LONG-TERM HYDROLOGY AND WATER QUALITY OF A DRAINED PINE PLANTATION IN NORTH CAROLINA

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ABSTRACT. *Long-term data provide a basis for understanding natural variability, reducing uncertainty in model inputs and parameter estimation, and developing new hypotheses. This article evaluates 21 years (1988-2008) of hydrologic data and 17 years (1988-2005) of water quality data from a drained pine plantation in eastern North Carolina. The plantation age was 14 years at the beginning of the investigation (1988) and 34 years at the end (2008). The 21-year average rainfall of 1517 mm was 9% higher than the 50-year (1951-2000) long-term average of 1391 mm observed at the nearest U.S. Weather Bureau station in Morehead City, North Carolina. Annual rainfall varied from 852 mm in the driest year (2001) to 2331 mm in the wettest year (2003) during the study period and was affected by several hurricanes and tropical storms. The runoff coefficient (ROC; drainage outflow expressed as a fraction of rainfall) varied from 0.05 in the driest year to as high as 0.56 in the wettest year (2003), with an average ROC of 0.32. Annual outflow (runoff) on this watershed was primarily subsurface flow to drainage ditches and was strongly correlated with rainfall (R^2 = 0.81). Outflows were greater, more continuous, and longer in winter than in other seasons. Outflow in winter was 59% of rainfall on average. March was the only month that never produced zero outflow. The lowest mean outflow occurred in the spring and was significantly different from the other three seasons. Consistent with theory for subsurface drainage, outflow from this poorly drained land is dependent on water table elevation and occurs when the water table is within about 1.1 m of the surface. The water table tended to be close to the surface during the winter and early spring with low ET demands, and during summer with hurricanes and tropical storms producing large outflows, but was drawn down to depths much deeper than the drains during long dry periods in summer and fall. As a result, annual outflow and annual average water table depth were only weakly correlated (R^2 = 0.52). There was no relationship (R^2 = 0.01) between the annual average water table depth and the annual average evapotranspiration (ET), calculated as the difference between annual rainfall and outflow. The estimated average annual ET of 1005 mm was close to the Penman-Monteith based average annual potential ET (PET) of 1010 mm for a grass reference. Although nitrogen (N) levels in the drainage water were elevated after fertilization of the stand in late 1988, these elevated levels declined substantially by 1995. Average annual concentrations of total N ranged from 0.51 to 2.23 mg L^{-1} with a long-term average of 1.10 mg L^{-1}. Annual average values for total P ranged from 0.01 to 0.12 mg L^{-1} with an average of 0.04 mg L^{-1}. The highest average annual concentrations for N and P occurred in 1989 (N) and 1990 (P) following fertilization in spring of 1989. The average annual total N and P loadings were 6.5 $\pm$5.3 kg ha^{-1} and 0.17 $\pm$0.11 kg ha^{-1}, respectively. Both concentrations and annual loadings were similar to other forested sites in the region. These long-term data should be useful for assessing the effects of land use change and management treatments on the hydrology and water quality of similar lands in the coastal region.*

Keywords. *Evapotranspiration, Nutrient concentration, Nutrient loading, Outflow, Potential evapotranspiration, Rainfall, Runoff coefficient, Water table.*

In recent years, there has been considerable public attention toward the hydrological and ecological functions of forested landscapes. Forests play an important role in regulating the regional hydrologic patterns of the southern U.S., where 55% of the region is covered by forests (Sun et al., 2002). Land use pressures and environmental set asides continue to decrease the industrial forest base, leading to more areas of intensive silvicultural practices, which may include minor drainage, harvesting, site preparation, bedding, fertilization, herbicides, and artificial regeneration. Hydrologic and water quality impacts of these forest management practices have been important environmental issues. Long-term hydrologic data are essential as a base line for assessment of best management practices for minimizing impacts on downstream water quality (Beltran, 2007; Beltran et al., 2010). These data also lead to a better understanding of the impact of forest cover on watershed hydrologic processes (Andreassian, 2004), which is necessary for the development and testing of hydrological and water quality models and for conservation of regional ecosystems. Long-term hydrologic monitoring programs are essential to evaluate effects of natural and human-induced changes on coastal water resources

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at both the local and global scales, including park units (McCobb and Weiskel, 2003). Resurrection of old paired watershed studies and maintenance of current long-term reference watershed records are needed to evaluate long-term effects due to forest succession and climate change, as well as to test the effects of new forestry practices (Jones et al., 2009). Jones et al. (2009) emphasized the need to continue and re-establish small watershed experiments to detect long-term trends and integrate hydrologic modeling with technological innovations in spatial and temporal analysis and long-term datasets. Long-term datasets from such watersheds provide an important opportunity for advancing our understanding of forest hydrologic science, the effects of climate change on water quantity and quality, and the impacts of both anthropogenic and natural disturbances (Furniss et al., 2010).

Long-term hydrologic data from small, paired, experimental forested watersheds at the Coweeta Hydrologic Laboratory in North Carolina have provided basic understanding of eco-hydrological processes for regional upland watersheds (Swank et al., 2001). Tajchman et al. (1997) analyzed 40 years of hydrologic data to determine water and energy balances of a 39 ha central Appalachian watershed covered with 80-year-old upland oaks and cove hardwoods. Endale et al. (2006) analyzed 45 years of monthly and annual rainfall-runoff characteristics of a small typical Southern Piedmont watershed in the southeastern U.S. and suggested that sustained hydrologic monitoring is essential to the understanding of rainfall-runoff relationships in agricultural watersheds.

However, only a few such observational studies have been conducted for the low-gradient forest ecosystems of southeastern coastal plains. Approximately, 1 million ha of plantation pine in this region are drained to improve soil trafficability for harvesting and planting operations and to improve tree productivity. Unlike upland watersheds, which are dominated by hillslope processes, the hydrology of these coastal plains watersheds is usually dominated by shallow water tables affected by weather and a close interaction of surface and subsurface flows.

A long-term forest hydrology study was initiated on a pine forest in Carteret County, North Carolina, in early 1988 to quantify the impacts of both silvicultural and water management practices on downstream hydrology and water quality. Continuous monitoring of three adjacent watersheds, drained by parallel ditches has provided a database for understanding processes, quantifying the water and nutrient budgets, and evaluating impacts of a range of management practices (McCarthy et al., 1991; Amatya et al., 1996, 1998, 2000, 2003; Sun et al., 2001, 2002; Beltran et al., 2010). The data have also been used to develop models for simulating hydrologic effects of various management practices and potential climate change on drained forests (McCarthy et al., 1992; Sun et al., 2000; Amatya and Skaggs, 2001; Tian et al., 2012). Both monitoring and modeling studies have provided a better understanding of hydrologic and nutrient cycling processes on various temporal scales.

The main objective of this article is to summarize the long-term (1988-2008) observations of hydrology and drainage water quality on a drained loblolly pine (*Pinus taeda* L.) forest in Carteret County, North Carolina. The study primarily discusses drainage outflows (on annual, monthly, and daily time scales) and evapotranspiration and its effects on water table in this pine forest ecosystem.

Methods

Site Description

The study site (fig. 1) is located at approximately 34° 48′ N and 76° 42′ W in Carteret County, North Carolina, and is owned and managed by Weyerhaeuser Company. The research site consists of three artificially drained experimental watersheds (D1, D2, and D3), each about 25 ha in size, established in 1988 on a 14-year-old plantation. Topography of the site is flat, and soils have shallow water tables. The soil is a hydric series, Deloss fine sandy loam (fine-loamy mixed, thermic Typic Umbraquult). Each watershed is drained by four 1.4 to 1.8 m deep parallel lateral ditches spaced 100 m apart that drain to a main roadside ditch via a collector ditch that was built for isolating the three watersheds (fig. 1). The lateral (east to west) boundary of each watershed was assumed to be the mid-plane between the lateral ditches at the edge of adjacent watersheds. Rows of pine trees planted on 0.4 m high beds parallel to the lateral ditches prevented surface runoff from watershed to the other. No other surface grading was necessary to establish the boundary between watersheds. Data on hydrology, soil, and vegetation parameters were collected from three experimental plots (each about 0.13 ha in area) in each watershed (fig. 1). Detailed description of the site is given elsewhere (McCarthy et al., 1991; Amatya et al., 1996).

Hydrologic Monitoring

Rainfall and Weather

Rainfall was measured with tipping-bucket rain gauges on the western side of each watershed (fig. 1). Until 1997, air temperature, relative humidity, wind speed, and solar radiation were continuously measured by an automatic weather station located 800 m west of the site. After 1997, a new station, which included a net radiometer, was installed at the center of watershed D2 and continued to function until September 2005.

Drainage Outflow

A 120° V-notched weir with an automatic stage recorder, located in a water level control structure at a depth of about 0.3 m from the bottom of the outlet ditch (fig. 1), was used to continuously measure drainage outflow in each watershed. Outflows occur, and are measured, only when the water elevation in the ditch exceeds about 0.3 m above the ditch bottom. In 1990, a pump was installed downstream from all three watersheds in the roadside collector ditch to prevent weir submergence during larger events. The pump assembly was renovated in late 2003, and the downstream collector ditch was cleaned in July 2004 to avoid potential submergence due to increasing vegetation and silt in the ditch. An additional recorder was placed downstream from the weirs in May 2005 to determine if weir submergence occurred and to correct flows in that event.

Water Table

Water table elevations were measured by a continuous water level recorder at two locations midway between the field ditches for each watershed (fig. 1). The measurements at these two locations were used to obtain an average elevation

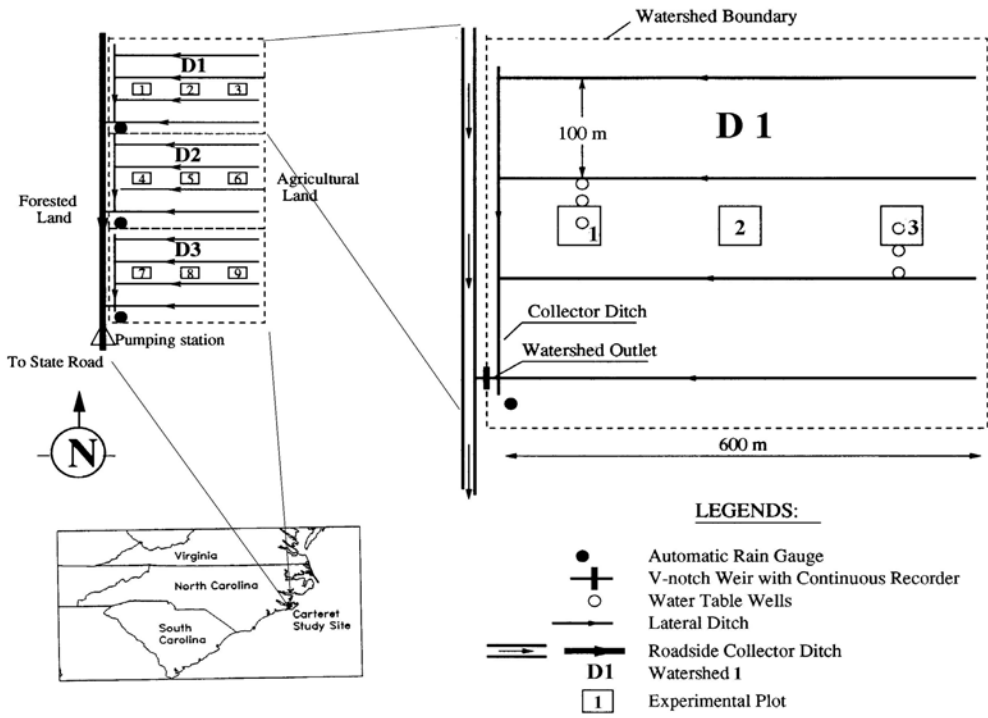

Figure 1. Location of three experimental watersheds and layout of a typical watershed with monitoring stations, Carteret County, North Carolina (after Amatya et al., 2000).

that was also converted into water table depth using average ground surface elevation. Refer to McCarthy et al. (1991), Amatya et al. (2003, 2000, 1996), and Beltran et al. (2010) for a detailed description of the instrumentation at the site and other measurements including interception, lateral seepage, leaf area index (LAI), and the history of the loblolly pine stand planted in 1974.

Water Quality

Two methods of water sampling (composite using automatic ISCO-2700 water samplers and manual grab sampling) at the weir outlet of each watershed (fig. 1) have been used since late 1989. For composite sampling during specific events, a 250 mL water sample was collected every 2 h; four consecutive samples were composited, making three samples per day. All samples collected until 1994 were frozen and analyzed at the Weyerhaeuser laboratory in New Bern, North Carolina. Samples collected since 1995 were analyzed in laboratories of the Soil Science Department at North Carolina State University. Grab samples were collected weekly during flow periods. Water samples were analyzed for NO_3+NO_2-N, NH_4-N, total Kjeldahl nitrogen (TKN), total phosphorus (TP), and total suspended solids (TSS). Details of procedures of event sampling and sample analysis in the laboratory were documented by Amatya et al. (1998, 2003) and Beltran et al. (2010).

Data Status and Analysis

Data presented in this article were collected from watershed D1 (fig. 1), which constituted the control watershed for several earlier studies. All three watersheds, planted in 1974, were commercially thinned in October 1988 and fertilized soon after that. This study analyzes results from D1 starting in January 1988 (stand age of 14 years) and continuing through December 2008 when the trees were 34 years old. There was no further human disturbance after thinning and fertilization in late 1988. However, the study site experienced several hurricanes and tropical storms during the period of observation, as will be shown below.

Procedures for processing rainfall, flow, water table, and weather data have been described in detail by Amatya et al. (1996, 2003). Net radiation was measured with a data logger (CR21, Campbell Scientific, Logan, Utah) at a height of about 6 m above grass at a station 800 m away from the study site from 1988 to 1997. From 1997 to 2001, net radiation was measured at a height of about 3 m above the emerging herbaceous vegetation on the adjacent site D2 (fig. 1), which was harvested in 1995 and replanted in 1997 (Sampson et al., 2011). Data were recorded with a data logger (CR10X, Campbell Scientific, Logan, Utah). When the pine trees on site D2 exceeded 3 m height in 2001, net radiation was measured at a 2 m height above the average canopy of the growing pine stand by using an adjustable boom fitted on a 20 m tall weather tower. Unfortunately, the tower was severely damaged by Hurricane Ophelia in September 2005. All weather data, including the net radiation from September 2005 to August 2007, were obtained from a full weather station located about 100 km north at Weyerhaeuser's Parker Tract pine forest study site, also in North Carolina (Beltran, 2007). Data from August 2007 to December 2008 were obtained from the Sutton Farm station (grass vegetation) located about 10 km away from the study site and managed and owned by Weyerhaeuser Company. These daily weather data measured above varying vegetation types were used to estimate daily potential evapotranspiration (PET) for a standard grass reference using the Penman-Monteith method (Monteith, 1965) as described by Amatya et al. (1995).

All daily data on rainfall, flows, net radiation, and PET for a grass reference were integrated to obtain annual totals (table 1). On an annual basis, actual evapotranspiration (ET) was calculated as the difference between annual rainfall and outflow. This assumes that water stored in the profile at the end of each year was relatively constant and that seepage from the watershed was negligible, although that may not always be the case (Sun et al., 2002). The calculated annual ET was compared with predictions by DRAINMOD-based models (Tian, 2011; Tian et al., 2010). SAS (2009) was used to conduct the seasonal flow frequency analysis for measured daily flows and daily water table elevations. All data analyses including the statistical tests were conducted using Microsoft Excel. Nutrients for water quality data were analyzed for the period 1988 to 2005 only; data from 2005 to 2008 have been reported elsewhere recently (Beltran et al., 2010; Tian et al., 2010).

Results and Discussion

Rainfall

Annual rainfall over the 21-year period of observation varied from a low of 852 mm in 2001 to a high of 2331 mm in 2003 with a coefficient of variation (COV) of 0.20 (table 1). The average precipitation of 1517 mm was 9% higher than the long-term 50-year average of 1391 mm for the nearest U.S. Weather Bureau Class A weather station (Morehead City). Annual precipitation in 13 out of 21 years was above normal, with the 2331 mm observed in 2003 exceeding the normal by more than 50%. Nine (1989, 1996, 1998, 1999, 2000, 2003, 2004, 2005, and 2007) out of the 21 years experienced hurricanes (fig. 2) with all, except 2004, having total annual rainfall more than 10% greater than normal (table 1). Another year (2002) had no hurricanes, but four tropical storms caused rainfall that year to exceed the normal by more than 15%. The lowest rainfall (852 mm), about 43% below normal, was recorded in 2001. Annual rainfall varied by as much as 127 mm between gauges 800 m apart (watersheds D1 and D3, see fig. 1) on the site, with the greatest variation occurring in June (not shown) (Amatya et al., 1996). Hydrologic impacts of extreme rain events caused by hurricanes and tropical storms during 1996-2000 were discussed by Shelby et al. (2005) for another study site in eastern North Carolina.

Measured monthly rainfall for the 21-year period is plotted along with the measured monthly outflow in figure 2. The lowest and highest monthly rainfall of 3 mm and 447 mm were measured in November 2007 and September 1996, respectively. The largest monthly rainfall amounts (255 to 447 mm) were all observed in September and associated with hurricanes, e.g., 1989 (Hugo, 397 mm), 1996 (Fran, 447 mm), 1999 (Dennis-Floyd, 378 mm), 2000 (Florence, 253 mm), 2003 (Isabelle, 355 mm), 2005 (Ophelia, 255 mm), and 2007 (Gabrielle/Humberto, 371 mm) (fig. 2).

Some other years were also affected by hurricanes and large tropical storms with monthly rainfall exceeding 260 mm in August 1988, July 1991, October 1993, July 1996, August 1998 (Hurricane Bertha), August 1999 (Dennis), July 2000, March 2003, August 2004 (Hurricane Gaston), and October 2005 (Hurricane Wilma). Impacts of the hurricanes and tropical storms caused the 21-year average summer (July-September) rainfall of 566 mm (SD = 158 mm) to be 37% of the average annual total (1517 mm) (table 2). All months of year 2001 yielded below-normal rainfall, except for June (fig. 2). On the contrary, 10 of the 12 months of 2003 had above-normal rainfall.

The monthly average distribution of rainfall shown in figure 3a is similar to the long-term average for Morehead City, North Carolina (not shown). However, the monthly amounts at the site were consistently higher than the long-term average for all months, except February and December. As shown above, frequent tropical storms and hurricanes caused Au-

Table 1. Measured annual hydro-meteorological parameters for the study watershed.

		Measured					Estimated		
Year	Rain (mm)	Average Temperature (°C)	Net Radiation (mm)	Flow (mm)	Water Table Elevation (m)		P-M PET (mm)	Runoff Coeff. (%)	ET (rain - flow, mm)
1988	1405	15.7	1355	209	1.69		1041	0.15	1196.0
1989	1875	16.3	1191	658	2.02		945	0.35	1217.0
1990	1235	17.4	1236	240	1.61		1031	0.19	995.0
1991	1575	16.6	1132	519	1.82		917	0.33	1056.0
1992	1619	16.1	1013	584	1.87		782	0.36	1035.0
1993	1513	15.9	1206	586	1.55		875	0.39	927.0
1994	1528	16.3	1236	436	1.51		896	0.29	1092.0
1995	1404	15.9	1191	459	1.64		849	0.33	945.0
1996	1707	15.8	1191	704	1.81		877	0.41	1003.0
1997	1382	16.1	1358	397	1.66		1075	0.29	985.0
1998	1658	17.7	1321	770	1.98		1007	0.46	888.0
1999	1363	16.7	1438	614	1.84		1072	0.45	749.0
2000	1718	15.6	1434	857	1.91		1023	0.50	861.0
2001	852	16.3	1121	45	1.22		1024	0.05	807.0
2002	1718	16.5	1348	426	1.66		919	0.25	1292.0
2003	2331	16.6	1498	1308	2.16		1097	0.56	1023.0
2004	1313	16.6	1522	389	1.72		1060	0.30	924.0
2005	1777	16.4	1538	798	1.72		1057	0.45	979.0
2006	1329	16.7	1590	247	1.98		1193	0.19	1082.0
2007	1201	16.9	1622	257	1.87		1254	0.21	944.0
2008	1360	16.7	1524	247	1.6		1215	0.18	1113.0
Mean	1517	16.4	1336	512	1.75		1010	0.32	1005
SD	300	0.5	173	284	0		124	0.13	133
COV	0.20	0.03	0.13	0.55	0.12		0.12	0.41	0.13

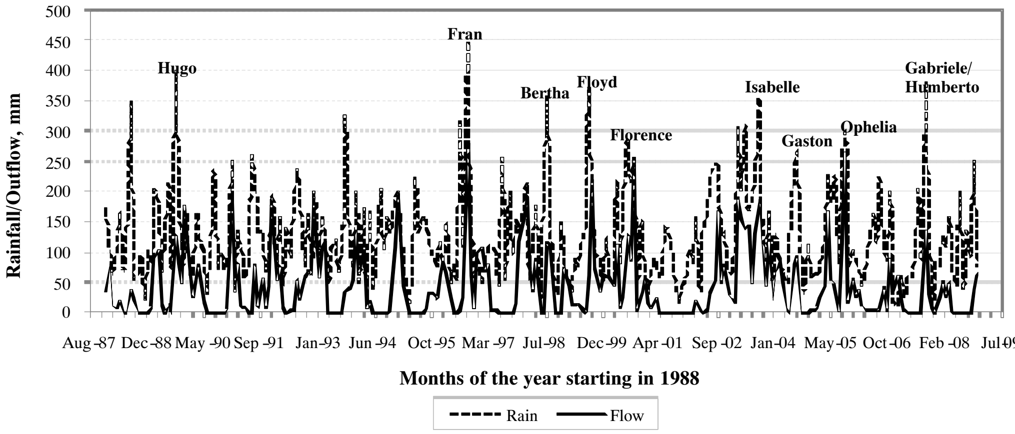

Figure 2. Measured monthly rainfall and outflow for the watershed for 1988 to 2008 period.

Table 2. Computed statistics for the 21-year measured total seasonal rainfall and outflow.

	Winter (Jan.-Mar.)			Spring (Apr.-June)			Summer (July-Sept.)			Fall (Oct.-Dec.)		
Parameter	Rain (mm)	Flow (mm)	Runoff Coeff.	Rain (mm)	Flow (mm)	Runoff Coeff.	Rain (mm)	Flow (mm)	Runoff Coeff.	Rain (mm)	Flow (mm)	Runoff Coeff.
Total	6594	3933	--	6727	1531	--	11876	2749	--	6664	2536	--
Average	314	187	0.59	320	73	0.18	565	131	0.19	317	121	0.34
SD	108	119	0.28	119	107	0.19	158	137	0.18	106	100	0.25
COV	0.34	0.63	0.48	0.37	1.46	1.03	0.28	1.05	0.96	0.33	0.82	0.75
Maximum	474	424	1.05	680	435	0.64	866	455	0.61	500	336	0.72
Minimum	95	18	0.05	177	0	0.00	289	0	0.00	116	0	0.00

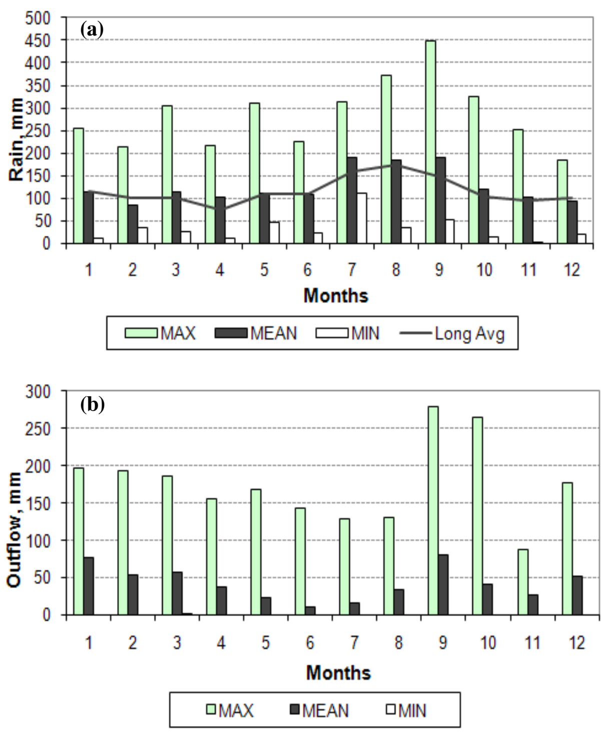

Figure 3. Distribution of (a) monthly rainfall (maximum, mean, and minimum) and (b) monthly outflow (maximum, mean, and minimum) using 21 years (1988-2008) of measured data at the Carteret site.

gust, September, and October to be the wettest months; maximum monthly rainfall exceeded 300 mm in March, May, and July, as well (fig. 3a). February had the lowest monthly rainfall on average.

Average seasonal rainfall amount was highest in summer (565 mm), but the summer of 2001 had the lowest total of 289 mm, followed by 291 mm in 1993. Interestingly, the average winter season rainfall of 314 mm was only 21% of the average annual total (table 2), compared to the summer season with rainfall of 565 mm (37% of the annual total). This is somewhat different from the respective long-term means of 22.8% and 34.7% of the long-term means observed at the Morehead City station. The other two seasons (spring and fall), like winter, had, on average, about 21% of the annual total. Statistical t-tests showed no significant difference (α = 0.05) among the mean rainfall of the winter, spring, and fall seasons. However, the summer season mean rainfall was significantly higher (α = 0.05) than that of the other three seasons. The variability of seasonal rainfall was highest (COV = 0.37) for spring and lowest (0.28) for summer.

Weather and PET

Mean annual air temperature varied from 15.6°C in 2000 to 17.7°C in 1998 with an average of 16.4°C (table 1). The high temperature in 1998 is consistent with the observation that 1998 was the warmest year before the year 2000 since instrumental measurements began in the 1800s (Hansen et al., 2006). The annual total net radiation in W m^{-2} (converted into depth of water-based (mm) equivalent; Jensen et al., 1990) varied from 1013 mm in 1992 to 1622 mm in 2007. The COV for net radiation was higher than that for the temperature (table 1). One reason for such a large variation in net radiation was due to shifting of the weather sensor from one location with one surface type to another location with different surface types, as stated in the Methods section above. The effects of vegetative surfaces on net radiation have been reported elsewhere (Gholz and Clark, 2002; Sun et al., 2010). Sun et al. (2010) reported 20% higher net radiation (1402 mm water equivalent) for a 13- to 16-year-old pine forest compared to 1166 mm water equivalent for a clear-cut stand in a three-year (2005-2007) study period near Plymouth, North Carolina. The annual net radiation continued to increase to more than 1500 mm water equivalent in 2005 when the trees were eight years old on the D2 site.

The annual P-M PET for a grass reference varied from as low as 782 mm in 1992 (the lowest measured net radiation) to as high as 1254 mm in 2007 (the highest measured net radiation), with an average of 1010 mm (table 1). This mean annual PET of 1010 mm for 1988-2008 is about 12% lower than the ten-year average PET at this site estimated using the Hamon method (Sun et al., 2002), which usually overestimates the PET. However, the annual P-M PET estimated by the DRAINMOD-Forest model (Tian, 2011; Tian et al., 2010) using the simulated LAI and stomatal conductance for this site varied from 978 mm for the driest year (2001) to as high as 1334 mm in 1988, with an average of 1092 mm (8% higher than our estimate). This was consistent with the results of Amatya et al. (2002) in which the average annual pine forest PET of 1044 mm for 1996-2001 was about 7.8% higher than the PET of 963 mm estimated for an adjacent grass reference site. These results may have implications for assessing whether the forest ET is limited by PET for a grass reference as well as the accuracy of model predictions of streamflows and the effect of change in vegetation type and silvicultural treatments on these flows. The commonly used P-M PET method with a standard grass reference, in this case, may result in a substantial underprediction of ET and overprediction of flows.

Outflows and Runoff Coefficients

Annual Outflows and Runoff Coefficients

Measured annual outflows and runoff coefficients (ROC), calculated as a ratio of annual outflow and rainfall for the study watershed, are presented in table 1. The term "runoff coefficient" is somewhat of a misnomer as applied in this article. Essentially all outflow from the site is subsurface drainage to the open ditches, as little water leaves the site as surface runoff. The site was bedded at planting, creating surface depressional storage greater than 15 cm. The beds weather, and depressional storage is reduced with time, but depressional storage generally remains greater than an estimated 7 to 8 cm throughout the life of the plantation. As a result, surface runoff is negligible, except during hurricane events when all or most of the field may be flooded. Nevertheless, we shall use the term runoff coefficient (ROC) throughout this article to mean the ratio of drainage outflow to rainfall, expressed as a decimal. Lateral groundwater seepage to or from the site estimated based on measured hydraulic gradients by Amatya et al.(1996) was found to be 3% or less of annual rainfall.

Annual outflow was more variable (COV = 0.55) from year to year than rainfall (COV = 0.20) (table 1), although they were correlated strongly (R^2 = 0.81). This is at least partially due to differences in antecedent conditions. For example, the years 1993 and 1994 had similar annual rainfall, but 33% higher ROC (0.39) was observed for 1993 compared to only 0.29 for 1994. The difference was likely due to wet antecedent conditions created by higher than average rainfall near the end of 1992. The ROC in 1994 was about 10% lower than the 20-year mean ROC (0.32). Annual rainfall in 1998 (1360 mm) was only 2% lower than in 1997 (1382 mm), but the ROC (0.29) in 1997 was 61% higher than in 2008 (0.18), primarily due to wet conditions in the later part of 1996 caused by Hurricane Fran and tropical storms (fig. 2). Another example is the years 2000 and 2002, which had the same annual rainfall (1718 mm). However, due to very dry conditions during most of 2001 (851 mm rain), the ROC (0.25) in 2002 was 50% less than the ROC (0.50) in 2000 (table 1), which had very wet antecedent conditions (later part of 1999) (fig. 2). These observations are consistent with the findings of Rose (2011), who demonstrated that a one-year period of antecedent drought lowered ROC for at least one year following the drought. In most cases, ROCs are significantly lower during the second year following a drought than they would be when preceded by normal or above-normal rainfall. To the contrary, 1998 was a year with a very wet winter and above-normal rainfall (1658 mm), like that of the *La Niña* effect, although the year itself, with the highest temperature of the century, had a super *El Niño* effect (Hansen et al., 2006). It was followed by a long dry period until the summer of 1999 (fig. 2) and then a series of tropical storms, resulting in high water table conditions but with lower than normal annual rainfall (1363 mm) (table 1). Interestingly, the runoff coefficient in both years (1998 and 1999) was about the same (0.45 to 0.46), indicating a strong influence of seasonal soil water storage caused by rainfall and ET on the ROC in this system. The effects of thinning the watershed in October 1988 were not detected, as no outflow occurred from October 1988 to January 1989 due to lower than average monthly rainfall in those months. The higher outflows starting in March 1989 might have also been caused by higher than normal rainfall in most of the 1989 months (fig. 2). The higher drainage outflows with ROC values exceeding 0.40 in four out of five years (1996-2000) with frequent hurricanes and tropical storms (fig. 2) are consistent with the results reported by Shelby et al. (2005) for another study site in eastern North Carolina.

Average annual outflow (1988-2008) from the watershed was 512 mm, which is equivalent to an average ROC of 0.32. The calculated median ROC value of 0.33 for the site was slightly higher than the median of 0.31 reported by Chescheir et al. (2003) for 100 site years of data from managed and natural forest stands in eastern North Carolina. According to these authors, the calculated ROC for this study site is also slightly higher than the 40-year mean annual ratio of excess water (rainfall - PET) to rainfall from regional weather stations (0.29 to 0.30).The potential effect of ET due to change in the forest canopy did not affect our values. This mature forest stand had a projected leaf area index (LAI) varying between about 2.0 m^2 m^{-2} in the dormant season to 5.0 m^2 m^{-2} in the peak growing season for all years (Tian et al., 2010), except in the early period of 1989-1993 following thinning in late October 1988 (Amatya et al., 1996). ROC values at this site are substantially higher than the six-year mean of 0.20 for a mature pine forest on organic soils in another eastern North Carolina site (Amatya et al., 2002; Shelby et al., 2005) and the ROC of 0.22 obtained from 20 years of data on a naturally drained forested watershed in the South Carolina coastal plain (Amatya et al., 2006). These lower values are very likely due to differences in annual rainfall. Average annual rainfall depths on the North Carolina site (Shelby et al., 2005) and the South Carolina site (Amatya et al., 2006) were 1167 and 1367 mm, respectively, compared to 1517 mm for our site.

The 21-year highest annual rainfall of 2331 mm in 2003 resulted in the maximum annual outflow of 1308 mm and an ROC of 0.56. Harder et al. (2007) found a similar ROC of 0.47 for 2003 at a naturally drained forested watershed in coastal South Carolina. All years with hurricanes had an ROC that exceeded the average value of 0.32 (table 1) as expected, with all but 1989 exceeding the value of 0.40. The large outflows measured at our site, especially during the periods affected by hurricanes and large tropical storms (e.g., 2000 and 2002) should be cautiously interpreted due to potential errors in measured data during weir submergence. For example, the weir was frequently submerged during March to December in the wettest year, 2003. However, backflow to the site itself was not evident during such large storm events. Outflow data were corrected for the periods of submergence by using values predicted by DRAINMOD (Skaggs, 1978) calibrated for this site. The year 2001, with the lowest rainfall (852 mm) during the period of observation, yielded only 45 mm of outflow (5.3% of rainfall). This was similar to the ROC of 0.07 observed on another eastern North Carolina site by our group (Amatya et al., 2002) and to results reported by Harder et al. (2007), who reported a value of 0.07 for a relatively dry year (2004) in South Carolina. This indicates that both the artificially drained and naturally drained low-gradient forest systems in this coastal plain region have similar hydrologic responses for extreme dry and wet conditions, although their mean values differ substantially.

Monthly Outflows

Measured monthly outflows for the 21-year (1988-2008) period are presented in figure 2. Monthly outflow varied from zero (no flow) to as much as 279 mm following hurricane Fran (447 mm rain) in September 1996. The second largest outflow (265 mm) occurred in October 2005 as a result of 299 mm of rain from two large tropical storms that followed Hurricane Ophelia (253 mm rain) in September (Beltran et al., 2010). Several months of below-normal rainfall in 2001 resulted in deep water table depths and no flow from May 2001 until February 2002 (fig. 2). Only three (2000, 2003, and 2005) of the six years with ≥1700 mm of rain (table 1) yielded measurable flow in all months of the year. Dry antecedent conditions in the previous year resulted in zero flows in the early months of 1989 and 2002.

Monthly distribution of measured maximum, mean, and minimum outflows is shown in figure 3b. The month of September had the highest average outflow (80 mm) as a result of hurricanes and tropical storms in that month. January had the next highest average outflow of 77 mm (fig. 2). March was the only month that always had flow in the 21-year study. While the winter season had flows in all years, there was no flow in the summers of six years (1990, 1993, 1994, 1997, 2001, and 2008), in the springs of three years (1995, 2001 and 2007), and in the falls of three years (1988, 1998, and 2001). The mean winter season (January-March) outflow of 187 mm and the corresponding ROC of 0.59 were the highest of all seasons, although average rainfall in winter was only about 21% of the annual (table 2). This was attributed to higher water table elevations caused by lower ET demand in the winter (Amatya et al., 1996). On the contrary, drainage outflow, as a percentage of rainfall (ROC = 0.19), was lowest in the summer (July to September) even though average rainfall (565 mm) was highest of all seasons. This was caused by high ET demands during the summer months. Both of these observations were consistent with the results of Chescheir et al. (2003) for 100 site years of data from eastern North Carolina forest stands. The runoff coefficient was higher (0.34) in fall (October-December) than in summer, primarily because of the effects of tropical storms and hurricanes in some years and reduced ET demands in this season. The measured ROC for spring is in the lower quartile, and the fall season ROC is in the higher quartile of data reported by Chescheir et al. (2003).

Statistical t-tests showed that only the mean spring outflow of 73 mm was significantly ($\alpha = 0.05$) different from the other three seasons (table 2). The smallest average outflow (11 mm) occurred in June followed by July (fig. 3b). The highest variability (COV = 1.46) of seasonal outflows occurred in the spring (April-June) followed by the summer (COV = 1.05), as expected (table 2). The lowest variability was observed in the winter. This was consistent with the earlier observations by Amatya et al. (1996) at this site, with relatively low ET resulting in high water table elevations and sustained drainage during the winter period. The seasonal ROC values varied considerably from year to year as affected by variability in rainfall and ET. For example, in spring 1992, only 10 mm of the 276 mm rainfall was lost to streamflow, with the remainder potentially lost to ET, which amounted to nearly 96% of the total rainfall. The effects of rainfall and antecedent conditions (e.g., ET and water table) on the characteristics of seasonal event outflow (e.g., event outflow volume, time to peak, event flow duration) have been reported for this site by Amatya et al. (2000) and for other coastal watersheds in North and South Carolina by Slattery et al. (2006) and La Torre Torres et al. (2011).

Daily Outflows

The daily flow dynamics of this watershed have been reported by Amatya and Skaggs (2001) and Sun et al. (2002) for 1988-1997, by Amatya et al. (2003) for 1995-2000, and by Beltran et al. (2007) for 2005-2007. The daily flow duration curves for the four seasons for the 21-year (1988-2008) period are presented in figure 4. The plot in figure 4a shows all data, whereas the plot in figure 4b is enlarged to details of medium to low flows (<10 mm d^{-1}). Flow occurred almost continuously (88% of time) during the winter and less frequently during other seasons (34% in spring, 30% in summer, and 55% in fall) (fig. 4b). Flow rates greater than 10 mm d^{-1} occurred 2.4% of the time in winter, 1.1% of the time in spring, 4.0% of the time in summer, and 2.1% of the time in fall.

These data are consistent with the observations made by Sun et al. (2002) for this and another flatwood watershed in Florida. Again, this pattern was attributed to lower ET demands and higher water tables producing outflows in the winter. Flows in winter were less than 14 mm d^{-1} 99% of the time (fig. 4a). For the same 99% frequency, flow rates for spring, summer, and fall seasons were 10.2, 20.3, and 12.5 mm d^{-1}, respectively. The weir at the watershed outlet was usually submerged when the flow rate exceeded 31 mm d^{-1}. The highest daily flow recorded during the winter was 30 mm, as compared to the 45 mm limit (estimated based on weir-outlet culvert capacity for high submergence) for large events in summer and fall. The percent of time that daily flow exceeded this rate was 0% in winter, 0.23% in spring, 0.41% in summer, and 0.31% in fall. This indicates that most submergence occurred for short periods of time during the summer and fall due to hurricanes and tropical storms. The high flow rates as

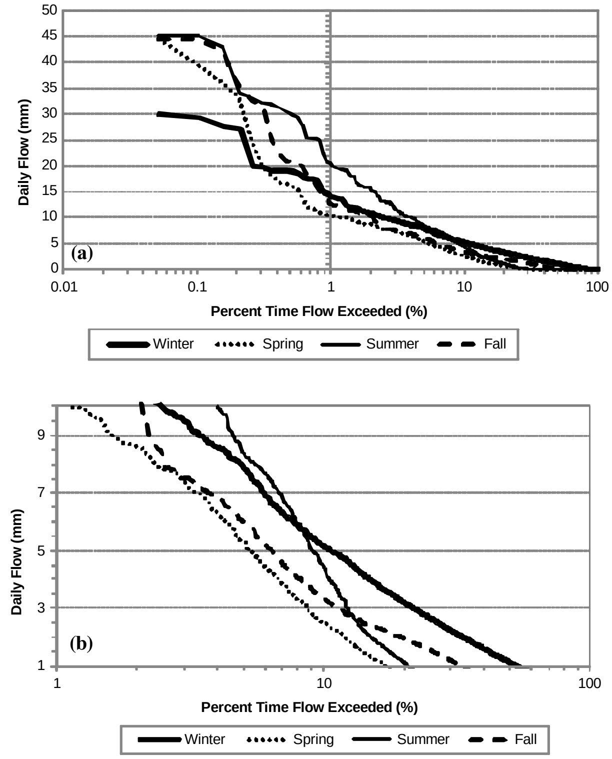

Figure 4. Measured seasonal daily flow duration curves (a) for all flows and (b) enlarged scale for low flows.

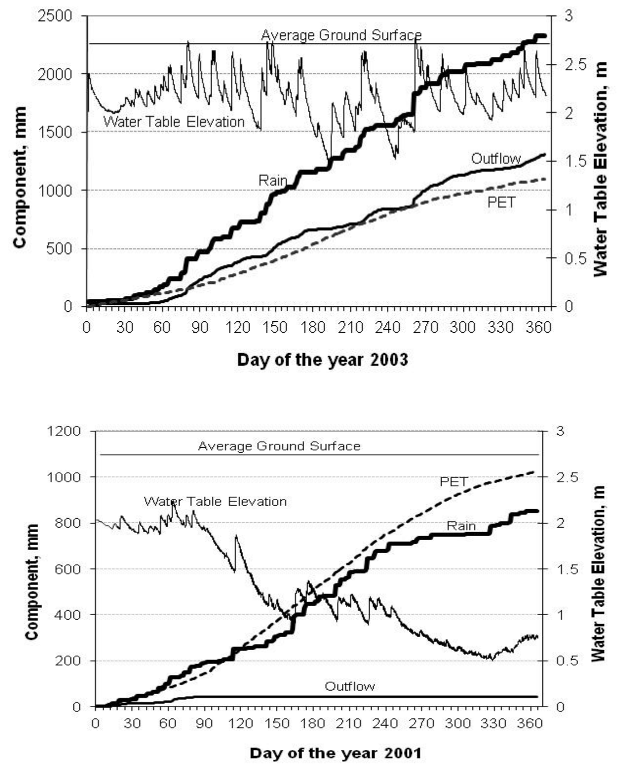

Figure 5. Daily cumulative rainfall, outflow, Penman-Monteith-based PET, and water table elevation in (a) a wet year (2003) and (b) a dry year (2001).

a result of hurricanes and tropical storms in summer and fall exceeded the wet winter flow rates 9% and 1% of the time, respectively (figs. 4a and 4b).

Note that the outflow processes on these relatively flat pine plantations are usually dominated by shallow subsurface drainage; the artificial beds created for planting trees generally preclude surface runoff (Amatya et al., 1996). The subsurface drainage rate is a function of water table elevation and hydraulic conductivity. Observations on these watersheds over long periods of time clearly show that outflows to streams are mainly controlled by the groundwater table and soil water storage as affected by rainfall and ET. High ET during the summer and fall months may lower the water table below the bottom of the drainage ditches and create relatively large volumes of water-free pore space, which is available to store infiltration from subsequent rainfall. Streamflow usually occurs only when this storage is filled and the soil profile is relatively wet, with the water table above the elevation of the weir in the ditch. Slattery et al. (2006) observed that low relief, poorly drained sites such as this one have a propensity for saturated overland flow, as compared to sandy, permeable top soils, which tend to have mostly subsurface flow. While the Deloss soil is classified as "very poorly drained" under natural conditions, it is relatively well drained on this site. Skaggs et al. (2006) showed that the field effective hydraulic conductivity of the surface layers on this site was more than an order of magnitude higher than expected for this soil under agricultural production. The high conductivity coupled with parallel ditches 1 m deep and 100 m apart provide relatively rapid subsurface drainage. Combined with the large surface depressional storage resulting from the bedded surface, the intensive subsurface drainage on the site effectively eliminates surface runoff in all but the largest storm events (tropical storms and hurricanes) when the watershed is essentially flooded. Response of daily water table depths to cumulative daily hydrologic components of rainfall, outflow, and PET are shown in figure 5 for wet (2003) and dry (2001) years.

WATER TABLE ELEVATIONS (DEPTHS) AND ET

Measured annual average water table elevations and evapotranspiration (ET), estimated as the difference between annual rainfall and outflow, are presented in table 1. The year 2003, with the highest rainfall, had the highest average water table elevation of 2.16 m (0.54 m depth) compared to an elevation of 1.22 m (1.48 m depth) in 2001, which had the lowest rainfall. The average water table elevation for the 20-year study period was 1.75 m (depth = 0.95 m). The water table in the wet year 2003 (fig. 5a) frequently rose near the ground surface (elevation = 2.7 m), resulting in large and prolonged outflows; the water table never dropped below an elevation of 1.5 m. To the contrary, water table elevations in the dry year (2001) fell below the 1 m depth of the weirs in the ditch (elevation of 1.7 m), and drainage ceased on day 76 (March 16); the water table continued to fall due to ET. The deep-rooted trees removed water from the profile to supply ET, drying out the profile and lowering the water table to an elevation of 0.5 m (depth of 2.2 m below the surface) by the end of November (day 330) (fig. 5b). About 346 mm of rainfall was required to fill up the dry profile and raise the water table above an elevation of 1.7 m before drainage began again on March 13 (day 72) in 2002 (not shown). Because of these reasons, the relationship of drainage outflow with water table depth on an annual basis was weak ($R^2 = 0.52$).

The results in figure 5 are consistent with earlier findings (Amatya et al., 1996; Skaggs et al., 2011; Cooper et al., 2006; Zhang and Schilling, 2006) that ET has the greatest impact on water table elevations for these shallow water table sites. However, there was no relationship between annual water table depth and ET, which is contrary to the findings of Cooper et al. (2006), who found a negative correlation for a site dominated by shrubby phreatophytes in the Colorado's San Luis Valley. Although the drainage outflow depends upon the water table depth, their relationship on an annual basis was also weak (R^2 = 0.52).

The cumulative rainfall exceeded the cumulative PET for most of 2003, resulting in drainage outflow over the whole year (fig. 5a). Conversely, cumulative rainfall in 2001 was greater than cumulative PET for barely two months (days 45 to 105), with most of the outflow occurring during that period (fig. 5b). Since the PET for mature pine is generally higher than that for a grass reference, estimated ET was clearly soil water-limited for 2001. This does not appear to be the case over the long term, as the 21-year mean annual ET/grass-PET ratio was near unity for this pine forest. Seasonal variability in ET as affected by water table depths and PET on this site were discussed by Amatya et al. (1996). Based on an analysis of ten years (1988-1997) of data from this site, Sun et al. (2002) noted that P (rainfall) > PET > ET. In their study using the Hamon method for calculating PET, the authors reported that this study site is not a water-limited system most of the year, with an ET/PET ratio of 0.92. However, ET is water-limited for very dry years, as would be expected, and as clearly shown above for 2001. The fact that the years with rainfall lower than the long-term mean of 1390 mm had estimated ET lower than the estimated PET (table 1) further validates this hypothesis.

The estimated annual ET varied from 749 mm in 1999 to 1292 mm in 2002 with an average of 1005 mm (table 1), which was about 3% lower than the average value of 1040 mm obtained by a water balance method for a 25-month calibration and a 34-month treatment period at this site (Amatya et al., 1996). This value was nearly the same as the mean annual PET (1010 mm) estimated for the grass reference (grass-PET), although the annual ET/PET ratio varied widely from 0.70 for 1999 to 1.41 for 2002. Recently, Tian et al. (2010) predicted a mean annual ET of 1057 mm for this pine forest using DRAINMOD-Forest. The 21-year estimated mean annual ET as a fraction of rainfall calculated as 0.68 for this 14- to 34-year-old stand was found to be lower than the three-year (2005-2007) mean of 0.88 found by Sun et al. (2010) using ET from an eddy flux study for the mid-rotation (13 to 15 years old) pine stand at the Parker Tract study site located about 100 km north of this site. The difference was mainly due to the much higher mean annual precipitation of 1500 mm measured at our study site (table 1) compared to a three-year mean of only 1238 mm at the Parker Tract site. Their measured average annual ET was 1087 mm. It varied from 1011 mm, which was 1% lower than the grass-PET in a dry year, to 1226 mm, which was 27% higher than the grass-PET. The mean annual ET/grass-PET ratio of 1.00 at our site was also about 11.5% lower than the Parker Tract site (1.13). Results from these studies in eastern North Carolina indicate that the mean annual ET of a pine forest stand is equal to or greater than the Penman-Monteith grass-PET. This may have important implications for modeling forest hydrology and water balances.

Errors in annual ET calculated in this study may have been caused by differences in soil water storage at the beginning and end of the year, as occurred in 2001 (fig. 5b), and by losses due to seepage that were assumed negligible. Errors in flow measurements caused by weir submergence and other factors would also affect the ET calculations.

Water Quality

Annual average nutrient concentrations for 1988-2005 are presented in table 3 for NO_3-N, TKN, total-N, and total-P. The NO_3-N concentration varied from 1.04 mg L^{-1} in 1990 to as low as 0.08 mg L^{-1} in 2001, when drainage outflow was lowest. The highest concentrations, near 1.0 mg L^{-1} both in 1989 and 1990, are very likely due to effects of fertilization in the spring of 1989 (Amatya et al., 1998).

Concentrations higher than the mean (0.47 mg L^{-1}) were also observed in the years 1992, 1997, 1998, and 1999. The higher rates in 1992, 1997, and 1998 may be due to higher subsurface drainage rates that occurred during the winters. Values of 0.48 mg L^{-1} and higher in 1999 and 2000 may also be attributed to large drainage outflows that occurred due to hurricanes and tropical storms in the summer of both of those years. Beltran (2007) reported high mean NO_3-N concentrations of 0.93 mg L^{-1} (flow weighted value = 1.0 mg L^{-1}) for this watershed for September and October 2005, when extreme rain events resulted in very large drainage outflows (fig. 2). The concentration fell then fell back to the mean value of 0.47 mg L^{-1} for the November 2005 to March 2007 period. Seasonal average nitrate concentrations of <0.54 mg L^{-1} reported for the 1990-1994 period (Amatya et al., 1998) were close to this long-term average (0.47 mg L^{-1}).

The 18-year (1988-2005) average annual NO_3-N loading of 3.2 kg ha^{-1} (table 3) was higher than the value of 2.5 kg ha^{-1} reported for the 1990-1994 period, probably due to inclusion of 1989 with effects of fertilization, and about the same as the five-year (1995-1999) average of 3.1 kg ha^{-1} (Amatya et al., 2003). Because concentrations were relatively constant, annual loading tended to be highest in years with the greatest outflows. Loadings were highest in 2000 (Hurricane Florence) and 1989 (Hurricane Hugo) (fig. 2). All other loadings greater than the average value also occurred in relatively wet years (1992, 1998, 1999, 2002, and 2003). By contrast, years with low flows generally had low NO_3-N loading. For example, 2001 had almost negligible loading due to very low flow. Both NO_3-N concentrations and loadings were much higher than those reported for forested lands in eastern North Carolina (Chescheir et al., 2003) but similar to those obtained by Diggs (2004) for drained pine forests on organic and high organic mineral soils.

TKN concentrations ranged from 0.34 mg L^{-1} in 1995 to 1.61 mg L^{-1} in 2002 (table 3). Values were not available for 1991. The high value of 1.23 mg L^{-1} in 1989 was almost certainly due to fertilization in late October 1988. The highest value in 2002 was due to a bias caused by a very high value of 3.7 mg L^{-1} for NH_4-N observed for a sample collected on August 11, 2002, and composited from an event of July 25, the cause of which was unknown. The site had been dry since April 7 with only small flow in June. Similarly, the 1999 value of 0.74 mg L^{-1}, which was higher than the mean of 0.68 mg L^{-1}, was probably due to the first flush effect of or-

Table 3. Annual average nutrient concentrations and loadings and their statistics. Shown are also the annual rainfall and outflow.

Year	Rain (mm)	Outflow (mm)	Annual Average Concentrations: NO_3-N (mg L^{-1})	TKN (mg L^{-1})	Total-N (mg L^{-1})	Total-P (mg L^{-1})	Annual Nutrient Loadings: NO_3-N (kg ha^{-1})	TKN (kg ha^{-1})	Total-N (kg ha^{-1})	Total-P (kg ha^{-1})
1988	1405	209	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1989	1875	658	1.00	1.23	2.23	0.033	6.58	8.09	14.67	0.22
1990	1235	240	1.04	0.54	1.58	0.119	2.50	1.30	3.79	0.29
1991	1575	519	0.29	--	--	0.025	1.51	--	--	0.13
1992	1619	584	0.68	0.44	1.12	0.029	4.27	1.79	6.06	0.11
1993	1513	586	0.35	0.36	0.71	0.01	2.81	1.79	4.60	0.04
1994	1528	436	0.20	0.43	0.63	0.035	0.95	1.04	1.99	0.05
1995	1404	459	0.23	0.34	0.57	0.06	1.05	1.51	2.56	0.23
1996	1707	704	0.43	0.44	0.87	0.05	2.30	2.98	5.28	0.36
1997	1382	397	0.55	0.54	1.09	0.03	2.97	2.10	5.07	0.14
1998	1658	770	0.70	0.64	1.34	0.03	4.18	5.48	9.66	0.22
1999	1363	614	0.62	0.74	1.36	0.01	5.10	5.18	10.28	0.08
2000	1718	857	0.48	1.09	1.57	0.02	8.04	13.39	21.43	0.22
2001	852	45	0.08	0.43	0.51	0.01	0.04	0.15	0.19	0.00
2002	1718	426	0.39	1.61	2.00	0.03	3.83	0.85	4.68	0.11
2003	2331	1308	0.22	0.45	0.67	0.03	3.56	2.62	6.18	0.36
2004	1313	389	0.29	0.38	0.67	0.03	1.33	1.94	3.27	0.04
2005	1777	798	0.39	0.38	0.67	0.09	2.73	1.38	4.11	0.23
Mean	1554.1	555.5	0.47	0.63	1.10	0.04	3.16	3.22	6.49	0.17
SD	308.2	284.3	0.27	0.37	0.53	0.03	2.07	3.40	5.32	0.11
COV	0.20	0.51	0.58	0.59	0.49	0.76	0.66	1.05	0.82	0.66

ganic matter accumulated in the ditches during the long dry summer period just prior to Hurricane Dennis (fig. 2) (Amatya et al., 2003). The 18-year mean annual value of 0.63 mg L^{-1} is higher than the seasonal concentrations of <0.44 mg L^{-1} observed for the 1990-1994 period (Amatya et al., 1998). The difference is attributed to increased values in 1989 and 1990 (after fertilization in 1988) as well as increases in NH_4-N concentrations following prolonged periods without outflow (1997, 1998, 1999, and 2001) and also increases in organic N from decomposition. Beltran (2007) found TKN as high as 0.98 mg L^{-1} for the two extreme wet months of September and October 2005 due to increased NH_4-N concentrations. TKN concentration had no relationships with drainage outflow and rain. The mean loading rate of TKN (3.22 kg ha^{-1}) was similar to that of NO_3-N (3.16 kg ha^{-1}), with the highest rates (13.4 kg ha^{-1} in 2000 and 8.1 kg ha^{-1} in 1989) resulting from both increased outflows and concentrations (table 3). The average annual TKN load of 3.5 kg ha^{-1} after 1995 was higher than that (1.65 kg ha^{-1}) for the 1990-1994 period (Amatya et al., 1998). Beltran (2007) reported a high loss rate of 8.1 kg ha^{-1} $year^{-1}$ for a very wet three-month period in 2005. However, the values decreased to 3.3 kg ha^{-1} $year^{-1}$ for NO_3-N and to 1.4 kg ha^{-1} $year^{-1}$ for TKN for the 2006-2007 period.

Total N calculated as the sum of NO_3-N and TKN concentrations varied from 0.51 mg L^{-1} in the dry year 2001 to as much as 2.23 in 1989, the year of fertilization (table 3). Beltran (2007) reported a mean total N value of 1.91 mg L^{-1} for two extreme fall months in 2005. However, the concentration was only 0.81 mg L^{-1} for the 2006-2007 period. The 18-year average total N concentration of 1.10 mg L^{-1} was similar to that found for forested lands in eastern North Carolina (Chescheir et al., 2003). No correlation was found between total N and outflow, nor between total N and rainfall. The highest total N loading (21.4 kg ha^{-1}) was estimated in the year 2000 as a result of the highest loadings of both NO_3-N and TKN. This was followed by 1989 (14.7 kg ha^{-1}) with the effects of fertilization and Hurricane Hugo. Again, due to an increase in both the NO_3-N and TKN loadings after 1995, the 17-year average total N loading of 5.9 kg ha^{-1} (excluding the year 1989 with effects of fertilization in 1988) was about 45% higher than that (4.1 kg ha^{-1}) observed for the 1990-1994 period. The highest total P concentration of 0.12 mg L^{-1} was observed in 1990 a year after fertilization (table 3). The smallest values were observed in the years 1993, 1999, and 2001. The average and standard deviation were 0.035 and 0.027 mg L^{-1}, respectively. The highest total P load of 0.36 kg ha^{-1} was observed in 1996 and 2003, both years with high outflows. The average P loading of 0.17 kg ha^{-1} was less than the value reported by Chescheir et al. (2003) for managed pine forest sites in eastern North Carolina.

Summary and Conclusion

The 21-year (1988-2008) study period at the experimental forest site in coastal Carteret County, North Carolina, was wetter than average. Average annual rainfall (1517 mm) during the study period was 9% higher than the 50-year (1951-2000) average of 1391 mm observed at nearby Morehead City, North Carolina. The average annual runoff coefficient of 0.32 is slightly higher than data reported earlier for the region. Seasonally, the highest runoff coefficient of 0.59 occurred during the winter when the water table is shallow and ET is low. The long-term data demonstrated that March was the only month and winter the only season when outflow never ceased in this pine forest system. All other months and seasons yielded zero flows at one or more times. This long-term study also highlighted the effects of hurricanes and tropical storms on drainage outflow dynamics. Outflow processes on these artificially drained sites are basically governed by shallow subsurface drainage, which is dependent on water table elevation, ditch spacing and depth, and hydraulic conductivity of the various layers of the soil profile. The water table elevation is, in turn, dependent on rainfall, ET, drainage, and soil water characteristics. Spring, summer, and annual drainage outflows were strongly related to rainfall, as expected. It was also determined that annual ET from the pine forest may be substantially higher than the PET estimated for a grass reference, consistent with the findings of Sun et al. (2010).

Fertilization applied in 1989 after a commercial thinning of the stand in late 1988 increased the nitrogen and phosphorus (total P) levels, which returned to normal long-term averages by 1995. Both the N and P concentrations were affected by low flow conditions. The first flush from a storm event after a long dry period increased decomposition of organic N and resulted in elevated TKN concentrations. The 17-year (excluding 1989 with fertilization effects) average total N loading was substantially higher than that for 1990-1994, indicating that short-term results may not capture the long-term effects due to variability in weather. High N and P loadings were generally associated with high drainage outflows. The long-term average annual NO_3-N concentrations were at least four times higher than the mean seasonal values (<0.1 mg L^{-1}) reported by Chescheir et al. (2003) for 50% of the forest study sites in eastern North Carolina. But both the average total N and P concentrations were similar. However, as with the drainage outflows, it is also important to evaluate the nutrient levels on a seasonal basis, which may vary widely (Beltran 2007; Amatya et al., 1998).

As a next step, these long-term data are being used to evaluate trends in hydro-meteorological parameters (e.g., rainfall, temperature, net radiation, PET, outflow, water table depth) and nutrient levels both annually as well as seasonally on this drained pine forest. The data will also be useful for developing and evaluating other simpler water balance models (e.g., Xiong and Guo, 1999). These long-term hydrology and nutrient data may serve as a baseline reference for evaluating the impacts of various management treatments on drained forested sites in the coastal region (Andreassian, 2004; Jones et al., 2009; Amatya et al., 2011). Most recently, Tian et al. (2010, 2012) used these 21-year data to calibrate and validate the DRAINMOD-Forest model to simulate forest hydrology, productivity, nutrients, and carbon cycling on this drained pine forest. Long-term studies, such as this, are important for disclosing the deviations from recovery trajectories following natural or management-related shifts in vegetation conditions occurring as regrowth proceeds, or as global climatic patterns shift (Keppeler et al., 2008).

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