Effects of Orifice-Weir Outlet on Hydrology and Water Quality of a Drained Forested Watershed

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ABSTRACT: *Orifice-weir structures at ditch outlets are proposed to reduce peak drainage rates during high flows and to store water during the growing season in poorly drained managed pine plantations. Two coastal watersheds, one conventionally drained (D1) and another with an orifice-weir outlet (D3), were monitored to examine the effects of this orifice treatment on drainage outflows and nutrient exports from drained pine plantations in eastern North Carolina. Five years (1995–1999) of measured hydrologic data showed that the daily water table elevation on D3 was 7 cm higher on average, but was 13.5 cm higher during wet periods compared to conventional drainage. The peak drainage rates from D3 were substantially dampened by the orifice-weir. Accordingly, average annual outflow was reduced by 18%. The reduction in outflow was as much as 34% in 1995. Taking the characteristic differences observed in concentrations between these two watersheds during the pretreatment phase into consideration, the measured average annual TKN concentration in the watershed with the orifice appeared to be higher, and total P and sediment lower than expected for conventional drainage. Despite the reduction of flow in all 5 yr, the measured exports of NO_3-N, TKN, and total N increased in the first 3 yr (except for TKN in 1995) and decreased in 1998 and 1999 with no significant effects because of the orifice-weir treatment. However, on an average annual basis, total sediment and total P export from D3 were reduced by 54% and 30%, respectively. These results showed that an orifice-weir at the drainage outlet can be used to reduce peak rates, annual drainage outflows, total P and sediment export. The orifice-weir outlet did not have an effect on the export of nitrogen components as happens when controlled drainage with a raised weir is used. South. J. Appl. For. 27(2):130–142.*

Key Words: *Pinus taeda* L., water management, drainage, peak flow rates, nutrient, sediment.

Forest stands in poorly drained soils of the lower coastal plains in the southeastern United States have been traditionally managed by providing artificial drainage to lower water table depths for improving trafficability and to reduce water logging stresses. There has been a growing concern that both peak drainage rates and pollutants carried with the fresh water outflows from these lands have increased, placing greater stress on the downstream ecosystem. In recent years, controlled drainage with riser structures has been gaining popularity on both poorly drained agricultural (Evans et al. 2000, Drury et al. 1996, Skaggs et al. 1994, Gilliam et al. 1978, Gilliam and Skaggs 1986) and forested lands (Allen et al. 1990, Campbell and Hughes 1980, Hughes 1982). Controlled drainage has the advantage of providing necessary drainage for crop or tree production while conserving water and minimizing nutrient and sediment losses to receiving streams and estuaries.

Controlled drainage is achieved by installing an adjustable control riser structure, usually a wooden flashboard(s) at the watershed outlet. Water level in the outlet is adjusted manually by adding or removing boards. These structures act like a sharp-crested rectangular weir when used as a flow-measuring device. Since these structures cannot accurately measure flow rates during low flow events, outlet structures with a sharp-crested V-notch weir have been widely used in research on controlled drainage (McCarthy et al. 1991, Amatya et al. 1996, 1998, Chescheir et al. 1998, Lebo and Herrmann 1998).

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McCarthy and Skaggs (1992) used a forestry version of DRAINMOD (Skaggs 1978) to evaluate effects of water management systems during a life cycle of a drained loblolly pine (*Pinus taeda* L.) plantation watershed in Carteret County in eastern North Carolina. The authors found that controlled drainage systems were successful in reducing drainage outflow rates and volumes and improving soil water conditions for tree growth. The effect of controlled drainage on the hydrology and storm events of the same pine plantation site during a 4-yr period (1990–1993) was reported by Amatya et al. (1996, 2000). These studies showed that the peak outflow rates from watersheds under controlled drainage were significantly reduced, and the total outflows were reduced to as much as 21% of gross rainfall, compared to 31% for watershed under conventional drainage (CVD). The extra amount of water thus stored in the watershed might have been lost through seepage or through increased evapotranspiration (ET). Amatya et al. (1998) reported that controlled drainage reduced drainage outflows by as much as 88% during the summer period and 39% during the spring period with an annual average reduction of 20 to 25%. Annual average fractions of nitrogen and phosphorus exports from forested watersheds under controlled drainage were reduced by 7 to 72% (depending on control treatment) as compared to the watershed with free drainage. It was concluded that water management using controlled drainage can be used to reduce total sediment and nutrient exports from pine plantations, primarily by reducing drainage outflows.

This study used a form of controlled drainage by having a weir plate with a flat top and an orifice (a circular hole) at the bottom of the plate (Figure 1) as a potential means of reducing peak outflow rates and nutrient export from drained lands. The orifice may be of different sizes and at different locations, and may discharge freely or in submerged condition. An orifice near the bottom of the weir would assure continuous, but reduced, downstream discharge as base flow, until the ditch is empty. During rainfall events, drainage water would be restricted to orifice flow until the ditch water level rises to the top of the weir, as opposed to the large discharge that may occur over a flat crested or V-notch weir. Especially for larger flow events, if the ditch water level due to previous rainfall is near the top of the weir when the storm begins, water would be discharged both from the orifice and over the flashboard weir. The discharge over the weir at high rates would occur for a shorter period because of the storage provided by the initially empty ditch. After rainfall ceases, orifice discharge would continue at a reduced rate for a period of time. This would lower the ditch water level providing storage for the next event. The orifice can be plugged during the growing season to conserve water for tree growth. The weir could be lowered or removed during the harvesting and planting for the regeneration period when the greatest drainage intensity is needed for trafficability. The potential of clogging the orifice and reducing the ditch storage as a result of sediment deposition upstream of the outlet on these forests is very minimal due to substantially lower sediment export compared to agricultural lands (Amatya et al. 1998). Furthermore, drainage ditches are usually cleaned after harvest and prior to planting. Although orifice outlets are frequently used in storm water detention basins, there is little published literature on use of orifices at ditch outlets for forest water management.

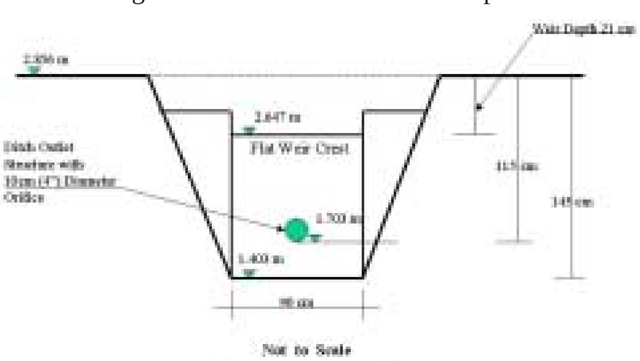

Figure 1. Schematic of a flat weir with an orifice hole installed on the riser structure at the ditch outlet of the watershed.

Amatya and Skaggs (1997) showed that the model DRAINLOB (McCarthy et al. 1992), a version of DRAINMOD for drained forested watersheds can be used to predict the effects of an orifice-weir outlet on forest drainage. However, the actual hydrologic and water quality effects of such an outlet depends on the size and depth of the orifice-weir outlet, which in turn, depend on the forest water management objectives followed by the soil type and drainage area as shown by Amatya et al. (1999). The authors presented a method to design an orifice-weir outlet for drained forests using the model DRAINLOB, modified for such an outlet. The main objectives of this study are to document the actual effects of an orifice-weir outlet on the hydrology and water quality of a drained loblolly pine (*Pinus taeda* L.) plantation. A 5-yr period (1995–1999) of data collected from two experimental watersheds in eastern North Carolina is presented and analyzed.

Site Description and Methodology

The study site (Figure 2) on a drained loblolly pine stand of midrotation age, located in Carteret County, North Carolina, is owned and managed by Weyerhaeuser Company. The site consists of three artificially drained 25 ha experimental

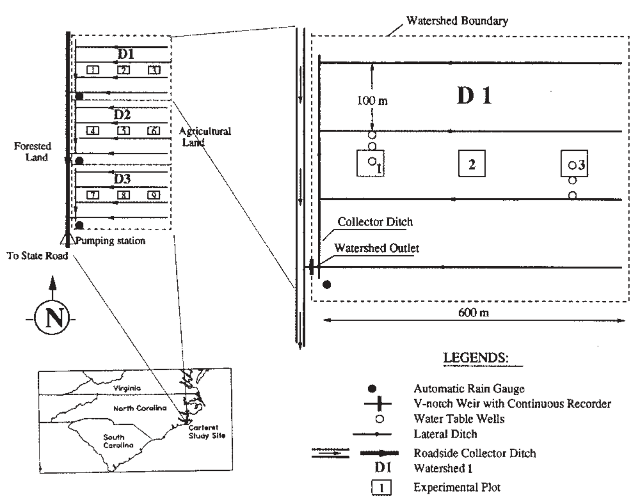

Figure 2. Schematic of the location and layout of the experimental watersheds D1, D2, and D3 at Carteret study site, North Carolina (after Amatya et al. 1998). D1 is the control with conventional drainage and D3 has an orifice-weir.

watersheds (D1, D2, and D3). The site is nearly flat (< 0.1% slope), poorly drained under natural conditions, and has a shallow water table (McCarthy et al. 1991). The hydric soil is a Deloss fine sandy loam (fine-loamy mixed, Thermic Typic Umbraquult). Each watershed is drained by four 1.2 to 1.6 m deep parallel field ditches spaced 100 m apart, and has two experimental plots for hydrological and tree parameter measurements. The ditches in the managed forest were cleaned in early 1987 before the study began. The watersheds have been continuously monitored since early 1988. Commercial thinning of the 14 yr old pine stands on these watersheds was carried out during August–October 1988. Fertilizer additions at the site were done at planting, and ages 7 and 15 yr. Results of pretreatment hydrologic calibration of these watersheds carried out between January 1988 and March 1990 were reported elsewhere (McCarthy et al. 1991, Amatya et al. 1996, 2000). Later, Amatya et al. (1996, 1998, 2000) reported the data on hydrologic and water quality effects of controlled drainage with a raised V-notch weir implemented between 1990 and 1994. Watershed D1 has been kept as a control with conventional free drainage at all times to compare treatment effects on two other watersheds, D2 and D3 (Figure 2). The stand age of the pine forest was 21 to 25 yr during the 5 yr (1995–1999) study period reported here.

In this research, only data from two watersheds (D1 and D3) (Figure 2) were used to study the hydrologic and water quality effects of an orifice-weir structure. An adjustable-height 120^{o} V-notch weir, located in a flashboard riser structure was installed at a depth of about 1.2 m (from the average ground surface) in the outlet ditch of the control watershed D1. This allows "free" conventional drainage and measurement of drainage outflow. A flat weir plate with a 0.1 m (4 in.) diameter orifice hole bored near the bottom (Figure 1) was installed in the riser structure at the outlet of D3. The top of the flat weir was positioned 0.2 m from the average ground surface near the weir. The bottom of the orifice hole was 1.15 m below average ground surface, about the same as the ditch bottom.

Rainfall was measured with a tipping bucket rain gauge in an open area on the western side of each watershed. The rain gauge was connected to an Omnidata datalogger until 1998 when it was replaced by a HOBO datalogger. Continuous breakpoint rainfall data measured by these automatic gauges were processed to obtain daily, monthly, and annual values. Data were verified using backup biweekly data from adjacent manual gauges as needed.

Water level elevations measured by Stevens Type F recorder with Omnidata datapod installed upstream of the outlets were used to calculate the flows over the V-notch weir for D1 as well as the composite orifice and flat weir structure at D3. Water table elevations at the midpoint between the ditches were measured using the Stevens Type F recorders installed in two plots in each of the watersheds. The reader is referred to McCarthy et al. (1991) for a detailed description of the site, measured data and methodology for hydrometeorology, soils, and vegetation.

Two methods of water sampling, composite and grab sampling, have been used since late 1989. Intakes of automatic water samplers (ISCO-2700) were installed 30 cm upstream of the weir outlets for collecting samples at 6 hr intervals during flow events. During an event, 250 ml of water was collected every 2 hr and composited to one 1000 ml bottle from four samples at 8 hr intervals, making three sample bottles per day. Until 1997, unpreserved labeled samples were collected weekly and then transported to the Weyerhaeuser laboratory at New Bern, NC, for analysis. Effective in 1997, all samples were taken to the soil chemistry laboratory in 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, NH_4, total Kjeldahl nitrogen (TKN), total phosphorus (TP), and total suspended solids (TSS). Laboratory analyses of TKN, NH_4, NO_3+NO_2 and TP were colorimetric and done according to USEPA (1979). TOC was analyzed according to ASTM (1988). Procedures of APHA (1989) were followed for analysis of TSS (total sediment). Due to only a small fraction of nitrite (NO_2) content in NO_3+NO_2-N, nitrate or NO_3-N will be used in the rest of the text.

Data monitoring for these treatments, installed on January 17, 1995 was continued through the end of 1999. However, data collection was still continued when the orifice-weir treatment in D3 was discontinued in January 2000, and the conventional free drainage was reinstalled as in the control watershed D1 to verify whether the behavior of these watersheds observed during the 1988–1990 calibration period still persisted. Flow rates were calculated using the standard V-notch weir equations with the measured upstream stage elevations for D1 and the orifice equation for D3. When the water level was above the crest of the V-notch, an equation for a truncated weir was used for D1. Similarly, when the water level was above the crest of the flat weir, flow rates from the orifice were composited with the rates flowing above the flat weir to obtain the total flow rates for D3. Instantaneous flow rates were integrated to obtain daily flow volumes. Concentrations of nutrients and sediment composited for a biweekly period were multiplied by the water volume for the period to obtain the nutrient export for that period. Sum of the exports of all periods during the year was the annual load.

In order to accurately assess the effects of the orifice-weir outlet on the hydrology during the treatment period, the characteristic differences observed in the water table elevations, outflows and concentrations between the watersheds during the calibration or pretreatment period (1988–1990) were taken into account (Amatya et al. 1998, 2000). That difference for the daily water table elevations was accounted for by using the 1988–1990 pretreatment relationship ($WTE3 = -0.17 + 1.07 WTE1$) with measured data from D1 (WTE1) to predict expected values for D3 (WTE3) in the 1995–1999 study period. Similarly, the expected daily flows from treatment watershed D3 for the study period were predicted by multiplying the measured values from D1 by a slope (= 0.91) with zero intercept of the regression of daily outflow of D3 and D1 for the pre-treatment data. The measured water table elevations and outflow from D3 were then compared with the expected water table elevation and outflow, respectively, from watershed D3 had it been under CVD. Similarly, the average ratios (D1/D3) from pretreatment characteristic differences observed in NO_3-N (3.4), TKN (1.4), and sediment concentrations (0.31) were used with flow data to estimate the expected annual exports from watershed D3 using observed data from D1 for the study period as shown by Amatya et al. (1998). Procedures available in MS EXCEL were used for statistical analyses including the paired t-tests for significance for data that were normal or near-normal. The Shapiro-Wilk statistic (SAS 1994) computed by SAS software version 8.1 was used to test the normality of the data used for *t*-test.

The effects of orifice-weir treatment on hydrology were evaluated using both graphical and statistical comparisons of measured and expected (a) daily water table elevations, (b) annual drainage outflows, (c) daily hydrographs, and (c) daily flow frequency duration data for watershed D3. For water quality parameters, mean monthly and annual expected and measured concentrations, and annual expected and measured exports were used to compare the effects.

Results and Discussion

Rainfall

Data analysis revealed that rainfall amounts from gauges in both watersheds (D1 and D3) were missing for intermittent periods until 1998 and for several periods in the year 1999, because of problems with the dataloggers and/or tipping buckets that had been in operation for more than 14 yr. These periods included Hurricanes Fran and Josephine in 1996, and Floyd and Irene in 1999. Missing and/or bad rainfall data were supplemented by data from adjacent watersheds. When all gauges were inoperable, data from Cozier Tract site, located 6.5 km to the north, were used until 1996, after which data from the gauge at the new weather station on watershed D2 were used (Figure 2).

Annual rainfall data measured on these two watersheds are presented in Table 1. Except for D3 in 1995 and D1 in 1999, annual rainfall on both the watersheds was consistently higher for the study period than the 40 yr long-term average at nearby Morehead City. The wettest year was 1996 when two hurricanes and a tropical storm contributed to an annual total of 1650 mm of rain. This was at least 20% more than the long-term average (Table 1). Near average rainfalls were recorded on the site in 1995, 1997, and 1999. Measured daily rainfall (average of gauges at D1 and D3) is plotted for the 5 yr study period, along with the water table elevations in Figure 3. Because of a large event (about 75 mm rain in 2 days) in early February and hurricane Bonnie in August (Day 240), rainfall in 1998 was at least 16% higher than normal. Although there were hurricanes and tropical storms in late summer of 1999, the winter and spring were relatively dry, so annual rainfall was only 2–3% higher than the long-term average. Monthly rainfall (not shown) was highly variable which is typical for this location. Measured rainfall in 32 out of 60 months was near or above normal rainfall. The annual rainfall on D3 was about 3% lower than that measured on D1, which was consistent with earlier data (Amatya et al. 1996, 2000).

Water Table Elevations

Despite frequent servicing, water table data either from one or both of the wells in D1 and D3 were intermittently lost in the later part of the study period (1997–1999). Water table data were available for both watersheds on 1,696 days out of 1,826 days of the 5 yr study period. In some cases only one of the two recording wells in each watershed was functioning. Amatya and Skaggs (2001) reported the difference of as much as 0.20 m in water table elevations measured at two midpoint wells of the same watershed for large events.

Response of measured water table elevations due to various rainfall events during each year of the 5 yr study period for D3 with orifice-weir is compared in Figure 3 with the expected values under CVD, based on D1 data. The elevations represent the average of two wells at the midpoint between the ditches. Both the expected and measured water tables had shallower depths during wet periods of winter and summer tropical storms, and deeper elevations during dry summer-fall periods. The water table rose near the surface (average elevation of 2.8 m) during Hurricane Fran in September (Day 249) of 1996 and Hurricane Bonnie in August (Day 239) of 1998. In both cases, the 24 hr rainfall was above

Table 1. Annual rainfall and outflow measured on control watershed (D1) and watershed (D3) with orifice-weir treatment. 40 yr average annual rainfall measured at Morehead City is 1,370 mm.

	Rainfall		Outflow		Expected*	(Rainfall–outflow)		(Outflow/rainfall) × 100	
Year	D1	D3	D1	D3	D3 outflow	D1	D3	D1	D3
	(mm)							(%)	
1988†	1,406	1,371	209	240	240	1,197	1,131	15	21
1989†	1,876	1,768	658	553	553	1,218	1,215	35	31
1995††	1,404	1,329	458	275	417	946	1,054	33	21
1996††	1,706	1,653	704	556	641	1,002	1,097	41	34
1997††	1,408	1,382	397	354	361	1,011	1,028	28	26
1998††	1,655	1,548	770	528	701	885	1,020	47	34
1999††	1,362	1,380	614	482	559	748	898	45	35
2000†	1,718	1,777	857	858	858	861	919	50	48
Average	1,507	1,458	589	439	536	918	1,019	39	30

* Expected outflow for conventional drainage is based on the calibration relationship developed using 1988–1990 data.
† 1988, 1989, and 2000 are the years when both the control watershed D1 and treatment watershed D3 are under the same conventional free drainage.
†† 1995–1999 is the study treatment period when D1 is under free drainage and D3 is under orifice-weir control.

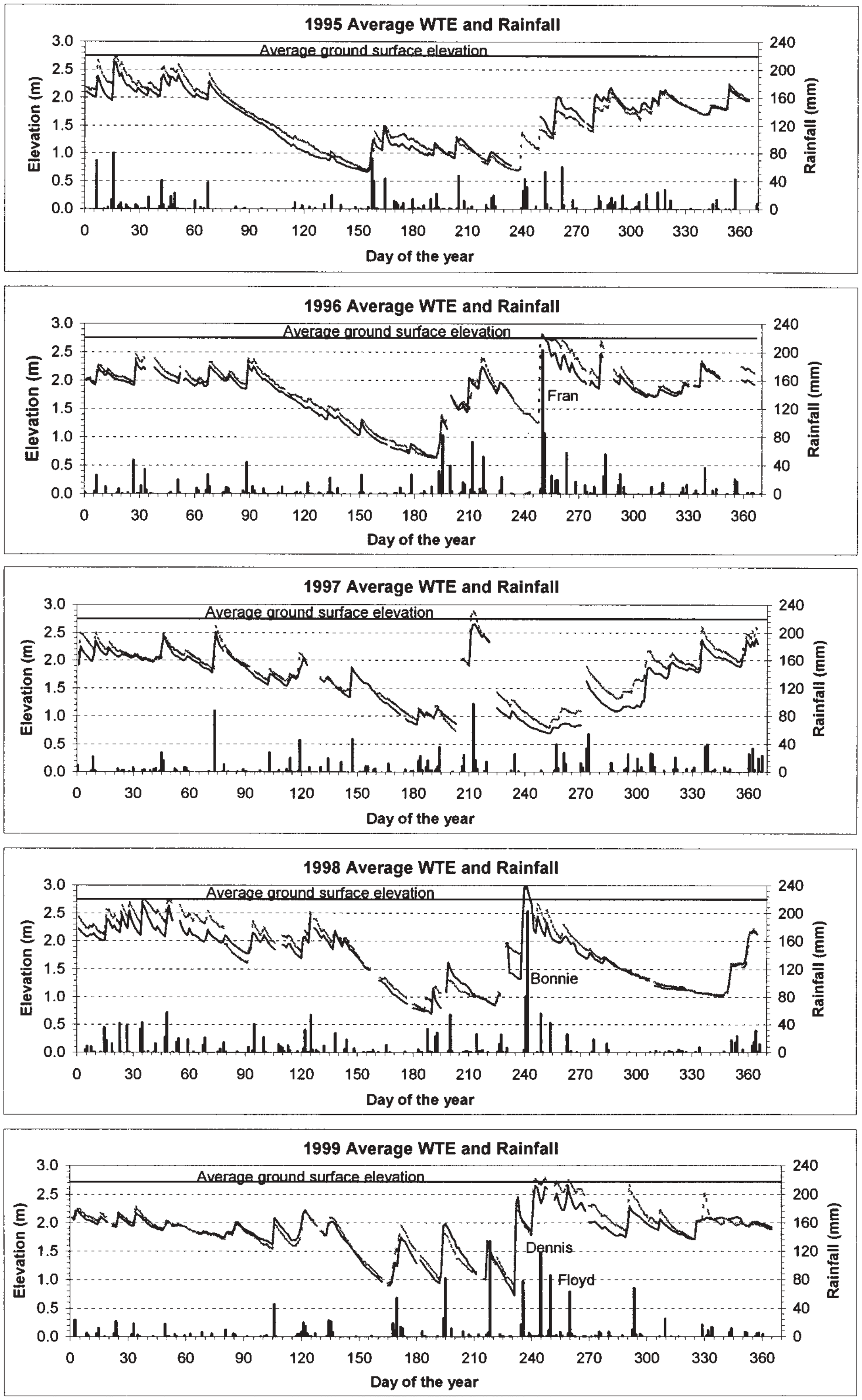

Figure 3. Measured (dotted line) and expected (solid line) daily average water table elevations for watershed D3 with an orifice-weir treatment. Daily rainfall is also shown on secondary axis with solid bars.

200 mm (Figure 3). As much as 118 mm of rainfall occurred in one day during Hurricane Dennis on Day 242 followed by another 70 mm during the return of Dennis about a week later in 1999. As a result, water table depths rose nearly to the surface. The water table rose to the surface again as a result of Hurricane Irene (Day 290). Because of reduced rainfall and increased ET during early summer (days 150–210) water table elevations dropped below 1.0 m (1.8 m depth) or deeper in all years.

For the period when water table elevations were higher than 2.0 m, the average water table elevation in D3 was higher by 13 cm compared to that for conventional drainage. This difference was significant at $\alpha = 0.01$. This increase in water table elevation on D3 occurred during the winter and during summer–fall hurricane and tropical storm events. However, the duration was only for a short period during the summer–fall events due to high ET demands. Although the increase during the winter lasted longer, the increase in water table elevation was small and there was little danger of detrimental effects for tree growth due to excessively wet conditions. The orifice-weir reduced drainage rates during the wettest periods causing the measured water table to remain higher for longer periods. When water table elevations were less than 1.5 m (depths greater than 1.3 m), the measured water table was still higher by 2 cm than expected, based on D1, but the difference was not significant. Recall that the bottom of the orifice is at a depth of 1.15 m, so drainage would cease for water table depths greater than that. This is near the bottom of the ditch so D1 would also cease drainage for water tables a few centimeters deeper, but the observed difference is in the expected direction. However, when the entire study period was considered, the increase in measured water table elevation of seven centimeters on D3 was statistically significant at $\alpha = 0.05$. This was also true for water elevations between 2 and 1.5 m on these watersheds.

Drainage Outflows

Daily flow rates in Figure 4 appeared to be consistent with daily rainfall shown in Figure 3. Daily flow pattern showed seasonality with negligible flow in June and July (days 151–212) and high winter flow events (Day 1-90) in all 5 yr. The lowest flow rates in winter and spring occurred in 1999 because of very dry antecedent conditions, as there was no flow since the fall of 1998. Most of the flow in 1999 resulted from hurricanes starting about day 240. The orifice-weir had a relatively large effect on peak flows during those events (Figure 4). Based on measured flows from D1, expected peak rates from D3 under CVD were near 30 mm/day for the events of Hurricane Dennis (Day 242 and Day 248-249) followed by Hurricane Floyd on Day 260 in 1999. Even larger flow rates would have occurred during late August and September (Day 240–270) of 1996 and 1998. No such events occurred in 1995 and 1997.

The orifice-weir on D3 substantially dampened measured peak flow rates for the daily rates between 5 and 30 mm/day when compared with expected data (Figure 4). The difference was smaller for the flow rates below 5 mm/day as well as for rates higher than 30 mm/day. For small flow rates, the orifice is not limiting flow, and drainage rates for both the measured and expected peak flow rates should be about the same. Similarly, for the high ditch water levels during big events, flow in D3 also occurs across the flat weir above the orifice resulting in large flow rates. Such a composite flow rate (flow from the orifice plus over the weir) may be comparable to that from the conventionally drained watershed with only a V-weir. Examples of the effects of orifice on dampening the peak flow rates during large events are shown in Figure 5 for events of days 27 and 34 in 1996. The expected flow rate from D3 and measured flow rate at D1 on Day 34 were more than three times higher than that measured for D3 with the orifice-weir. The duration of the event hydrograph in D3 with orifice-weir was prolonged compared to D1 and expected flows from D3 had it been under conventional drainage. This is because uniform release of water from the orifice slowly emptied the ditch in contrast to much more rapid discharge from the V-weir. This pattern was observed for other events as well (not shown). The reduction in peak flow rates using the orifice-weir treatment is further demonstrated by the daily flow–duration data in Figure 6. The flow rates below 3 mm/day that occurred 85% of the time were similar for both measured and expected conditions in D3 and also for D1. Daily flows higher than 15 mm/day occurred only about 0.3% of the time for the measured data from D3 with the orifice-weir, as compared to about 1% of the time for CVD based on data from D1. This clearly indicates that the orifice-weir treatment reduced the peak flow rates, and hence has a potential to reduce exports of nutrient and sediment as well.

Measured data in D3 showed consistent reduction in annual outflows by as much as about 34% in 1995 with an average annual reduction of about 18% compared to the expected (Table 1). This amount would be equivalent of 97 mm of water for an average annual expected outflow of 536 mm for the 5 yr period. This additional water stored in treatment watershed D3 was assumed to be lost to ET and/or seepage. This is consistent with the earlier study conducted by Amatya et al. (1996) on these watersheds with controlled drainage treatments. The difference in annual outflow between the measured and expected was statistically significant at $\alpha = 0.05$.

Water Quality Parameters

NO_3-N

Monthly average measured concentrations for D3 are plotted in Figure 7 along with values expected for CVD based on measurements for D1. Monthly drainage outflows are plotted at the top. Water quality data were not available for the months with zero or very low flows. Concentrations generally tended to follow the trend of the measured monthly outflows with higher values in winter, consistent with results from an earlier study (Amatya et al. 1998). Exceptions occurred for summer tropical storm events in 1996 and 1999. The highest NO_3-N concentrations expected for conventional drainage were observed in August 1998 (Hurricane Bonnie), and February and August 1999. They represented the effect of first flush phenomenon following relatively dry periods prior to these events. However, the largest single observation of 4.1 mg l^{-1} occurred in February 1999. The reasons for high values during this month are not well understood. The measured water table elevation in D3 with orifice-weir treatment was elevated compared to CVD for the large events (Figure 3). This might enhance denitrification causing lower measured NO_3-N concentrations in D3 for those events, which were much lower than the expected for CVD based on D1, except for August 1999 (Hurricane Dennis). Measured concentrations were close to the expected for this month with about 200 mm outflow for both scenarios. On an average monthly basis, the difference in NO_3-N concentrations between the measured and expected data was small, indicating no effects of orifice-weir treatment. Al-

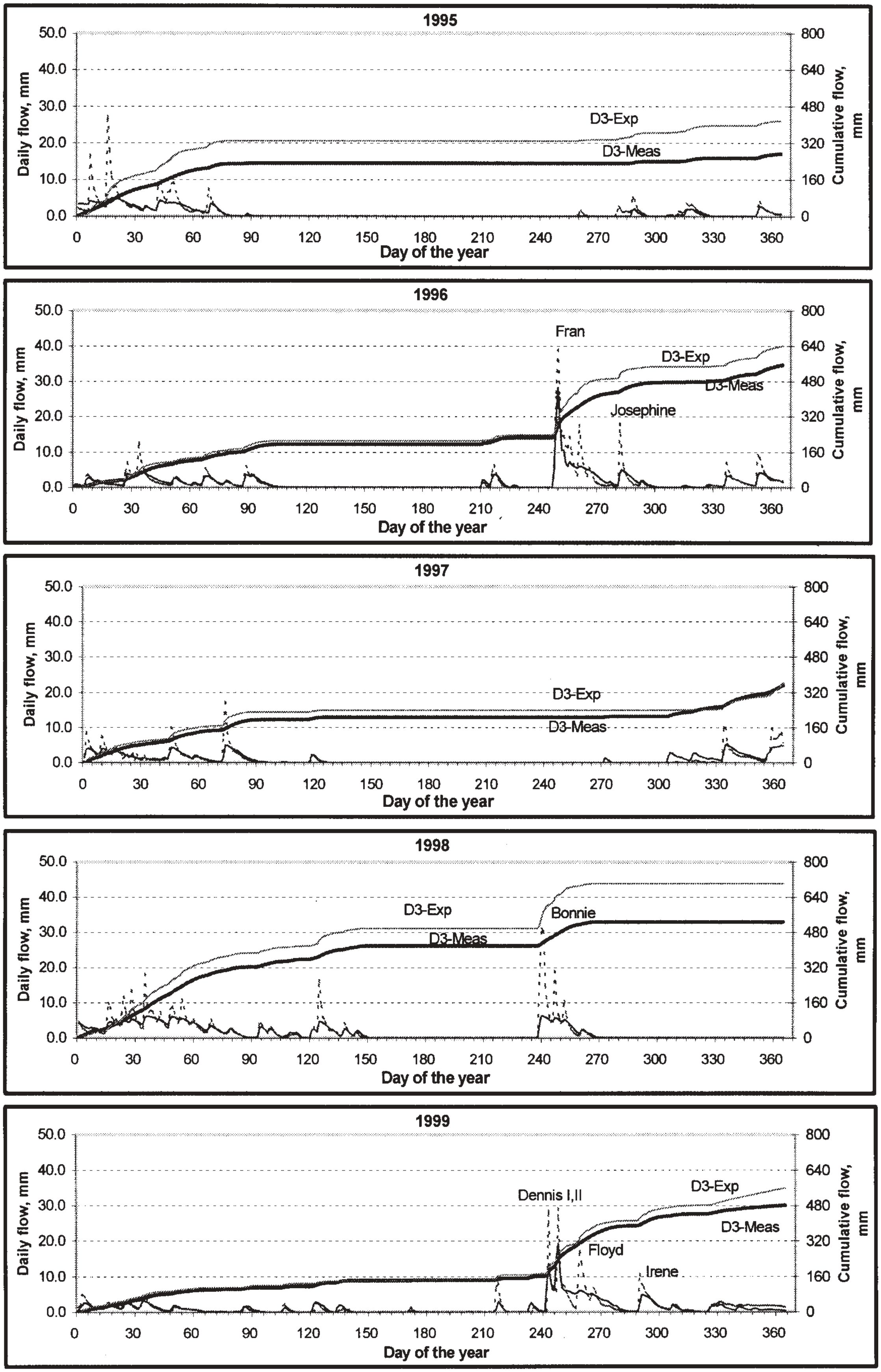

Figure 4. Measured (thick solid) and expected (thin dotted) daily flows and measured (thick solid) and expected (thin solid) daily cumulative outflows measured at watershed D3 with an orifice-weir treatment at Carteret site.

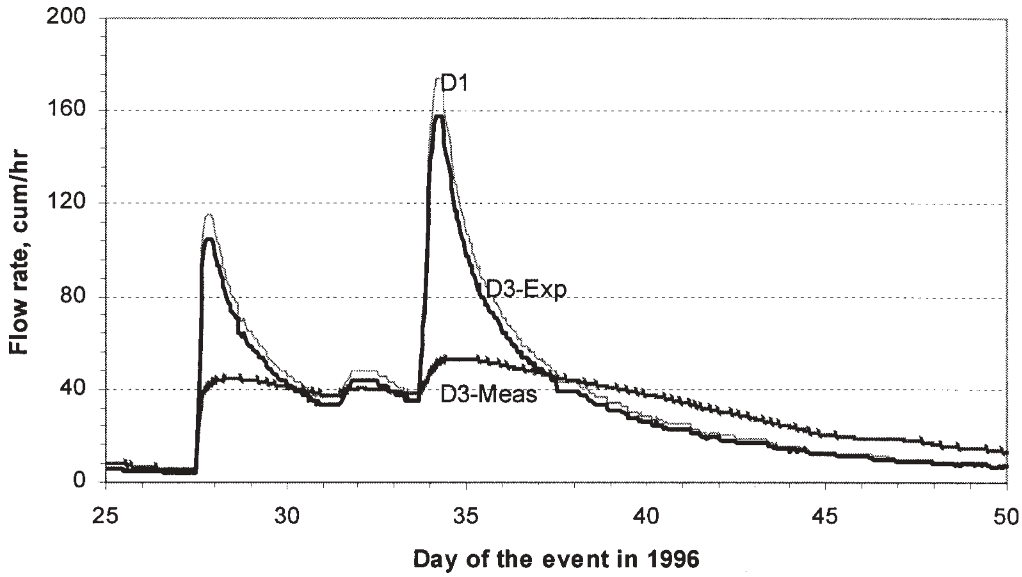

Figure 5. Comparison of hourly event hydrographs for expected (dark solid) and measured (light solid) with flow data from the watershed with orifice-weir treatment (D3) for the event of Day 27, 1996 at Carteret site. Data from watershed D1 (thin line) under conventional drainage is also presented.

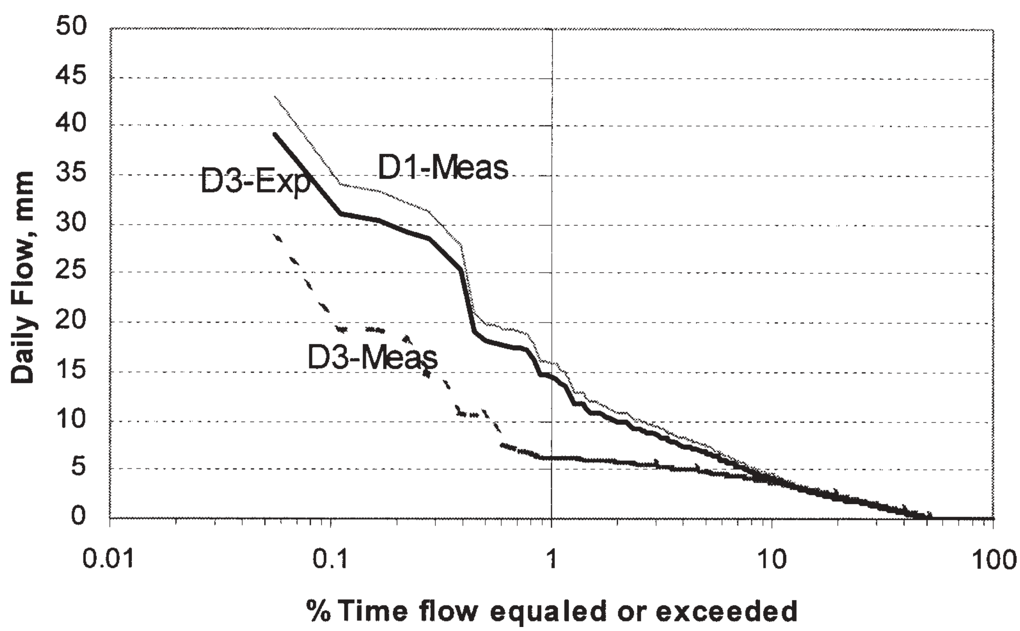

Figure 6. Comparison of daily flow duration for expected (thick solid) and measured (thick broken solid) flow data from the watershed with the orifice-weir treatment (D3) at Carteret site. Data from watershed D1 (thin solid) under conventional drainage is also shown.

though the measured average annual concentration of 0.51 mg l^{-1} in D1 was found to be significantly different ($\alpha = 0.01$) from 0.14 mg l^{-1} in D3 (Table 2), there was no difference between measured data for D3 and that expected for D3 under conventional drainage. This indicates that the difference between D1 and D3 was clearly a reflection of the characteristic differences between the two watersheds found during the 1988–1990 pretreatment period (Amatya et al. 1998). As much as three to four times higher NO_3-N concentrations for D1 compared to D3 were reported by Amatya et al. (1998) for that pretreatment period. This was found to be true for year 2000 also with the same pretreatment scenario, as shown by the measured annual average NO_3-N concentrations of 0.39 mg l^{-1} and 0.11 mg l^{-1} for D1 and D3, respectively (Table 2). This indicates that the characteristic differences between the watersheds still persist.

Data in Figure 7 shows that the majority of nitrate export from both watersheds occurred during the high flow events of the winter (January–March) and the hurricanes or tropical storms in the summer-fall periods

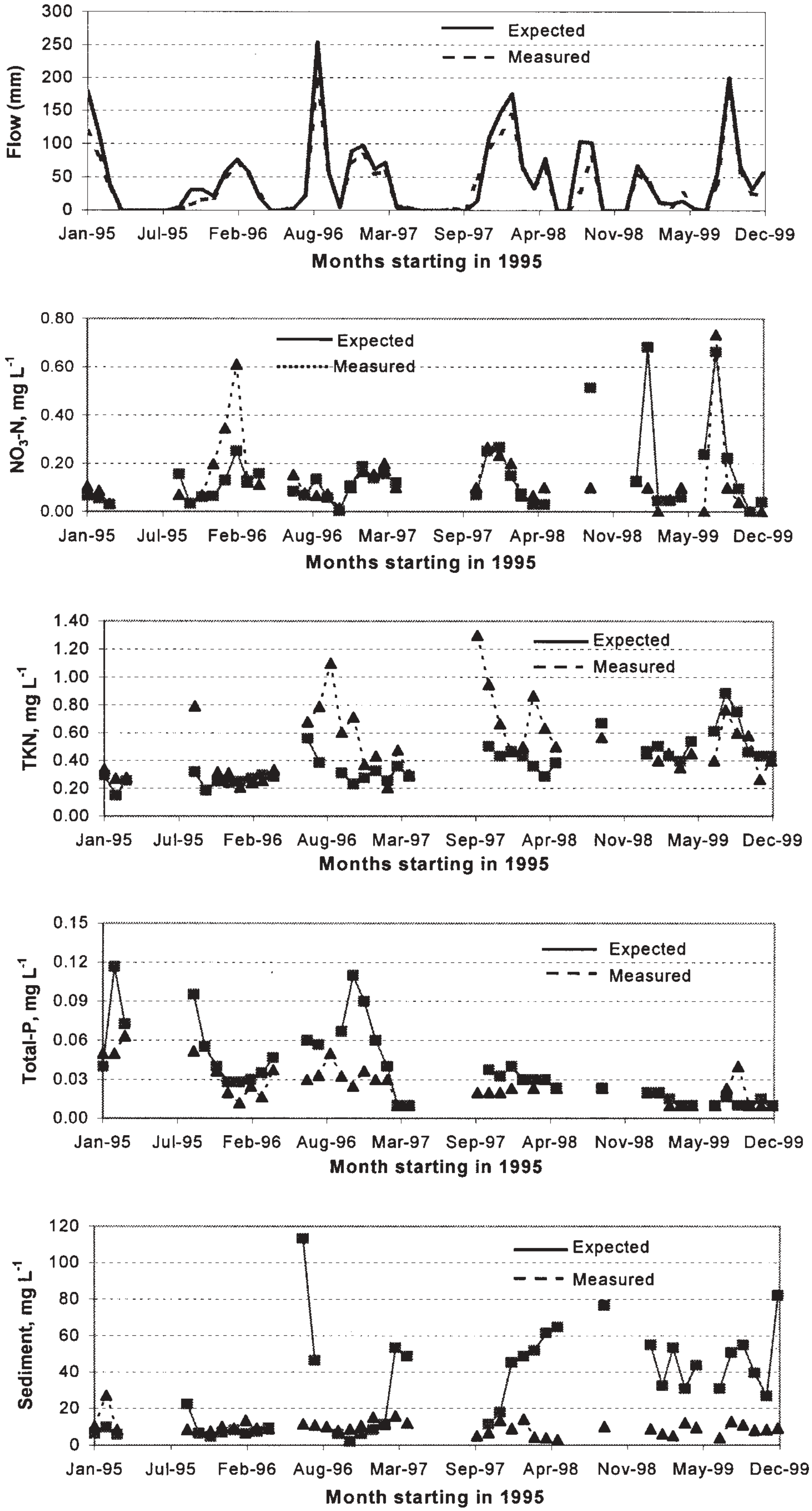

Figure 7. Expected (solid line) and measured (broken line) monthly flows for the 1995–1999 period are shown for watershed D3 with orifice at the top panel. Other four panels are for expected (solid line with square) and measured (dotted line with triangle) monthly mean concentrations of NO_3-N, TKN, Total P, and Total Sediment, respectively, for D3.

Table 2. Measured and expected annual average nutrient and sediment concentrations (mg l^{-1}) measured at the outlet of watershed (D3) with orifice-weir treatment.

	NO_3-N*			TKN†			Total N*			Total P†			Sediment†		
Year	D1	EX	MS	D1	EX	MS	D1	EX	MS	D1	EX	MS	D1	EX	MS
1995	0.23	0.07	0.09	0.34	0.24	0.39	0.57	0.31	0.48	0.06	0.06	0.05	2.8	9.0	12.2
1996	0.43	0.13	0.19	0.44	0.32	0.48	0.87	0.44	0.68	0.05	0.05	0.03	6.1	19.8	9.9
1997	0.55	0.16	0.17	0.54	0.39	0.65	1.09	0.55	0.82	0.03	0.03	0.02	7.3	23.6	11.6
1998	0.70	0.21	0.11	0.64	0.46	0.60	1.34	0.67	0.71	0.03	0.03	0.03	18.9	60.8	6.3
1999	0.62	0.18	0.12	0.74	0.53	0.48	1.36	0.71	0.60	0.01	0.01	0.02	14.1	45.5	8.9
2000	0.39	—	0.11	1.02	—	0.52	1.41	—	0.63	0.02	—	0.02	18.8	—	10.3
Average††	0.51	0.15	0.14	0.54	0.39	0.52	1.05	0.54	0.66	0.04	0.04	0.03	9.8	28.3	9.8

NOTES: D1 = Measured concentration for control watershed under conventional drainage (CVD); EX = Expected concentration for watershed (D3) under conventional drainage taking differences from pretreatment period into account; MS = Measured concentration for watershed (D3) with orifice-weir.

* Statistically not different at $\alpha = 0.10$.

† Statistically different at $\alpha = 0.10$ between expected and measured concentrations for watershed (D3) with orifice-weir.

†† Average is only for the 5 yr (1995–1999) period. Data for 2000 is also shown when both watersheds D1 and D3 were under conventional drainage.

(July–September). Measured nitrate export shown in Table 3 indicates an increasing trend over time for the watershed D1 with 1.05 kg ha^{-1} in 1995 increasing to 5.1 kg ha^{-1} in 1999, with an average of 3.12 kg ha^{-1}. This is possibly due to the slightly increasing trend in the concentration (Table 2 and Figure 7), the reason for which is not clear. When D1 data were used with pretreatment ratios to predict expected values for D3 under CVD, measured annual average NO_3-N concentrations in D3 were found to be higher than expected for all years, except in 1998 and 1999 (Table 2). As a result, despite reduced annual outflow ($\alpha = 0.05$) in all years, compared to expected outflow in D3 (Figure 4), the orifice-weir treatment in D3 seemed to increase the export from 1995 to 1997 and then sharply decreased in the following years (Table 3). The average annual decrease was only 4%. Obviously, the large reductions in 1998 and 1999 were attributed to decrease in both the measured concentrations and outflows. However, the reason for the increase in concentration in the first 3 yr followed by the decrease in the last 2 yr compared to the expected values (Table 2) was not known. The slight (4%) average annual decrease of NO_3-N export compared to the expected data was not significantly different at $\alpha = 0.10$ (Table 3). These results support the conclusion that, although the orifice-weir on D3 reduced peak drainage rates and annual outflow, it did not significantly affect nitrate export.

TKN

Measured monthly mean TKN concentrations tended to follow the flow pattern (Figure 7). But unlike NO_3-N, the values did not decrease to near zero, but instead remained higher than about 0.2 mg l^{-1} for the study period. Results in Figure 7 indicate that the monthly mean values in watershed (D3) with orifice-weir treatment were generally similar to the expected data, except for some large flow events. There was less variability in TKN than in NO_3-N during the year. The highest monthly average values of more than 0.75 mg l^{-1} (Figure 7) were observed immediately after the large outflow events in September 1996 (Hurricane Fran), September 1997, February 1998, and August–September 1999 (Dennis and Floyd). This was not the case with the expected results for CVD, indicating an overall increase in TKN concentrations due to orifice-weir treatment. Some of this occurred due to increase in NH_4-N concentrations following a prolonged period without outflow, a phenomenon probably caused by the decomposition of organic matter. NH_4-N contributed as much as 50% of measured TKN for some events in 1996 (not shown). That year had the highest NH_4-N concentration of 0.52 mg l^{-1}. In most other instances, organic N (TKN – NH_4-N) made up most of the observed increase, as NH_4-N values were much lower (average annual value = 0.05 mg l^{-1}) than TKN. This is consistent with results of a previous study (Amatya et al. 1998). The average annual measured TKN concentrations

Table 3. Measured and expected annual export (kg/ha) of the nutrients and sediment for watershed (D3) with orifice-weir treatment.

	NO_3-N*			TKN*			Total N*			Total P†			Sediment†		
Year	D1	EX	MS	D1	EX	MS	D1	EX	MS	D1	EX	MS	D1	EX	MS
1995	1.05	0.28	0.31	1.51	1.02	0.92	2.56	1.30	1.23	0.23	0.27	0.12	10.5	37.5	37.4
1996	2.30	0.81	0.97	2.98	2.03	2.31	5.28	2.84	3.28	0.36	0.30	0.13	28.0	126.9	57.0
1997	2.97	0.59	0.75	2.10	1.40	2.06	5.07	1.99	2.81	0.14	0.11	0.08	24.8	85.3	48.5
1998	4.18	1.45	0.82	5.48	3.22	2.80	9.66	4.67	3.62	0.22	0.21	0.14	129.9	426.2	48.9
1999	5.10	1.02	0.68	5.18	2.96	2.73	10.28	3.98	3.41	0.08	0.08	0.10	90.8	254.1	48.4
Average	3.12	0.83	0.71	3.45	2.13	2.16	6.57	2.96	2.87	0.21	0.19	0.11	56.8	186.0	48.0

NOTES: D1 = Measured annual export for control watershed under conventional drainage; EX = Expected annual export for watershed (D3) under conventional drainage taking differences from pretreatment period into account; MS = Measured annual export for watershed (D3) with orifice-weir.

* Statistically not different at $\alpha = 0.10$.

† Statistically different at $\alpha = 0.10$ between expected and measured exports for watershed (D3) with orifice-weir.

for D1 and D3 were 0.54 and 0.52 mg l^{-1}, respectively (Table 2). The measured average annual concentration of 0.52 mg l^{-1} (Table 2) was about 33% higher than the value of 0.39 mg l^{-1} expected for D3 under conventional drainage. This difference was significant ($\alpha = 0.05$), indicating that the orifice-weir treatment does increase the TKN concentration. The fact that the ratio of measured concentration of D1 and D3 for the year 2000 (Table 2) with pretreatment scenario was similar to data from the 1988–1990 calibration period further supports this conclusion. The treatment on watershed D3 does reduce and dampen the peak flow rates by slowly releasing the water stored in the ditches compared to CVD on D1. The increased retention time of water in the ditch and the increased duration of flow rates (Figures 4 and 6) may have resulted in increased release of organic N, which would have contributed to increased TKN concentrations in D3.

As with the NO_3-N, the majority of the measured annual TKN export from both the watersheds occurred in the winter and summer-fall tropical storms, which gave rise to higher drainage outflows. Unlike NO_3-N, the measured TKN export from D3 did not show any definite increasing or decreasing trend (Table 3). The expected annual TKN export from D3 under CVD, based on D1 data corrected with the pre-treatment relationship is also shown. The slight increased export of 2.16 kg ha^{-1} compared to an expected value of 2.13 kg ha^{-1} was not statistically significant (Table 3). This indicates that despite the significant increase in concentration, the orifice-weir treatment had no effect on TKN export.

Total N

Total N was computed as the sum of the concentrations of NO_3-N and TKN for all periods in both watersheds. Data in Table 2 showed that the average annual concentration of TKN portion of the total N was slightly larger than NO_3-N for D1 but more than three times larger for D3 with the orifice-weir. However, the TKN portion of total N expected for D3 under CVD was about 2.5 times larger than the NO_3-N. On average, the annual total N concentration of 0.66 mg l^{-1} was not different from expected data of 0.54 mg l^{-1}. Total annual N exports from the orifice-weir treatment (D3) ranged from 1.23 kg ha^{-1} in 1995 to 3.63 kg ha^{-1} in 1998. The percentage of TKN in total N exported from D3 with an orifice-weir outlet was very high, varying from 70 to 80% with an annual average of 75%. This was mainly due to elevated TKN in D3 compared to that expected based on D1 (Table 2). Data in Table 3 show that measured total N export from D3 increased compared to the expected data without the treatment in only 2 out of 5 yr with an average annual increase of only 4%. This increase was not statistically significant ($\alpha = 0.10$) indicating that the total N export is not affected by this orifice-weir treatment.

Total P

Except for one instance in February 1995, when the P concentration was 0.29 mg l^{-1}, measured maximum daily concentrations were below 0.11 mg l^{-1} (not shown). Measured monthly average concentrations of total P for D3 were lower than expected for CVD based on results for D1, for most of the events, except for September 1999 (Figure 7). The expected data for D3 without orifice-weir control were as high as 0.12 mg l^{-1} for an event in 1995 compared to 0.06 mg l^{-1} or less for measured values during the study period. Accordingly, average annual total P concentration for D3 was 0.03 mg l^{-1} compared to 0.04 mg l^{-1} expected for D3 under CVD (Table 3). But these values were statistically significant ($\alpha = 0.05$) indicating that the treatment with an orifice-weir reduced P concentration on D3. Average concentration for year 2000 (Table 2) was the same for both D1 and D3 supporting the earlier pretreatment observation (Amatya et al. 1998).

Like all other nutrients considered, total P export rates for both watersheds were greatest during the winter and during high flow events in the summer-fall. But even then annual exports from the freely draining watershed D1 were not higher than 0.36 kg ha^{-1} (Table 3). Measured annual exports from treatment watershed (D3) were lower than expected for CVD for all years except 1999. The orifice-weir treatment reduced total P export by 0.08 kg ha^{-1} yr^{-1} on average (Table 3), which was statistically significant ($\alpha = 0.10$).

Total Sediment

Total sediment concentrations expected for D3 under CVD tended to follow the monthly flow pattern. However, this trend did not quite hold for the measured data with the orifice-weir (Figure 7). Measured mean monthly concentration for D1 was the same as that for D3 (9.8 mg l^{-1}), but D1 had a higher variability (standard deviation = 8 mg l^{-1}) than D3 (standard deviation = 4 mg l^{-1}). The highest monthly value of 35 mg l^{-1} observed in D1 in September 1996, projected to an expected value of 118 mg l^{-1} from D3 if that watershed had been under CVD. Measured annual average concentrations from D3 were lower than the values expected for CVD on that watershed for all years except 1995. On average, the expected annual total sediment concentration of 28.3 mg l^{-1} from D3 under CVD was much higher than the measured value of 9.8 mg l^{-1} with the orifice-weir treatment. However, there was little difference between the measured mean annual concentrations of watersheds D1 and D3, indicating that either the concentrations from D3 have decreased or those from D1 have increased since the pre-treatment period. Field observations show that the soil erosion on the ditch bank near the outlet of D3, one of the reasons suspected for high sediment losses in a previous study, seems to have stabilized. This is indicated by the decreasing ratio of measured annual average concentrations between D3 and D1 from 1995 to 1999. The concentrations of D1 tend to show an increasing pattern. This trend continued through the year 2000 when both watersheds were under the same CVD treatment, yielding a somewhat higher average total sediment concentration of 18.8 mg l^{-1} for D1 compared to 10.3 mg l^{-1} for D3 (Table 2).

Despite somewhat higher annual outflows (Table 1), the export of sediment from D1 was lower than that from D3 from 1995 to 1997 (Table 3), mainly because of lower concentrations in D1 compared to D3. However, as the concentrations in D3 continued to decrease, the annual export from D1 overtook that from D3 in 1998 and 1999. This was also because of increased concentrations observed in D1 during these years (Table 2). Accordingly, the expected annual exports for D3 under CVD varied from as much as 426 kg ha^{-1} in 1998 to 37 kg ha^{-1} in 1995. The average annual measured export of 48 kg ha^{-1} yr^{-1} was significantly lower ($\alpha = 0.10$) than the expected export of 186 kg ha^{-1} yr^{-1}. The reduction on an average annual basis was 54% (Table 4). However, sediment export in both cases (D1 and D3) was low.

Summary and Conclusions

Two watersheds [one conventionally drained (D1) and another (D3) with an orifice-weir outlet treatment] were monitored for 5 yr (1995–1999) to examine the effects of this treatment on drainage outflows and nutrient export from drained pine plantation in eastern North Carolina. Pretreatment (1988-90) calibration relationships between these two watersheds were used to predict expected results for the treatment watershed D3 had it been in conventional drainage as was D1. The 0.1 m diameter orifice, installed on a weir plate, was located near the ditch bottom to provide a uniform discharge while the weir plate holds water behind it. For the wet periods with water table depths shallower than 0.8 m, average water table elevation was increased by about 13 cm on the treatment watershed. The increase on an average annual basis was 7 cm. However, this increase in water table elevation was not sufficient to cause anaerobic conditions in the root zone, which would detrimentally affect tree growth. The orifice-weir decreased peak flow rates for most large events and increased their duration. Compared to results expected for conventional drainage on the same watershed, annual outflow was reduced by 18% on average annual basis.

The orifice-weir increased average annual concentration of TKN and decreased total P and sediment concentrations compared to expected results for conventional drainage. However, the orifice-weir treatment did not have a significant effect on average annual concentrations of NO3-N and total N. Accordingly, despite the reduction in annual outflows, the measured exports of NO_3-N, TKN and total N increased in the first three years (except for TKN in 1995) and decreased in 1998 and 1999 with no significant overall effects of the orifice-weir treatment. Measured total P exports from the treatment watershed were reduced in 4 out of 5 yr, and total sediment in all 5 yr. On average annual basis, total sediment and total P exported from the watershed with orifice were reduced by 54% and 30%, respectively. However, results for sediment should be cautiously interpreted because sediment concentrations from D3 in year 2000 were lower, compared to D1, than during the earlier pretreatment period.

The results showed that water management with an orifice-weir outlet can be used on drained pine plantations to substantially dampen peak drainage rates. The treatment also reduced annual outflow, total P, and sediment export. However, the results did not show that the orifice-weir had an effect on export of total nitrogen and its components as was found for the controlled drainage treatment in an earlier study. Analysis of data from 2000 with conventional drainage on both watersheds indicated that the differences in nutrient characteristics observed during the pretreatment phase (1989–1990) still persist on these watersheds with no change in processes affecting N concentrations from those observed during the pretreatment period, supporting their true effects of treatment. This study indicates that an orifice-weir outlet can be used to reduce peak flow rates from drained pine plantations for conditions where large rates of fresh water outflows cause detrimental environmental effects and conserve water for tree growth. This study examined only the effects of a 10 cm diameter orifice (near the ditch bottom) with a flat weir near the top. Effects of different orifice sizes, weir depths and their locations on peak flow rates and soil water storage as affected by soil type and climatic variation have been addressed in a separate manuscript (Amatya et al. 1999), which will be submitted later for publication.

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