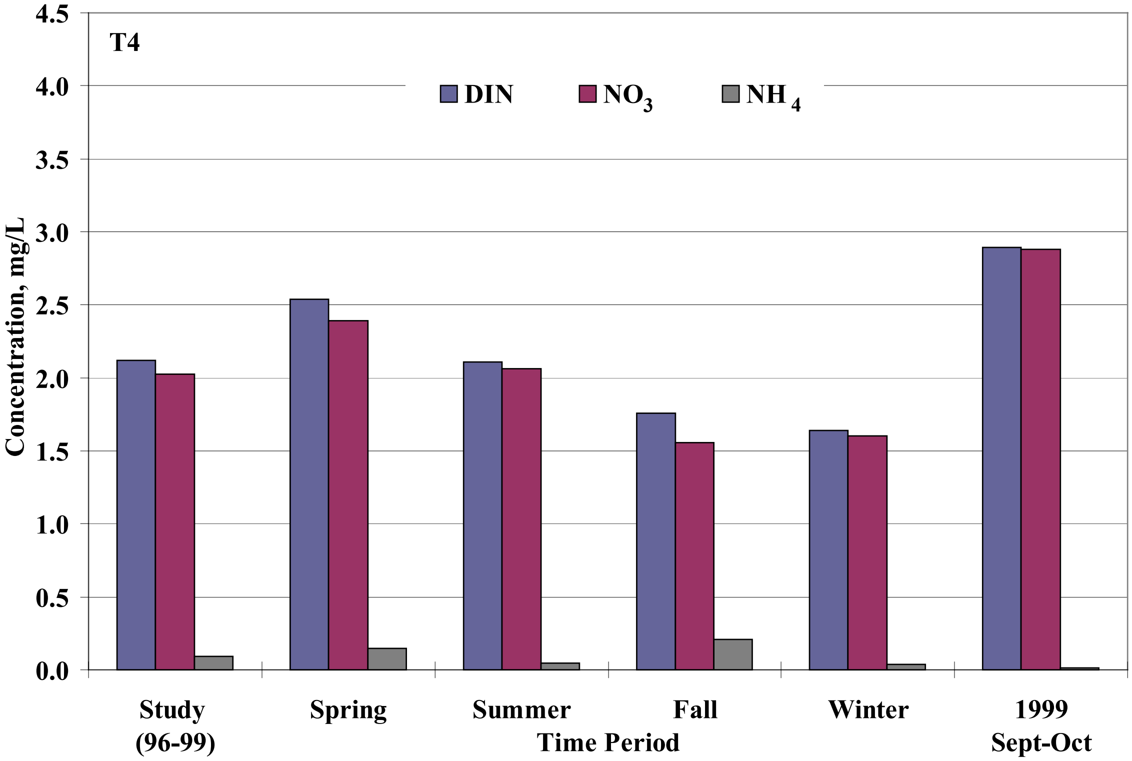

Figure 73. Average seasonal proportions of nitrate and ammonium concentrations (components of dissolved inorganic nitrogen), compared to Sept. - Oct. 1999 concentrations for station T4.

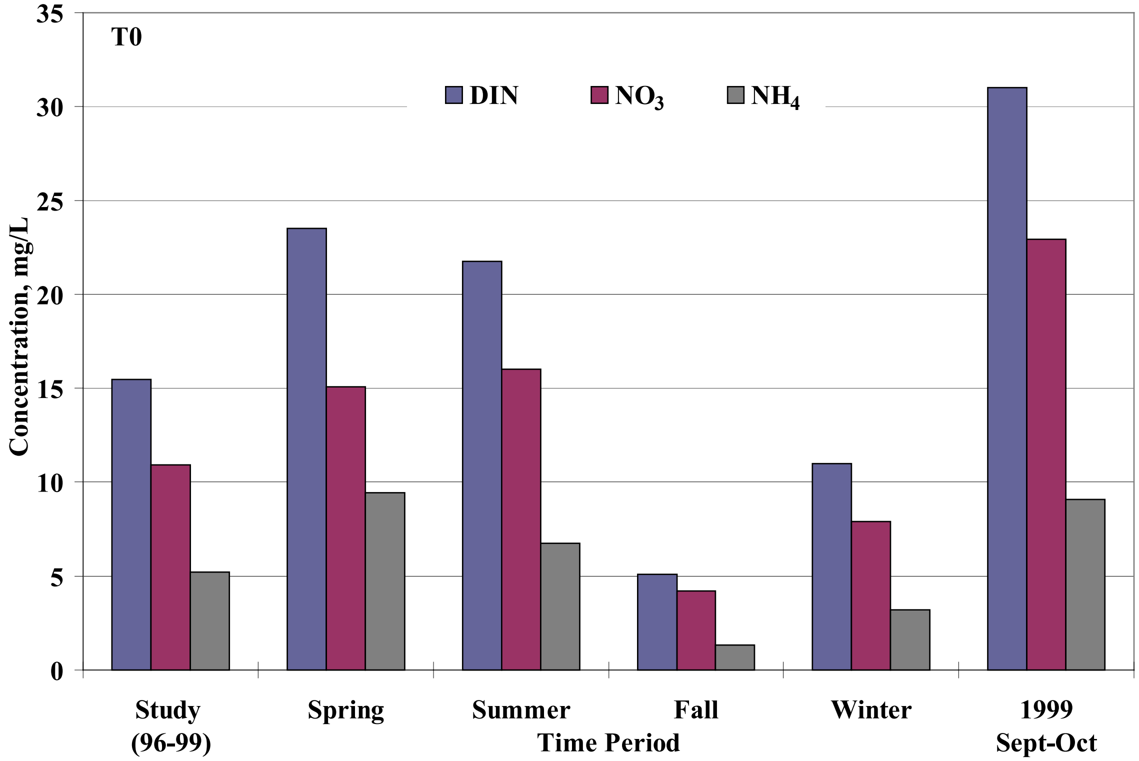

Figure 74. Average seasonal proportions of nitrate and ammonium concentrations (components of dissolved inorganic nitrogen), compared to Sept. - Oct. 1999 concentrations for station T0.

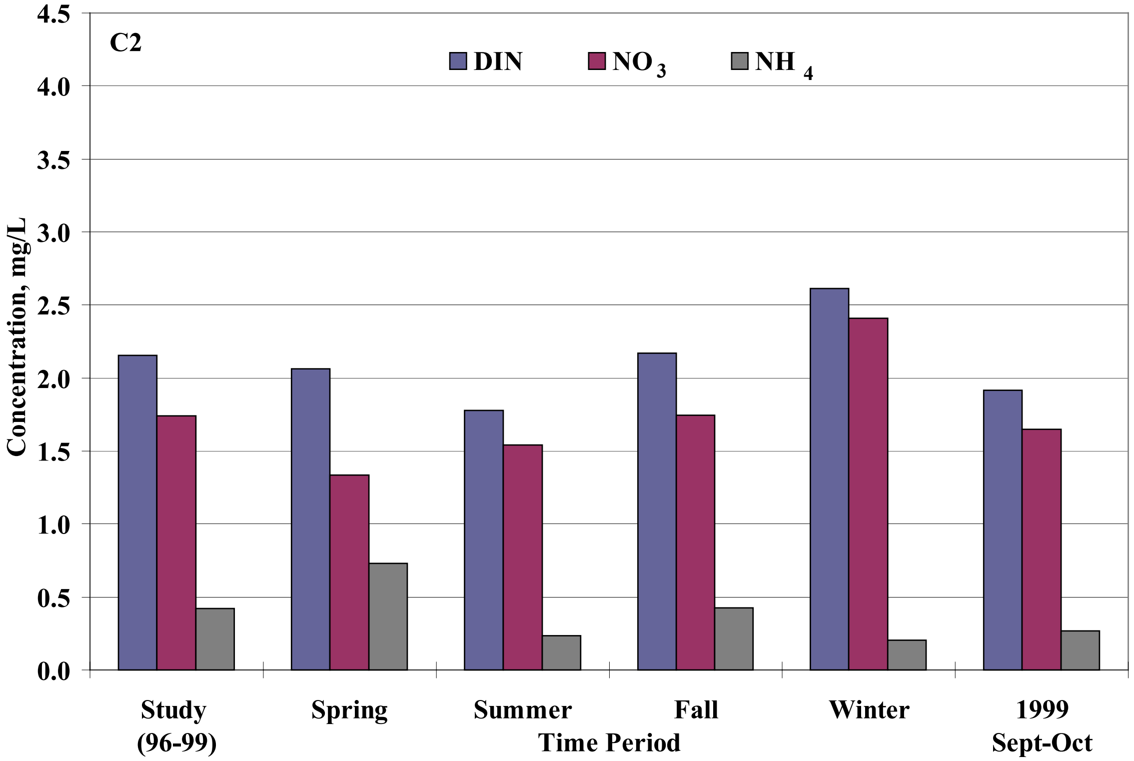

Figure 75. Average seasonal proportions of nitrate and ammonium concentrations (components of dissolved inorganic nitrogen), compared to Sept. - Oct. 1999 concentrations for station C2.

The next series of bar charts display average seasonal concentration data for total phosphorus (TP), orthophosphate (OP), and sediment (actually total suspend solids), for stations S4, T4, T0, and C2 (Figures 76 through 79). The TP and OP concentrations are displayed on the left y-axis (mg/L) and the sediment concentrations are displayed on the right y-axis (mg/L), otherwise the sediment concentrations would overshadow the phosphorus concentrations.

Overall the observed sediment concentrations are low- the relatively flat topography of the watershed does not have a high erosion potential. As expected, slightly higher levels of sediment concentration were detected in the agricultural canals (T4 and T0) due to tillage and disturbed soil on the cropped land (Figures 77, 78). The highest seasonal average concentrations of sediment were measured in the winter for station T4 (~ 88 mg/L), but in the spring for station T0 (~ 85 mg/L). Normally, these are months where the fields contain the least amount of vegetative cover. Phosphorus is commonly bound as calcium or iron phosphates and adsorbed to soil particles or incorporated into organic matter, thus it is expected that higher sediment loss will correspond to higher total phosphorus loss as well. Indeed higher TP concentrations were observed in the agricultural canals. Dissolved OP was present in higher concentrations at T4 and T0 as well (Figures 77, 78).

Overall, TP and OP, and sediment concentrations are highest from station T0, the agricultural area that includes pasture land where swine lagoon effluent is applied (Figure 78). The levels of phosphorus in this subwatershed are elevated due to the animal waste. For station T0, the highest TP and OP levels were measured in the spring months, approximately 1.4 mg/L and 0.69 m/L respectively. Dunne and Leopold (1978) suggested that long-term eutrophication is usually prevented if total phosphorus and orthophosphate levels do not exceed 0.5 mg/l and 0.05 mg/l, respectively. This suggests that the freshwater drainage canals draining T0 are at risk for eutrophication, or the overgrowth of vegetation due to the excess of P in the system (when additional N is present for uptake as well). T0 is a component of T4, which has relatively low TP and OP concentrations.

In S4 and the other forested stations, the highest levels of TP and OP were generally recorded during the summer months and the lowest levels during the winter months, but there is not a substantial seasonal variation of phosphorus loss from the forested watersheds (Figure 76). Little phosphorus is added to these managed forests and there is little sediment loss or sediment-bound phosphorus loss from this land area.

Based on the data, it appears that TP, OP, and sediment concentrations were not especially elevated during the hurricanes and related storms during the fall of 1999, compared to average concentrations during the 4-year study, with some exceptions. Concentration of OP appears to be elevated during the 1999 storms for subwatershed T4. Also, TP and OP are both elevated during the 1999 storms for station C2.

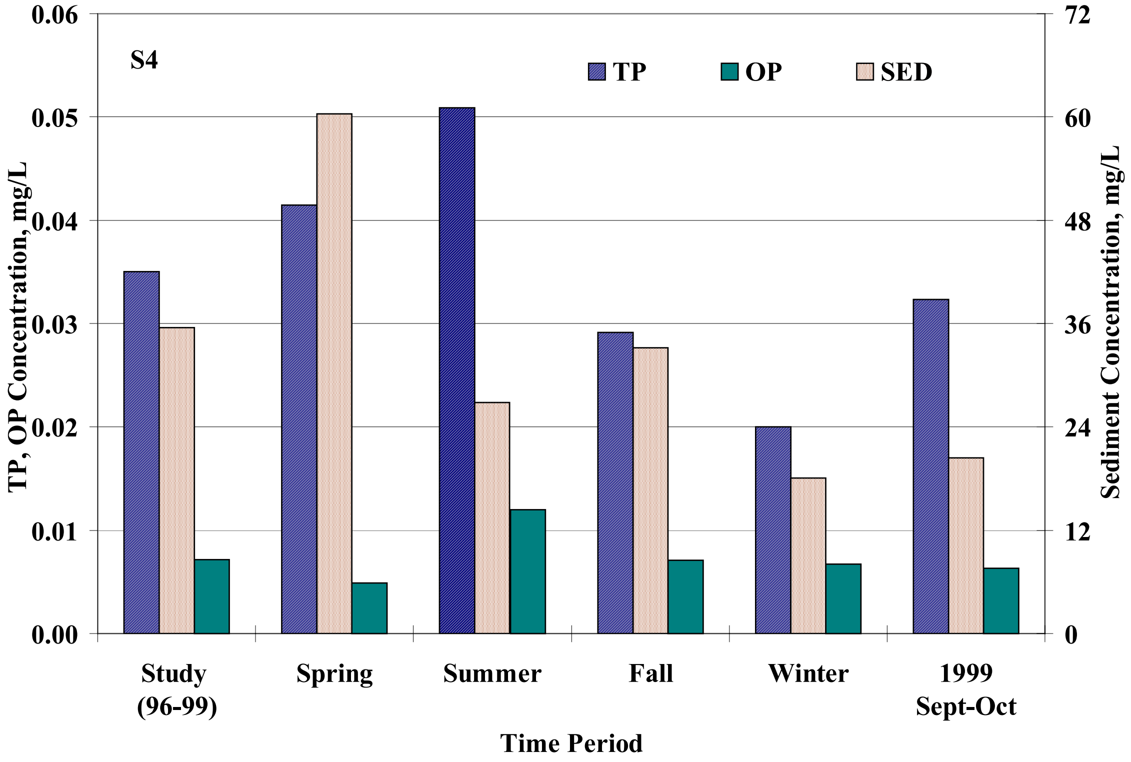

Figure 76. Average seasonal total phosphorus, orthophosphate, and sediment concentrations compared to September 1999 concentrations for station S4.

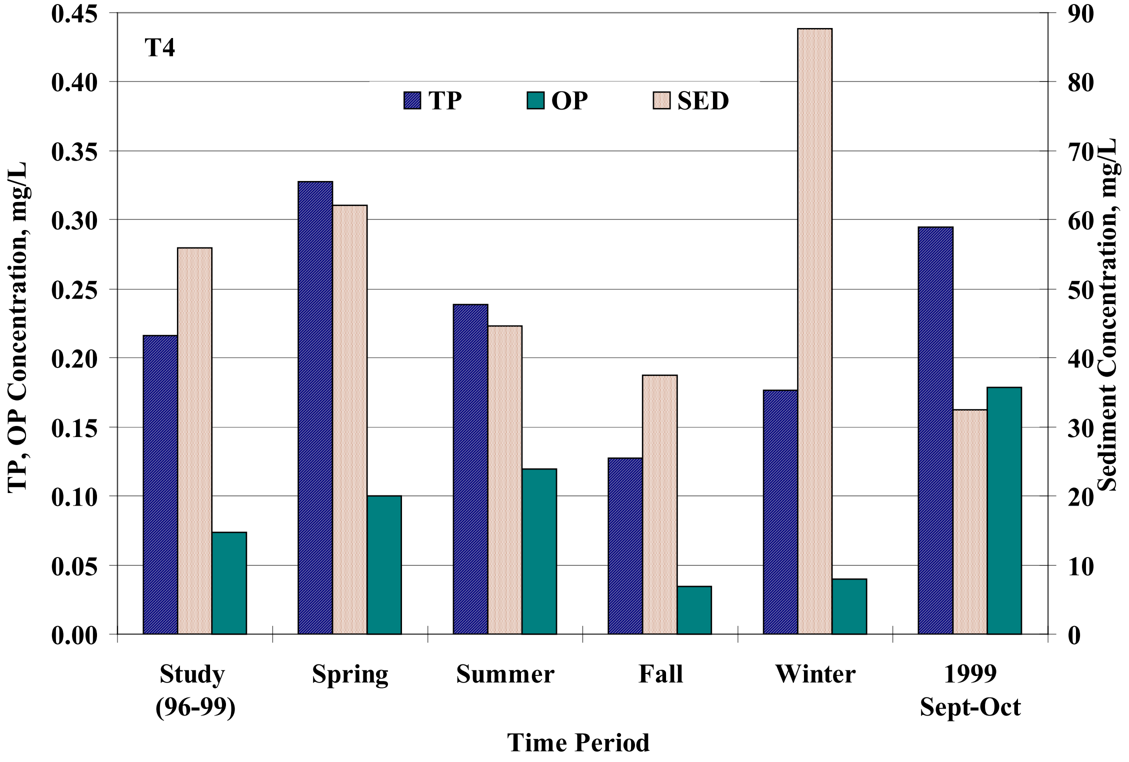

Figure 77. Average seasonal total phosphorus, orthophosphate, and sediment concentrations compared to September 1999 concentrations for station T4.

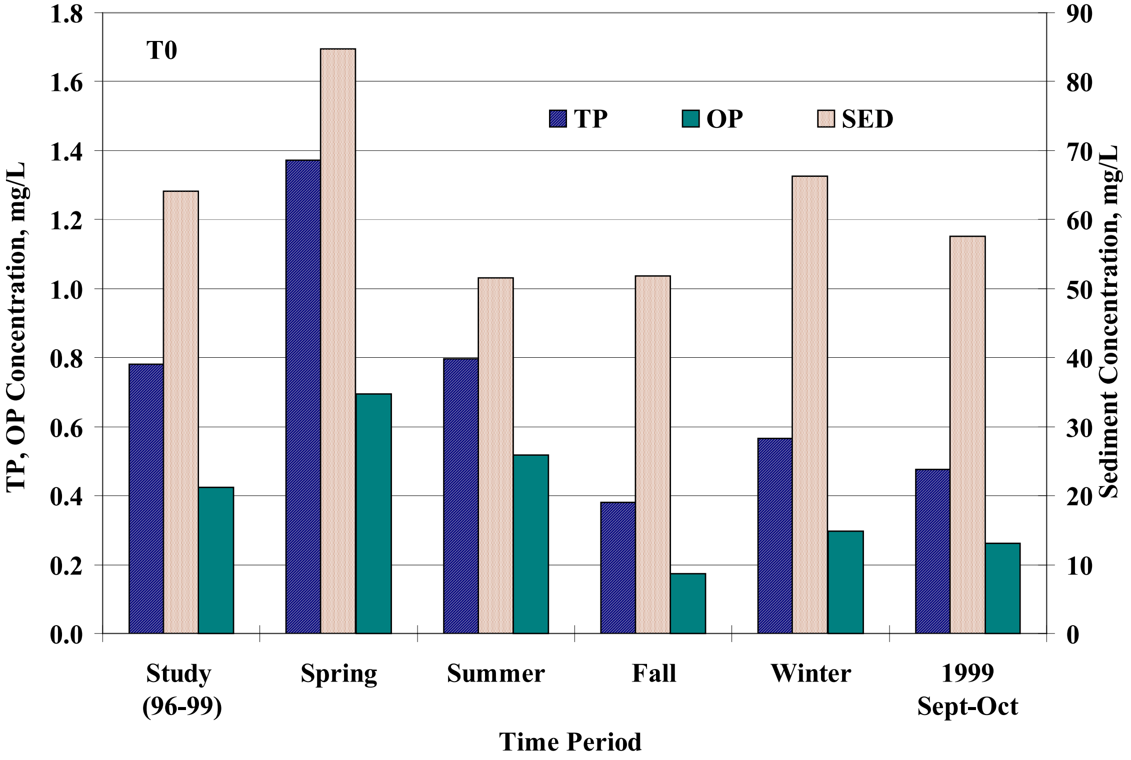

Figure 78. Average seasonal total phosphorus, orthophosphate, and sediment concentrations compared to September 1999 concentrations for station T0.

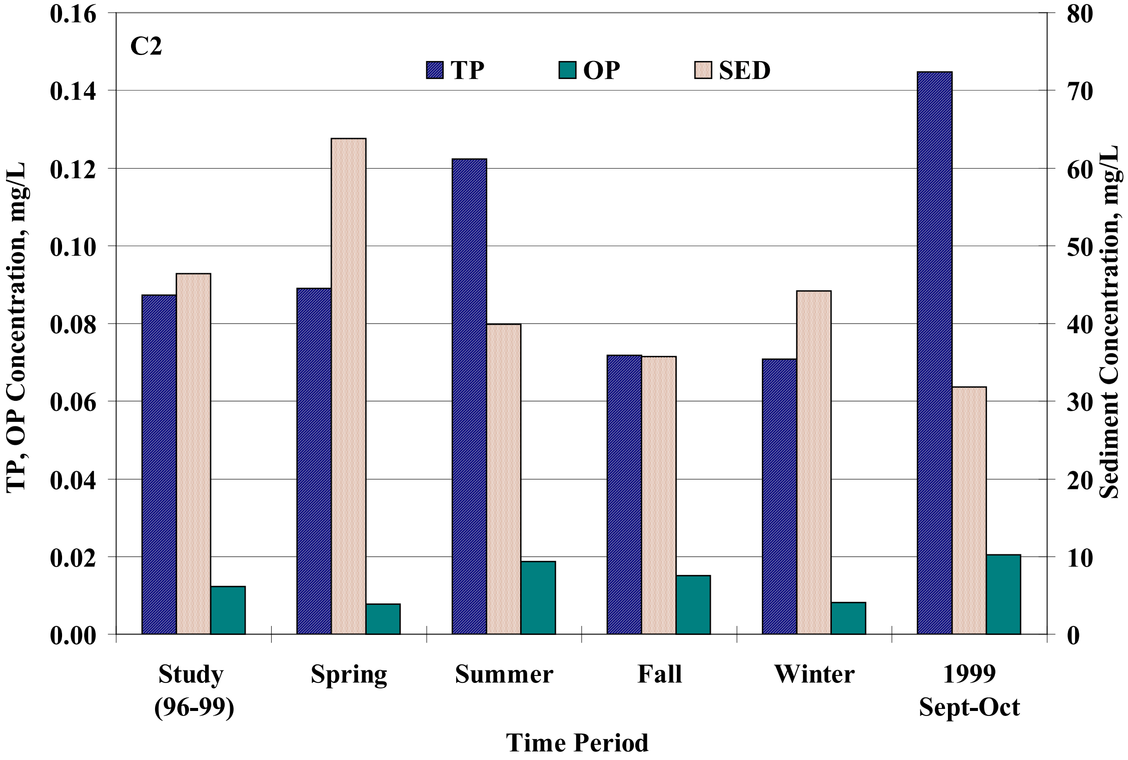

Figure 79. Average seasonal total phosphorus, orthophosphate, and sediment concentrations compared to September 1999 concentrations for station C2.

Nutrient Loads

For each station, daily flow and nutrient concentration values were used to produce a daily load (kg) for each nutrient measured; these data are presented per watershed area for each station (Figures 80 through 95). Cumulative loads (kg/ha) of TN, DIN, NO_3-N, ON, and NH_4-N are presented together for each station, for years 1996 through 1999. Comparably, TP, OP-P, and sediment cumulative loads (kg/ha) are presented together; sediment load values are presented on a secondary y-axis. The cumulative load plots can be used to visualize the magnitude and timing of nutrient and sediment load increases. The validity of these loads are only as accurate as the estimations of daily stream/canal flow volume and daily nutrient/sediment concentration.

When comparing S4 and T4, the magnitude of the N losses for the study period are similar for these stations on a kg/ha basis (Figures 90 and 94). The N losses for S4 are higher than observed in other studies. Chescheir et al. (2002) reported that annual TN exports from 75% of their forested study sites 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. The magnitude of TP and OP losses for the study period is nearly ten times greater for T4, compared to S4 (Figures 95 and 91).

Another trend observed in the load/area plots is in regard to the percentage of TN that comes from NO_3-N. For the study period, the total N load from T4, which has a large N load due to fertilizing crops, is dominated by NO_3-N to a greater degree than the forested area S4. Also, due to tillage practices and cropping, the four-year, cumulative sediment load (kg/ha) for T4 is more than three times greater than for S4.

Surprisingly, for the study period, cumulative DIN load is greater than the ON load for the large forested subwatershed S4 (Figure 90), though the ON load is greater for S4's component fields F6 and F7 (Figures 86 and 88).

The negative water quality impact that animal waste within a watershed is again confirmed by the T0 data (Figures 92 and 93). Compared to its parent subwatershed T4, overall nitrogen and phosphorus cumulative loads are much greater for T0 (Figures 92 and 93 vs. Figures 94 and 95). Also, due to the animal waste applied, a greater proportion of DIN is NH_4 in subwatershed T0, compared to T4.

Comparing the forested stations to the primarily agricultural stations, nutrient and sediment load increases appear to occur more frequently throughout the year in the agricultural areas than in the forested areas. This relates to the agricultural area’s responsiveness to rainfall events that was observed in the stream flow data plots.

Cumulative load per watershed area is presented for the mixed use subwatershed C2 only for 7/30/99 through 11/29/99 (Figures 82, 83). Even though limited C2 load data is available, it appears that the kg/ha loads from this subwatershed are relatively high, compared to its component field, F3 (Figures 80, 81). The loads for C2 may be more on the scale of the primarily agricultural watershed T4. Much of C2 is composed of organic soils, which contain relatively high amounts of organic nitrogen sources; providing explanation for why cumulative ON load is greater than DIN load for the study period. The contrary is true for the component field F3- field F3 is on mineral soils and its cumulative DIN load exceeds the ON load (Figure 80).

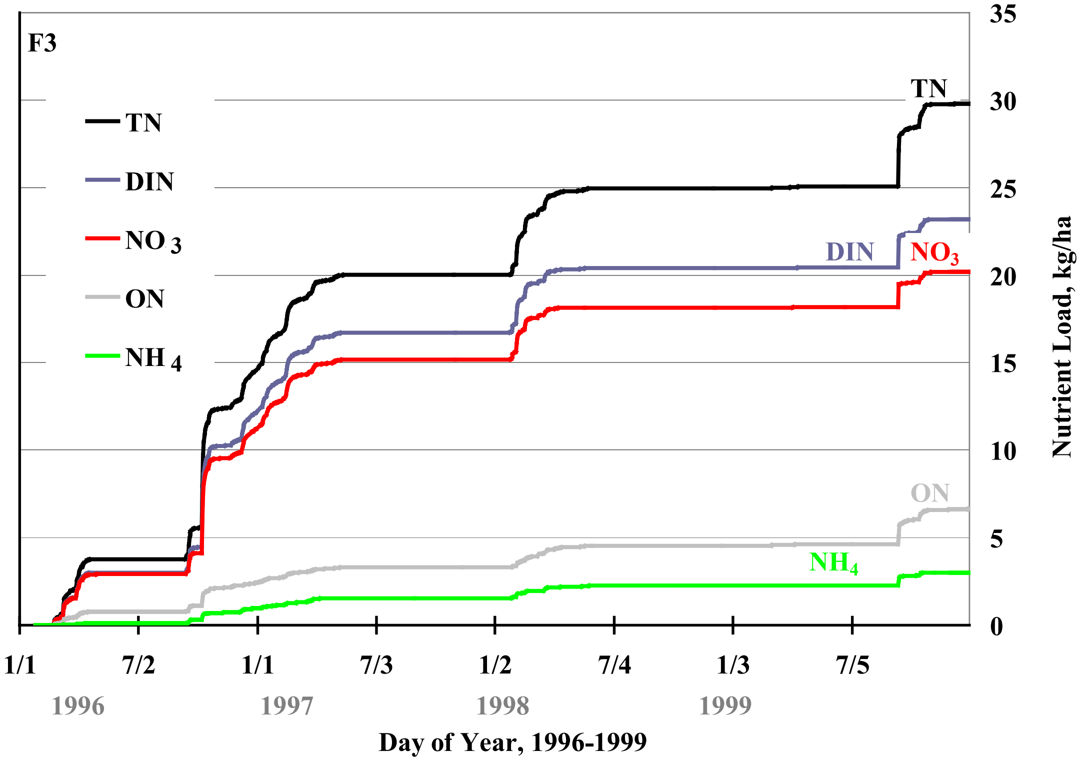

Figure 80. Cumulative nitrogen loads (kg/ha) for F3, over entire study period (1996-99).

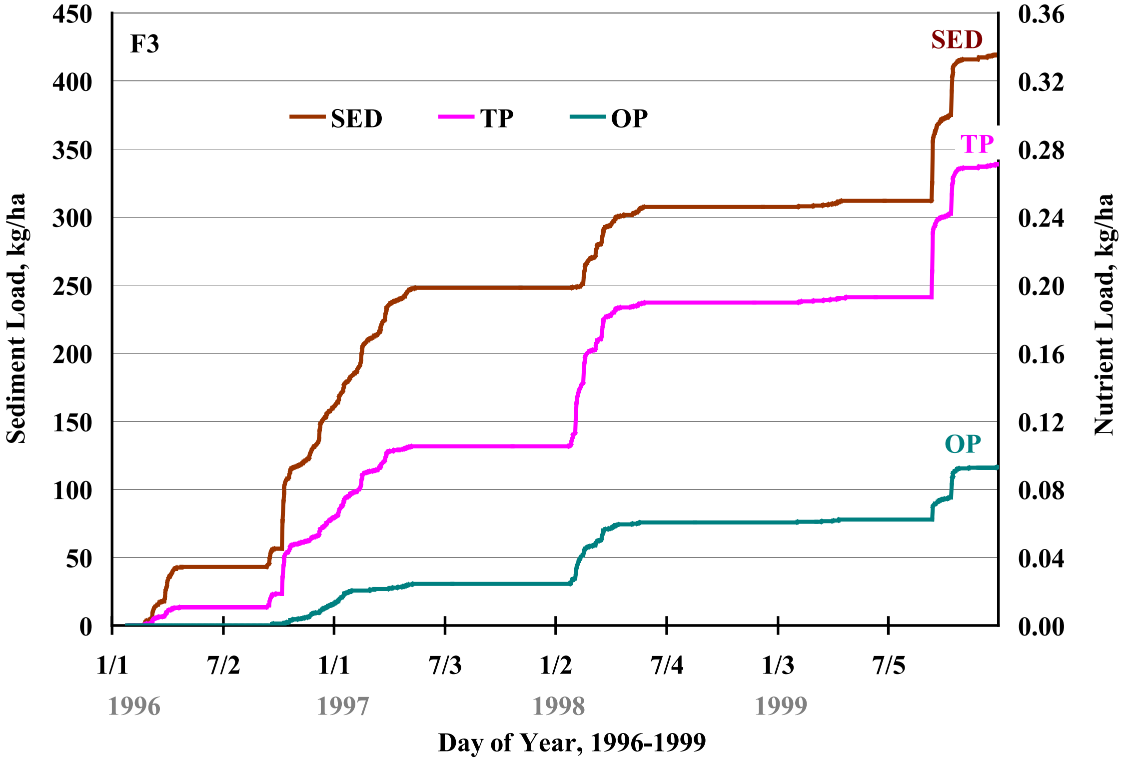

Figure 81. Cumulative sediment and phosphorus loads (kg/ha) for F3, from7/30 through 11/29 (1999).

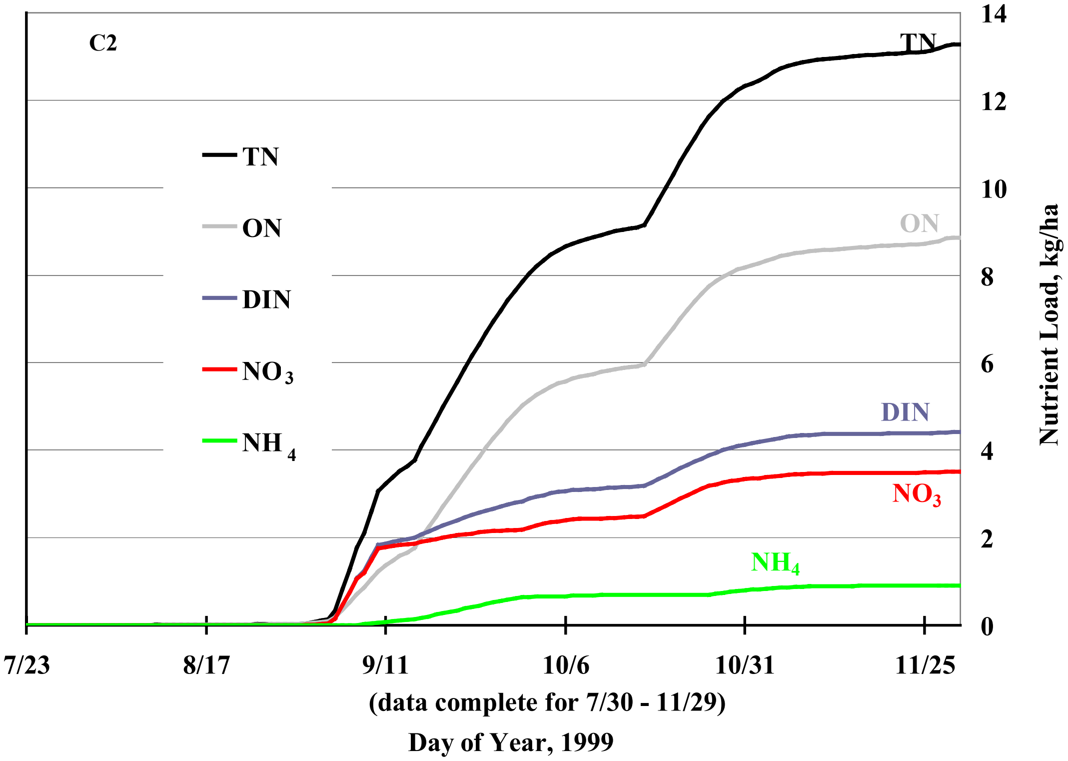

Figure 82. Cumulative nitrogen loads (kg/ha) for C2, from7/30 through 11/29 (1999).

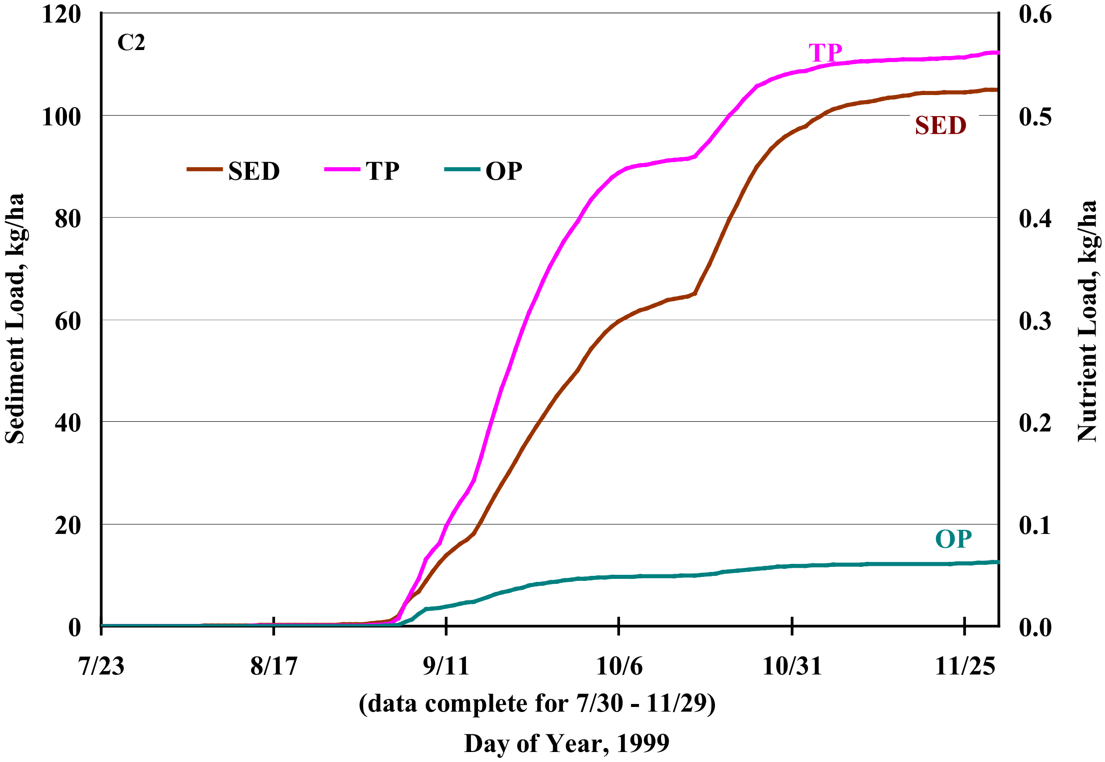

Figure 83. Cumulative sediment and phosphorus loads (kg/ha) for C2, from7/30 through 11/29 (1999).

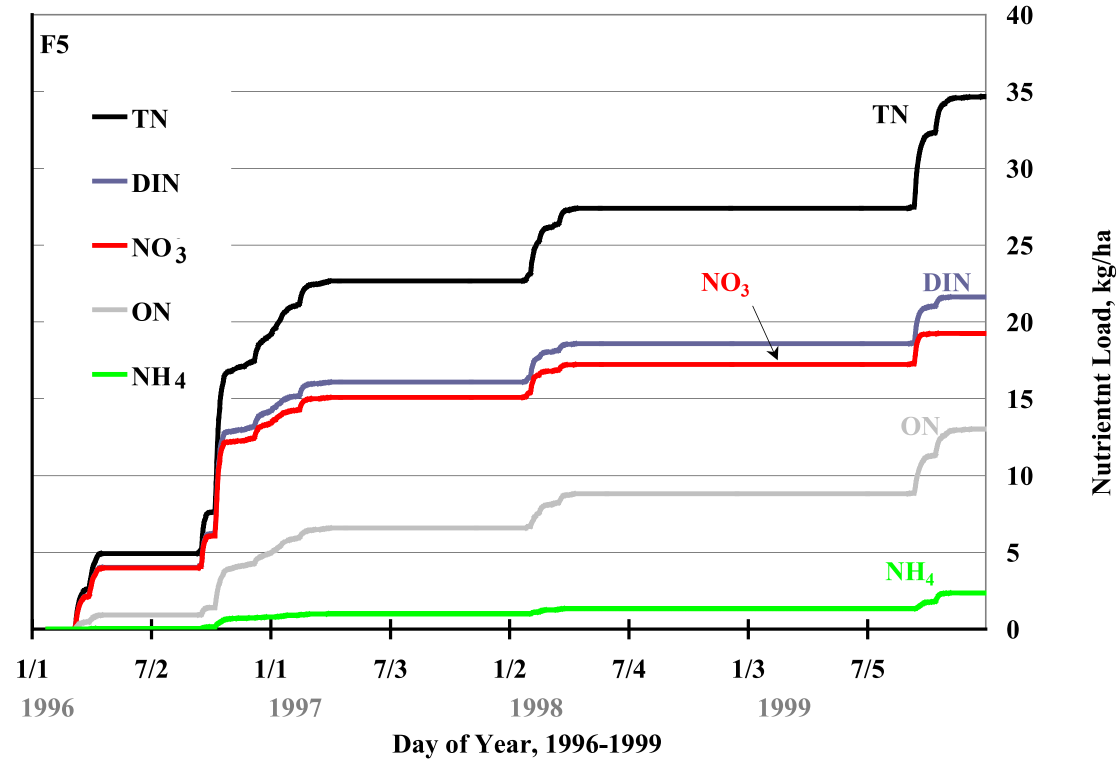

Figure 84. Cumulative nitrogen loads (kg/ha) for F5, over entire study period (1996-99).

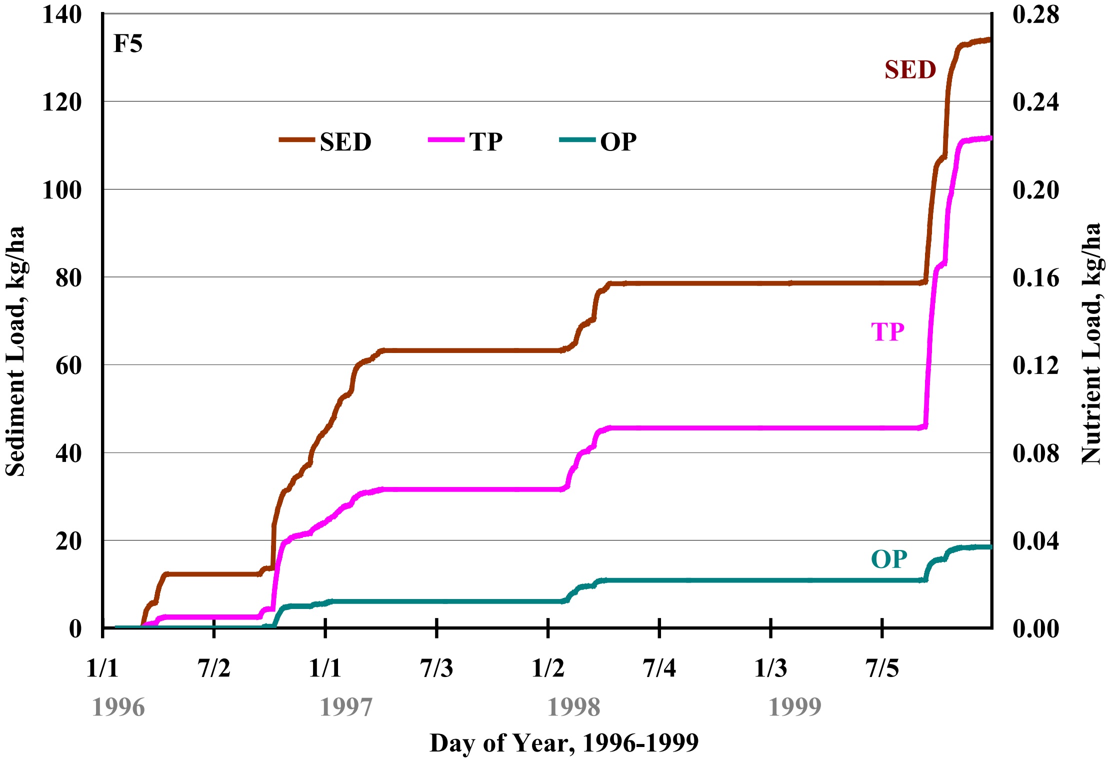

Figure 85. Cumulative sediment and phosphorus loads (kg/ha) for F5, over entire study period (1996-99).

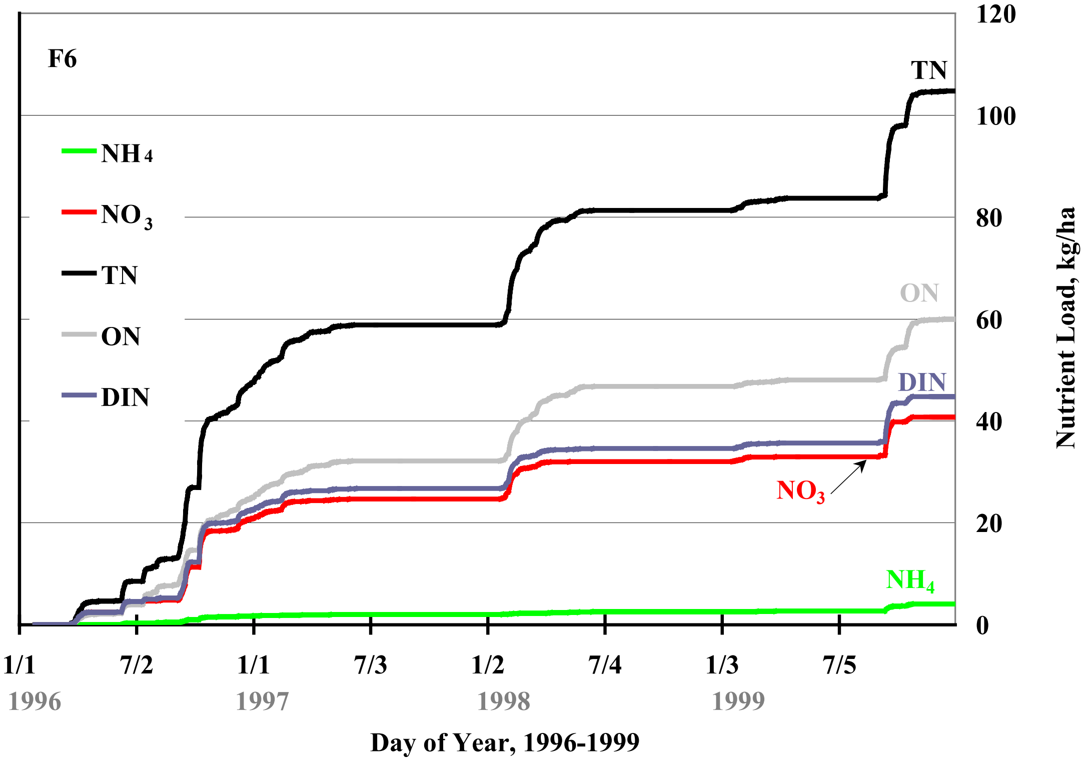

Figure 86. Cumulative nitrogen loads (kg/ha) for F6, over entire study period (1996-99).

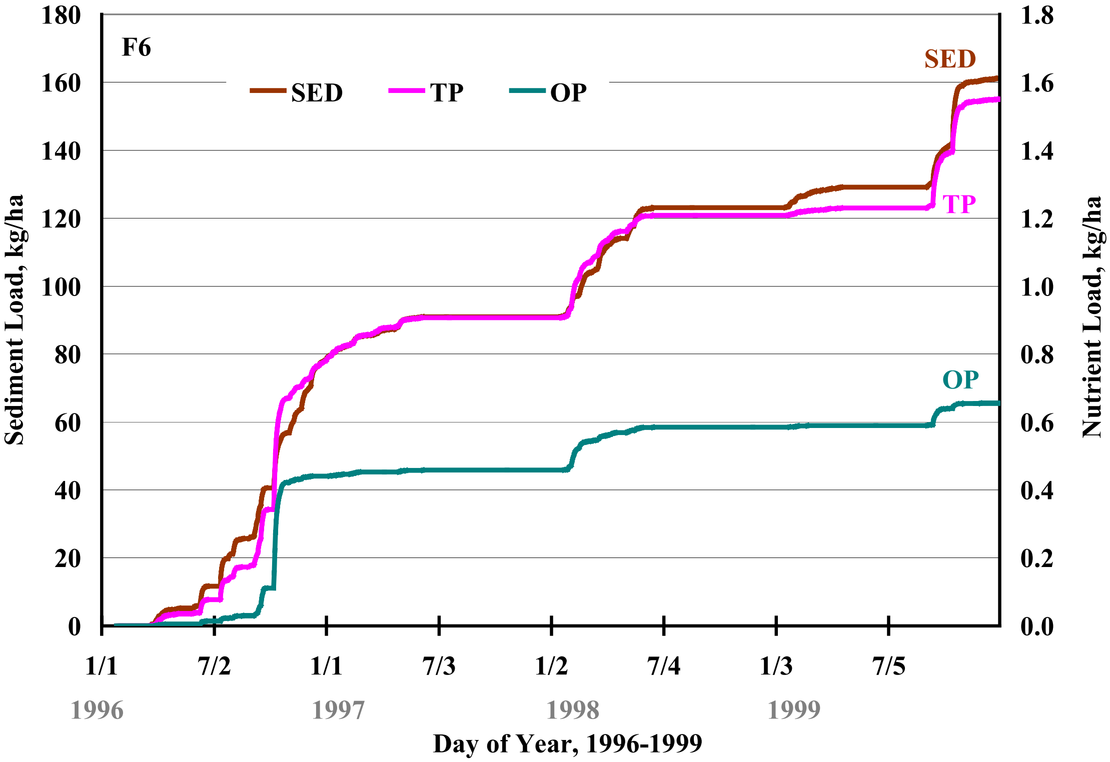

Figure 87. Cumulative sediment and phosphorus loads (kg/ha) for F6, over entire study period (1996-99).

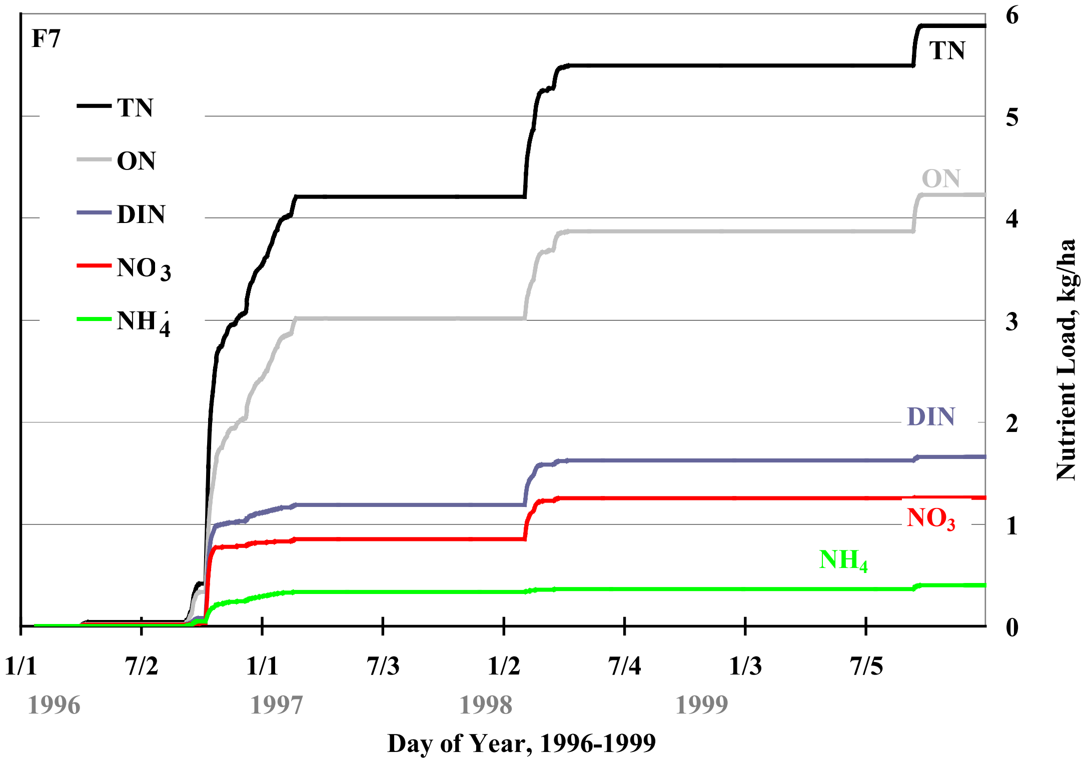

Figure 88. Cumulative nitrogen loads (kg/ha) for F7, over entire study period 1996-99).

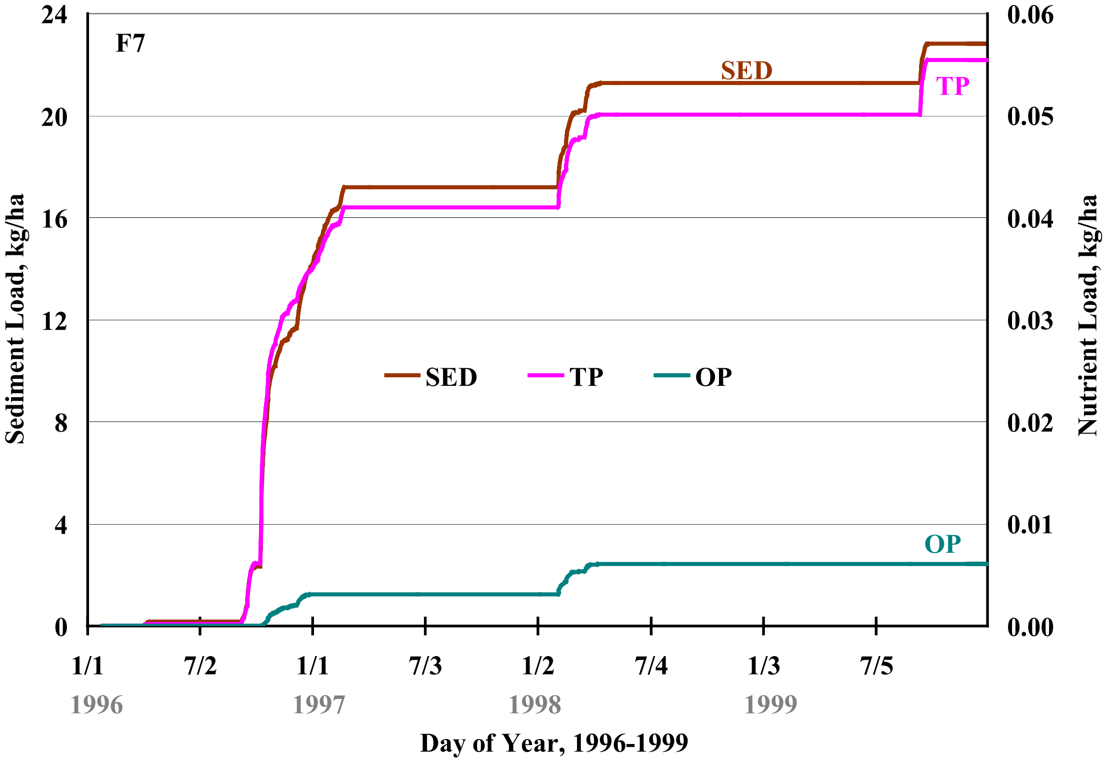

Figure 89. Cumulative sediment and phosphorus loads (kg/ha) for F7, over entire study period (1996-99).

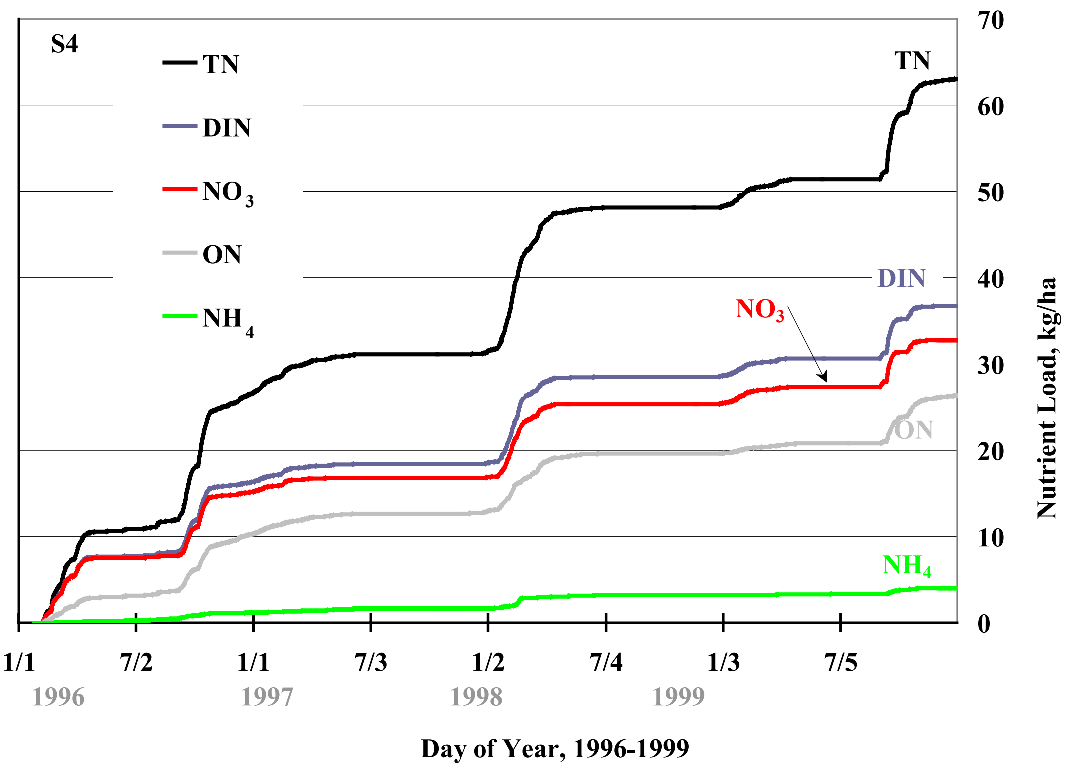

Figure 90. Cumulative nitrogen loads (kg/ha) for S4, over entire study period (1996-99).

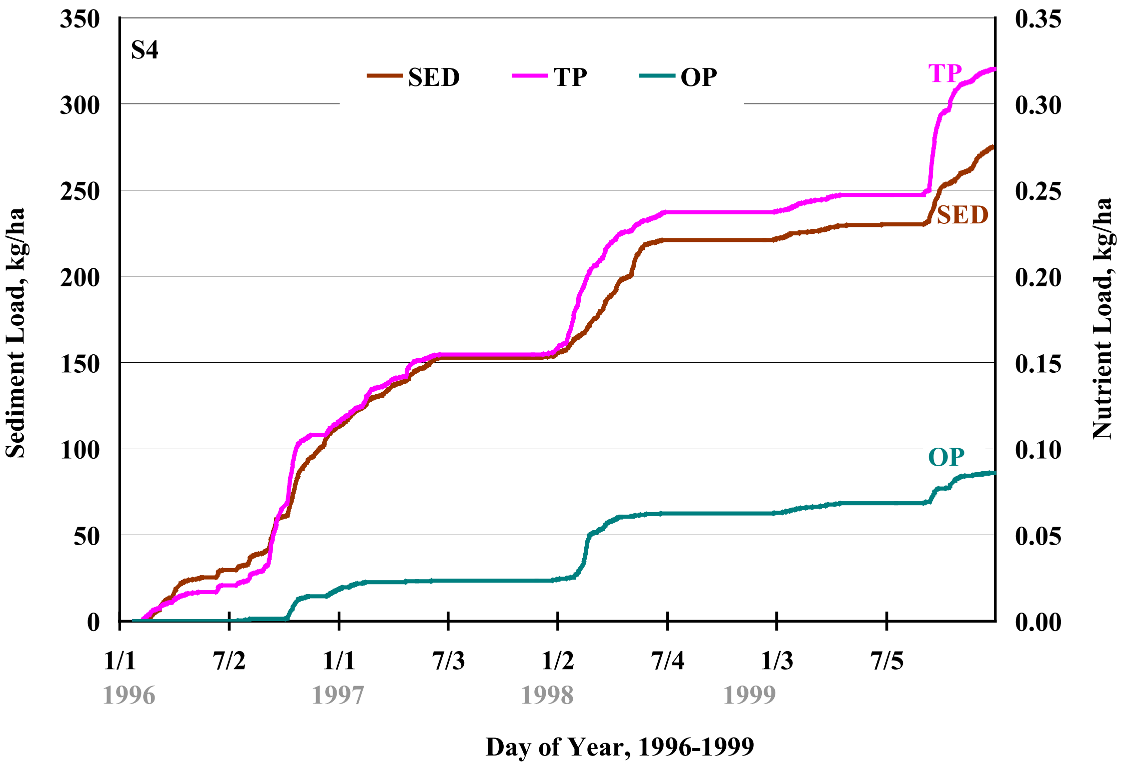

Figure 91. Cumulative sediment and phosphorus loads (kg/ha) for S4, over entire study period (1996-99).

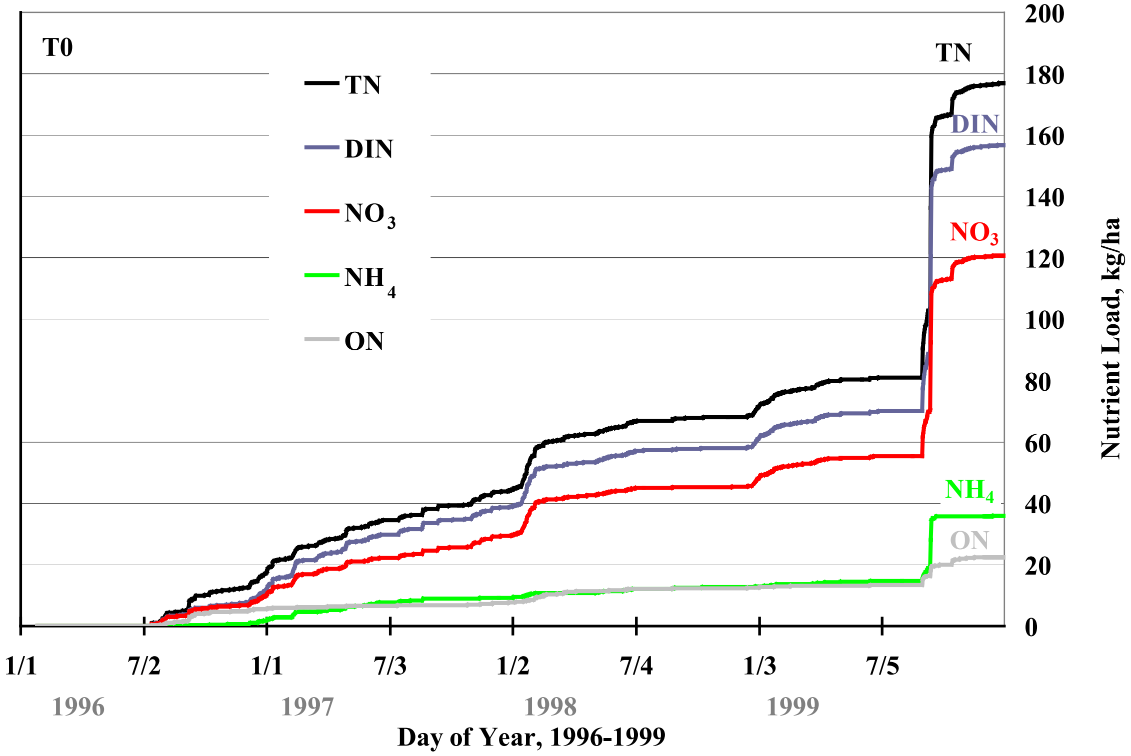

Figure 92. Cumulative nitrogen loads (kg/ha) for T0, over entire study period (1996-99).

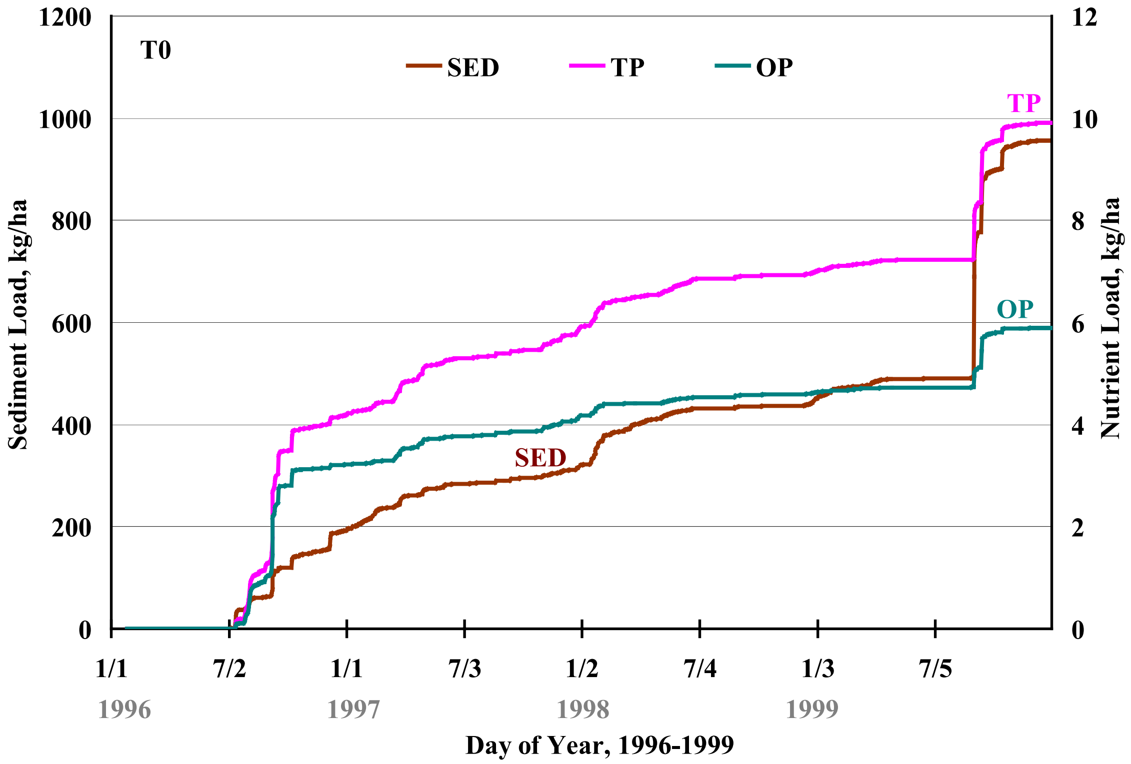

Figure 93. Cumulative sediment and phosphorus loads (kg/ha) for T0, over entire study period (1996-99).

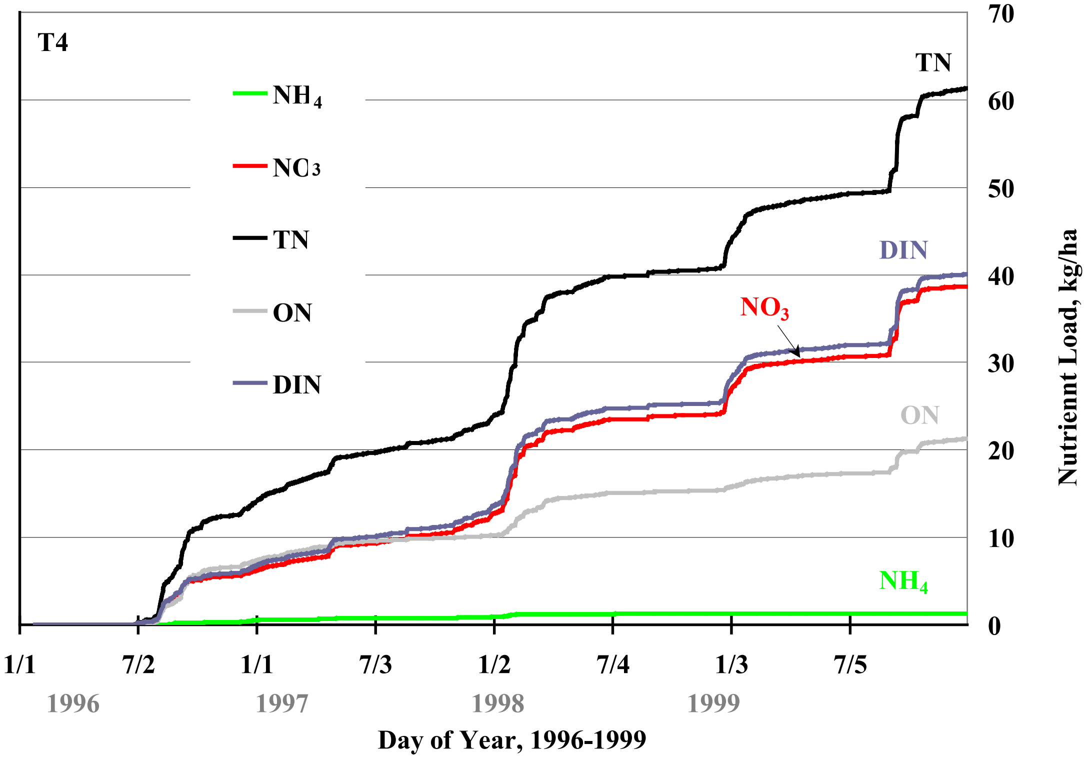

Figure 94. Cumulative nitrogen loads (kg/ha) for T4, over entire study period (1996-99).

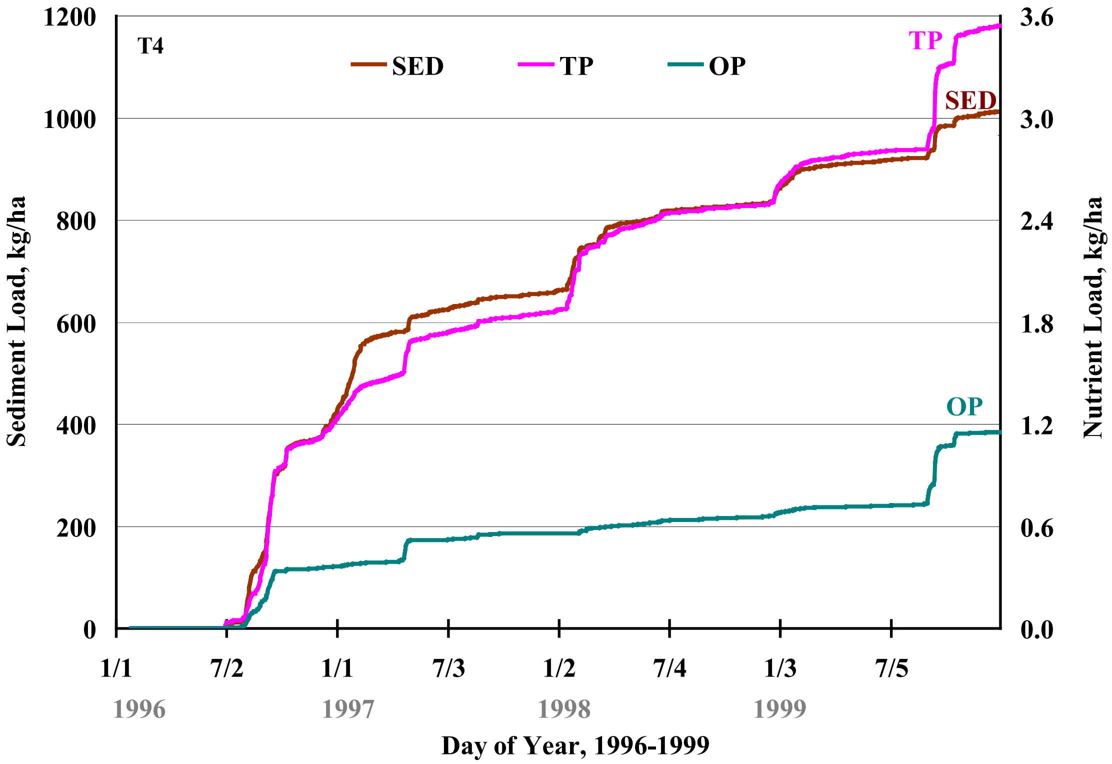

Figure 95. Cumulative sediment and phosphorus loads (kg/ha) for T4, over entire study period (1996-99).

As alluded to earlier, each subwatershed and field has different proportions of each form of nitrogen (Table 12). Crops in the primarily agricultural subwateshed T4 are fertilized; thus the outflow has a larger proportion of TN and DIN as NO_3 (compared to S4 and its component fields). In contrast, a much lower proportion of TN is present as NO_3 for stations F6, F7, and C2 (part of 1999 only). The DIN in drainage water from T0 has a lower proportion of NO_3 (and thus a higher proportion of NH_4) compared to T4. This is attributable to the higher levels of NH_4 present in the animal waste applied within T0.

Table 12. Percentage of total nitrogen load (TN) and dissolved inorganic nitrogen load (DIN) that is nitrate-nitrogen (NO_3); values taken over the entire study period (1996-99), except station C2 (1999 only).

Station	% NO_3 / TN	% NO_3 / DIN
S4	52%	89%
F5	56%	89%
F6	39%	91%
F7	21%	76%
T0	68%	77%
T4	63%	97%
C2 (1999 only)	26%	80%
F3	68%	87%

Average loads for sediment and nutrients over the 1996 through 1999 study period are given on a seasonal basis, in Table 13. As in previous seasonal analyses, spring is considered April, May, and June; summer is considered July, August, and September; fall is considered October, November, and December; and winter is January, February and March. For station S4 the longterm average seasonal sediment and nutrient load data indicates that most losses occur in this subwatershed in the winter months (Jan. - Mar.). In general, higher flows occur during the winter months, which results in greater nutrient losses as well. Similarly, seasonal patterns of nutrient loss are given in Table 13 for the forested fields F5, F6, and F7.

In the agricultural subwatershed T4, high N losses are also seen in the winter months- a time when PET is low and drainage is greater. The greatest nitrate losses from T4 occur during the winter (Jan. - Mar.). Nitrate is highly soluble and is commonly lost through sub-surface drainage, which occurs mainly during the winter on this agricultural site. High losses occur in T4 during the summer as well (July - Sept.), due to convective thunderstorms. For station T0 the highest losses (kg/ha) occur for all nutrients and sediment during the summer. Brief, intense summer storms can create flushes of nutrient and sediments into the drainage canals, via surface drainage. Subwatersheds T4 and T0 have a higher potential to lose sediment and sediment-bound nutrients during storm events because of their potential for surface drainage.

Table 13. Nutrient and sediment loads per area (kg/ha) for each season, averaged over the entire study period for each station.

S4, 2948 ha

Study Avg.	TP	OP	TKN	NH_4	NO_3	SED	TN	ON	DIN
Spring	0.01	0.002	0.8	0.2	0.5	16.1	1.4	0.7	0.7
Summer	0.02	0.002	1.7	0.3	1.9	12.2	3.5	1.4	2.1
Fall	0.02	0.01	2.0	0.2	1.4	20.6	3.4	1.8	1.6
Winter	0.03	0.01	3.1	0.4	4.3	20.0	7.5	2.7	4.8

F5, 127 ha

Study Avg.	TP	OP	TKN	NH_4	NO_3	SED	TN	ON	DIN
Spring	0.001	0.0001	0.1	0.01	0.3	1.7	0.4	0.1	0.3
Summer	0.02	0.002	0.8	0.1	1.0	6.5	1.8	0.7	1.1
Fall	0.03	0.004	1.7	0.3	1.9	15.5	3.6	1.4	2.2
Winter	0.01	0.003	1.2	0.1	1.6	9.9	2.9	1.1	1.8

F6, 90 ha

Study Avg.	TP	OP	TKN	NH_4	NO_3	SED	TN	ON	DIN
Spring	0.04	0.01	2.0	0.2	1.0	6.6	3.0	1.8	1.1
Summer	0.1	0.04	4.6	0.4	3.5	9.9	8.1	4.2	3.9
Fall	0.2	0.1	4.4	0.3	2.6	14.8	7.0	4.1	2.9
Winter	0.1	0.03	5.0	0.1	3.1	9.0	8.2	4.9	3.3

T4, 710 ha

Study Avg.	TP	OP	TKN	NH_4	NO_3	SED	TN	ON	DIN
Spring	0.1	0.0	0.5	0.04	0.9	22.5	1.5	0.5	1.0
Summer	0.4	0.2	2.2	0.1	3.2	102.5	5.4	2.2	3.2
Fall	0.2	0.04	1.1	0.1	2.0	47.2	3.1	1.0	2.1
Winter	0.3	0.03	2.4	0.1	4.7	108.2	7.1	2.2	4.9

T0, 50 ha

Study Avg.	TP	OP	TKN	NH_4	NO_3	SED	TN	ON	DIN
Spring	0.2	0.1	1.4	1.1	1.9	15.7	3.3	0.3	3.1
Summer	1.5	1.0	8.6	5.8	16.7	135.3	25.3	2.8	22.5
Fall	0.4	0.2	1.9	0.6	4.8	43.6	6.7	1.3	5.4
Winter	0.4	0.2	2.2	1.4	6.7	44.5	8.9	1.2	8.2

Table 14. Nutrient and sediment loads per station area (kg/ha) for each station for each year of study, for September and October of 1999, and for the total study period, 1996-99.

Load/Area (kg/ha)

S4 (Area=2948 ha)

Time	TP	OP	TKN	NH_4	NO_3	SED	TN	ON	DIN
4-yr Avg.	0.1	0.02	7.5	1.0	8.2	68.3	15.7	6.5	9.2
1996	0.1	0.02	11.4	1.1	15.2	112.7	26.6	10.3	16.3
1997	0.0	0.01	2.9	0.5	1.6	40.4	4.5	2.4	2.1
1998	0.1	0.04	8.2	1.5	8.6	66.4	16.8	6.7	10.1
1999	0.1	0.02	7.5	0.8	7.3	53.6	14.8	6.7	8.1
Sept.-Oct. 1999	0.1	0.01	5.2	0.6	5.2	27.3	10.4	4.6	5.8

F6 (Area=90 ha)

Time	TP	OP	TKN	NH_4	NO_3	SED	TN	ON	DIN
4-yr Avg.	0.4	0.2	16.0	1.0	10.2	40.3	26.2	15.0	11.2
1996	0.8	0.4	26.7	1.7	20.9	78.4	47.6	25.0	22.6
1997	0.1	0.02	7.4	0.3	3.8	12.6	11.2	7.1	4.1
1998	0.3	0.1	15.1	0.5	7.4	32.1	22.5	14.6	7.9
1999	0.3	0.1	14.7	1.5	8.7	38.1	23.4	13.2	10.2
Sept.-Oct. 1999	0.3	0.1	12.5	1.3	7.7	29.8	20.3	11.2	9.1

F5 (Area=127 ha)

Time	TP	OP	TKN	NH_4	NO_3	SED	TN	ON	DIN
4-yr Avg.	0.04	0.01	3.0	0.5	3.7	26.0	6.7	2.5	4.2
1996	0.03	0.01	3.0	0.4	7.1	23.7	10.1	2.6	7.5
1997	0.02	0.001	2.5	0.3	2.3	25.3	4.8	2.2	2.6
1998	0.03	0.01	2.5	0.3	2.1	15.0	4.6	2.2	2.4
1999	0.1	0.01	3.5	0.7	1.3	36.6	4.8	2.8	2.0
Sept.-Oct. 1999	0.1	0.01	3.4	0.7	1.5	35.7	4.9	2.7	2.2

F3 (Area=47 ha)

Time	TP	OP	TKN	NH_4	NO_3	SED	TN	ON	DIN
4-yr Avg.	0.1	0.02	2.4	0.8	5.0	104.8	7.5	1.7	5.8
1996	0.1	0.01	3.4	1.0	11.2	160.3	14.6	2.4	12.2
1997	0.04	0.01	1.5	0.6	3.9	87.6	5.4	0.9	4.5
1998	0.1	0.04	1.9	0.7	3.0	59.6	4.9	1.2	3.7
1999	0.1	0.03	2.9	0.8	2.0	111.9	4.9	2.1	2.8
Sept.-Oct. 1999	0.1	0.03	2.7	0.7	2.0	103.3	4.7	1.9	2.7

Table 14 (continued).

Load/Area (kg/ha)

T4 (Area=710 ha)

Time	TP	OP	TKN	NH_4	NO_3	SED	TN	ON	DIN
4-yr Avg.	0.9	0.3	5.6	0.3	9.5	252.0	15.1	5.3	9.8
1996	1.2	0.4	7.9	0.5	6.2	427.0	14.1	7.3	6.8
1997	0.6	0.2	3.1	0.3	5.6	229.5	8.7	2.8	5.9
1998	0.7	0.1	5.9	0.4	13.9	198.8	19.8	5.5	14.3
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

T0 (Area=50 ha)

Time	TP	OP	TKN	NH_4	NO_3	SED	TN	ON	DIN
4-yr Avg.	2.4	1.4	13.9	9.0	30.1	236.5	44.0	5.5	39.1
1996	4.2	3.2	7.4	1.8	9.9	192.9	17.3	5.6	11.8
1997	1.6	0.9	7.1	7.4	19.3	117.3	26.4	1.8	26.7
1998	1.1	0.5	8.4	3.6	18.5	130.5	26.9	4.9	22.1
1999	2.9	1.3	32.8	23.0	72.7	505.4	105.5	9.8	95.6
Sept.-Oct. 1999	2.6	1.2	29.7	21.1	63.6	453.0	93.3	8.6	84.7

Total nutrient and sediment loads per station area (kg/ha) are shown for each year with the average loads for the entire study period and the load for September and October of 1999 when the hurricanes occurred (Table 14). When comparing S4 to its component field stations, it appears that station F6 has higher longterm loads than S4 or the other field stations.

When comparing T4 and S4, TN and NO_3-N losses per hectare for each year appear slightly greater for station T4, but over the study the losses are very similar for both stations. Losses in 1999 were similar to the 4-year average losses. Total annual nitrogen load from T4 was 18 kg/ha in 1999, compared to the 4-year annual average load of 15 kg/ha. Total annual nitrogen load from S4 was 15 kg/ha in 1999, compared to the

4-year annual average load of 16 kg/ha. The nitrogen export observed in S4 was high compared to other studies (Chescheir et al. 2002).

Area T0, the agricultural area (within T4) receiving swine lagoon effluent produced on average 44 kg/ha of TN, 30 kg/ha NO_3, and 2 kg/ha TP. In 1999 the annual export from the area receiving animal waste was 106 kg/ha of TN, 73 kg/ha NO_3, and 3 kg/ha TP.

The high export of nitrogen from subwatershed S4 and its fields F5 and F6 is related to the site soil (high organic material). The loads from S4, F5, and F6 are consistently higher than loads from other forested sites in North Carolina (Chescheir et al. 2002). For S4 the 4-year average export of TN was 15.7 kg/ha. For S4, average (4-year) DIN loss was 9.2 kg/ha and ON was 6.5 kg/ha. Likewise average per hectare exports of nitrogen from F5 (6.7 kg/ha for TN, 4.2 kg/ha for DIN, and 2.5 kg/ha for ON)and F6 (26.2 kg/ha for TN, 11.2 kg/ha for DIN, and 15.0kg/ha for ON) were high (Table 14). The average export of N from the forested site on mineral soil (F3, within C2) was lower (7.5 kg/ha for TN, 5.8 kg/ha for DIN, and 1.7 kg/ha for ON), but this is still high compared to the studies by Chescheir et al (2002).

As expected, sediment losses were greater for the agricultural station T4 due to the tillage of cropland and less continuous crop cover. But, because of the flat topography, sediment losses from the agricultural land are still low. Total annual phosphorus load from T4 was 0.9 kg/ha in 1999, the same as the 4-year annual average load. Total annual phosphorus load from S4 was 0.1 kg/ha in 1999, the same as the 4-year annual average load.

The high levels of TP and OP measured in the T4 subwatershed are attributable to the swine lagoon effluent that is land-applied in the area T0. TP loss from T0 is nearly three times greater than the TP loss from subwatershed T4 (Table 14). Likewise the OP loss per hectare from T0 is roughly five times greater that the OP loss from T4. So it is clear that this small area (50 ha or less) that receives the swine waste is a major contributor to the overall phosphorus and nitrogen losses from T4 (710 ha).

High nutrient loads were measured during 1996 for station T4, even though the data record for this station did not begin until April 28 of that year (S4 record began Feb. 8, 1996). High nutrient loads were also measured during 1996 for T0; the data record for T0 began July 3, 1996. During 1996, losses from all stations were great in the fall due to hurricanes Bertha and Fran, and tropical storm Josephine. The total annual rainfall was greatest for 1996 (~146 cm). The subsequent year, 1997, was the driest year of the study (~99 cm of rainfall) and likewise resulted in lower nutrient losses (kg/ha) for each station. Total annual nutrient losses/ha were similar for years 1998 and 1999. Rainfall totals for 1998 and 1999 were approximately 122 cm and approximately 130 cm respectively. But, the primary rainfall resulting in nutrient losses in 1998 occurred predominately in the winter months during El Nino related storm events. Year 1999 was very dry until the fall, when hurricanes Dennis, Floyd, and Irene occurred. So, overall 1999 nutrient loads were primarily due to the hurricanes. In general, 1999 resulted in total annual nutrient loads similar to that observed in previous years (1996-98) for the forested field stations and for the agricultural stations.

On an annual basis and over a large land area the year of the hurricanes (1999) did not produce larger than average nutrient and sediment 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 and sediment lost during the hurricanes of 1999 was approximately the same as an average year.

Table 15. Estimates of overall flow weighted nutrient and sediment concentrations (mg/L) for each station for each year of study, for September and October of 1999, and for the total study period, 1996-99.

Flow Weighted Concentration (mg/L)

S4

Time	TP	OP	TKN	NH_4	NO_3	SED	TN	ON	DIN
Total Study	0.03	0.01	2.6	0.3	2.8	23.7	5.4	2.3	3.2
1996	0.02	0.004	2.4	0.2	3.2	24.0	5.7	2.2	3.5
1997	0.03	0.004	2.2	0.4	1.2	29.5	3.3	1.8	1.5
1998	0.03	0.01	2.9	0.5	3.0	23.6	6.0	2.4	3.6
1999	0.03	0.01	2.8	0.3	2.7	20.2	5.6	2.5	3.1
Sept-Oct, 99	0.04	0.01	3.0	0.4	3.0	15.9	6.1	2.7	3.4

F7

Time	TP	OP	TKN	NH_4	NO_3	SED	TN	ON	DIN
Total Study	0.04	0.004	3.4	0.3	0.9	16.9	4.3	3.1	1.2
1996	0.05	0.004	3.6	0.4	1.1	18.8	4.7	3.2	1.5
1997	0.03	0	3.2	0.2	0.2	15.1	3.3	2.9	0.4
1998	0.03	0.01	3.0	0.1	1.4	13.8	4.3	2.9	1.5
1999	0.1	0	3.8	0.4	0.01	15.1	3.8	3.5	0.4

F6

Time	TP	OP	TKN	NH_4	NO_3	SED	TN	ON	DIN
Total Study	0.1	0.04	4.1	0.3	2.6	10.3	6.7	3.8	2.9
1996	0.1	0.1	4.4	0.3	3.5	13.1	7.9	4.2	3.8
1997	0.1	0.01	3.3	0.1	1.7	5.6	5.0	3.2	1.8
1998	0.1	0.03	3.7	0.1	1.8	7.9	5.5	3.6	1.9
1999	0.1	0.02	4.4	0.5	2.6	11.4	7.0	4.0	3.1
Sept-Oct, 99	0.1	0.02	4.6	0.5	2.8	10.9	7.4	4.1	3.3

F5

Time	TP	OP	TKN	NH_4	NO_3	SED	TN	ON	DIN
Total Study	0.04	0.01	3.0	0.5	3.7	26.0	6.7	2.5	4.2
1996	0.03	0.01	3.0	0.4	7.1	23.7	10.1	2.6	7.5
1997	0.02	0.001	2.5	0.3	2.3	25.3	4.8	2.2	2.6
1998	0.03	0.01	2.5	0.3	2.1	15.0	4.6	2.2	2.4
1999	0.1	0.01	3.5	0.7	1.3	36.6	4.8	2.8	2.0
Sept-Oct, 99	0.1	0.01	3.4	0.7	1.5	35.7	4.9	2.7	2.2

F3

Time	TP	OP	TKN	NH_4	NO_3	SED	TN	ON	DIN
Total Study	0.02	0.01	0.7	0.2	1.6	32.4	2.3	0.5	1.8
1996	0.02	0.003	0.8	0.2	2.7	38.7	3.5	0.6	2.9
1997	0.02	0.005	0.6	0.2	1.6	35.5	2.2	0.4	1.8
1998	0.03	0.01	0.6	0.2	0.9	17.8	1.5	0.4	1.1
1999	0.03	0.01	1.0	0.3	0.7	37.5	1.6	0.7	0.9
Sept-Oct, 99	0.03	0.01	1.0	0.3	0.7	37.6	1.7	0.7	1.0

Table 15 (continued).

Flow Weighted Concentration (mg/L)

T4

Time	TP	OP	TKN	NH_4	NO_3	SED	TN	ON	DIN
Total Study	0.2	0.1	1.1	0.1	2.0	51.4	3.1	1.1	2.0
1996	0.2	0.1	1.3	0.1	1.0	71.9	2.4	1.2	1.1
1997	0.2	0.1	1.0	0.1	2.0	71.5	3.0	0.9	2.1
1998	0.1	0.02	1.1	0.1	2.6	37.1	3.7	1.0	2.7
1999	0.2	0.1	1.1	0.01	2.4	29.7	3.4	1.1	2.4
Sept-Oct, 99	0.2	0.1	1.0	0.01	2.2	23.5	3.2	1.0	2.2

T0

Time	TP	OP	TKN	NH_4	NO_3	SED	TN	ON	DIN
Total Study	0.6	0.4	3.5	2.2	7.5	59.1	10.9	1.4	9.7
1996	0.8	0.6	1.5	0.4	1.9	38.0	3.4	1.1	2.3
1997	0.7	0.4	3.2	3.2	8.3	54.0	11.5	0.9	11.5
1998	0.4	0.2	2.9	1.2	6.3	44.6	9.2	1.7	7.6
1999	0.5	0.2	5.7	4.0	12.6	87.4	18.3	1.7	16.5
Sept-Oct, 99	0.6	0.3	6.6	4.7	14.1	100.8	20.8	1.9	18.8

C2

Time	TP	OP	TKN	NH_4	NO_3	SED	TN	ON	DIN
1999 (7/30 – 1/29)	0.1	0.01	2.1	0.2	0.7	22.3	2.8	1.9	0.9
Sept-Oct, 99	0.2	0.02	2.8	0.2	1.0	29.9	3.8	2.5	1.3

The table above (Table 15) displays the overall flow-weighted concentration of nutrient or sediment for each station, for each year in the study, for September and October of 1999 (Hurricanes Dennis, Floyd, and Irene), and for the overall study. The flow-weighted concentrations were derived by dividing the total nutrient or sediment load for each time period by the total volume of flow for that time period. This value gives a convenient estimate of the average nutrient loss per flow volume for forested and agricultural conditions. There are variabilities in these values from year to year due to the differences in weather patterns.

Nitrogen concentrations observed in drainage water from fields F5 and F6, and subwatershed S4 were abnormally high compared to those observed in other water quality studies (Chescheir et al., 2002) of forested lands. Overall flow-weighted concentrations of N observed from subwatershed S4 were 5.4 mg/L for TN, 2.3 mg/L for ON, 2.8 mg/L for NO_3-N, and 0.4 mg/L for NH_4-N. Similarly, overall flow-weighted concentrations of N observed from fields F5 and F6, respectively, were 9.1 and 6.7 mg/L for TN, 3.6 and 3.8 mg/L for ON, 3.4 and 2.6 mg/L for NO_3-N, and 2.1 and 0.3 mg/L for NH_4-N. The high concentrations of N in waters from these areas are likely due to the organic soils present and the unusually high hydraulic conductivities of those soils.

In water quality modeling it is often very difficult to estimate expected nutrient losses from particular areas. These data can be used for validating or calibrating water quality prediction models.

Load Probability

Hurricane Floyd and the related storms of 1999 produced high flows and correspondingly high nutrient and sediment loads. It is important to quantitatively determine if the loads produced by hurricane Floyd and the other storms of 1999 were much greater than those in the past. Probability of load exceedance plots were produced for subwatersheds S4 and T4 to illustrate the magnitude of the daily loads produced by the storms of 1999, compared to other events on record (Figures 96 and 101). Recall the daily flow probability plots for these two stations (Figures 57 and 58): for S4, the highest peak flows were noted for hurricane Floyd (1999) and tropical storm Josephine (1996) and for T4, the highest peak flows were noted for hurricanes Floyd and Irene (1999) and for the El Nino related storms of 1998. Comparing that data to the load probability data, it is evident that not all peak loads occurred during the greatest storm events. This illustrates the importance of a storm's "timing" with regard to the nutrient and sediment load it will produce. Each watershed, and even each nutrient appears to be sensitive to different types of storm events.

For subwatershed S4, hurricane Floyd of 1999 produced greater ON, TN, and DIN loads than other storms on record (Figure 97). Tropical storm Josephine (1996) produced high loads as well. Hurricane Floyd also produced the largest ON, TN, and DIN daily load in subwatershed T4, followed by the El Nino storms (1998) and then hurricane Irene- even though daily flow from Irene was greater than daily flow from El Nino. Hurricanes Floyd and Irene occurred during the fall, while the El Nino storms occurred in February, when wetter antecedent moisture conditions existed.

For phosphorus, Floyd produced the greatest TP daily load in both S4 and T4 (Figures 98 and 99), followed by Josephine (S4) and Irene (T4). For OP, the El Nino storms of 1998 produced the greatest daily load in subwatershed S4, followed by hurricane Floyd. This would indicate a relationship between this form of phosphorus and the conditions found in the forested watershed during cool temperatures. Additionally, the highest average OP concentrations were measured at the S4 outlet during spring months (April, May, June). In T4, Floyd produced the largest daily OP load, followed by hurricane Irene (same as TP).

Hurricane Floyd (1999) produced the greatest daily sediment load in both T4 and S4 (Figures 100 and 101). In S4, El Nino caused very high daily sediment loading. A post-hurricane Fran storm (1996) produced a high daily sediment load in subwatershed T4.

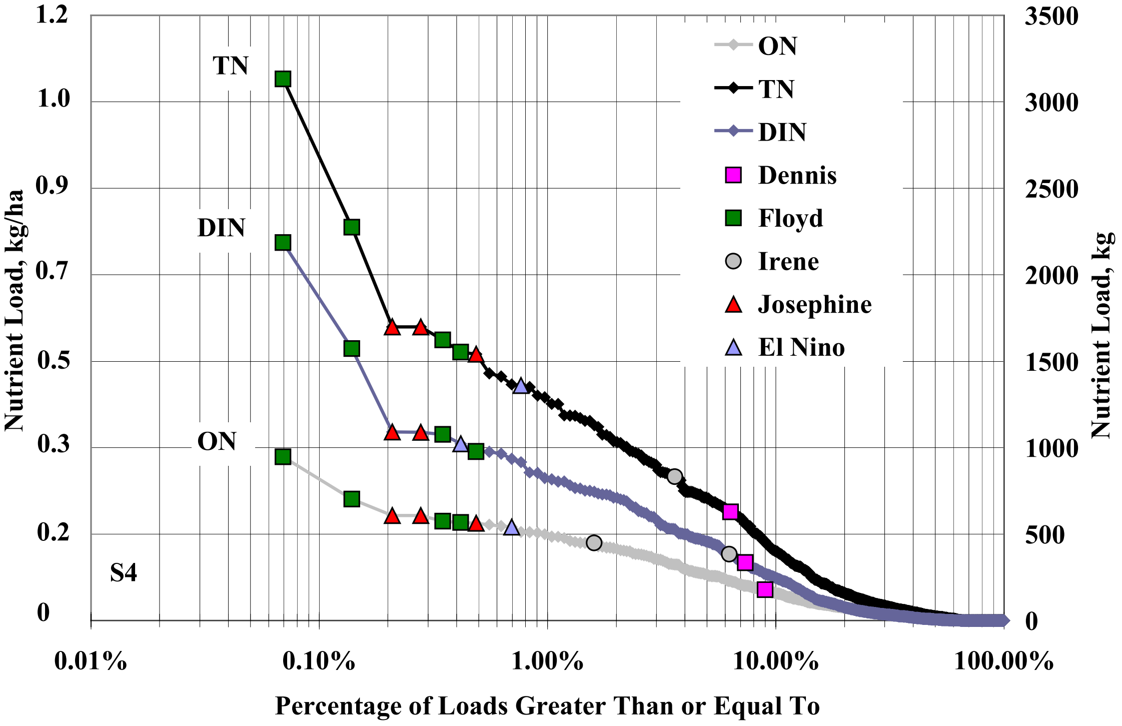

Figure 96. Subwatershed S4: ON, TN, and DIN probability of load exceedance over years 1996-99.

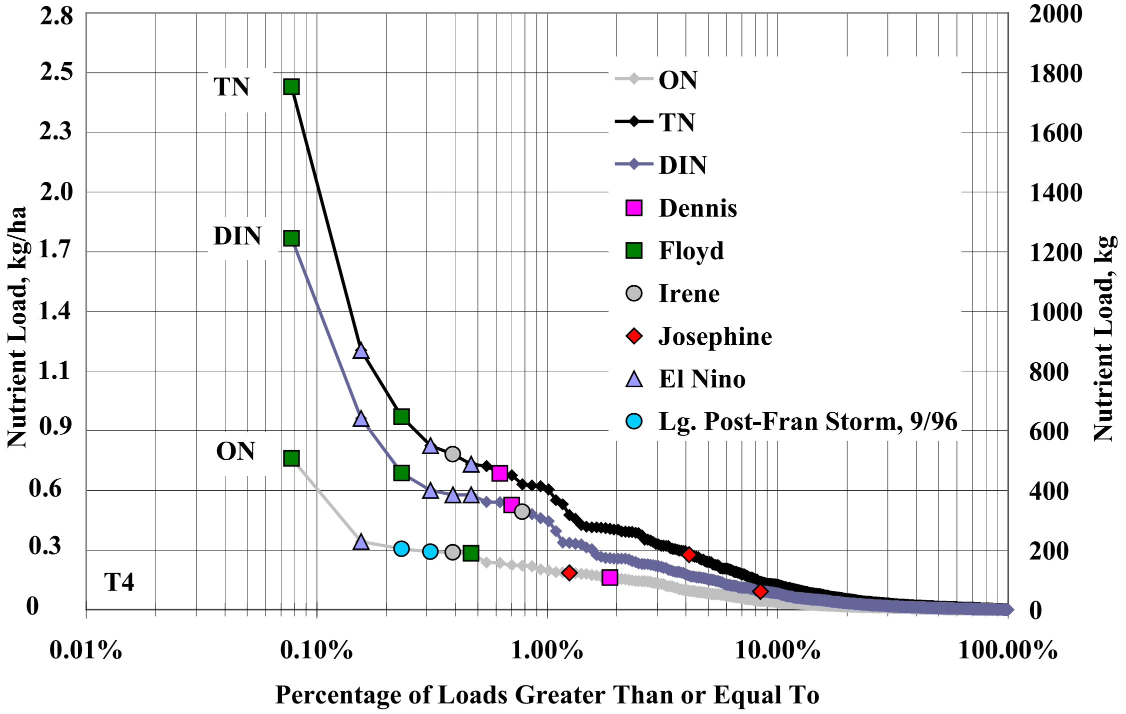

Figure 97. Subwatershed T4: ON, TN, and DIN probability of load exceedance over years 1996-99.

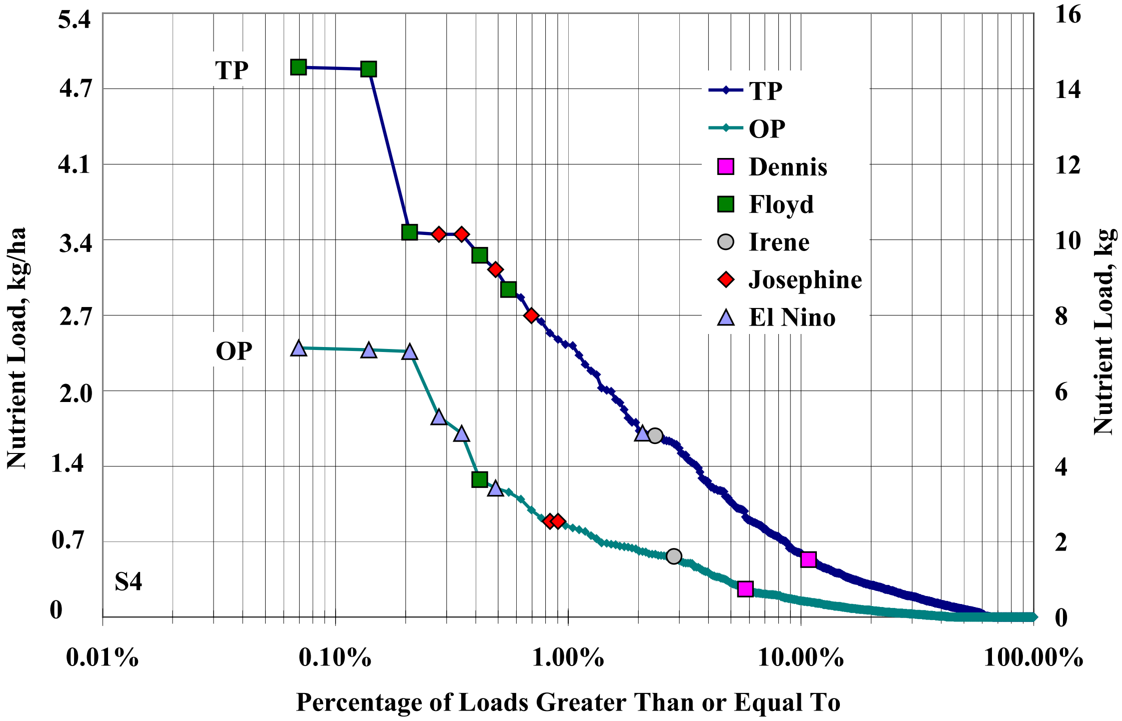

Figure 98. Subwatershed S4: TP and OP probability of load exceedance over years 1996-99.

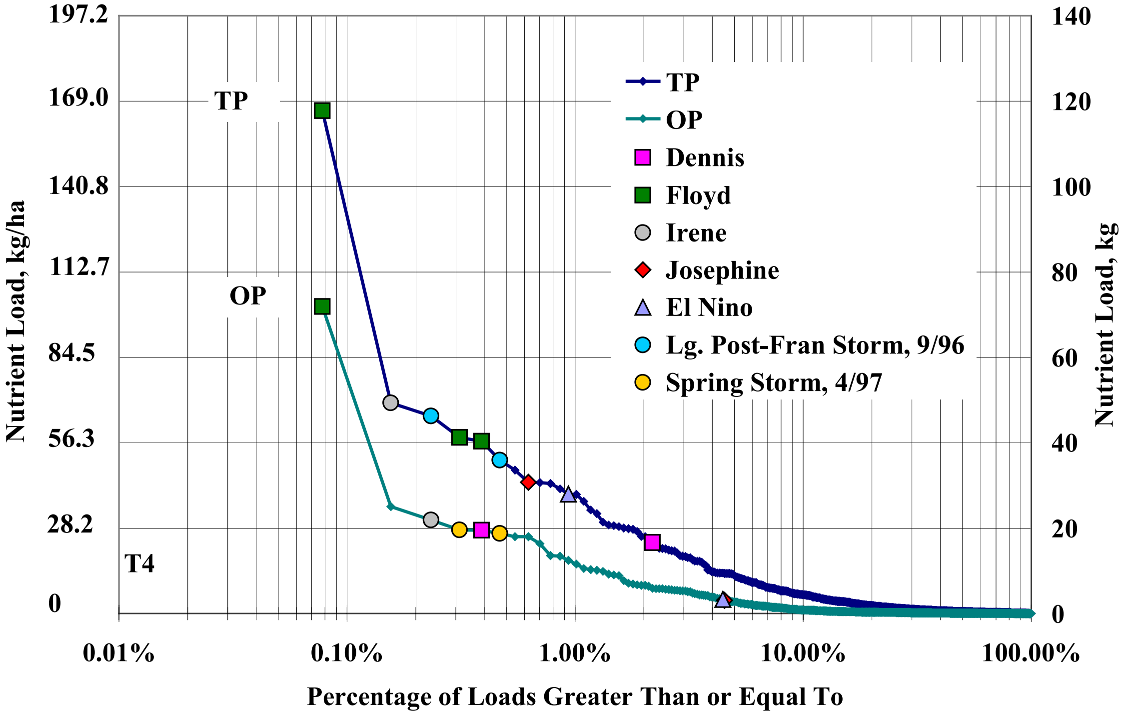

Figure 99. Subwatershed T4: TP and OP probability of load exceedance over years 1996-99.

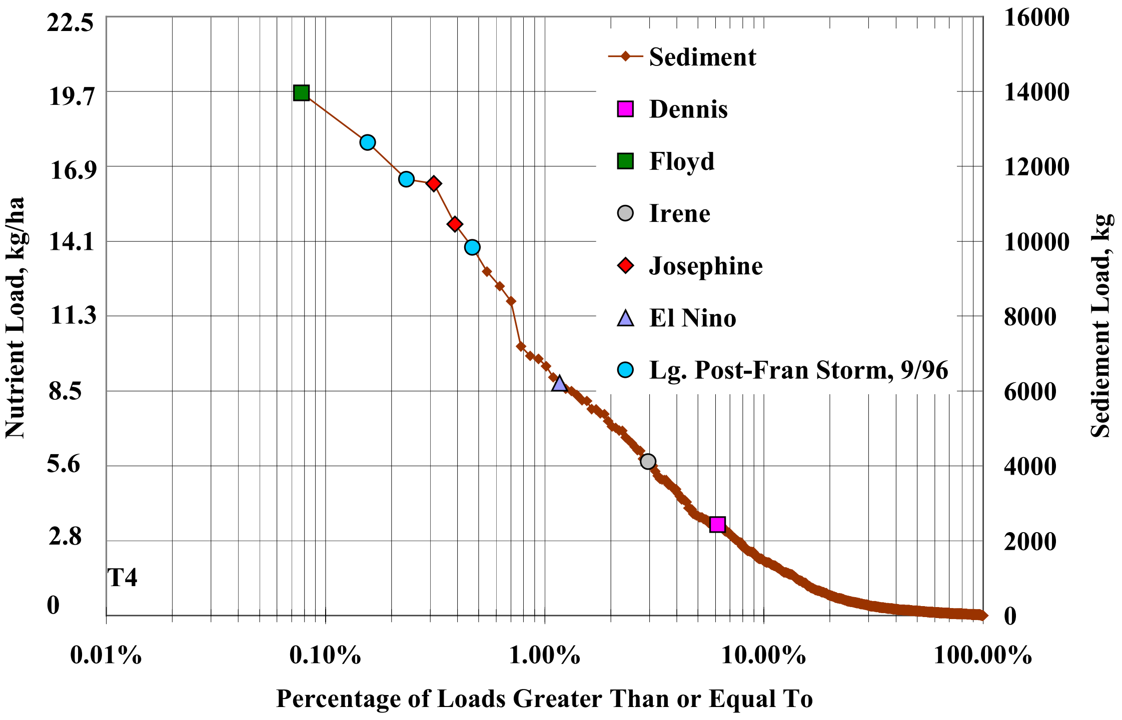

Figure 100. Subwatershed S4: sediment probability of load exceedance over years 1996-99.

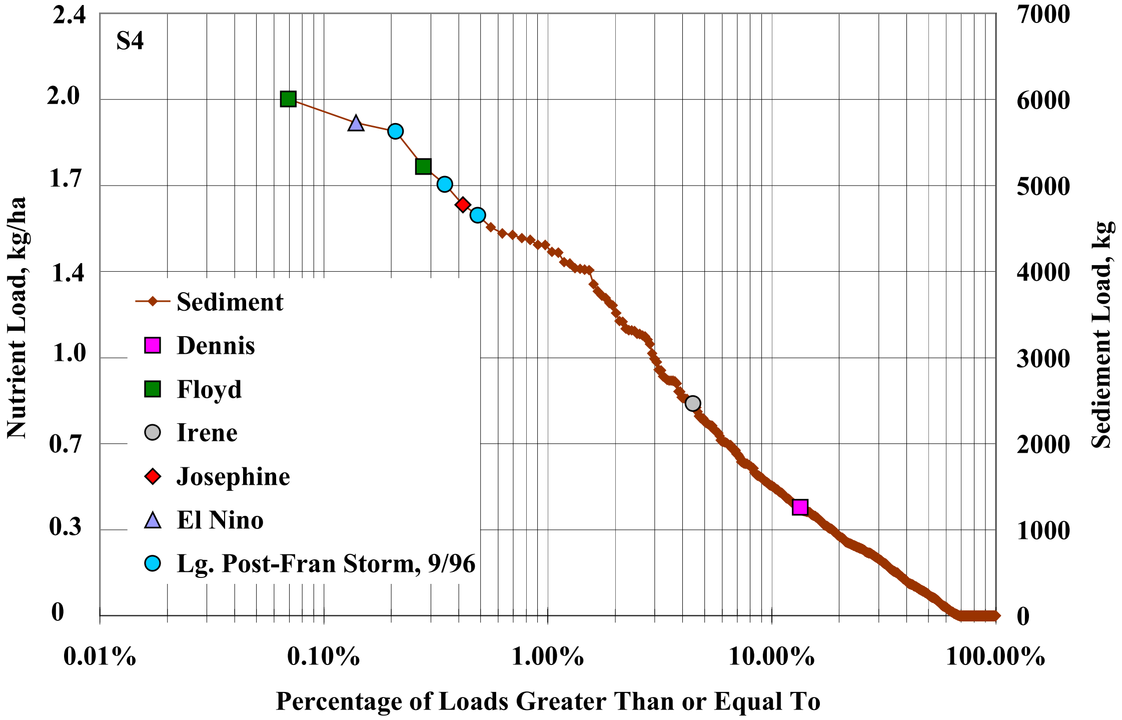

Figure 101. Subwatershed T4: sediment probability of load exceedance over years 1996-99.

Conclusion

This thesis compiles and evaluates a large, continuous data set (hydrology and water quality) from a multi-landuse watershed in the coastal plain of North Carolina. From 1996 through 1999 a variety of data was collected from this heavily monitored watershed, including precipitation, drainage (ditch or canal flow), water table fluctuation, and nutrient and sediment loss. The watershed is divided into subwatershed and field stations, such that data were obtained for a large managed forest area, fields within the forested subwatershed, a large agricultural area, a unit within the agricultural area receiving land-applied swine waste, and a large subwatershed comprised of managed forest and agriculture. A case study presentation was utilized to note the differences in hydrologic and water quality response of each unique land area for each unique precipitation event. The storm events captured in the data record include large winter storms (El Nino), as well as extreme fall events (hurricanes).

Results of this study document the differences in response of each station with regard to land use and storm type. Year 1999 is compared to other years of record. Year 1999 was one of extremes; an extremely dry spring and summer were following by an unprecedented series of hurricanes/tropical storms that produced record amounts of rainfall. The hurricanes and related storms of 1999 produced record flow and nutrient loads throughout the research watershed.

The hurricanes and related storms of 1999 brought excessive rainfall to North Carolina; the research watershed received approximately 555 mm of rainfall during September and October, the wettest such period in 49 years of record. Prior to the hurricane season, the area experienced a very dry spring and summer (565 cm for Feb.

through Aug.). The period from February through August of 1999 was the third driest such period in 49 years of record.

Soil type and landuse had an influence on the hydrologic response of each subwatershed to the hurricanes of 1999. The forested subwatershed (S4) has mostly organic soils with a large amount of drainable pore space, compared to the mineral soils of the agricultural subwatershed (T4). These pores were filled by the first hurricane, hurricane Dennis, which effectively made two passes over the watershed. During the first occurrence of hurricane Dennis, the forested subwatershed produced no flow, the agricultural watershed produced 2.9 mm of flow, and the mixed-use watershed (C2) produced 2.4 mm of flow. With the second pass of Dennis, the pores of forested soils were eventually filled and 10.8 mm of flow occurred. In the agricultural subwatershed and the mixed-use subwatershed five to six times more flow occurred (59.1 mm and 64.5 mm, respectively). When hurricane Floyd arrived, the flow response was similar for all subwatersheds since the soils were saturated (108.9 mm from S4, 164.2 mm from T4, and 163.3 from C2). Overall, the forested subwatershed, with organic soils, has a larger reservoir (soil pores) to fill before outflow occurs. Additionally, the continuous tree cover exerts a larger evapotranspiration demand than the less vegetated, agricultural subwatershed.

Daily flow rates measured across the research watershed were the greatest during hurricane Floyd than for any other time in the four-year study period. Daily flows observed for the agricultural subwatershed were generally greater than for the forested subwatershed or for the mixed-use subwatershed throughout the study, and during the hurricanes of 1999. Total annual flow from the agricultural and forested subwatersheds in

1999 was similar to average annual flow for the three previous years, but that flow was concentrated in the months of September and October. Sixty-four and 66 percent of the 1999 annual flow occurred in the months of September and October for the forested and agricultural subwatersheds respectively.

Total annual nitrogen load from an agricultural subwatershed was 18 kg/ha in 1999, compared to the 4-year annual average load of 15 kg/ha. Total annual nitrogen load from a forested subwatershed was 15 kg/ha in 1999, compared to the 4-year annual average load of 16 kg/ha. Total annual phosphorus load from an agricultural subwatershed was 0.9 kg/ha in 1999, the same as the 4-year annual average load. Total annual phosphorus load from a forested subwatershed was 0.1 kg/ha in 1999, the same as the 4-year annual average load.

From the data analyzed it appears that soil type has a large influence on nitrogen export in the forested areas. Larger than expected TN, DIN, and NO_3 loads were measured for S4 and its component fields. The managed forest stands on organic soils in this study produced as much nitrogen as agricultural areas on mineral soils. Compared to other studies the nitrogen export from these forested areas were unusually high.

Land applied swine lagoon effluent within an agricultural area resulted in drainage with excessively high concentrations of TN, NO_3, DIN, TP, and OP. Annually, this area produced on average 44 kg/ha of TN, 30 kg/ha NO_3, and 2 kg/ha TP. In 1999 the annual export from the area was 106 kg/ha of TN, 73 kg/ha NO_3, and 3 kg/ha TP.

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Appendix A

Soil parameters used to predict station F3 flow with DRAINMOD

Appendix A.1. Soil parameters used to predict station F3 flow with DRAINMOD.

Soil Inputs for DRAINMOD simulation of field F3
(Inputs derived from calibration using field data)

Soil Water Characteristic

theta, cm^3/cm^3	head,cm
0.3655	0
0.3535	-1
0.341	-3
0.3325	-10
0.327	-20
0.3205	-30
0.3155	-40
0.3105	-50
0.3	-80
0.282	-150
0.274	-200
0.255	-300
0.233	-400
0.2085	-500
0.19	-600
0.165	-1000
0.15	-1500
0.136	-3000

Drainage Volume & Upward Flux

water table,cm	vol drained, cm	upward flux, cm/hr
0	0	1
10	0.4	0.5
20	1	0.2
30	1.7	0.0625
40	2.5	0.02
50	4	0.0125
60	5.4	0.0075
80	10.4	0.0075
100	12.4	0.004
120	13	0.003
140	13.6	0.003
160	14.2	0.002
180	14.8	0.001
200	15.4	0.0005
220	16	0.0005
240	16.6	0.0005
250	6.9	0
1000	100	0

Infiltration

water table, cm	coefficient A	coefficient B
0	0	0
50	1.2	0.75
100	6.5	1.2
150	10	1.5
200	12	1.5
500	15	1.5

Appendix B

Monthly water balance calculations, including rainfall, PET, flow, and change in soil water storage:

1. **Station F3**
2. **Station F5**
3. **Station F6**
4. **Station H2**

Appendix B.1. F3 water balance calculations.

F3 **1999**	**Water Table Depth (WTD) cm**	**Volume Drained cm**	**WTD difference: end day - start day cm**	**status**	**(A) Vol. Drained diff: -(end day - start day) cm**	**(B) rain - PET - flow cm**	**Error in Balance (B) - (A) cm**	**rain, R1 cm**	**PET cm**	**flow cm**
jan										
start day	230	16.8								
end day	102	12.5	-127	gaining H2O	4.3	5.2	1.0	9.2	4	0.0
feb										
start day	102	12.5								
end day	81	10.5	-21	gaining H2O	2.0	2.0	0.1	7.1	4.8	0.2
mar										
start day	81	10.5								
end day	69	7.7	-12	gaining H2O	2.8	0.0	-2.8	7.9	7.4	0.5
apr										
start day	69	7.7								
end day	103	12.5	33	losing H20	-4.8	-5.3	-0.5	6.5	11.1	0.6
may										
start day	103	12.5								
end day	143	13.7	40	losing H20	-1.2	-3.1	-1.9	9.8	12.9	0.0
jun										
start day	143	13.7								
end day	167	14.4	24	losing H20	-0.7	-4.6	-3.9	7.4	12	0.0
jul										
start day	166	14.4								
end day	230	16.3	64	losing H20	-1.9	-12.0	-10.1	3.8	15.8	0.0
aug										
start day	230	16.3								
end day	247	16.8	16	losing H20	-0.5	3.8	4.3	17.6	13.8	0.0
sep										
start day	247	16.8								
end day	57	5.0	-189	gaining H2O	11.8	16.0	4.3	40.9	8	16.8
oct										
start day	58	5.1								
end day	65	6.6	7	losing H20	-1.6	1.2	2.8	19.6	7.7	10.7
nov										
start day	65	6.6								
end day	62	5.9	-3	gaining H2O	0.7	-0.5	-1.2	5.8	6	0.3
dec										
start day	62	5.9								
end day	64	6.4	2	losing H20	-0.4	-1.5	-1.1	3.2	4	0.7
				Annual Totals:	**10.4**	**1.4**		**138.7**	**107.5**	**29.8**

Appendix B.2. F5 water balance calculations.

F5 1999	Water Table Depth (WTD) cm	Volume Drained cm	WTD difference: end day - start day cm	status	(A) Vol. Drained diff: -(end day - start day) cm	(B) rain - PET - flow cm	Error in Balance (B) - (A) cm	rain, R6 cm	PET cm	flow cm
jan										
start day	165	26.5								
end day	95	18.0	-70	gaining H2O	8.5	4.9	-3.5	8.9	4	0.0
feb										
start day	95	18.0								
end day	79	16.1	-16	gaining H2O	1.9	1.0	-0.9	5.8	4.8	0.0
mar										
start day	79	16.1								
end day	89	17.4	11	losing H20	-1.4	-0.4	0.9	7.0	7.4	0.0
apr										
start day	89	17.4								
end day	144	21.4	55	losing H20	-3.9	-5.2	-1.2	5.9	11.1	0.0
may										
start day	144	21.4								
end day	162	25.7	18	losing H20	-4.3	-1.9	2.4	11.0	12.9	0.0
jun										
start day	162	25.7								
end day	156	24.1	-6	gaining H2O	1.6	-0.9	-2.5	11.1	12	0.0
jul										
start day	156	24.1								
end day	181	31.3	25	losing H20	-7.2	-9.9	-2.7	5.9	15.8	0.0
aug										
start day	181	31.3								
end day	188	33.5	7	losing H20	-2.2	4.8	7.0	18.6	13.8	0.0
sep										
start day	188	33.5								
end day	41	5.4	-147	gaining H2O	28.1	21.6	-6.5	38.5	8	8.9
oct										
start day	42	5.4								
end day	45	6.17	3	losing H20	-0.8	3.8	4.5	16.6	7.7	5.1
nov										
start day	Missing water table data									
end day										
dec										
start day	Missing water table data									
end day										
				Annual Totals:	**20.3**	**17.7**		**129.2**	**97.5**	**14.0**

Appendix B.3. F6 water balance calculations.

F6 **1999**	**Water Table Depth (WTD) cm**	**Volume Drained cm**	**WTD difference: end day - start day cm**	**status**	**(A) Vol. Drained diff: -(end day - start day) cm**	**(B) rain - PET - flow cm**	**Error in Balance (B) - (A) cm**	**rain, R6 cm**	**PET cm**	**flow cm**
jan										
start day	60	16.5								
end day	49	14.4	-11	gaining H2O	2.1	4.0	1.9	8.9	4	0.9
feb										
start day	49	14.4								
end day	48	14.2	-1	gaining H2O	0.2	-0.7	-0.8	5.8	4.8	1.7
mar										
start day	48	14.2								
end day	46	13.8	-2	gaining H2O	0.4	-1.4	-1.8	7.0	7.4	1.0
apr										
start day	47	13.8								
end day	78	17.1	32	losing H20	-3.2	-5.7	-2.5	5.9	11.1	0.5
may										
start day	78	17.1								
end day	94	17.3	16	losing H20	-0.3	-1.9	-1.6	11.0	12.9	0.0
jun										
start day	95	17.3								
end day	106	17.5	11	losing H20	-0.2	-0.9	-0.7	11.1	12	0.0
jul										
start day	106	17.5								
end day	157	23.4	50	losing H20	-5.9	-9.9	-4.0	5.9	15.8	0.0
aug										
start day	157	23.4								
end day	129	18.3	-28	gaining H2O	5.1	4.8	-0.3	18.6	13.8	0.0
sep										
start day	128	18.3								
end day	42	12.8	-87	gaining H2O	5.5	14.3	8.8	38.5	8	16.2
oct										
start day	42	12.8								
end day	45	13.6	4	losing H20	-0.7	-2.2	-1.5	16.6	7.7	11.1
nov										
start day	45	13.6								
end day	48	14.2	3	losing H20	-0.6	-1.7	-1.1	5.7	6	1.5
dec										
start day	48	14.2								
end day	52	14.9	3	losing H20	-0.7	-1.2	-0.5	3.2	4	0.4
				Annual Totals:	**1.6**	**-2.6**		**138.2**	**107.5**	**33.3**

Appendix B.4. H2 water balance calculations.

H2					(A)	(B)				
1999	Water Table Depth (WTD) cm	Volume Drained cm	WTD difference: end day - start day cm	status	Vol. Drained diff: -(end day - start day) cm	rain - PET - flow cm	Error in Balance (B) - (A) cm	rain, Avg R2,R3 cm	PET cm	flow cm
jan										
start day	41	0.48								
end day	66	1.24	26	losing H20	-0.8	-3.5	-2.8	9.2	3.8	9.0
feb										
start day	66	1.24								
end day	63	1.14	-3	gaining H2O	0.1	-3.8	-3.9	5.6	5.2	4.2
mar										
start day	63	1.12								
end day	62	1.10	-1	gaining H2O	0.02	-6.2	-6.3	7.1	8.6	4.8
apr										
start day	62	1.10								
end day	93	2.32	31	losing H20	-1.2	-9.9	-8.7	3.9	11.5	2.3
may										
start day	93	2.32								
end day	73	1.49	-20	gaining H2O	0.8	-8.7	-9.6	8.0	12.2	4.6
jun										
start day	73	1.49								
end day	87	2.01	14	losing H20	-0.5	-6.7	-6.2	7.0	11.4	2.3
jul										
start day	87	2.01								
end day	94	2.36	7	losing H20	-0.3	-6.3	-6.0	8.1	14.1	0.3
aug										
start day	94	2.37								
end day	45	0.574	-49	gaining H2O	1.8	2.1	0.3	15.4	12.1	1.2
sep										
start day	44	0.56								
end day	59	1.01	15	losing H20	-0.4	4.0	4.4	40.7	7.2	29.5
oct										
start day	60	1.02								
end day	72	1.45	12	losing H20	-0.4	-1.5	-1.1	16.7	5.1	13.1
nov										
start day	72	1.45								
end day	69	1.35	-3	gaining H2O	0.1	-0.3	-0.4	5.7	3.2	2.8
dec										
start day	69	1.36								
end day	78	1.67	9	losing H20	-0.3	-1.9	-1.6	4.0	3.9	2.0
				Annual Totals:	**-1.2**	**-42.8**		**131.5**	**98.3**	**76.1**