# Hydrologic effects of size and location of harvesting on a large drained pine forest on organic soils

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## Summary

A calibrated DRAINWAT model was used to evaluate long -term hydrologic effects of conversion to agriculture of a 30 km$^2$ pine forest on mostly organic soils in North Carolina, USA. Fifty years of weather data were used for determining baseline outflows. Simulation revealed that increased mean annual outflow was significant only for a 75% conversion at both upstream and downstream locations, with minimal changes for up to 25% conversion. While the high flow rates > 10 mm day$^{-1}$ increased from 3 to 18% for 25 % to 50% conversion, the frequency increased three-fold and was consistently higher for downstream location than the upstream.

**Key index words**: DRAINMOD, agricultural crop, outflow, peak flow rate, evapotranspiration

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## Introduction

In recent years there has been a great concern about the impact of land use change on the flooding, watershed outflows (yields), and quality of waters draining from the lands into downstream water bodies. This is particularly true in the Atlantic and Gulf Coast regions of the USA due to rapid growth in population and increased pressure to develop forested lands, most of which are in proximity to ecologically sensitive waters. It is also likely that current high commodity prices will lead to increased conversion of forested lands to agriculture. Converting forested lands to the production of agricultural crops nearly always reduces evapotranspiration (ET) and increases runoff (Sun *et al.*, 2005; Skaggs *et al.*, 2004). The relationship between catchment vegetation type and the variability of runoff as affected by vegetation manipulation of ET has important implications for sustainable water resources management and development. Recent experimental studies conducted on North Carolina (NC) coastal plain watersheds (Fig. 1) compared the average annual runoff and its temporal distribution from agricultural lands to those from pine forest (Shelby *et al.*, 2005; Amatya *et al.*, 2002). They found almost a two-fold higher average annual runoff from agricultural lands than from forested sites. However, there is less information known on effects of size and location of the converted land within a watershed.

Land managers and regulatory agencies often need this information to evaluate impacts of land use changes. Since long-term measurements are often cost prohibitive, watershed-scale hydrologic and water quality models (SWAT, HSPF, MIKE -SHE) are frequently used to simulate effects of land use change and management scenarios (Gassman *et al.*, 2007; Weber *at al.*, 2001; Sun *et al.*, 2005). However, only a few models are capable of reliably simulating the hydrology of poorly drained soils, especially in low-gradient forested landscapes. DRAINMOD (Skaggs, 1978) is a process-based field scale hydrology and water management model widely used in evaluating effects of land use change and managem ent practices on drainage water quantity and quality for poorly drained high water table soils (Skaggs *et al.*, 1991). DRAINLOB (McCarthy *et al.*, 1992), a forestry version of DRAINMOD, has been successfully tested with ten years of data on a drained pine forest watershed (Amatya and Skaggs, 2001). DRAINWAT (Amatya *et al.*, 1997) is an extended watershed-scale forest hydrologic model based on DRAINLOB. The main objective of this study was to apply DRAINWAT to evaluate hydrologic effects of changing the land use from forest to agriculture at various locations and scales within the watershed.

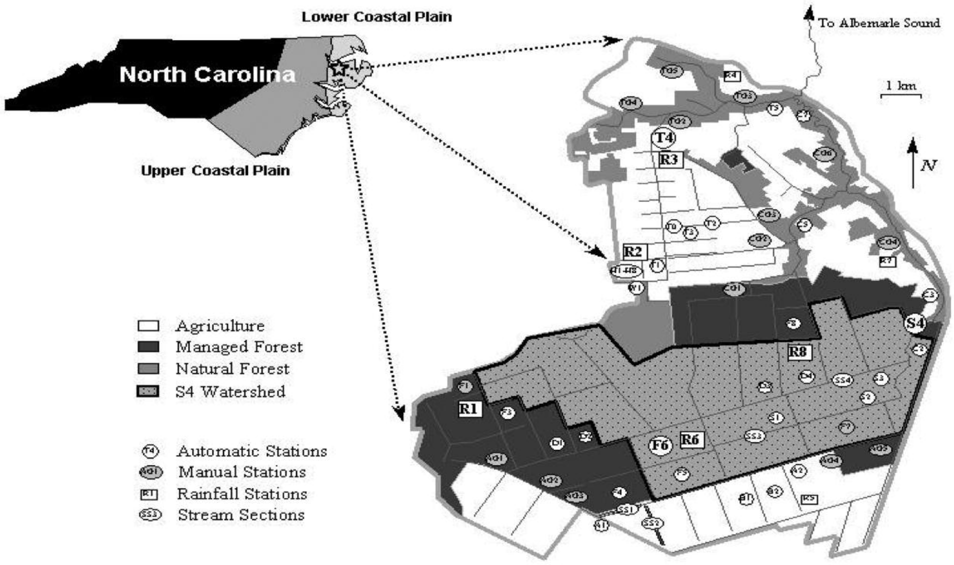


**Figure 1.** Location map an d the layout of the forested watershed (S4) near Plymouth, NC.

## Materials and methods

**Site description:** The study site (S4) is about 2950 ha in area within Parker Tract forest owned and managed by Weyerhaeuser Company. The watershed (S4) is part of a 10,000 ha large watershed located near the town o f Plymouth in Washington County, North Carolina (NC) (Fig. 1). This relatively flat site is drained by collector canals receiving drainage from lateral ditches, which are mostly 100 m apart. Seven mineral and organic soils are present in the watershed (Table 1). The mineral soils in the northern part of the watershed are very poorly drained Portsmouth, Cape Fear and Wasda series, while organic soils, Belhaven and Pungo, are predominant in the southern half of the watershed. Surface vegetation ranges from unharvested second growth mixed hardwood and pine forest to loblolly pine plantation (*Pinus taeda L.*) of various stand ages. Three automatic rain gauges backed up by manual gauges in and around the site and an on-site weather station provided the weather data for the study. The outflow at the S4 outlet was measured using dual-span V-notch weir equipped with a datalogger. Detailed description of the site including instrumentation and monitoring procedures can be found elsewhere (Chescheir *et al.*, 1998).

**DRAINWAT Model (Amatya *et al.*, 1997):** DRAINmod (Skaggs, 1978) for WATersheds was developed linking DRAINLOB (McCarthy *et al.*, 1992) with the overland flow, ditch and in stream flow routing components of the FLD&STRM model (Konyha and Skaggs, 1992). The distributed model operates as a sequenced set of simulations so that simulated outflow from each 'field' (subwatershed) delineated with relatively uniform soil and stand conditions is first combined into the collector ditch of the subwatershed. The simulated outflow from one or more subwatersheds is then routed through the channel system to the watershed outlet. Use of the instantaneous unit hydrograph, based on time of concentration takes into account the time that is required for surface runoff to travel across the surface to the ditch and then further routed through the ditch network into the outlet of each subwatershed. These outflows are then used as lateral inflows for the in-stream routing component of the model. DRAINWAT, like FLD&STRM, uses numerical solution to the 1 -D St. Venant equations to compute depth and flows at selected nodes along the stream or collector ditches. The model is also capable of taking the unsteady state flow conditions such as backwater effects, tidal surges, reservoir storages, etc (Konyha and Skaggs, 1992) into account while simulating the hydrology of poorly drained lands with mixed land use and their in-stream transport hydraulics. The model has been successfully tested for predicting outflow rates in lower coastal plain watersheds with varying sizes and land uses (Konyha and Skaggs, 1992; Amatya *et al.*, 1997). Recently the model has also been successfully tested with five years of data (1996 -00) for predicting the outflow rates and nitrogen transport for this study watershed (S4) (Amatya *et al.*, 2004). Precipitation measured at a gauge located at the center of the watershed (R6) was use d in that study. Weather data measured at an automatic station located at the center of the watershed was used to estimate Penman -Monteith PET for the forest reference (Amatya *et al.*, 2002) that was input into the model. These results are briefly described herein. The soil hydraulic properties (Table 1) and ditch channel routing parameters used in that study were used herein to describe the hydrologic effects of land use conversion of different scales and locations using 50 -years (1951-2000) of historical weather data from the U.S. Weather Bureau station at Plymouth, North Carolina.

**Table 1.** Main soil hydraulic properties of forested watershed (S4).

| Soil parameter | Soil Type | | | | | |
|---|---|---|---|---|---|---|
| | Belhaven | Cape Fear | Pungo | Portsmouth | Wasda | Agricultural |
| Impermeable layer depth (cm) | 270 | 300 | 250 | 240 | 200 | 240 |
| Hydraulic conductivity (cm/hr) (Depth range, cm) | 20(0-30)<br>1(30-80)<br>0.01 (80-270) | 15(0-100)<br>45(100-300) | 10(0-30)<br>1.7(30-150)<br>5.0(150-250) | 50(0-30)<br>10(30-50)<br>10(50-240) | 20(0-30)<br>0.4(30-80)<br>1(80-200) | 20.0(0-35)<br>1.0(35-75)<br>0.01(75-240) |
| Saturated water content ($cm^3/cm^3$) | 0.73 | 0.48 | 0.69 | 0.37 | 0.76 | 0.61 |
| Wilting point ($cm^3/cm^3$) | 0.45 | 0.22 | 0.40 | 0.13 | 0.45 | 0.36 |
| Rooting depth (cm) | 45 | 45 | 45 | 45 | 45 | 3 - 30 |
| Surface storage (cm) | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 0.50 |

Simulations used temperature-based Thornthwaite PET method, as complete weather data for using the process-based Penman-Monteith method was not available for the historic period. However, the Thornthwaite monthly PET was adjusted in the model using monthly correction factors calibrated with the Penman-Monteith-based PET from Amatya *et al.* (1995b, 2002) for both forested and agricultural vegetation at this location. This was done as the PET rate varies depending upon the reference vegetation. Interception was not simulated as leaf area index data were not available. Stand age of the current vegetation was assumed throughout the simulation period.

**Modeling scenarios:** At first a baseline scenario with all 27 fields (subwatersheds) of the watershed in their existing condition was simulated. The results on hydrology (outflows) and ET were saved as the baseline scenario. Five other hypothetical scenarios involving the conversion of approximately 10%, 25%, 50%, 75%, and 100% of the 2950 ha pine forest into agricultural crops were simulated. Further simulation scenarios were created for each of these percent ages of land use change at upstream and downstream locations of the watershed. Altogether 10 sets of model simulations were conducted using the 50-year long-term weather data. An agricultural field was simulated primarily by changing the reference-ET (or PET) to that of a short crop rather than pine forest vegetation (Amatya *et al.*, 1995b, 2002). Soil hydraulic properties, surface storage, and rooting depth were also changed to values consistent with agricultural crops (Table 1). Results from each of these scenarios were tabulated together with the baseline scenario to evaluate the effects of size and location of land use change on the percent change in watershed mean annual and maximum outflow, maximum annual and minimum annual flow as well as mean daily and maximum outflow rates and their time distribution.

**Model Testing:** Amatya *et al.* (2004) demonstrated that the model-predicted outflows and their time distribution for five years (1996-2000) were in good agreement with measured data for the watershed. Predictions correlated well with the measured data ($R^2$ = 0.90, p<0.001). The predicted total cumulative monthly outflow of 1554 mm at the end of the five-year period was only 4 mm higher than the measured amount of 1550 mm. The average absolute monthly deviation varied from 5 mm in 1997 to 11.8 mm in 1998 (average = 8.2 mm) and the yearly Nash-Sutcliffe coefficient ranged from 0.79 to 0.91 (average = 0.89), which is considered good. These analyses indicate that the model adequately describes monthly and annual drainage outflows for the subject watershed.

**Scenario analyses:** Results of simulations of the hydrologic effects of converting various sizes of forested lands to agricultural croplands are presented in Table 2 for both upstream (US) and downstream (DS) locations.

**Table 2.** Hydrologic effects of size and location of land use change from pine forest to agricultural crops.

| Forest lands converted to Agricul-tural crop % of 2950 ha | Annual Outflows Mean Annual mm | Annual Outflows Increase in Mean Annual % | Annual Outflows Maximum Annual mm | Annual Outflows Increase in MAX Annual % | Annual Runoff Coefficient % | Daily Outflows Maximum Daily Flow mm | Daily Outflows Increase in MAX Daily Flow % | In 18263 days Number of Days Daily Flow = Zero mm | > 0 -1 mm | 1 - 5 mm | 5 - 10 mm | > 10 mm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **For % of Agricultural crop lands in Downstream locations** | | | | | | | | |
| 0 | 308 | 0.0 | 617 | 0.0 | 23.9 | 19.1 | 0.0 | 6001 | 6967 | 4924 | 340 | 31 |
| 10 | 317 | 3.0 | 632 | 2.5 | 24.6 | 19.1 | 0.0 | 6060 | 6824 | 5018 | 327 | 34 |
| 25 | 327 | 6.2 | 644 | 4.4 | 25.4 | 19.6 | 2.6 | 5653 | 7540 | 4529 | 489 | 52 |
| 50 | 347 | 12.7 | 670 | 8.7 | 26.9 | 22.6 | 18.3 | 5257 | 8232 | 3995 | 630 | 149 |
| 75 | 381 | 23.7 | 730 | 18.4 | 29.6 | 23.1 | 20.9 | 4995 | 8681 | 3452 | 925 | 210 |
| 100 | 394 | 28.0 | 728 | 18.1 | 30.6 | 24.6 | 28.8 | 5680 | 8520 | 2608 | 1168 | 287 |
| | | | | **For % of Agricultural crop lands in Upstream locations** | | | | | | | | |
| 10 | 322 | 4.6 | 647 | 4.9 | 25.0 | 19.5 | 2.1 | 5550 | 7681 | 4604 | 391 | 37 |
| 25 | 344 | 11.7 | 683 | 10.8 | 26.7 | 19.9 | 4.2 | 5224 | 7579 | 4829 | 582 | 49 |
| 50 | 352 | 14.3 | 681 | 10.4 | 27.3 | 20.5 | 7.3 | 4776 | 8781 | 3751 | 880 | 75 |
| 75 | 372 | 20.8 | 697 | 13.0 | 28.9 | 22.7 | 18.8 | 4569 | 9392 | 3017 | 1117 | 168 |

All outflow characteristics increased with an increase in percent of agricultural cropland, as expected. A 10% conversion to agricultural land caused an increase in mean annual and maximum outflows of only 3% for DS and < 5% for the US cases. There was no difference in maximum daily flow rate of 19.1 mm although there was a very little increase (from 31 to 34 days for DS and to 37 days for US) in frequency of high flow rates > 10 mm day$^{-1}$. The increases in the mean annual, maximum annual outflow, and the maximum daily flow rate were only about 6% for DS and < 12% for US for a 25% change in land use. However, the frequency of high flow rates > 10 mm day $^{-1}$ increased appreciably from 31 for the base line to 52 for DS and 49 for US scenarios, respectively. A substantial increase in both the mean annual outflow (13%) as well as maximum daily flow rate (18%) was observed when 50% of the forest cover was converted to agriculture in DS location. Similarly, the frequency of high flows > 10 mm day$^{-1}$ tripled in this case for DS compared to the base line (Table 2).

However, the increase in mean annual outflow was statistically different (paired t-test; a= 0.05) only for a 75% conversion, which yielded 381 mm outflow (24% increase) compared to 308 mm for the base line. When the whole 100% (2950 ha) forest area was converted to the agriculture, the mean annual predicted outflow increased by about 28% to as much as 394 mm for a mean annual rainfall of 1288 mm. The maximum annual outflow increased from 617 mm for the base line to nearly 730 mm for 75% and 100% agricultural scenarios, a more than 18% increase. Interestingly, the predicted increases in both the mean annual outflow and maximum annual outflow were higher for the upstream scenario than the downstream for conversions up to 50% of the forest. However, the percent increase in maximum daily flow rate as well as the frequency of flows <10 mm day$^{-1}$ was twice as much for the DS case as for the US (Table 2). As expected, for the 75% land use conversion, all outflow characteristics were greater for the DS scenario than the US. Notably, the high flow frequency increased almost by 10 times in DS case compared to little more than five times for the US case when all forest was converted to agriculture. The 6001 days of predicted zero flows out of 18263 (~33% time) was the longest period observed for all forest base line scenario (Table 2). However, the 100% agricultural scenario did not necessarily yield the shortest period of ze ro flows. This was observed for the 50% conversion in US case (4776 days – 26%). Similarly, frequency of zero flows was higher for all land use conversion scenarios in DS location than the US. No specific pattern was, however, observed for other low and medium flow rates > 0 and <10 mm day $^{-1}$.

## Discussion/conclusion

Based on the assumptions made in our simulation analyses, converting forestland to agricultural crop land can increase both the mean annual and maximum outflows as well as magnitude and frequency of high flow rates for all sizes and locations. However, conversion of up to 25% area of the 30 km$^2$ pine forest to agriculture was predicted to have only minimal hydrologic effects. The mean annual outflow was significantly different from the baseline only for a 75% land use conversion. Conversion of up to 50% of the forest lands on the tract had substantial hydrologic impact with increased maximum daily fl ow rates as well as the frequency of high flow rates > 10 mm day$^{-1}$. Although the conversion of less than 50% in DS location had less impact on mean annual and maximum outflows, the frequency of daily high flow rates was consistently higher for all land use conversion in downstream location than the upstream. This may have a great implication to land managers in terms of flooding and nutrient loading impacts.

The effects of land use conversion from matured pine forest to the agricultural crops were primarily attributed to reduction in evapotranspiration (ET). For example, the all forest scenario had a mean annual predicted ET of 1008 mm compared to only 924 mm for 100% agricultural land case. Similar findings of reduced ET for the agricultural crops compared to the pine forest were reported by Skaggs *et al.* (2004, 1991). Although these percentage results are somewhat higher than that reported by Fernandez *et al.* (2007) study in which outflow increased by 16% when the percentage of agriculture land use was increased from current 50% conditions to 100% in a mixed watershed in eastern NC, their mean annual outflow of 437 mm was actually higher than the 394 mm reported in this study. Skaggs *et al.* (1991) predicted an increase of about 19% (421 mm) when a pine forest (356 mm) was converted to agricultural crop land. But the mean annual rainfall in that case was 1354 mm. This indicates that the increase in outflow due to land use conversion also depends upon the climatic variation. Also it is important to note that only one soil type (Belhaven muck) was considered in this study.

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