# Effect of Drainage and Management Practices on Hydrology of Pine Plantation

R. Wayne Skaggs[1], D.M. Amatya[2], G.M. Chescheir[3], C. D. Blanton[4] and J.W. Gilliam[5]

## Abstract

This paper reviews results of long-term studies, initiated in the late 1980s, to determine the hydrologic and water quality impacts of drainage and related water and forest management practices on a poorly drained site in Carteret County, North Carolina. Three watersheds, each approximately 25 ha, were instrumented to measure and record drainage rate, water table depth, rainfall and meteorological data. Data continuously collected on the site since 1988 include response of hydrologic and water quality variables for nearly all growth stages of a Loblolly pine plantation. Studies were conducted to develop and test models for predicting the hydrology of drained forested lands, and to determine the effects of thinning, harvesting, regeneration, controlled drainage, and related water management practices on hydrology and drainage water quality. This paper summarizes the principal findings of those studies. Data for drainage outflow rates and water table elevations were used to determine field effective hydraulic conductivity, K, of the profile at various stages of the production cycle. K values of the top 90 cm of the profile for mature plantation forest were 60 to 95 m/day, which are 20 to 30 times the values given in the soil survey for the Deloss series. Harvest did not appear to affect those values, but site preparation for regeneration, including bedding, reduced the effective K to values typically assumed for this series, 3.6 m/d for the top 45 cm and 1.6 m/d for deeper layers.

**KEYWORDS.** Water table, Drainage, Forest, Evapotranspiration, Hydraulic Conductivity, Controlled Drainage, Harvesting

## Introduction

This paper reviews the results of long-term hydrologic studies on a loblolly pine plantation, initiated in the mid 1980s on the Carteret 7 watershed in the North Carolina Lower Coastal Plain. The studies were designed to determine the effects of water management and silvicultural practices on hydrology and drainage water quality. About 55% of the land area in the southern US is covered by forests. The percentage may be even higher in the lower coastal plain where nearly flat, poorly drained soils limit productivity because of excessive soil water conditions. Drainage has been practiced for many years on these lands to increase commercial production. Approximately 1 million ha of plantation pine in the lower coastal plain along the Atlantic coast are drained to improve productivity. Drainage is needed to improve soil trafficability for harvesting and planting operations and to reduce stresses caused by excessive soil water conditions. Forest drainage systems generally consist of parallel open ditches spaced 100 to 200 m apart which outlet to a network of collector and main canals. While there have been numerous studies on the effect of drainage systems on hydrology and drainage water quality on agricultural lands (e.g., Robinson and Rycroft, 1999; Gilliam et al., 1999; Ayars and Tanji, 1999) there have only been a few published studies on such effects on forested lands. Long-term hydrologic data are essential as base line data for the assessment of management practices for reducing the impacts on downstream water quality and to help us develop a better understanding of the processes affecting hydrology and drainage water quality. These data are also needed to test and further develop eco-hydrologic models for describing the response of the system on larger time and spatial scales.

## Methods

The research was conducted on a site in Carteret County, North Carolina, which is owned and managed by Weyerhaeuser Company. The research site is described in detail by Amatya et al. (2006, this volume); only a brief description will be given here. The site consists of three artificially drained experimental watersheds (D1, D2, and D3), each about 25 ha in size. The Deloss fine sandy loam soil on the site is classified as very poorly drained with a shallow water table under natural conditions; the topography is flat. Each watershed is drained by four parallel lateral ditches about 1.5 m deep, spaced 100 m apart. Drainage water outflow is continuously measured at the outlet of each watershed by recording the water level upstream from a 120° V-notched weir, with the bottom of the "V" about 1.2 m below average soil surface elevation. A pump in the outlet downstream from all three watersheds was installed to prevent weir submergence during large runoff events. Water table elevations were measured by recorders at two locations midway between the field ditches for each watershed. The reader is referred to McCarthy et al. (1991) and Amatya et al. (2003b; 2000; 1996) for a detailed description of the site and other measurements including weather data, interception, lateral seepage, and leaf area index (LAI).

The research project was initiated in 1986 and the first data collected in 1987 in a rainfall interception study (McCarthy et al. 1991). Hydrologic data collection began in 1988 when the loblolly pine trees were 15 years old. Commercial thinning was conducted in all three watersheds in 1988 and fertilizer was applied in 1989. Since that time, watershed D1 has been maintained as the control with standard drainage and silvicultural practices. The other two watersheds have been subjected to a range of silvicultural and water management practices, and studies have been conducted on the hydrologic and water quality impacts of those practices over the 20 year history of this site. The studies are summarized in Table 1.

**Table 1. Summary of studies on the Carteret 7 Experimental Watersheds**

| Subject of Study | Dates | Principle References, Theses and Journal Articles Describing Results |
|---|---|---|
| General Hydrology | 1988-2005 | McCarthy (1990); McCarthy et al. (1991; 1992); McCarthy and Skaggs (1992); Amatya (1993); Amatya et al. (1997); Richardson and McCarthy (1994); Chescheir et al.(2003); Sun et al.(2002; 2005)Amatya et al.(2006a, this vol.) |
| Controlled Drainage, Orifice Weir | 1990-1999 | Amatya et al. (1996; 1998; 2000; 2003); Amatya and Skaggs(1997) |
| Methods for Predicting ET | 1990- | McCarthy et al.(1992); Amatya et al.(1995); Lu et al.(2003); Lu(2002); |
| Hydrologic Simulation Models | 1988-2005 | McCarthy(1990); McCarthy and Skaggs(1991; 1992); McCarthy et al.(1992); Amatya (1993); Amatya et al.(1997b; 2001; Amatya and Skaggs (201) |
| Effects of Harvesting and Regeneration | | Blanton et al.(1998); Amatya et al. (2006b, this volume); Sun et al.(2001) |
| Water Quality Impacts | 2005-2006 | Smith (1994); Amatya et al.(1998; 2003); Chescheir et al.(2003) |
| Effects of Fertilization | 2005- | Watershed 3 fertilized in 2005, no results yet. |

[1]William Neal Reynolds Distinguished University Professor, Biological & Agricultural Engineering Department, North Carolina State University, Raleigh, NC 27695-7625, email: Skaggs@eos.ncsu.edu; [2] Research Hydrologist, USDA Forest Service, Center for Forested Wetlands Research, Charleston, SC 29414. [3]Research Assistant Professor, Biological and Agricultural Engineering, N. C. State, [4]Former graduate Assistant, Biological and Agricultural Engineering, N.C. State, [5] William Neal Reynolds Professor, Department of Soil Science, N.C. State, Raleigh, NC 27695-7619.

## HYDROLOGY

Trees on the watersheds were 15 years old when observations began in 1988. The hydrology has been intensively measured for over 17 years with results documented in several publications (Table 1). Amatya et al. (2006a, this volume) summarized the hydrology of watershed D1 for the 17 year period as the trees aged from 15 to 32 years. These results will be only briefly summarized herein. Watershed D2 was harvested in June1995 and replanted in January 1997, so we have hydrologic data for the effects of harvesting and regeneration, as well as for years 1-7 of the production cycle.

The principle hydrologic components for drained forested watersheds in the coastal plain are rainfall, evapotranspiration (ET), subsurface drainage, and surface runoff. Deep and lateral seepage are generally small for these flat poorly drained watersheds (McCarthy et al., 1991). Most of the drained plantation soils are bedded such that surface depressional storage is large (several cm) and surface runoff is small and, in most cases negligible. Rainfall interception is relative large, amounting to 18 to 27% of total rainfall (McCarthy et al., 1991). Intercepted rainfall is ultimately evaporated and is usually considered, in a water balance, as part of the ET component. Based on an analysis of data from the D1 watershed for the 17 year period of record, Amatya et al. (2006) reported the following statistics for the water balance components. Annual rainfall ranged from 852 to 2331 mm with an average of 1538 mm. Annual outflow, the sum of subsurface drainage and surface runoff, averaged 541 mm, and ET, calculated as the difference in rainfall and outflow, averaged 997mm per year. The annual runoff coefficient (which would be better called the outflow coefficient in this case) is defined as the ratio of outflow to rainfall, and averaged 33% for the 17 year period of observation. It ranged from 5% in the very dry year 2001 to 56% in the year of highest rainfall, 2003. Annual ET, calculated as the difference between rainfall and outflow averaged 997 mm, which was about 3% higher than the Penman-Monteith based annual potential ET (PET).

The drainage systems used for forested lands are in many respects similar to those used for agricultural lands in the region, with 100m spacings of the parallel open ditch drains common to both. However, there are important differences in the way they function and in their effect on outflow rates and hydrology. Figure 1 shows the relationship between subsurface drainage rate, q (in cm/day) and the water table elevation, m, at a point midway between parallel ditches for the for data collected in the winter months of 1995-1997 on watershed D1. The relationship between q and m can be estimated by the Hooghoudt equation (van der Plough et al., 1999) as

$$q = 4\, K_e\, m\, (2d_e+m)/L^2 \qquad (1),$$

where $K_e$ is the effective or average lateral hydraulic conductivity of the profile, $d_e$ is the equivalent depth from the bottom of the drain to the restrictive layer and L is the ditch spacing. The field effective lateral hydraulic conductivity of the profile, $K_e$, was back-calculated from the observed q(m) data using Equation 1. The profile was divided into 3 layers, according to the description in the county Soil Survey (SCS, 1978), and the conductivity of the individual layers obtained from $K_e$ values, starting at the bottom of the profile (Table 1). Values from the county Soil Survey are also given in Table 1 for reference. These values (given as a range) were originally estimated for typical agricultural land uses.

The q versus m data plotted in Fig. 1 form a very well defined relationship that is accurately described by the Hooghoudt equation. The field effective $K_e$ values, however, are high, especially in comparison with the published range for this soil series, and they vary substantially with water table depth. Assuming a profile depth (depth from the surface to a restrictive layer) of 280 cm, Ke was determined to be 5, 10 and 22 m/day for midpoint water table elevations (m values) of 30, 60, and 100 cm, respectively. $K_e$ may be calculated directly from the K values of the profile layers as follows for any water table depth, $(D_1+D_2+D_3)K_e= D_1K_1+D_2K_2+D_3K_3$,

Where D1 is the depth of layer 1 that is below the water table, D2 is the depth of layer 2 and D3 is the depth of Layer 3.

**Table 2. Effective lateral hydraulic conductivity in m/day calculated from measured drainage rate and water table elevations and obtained from the County Soil Survey.**

| Depth Range,cm | D1 | D2 Pre-Harvest | D2 Post-Harvest | D2 Post- Bedding | K, Deloss, from Soil Survey |
|---|---|---|---|---|---|
| 0 – 45 | 95 | 60 | 60 | 3.6 | 1.2 – 3.6 |
| 45 – 90 | 36 | 55 | 55 | 1.6 | 0.36 – 1.6 |
| 90 – 280 | 1.6 | 1.6 | 1.6 | 1.6 | 0.36 – 1.6 |

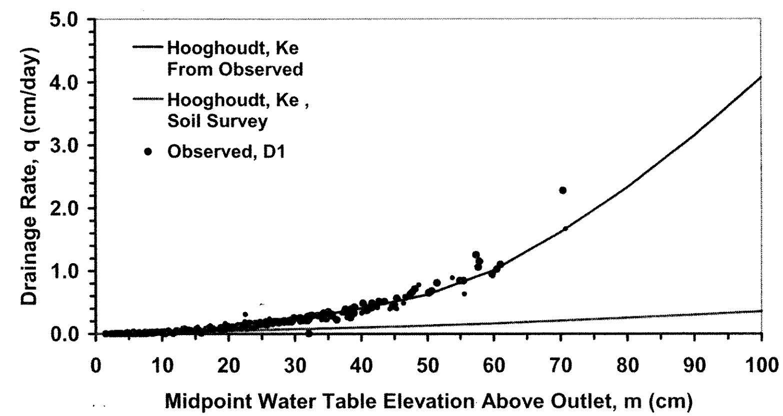


**Figure 1. Relationship between drainage rate and water table elevation above water level in ditch as observed for watershed D1 and calculated by Hooghoudt Equation for D1 and from K data in Soil Survey.**

The high K values in the top 90 cm of the profile (Table 1) are attributed to the presence of large pores that result from tree roots and biological activity that is uninterrupted for many years in a forest. Similar high K values were reported by Grace (2003) for an organic soil on the Parker tract in eastern NC, and by Skaggs et al. (2004) for a mineral soil on the same tract. Both sites were in plantation forest. The high K values and consequent rapid drainage rates resulted in very few data points for m values greater than 60 cm for watershed 1 (Figure 1). The profile drained rapidly and the water table rarely rose to an elevation greater than 60 cm above the water level in the ditches. Drainage rates on this forested site were particularly rapid compared to those predicted using published hydraulic conductivity values for the Deloss soil series (Figure 1). These values, which are characteristic of this soil for agricultural land uses, resulted in predicted drainage rates that were close to those measured on D1 for deep water tables (m less than 15 cm), but less than 10% of the measured D1 drainage rates for water table depths less than 40 cm (m values greater than 60 cm).

The rapid drainage rates observed on D1 will not occur on all forested sites, and not for all conditions on these sites, as will be shown later in this paper. A more complete picture of the relationship between drainage rate and water table depth is given in Figures 2 and 3. The

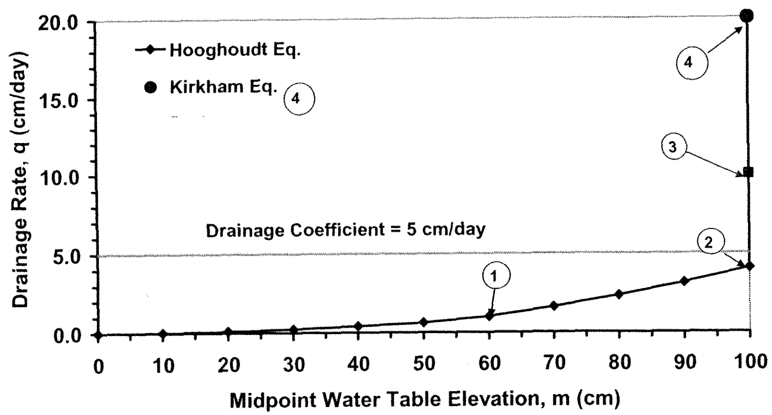


**Figure 2. Relationship between drainage rate, q, and midpoint water table elevation, m. The circled numbers on the plot indicate the drainage rates corresponding to the numbered water table positions in Figure 3 below. Drainage rates are limited by the drainage coefficient, which is the hydraulic capacity of the outlet.**

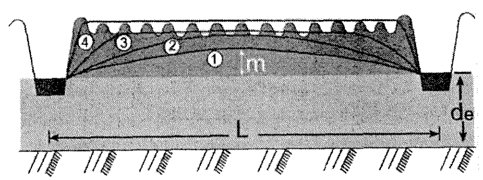


**Figure 3. Water table positions corresponding to the flow rates in Figure 2 above**

drainage rate is plotted as a function of m in Figure 2; the water table shape corresponding to various depths is shown in Figure 3. Most of the time the water table is below the ground surface and has an elliptical shape as illustrated by positions 1 and 2 in Figure 3 with corresponding drainage rates indicated by points 1 and 2 in Figure 2. When rainfall rates are high or drainage rates are slow (because of tight soils or wide drain spacings, for example), the water table may rise to the surface, as shown by position 3 (Figure 3). In this case the midpoint water table elevation is about the same as for position 2, but the lateral hydraulic gradient and the rate that subsurface water moves to the ditches (and the drainage rate) increased substantially as indicated by point 3 in Figure 2. This condition will lead to ponded water on the surface. The experimental watersheds are bedded, as indicated by the irregular surface in Figure 3. Most plantation forests on poorly drained soils in North Carolina are bedded to provide a well-drained zone for the young tree. The beds have an important effect on hydrology as they provide relatively large surface depressional storage which must be filled before runoff can take place. If rainfall continues at a rate greater than the drainage rate, the surface will become completely ponded (position 4 in Figure 3) and the subsurface drainage rate will be maximized (point 4, Figure 2). This drainage rate may be predicted with methods developed by Kirkham (1957). Continued rainfall at rates greater than the drainage rate will result in surface runoff. Because of large surface depressional storage and rapid subsurface drainage rates, surface runoff from the Carteret 7 watersheds was rare, only occurring during hurricanes and intensive tropical storms.

In most cases drainage rates are limited by the rate water will move through the soil profile to the ditches as discussed above. Another factor controlling drainage rates, especially during extreme events, is the hydraulic capacity of the drainage network, commonly referred to as the drainage coefficient, DC. This capacity is dependent on the size and slope of the outlet drainage ditches and canals. When water moves to the field drains at rates greater than the DC, the drainage rate i limited to the DC, as shown in Figure 2, and water will back up in the ditches and the surface wil likely become ponded. A pump was installed to increase the DC to about 7 cm/day on the experimental sites. However, the DC is also limited by ditch capacity which was sometimes reduced due to vegetation and silting, so the effective DC was about 5 cm/day for most of the period of observation. Although this is a relatively high DC, it is less than the maximum rate that water will drain to the ditches, as shown in Figure 2. Nearly all occasions of surface ponding during the 17 years of observations have resulted from limitations of the outlet capacity, often as a result of pump failure due to loss of electrical power. Such failures usually resulted in submergence of the outlet weirs and a short term loss of flow record.

## EFFECT OF HARVESTING AND REGENERATION

The effect of harvesting and regeneration was studied in 1995 and following and is discussed in detail by Amatya et al. (2006b, this volume). Watershed D2 was harvested in July 1995 at a stand age of 21 years. The watershed was bedded and prepared for planting in October 1996 and planted in February 1997. Continuous flow and water table records were analyzed to determine the hydrologic and water quality effects and their change with time after replanting. Harvest reduced ET and water table depth and increased drainage outflow and runoff coefficient comparec to the control (D1) which was not harvested. Results for the control were used with calibration from previous years to determine expected outflows from unharvested D2 on an annual basis. These values were compared to measured outflows for D2 to determine the effects of harvest. Results are summarized in Table 3 for the 5 year period following harvest 1995-1999. Analysis oi the flow data through 2004 indicated that outflow from D2 may not have yet returned to the base line conditions prior to harvest.

**Table 3. Summary of hydrologic components for the control watershed D1 and of the effects of harvesting and regeneration on ET and drainage. Values for D2 (expected) are based on measurements for D1 multiplied by the ratio D2/D1 for the calibration period (after Amatya et al., 2006, this volume).**

| | Hydrology Conventional Drainage D1, 1988-2004 | Harvesting and Regeneration 1995-1999 | | |
|---|---|---|---|---|
| | | D2 (expected) | D2(harvested) | %Change |
| Rainfall (mm) | 1538 | 1307 | 1307 | |
| ET (mm) | 997 | 833 | 598 | 28 % |
| Drainage (mm) | 541 | 474 | 709 | 49 % |
| Runoff Coefficient | 0.33 | 0.32 | 0.51 | 59 % |

The biggest effect of harvesting is the removal of growing plants which substantially reduces ET and increases drainage outflow (Table 3). Harvesting and site preparation for new planting may also affect soil properties resulting in further hydrologic changes. Grace et al. (2005) found that harvesting reduced both the hydraulic conductivity and the drainable porosity of an organic soil. Blanton et al. (1998) determined that harvesting significantly reduced drainable porosity of the D2 site based on an analysis of pre- and post-harvest soil water characteristic data. Daily drainage flows from watershed D2 are plotted versus midpoint water table elevation, m, in Figure 4. All data plotted are for the cool season period of Nov. 1 –April 15 to reduce the effects of ET on water table shape. Pre-harvest data were obtained for the period Jan. 1 – April 15, 1995. The site was harvested in July 1995 so the post-harvest data were for the period Nov. 1, 1995 – April 15, 1996. The site was bedded and prepared for planting in October 2006, so the data labeled as post-bedding were collect during the period Nov. 1, 1996- April 15, 1997.

Results in Figure 4 indicate little difference between the q(m) relationships for pre- and post-harvest, but drainage rates after bedding are clearly reduced for water table elevations greater than m = 15 cm. That is, the bedding process apparently reduced substantially the hydraulic conductivity of the top 90 cm of the soil profile. The Hooghoudt equation was used as described earlier for watershed D1 (Figure 1) to estimate the hydraulic conductivity by soil layer for the pre- and post-harvest and post bedding conditions. Results are summarized in Table 1. Relationships for q(m) predicted with the Hooghoudt equation, using K values for D2 (Table 1) to determine $K_e$, are plotted in Figure 4. The predicted relationship for watershed D1 is plotted in Figure 4 for comparison. The hydraulic conductivity for the top 45 cm of the profile in D2 (pre-bedding) is smaller than for D1. However, K for the 45 to 90 cm depth for D2 is larger than D1 (Table 1).

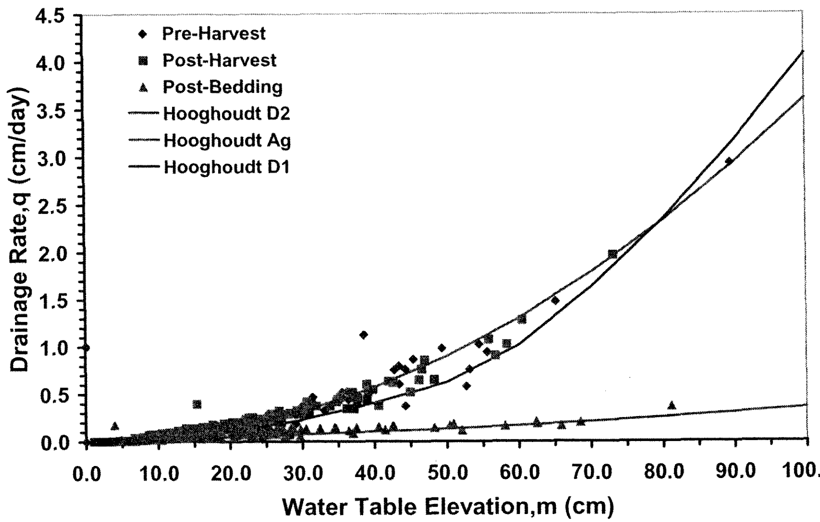


**Figure 4. Effect of harvesting and bedding on the relationship between drainage flow rate and water table elevation, m, for Watershed D2 at Carteret 7. D2 was harvested in July, 1995 with site preparation and bedding in October, 1996. Data plotted are for the period Nov. 1 – April 10 in 1995, 1996 and 1997.**

The relationship for post-bedding is much reduced compared to pre- and post-harvest conditions. Predictions by the Hooghoudt equation, using the high end of the range of K values given in the Soil Survey for Deloss soil (Table 1), agreed very well with the observations for post-bedding condition (Figure 4). Apparently the bedding process destroyed the macro-pores in the surface layers such that the profile had effective K values similar to that expected for agricultural crop production. These data indicate that it was not the harvesting process that reduced the K values in the top part of the profile back to levels expected for agricultural uses on this soil series, but the bedding process prior to replanting.

## CONTROLLED DRAINAGE

The drainage intensity needed for agricultural and silvicultural production varies with season and stage of the production cycle. For plantation forest the most critical stage is in the first years after planting when the seedlings require protection from high water table and excessive soil water conditions. ET is reduced during this stage so drainage to lower the water table and provide suitable conditions for tree growth is more critical than later in the production cycle. For similar reasons, drainage is more critical in winter than in summer when the water table is may be relatively deep due to ET alone. Drainage in excess of that needed should be avoided as it removes water that could be used by the growing trees. Drainage can be reduced or managed on temporal basis through the process of controlled drainage, CD (Gilliam et al.,1979; Evans et al., 1995). CD is cost shared in North Carolina as a Best management Practice to conserve water and reduce nitrogen and phosphorus losses to surface waters. CD is normally accomplished in foreste lands by the installation of a weir in the drainage outlet ditch such that the water level in the ditch must exceed the elevation of the weir for drainage water to leave the system.

Experiments were conducted during the period March 1990 to May 1994 to determine the effect c CD on hydrology and drainage water quality on the Carteret 7 site (see Amatya et al.1996; 1998 for details). Watershed D1 was maintained in conventional drainage with the weir level 1 m belo the surface while CD was practiced on D2 with the weir held at 1m below the surface from Dec. 1 to June 15 and 0.6 m from June 15 to Nov. 30. The purpose of this treatment was to conserve water during the growing season. Watershed D3 was also in CD with the objective of reducing drainage outflows during the spring. Weir depths were 1m below the surface from Dec. 1 to Mar. 15, 0.4 m from Mar. 16 to June 15 and 0.8 m from June 15 to Nov. 30. Results from the three yea treatment period (1990-1992) indicated that CD on D2 and D3 reduced drainage outflows to 21 and 26% of rainfall, respectively compared to 30.5% for D1 under conventional drainage (Amaty et al., 1996). A later analysis for the two year period 1992-1993 considered the characteristic differences in the watersheds due to small differences in rainfall and soil properties (Amatya et al. 1998). This study showed that the CD reduced outflows by 25 and 20 %, on D2 and D3, respectively, compared to the conventionally drainage. CD increases both ET and seepage from the watershed (Amatya et al., 1996). It should be noted that about 58% of total annual outflow occurs during winter and that neither of the CD treatments included this period. The effect of CD on drainage outflows would likely been much greater had the practice been implemented during the winter months.

Controlled drainage works by storing water in the ditches and reducing the gradient for subsurface drainage. During a storm event the weir in the ditch prohibits drainage from the system until the water level in the ditches rises to the weir elevation. Depending on the initial conditions, the weir may delay the onset of outflow from the watershed, raise the water table and reduce the total amount drained, compared to watersheds with conventional drainage. An example of the effect of CD on the outflow hydrograph (from Amatya et al., 2000) is shown in Figure 5 for a storm startin on August 20, 1992. Conditions were relatively wet when rainfall began and flow from D1 under conventional drainage (with the outlet weir 100 cm below the surface) was 156 $m^3/hr/km^2$. Results for event duration, peak outflow rate, and total outflow are given in Table 4. Watershed D2 was in CD with a weir depth of 60 cm during the event. The water level in the outlet ditch wa below the weir and there was no flow when the event began. In this case CD reduced the duration of the flow event from 10.4 to 3 days, the peak outflow rate from 433 to 135 $m^3/hr/km^2$ and total event outflow from 24 .6 to 3 mm (Table 4). D3 was also in CD with a weir depth of 80 cm, half way between the weir depths for D2 and D1. Results were intermediate between those for D1 and D2 as expected (Table 4 and Figure 5).

While sediment and nutrient transport from these flat, forested watersheds are low compared to other land uses (Chescheir et al., 2003), CD was effective in reducing those loads to surface waters. Annual phosphorus and $NH_4$-N loads were reduced by 7 to 70% by CD, sediment by up to 47%, and $NO_3$-N and TKN, by up to 16 and 45%, respectively (Amatya et al., 1998).

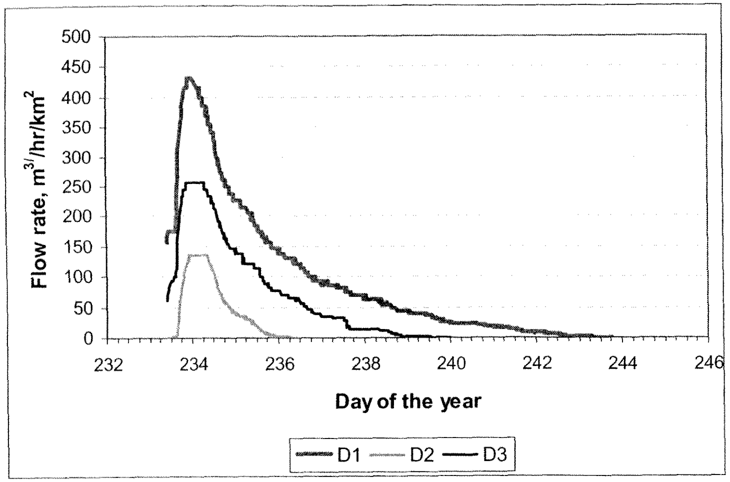


**Figure 5. Effect of controlled drainage on outflow hydrographs for an event starting on August 20, 1996. Watershed D1 was in conventional drainage with weir 100 cm below the surface, D2 controlled drainage with weir at 60 cm below surface and D3 controlled drainage with weir depth of 80 cm. From Amatya et al.(2000)**

**Table 4. Effect of CD on event duration, peak outflow rate and total event outflow for a storm August 20, 1992 (after Amatya et al., 2000)**

| Watershed | Treatment | Weir Depth (cm) | Total Rainfall (mm) | Event Duration (days) | Initial Flow Rate ($m^3/hr/km^2$) | Peak Flow Rate ($m^3/hr/km$) | Event Outflow (mm) |
|---|---|---|---|---|---|---|---|
| D1 | Conventional Drainage | 100 | 32.5 | 10.4 | 156 | 433 | 24.6 |
| D2 | CD | 60 | 30.5 | 3.0 | 0 | 134 | 3.7 |
| D3 | CD | 80 | 29.0 | 6.5 | 60 | 256 | 12.4 |

CD has the greatest effect on reducing drainage rates and outflow volumes for events with relatively dry initial conditions such that the water table is deep and the water level in the drains is near the bottom of the ditch. Under these conditions a relatively large volume of water may be stored in the profile and in the network of drainage ditches before outflow will occur. However, the effectiveness of CD for succeeding storms may be substantially reduced as the system is saturated and the ditches are full. In this case outflow rates may be equal or greater than would be obtained under conventional drainage. High rates of freshwater outflows are an environmental concern in coastal areas because of their potential effect on salinity fluctuations. Outflow rates could be reduced by using control drainage in combination with a leaky weir that would allow the water level in the ditches to recede over time and thus more quickly reclaim storage capacity in the ditch network. Experiments were conducted to determine the effectiveness of a weir, with an orifice near the bottom of the ditch, in reducing outflow rates from pine plantation watersheds. The orifice weir was installed in watershed D3 and outflow rates were monitored during the 3-year period 1996-1998. Results were reported by Amatya et al. (2003). An example of results is shown in Figure 6 for three rainfall events in early 1996. Results obtained for D1 under conventional drainage were used with calibration factors to plot the expected outflow rates for D3 without a weir. These values may then be compared with outflow rates measured for D3 to determine the effectiveness of the orifice weir. Results indicate that the orifice weir substantially reduced peak outflow rates for the two larger events during this period. For example, the expect peak outflow rate was 160 $m^3/hr$ for D3 without control, as compared to an actual value of less than 60 $m^3/hr$ with the orifice weir. There was much less difference in the peak outflow rates for the small event starting on day 31. These results are consistent with results from the 3-year experiment. A flow frequency diagram presented by Amatya et al. (2000) indicated that when da flows were less than 4 mm/d, which occurred about 90% of the time, there was no difference in outflow rates with and without the orifice weir. The orifice weir substantially reduced outflow rates for larger flows. For example, daily flows exceeded 15 mm/day during about 1% of the days. These flow rates were reduced to 6 mm/day with the orifice weir. For even larger flow rates, those occurring in only 0.1% of the days, the orifice weir reduced daily flows from 31 to 2 mm. In this case, flow occurs both through the orifice and over the weir. The reader is referred t Amatya et al. (2000) for details on this study.

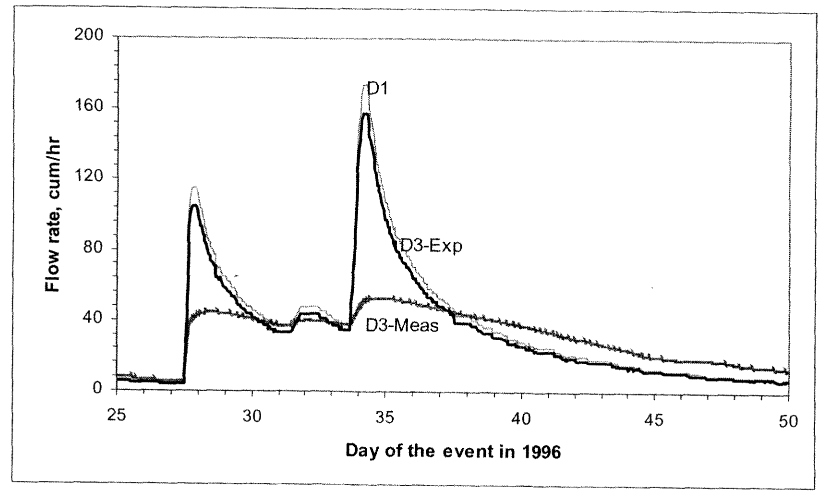


**Figure 6. Outflow hydrographs for watershed D1 under conventional drainage, expected outflows from D3 under conventional drainage (based on D1 flows with a calibration factor) and measured outflows for D3 with the outlet controlled with an orifice weir (from Amatya et al., 2000).**


**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 necessary support for field data collection and processing. The efforts of Wilson Huntley and Charles Frick of BAE, NCSU are also acknowledged.


## REFERENCES


1. Amatya, D.M. 1993. Hydrologic Modeling of Drained Forested Lands. Ph.D. Dissertation, Biological & Agricultural Engineering, North Carolina State University, Raleigh, NC, 210 p.
2. Amatya, D.M. and R.W. Skaggs. 2001. Hydrologic modeling of pine plantations on poorly drained soils. *Forest Science.* 47(1): 103–114.

3. Amatya, D.M., J.W. Gilliam, R.W. Skaggs, M.E. Lebo and R.G. Campbell. 1998. Effects of controlled drainage on forest water quality. *Journal of Environmental Quality*. 27: 923–935.

4. Amatya, D.M., J.D. Gregory, and R.W. Skaggs. 2000. Effects of controlled drainage on storm event hydrology in a loblolly pine plantation. *Journal of the American Water Resources Association*, 36(1):175-190.

5. Amatya, D.M., R.W. Skaggs, C.D. Blanton, and J.W. Gilliam. 2006b. Hydrologic and water quality effects of harvesting and regeneration on a drained pine forest. . Proc, Int'l Conference on Hydrology and Management of Forested Wetlands, ASABE, St Joe, MI.

6. Amatya, D.M., R.W. Skaggs, J.W. Gilliam, and J.E. Hughes. 2003. Effects of an orifice-weir outlet on the hydrology and water quality of a drained forested watershed. *South. J. Appl. For.*, 27(2): 130-142

7. Amatya, D.M., R.W. Skaggs, and J.W. Gilliam. 2006a. Hydrology and water quality of a drained loblolly pine plantation in Coastal North Carolina. Proc, Int'l Conference on Hydrology and Management of Forested Wetlands, ASABE, St Joe, MI. This volume

8. Amatya, D.M., R.W. Skaggs and J.D. Gregory. 1995. Comparison of Methods for Estimating REF-ET. *J. of Irrigation & Drainage Engr.*, Nov./Dec. 1995, Vol. 121, No. 6, pp: 427-435.

9. Amatya, D.M., R.W. Skaggs, and J.D. Gregory. 1996. Effects of Controlled Drainage on the Hydrology of a Drained Pine Plantation in the Coastal Plains. *J. of Hydrology*, 181: 211-232.

10. Amatya, D.M., R.W. Skaggs and J.D. Gregory. 1997a. Evaluation of a Watershed Scale Forest Hydrologic Model. *Journal of Agricultural Water Management*, 32(1997):239-258.

11. Amatya, D.M., R.W. Skaggs, J.D. Gregory, R.B. Herrmann. 1997b. Hydrology of a drained forested pocosin watershed. *J. of the American Water Resources Association,* 33(3):535-546.

12. Ayars, J.E. and K.K. Tanji. 1999. Effects of drainage on water quality in arid and semiarid irrigated lands. R.W. Skaggs and J. van Schilfgaarde (ed.) Agricultural Drainage, SSSA, Madison WI.

13. Blanton, C.D., R.W. Skaggs, D.M. Amatya, and G.M. Chescheir. 1998. Soil Hydraulic Property Variations During Harvest and Regeneration of Drained Coastal Pine Plantations. Paper no 982147 presented at the 1998 ASAE Int'l Meeting, July 1998, Orlando, FL.

14. Chescheir, G.M., M.E. Lebo, D.M. Amatya, J. Hughes, J.W. Gilliam, R.W. Skaggs, and R.B. Herrmann. 2003. Hydrology and Water Quality of Forested Lands in Eastern North Carolina. *Technical Bulletin No. 320,* North Carolina ARS, N. C. State University, Raleigh, NC, 79 p.

15. Evans, R.O., R.W. Skaggs and J.W. Gilliam. 1995. Controlled versus conventional drainage effects on water quality. *J. Irrigation and Drainage*, 121(4):271-276.

16. Gilliam, J.W., J.L. Baker and K.R. Reddy. 1999. Water quality effects of drainage in humid regions. P. 801-830 In R.W. Skaggs and J. van Schilfgaarde (ed.) *Agricultural Drainage*, SSSA, Madison WI.

17. Gilliam, J.W., R.W. Skaggs, and S.B. Weed. (1979). "Drainage control to diminish nitrate loss from agricultural fields". *J. Environ. Qual.* 8:137-142.

18. Grace, J.M.,III. 2004. Forest operations impact on forest soil and water on poorly drained organic soil watersheds in North Carolina. PhD Dissertation, N.C. State Univ., Raleigh, 319 p.

19. Grace, J.M.,III, R.W. Skaggs and K.D. Cassel.2005. Soil physical changes associated with forest harvesting operations on an organic soil. *Journal SSSA*, submitted.

20. Kirkham, D. 1957. The ponded water case. P139-181 In J. N. Luthin (ed.) *Drainage of Agricultural Lands*. Agronomy Monograph 7, ASA, Madison, WI.

21. Lu, Jianbiao. Modeling Regional Evapotranspiration for Forested Watersheds Across the Southern United States. 2002. M.S. Thesis., Dept. of Forestry, N.C. State Univ., Raleigh, NC.

22. Lu, J., G.Sun, S.G. McNulty, and D.M. Amatya. 2003. Modeling Actual ET from Forested Watersheds across the Southern United States. *J. Amer. Wat. Res. Assoc.*, 39(4):887-896.

23. McCarthy, E.J. 1990. Modification, Testing and Application of a Hydrologic Model for a Drained Forested Watershed. Ph.D. Dissertation, Biological & Agricultural Engineering, North Carolina State University, Raleigh, NC.

24. McCarthy, E.J. and R.W. Skaggs. 1992. Simulation and Evaluation of Water Management Systems for a Pine Plantation Watershed. *South. J. App. For.*, Vol.16:48-56.

25. McCarthy, E.J. and R.W. Skaggs. 1992. A Simplified model for predicting drainage rates foı changing boundary conditions. *Trans. Amer. Soc. Agr. Eng.* 34(2):443-448.

26. McCarthy, E.J., J.W. Flewelling, and R.W. Skaggs. 1992. Hydrologic Model for Drained Forested Watershed. *ASCE J. of Irrigation & Drainage Engineering*, Vol. 118, No. 2, March/April, 1992, pp:242-255

27. McCarthy, E.J., R.W. Skaggs, and P. Farnum. 1991. Experimental determination of the hydrologic components of a drained forest watershed. *Trans. Amer. Soc. Agr. Eng.*, 34(5):2031-2039.

28. Richardson, C.J. and E.J. McCarthy. 1994. Effect of land development and forest manageme on hydrologic response in southeastern coastal wetlands: A review. *Wetlands*,14(1), pp:56-71

29. Robinson, M. and D.W. Rycroft. 1999. The impact of drainage on streamflow. P.767-800 In R.W. Skaggs and J. van Schilfgaarde (ed.) *Agricultural Drainage*, SSSA, Madison WI.

30. SCS. 1978. Soil Survey of Carteret County North Carolina. USDA, SCS. 155p

31. Skaggs, R.W., G.M. Chescheir, G.P. Fernandez, and D.M. Amatya. 2004. Effects of Land Use on the Hydrology of Drained Coastal Plain Watersheds. In M.S. Altinakar, S.S.Y. Wang, K.P Holz. and M. Kawahara (eds.) Proc. of the 6th Int'l Conf. on Hydro-Science and Engineering Brisbane, Australia, May 31-June 3.

32. Smith, K.L. 1994. Assessing Water Quality Impacts of Forest Management Activities in Pocosin Wetlands in eastern North Carolina. M.S. Thesis,University of Georgia, Athens, GA.

33. Sun, G., S.G. McNulty, D.M. Amatya, R.W. Skaggs, L.W. Swift Jr., J.P. Shepard, and H. Riekerk. 2002. A comparison of the watershed hydrology of coastal forested wetlands and the mountainous uplands in the southern US. *J. of Hydrology*, 263(2002):92-104.

34. Sun, G., S.G. McNulty, J.Lu, D.M. Amatya, Y. Liang, and R.K. Kolka. 2005. Regional annua water yield from forest lands and its response to potential deforestation across the southeastern United States. *J. of Hydrology*, 308(2005):258-268.

35. Sun, G., S.G. McNulty, J.P. Shepard, D.M. Amatya, H. Riekerk, N.B. Comerford, R.W. Skaggs, and L. Swift, Jr. 2001. Effects of Timber Management on Hydrology of Wetland Forests in the Southern United States. *Forest Ecology and Management,* 143(2001):227-236.

36. Van der Ploeg, R.R., R. Horton and D. Kirkham. (1999). "Steady flow to drains and wells". P213-264 In R.W. Skaggs and J. van Schilfgaarde (ed.) *Agricultural Drainage*, SSSA, Madison WI