Hydrology and Management of Forested Wetlands
Proceedings of the International Conference 8-12 April 2006
Publication Date 8 April 2006
ASABE Publication Number 701P0406.

WATER BALANCE OF DRAINED PLANTATION WATERSHEDS IN NORTH CAROLINA

J. M. Grace III[1] and R.W. Skaggs[2]

ABSTRACT

A 3-year study to evaluate the effect of thinning on the hydrology of a drained loblolly pine (*Pinus taeda L.*) plantation was conducted in eastern North Carolina. The study utilized a paired watershed design with a 40-ha thinned watershed (WS5) and a 16-ha control watershed (WS2). Data from the field experiment conducted from 1999-2002 was used to perform a water balance over pre- and post-thinning monitoring periods to gain a better understanding of the interaction of hydrologic components on drained forested organic soil watersheds. Components included in the water balance were watershed outflow, change in soil water storage in the soil profile (ΔPS), and evapotranspiration (ET) (dry canopy transpiration + soil water evaporation + interception losses). Outflow accounted for 10 percent of the total observed precipitation for WS2 and 15 percent for WS5. The ΔPS based on field measurements was 20 and -3 mm over the entire study period for WS2 and WS5, respectively. Gross ET during the 3-year study period (2000-2002) represented 89 percent of total precipitation for WS2 and 85 percent for WS5 based on the field water balance. The field-based water balance was compared to DRAINMOD predicted water balance components over the entire study period. Predicted water balance components; outflow, ΔPS, and ET, were in close agreement with field-based water balance components over the study period. The differences in water balance components for the watersheds are primarily attributed to the reduced ET on WS5 as a result of the thinning operation.

KEYWORDS. Hydrology, Forest, Thinning, Water Management, Water Balance, Organic Soils

INTRODUCTION

A variety of forest types ranging from wetlands to uplands constitute the southern forest land base. Many of these southern forests are intensively managed and account for as much as 60 percent of U.S. production (Prestemon and Abt, 2002). Increased production from southern forests can be primarily attributed to intensive management practices and production from forests in terrain, such as wetlands and poorly drained sites that would have limited pine productivity without alternative management practices. Intensive forest management practices including drainage, thinning, site preparation, and fertilization, are utilized to increase site productivity and reduce rotation time. These practices are tools used by forest managers to manage forestlands for timber production while maintaining or improving the resource quality. These practices are essential to meet the ever-increasing demands for timber products.

Forested wetlands constitute approximately half of the 40 million ha of wetlands in the continental U.S (Wilen and Frayer, 1990). Wetlands are multi-faceted and provide a number of valuable environmental functions. They improve water quality by trapping and, in some cases, transforming pollutants such as sediment, nutrients, and chemicals. Wetlands also provide flood control, erosion control, groundwater recharge and discharge, and flow stabilization.

[1] U.S. Department of Agriculture, Forest Service, Southern Research Station, Forest Operations Research, 520 Devall Drive, Auburn, AL 36830. Phone: 334-826-8700. Fax: 334-821-0037. e-mail: jmgrace@fs.fed.us

[2] Biological and Agricultural Engineering Dept., North Carolina State University, Raleigh, NC.

Wetlands in the Southeastern states-- Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina-- account for nearly half (47 percent) of the wetlands in the continental United States (Hefner et al., 1994). Drainage is a common water management practice used to improve productivity and trafficability on coastal forestlands in the southern U.S. A network of drainage ditches and canals are commonly used to lower water tables on these lands, allowing species that are less water tolerant to be highly productive.

Common forest management practices on poorly drained southern forests include harvesting, thinning, fertilization, site preparation, improved drainage, and road construction and maintenance. Heavy mechanized equipment used to carry out prescriptions can also result in compaction, which increases surface runoff by reducing infiltration. The interaction of increased soil moisture and reduced infiltration generally results in increased forest outflow (water yield). Increases in forest outflow and water table rise have been observed following removal of timber and reduction in basal area, which increases available water by reducing evapotranspiration (Dube et al., 1995; Hibbert, 1966; Lebo and Herrmann, 1998; Richardson and McCarthy, 1994; Riekerk, 1983; Williams and Lipscomb, 1981). In addition, the combination of conditions resulting from harvesting has been reported to increase the amount of sediment and nutrients transported to water systems (Brown et al., 1973; Grace, 2004b; Grace, 2005; Harr and Fredriksen, 1988; Kochenderfer and Wendel, 1983; Leaf, 1970; Troendle, 1983; Troendle and King, 1987).

Drained plantation pine accounts for 1 million hectares in the coastal plain region from Virginia to Florida (McCarthy and Skaggs, 1992). Forest management operations have been reported to affect annual and seasonal outflow characteristics from these drained forest watersheds. The effect of management operations on hydrology and water quality in upland systems has been the primary focus of investigations on this subject. Little information is available on the effects of forest management on poorly drained or forested wetland landscape. Water yield and quality issues surrounding operations on forest watersheds, including poorly drained watersheds, have been an area of concern in recent years. This increased sensitivity to hydrologic impacts of forest operations has demanded progress in understanding and predicting impacts on poorly drained systems. Management prescriptions (e.g., thinning and harvesting) typically make the hydrologic processes more complex because they typically result in making poorly drained sites even wetter.

The hydrologic responses to forest operations in forested wetlands and drained forested systems are not well understood. This is especially true when the soils are organic. These lands, which are poorly drained in their natural condition, can behave differently than their un-drained counterparts. The complex interactions among evapotranspiration, runoff, infiltration, drainage, water table position, soil water distribution, and precipitation can make hydrologic water balances in drained watersheds difficult to quantify (Amatya et al., 1994). Forest management practices on these lands can affect hydrologic parameters, further complicating quantification of the water balance.

Data from a field experiment conducted from 1999-2002 was used to perform a water balance over pre- and post-thinning monitoring periods. The objectives of this paper were to describe the interactions of various hydrologic components and evaluate the effects of thinning on the hydrologic components of a drained loblolly pine (*Pinus taeda L.*) plantation watershed.

METHODS

The study area is located in the North Carolina Tidewater region in Washington County near Plymouth, North Carolina (Figure 1). The study area is flat and poorly drained in its natural condition with an average ground elevation of 4.1 – 4.5 m above mean sea level. The study area is artificial drained by a series of parallel drainage ditches spaced 100 m apart and 0.9 to 1.3-m deep. The parallel ditches drain to a roadside collector canal instrumented with a 120o V-notch weir located in a riser barrel structure. The soil is an organic Belhaven muck series (loamy, mixed, dysic, thermic Terric Mediprists). Soil organic matter contents are greater than 80 percent in the top 60 cm of the soil profile (O_a horizon). Bulk density, saturated hydraulic conductivity, soil water characteristics, and volume drained relationships were previously reported by Grace (2004a).

In 1999, the original 56-ha watershed was bisected into two subwatersheds, hereafter referred to as WS2 and WS5, by plugging the canal and installing an additional 120^o V-notch weir. The smaller 16-ha watershed, WS2, served as an un-thinned control watershed (Figure 1). A fifth-row thinning with selection was prescribed and conducted on the 40-ha watershed, WS5, in April 2001. The treated watershed was thinned from 1060 trees per hectare and basal area of 170 m^2 ha^{-1} to 320 trees per hectare and basal area of 51 m^2 ha^{-1}.

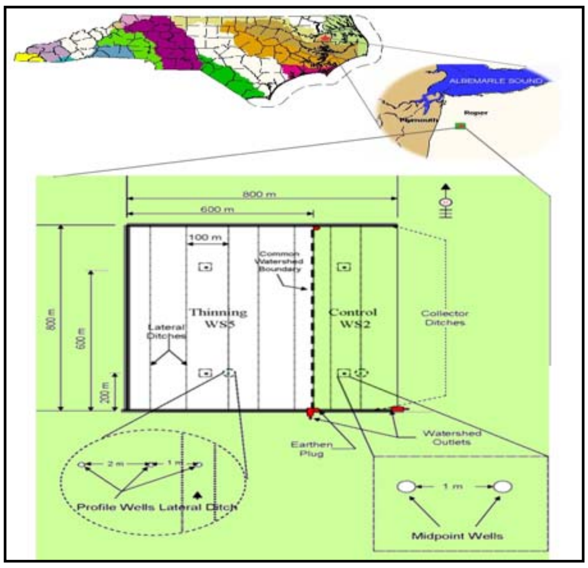

Figure 1. Location of study watersheds within the Tidewater region of North Carolina showing locations of water table wells, lateral ditches, and watershed outlets.

Figure 2. Typical outlet station setup with data logger enclosure, chart recorder, riser structure containing V-Notch weir, and backup ultrasonic water level logger.

Field Measurements

Watershed outflow, water table, precipitation, and weather parameters were intensively monitored over a 3-year period from December 1999 to January 2003. Stream stage in the collector canal was measured and recorded with submerged pressure transducers in conjunction with data loggers and chart recorders (Figure 2). In addition, backup measurement of stage was recorded using ultrasonic water level sensors and data loggers. Watershed outflow was determined using stage measurements for each subwatershed over the study period.

Water table depths were measured and recorded hourly with submerged pressure transducers in combination with data loggers at replicate midpoint wells and three profile wells. Precipitation was measured with tipping bucket rain sensors in combination with data loggers located within ½ km of the study watersheds. Recorded continuous breakpoint precipitation was converted to hourly rainfall.

Meteorological data were obtained from a 22-m high weather station tower located in the middle of a young plantation pine forest within 1 km of the study watersheds. The weather station is equipped with a Campbell Scientific CR 10X data logger and automatic sensors for continuous monitoring of air temperature, soil temperature, relative humidity, wind speed, wind direction, solar and net radiation. Half-hour average readings of all variables were recorded for use in estimating potential evapotranspiration. Sensors and weather station characteristics were described in detail by Amatya et al. (2000). Data from the Tidewater Research Station located 5 km to the north of the study sites were used during brief periods when temperature and relative humidity data were not available due to sensor malfunction.

RESULTS AND DISCUSSION

Leaf Area Index

Leaf area index (LAI) was estimated using methods defined by McCarthy and Skaggs (1992). This method involves calculating average leaf area per tree and projecting it on a per unit area basis. Tree leaf area was estimated using specific leaf area and dry foliage biomass. Specific leaf area ranging from 9 to 14 m^2 kg^{-1} was estimated for loblolly pine over a range of ages and canopy positions (Shelton and Switzer, 1984). Dry foliage weight was estimated using biomass regression equations for thinned and unthinned loblolly pine developed by Baldwin (1987). McCarthy and Skaggs (1992) used a normalized sinusoidal relationship between LAI and day of the year to estimate LAI by accounting for the seasonal variation of LAI (Figure 3). This relationship was used to estimate LAI for each day of the year.

The relationship given below was modified to estimate LAI for the watersheds during the three-year study period (2000-2002) which was characterized by weather conditions ranging from extremely dry to extremely wet. The drought conditions in 2001 likely had an effect on the LAI of the plantation watersheds. In an attempt to characterize the effect of drought conditions on LAI during 2001, peak LAI was reduced 10 percent during this year. Based on previous research, climate conditions and nutrition are reported to be limiting factors to production of loblolly pine (Albaugh et al., 1998; Vose and Allen, 1988; Woodman and Furiness, 1988). Annual needle biomass from unthinned loblolly pine stands has been reported to decline as much as 29 percent in drought conditions (Hennessey et al., 1992). A reduction in annual stand productivity would be expected with a reduction in needle biomass based on the relationship between LAI and annual net productivity developed by Vose and Allen (1988). Estimated LAI relationships for the thinned (WS5) and unthinned (WS2) watersheds are presented in Figure 4. The 5th row thinning resulted in a 50 percent reduction in LAI on day 460.

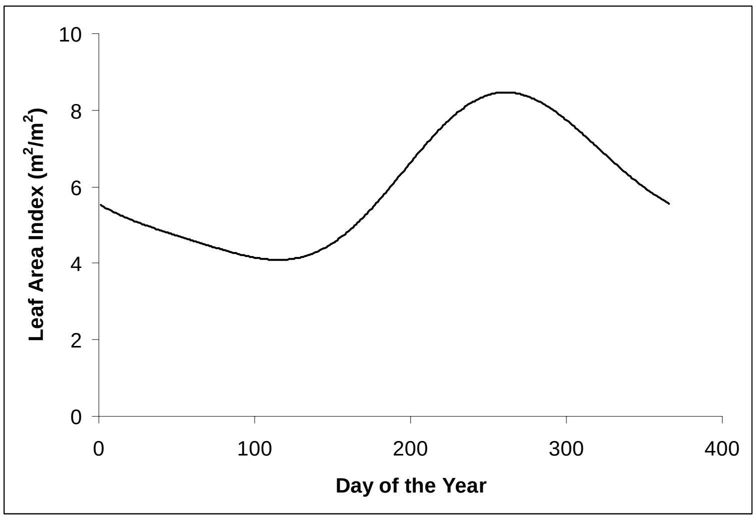

Figure 3. LAI relationship developed by McCarthy et al. (1992) for 14-year old plantation loblolly pine in Carteret County, NC.

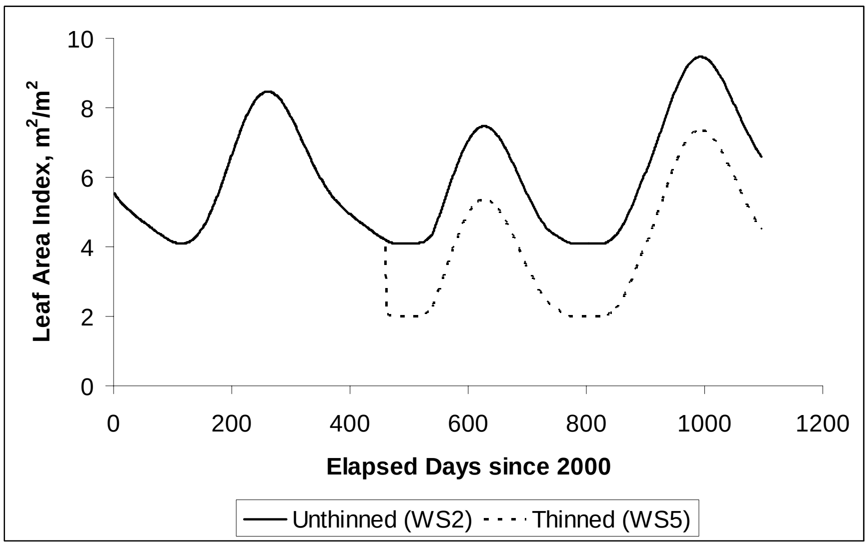

Figure 4. Estimated LAI used in determination of PET by the Penman-Monteith method for the WS2 and WS5 watersheds over the 3-year study period.

PET Estimation

The Penman-Monteith (P-M) method (Monteith, 1965) was utilized to calculate potential evapotranspiration (PET). The method uses measured hourly weather parameters, estimated LAI relationships, and a stomatal conductance (g_s) function developed by McCarthy et al. (1992) and further modified by Amatya et al. (1996) to determine PET. Cumulative PET for each study year for the watersheds is plotted in Figure 5. PET totaled 1100 mm for 2000 for both watersheds during this calibration year (Figure 5). Thinning in April 2001 reduced LAI for WS5 (Figure 4). This resulted in reduction in PET to 900 mm for 2001, which was 360 mm less than for WS2 (1260 mm total) (Figure 5). Similarly, PET calculated for the thinned watershed was 950 mm during 2002, which was less than the 1190 mm calculated for the unthinned watershed.

Water Balance

Outflow, water table depth, and weather data were used to perform a water balance on the two study watersheds over the 3-year study period (January 1, 2000-December 31, 2002) (Table 1). The water balance for watersheds is given by:

$$P = D + ET + \Delta PS$$

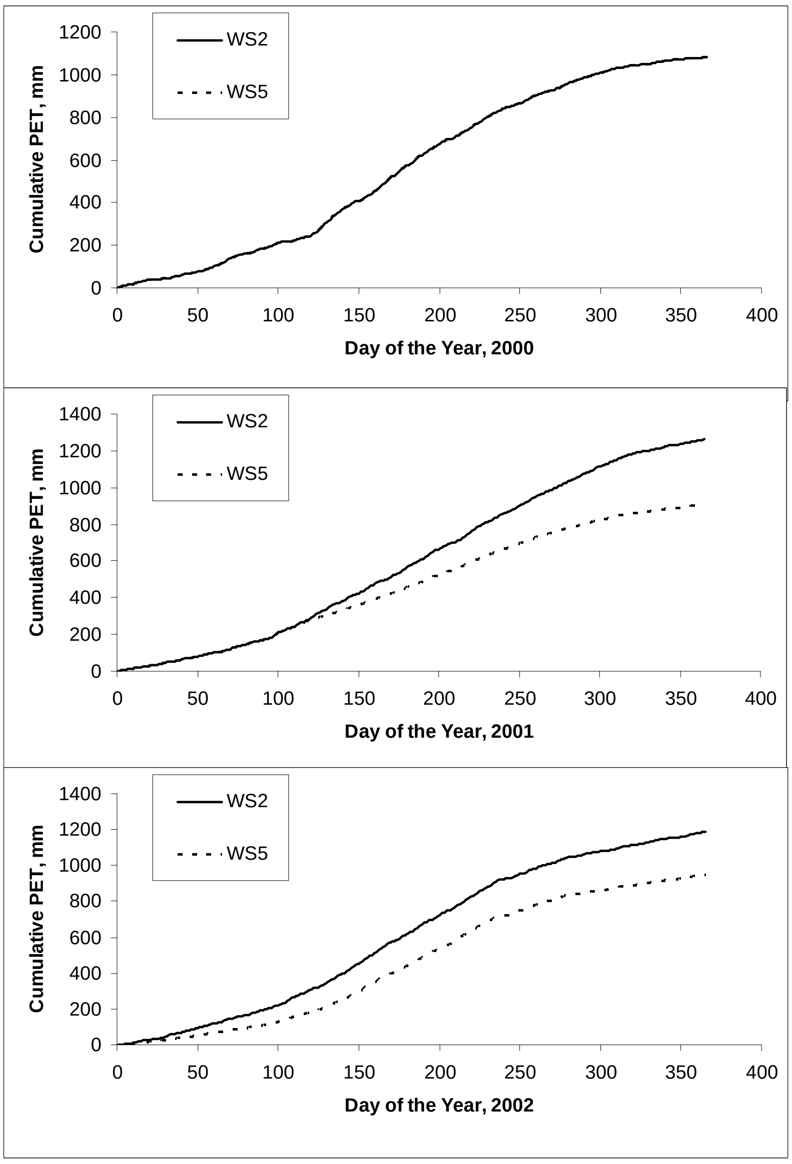

Figure 5. Cumulative Penmen-Monteith PET for WS2 and WS5 for each study year (2000-2002).

where P represents the total precipitation (mm), D is watershed outflow (mm), ΔPS is the increase in soil water storage in the soil profile (mm), and ET represents the residual term in the water balance (mm) (*dry canopy transpiration + soil water evaporation + interception losses*). The increase in soil water storage was determined from the drained volume versus water table depth relationships (assuming drained to equilibrium conditions) for the watersheds based on the water table depth at the beginning and at the end of periods over which the water balance was computed.

Outflow for WS2 and WS5 was 164 and 169 mm during the pre-thinning period based on the field-based water balance from January 2000 – April 2001 representing 12 and 13 percent of total precipitation, respectively. Outflow from WS5 during the period following thinning (May 2001 – December 2002) was 340 mm (Table 1), which represents 17 percent of the total precipitation during the period based on field measurements. WS2 outflow was only 168 mm or 9 percent of the total precipitation for the un-thinned condition during the same period. The pre- and post-thinning period outflow combined for each watershed based on field measurements accounted for 10 and 15 percent of total precipitation during the 3-year period for WS2 and WS5, respectively. The difference in outflow from the watersheds illustrates the effect of reduced ET due to timber removal. The reduction in ET following the thinning translated to nearly a two-fold increase in outflow from the WS5 watershed.

Table 1. Water balance estimates for the pre-thinning period (Jan. 1, 2000 - April 25, 2001), post-thinning period (April 26, 2001-Dec. 31, 2002), and the overall study period (Jan. 1, 2000-Dec. 31, 2002) based on field measurements of precipitation, water table depths, and outflow and DRAINMOD predictions.

Period	Component	Observed		Predicted	
		WS2	WS5	WS2	WS5
Jan. 2000 – April 2001	Precipitation, mm	1350	1350	1350	1350
	Outflow, mm	164	169	134	130
	ΔPS, mm	-45	-9	-19	-43
	ET, mm	1231	1190	1235	1263
May 2001-Dec. 2002	Precipitation, mm	1944	1944	1944	1944
	Outflow, mm	168	340	169	397
	ΔPS, mm	+66	+6	+57	+20
	ET, mm	1710	1598	1718	1527
Overall Jan. 2000-Dec. 2002	Precipitation, mm	3294	3294	3294	3294
	Outflow, mm	332	508	303	527
	ΔPS, mm	+20	-3	+38	-24
	ET, mm	2942	2789	2953	2790

The hydrology of the study watersheds was previously reported as adequately predicted by DRAINMOD over the study period (Grace, 2004a). Field-based measurements for water balance components were compared with model predicted (DRAINMOD) water balance components for the thinned and unthinned watersheds during the 3-year study period (January 1, 2000-December 31, 2002) (Table 1). Water balance estimates based on DRAINMOD predictions were consistent with the field-based water balance components. Predicted outflow for WS2 and WS5 accounted for 10 percent of the total precipitation during the pre-thinning period. During the period following the thinning of WS5, predicted outflow accounted for 20 percent of the total precipitation during the period based on model predictions. Predicted WS2 outflow accounted for only 9 percent of the total precipitation during the same period. The water balance results indicate that ET accounted for a greater proportion of the total precipitation on WS2 than for WS5 following thinning.

The gross ET (sum of dry canopy transpiration, soil water evaporation, and interception losses) determined from the field-based water balance represented 91 and 88 percent of the total precipitation during the pre-thinning period for WS2 and WS5, respectively. The predicted gross ET during the calibration period represented 91 and 93 percent of precipitation for the watersheds, respectively. WS2 gross ET based on the field water balance during the period following thinning of WS5 accounted for 88 percent of precipitation. The percentage of WS5 precipitation that was lost to gross ET was 82 percent during the post-thinning period based on the field-based water balance. In comparison, predicted gross ET during the period following thinning accounted for 88 and 79 percent of precipitation for WS2 and WS5, respectively. Gross ET determined from the field-based water balance over the 3-year period represents 89 and 85 percent of total precipitation for the WS2 and WS5 watersheds, respectively (Table 1). These values are close to results predicted for WS2 and WS5, which were 90 and 85 percent of the total precipitation over the 3-year study period.

The change in soil water storage (ΔPS) for WS5 was 36 mm more than WS2 for the pre-thinned condition based on field measurements (Table 1). The relationship was reversed during the 20-month period following thinning of WS5. During this period, ΔPS for WS2 was 60 mm more than the thinned WS5 watershed. The ΔPS for WS5 over the entire monitoring period, including pre- and post-thinning periods, was -3 mm based on field-based measurements. In contrast, WS2 had a 20 mm increase in ΔPS over the entire monitoring period. The trends in soil water storage for the watersheds suggest that WS2 was a wetter site during the period following thinning. This result would be a contradiction to the outflow component of the water balance and the paired-watershed analysis previously reported by Grace (2004a). However, a closer look at the hydrology reveals that during the period following thinning the water table was closer to the surface on WS5 than for WS2. The difference in soil water storage over this period was primarily due to the fact that the water table at WS2 was deeper than at WS5 at the initiation of the period. In addition to a deeper water table at the initiation of the period, the excessively wet conditions for the study area during the last 3 months of the study period resulted in both watersheds having high water tables at the end of the period. The soil water deficit that existed for WS2 during the majority of the period following thinning of WS5 was easily satisfied by the above mentioned period of high precipitation which resulted in the increased soil water storage in the soil profile.

The predicted ΔPS was in good agreement with observed soil water storage during the pre-thinning period for both watersheds. Predicted soil water storage was 26 mm more than the estimated storage based on measured water table depths and drained volume versus water table depth relationships during the pre-thinning period for WS2 and 34 mm for WS5. Predictions showed the same agreement during the period following thinning of WS5 for WS2 with only a 9 mm difference in predicted and observed. Storage predictions were within 14 mm of observed storage for the thinned condition for WS5.

SUMMARY AND CONCLUSIONS

A 3-year study to evaluate the effect of thinning on the hydrology of a drained loblolly pine plantation was conducted in eastern North Carolina. Data from the field experiment conducted from 1999-2002 were used to perform a water balance over pre- and post-thinning monitoring periods to gain a better understanding of the interaction of hydrologic components on drained organic soil watersheds. The study utilized a paired watershed design with a 40-ha thinned watershed (WS5) and a 16-ha control watershed (WS2). Cumulative PET determined from the Penman-Monteith method was 1100 mm for 2000 for the study watersheds. Thinning in April 2001 reduced LAI for WS5 and resulted in a 360 mm reduction in PET for 2001 in comparison to WS2. Similarly, a 240 mm reduction PET was estimated for WS5 during the subsequent year.

Outflow accounted for 10 and 15 percent of the total precipitation over the study period based on field measurements for WS2 and WS5, respectively. During the post-thinning period, outflow per unit area from WS5 was a greater than from WS2. This difference is primarily attributed to the reduction in ET resulting from removal of trees during the thinning operation. Gross ET during the 3-year study period (2000-2002) (sum of dry canopy transpiration, soil water evaporation, and interception loses) based on the field-based water balance represented 89 and 85 percent of total precipitation for WS2 and WS5, respectively.

DRAINMOD model predictions were in agreement with the field-based water balance components over each individual period as well as the overall study period. DRAINMOD predicted gross ET during the study period was in good agreement with the field based water balance. Similarly, predicted soil water storage was in good agreement with observed storage during the study period. Predicted soil water storage for WS2 was within 26 and 9 mm of observed storage during the pre- and post-thinning periods, respectively. Predicted soil water storage for the thinned watershed was within 34 and 14 mm of observed storage during the pre- and post-thinning period, respectively.

Acknowledgements

This work was accomplished with the support of the Biological and Agricultural Engineering Department at NC State University, the USDA Forest Service Forest Operations Research Unit (SRS-4703), and Weyerhaeuser Company, Inc. The authors would like to acknowledge the assistance in PET calculations provided by Devenda Amatya of the USDA Forest Service. The authors would also like to acknowledge the contributions of Preston Steele, Jr. of the USDA Forest Service and Sandra McCandless, Joe Bergman, Cliff Tyson, Joe Hughes, and Jami Nettles of Weyerhaeuser Company.

REFERENCES

1. Albaugh, T.J., H.L. Allen, P.M. Dougherty, L.W. Kress, and J.S. King. 1998. Leaf area and above- and belowground growth responses of loblolly pine to nutrient and water additions. *Forest Science* 44(2): 317-328.
2. Amatya, D.M., R.W. Skaggs, G.M. Chescheir, and G.P. Fernandez. 2000. Solar and net radiation for estimating potential evaporation from three vegetation canopies. ASAE Paper No. 002135. ASAE, St. Joseph, MI. 19 p.
3. Amatya, D.M., R.W. Skaggs, and J.D. Gregory. 1994. Hydrologic modeling of drained forested watersheds. In: p. 27-55; Water Management in Forested Wetlands, 26-28 April 1994, Atlanta, GA; US EPA; Washington, D.C.
4. Amatya, D.M., R.W. Skaggs, and J.D. Gregory. 1996. Effects of controlled drainage on storm event hydrology of drained pine plantations in the North Carolina coastal plain. *Journal of Hydrology* 181: 211-232.
5. Baldwin, V.C. Jr. 1987. Green and dry-weight equations for above-ground components of planted loblolly pine trees in the West Gulf Region. *Southern Journal of Applied Forestry* 11: 212-218.
6. Brown, G.W., A.R. Gahler, and R.B. Martson. 1973. Nutrient losses after clear-cut logging and slash burning in the Oregon Coast Range. *Water Resources Research* 9(5): 1450-1453.
7. Dube, S., A.P. Plamondon, and R.L. Rothwell. 1995. Watering up after clear-cutting on forested wetlands of the St. Lawrence lowland. *Water Resources Research* 31(7): 1741-1750.
8. Grace, J.M. III. 2004a. Forest operations impact on forest soil and water on poorly drained organic soil watersheds in North Carolina. Ph.D. dissertation. Raleigh, NC: North Carolina State University. 319 p.
9. Grace, J.M. III. 2004b. Soil erosion following forest operations in the Southern Piedmont of central Alabama. *Journal of Soil and Water Conservation* 59(4): 160-166.
10. Grace, J.M. III. 2005. Forest operations and water quality in the South. *Transactions of the ASAE* 48(2): 871-880.
11. Harr, D.R. and R.L. Fredriksen. 1988. Water quality after logging small watersheds within the Bull Run Watershed, Oregon. *Water Resources Bulletin* 24(5): 1103-1111.
12. Hefner, J.M., B.O. Wilen, T.E. Dahl, and W.E. Frayer. 1994. Southeast wetlands; Status and trends, mid-1970's to mid-1980's. U.S. Department of the Interior, Fish and Wildlife Service, Atlanta, Georgia. 32 pp.

13. Hennessey, T.C., P.M. Dougherty, B.M. Cregg, and R.F. Wittwer. 1992. Annual variation in needle fall of a loblolly pine stand in relation to climate and stand density. *Forest Ecology and Management* 51(4): 329-338.

14. Hibbert, A.R. 1966. Forest treatment effects on water yield. Proceedings of the International Symposium on Forest Hydrology, Penn State University, Pennsylvania, August 29 – September 10, 1965.

15. Kochenderfer, J.N. and G.W. Wendel. 1983. Plant succession and hydrologic recovery on a deforested and herbicided watershed. *Forest Science* 29: 545-558.

16. Leaf, C.F. 1970. Sediment yields from central Colorado snow zone. American Society of Civil Engineering, Journal of Hydraulics Division 96(HY1): 87-93.

17. Lebo, M.E. and R.B. Herrmann. 1998. Harvest impacts on forest outflow in coastal North Carolina. *Journal of Environmental Quality* 27(6): 1382-1395.

18. McCarthy, E.J. and R.W. Skaggs. 1992. Simulation and Evaluation of Water Management Systems for a Pine Plantation Watershed. *Southern Journal of Applied Forestry* 16(1): 48-56.

19. McCarthy, E.J., J.W. Flewelling, and R.W. Skaggs. 1992. Hydrologic model for drained forest watershed. *Journal of Irrigation and Drainage Engineering* 118(2): 242-255.

20. Monteith, J.L. 1965. Evaporation and the environment. In: pp. 205-234; The State and Movement of Water in Living Organisms, XIXth Symp., Society for Exp. Biol., Swansea, Cambridge Univ. Press, New York, NY.

21. Prestemon, J.P. and R.C. Abt. 2002. Timber products supply and demand. In: Pp. 299-326, Southern Forest Resource Assessment; D.N. Wear and J. Greis (eds.). USDA Forest Service, Southern Research Station, General Tech. Report SRS-53, Asheville, NC.

22. Richardson, C.J. and E.J. McCarthy. 1994. Effect of land development and forest management on hydrologic response in southeastern coastal wetlands: A review. *Wetlands* 14: 56-71.

23. Riekerk, H. 1983. Impacts of silviculture on flatwood runoff, water quality, and nutrient budgets. *Water Resource Bulletin* 19(1): 73-79.

24. Shelton, M.G. and G.L. Switzer. 1984. Variation in the surface area relationships of loblolly pine fascicles. *Forest Science* 30(2): 355-363.

25. Troendle, C.A. 1983. The potential for water yield augmentation from forest management in the Rocky Mountains. *Water Resources Bulletin* 19(3): 359-373.

26. Troendle, C.A. and R.M. King. 1987. The effect of partial and clearcutting on streamflow at Deadhorse Creek, Colorado. *Journal of Hydrology* 90: 145-157.

27. Vose, J. and H.L. Allen. 1988. Leaf area, standard growth, and nutrition relationships in loblolly pine. *Forest Science* 34(3): 547-563.

28. Wilen, B.O. and W.E. Frayer. 1990. Status and Trends of US wetlands and deepwater habitats. *Forest Ecology and Management* 34: 181-192.

29. Williams, T.M. and D.J. Lipscomb. 1981. Water table rise after cutting on coastal plain soils. *Southern Journal of Applied Forestry* 5(1): 46-48.

30. Woodman, J.N. and .S. Furiness. 1988. Potential effects of climate change on U.S. Forests: case study of California and the southeast. USEPA Report No. 68-03-3430. USEPA Office of Policy, Washington, DC. 36 p.