# Effects of controlled drainage on the hydrology of drained pine plantations in the North Carolina coastal plain

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## Abstract

This paper presents results of a 5 year study to characterize the hydrology (rainfall, interception, evapotranspiration (ET), soil water storage, drainage rate, lateral seepage, and water table fluctuations) of three identical drained, pine-forested watersheds in Carteret County, North Carolina. During the 2 year calibration period (1988–1989), all three watersheds were operated in conventional drainage mode with the weirs in the outlet ditch approximately 1.0 m below the soil surface. About 17% of the total rainfall was intercepted and subsequently evaporated and 53% was removed by transpiration and evaporation from the soil during this period. Drainage removed about 28% and the remaining 3% was lost by lateral seepage. During the 3 year controlled drainage treatment period (1990–1993), drainage in Watershed 2, managed for tree growth, was reduced to 21% of gross rainfall as compared with 30.5% for Watershed 1 under free drainage. Watershed 3, managed to minimize offsite impacts, yielded 26% of gross rainfall as drainage. Interception loss accounted for about 14.5% of the gross rainfall. ET amounts computed as the residual in a water balance, were 50%, 60%, and 55% of total rainfall for Watersheds 1, 2, and 3, respectively. The effects of controlled drainage on water table depths, drainage and ET were demonstrated for seasonal and year-to-year variation in rainfall. The controlled drainage treatments affected both drainage volumes and daily peak outflow rates. The treatment in Watershed 3 was more effective in reducing peak outflow rates.

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## 1. Introduction

Controlled drainage has become a practice of great interest in both agricultural production and forestry. Several researchers have emphasized the importance of good water management to provide the necessary drainage for forest production while conserving water and minimizing detrimental downstream effects (McCarthy et al., 1991; Skaggs et al., 1991). Gregory (1988) recommended that forest water management include a drainage system, flow control structures and silvicultural practices that influence interception and evapotranspiration (ET) losses, infiltration, and storage and movement of water. He stressed the importance of long-term studies of the water balance over the four hydrologic phases (preharvest, regeneration, developing stand, and maturing stand) of stand life. Such long-term studies on hydrologic parameters for a drained wetland ecosystem have not been reported.

The water balance of a drained forest on shallow water table soils depends on the interaction of precipitation, interception, ET, infiltration, surface runoff, subsurface drainage, deep seepage, and changes in soil water storage. In this study, the sum of wet canopy evaporation of the intercepted water, dry transpirational losses and soil evaporation was defined as total evaporation or total evapotranspiration (TE). TE, water table position, soil water distribution and the resultant drainage rate are difficult to quantify for a drained forest. The use of controlled drainage during part or all of the year further complicates hydrologic and water quality impacts. Studies reported to date have lacked suitable measurement techniques or have not measured all relevant components.

TE is a major component of the forest water balance. Most studies on the water balance of forested watersheds have used measurements of rainfall, drainage and runoff, and soil water storage to estimate TE by difference (Reikerk, 1985; Almeida and Reikerk, 1990). Stewart (1977) emphasized that accounting for water loss by transpiration and by wet canopy evaporation in calculating total evaporation loss improves the accuracy of the total water balance for forested areas. Similarly, Singh and Szeicz (1979) reported that if transpiration only had been used instead of interception when the canopy was wet, the error in the water balance of a hardwood forest would have been significantly larger.

Previous studies have shown that the Penman–Monteith equation, obtained by incorporating a stomatal conductance term in the original Penman equation, is the most accurate method of estimating actual transpiration rates (Rutter et al., 1972; Stewart, 1984; McNaughton and Jarvis, 1984). The method can also be used for estimating potential evaporation of intercepted water from a completely wet canopy by assuming an infinitely large stomatal conductance with a variable aerodynamic resistance (Rutter et al., 1972; Stewart, 1977; Whitehead, 1986). The water balance of the drained loblolly pine (*Pinus taeda* L.) stands considered in this study was described by McCarthy et al., (1991) based on data collected during the watershed calibration period 1988–1989. The study included measurement or direct estimate of all important water balance parameters except deep seepage, which was assumed negligible. Direct estimates of dry transpiration and wet canopy evaporation losses were computed by the Penman–Monteith method with hourly weather data, a

constant aerodynamic resistance factor, and a stomatal conductance function. Soil evaporation was computed as a function of potential evaporation and leaf area index.

The main objective of this paper is to describe the effects of controlled drainage on the hydrology of the drained loblolly pine plantation and to discuss the water balance for each treatment of the plantation over a 5 year period. This period included the calibration period (1988–1989) described by McCarthy et al. (1991) and three additional years (1990–1993) of controlled drainage treatments. Data from the calibration period were reanalyzed based on new estimates for leaf area index, canopy capacity, stomatal conductance and aerodynamic resistance.
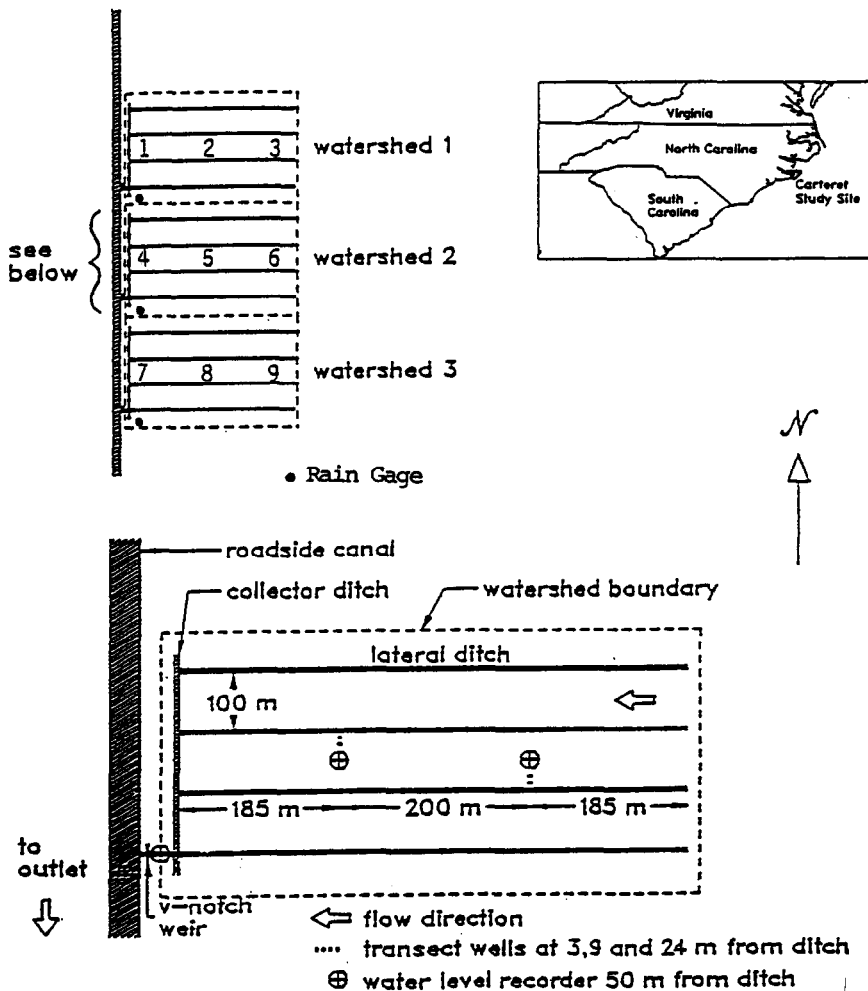


Fig. 1. Experimental layout of three watersheds at Carteret 7, NC (after McCarthy et al., 1991).

## 2. Methods

### 2.1. Site description and measurements

The study site (Fig. 1) on a drained loblolly pine forest of mid-rotation age, located in Carteret County, North Carolina, is owned and managed by Weyerhaeuser Company. The site is approximately located at 34°48′N, 76°42′W. Instrumentation of the research site and the experimental methods used on this intensively managed loblolly pine plantation are described briefly below. The reader is referred to McCarthy et al., (1991) and Amatya (1993) for a detailed description of the site and methods.

The research site consists of three artificially drained experimental watersheds, each about 25 ha in size. The watersheds are surrounded by extensive forests to the north, south and the west and by agricultural lands to the east. The site is poorly drained and nearly flat, with shallow water table under natural conditions. The soil is a hydric series, Deloss fine sandy loam (fine-loamy mixed, Thermic Typic Umbraquult). Each watershed is drained by four parallel lateral ditches of 1.4–1.8 m depth spaced 100 m apart (Fig. 1). Data on hydrology, soil and vegetation parameters were collected from three rectangular experimental plots (each about 0.13 ha in area) in each watershed (Fig. 1).

Rainfall was measured with a Qualimetric tipping bucket rain gauge with data-logger (Omnidata, Logan, UT) in an open area of about 70 m by 50 m on the west side of each watershed (Fig. 1). The distance between the rain gauges was 400 m. Air temperature, relative humidity, wind speed and net radiation were measured every minute and averaged on an hourly basis by a CR-21 datalogger (Campbell Scientific, Logan, UT) at a weather station located about 800 m from the study site. It is in an open area measuring about 0.30 ha with grass of 0.3–0.4 m height as ground vegetation. Temperature, humidity and net radiation were measured at a height of about 1.3 m and wind speed was measured at a height of 12 m from the ground. When data were missing, daily values obtained from the weather station at Cherry Point Marine Corps Air Station, 40 km from the site, were used to simulate hourly data (McCarthy et al., 1991).

An adjustable height 120° V-notched weir, located in a water level control structure with adjustable plate (flashboard riser) in the outlet ditch of each watershed, allowed control and measurement of drainage outflow. Upstream of each weir, water levels were recorded at 6 min intervals by water level recorder (Type F, Leopold and Stevens, Beaverton, OR) with datalogger (Omnidata). An additional recorder was placed downstream from the weirs to determine if weir submergence occurred and to estimate flows in that event. A pump was installed downstream from all three watersheds in the main collector ditch in January 1991, to prevent weir submergence during larger events. The weirs were submerged several times during larger events of 1988, 1989 and 1990. Because of its slightly lower elevation, Watershed 3 experienced weir submergence more often than the other two watersheds.

Water table depths were measured by water level recorder (Leopold and Stevens) with datalogger (Omnidata) at two locations midway between the field ditches for

Table 1
History of the loblolly pine stand on the experimental watersheds at Carteret 7, NC (source: J. Hughes, personal communication, 1991)

| Year | Stand activity | Fertilizer element | Rate (kg ha$^{-1}$) | Application method |
|------|---------------|-------------------|---------------------|--------------------|
| 1972 | Clearcut | | | |
| 1973 | Site preparation and field ditching | P[a] | 45 | Incorporated into beds |
| 1974 | Trees planted | | | |
| 1980 | Pre-commercial thinning | | | |
| 1981 | Fertilizer application | N[b] | 169 | Aerial |
| 1988 | Commercial thinning | | | |
| 1989 | Fertilizer application | N[c] | 225 | Ground |
| | | P[c] | 28 | Ground |

[a] In 225 kg ha$^{-1}$ of triple superphosphate.
[b] In 367 kg ha$^{-1}$ of urea.
[c] In 140 kg ha$^{-1}$ of diammonium phosphate and 435 kg ha$^{-1}$ of urea.

each watershed (Fig. 1). Water table depths in a transect of wells across each watershed were measured periodically by dip-stick method to determine the shape of the water table and to calculate the change in soil water storage over periods of time. Soil water content in the unsaturated zone above the water table was measured periodically (every 2–3 weeks) with a Neutron Moisture Gauge (3220 Series, Troxler International, Research Triangle Park, NC) in four locations per plot with two plots per watershed. Water levels in ditches adjacent to the watershed boundaries were manually measured periodically to compute lateral seepage. Saturated lateral hydraulic conductivity of the Deloss fine sandy loam soil was measured using the auger-hole method in several locations and verified with analytical solutions described by McCarthy et al. (1991).

The loblolly pine stand was planted in 1974 at a 1.74 m by 2.74 m spacing (2100

Table 2
Mean annual diameter (diameter at breast height, d.b.h.), height, basal area and volume increment of live trees by watershed (Source: J. Hughes, personal communication, 1993)

| Year | Diameter increment (mm year$^{-1}$) | | | Height increment (m year$^{-1}$) | | | Basal area increment (m$^2$ ha$^{-1}$) | | | Volume increment (m$^3$ ha$^{-1}$) | | |
|------|------|------|------|------|------|------|------|------|------|------|------|------|
| | WS 1 | WS 2 | WS 3 | WS 1 | WS 2 | WS 3 | WS 1 | WS 2 | WS 3 | WS 1 | WS 2 | WS 3 |
| 1987 | 5.7 | 5.7 | 5.7 | 0.81 | 0.89 | 0.88 | 2.0 | 1.9 | 2.0 | 24 | 22 | 24 |
| 1988 | 2.8 | 2.8 | 2.7 | 0.82 | 0.77 | 0.83 | −16.9 | −16.3 | −15.8 | −95 | −90 | −89 |
| 1989 | 9.7 | 9.0 | 9.4 | 1.28 | 1.32 | 1.37 | 1.4 | 1.4 | 1.4 | 14 | 14 | 15 |
| 1990 | 12.0 | 12.3 | 11.4 | 0.60 | 0.64 | 0.54 | 1.8 | 1.8 | 1.9 | 19 | 19 | 18 |
| 1991 | 11.8 | 11.7 | 12.9 | 0.58 | 0.54 | 0.66 | 1.9 | 1.9 | 2.4 | 19 | 18 | 22 |
| 1992 | 11.2 | 10.9 | 8.1 | 0.67 | 0.86 | 0.76 | 1.61 | 1.64 | 1.29 | 18 | 20 | 16 |

trees ha$^{-1}$); the history is given in Table 1. Data given in Table 2 represent diameter, height, basal area and volume increments of the stands in three watersheds for the 5 year period. Estimated basal area of 32.6 m$^2$ ha$^{-1}$ was reduced to 16.1 m$^2$ ha$^{-1}$ by commercial thinning in October 1988. Litterfall collected monthly from eight litter traps of 1.2 m diameter, randomly placed within each of the three plots in each watershed was used to estimate leaf area index (LAI). LAI data from early 1988 to 9 May 1989 were reported by McCarthy et al. (1991). The LAI for the rest of the study period was estimated by the method of Vose and Allen (1988) described by A. Sampson (personal communication, 1995). Actual estimates of needle litterfall were used to model autumn foliage senescence of the previous cohort for that year. Estimates of foliage mass were converted to LAI using Specific Leaf Area (SLA) estimates obtained throughout the year. The product of SLA (m$^2$ g$^{-1}$) and needle litterfall mass (g m$^{-2}$) with an appropriate conversion factor of 2.84 (Vose and Allen, 1988) yields the total leaf area. Linear regression was used to develop Li-Cor (LI-2000 Plant Canopy Analyzer, Li-Cor, Lincoln, NE) corrected estimates of LAI for the periods where litterfall were not available. The daily LAI function for the 5 year period is plotted in Fig. 2. Stomatal conductance was measured approximately every three weeks with a porometer (LI-1600 Steady State Porometer, Li-Cor) in each of two plots of the three watersheds. Measurements of water table depths at the transect wells, neutron meter readings, and foliage samples were also taken at the time of porometer readings on Plots 1, 3, 4, 6, 7, and 9 of the watersheds (Fig. 1).

A rainfall interception study was conducted on the site in 1987 and again in 1989 to quantify throughfall precipitation, stemflow, and canopy storage capacity (McCarthy et al., 1991). For each rainfall event, 20 randomly placed buckets were used to collect throughfall precipitation on each watershed. Stemflow was collected on ten sample trees. These measurements were taken in one plot of each watershed.
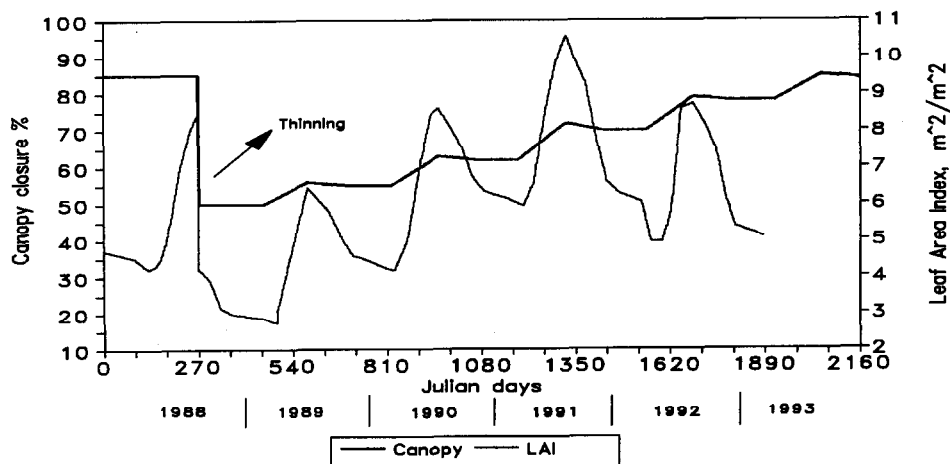


Fig. 2. Average leaf area Index (LAI) and present canopy closure of the loblolly pine stands on the three watersheds at Carteret 7, NC, for the period 1988–1993.

## 2.2. Study design and treatments

Hydrologic calibration of the watersheds took place between 2 February 1988 and 19 March 1990 when all three watersheds were treated identically in terms of weir level in the outlet ditch. During this period, the weir depths were varied among depths of 1.0 m, 0.8 m and 0.6 m from the ground surface in all watersheds at the same time. This was done with the objective of describing the hydrology of the system and to ensure that the hydrologic response to weir level treatments was similar among the watersheds (McCarthy et al., 1991).

From 19 March 1990 to 16 March 1993, three water level management treatments were studied with the following objectives:

(A) Watershed 1: conventional or 'free' drainage. The weir level (bottom of notch) at the ditch outlet of the watershed was set at a depth of 1.0 m below the mean surface elevation of the watershed for the duration of the study. Generally, the average effective depth of lateral ditches in drained forested lands in the region is about 1.0 m from the surface. When this study was initiated, all lateral ditches were uniformly cleaned to a depth of 1.4 m to provide for uniformity and to allow for free board and operation of flashboard risers.

(B) Watershed 2: higher weir levels (shallower depth) during the growing season to conserve soil water to enhance tree growth. Weir depth at the ditch outlet of the watershed was set at 1.0 m from 1 December to 15 June and at 0.6 m from 16 June to 30 November.

(C) Watershed 3: raised weir levels (shallower depth) during spring months to reduce drainage outflows and minimize downstream impacts. Weir depth at the ditch outlet of the watershed was set at 1.0 m from 1 December to 15 March, at 0.4 m from 16 March to 15 June and at 0.8 m from 16 June to 30 November.

The dates and times of V-notch weir settings used for computation of drainage outflows across the weir, and the periods of time of weir submergence at the watershed outlets, have been reported by Amatya (1993).

## 2.3. Water balance and its components

All components of the water balance except deep seepage were either directly measured or calculated from measured variables. The water balance for the entire forest watershed was described by

$$R = I + D + \text{ET} + DS \pm L \pm \Delta S_a \tag{1}$$

where $R$ is total rainfall (mm), $I$ is forest canopy interception loss (mm), $D$ is drainage system outflow (mm), ET is dry canopy transpiration and soil water evaporation (mm), $DS$ is deep seepage (mm), $L$ is lateral seepage across watershed boundaries (mm) and $\Delta S_a$ is change in soil air or soil water volume (mm). Water balance components were expressed as volumes per unit area. Rainfall records, measured with tipping bucket rain gauges, were processed to obtain hourly totals for the water balance.

Forest canopy interception loss was calculated with a rainfall interception model

described by McCarthy et al. (1991). The method uses the hourly canopy water balance suggested by Rutter et al. (1972) with hourly rainfall, daily LAI, canopy capacity, canopy closure and hourly weather parameters as main input parameters.

The method of Leyton et al. (1967) was used to evaluate the maximum canopy storage capacity of the stand using rainfall, throughfall and stemflow data collected for 38 storm events up to April 1992. This was verified with daily canopy capacity estimated as a function of LAI (Spittlehouse and Black, 1981):

$$C = (0.2 \text{ mm})(\text{LAI}) \tag{2}$$

where $C$ is canopy storage capacity (mm) and LAI the leaf area index ($m^2$ $m^{-2}$).

Before the thinning, canopy closure was estimated to be 85%. After thinning in October 1988, closure was reduced to about 50% as shown in Fig. 2. The canopy closure function over the life of a pine plantation after thinning was based on estimates by McCarthy et al. (1991). A visual estimate at the research site during February 1992 indicated canopy closure was about 70%, representing a 20% increase after thinning in October 1988 and fertilization in 1989. Daily canopy closure was assumed to be a simple linear function that approximately follows the pattern of LAI function. It increases rapidly from 1 May to 1 August, when LAI attains a peak, and drops slowly from 1 August to 30 November. No growth was assumed during the period 1 December–30 April. It was assumed that recovery of the full canopy cover of 85% would be attained by 1994. The plot in Fig. 2 illustrates the canopy growth function as compared with LAI.

In the water balance model, ET is assumed to be the sum of dry transpiration ($E_t$) and soil evaporation ($E_s$). McCarthy et al. (1991) and Amatya (1993) estimated transpiration losses for the fraction of the canopy that is dry using the Penman–Monteith method. Assuming the similarity of the total aerodynamic transfer coefficients $g_a$ (equal to $1/r_a$), for sensible heat and water vapor, the equation was written in the following form (Whitehead and Kelliher, 1991):

$$E_t = \left[1 - \frac{C_{j-1}}{S}\right] \left\{ \frac{sn_r + (\rho c_p D / r_a)}{\lambda [s + \gamma(1 + r_c / r_a)]} \right\} \tag{3}$$

where $C_{j-1}$ is water stored in the canopy in the $(j-1)$th time period, $S$ is canopy storage capacity, $s$ is slope of the curve relating saturated vapor pressure to temperature at the appropriate air temperature, $\gamma$ is psychrometric constant, $c_p$ is specific heat of air, $\rho$ is density of air, $\lambda$ is latent heat of vaporization, $n_r$ is net radiation, $D$ is vapor pressure deficit, $r_a$ is aerodynamic resistance, and $r_c$ is canopy resistance. Tree canopy resistance, $r_c$, is given by $1/(\text{LAI}g_s)$ where $g_s$ is stomatal conductance. Hourly stomatal conductance ($g_s$) was calculated based on a regression submodel developed by using the measured porometer data averaged from the three watersheds with corresponding hourly weather variables such as air temperature, net radiation, air saturation deficit and a seasonal factor (Amatya, 1993). Soil evaporation was estimated as a proportion of the total evaporative potential, which was inversely related to the function of the LAI (McCarthy et al., 1991).

As the dry canopy transpirational losses estimated by the Penman–Monteith method using the above approach were lower than expected for unlimiting soil

water conditions as reported by Amatya (1993), ET as the sum of dry transpiration and soil evaporation was calculated as the residual term in the water balance. In that case, evaporative losses owing to canopy interception were estimated using the Penman–Monteith method with zero canopy resistance. When the leaves are wet, $g_s \approx \infty$ or $r_c \approx 0$, and $E_i$ for the fraction of the canopy that is wet is calculated by using the simplified Penman–Monteith equation:

$$E_i = \frac{C_{j-1}}{S} \left[ \frac{sn_r + (\rho c_p D / r_a)}{\lambda(s + \gamma)} \right] \tag{4}$$

The aerodynamic resistance term $(r_a)$ in the Penman–Monteith equation as described by McCarthy et al. (1991) was recalculated as a function of canopy height, displacement height, roughness and wind speed (Rutter et al., 1972). A velocity profile method (Chow et al., 1988) was used to convert the wind speed measured at 12 m height into estimated velocity at 2 m above average canopy height.

Soil infiltration was assumed to be equal to throughfall precipitation $(R - I)$. The surface runoff to the ditches is negligible on the site because of the nearly flat natural land slope and the relatively large depressional storage that results from bedding of the site during planting. Outflow occurred mainly by subsurface drainage to the ditches; drainage outflow rates were computed using the 120° V-notch weir equation and water elevations measured upstream of the weir. Corrections for flows owing to weir submergence were performed using submerged weir equations. A FORTRAN program was used to compute daily cumulative outflows by numerical integration of the instantaneous rates.

Deep seepage was assumed to be negligible because the soil profile has a restrictive layer at about 2.8 m from the surface. Subsurface lateral seepage across the watershed boundaries was estimated by using the water levels of lateral and boundary ditches and applying the Dupuit–Forchheimer assumptions (Chescheir et al., 1986). The assumptions are: (1) streamlines are horizontal and the equipotentials are vertical; (2) the hydraulic gradient is assumed to be equal to the slope of the water table and is invariant with depth. During the weir treatment periods when the water levels in ditches in adjacent watersheds differed, the method described by Chescheir et al. (1986) was used to estimate the lateral seepage.

In the water balance calculations, drainage volume relationships derived from soil core data and neutron measurements of soil water content were used to make independent estimates of the air volume in the unsaturated zone. Water balances can be conducted between any of the days for which the change in soil air volume $\Delta S_a$ could be calculated based on transect well and neutron meter readings. Water table data from the transect wells were used to determine water table position between the ditches, thus defining the boundary between the saturated and unsaturated zones.

Water balances based on field measurements were computed for both the calibration and treatment periods to compute ET losses in each of the watersheds under different treatments. Water balances were also computed for different seasons within the treatment periods to study the ET rates as affected by water table treatments in each of the watersheds. For the dry periods with deeper water table depths, neutron meter measurements were used to estimate soil water storage in the water balance,

and for the wetter periods with shallower water table depths, transect well measurements were used. This was done to minimize the errors in water balance, as suggested by McCarthy et al. (1991) and Amatya (1993).

### 2.4. Rainfall–drainage outflow analyses

Hourly rainfall data from the gauging stations were analyzed to obtain daily, monthly and annual totals for each watershed. Daily totals were used to perform double mass curve analyses for each pair of watersheds. A double mass curve is a graph of cumulative catch at the rain gauge of interest versus the cumulative catch of another gauge in the same vicinity. This analysis is usually performed to examine the consistency of gauges and/or to estimate or adjust missing data. Mean monthly, monthly, and annual rainfall data were used to describe the annual and seasonal variation as well as variation among the watersheds. The gross annual evaporation as the difference between gross rainfall and drainage outflow data was compared with annual reference evapotranspiration (REF-ET) computed by the Penman–Monteith method using a grass reference for the data from the weather station at the study site (Amatya et al., 1995). Frequency analyses of daily drainage outflows were performed for both calibration and treatment periods.

## 3. Results and discussion

### 3.1. Outflow processes

Outflow processes on the Carteret 7 site are typical of those in pine plantations with pattern drainage systems on pocosins and wet flats throughout the Southeast. On undrained sites with natural pine or pine–hardwood stands, outflow occurs as very slow subsurface drainage or seepage with slow surface runoff during high rainfall periods. These processes are dominated by shallow water tables that result from the combination of very low relief, microtopography that produces high surface detention storage, and aquitards within a few meters of the surface. On the Carteret 7 site, average slope is about 0.1% and saturated hydraulic conductivity measured by auger hole method in the upper soil layers ranged from 0.4 to 17.8 m day$^{-1}$, with an average of about 3.9 m day$^{-1}$ (McCarthy et al., 1991). A restrictive layer that begins at an average depth of about 2.8 m limits vertical seepage.

Outflow processes on drained pine plantations consist principally of subsurface flow to the lateral ditches and then channel flow to the watershed outlet. The purpose of bedding (20 cm average height) during site preparation is to create well-drained microsites on the bed tops for planting the seedlings. The ridge and valley microtopography created by bedding enhances surface detention storage capacity and precludes surface runoff (overland flow) except for the highest rainfall events. High infiltration capacity in the surface soil layer results in complete infiltration of the net rainfall that reaches the surface. Subsurface drainage to the ditches is coupled with relatively slow channel flow in much of the drainage system. Low relief, high

roughness in the ditches, and limited capacity of the outlets limit the discharge rates. In the case of the small, artificial watersheds at Carteret 7, outflow also occurs as lateral seepage (positive or negative) across the watershed boundaries. It was separately accounted for by lateral seepage estimates.

### 3.2. Rainfall

Mean monthly rainfall averaged over a 5 year (1988–1992) period for three water-sheds is presented in Fig. 3. July and August receive the largest amounts of rain, and the smallest amount occurs in February and June. More than 35% of the total annual rainfall in these years occurred during July–September. This pattern is consistent with long-term means observed in Morehead City (15 km from Carteret 7) and is due primarily to the frequent intense storms and infrequent hurricanes which occur during the summer in the coastal areas. Mean annual rainfall averaged over 5 years (1988–1992) for all three watersheds was 1500 mm, which is 12% higher than the long-term annual rainfall of 1340 mm at Morehead City. Variations in year-to-year total rainfall among the watersheds as compared with the long-term annual mean are shown in Table 3. Thus, 1989 was the wettest and 1990 the driest of the study years.

A wide variation in rainfall during some months was observed among the water-sheds despite the similarity of gauging stations and their locations in each of the watersheds. The rain gauge at Watershed 1 is about 800 m north of the rain gauge at Watershed 3. Watershed 1 recorded both the highest annual rainfall and the highest mean monthly rainfall for 11 of the 12 months (Fig. 3). Watershed 3 had the lowest mean monthly rainfall for 10 of 12 months. Watershed 1 had 26% and 29% more rainfall than Watershed 3 in August 1990 and July 1992, respectively. However, in June 1991, 27% more rainfall was recorded at Watershed 3 than in Watershed 1. In general, such large differences in rainfall amounts were observed during the stormy summer months. Gauges at Watersheds 2 and 3 consistently recorded lower rainfall
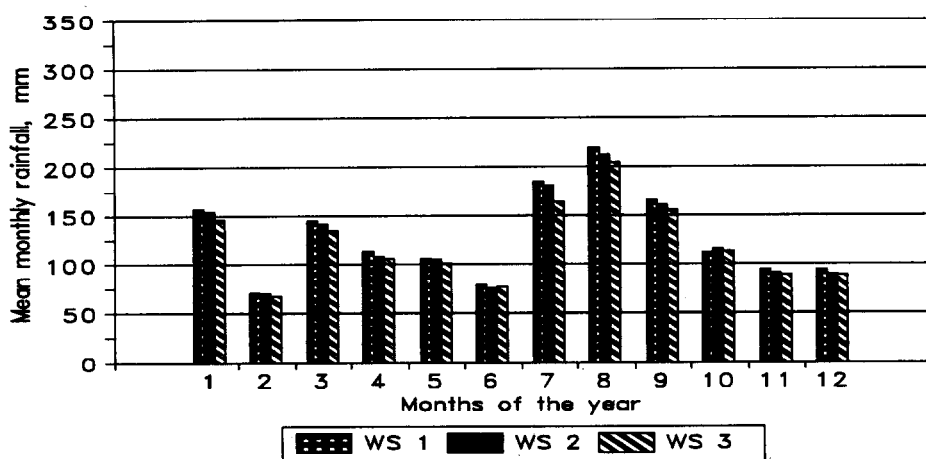


Fig. 3. Mean monthly rainfall averaged over a 5 year period for three watersheds at Carteret 7, NC.

Table 3
Annual rainfall, drainage, gross total evaporation and Penman–Monteith REF-ET for a 5 year (1988–1992) period

| Year | Rainfall (mm) | | | Drainage (mm) | | | Gross total evaporation (mm) | | | Annual REF-ET (mm) |
|------|------|------|------|------|------|------|------|------|------|------|
|      | WS 1 | WS 2 | WS 3 | WS 1 | WS 2 | WS 3 | WS 1 | WS 2 | WS 3 | |
| 1988 | 1406 | 1380 | 1371 | 209 | 255 | 240 | 1197 | 1125 | 1131 | 1041 |
| 1989 | 1876 | 1829 | 1768 | 658 | 642 | 553 | 1218 | 1187 | 1215 | 945 |
| 1990 | 1236 | 1192 | 1109 | 240 | 193 | 150 | 996 | 998 | 958 | 1031 |
| 1991 | 1575 | 1508 | 1478 | 492 | 313 | 472 | 1083 | 1195 | 1006 | 917 |
| 1992 | 1619 | 1616 | 1519 | 584 | 363 | 447 | 1035 | 1253 | 1072 | 782 |

Gross total evaporation = rainfall – drainage. REF-ET, reference ET computed by Penman–Monteith for grass reference (Amatya et al., 1995). Long-term mean annual rainfall for Morehead City, NC, is 1339 mm.

as compared with the gauge at Watershed 1. The difference in cumulative rainfall was greatest between Watershed 1 and Watershed 3 (Amatya, 1993). The average annual rainfall at Watershed 1 was higher by 2.4% and 6% than at Watersheds 2 and 3, respectively. As the rainfall data collected from the automatic tipping bucket rain gauges were always verified from the nearby standard manual rain gauge, it is unlikely that differences between watersheds are due to instrumental errors. Effects of wind, wind direction and the prevailing direction of storm movement are the more likely causes of the differences.

## 3.3. Interception

Interception loss depends on both weather and forest canopy characteristics such as canopy closure, LAI, and canopy capacity. The amount of water intercepted by the canopy during a given hour or day may be lost by evaporation at a later time, but not necessarily during the same day. Based on the storage in the canopy and prevailing environmental conditions, both evaporation from wet surfaces and dry transpiration can occur during a given period. Water would evaporate from the wet surfaces at the beginning of the period followed by transpiration at the end.

Canopy capacity, estimated by the method of Leyton et al. (1967) and using data of storm events up to 1992, was 1.9 mm (Amatya, 1993) as compared with 1.2 mm reported by McCarthy et al. (1991) for 1989. The earlier study by McCarthy et al. (1991) assumed a constant aerodynamic resistance ($r_a$) of 5.98 for estimating dry transpiration as well as wet canopy evaporation using the Penman–Monteith method. However, analysis using Eq. (4) showed that the estimated wet canopy evaporative losses were very sensitive to change in aerodynamic resistance (Amatya, 1993). The method with constant $r_a$ overpredicted interception loss by as much as 42%. This was consistent with the studies reported by Whitehead and Kelliher (1991), who reported that tree height (which determines aerodynamic roughness), wind speed and vapor pressure deficit are the critical factors affecting wet canopy evaporation

Table 4
Fieldbased water balance estimates for the calibration period, Day 33–809 (2 February 1988–19 March 1990)

| Water balance component | Watershed | | |
|---|---|---|---|
| | WS 1 | WS 2 | WS 3 |
| Gross rainfall (mm) | 3273 | 3194 | 3113 |
| Interception loss (mm) | 549 | 543 | 530 |
| Drainage volume (mm) | 931 | 892 | 864 |
| Lateral seepage (mm) | 104 | 105 | 56 |
| Change in soil water storage (mm) | −7 | 0 | −13 |
| Water balance ET (mm) | 1696 | 1654 | 1676 |
| Total ET (mm) | 2245 | 2197 | 2206 |
| Mean daily total ET (mm) | 2.9 | 2.8 | 2.8 |

WS 1, free drainage; WS 2, tree growth; WS 3, Minimum spring runoff (offsite impacts). Evapotranspiration (ET) − transpiration + soil evaporation. Water balance ET − residual term in water balance. Total ET = water balance ET + interception loss.

rate (evaporation during and immediately after rainfall). Canopy interception loss as high as 1.1 mm h$^{-1}$ was estimated for a storm event of 22 July 1988. Interception loss was also found to be sensitive to change in the LAI parameter.

The interception loss per storm ranged from 5 to 25% of the gross rainfall. Water balance estimates given in Table 4 for the calibration period yielded an interception loss of about 17.5% of the total rainfall for all three watersheds, in comparison with 15% for the treatment period given in Table 5. The lower interception during the treatment period is the result of thinning in October 1988. Some of the variability in interception loss between watersheds is due to the variability in rainfall among the watersheds.

Table 5
Field-based water balance estimates for the treatment period, Day 809–1846 (19 March 1990–19 January 1993)

| Water balance component | Watershed | | |
|---|---|---|---|
| | WS 1 | WS 2 | WS 3 |
| Gross rainfall (mm) | 4446 | 4333 | 4131 |
| Interception loss (mm) | 636 | 609 | 606 |
| Drainage volume (mm) | 1357 | 896 | 1086 |
| Lateral seepage (mm) | 235 | 255 | 168 |
| Change in soil water storage (mm) | −38 | −60 | −23 |
| Water balance ET (mm) | 2256 | 2633 | 2294 |
| Total ET (mm) | 2892 | 3242 | 2900 |
| Mean daily total ET (mm) | 2.8 | 3.1 | 2.8 |

WS 1, free drainage; WS 2, tree growth; WS 3, Minimum spring runoff (offsite impacts). Evapotranspiration (ET) = transpiration + soil evaporation. Water balance ET = residual term in water balance. Total ET = water balance ET + interception loss.

Table 6
Measured water balance parameters (in millimetres) for different periods of treatment in 1990–1993

|  | Day 816–Day 894 26 Mar. 1990–12 June 1990 | | | Day 909–Day 1061 17 June 1990–26 Nov. 1990 | | | Day 1166–Day 1222 11 Mar. 1991–6 May 1991 | | |
|---|---|---|---|---|---|---|---|---|---|
|  | WS 1 | WS 2 | WS 3 | WS 1 | WS 2 | WS 3 | WS 1 | WS 2 | WS 3 |
| Rainfall | 361 | 347 | 334 | 590 | 567 | 515 | 176 | 157 | 148 |
| Intercept | 38 | 36 | 34 | 98 | 96 | 90 | 23 | 21 | 22 |
| Drainage | 130 | 102 | 36 | 0 | 0 | 0 | 35 | 36 | 0 |
| Lateral seepage | 13 | 9 | 13 | 28 | 27 | 19 | 20 | 19 | 17 |
| Change in soil water storage | -49[a] | -48[a] | -45[a] | 57[b] | 37[b] | -11[b] | -8[a] | -7[a] | -12[a] |
| Water balance (ET) | 229 | 248 | 296 | 407 | 407 | 417 | 106 | 88 | 121 |
| Total ET | 267 | 284 | 330 | 505 | 503 | 507 | 129 | 109 | 143 |
| Mean daily total ET | 3.4 | 3.6 | 4.2 | 3.3 | 3.3 | 3.3 | 2.3 | 1.9 | 2.5 |

|  | Day 1271–Day 1435 24 June 1991–5 Dec. 1991 | | | Day 1558–Day 1628 6 Apr. 1992–15 June 1992 | | | Day 1628–Day 1789 15 June 1992–23 Nov. 1992 | | |
|---|---|---|---|---|---|---|---|---|---|
|  | WS 1 | WS 2 | WS 3 | WS 1 | WS 2 | WS 3 | WS 1 | WS 2 | WS 3 |
| Rainfall | 833 | 816 | 801 | 243 | 243 | 228 | 812 | 812 | 743 |
| Intercept | 134 | 125 | 130 | 33 | 33 | 34 | 112 | 113 | 111 |
| Drainage | 155 | 23 | 91 | 4 | 3 | 0 | 173 | 18 | 94 |
| Lateral seepage | 32 | 48 | 24 | 14 | 13 | 11 | 29 | 39 | 18 |
| Change in soil water storage | 156[b] | 170[b] | 149[b] | -13[a] | -16[a] | -19[a] | 32[b] | 156[b] | 33 |
| Water balance (ET) | 356 | 450 | 407 | 205 | 210 | 202 | 465 | 486 | 487 |
| Total ET | 490 | 575 | 537 | 238 | 243 | 236 | 577 | 599 | 598 |
| Mean daily total ET | 3.0 | 3.5 | 3.3 | 3.4 | 3.4 | 3.3 | 3.6 | 3.7 | 3.7 |

WS 1, free drainage; WS 2, tree growth; WS 3, minimum spring runoff (offsite impacts).
Evapotranspiration (ET) = transpiration + soil evaporation. Water balance ET = residual term in water balance. Total ET = water balance ET + interception loss.
[a] Air volume measured by drainage volume curve method for spring season.
[b] Air volume measured by Neutron Meter method for summer–autumn season.

## 3.4. Evapotranspiration

Evapotranspiration (ET) as the sum of dry canopy transpiration and soil evaporation was shown to be a significant component (65% of total rainfall) of the forest water balance (McCarthy et al., 1991). Analyses of data up to 1991 were used to show the effects of previous days' rainfall on ET losses and seasonal pattern of ET for these watersheds (unpublished data). Evapotranspiration was shown to have the greatest impact on water table elevations, indicating that optimizing leaf area, which increases ET, will lower water tables during the growing season. Sensitivity analyses showed that stomatal conductance has a significant effect on dry canopy transpiration estimated by the Penman–Monteith method (Amatya, 1993). However, transpiration loss was not found to be sensitive to changes in $r_a$. Detailed results of the effects of ET on drainage and water table depths are discussed in the following sections.

Total evaporation (TE) as the sum of dry transpiration, soil evaporation and evaporation of intercepted rainfall was calculated to be 70% of the gross rainfall for the water balance for the calibration period (Table 4). Whitehead and Kelliher (1991), using methods similar to those described herein, estimated transpiration and evaporative losses from a 13-year-old *Pinus radiata* stand in northern New Zealand to be about 50% and 22%, respectively, of the annual rainfall. The mean daily total evaporation for the three watersheds ranged between 2.8 and 2.9 mm during the calibration period. During the controlled drainage treatment, total evaporation for the watersheds ranged between 65% of gross rainfall for Watershed 1 (free drainage) and 74% for Watershed 2 under the tree growth treatment (Table 5). As a result, the evaporative losses for Watershed 2 were about 17% and 15% higher than those for Watersheds 1 and 3, respectively.

Seasonal water balance estimates during the years with controlled drainage are presented in Table 6. In the summer of 1991, ET estimates for watersheds with controlled drainage were higher than for watershed under free drainage as a result of lower drainage outflows. There was adequate soil water in summer 1992 to supply ET demands. The mean daily total evaporation rate was as high as 3.7 mm during that period. The grass reference mean daily REF-ET for that period was about 25% lower than the estimated mean daily total evaporation rate. Past studies have shown that in forested watersheds, TE losses can exceed the grass reference REF-ET rates simply because of the effects of surface roughness of taller trees and heat advection from surrounding areas.

McCarthy et al. (1991) estimated potential ET of 10.3 mm day$^{-1}$ for the summer period (Days 140–209, 1988) assuming a stomatal conductance of 0.08 mol m$^{-2}$ s$^{-1}$, which was the highest observed on the site during that period. This average PET value of 10.3 mm day$^{-1}$ is much higher than published data for this region (Amatya et al., 1995). This high value of PET is probably due to an assumption of a constant aerodynamic resistance in the Penman–Monteith method together with an assumption of constant stomatal conductance. Assuming an aerodynamic resistance as a function of wind speed, however, a more reasonable value for the average PET of 5.6 mm day$^{-1}$ was estimated for the same summer period. The annual REF-ET calculated by the Penman–Monteith grass reference method (Amatya et al., 1995)
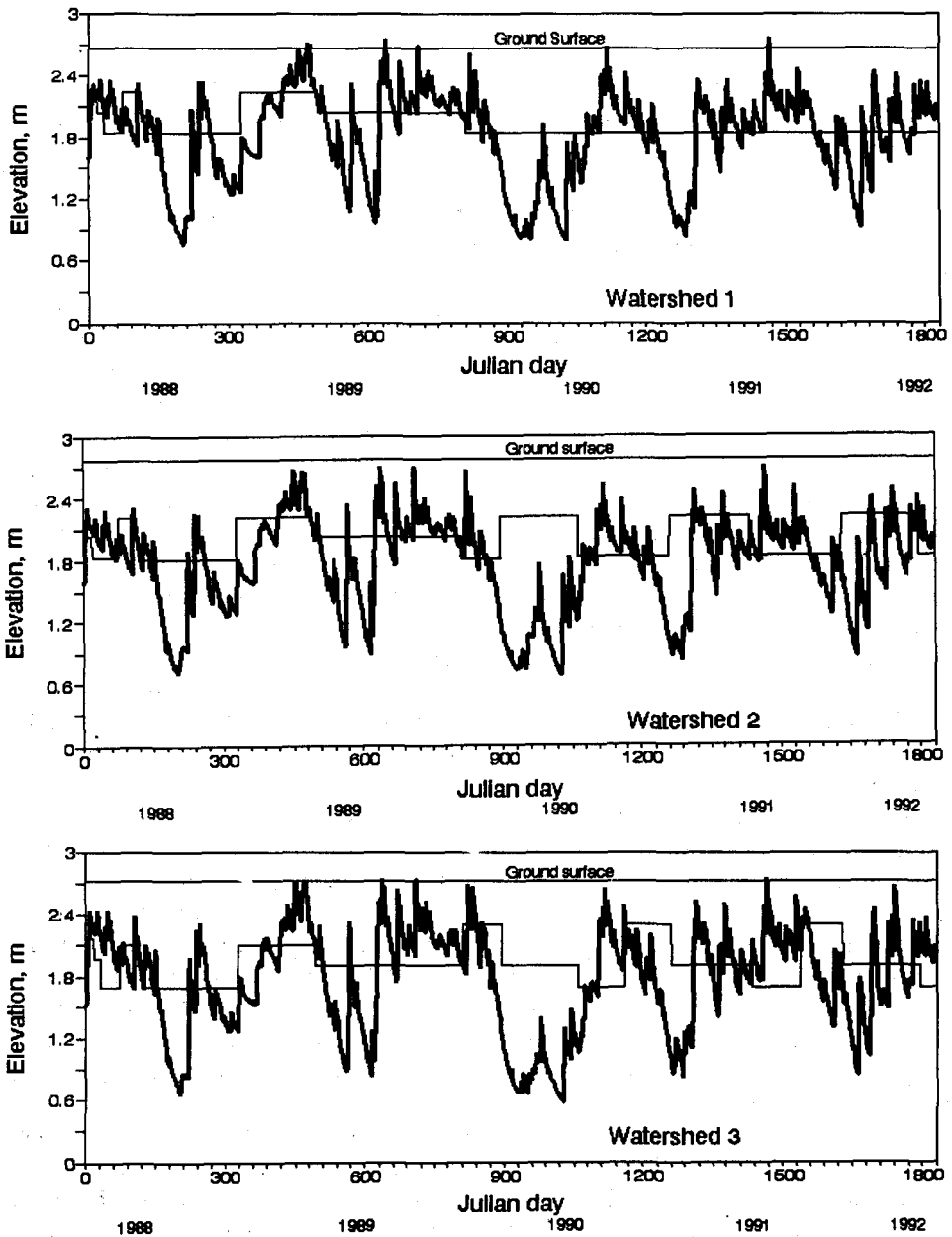
Fig. 4. Measured midpoint water table elevations (thick continuous line) and weir elevations (thin continuous line) for the period 1988–1992 for three watersheds at Carteret 7, NC. The second thin continuous line at the top of each graph is the average ground surface elevation.

is listed in Table 3. Highest annual REF-ET was calculated for the year 1988 followed by 1990.

The gross annual evaporation as the difference between gross precipitation and drainage outflows (runoff) for the 5 years of the record period is presented in Table 3. The gross annual evaporation is composed of ET, evaporation of intercepted rainfall, lateral and deep seepage, and the difference in soil water storage. Deep seepage was assumed negligible for this study and the difference in soil water storage between the beginning and end of a long-term water balance was usually small. Although the average 1989 total annual rainfall for the three watersheds was about 31% higher than in 1988, the gross average evaporation for three watersheds was only about 5% higher in 1989 than in 1988, indicating that neither the soil moisture nor the LAI was a significant factor limiting ET losses for those years. Furthermore, lower REF-ET and reduced LAI were observed in 1989 after thinning in October 1988. That the nearly equal gross evaporation was lower than annual REF-ET in all three watersheds in 1990 was probably due to ET being limited by soil water deficits during the dry summer months. Except for 1990, the estimated annual REF-ET was consistently lower than gross total ET. The difference was always greater than 10% and as much as 27.5% (in 1989) for all three watersheds. In 1990 REF-ET was higher, but just by 5%. These results show that the availability of soil water during the growing season when REF-ET is high makes a significant difference in water loss by ET.

### 3.5. Water table depths, drainage and lateral seepage

Daily water table depths measured at the midpoint of each of the three watersheds and corresponding weir elevations are presented in Fig. 4. The flow frequency duration curves of observed daily flows are plotted in Fig. 5(a) for the calibration period. They show that frequency and duration of daily flows for Watersheds 1 and 2 are almost the same. More than 95% of time, daily flows from all three watersheds were almost the same. Daily flows greater than about 7 mm occurred 5% of the time in all three watersheds. However, the magnitude of the largest flows in Watershed 3, for example, was substantially less than those in Watersheds 1 and 2. The largest flow rate, observed about 0.1% of the time in Watershed 3, was about half that observed in other two watersheds.

The effects of water table treatment on drainage flows are clearly shown by the comparison of flow duration curves for the treatment period in Fig. 5(b). This plot excludes daily flow data for the winter period when all weirs were at the same depth (Fig. 4). Flow occurred for a smaller percentage of time in Watersheds 2 and 3 than in Watershed 1, and flows of the same frequency were always smaller in Watersheds 2 and 3 than in Watershed 1. Watershed 3, with the weir set to reduce offsite impacts during the spring (Fig. 4), resulted in the lowest flows for about 96% of the time (Fig. 5(b)). However, it yielded higher frequency of larger flows (more than 2 mm day$^{-1}$) than Watershed 2, which had a shallower weir during the summer. The larger peak flows in Watershed 3 were the result of larger events of the summer storms when the weir level in Watershed 3 was 0.20 m lower than in Watershed 2. However, the comparison of flow duration curves for the period from middle of March to middle
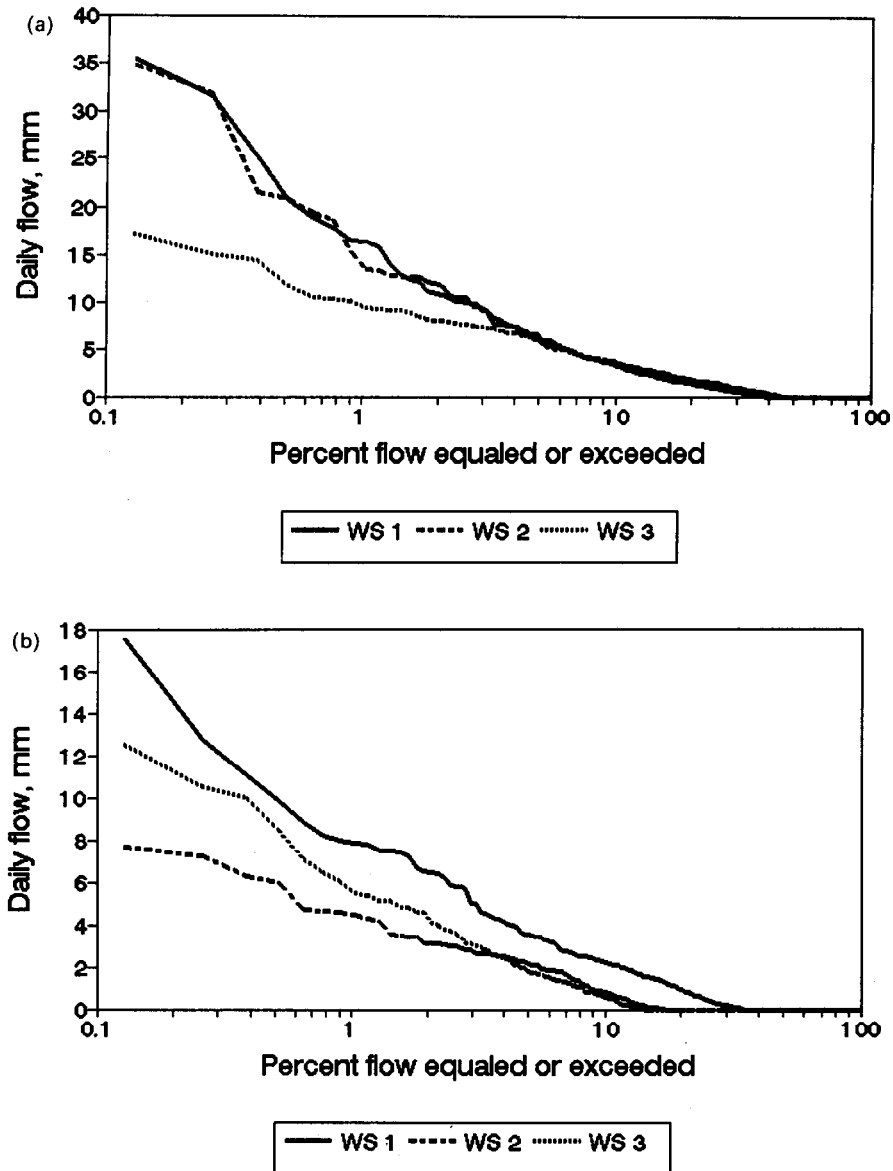
Fig. 5. (a) Flow duration curves of observed daily drainage flows for calibration period (2 February 1988–19 March 1990) for three watersheds at Carteret 7, NC. (b) Flow duration curves of observed daily drainage flows for treatment period (19 March 1990–16 March 1992) for three watersheds at Carteret 7, NC. Flows from winter period, when all the weirs at the same depth, were excluded. (c) Flow duration curves of observed daily drainage flows for treatment period in the spring (15 March–15 June) during 1990–1993 period for three watersheds at Carteret 7, NC.

of June in Fig. 5(c) clearly illustrates the significant impact of controlled drainage in reducing peak flow rates and total flow volumes in Watershed 3 as compared with the other two watersheds during the spring season.

Annual observed drainage outflow volumes over the 5 year period are presented in Table 3. In 1988, the drainage volume of Watershed 1 was about 22% lower than that of Watershed 2 and about 15% lower than that of Watershed 3. The main reasons for these differences were the higher weir level in Watershed 1 in January (Fig. 4). In 1989, the drainage volumes in Watersheds 1 and 3 were similar. However, the 16% lower drainage volume in Watershed 3 as compared with Watershed 1 was due to errors in flow measurements during the submerged events of 1989. At a somewhat lower elevation, Watershed 3 was submerged longer than the other two watersheds. The annual drainage volume data for 1990, 1991 and 1992 reflect the effects of the water table treatment. As expected, Watershed 1 (conventional drainage) with the weir at 100 cm depth yielded the highest annual drainage volumes in all 3 years. In comparison with Watershed 1, drainage from Watershed 2 (controlled drainage) was 20%, 36% and 38% lower in 1990, 1991 and 1992, respectively.

About 28% of the gross rainfall for each watershed was accounted for as drainage in the water balance for the calibration period (Table 4). Lateral seepage was slightly more than 3% of gross rainfall. However, seepage from Watershed 3, situated on the lowest elevation, was approximately half that estimated for the other watersheds.

The effect of treatment on total drainage volume was most marked in Watershed 2, which had a drainage volume of about 21.5% of gross rainfall (Table 5). The drainage volume for Watershed 3 was 27% of rainfall as compared with 30% for Watershed 1 (conventional drainage). Higher ditch water levels during controlled drainage
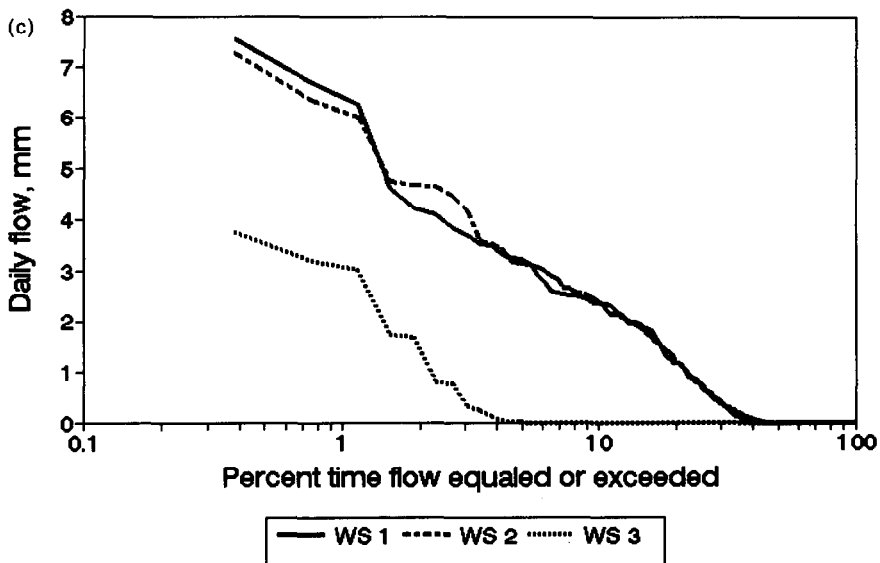


Fig. 5. (continued).

increased lateral seepage from the watersheds. As expected, lateral seepage was greatest for Watershed 2 at 5.9% of the rainfall. Lateral seepages for Watershed 1 and 3 were about 5.3% and 4.0% of the rainfall, respectively.

The effects of weir treatment are especially noticeable during the relatively wet summer of 1991, when Watershed 2, with a raised weir (Fig. 4), produced much lower drainage as compared with Watershed 1 (Table 6). Much of the water conserved by controlled drainage in Watershed 2 was apparently lost to ET, lateral and/ or deep seepage. As deep seepage is assumed negligible for the region, the loss was primarily the result of ET. Impacts of the controlled drainage treatment were smaller in the summer of 1992, probably because of higher antecedent moisture conditions than in 1991. The effects could not be observed in 1990 because of the long dry summer with deeper water table depths (Fig. 4) with no outflow from all three watersheds. Rainfall that did occur was stored in the dry soil and removed by ET. There was relatively little difference in available soil water and, as a result, losses owing to ET and drainage in that period. The 0.40 m weir depth of Watershed 3 resulted in considerably lower drainage volumes during the springs of 1990 and 1991 and no flow at all during the spring of 1992 as compared with conventional drainage in Watershed 1. A 0.20 m difference in weir level from June to November resulted in consistently lower drainage from Watershed 3 than from Watershed 1.

## 4. Conclusions

Mean annual rainfall of 1500 mm averaged over three watersheds for 5 years was about 12% above the long-term average rainfall of 1340 mm recorded at Morehead City. Spatial variation in annual rainfall was noted among the three adjacent watersheds. Wet canopy interception losses accounted for about 15% of the gross rainfall during the calibration period. Dry transpiration and soil evaporation together (ET) contributed as much as 54% of rainfall. However, for the treatment period, ET losses of as much as 61% were estimated for Watershed 2, which had a higher water table treatment during the growing season. This resulted in total evaporation including interception losses of 75% of gross rainfall. Total evaporation in Watershed 2 under controlled drainage was about 12% higher than in Watershed 1 under conventional drainage.

Soil drainage was the second most important component in the water balance. It was affected by water table treatment only for periods when water table was high. That effect of treatment on drainage was typically of shorter duration and was controlled by rainfall and ET. Most of the drainage occurred when ET was low during the winter periods with frequent long duration rainfall. For example, drainage alone accounted for 82% of the losses of the gross rainfall, and ET about 16% during the winter of 1992. A small portion of total rainfall was lost from the watersheds by lateral seepage. The largest estimate of lateral seepage, about 8% of gross rainfall, occurred in the spring of 1991.

Analyses of drainage outflow data clearly reflected the characteristics of drained forested watersheds and effects of weir treatments imposed on them. During the 3

year treatment period, drainage outflow volumes and peak rates were reduced by controlled drainage. This was most significant for Watershed 3, which was intended for reducing off-site impacts during the spring months. The frequency of smaller flows less than 3 mm day$^{-1}$ were almost the same in Watersheds 2 and 3 with two different treatments. However, effects of treatment on water tables were of short duration. Data for 3 years of treatment showed that controlled drainage can increase ET rates during periods when PET rates are high and soil water conditions may be limiting. Similarly, analyses of short-term water balances showed no difference in ET and drainage rates for watersheds under controlled drainage during extremely dry periods.

Studies need to be continued to provide additional experimental evidence of the effect of controlled drainage on the hydrology of drained forested soils, particularly as it affects partitioning of water lost by total evaporation and drainage.

## Acknowledgments

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