HYDROLOGY AND WATER QUALITY OF A DRAINED LOBLOLLY PINE PLANTATION IN COASTAL NORTH CAROLINA

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ABSTRACT

This paper evaluates 17 years (1988-2004) of hydrologic and 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 30 years at the end (2004). The 17-year average rainfall of 1538 mm was 11% higher than the 50-year (1951-2000) long-term data of 1391 mm observed at the nearest US Weather Bureau station in Morehead City, NC. Annual rainfall (and drainage outflow expressed as a % of rainfall) varied from as low as 852 mm (5 % outflow) in the driest year (2001) to as high as 1308 mm (56% outflow) in the wettest year (2003), with an average of 33%. The daily outflows occurred much more frequently in winter resulting in 62% of rain as outflow than other seasons. The drainage outflow (runoff) on this watershed was primarily subsurface flow to drainage ditches and was related to water table depth as shown by a good correlation between the annual outflow and the average water table depth ($R^2 = 0.75$), which in turn, also correlated well with the rainfall ($R^2 = 0.69$). The water table depths tended to be close to the surface mostly during the winter and early spring, and during summer tropical storms, but were as deep as 2.5 m during the dry summer-fall periods. 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, indicating that the ET may not have been limited by soil moisture conditions during the study period at the site. This was also indicated by the estimated average annual ET of 997 mm, which was 2.8% higher than the Penman-Monteith based annual potential ET (PET) for a grass reference that varied between 782 mm to 1097 mm with an average of 970 mm. Although nitrogen (N) levels in drainage water were elevated after commercial thinning of the stand in late 1988 followed by fertilization, these elevated levels reduced substantially by 1995. Average annual concentrations of total N ranged from 0.57 mg L^{-1} to 2.0 mg L^{-1} with a long-term average of 1.11 mg L^{-1}. Annual average values for total P ranged from 0.01 to 0.06 mg L^{-1}, with an average of 0.03 mg L^{-1}. The average annual total N and P loadings were (6.9 ±5.8) kg ha^{-1} and (0.17 ±0.12) kg ha^{-1}. Both concentrations and annual loadings were similar to other forested sites in the region.

KEYWORDS. Water table, drainage outflows, Forest, Evapotranspiration, Nutrient concentrations, nutrient loadings.

INTRODUCTION

Forests are an important part of the ecosystem and play a great role in regulating the regional hydrologic patterns of the southern US where 55% of the region is covered by forests (Sun et al. 2002). Land use pressures and environmental set asides tend to decrease the industrial forest base, leading to more areas of intensive silvicultural practices, which may include drainage, harvesting, site preparation, bedding, fertilization, herbicides, and artificial regeneration. Hydrologic and water quality impacts of these sustainable forest management practices continue to be important environmental issues. Long-term hydrologic data are essential as base line data for assessment of best management practices for minimizing the impacts on downstream water quality (Amatya et al., 2003b). These data also lead to a better understanding of the hydrologic processes necessary for the testing of eco-hydrological models, and for conservation of regional ecosystems.

Long-term hydrologic data from small, paired, experimental forested watersheds at the Coweeta Hydrologic Laboratory in North Carolina (NC) integrated with an ecosystem approach have provided basic understanding of eco-hydrological processes for regional upland watersheds (Swank et al. 2001). Tajchman et al. (1997) reported the water and energy balance of a 39 ha central Appalachian watershed covered with 80-yr old upland oaks and cove hardwoods using 40 years of hydrologic data. However, there are few such observational studies done for the forest ecosystems that occur along the lowlands of southeastern coastal plains. Approximately, 1 million hectares of plantation pine in this region are drained to improve soil trafficability for harvesting and planting operations and to improve tree productivity. Unlike the upland watersheds dominated by hillslope processes, hydrologic processes on these lands are usually dominated by shallow water tables, affected by rainfall and evapotranspiration (ET).

A long-term forest hydrology and water management study was initiated at three experimental pine forests at Carteret County, North Carolina in early 1988 to quantify the potential impacts of both silvicultural and water management practices on downstream hydrology and water quality. Continuous monitoring on these watersheds has provided a database for quantifying the water and nutrient budgets and evaluating such impacts using a paired watershed approach (McCarthy et al., 1991; Amatya et al., 1996; 1998; 2000; 2003a). It has also provided a data base for developing models for simulating hydrologic effects of various management practices on these drained forests (McCarthy et al., 1992; Amatya and Skaggs, 2001). Both monitoring and modeling studies have provided a better understanding of hydrologic processes including water budget on various temporal scales on these watersheds. The authors are not aware of other long-term field studies documenting the hydrology of a drained coastal pine forest.

The main objective of this study was to evaluate long-term (1988-2004) hydrology and water quality data in context of the previous studies on a drained mid-rotation loblolly pine (*Pinus taeda* L.) forest in Carteret County, North Carolina. The second objective is to explore potential seasonal and annual relationships among the various hydrologic processes including the flow frequency duration that might be used to help forest managers and decision makers assess hydrologic and water quality impacts on these and other similar drained forested lands.

METHODS

Site Description:

The study site (Figure 1) is located at approximately 34° 48' N latitude and 76° 42' W longitude 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. 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 (Figure 1). Data on hydrology, soil and vegetation parameters were collected from three experimental plots (each about 0.13 ha in area) in each watershed (Figure 1).

Monitoring:

Rainfall was measured with a tipping bucket rain gauge with a datalogger on the western side of each watershed (Figure 1). Air temperature, relative humidity, wind speed and solar radiation were continuously measured by an automatic weather station located 800m away until 1997 after which a new station including a net radiometer was installed at the center of the treatment watershed (D2). A 120° V-notched weir with an automatic stage recorder, located in a water level control structure at a depth nearly equal to the bottom of outlet ditch (Figure 1), was used to measure drainage outflow in each watershed. An additional recorder was placed downstream from the weirs to determine if weir submergence occurred and to correct flows in that event. In 1990, a pump was installed downstream from all three watersheds in the roadside collector ditch to

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prevent weir submergence during larger events. The pump and associated pipes were replaced and repaired in late 2003 to avoid any possible disruption due to failure of the pump assembly. Collector ditches were cleaned in July 2004 to avoid submergence due to increasing vegetation and silts. Water table elevations were measured by a continuous water level recorder at two locations midway between the field ditches for each watershed (Figure 1). The reader is referred to McCarthy et al. (1991) and Amatya et al. (2003a; 2000; 1996) for a detailed description of the site and other measurements including interception, lateral seepage, leaf area index (LAI), and the history of the loblolly pine stand planted in 1974.

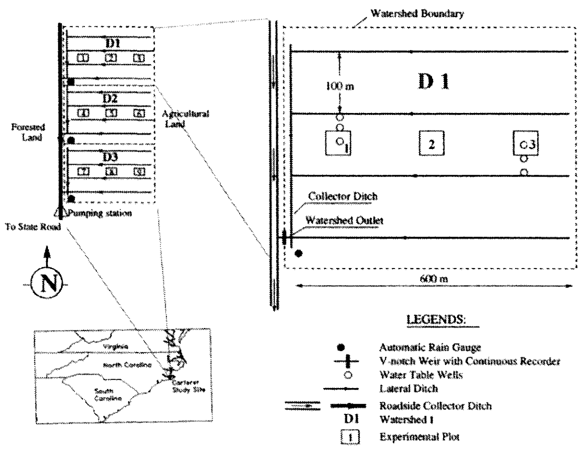

Figure 1. Layout of the experimental Carteret 7 watersheds in Carteret County.

Two methods of water sampling (composite using automatic water samplers ISCO-2700 and manual grab sampling) at the weir outlet of each watershed (Figure 1) have been used since late 1989. For composite sampling during an event, 250 mL of water was collected every two hours; 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 taken to the soil-chemistry laboratory of the Soil Science Department at North Carolina State University in Raleigh, NC. Grab samples were collected weekly during the flow events of the study period. 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 have been documented by Amatya et al. (1998; 2003a).

The study watershed is watershed D1 (Figure 1), which is a control of the paired system (D1, D2 and D1, D3) and has not been disturbed since the establishment in 1988. However, all three watersheds, planted in 1974, were commercially thinned in October 1988 immediately after which they were fertilized. This study describes (the pre- (1988) and post thinning (1989-04) hydrology and water quality of the pine forest starting at the stand age of 14.

Procedures of processing rainfall, flow, water table and weather data have been described in detail by (Amatya et al., 1995; 1996; 2000). All daily data on rainfall, flows, net radiation, and potential evapotranspiration (PET) for a grass reference were integrated to obtain the annual totals (Table 1). However, air temperature, water table elevations and depths were obtained as the annual average. On an annual basis, actual evapotranspiration (AET) was calculated as a difference of annual rainfall and outflow assuming a negligible storage change (Sun et al., 2005). The calculated annual AET was compared with the predictions by the forestry version of DRAINMOD (Amatya and Skaggs, 2001) as well as with the estimates by the method of Zhang et al. (2001). SAS (1994) was used to conduct the seasonal flow frequency analysis for measured daily flows. Results using simpler relationships were compared, where appropriate, with previous studies. All data analyses including the statistical tests were conducted using the MS-EXCEL (2000).

RESULTS AND DISCUSSION

Rainfall

Annual rainfall over the 17-year period of observation varied from a low of 850 mm in 2001 to a high of 2330 mm in 2003 with a coefficient of variation (COV) of 0.20 (Table 1). The average precipitation of 1538 mm in this period was 11% higher than the 50-year average of 1391 mm for the nearest weather station (Morehead City). No definite trend was found in the annual measured rainfall at this site. The monthly average distribution of rainfall (Figure 2) is similar to the 50-year long-term average. However, the monthly amounts at the site were consistently higher for all months except February and June. Frequent tropical storms and hurricanes caused July, August and September to be the wettest months; February was the driest month, on average. The maximum monthly rainfall of 448 mm, 397mm, and 355 mm were all observed in September with hurricanes such as 1996 (Fran), 1989 (Hugo), and 2003 (Isabelle). Some other years were also affected by hurricanes (Bertha, Fran, and Josephine in 1996; Bonnie in 1998; Floyd and Irene in 1999; Isabelle in 2003; Gaston in 2004). As a result, the 17-year average summer (July-September) total of 578 mm rain was 38% of the average annual (1538 mm). All other three seasons have almost similar (20-22%) amounts. This is consistent with long-term means observed at the Morehead City station (Amatya et al., 1996). The lowest monthly rainfall of 12 mm was measured in April 1994. Annual rainfall varied by as much as 127 mm between the gauges 800 meters apart (watersheds D1 and D3, see Fig. 1) on the site, with the greatest variation occurring in June (not shown) (Amatya et al., 1996).

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

Year	Rain mm	Avg Temp deg C	Net Radiation mm	P-M PET mm	Flow mm	Runoff Coeff. %	WT Elevation m	WT Depth cm	AET = Rain-Flow mm	Zhang et al., AET mm
1988	1406	15.7	1355	1041	209	0.15	1.69	101	1197	1010
1989	1876	16.3	1191	945	658	0.35	2.02	68	1218	1075
1990	1236	17.4	1236	1031	240	0.19	1.61	109	996	937
1991	1575	16.6	1132	917	519	0.33	1.82	88	1056	992
1992	1619	16.1	1013	782	584	0.36	1.87	83	1035	900
1993	1514	15.9	1206	875	585	0.39	1.55	115	929	949
1994	1528	16.3	1236	896	437	0.29	1.51	119	1091	966
1995	1404	15.9	1191	849	457	0.33	1.64	106	947	905
1996	1646	15.8	1191	877	705	0.43	1.81	89	941	980
1997	1382	16.1	1358	1075	395	0.29	1.66	104	987	1016
1998	1658	17.7	1321	1007	770	0.46	1.98	72	888	1071
1999	1377	16.7	1438	1072	614	0.45	1.84	86	763	1013
2000	1718	15.6	1434	1023	857	0.50	1.91	79	861	1097
2001	852	16.3	1121	1024	45	0.05	1.22	148	807	730
2002	1718	16.5	1348	919	426	0.25	1.66	104	1292	1025
2003	2331	16.6	1498	1097	1308	0.56	2.16	54	1023	1272
2004	1313	16.6	1522	1060	389	0.30	1.72	98	924	981
Mean	1538	16.4	1282	970	541	0.33	1.75	95	997	995
STDEV	310	0.6	142	94	286	0.13	0.22	22	143	111
COV	0.20	0.03	0.11	0.10	0.53	0.39	0.13	0.23	0.14	0.11

Outflows and Runoff Coefficients

Measured annual outflows and runoff coefficients 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 paper. Essentially all outflow from the site is subsurface drainage to the open ditches, as there is little water which leaves the site before soil infiltration. Nevertheless, we shall use the term runoff coefficient to mean the ratio of outflow to rainfall, expressed as a percentage.

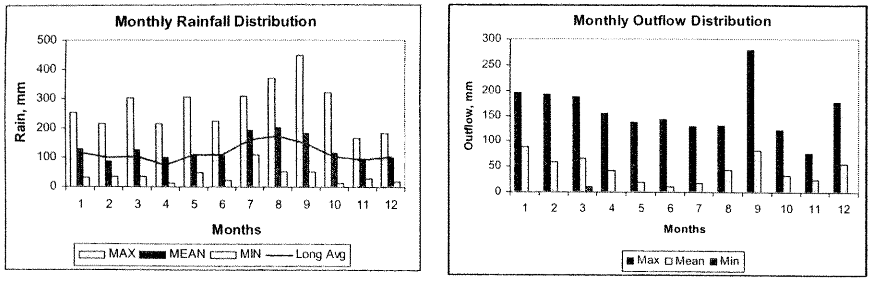

Figure 2. Monthly maximum, average, and minimum rainfall (left) and drainage outflow (right).

A review of the data indicates that annual outflow is quite variable (COV = 0.53) from year-to-year compared to rainfall (COV = 0.20). The watershed yielded an average annual outflow of 541 mm, which is equivalent to an average runoff coefficient of 33%. This is slightly higher than earlier value (0.30) for this site based on data through 1995 (Chescheir et al., 2003). This was expected due to more nearly eight out of 10 years with above normal rainfall since 1995. The highest rainfall of 2331 mm in 2003 resulted in a maximum annual outflow of 1308 mm equivalent to 56% runoff. However, these large outflows, especially during the periods affected by hurricanes and tropical storms, need to be cautiously interpreted due to potential errors in measured data when the weir was submerged. For example, data from March to December for the year 2003 was generated using the DRAINMOD model (Skaggs, 1978) calibrated for this site. Year 2001 with the lowest rainfall yielded 45 mm of outflow, which was only 5.3% of rainfall. Average monthly distribution of outflows is shown in the right plot of Figure 2. The month of September with the highest average outflow (279 mm) coincided with the high rainfall caused by frequent hurricanes and tropical storms in that month. January had the second highest outflow although the rainfall was similar to long-term average (Figure 2 – left). The high outflow was caused by reduced ET resulting in shallow water tables. The smallest average outflow occurred in the month of June. Relatively smaller outflows were observed in May due to increased ET and in November due to reduced rainfall.

Outflow from the watershed averaged 62% (runoff coefficient) of the total average rainfall in winter (January-March) (Table 2) although the rainfall was only about 22% of the average annual total. This was consistent with the earlier observations by Amatya et al. (1996) at this site. This was due to long sustained drainage caused by high water table elevations and low ET during this period. The runoff coefficients for spring (April-June) and summer (July-September) were only about 20% of the average rainfall for these periods, leaving most of the water for ET. Amatya et al. (1996) found the drainage loss of only 4 mm and ET loss of 238 mm or as much as 98% of the total rainfall for the spring of 1992. Even with the highest average rainfall amount during the summer (July-September) the drainage outflow was only 20%. Again because of lower ET demands, the outflow in the fall (October-December) increased to 33%, on average, of the rainfall.

Table 2. Computed statistics for 17-year measured total seasonal rainfall and outflow.

Parameters	Winter (Jan-Mar)			Spring (Apr-Jun)			Summer (Jul-Sep)			Fall (Oct-Dec)		
	Rain mm	Flow mm	Runoff Coefficient	Rain mm	Flow mm	Runoff Coefficient	Rain mm	Flow mm	Runoff Coefficient	Rain mm	Flow mm	Runoff Coefficient
Total	5795	3612		5322	1212		9832	2414		5270	1927	
Average	341	212	0.62	313	71	0.19	578	142	0.20	310	113	0.33
Std Dev	96	115	0.27	117	106	0.19	165	147	0.20	108	95	0.26
COV	0	1	0.44	0	1	1.00	0	1	0.97	0	1	0.80
Max	474	424	1.03	680	435	0.64	867	455	0.61	500	308	0.72
Min	168	18	0.05	177	0	0.00	289	0	0.00	116	0	0.00

The daily flow duration curves for the four seasons for the 17-year period are presented in Figure 3. The upper plot (a) shows all data whereas the lower plots (b) is enlarged to indicate medium to low flows (<10 mm day^{-1}). Daily flow occurred much more frequently (almost 88% of time) during the winter than other seasons (34% in spring, 31% in summer, and 55% in fall). Again this was due to higher water table and lower ET demands in the winter. Clearly in winter the flows are steadier than other seasons for at least 99% of time for flows less than 17 mm day^{-1}. For the same frequency, the flow rates for the spring, summer and fall were 10, 25, and 11.5 mm day^{-1}, respectively. The watershed outlet generally records highly submerged flows when the daily flow rate exceeds 31 mm day^{-1}. The highest daily flow recorded during the winter was 30 mm compared to 60 mm in the summer. The percent time daily flow exceeded this rate was 0% in winter, 0.1% in spring, 0.4% in summer and 0.12% in fall, respectively. This indicates that most submergence occurred during the summer with frequent hurricanes and tropical storms. The medium flows less than 10 mm day^{-1} occurred 3% in winter, 0.9% in spring, 5% in summer, and 3.3% in fall, respectively.

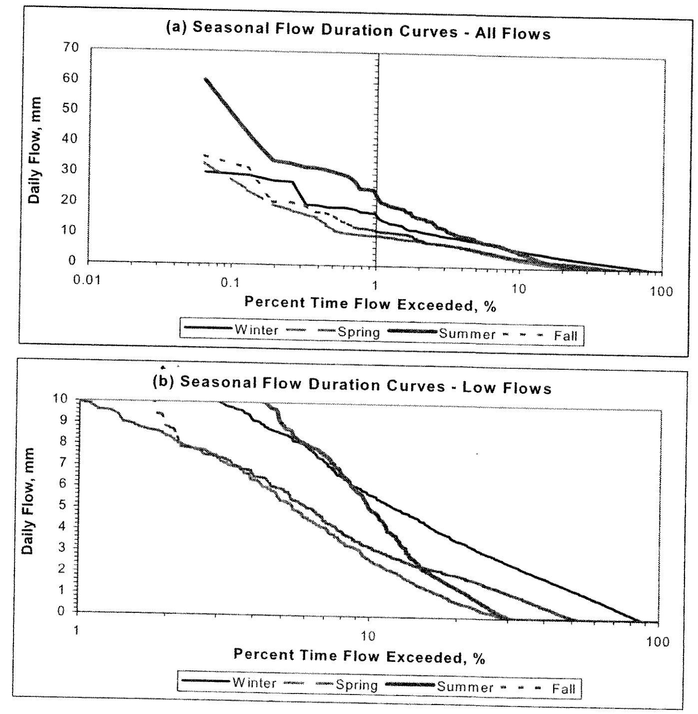

Figure 3. Measured seasonal daily flow duration curves (a) for all flows and (b) enlarged scale for low flows.

Note that the outflow processes on these pine plantations with ditches on flat lands are basically driven by shallow subsurface drainage and the artificial beds created for planting trees generally precludes surface runoff (Amatya et al., 1996). This subsurface drainage rate is a function of average water table position and hydraulic conductivity (McCarthy and Skaggs, 1992). Daily cumulative water balances for wet (2003) and dry years (2001) (Figure 3) illustrate the effects of mid-point water table position on drainage outflows. Amatya and Skaggs (2001) tested the forestry version of DRAINMOD (Skaggs, 1978; McCarthy et al., 1992) using ten years (1988-97) of weather data to predict the daily flow data from this site. The predictions for the daily water table elevations and flow rates were within 15 cm and 0.61 mm, respectively.

Water Table Depths (Elevations) and Evapotranspiration

Annual average water table depths and total evapotranspiration (ET), calculated as a difference between the annual rainfall and outflow, are presented in Table 1. Year 2003 yielded the shallowest water table depth of 53 cm compared to 148 cm in 2001. The average depth for the study period was 95 cm. Water table depth was so shallow in the wet year 2003 (Figure 4- left) that it frequently came up near the ground surface (elevation =2.7 m) during the wet events from March to December (Days 70 to 350) and never dropped below an elevation of 1.5 m even during the dry summer months of July-August (Days 180-240). To the contrary, water table elevations in the dry year, 2001, were well below 1 m by August (Day 244) and hit a low of 0.5 by the end of November (Day 330) creating a large soil water deficit (Figure 4 – right). This was caused by higher ET and lower rainfall during the later part of the year. Thus calculated ET in 2001 was comprised of 95% of the total rainfall, while it was only 44% in the wet year of 2003 with an average of 67% for the 17-year period. This was consistent with earlier results (Amatya et al., 1996) that ET has the greatest impact on water table elevations, indicating that optimizing leaf area, which increases ET, will lower water tables during the growing season. The plots also indicate that the drainage outflow from the watershed ceases when the water table elevation drops below about 1.8 m or 90 cm depth. Water table rose near and even was ponded on the surface during Hurricanes Hugo in September 1989, Fran in September 1996, Bonnie in August 1998, Floyd in September 1999, and Isabelle in September 2003.

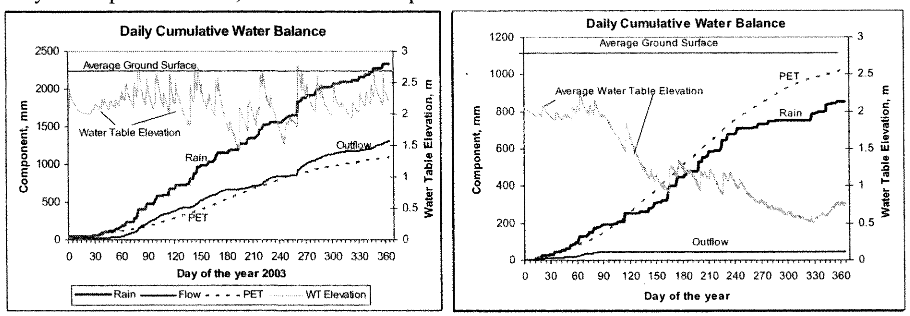

Figure 4. Daily cumulative rainfall, outflow, Penman-Monteith-based potential evaopotranspiration (PET) and water table elevation measured in a wet year 2003 (left plot) and a dry year (2001) (right plot).

Annual Penman-Monteith PET for a grass reference was calculated using the daily average weather data. It varied from 782 mm in 1992 to as much as 1097 mm in the wet year 2003, with an average of 970 mm (Table 1). Similarly, the annual actual ET (AET), calculated as a difference of rainfall and outflow assuming a negligible storage change, varied from 763 mm in 1999 to 1292 mm in 2002 with an average of 997 mm. This indicates that the average annual AET for the pine forest is about 3% higher than the PET based on the grass reference. Errors in annual AET calculated in this way may be caused by differences in soil water storage at the beginning and end of the year, as occurred in 2001, and by losses due to seepage. Errors in flow measurements caused by weir submergence and other factors would also affect the AET calculations. Annual AET was compared with the total ET, including canopy interception loss, predicted by the forestry version of DRAINMOD (Amatya and Skaggs, 2001) for the first 10 years (1988-97). The 10-year average AET of 997 mm (Table 1) calculated as the difference between rainfall and outflow was about 4.6% lower than that predicted by the model (1045 mm). The relative error was within 12% (overprediction) with a mean of only 0.2%, indicating that for this period the assumption of negligible storage was perhaps adequate. On the other hand, a simpler method using annual precipitation and PET with a vegetation factor (w=2) suggested by Zhang et al. (2001) and modified by Amatya et al. (2002) with w= 3 for pine forest underestimated the average annual AET by about 2.5% compared to the calculated value (Table 1). A vegetation factor (w) of 3.3 provided the least difference in 17-year average compared to the calculated average annual AET for this managed pine forest. Sun et al. (2005) used a value of 2.8 for calibrating regional AET for Southeastern watersheds on pine and deciduous forests.

The cumulative rainfall exceeded the cumulative potential evapotranspiration (PET) most of 2003, indicating surplus moisture, which resulted in drainage outflow over the whole year. Conversely, cumulative rain was above the PET for barely two months (Days 45-105) in 2001 with most of the outflow occurring during that period. The soil-water deficit in 2001 was calculated to be 89 mm based on the drainage volume –water table relationship (McCarthy et al., 1991). This resulted in a calculated AET of about 896 mm compared to the PET of 1024 mm.

Annual and Seasonal Hydrologic Relationships

Relationships among annual rainfall, outflow, water table depth, AET, and PET, based on 17-years of measured data, are plotted in Figure 5. Some of the relationships are expected. For example, annual outflow was linearly dependent on annual rainfall ($R^2 = 0.79$). Both the slope and intercept parameters were significant ($p<0.001$). The relationship indicates that the outflow would cease when rainfall is lower than 880 mm (Table 1). However, it is not difficult to envision circumstances for which this would not be the case (e.g., high water tables and drainage in January when there is little rain, followed by very dry conditions for the rest of the year).

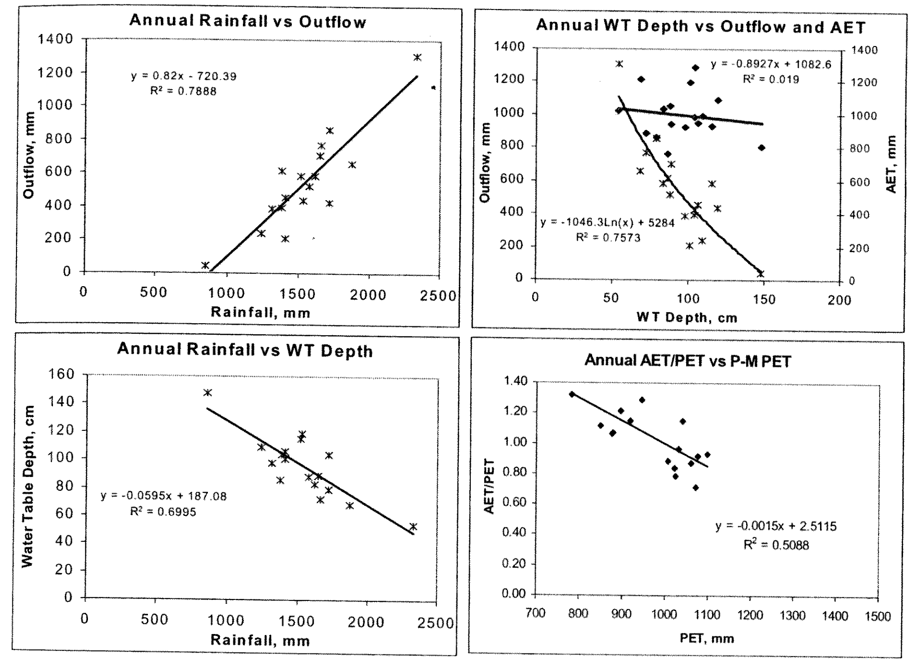

Figure 5. Hydrologic relationships using 17-years of measured data for a drained forested watershed.

When the outflows were correlated with rainfall on a seasonal basis as was done for the flow duration curves above, relationships only for the spring (April-June) and summer (July-September) were strong ($R^2 > 0.74$) (Figure 6) and both intercept and slope parameters were significant ($p < 0.0004$). However, relationships were weaker ($R^2 < 0.42$) and only the slope parameter was significant ($p < 0.008$) for fall (October-December) and winter (January-March) seasons. These weaker relationships could be attributed to antecedent conditions that usually occurred at the end of the years or during the summer. For example, the very dry conditions in most of the year 2001 resulted in significantly lower outflow (18 mm) in winter of 2002 despite of average seasonal rain (342 mm). Similarly, the relatively dry spring in the spring of 1997 resulted in zero outflow in the following summer even with a rainfall amount of 500 mm, which was only

12% lower than the average total summer rainfall. Similar phenomena were observed in other periods of other years. Detailed seasonal water budgets for this watershed for the years through the year 1992 were provided by Amatya et al. (1996) and McCarthy et al. (1991).

The relationship between annual outflow and water table depth (Figure 4) was strong ($R^2 = 0.76$) and parameters were significant ($p < 0.0001$), as expected. However, daily drainage rates and water table elevations at this site were found to be non-linearly related (not shown). Such relationships can be used to estimate field effective saturated hydraulic conductivity of soil drainage (Diggs, 2004). The annual average water table depth also correlated fairly well ($R^2 = 0.69$) with annual rainfall, which again should be expected. The p-value was significant ($p<0.0001$) for both the slope and intercept parameters. On the other hand, no relationship ($R^2 = 0.02$) was found between the annual AET and the water table depth. The slope of –0.89 was not significant even at $p<0.10$. The fact that the intercept parameter (= 1086 mm) was significant ($p<0.0001$) shows that the maximum AET of 1086 mm can be expected for the zero water table depth at the surface with unlimited soil water conditions. This seems to be consistent with both the calculated (Table 1) and DRAINMOD predicted AET values (Amatya and Skaggs, 2001).

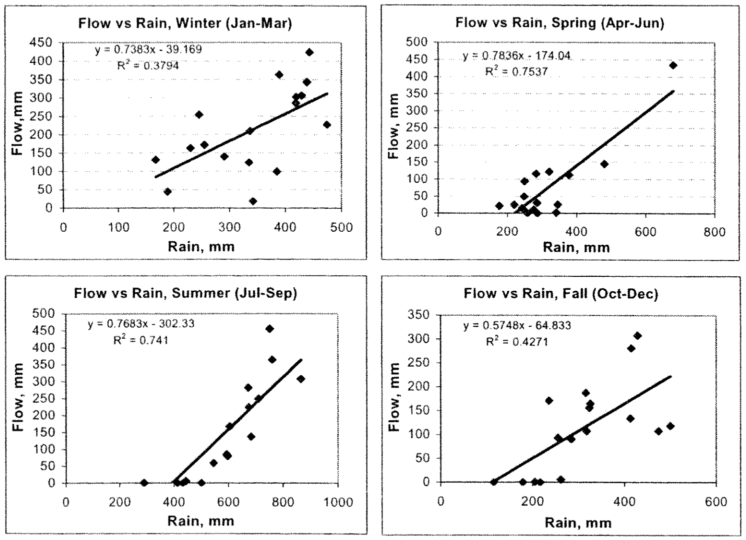

Figure 5. Seasonal relationships of outflow and rainfall using 17-years of measured data.

Although the relationship between AET and the ratio of AET/PET (Figure 4) was only fair ($R^2 = 0.52$), both the slope and intercept parameters were significant (<0.001). Data shows that when the grass reference PET is more than 1000 mm the ratio is between 0.8 and 1 indicating that AET is not more than the PET. However, when the PET is between about 800 to 950 mm the ratio is higher than 1.0 indicating that the forest AET is higher than the grass PET. It should be noted that all these hydrologic relationships reflect the effects of thinning that occurred in late 1988.

Water Quality

Annual average nutrient concentrations 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. Concentrations higher than the mean (0.5 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. Annual NO_3-N concentration was not correlated with either annual outflow or rainfall. Seasonal average nitrate concentrations of <0.54 mg L^{-1} reported for the 1990-94 period (Amatya et al., 1998) was close to this long-term average (0.5 mg L^{-1}). The 17-year average annual loading of 3.3 kg ha^{-1} (Table 3) was higher than the value of 2.5 kg ha^{-1} reported for the 1990-94 period, but lower than the five-year (1995-99) average of 3.1 kg ha^{-1} (Amatya et al., 2003a). This was possibly due to the fact that the annual NO_3-N loading tended to be highest in years with the greatest outflows. Loadings were highest in 2000 and 1989 (hurricane Hugo). All other loading rates greater than the average also occurred in relatively wet years (1992, 1998, and 1999). By contrast, years with low flows generally had low NO_3-N loading. For example year 2001 had almost negligible loading due to very low flow. Both NO_3-N concentrations and loadings were 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 soils with more organic matter than at the study site.

TKN concentrations were not available in 1991 and 2003 (Table 3). Values ranged from 0.34 mg L^{-1} in 1995 to 1.61 mg L^{-1} in 2002. The high value of 1.23 mg L^{-1} in 1989 was potentially due to the fertilization. The highest value in 2002 was due to a very high value of NH_4-N observed in this year, the cause of which was unknown. Similarly, the 1999 value of 0.74 mg L^{-1}, which was higher than the mean of 0.68 mg L^{-1} was possibly due to the first flush effect of organic matter accumulated in the ditches during the long dry summer period just prior to hurricane Dennis (Amatya et al., 2003a). The 17-year mean annual value of 0.68 mg L^{-1} is much higher than the seasonal concentrations of < 0.44 mg L^{-1} observed for the 1990-94 period (Amatya et al., 1998) due to increased TKN observed after 1995 (Amatya et al., 2003a). The authors attributed it to increases in NH_4-N concentrations following a prolonged period without outflow (1997, 1998, 1999, and 2001) and also increases in organic N from decomposition. TKN also had no relationships with drainage outflow and rain. Loading rates of TKN were similar to that of NO_3-N with the highest rate (13.4 kg ha^{-1}) in 2000 followed by 1989 (8.1 kg ha^{-1}). Due to both increased concentrations and outflows for most of the years after 1995 the average annual TKN loading of 3.5 kg ha^{-1} was higher than that (1.65 kg ha^{-1}) for the 1990-94 period (Amatya et al., 1998).

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

Year	Rain	Outflow	Annual Average Concentrations				Annual Nutrient Loadings			
			NO3-N	TKN	Total-N	Total-P	NO3-N	TKN	Total-N	Total-P
	mm	mm	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
1988	1406	209	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1989	1876	658	1.00	1.23	2.23	0.033	6.58	8.09	14.67	0.22
1990	1236	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	1514	585	0.35	0.36	0.71	0.01	2.81	1.79	4.60	0.04
1994	1528	437	0.20	0.43	0.63	0.035	0.95	1.04	1.99	0.05
1995	1404	457	0.23	0.34	0.57	0.06	1.05	1.51	2.56	0.23
1996	1646	705	0.43	0.44	0.87	0.05	2.30	2.98	5.28	0.36
1997	1382	395	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	1377	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	0.26			0.03	3.26			0.39
2004	1313	389								
Mean	**1538.4**	**541.1**	**0.49**	**0.68**	**1.20**	**0.03**	**3.29**	**3.51**	**6.94**	**0.17**
STDEV	**310.3**	**286.5**	**0.28**	**0.39**	**0.55**	**0.03**	**2.15**	**3.73**	**5.81**	**0.12**
COV	**0.20**	**0.53**	0.58	**0.58**	**0.46**	**0.78**	**0.65**	**1.06**	**0.84**	**0.67**

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). No correlation was found between total N and outflow. Although there was only a slight correlation ($R^2 = 0.30$) between annual total N concentration and annual rainfall, the slope parameter was significant at $\alpha = 0.05$. Highest total N loading (21.4 kg ha^{-1}) was estimated in the year 2000 as a result of both the highest loadings of NO_3-N and TKN. This was followed by 1989 (14.7 kg ha^{-1}) with fertilization and Hurricane Hugo. Again, due to increase in both the NO_3-N and TKN loadings after 1995, the 17-year average total N loading of 6.9 kg ha^{-1} was more than 50% higher than that (4.1 kg ha^{-1}) observed for the 1990-94 period. The average total N concentration of 1.20 mg L^{-1} was similar to that found for forested lands in eastern North Carolina (Chescheir et al., 2003).

Like for NO_3-N, highest total P concentration of 0.12 mg L^{-1} was observed in 1990 a year after fertilization followed by 1995 (0.06 mg L^{-1}) (Table 3). Smallest values were observed in the years 1993, 1999, and 2001. The average and the standard deviation were 0.035 mg L^{-1} and 0.027 mg L^{-1}. The highest total P load of 0.36 kg ha^{-1} was observed in 1996 with a high outflow and the third highest concentration (0.05 mg L^{-1}). This was followed by 1990 a year after fertilization. The average P loading of 0.17 kg ha^{-1} was less than the value reported by Chescheir et al. (2003).

CONCLUSIONS

The 17-year (1988-04) study period at a drained pine forested watershed in coastal North Carolina was wetter than average as shown by 11% higher rainfall (1538 mm) than the 50-year (1951-2000) average of 1391 mm observed at the nearest Morehead City station. This resulted in an average annual runoff coefficient of 0.33, slightly higher than data reported earlier for the region. The highest frequency (98% of the time) of daily flows resulting in the highest runoff coefficient of 0.62 occurred during the winter. The outflow process on the study site is basically governed by shallow subsurface drainage outflow, which is dependent upon water table position controlled by rainfall and ET. Both seasonal (for spring and summer only) and annual drainage outflows yielded strong relationships with the rainfall, as expected. There was no relationship ($R^2 = 0.01$) between the annual average water table depth and the annual average actual evapotranspiration (AET), calculated as a difference between annual rainfall and outflow, indicating that the AET may not have been soil moisture limited during the study period at the site. It may also be concluded from the data that AET from the pine forest may be higher by as much as a factor of 1.25 than PET estimated for a grass-reference. The vegetation factor (w = 2) suggested by Zhang et al (2001) for estimating annual AET was calibrated to be w = 3.3 for this uniform managed pine forest.

Fertilization applied in the year 1989 after a commercial thinning of the stand in late 1988 did increase the nitrogen and phosphorus (total P) levels, which were substantially reduced 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 and increased decomposition of organic N may result in high TKN concentrations. The 17-year average total N loading seems to have substantially increased compared to the data from 1990-94. The high N and P loadings were generally associated with high drainage outflows. However some of these data (such as for 2000, 2003) should be cautiously interpreted due to potential errors in outflow estimates caused by weir submergence. The long-term average annual NO_3-N concentrations were higher than those recently published by Chescheir et al. (2003) for the forested lands in eastern North Carolina. But both the average total N and P concentrations were similar. These long-term hydrology and nutrient data and results serve as an important base-line reference for evaluating the impacts of various management treatments on drained forested sites in the coastal region.

Acknowledgements

This study is supported by National Council of Industries for Air & Stream Improvement (NCASI), Inc and Weyerhaeuser Company. The authors would like to acknowledge the contributions of Weyerhaeuser personnel Sandra McCandless, Joe Hughes, Joe Bergman, Cliff Tyson, and Jami Nettles for providing support including field data collection and processing.

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