Hydrologic Effects of Size and Location of Fields Converted from Drained Pine Forest to Agricultural Cropland

Hyun Woo Kim[1]; Devendra M. Amatya[2]; George M. Chescheir[3];
Wayne R. Skaggs[4]; and Jami E. Nettles[5]

Abstract: Hydrological effects of land-use change are of great concern to ecohydrologists and watershed managers, especially in the Atlantic coastal plain of the southeastern United States. The concern is attributable to rapid population growth and the resulting pressure to develop forested lands. Many researchers have studied these effects in various scales, with varying results. An extended watershed-scale forest hydrologic model, calibrated with 1996–2000 data, was used to evaluate long-term hydrologic effects of conversion to agriculture (corn–wheat–soybean cropland) of a 29.5-km^2 intensively managed pine-forested watershed in Washington County in eastern North Carolina. Fifty years of weather data (1951–2000) from a nearby weather station were used for simulating hydrology to evaluate effects on outflows, evapotranspiration, and water table depth compared with the baseline scenario. Other simulation scenarios were created for each of five different percentages (10, 25, 50, 75, and 100%) of land-use conversion occurring at upstream and downstream locations in the pine-forest watershed. Simulations revealed that increased mean annual outflow was significant ($\alpha = 0.05$) only for 100% conversion from forest (261 mm) to agricultural crop (326 mm), primarily attributed to a reduction in evapotranspiration. Although high flow rates $>5\ \mathrm{mm\,day^{-1}}$ increased from 2.3 to 2.6% (downstream) and 2.6 to 4.2% (upstream) for 25 to 50% conversion, the frequency was higher for the upstream location than the downstream. These results were attributed to a substantial decrease in soil hydraulic conductivity of one of the dominant soils in the upstream location, which is expected after land-use conversion to agriculture. As a result, predicted subsurface drainage decreased, and surface runoff increased as soil hydraulic conductivity decreased for the soil upstream. These results indicate that soil hydraulic properties resulting from land-use conversion have a greater influence on hydrologic components than the location of land use conversion. **DOI: 10.1061/(ASCE)HE.1943-5584.0000566.** © *2013 American Society of Civil Engineers.*

CE Database subject headings: Land use; Hydraulic conductivity; Peak flow; Evapotranspiration; Drainage; Agriculture; Hydrologic aspects.

Author keywords: DRAINWAT; Land-use change; Soil hydraulic conductivity; Outflow; Peak flow rate; Evapotranspiration.

Introduction

In recent years there has been great concern about the effect of land-use change on flooding, watershed outflows (yields), and quality of waters draining from the lands into downstream (DS) water bodies (Wilk et al. 2001; Tang et al. 2005; Thanapakpawin et al. 2007; Li et al. 2011). Land-use change may occur because of change in vegetation, such as deforestation, afforestation, urbanization, and other kinds of land development. The relationship between catchment vegetation type and the variability of runoff, as affected by the impact of vegetation manipulation on evapotranspiration (ET), has important implications for sustainable water-resources management and development (De Wit 2001).

Wilk et al. (2001) reported that deforestation increased the volume of outflow at watershed scale in a 12,100-km^2 catchment in northeast Thailand only when runoff ratio was very low. Even though they reported that forest clearance increased the outflow on small catchments of a few hectares, they could not find any substantial changes or trends in any water-balance terms as the forest area of the large watershed decreased from 80 to 27% between 1957 and 1995.

Thanapakpawin et al. (2007) reported that conversion of forested lands to agricultural lands in the upstream (US) part of a watershed led to slightly higher annual outflows (301-mm annual average, 55.1-mm maximum daily flow) than those of mid- or downstream conversion (297-mm annual average, 54.3-mm maximum daily flow). After they considered the irrigation effect, the magnitude of difference was slightly greater. The annual average outflow was 256 mm, and the maximum daily outflow was 49.6 mm for upstream conversion. For downstream conversion,

---

[1] Research Scientist, Dept. of Water Environmental Engineering Research, National Institute of Environmental Research, Environmental Research Complex, Kyungseo-dong, Seo-gu, Incheon 404-708, Republic of Korea. E-mail: kim4hydro@korea.kr

[2] Research Hydrologist, USDA Forest Service, Center for Forested Wetlands Research, 3734 Highway 402, Cordesville, SC 29434 (corresponding author). E-mail: damatya@fs.fed.us

[3] Research Associate Professor, Dept. of Biological and Agricultural Engineering, North Carolina State Univ., Campus Box 7625, Raleigh, NC 27695.

[4] William Neal Reynolds Distinguished Univ. Professor, Dept. of Biological and Agricultural Engineering, North Carolina State Univ., Campus Box 7625, Raleigh, NC 27695.

[5] Principal Scientist, Weyerhaeuser Company, P.O. Box 2288, Columbus, MS 39704.

Note. This manuscript was submitted on November 8, 2010; approved on December 28, 2011; published online on January 2, 2012. Discussion period open until October 1, 2013; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Hydrologic Engineering***, Vol. 18, No. 5, May 1, 2013. © ASCE, ISSN 1084-0699/2013/5-552-566/$25.00.

J. Hydrol. Eng. 2013.18:552-566.

these values decreased to 235 mm for annual mean outflow and 46.5 for maximum daily outflow.

It is well known that land-use change influences the hydrology [primarily through changes in ET, surface, and subsurface flow, as affected by water table depth (WTD)] and biogeochemistry of watersheds. As land-use changes from unaltered natural landscapes such as forests and wetlands to agricultural and urban areas, surface runoff (SRO) and anthropogenic chemical and wastewater inputs almost always increase (Tong and Chen 2002; Fitzpatrick et al. 2007; Qi et al. 2009). Physical alteration of the landscape attributable to land-use change also affects the hydrogeologic dynamics of watersheds (Tang et al. 2005).

The effects of land-use change in the Atlantic and Gulf Coast regions of the United States are of even greater concern because of rapid growth in population and increased pressure to develop forested lands, most of which are in proximity to ecologically sensitive waters. It seems likely that demand for increased agricultural production to feed a rapidly expanding global population, coupled with current high commodity prices, will lead to increased conversion of forested lands to agriculture. The need to produce biofuel-based crops like switchgrass will potentially add to the pressure for conversion. Converting forested lands to the production of agricultural crops nearly always reduces ET and increases runoff (Skaggs et al. 1991, 2011; Sun et al. 2005; Amatya et al. 2008; Amatya and Trettin 2007).

Recent experimental studies conducted in North Carolina coastal plain watersheds (Fig. 1) compared the average annual runoff and its temporal distribution from agricultural lands with those from pine forest (Shelby et al. 2005; Amatya et al. 2002). They found an almost twofold-higher average annual runoff from agricultural lands than from forested sites. However, less such information is known on hydrologic effects of size and location of land conversion within a watershed. Land managers and regulatory agencies often need this information to evaluate actual effects of land-use changes.

Long-term measurements to examine such effects are cost-prohibitive in most cases; therefore, watershed-scale hydrologic and water-quality models are frequently used to simulate effects of land-use change and management scenarios (Weber et al. 2001; Sun et al. 2005; Fernandez et al. 2007; Gassman et al. 2007; Amatya et al. 2008, 2011). In recent years, several different types of models have been developed and applied to estimate the effects of land-use conversion [a conceptual rainfall-runoff model by Nandakumar and Mein (1997); Hydrologiska Byrans Vattenbalans-avdeling (HBV) model by Wilk et al. (2001); BASINS by Tong and Chen (2002); DRAINMOD by Skaggs et al. (2011); LTM and L-THIA by Tang et al. (2005); DHSVM by Thanapakpawin et al. (2006); IBIS and THIMB by Li et al. (2007); and MODFLOW and HSPF by Cho et al. (2009)]. Recently, Qi et al. (2009) used the USGS PRMS model to evaluate streamflow response to climate and land-use changes in coastal North Carolina. The authors reported a 14–20% increase in streamflow as a result of converting forest, which made up 69% of their 377-km^2 watershed, to agricultural crops. Only a few models are capable of reliably simulating the hydrology of poorly drained soils, especially in low-gradient forested landscapes. One such model is DRAINMOD (Skaggs 1978), a process-based

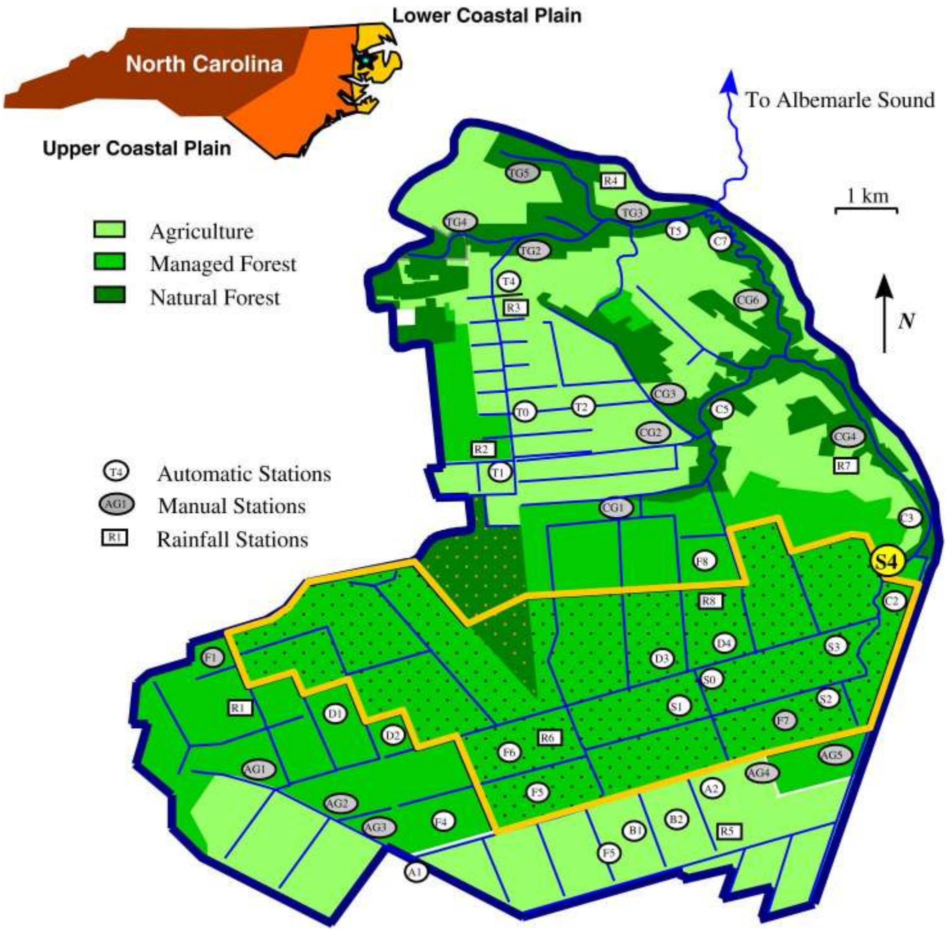

Fig. 1. Location map and layout of forested watershed near Plymouth, North Carolina

field-scale hydrology and water-management model widely used in evaluating effects of land-use change and management practices on drainage water quantity and quality for poorly drained high water table soils (Skaggs et al. 1991, 2011). DRAINLOB (McCarthy et al. 1992), a forestry version of DRAINMOD, has been successfully tested with 10 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. It has also been applied successfully for predicting hydrology and nitrogen transport (Amatya et al. 2004) on a large 2,950-ha managed pine forest in eastern North Carolina. Amatya et al. (1995a) also used this model to study hydrologic effects of wetland size and location in an agricultural landscape.

More recently, DRAINWAT was applied to investigate the hydrologic status of one of the subwatersheds (1,100 ha) of Open Grounds Farm in eastern North Carolina. Effects of several input parameters, including potential evapotranspiration (PET) calculation methods, Manning roughness coefficient, maximum depressional storage, and channel-bed slope, were compared to examine their sensitivity in outflow simulation, and the calculated PET was observed to be the most sensitive among them (Kim 2009; Kim et al. 2012).

The main objective of this study was to apply DRAINWAT to evaluate the hydrologic effects of changing the land use from existing pine forest to a corn–wheat–soybean (CWS) rotation at various locations and scales within a 29.5-km^2 watershed in Plymouth, North Carolina. The CWS rotation considered in this paper is the most frequently used agricultural production system in eastern North Carolina. Ten scenarios with five different percentages (10, 25, 50, 75, and 100%) of watershed area conversion at two locations (downstream and upstream) were considered for this study. This is an extended, more refined version of the preliminary work by Amatya et al. (2008).

Materials and Methods

Site Description

The study watershed (S4) is approximately 2,950 ha (29.5 km^2) in area within Parker Tract forest, owned and managed by Weyerhaeuser Company. The S4 watershed is located in the lower coastal plain in eastern North Carolina and is part of the 10,000-ha (100 km^2) Kendricks Creek watershed located near the town of Plymouth in Washington County, North Carolina (Fig. 1). The site is very flat, and land slope is approximately 0.5 m/km. The S4 watershed is drained by collector ditches receiving drainage from lateral ditches. The collector ditches ultimately discharge into a main canal and natural stream where the monitoring outlet is located (Fig. 1). The study watershed borders with a large agricultural landscape in the south. The North Carolina State Agricultural Research Service's Tidewater Research Station (TRS) is located approximately 1 km to the north. The study watershed also includes part of a 137-ha forested wetland to the north (Fig. 1, F13). Detailed description of the S4 and Kendricks Creek watersheds can be found in Chescheir et al. (1993, 1998) and Amatya et al. (2002).

Average daily maximum temperature at TRS is 31°C during the summer, and the average daytime winter temperature is 13°C. Summer normally has the most rainfall of all seasons, and August is the wettest month (142 mm). Autumn is the driest season, and November is the driest month (81 mm). The average annual rainfall is 1,288 mm. Severe weather can have acute effects on water quality. Shelby et al. (2005) studied the effect of severe weather on hydrology and water quality in 1999. They found that several hurricanes in September and October 1999 produced total nitrogen and total phosphorus loads for those events that were nearly equal to long-term average loads for an entire year.

Hydrometeorologic Data

Three automatic tipping-bucket rain gauges backed up by manual gauges—one (R6) in field F6 and two others in field F1 (R1) and F8 (R8) adjacent to the site—were available for rainfall data (Fig. 1). An on-site Campbell Scientific CR10X weather station in field F6 provided the weather data for the study. The weather data, including air temperature, relative humidity, wind speed, and solar and net radiation, were recorded every 30 min. Outflow of the watershed at the S4 outlet was measured using a dual-span, 120° V-notch weir equipped with a continuous data-logger. Detailed description of the site, including instrumentation and monitoring procedures, can be found elsewhere (Shelby et al. 2005; Chescheir et al. 1998; Amatya et al. 2002). Long-term weather data for precipitation and air temperature were obtained from the U.S. Weather Bureau station at TRS (approximately 5 km north of the study site) near Plymouth, North Carolina.

DRAINWAT Model

The DRAINWAT [DRAINMOD (Skaggs 1978) for watersheds] model was developed (Amatya et al. 1997) by linking DRAINLOB (McCarthy et al. 1992) with the overland flow and ditch and in-stream flow routing components of the FLD&STRM model (Konyha and Skaggs 1992). In DRAINWAT, the water-balance components of individual fields in a watershed are predicted using DRAINLOB and then coupled with the ditch and canal routing component of FLD&STRM to improve the model's capability in simulating the water-balance components of both forested and agricultural areas at watershed scale (Amatya et al. 1997).

DRAINLOB, a forestry version of DRAINMOD, was developed by replacing the Hooghoudt equation of subsurface flow with the solutions of Boussinesq equations to increase prediction accuracy of subsurface drainage (DRN) (McCarthy et al. 1992). In this model, evapotranspiration and subsurface flow components of DRAINMOD were also modified, and an interception component was added to consider these hydrologic processes (Amatya et al. 1997). FLD&STRM, a medium-scale agricultural hydrology model, was modified from DRAINMOD by adding an overland flow routing and a stream routing module. The distributed model, DRAINWAT, operates as a sequenced set of simulations so that DRAINLOB-simulated outflow from each field (subwatershed), delineated with relatively uniform soil and stand conditions, is first combined into the collector ditch of the subwatershed (Konyha and Skaggs 1992; Amatya et al. 1997; Kim 2009). The simulated outflow from one or more subwatersheds is then routed through the channel system to the watershed outlet. Using the instantaneous unit hydrograph on the basis of time of concentration takes into account the time that is required for surface runoff to travel across the surface to the ditch and then to be 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 one-dimensional Saint-Venant equations to compute depth and flows at selected nodes along the stream or collector ditches. Details of modeling procedures and parameterization are described in Amatya (unpublished data, 1993) and Kim (2009).

The model has been successfully tested for predicting outflow rates in lower coastal plain watersheds with varying sizes and land uses that may often be affected by unsteady flow conditions such as backwater effects (Konyha and Skaggs 1992; Amatya et al. 1997). A detailed sensitivity analysis of both the field hydrology and ditch/canal routing parameters for flow in canals and streams was conducted by Konyha and Skaggs (1992), Kim (2009), and Kim et al. (2012). Diggs (2004) used a similar approach (DRAINMOD with Penman–Monteith PET, without an interception component) to predict outflows from another drained pine-forest site in the Parker Tract with good results.

The model was validated with 5 years of data (1996–2000) for predicting the outflow rates and nitrogen transport for this study watershed (S4) (Amatya et al. 2004). However, forest canopy evaporation caused by rainfall interception was not simulated because the data on canopy storage and coverage, leaf area index (LAI), and stomatal conductance for all stands in the watershed were not available. Instead, the Penman–Monteith PET for the forest reference estimated using the measured daily LAI function and maximum stomatal conductance for the pine forest with weather variables measured above its canopy was used in DRAINMOD to simulate ET (Amatya et al. 2004). The maximum stomatal conductance value was obtained from the Carteret study site (McCarthy et al. 1992; Amatya et al. 1996). The authors showed that the model-predicted outflows and their time distribution for 5 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 1,554 mm at the end of the 5-year period was only 4 mm higher than the measured amount of 1,550 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 on the basis of criteria recently developed (Moriasi et al. 2007). These analyses indicate that the model adequately describes daily and monthly drainage outflows for the study watershed. The fact that the average rainfall of 1,249 mm for the-5-year period was only 3% lower than that for the 50-year period simulated, and the mean outflow of 263 mm for the same period was also close to the 50-year average of 261 mm as will be shown later, further indicates that the calibrated model captures the average baseline hydrological conditions of the 50-year period. The validated model was applied in this paper to evaluate the hydrologic effects of conversion of the current pine forest into agricultural crop.

Modeling Scenarios

At first, a baseline scenario with all 27 fields (subwatersheds delineated for the S4 watershed) (Fig. 2) in their existing condition (all pine forest) was simulated. The results on hydrology (outflow for the whole watershed, ET, water table depth) were saved for this baseline scenario. Five other hypothetical scenarios involving the conversion of approximately 10, 25, 50, 75, and 100% of the 2,950-ha pine forest to a CWS crop rotation were simulated.

Further simulation scenarios were created for each of these percentages of land-use change occurring at upstream and downstream locations of the watershed. Fig. 2 is a sample schematic layout for conversion of 25% upstream [Fig. 2(a)] and 50% downstream [Fig. 2(b)] of the watershed. Fields were selected arbitrarily (visual basis) to obtain the desired percentage conversion for upstream and downstream portions of the watershed. Altogether, 10 sets of model simulations were conducted using a 51-year (1950–2000), long-term weather data set obtained from the U.S. Weather Bureau Station at Plymouth, North Carolina. The simulation of the first year (1950) was used to define initial conditions for January 1, 1951, so results for that year were not used in the analysis. The scenarios considered were summarized and tabulated in Table 1.

Model Parameterization for This Study

Hydrologic effects of conversion from original pine forest to the agricultural crop rotation were simulated by changing soil hydraulic properties, surface storage, rooting depth, and the reference ET (REF-ET) (or PET) for the forest fields to values consistent with agricultural crops (Table 2).

Drainage Design Parameters

The individual fields of the watershed are drained by lateral ditches that are 0.6–1.2 m deep and mostly 100 m apart. The lateral ditches discharge to collector ditches 1.8–2.5 m deep and 800 m apart (Fig. 3); these ditches, in turn, discharge to main canals, which are 1.8–3.0 m deep, and then finally to the natural stream. Bed slope was 0.5 m/km, and Manning roughness coefficients ranged from 0.035 (upstream) to 0.050 (downstream) for baseline simulation. These values remained the same for both the baseline and the conversion scenarios for earthen ditches and canals.

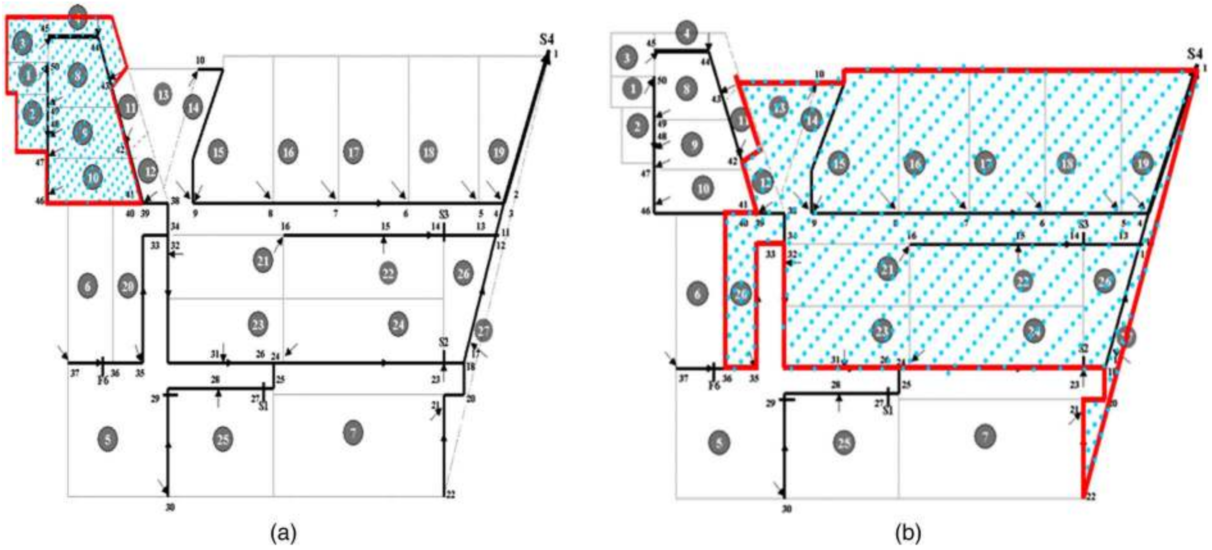

Fig. 2. Examples of field diagram (not to scale): (a) 25% upstream; (b) 50% downstream

Table 1. Spatial Distribution of Land-Use Conversion within 2,950 Ha for Various Scenarios

Conversion to agricultural cropland (%)	Location	Field number converted to agricultural cropland	Area (ha)	Percent of watershed area
10	Downstream	18, 19, 26	267	9.1
	Upstream	1, 3, 8	301	10.2
25	Downstream	18, 19, 26, 21, 22, 23, 24, 27	727	24.6
	Upstream	1, 3, 8, 2, 4, 9, 10	766	26.0
50	Downstream	18, 19, 26, 21, 22, 23, 24, 27, 12, 13, 14, 15, 16, 17, 20	1,492	50.6
	Upstream	1, 3, 8, 2, 4, 9, 10, 5, 6, 7, 11, 12, 25	1,493	50.6
75	Downstream	18, 19, 26, 21, 22, 23, 24, 27, 12, 13, 14, 15, 16, 17, 20, 2, 4, 8, 9, 10, 11	2,211	75.0
	Upstream	1, 3, 8, 2, 4, 9, 10, 5, 6, 7, 11, 12, 25, 13, 14, 15, 20, 21, 22, 23	2,187	74.1

Note: Dominant soil types [and, in parentheses, their symbols as per the SCS (1981)] that are within the fields indicated by the numbers shown in Fig. 2: Belhaven (Ba): 5, 6, 7, 10, 12, 14, 15, 16, 17, 20, 21, 22, 23, 24, 25; Cape Fear (Cf): 1, 2, 3, 4, 8, 9, 11, 18; Portsmouth (Pt): 19; Wasda (Wd): 26, 27; and Portsmouth (Pt) modified for the wetland field: 13.

Table 2. Soil Hydraulic Properties for Major Soil Types

		Soil types			
Land use	Properties	Ba	Cf	Pt	Wd
Pine forest	Impermeable layer depth (cm)	240	250	240	200
	Hydraulic conductivity (cm/h) (Depth range, cm)	700 (0–30) 350 (30–45) 10 (45–60) 5 (60–240)	700 (0–30) 650 (30–40) 100 (40–50) 40 (50–70) 5 (70–250)	50 (0–30) 10 (30–50) 10 (50–240)	20 (0–30) 0.4 (30–80) 1 (80–200)
	Saturated water content (cm^3/cm^3)	0.72	0.64	0.37	0.37
	Wilting point (cm^3/cm^3)	0.37	0.57	0.15	0.15
	Rooting depth (cm)	45	45	45	45
	Surface storage (cm)	10.0	10.0	10.0	10.0
Agricultural crop	Impermeable layer depth (cm)	270	240	215	200
	Hydraulic conductivity (cm/h) (Depth range, cm)	20 (0–30) 1 (30–80) 0.01 (80–270)	5 (0–36) 14 (36–42) 2 (42–65) 0.1 (65–240)	15 (0–30) 2 (30–100) 8 (100–215)	20 (0–30) 0.4 (30–80) 1 (80–200)
	Saturated water content (cm^3/cm^3)	0.73	0.49	0.37	0.76
	Wilting point (cm^3/cm^3)	0.45	0.17	0.17	0.45
	Surface storage (cm)	0.25	0.25	0.25	0.25

Note: SCS symbols: Ba = Belhaven; Cf = Cape Fear; Pt = Portsmouth; Wd = Wasda.

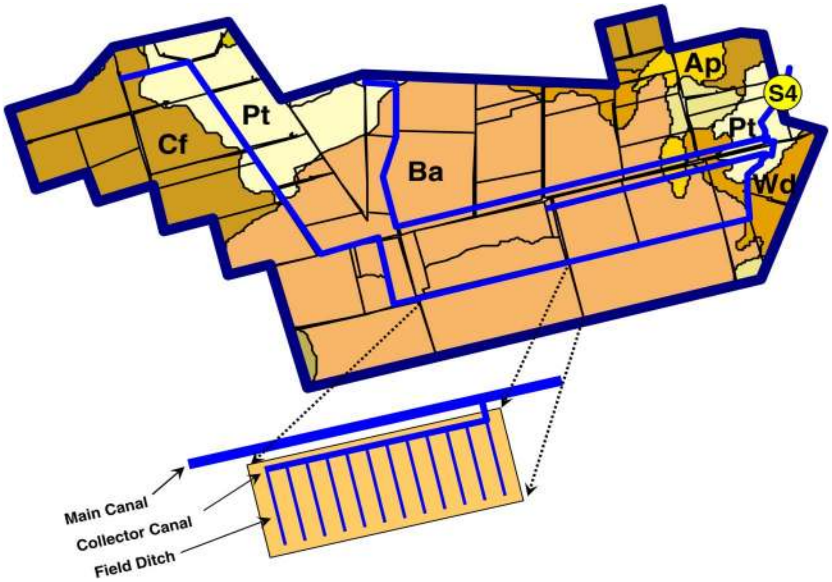

Fig. 3. Soil series classification of 10,000-ha watershed study site using ARCINFO geographic information system–based SCS soil coverage of Washington County, North Carolina

Soil Hydraulic Properties

Three mineral soils and one organic soil are present in the watershed (Fig. 3 and Table 2). The mineral soils in the northern part (upstream) of the watershed are very poorly drained Cape Fear loam (Cf) (fine, mixed, semiactive, thermic Typic Umbraquults), Wasda (Wd) (fine-loamy, mixed semiactive, acid, thermic Histic Humaquepts), and Portsmouth fine sandy loam (Pt) (fine-loamy over sandy or sandy-skeletal, mixed, semiactive, thermic Typic Umbraquults), whereas organic Belhaven muck (Ba) (loamy, mixed, dysic, thermic Terric Haplosaprists) is predominant in the southern half of the watershed, as presented in a soil survey report by the Soil Conservation Service (SCS 1981).

There were 27 delineated fields in the watershed (Fig. 2). Field 13 is a natural wetland with no interior drainage ditches, and specific soil hydraulic properties of the Portsmouth series identified for the wetland were considered for simulation from previous studies (Chescheir et al. 1994; Amatya et al. 2008). The writers' long-term experiences on the hydrology of the poorly drained soils in the Atlantic coastal plain (Skaggs et al. 1991; Amatya and Skaggs 2001; Skaggs et al. 2011) have indicated that the forests have much higher hydraulic conductivity in the topsoil layer than agricultural croplands because forest topsoil is generally mixed with litter, roots, and organic matter. Higher hydraulic conductivity of the topsoil layer eventually increases the subsurface drainage substantially. In addition, the forests on this type of drainage system have a high surface depressional storage attributable to the raised-bed plantation's potentially reducing the surface overland flow, which generally occurs only after all the surface storage is filled up with water. On the contrary, agricultural lands have small microtopography with much smaller surface depressional storage potentially increasing the overland flow. Based on this assumption from the writers' previous experiences, most of the soil hydraulic properties and the input parameters for the fields in pine forests (Table 2) were obtained from two references (SCS 1981; Diggs 2004). Soil properties for the fields converted to agricultural croplands (Table 2) were determined on the basis of the other field study results (Skaggs and Nassehzadeh-Tabrizi 1986; Burchell 2003). Hydraulic conductivity values for Cape Fear soil were changed from 650 to 5 cm/h for the second layer (30- to 40-cm depth), from 100 to 2 cm/h for the third layer (40- to 50-cm depth), and from 40 to 2 cm/h after conversion to cropland on the basis of Skaggs et al. (2011), who found field-effective hydraulic conductivity in the top 70 cm of the drained forest site more than two orders of magnitude greater than that of corresponding layers of the same soil series on agricultural cropland. Soil hydraulic conductivity of wetland was also changed from 99- to $50-\mathrm{cm/h}$ depth in the first layer (0–35 cm). Hydraulic conductivities of all other soils in different layers were assumed to remain the same after conversion.

Surface Depressional Storage

Surface depressional storage is another important parameter that is generally very different in forested lands compared with agricultural cropland because of the nature of microtopography and surface drainage. Surface storage for forested land is generally one order of magnitude higher than that of the agricultural lands owing to the bedding that occurs when plantation forests are planted on poorly drained soils, natural depressions that are not filled, and increased microtopography created by litter layer. Depressional storage is an input to DRAINMOD and has a large impact on predicted surface runoff and peak flow rate when the water table rises to the soil surface (Skaggs et al. 1991).

Skaggs et al. (1991) used a surface-storage value of 2.5 cm for their baseline simulation in a natural pocosin with no drainage ditches and tested the impact of various depressional-storage values from 0.5–30.0 cm on annual average ET and runoff. Amatya and Skaggs (2001) used 7.5 cm for bedded pine forest in eastern North Carolina. For the agricultural lands, Skaggs and Nassehzadeh-Tabrizi (1986), Brevé et al. (1997), and Youssef et al. (2006) used depressional-storage values of 0.25–1 cm. Amoah (2008) developed a method to estimate depressional storage using digital elevation models (DEMs) with values between 1 and 10 cm for forested lands in watersheds in South Carolina. The depressional-storage value used in this simulation study was 10.0 cm for fields with pine forests (Table 2) (Skaggs et al. 2011) and 0.25 cm for fields with CWS agricultural crops (Table 2).

Vegetation Parameters and Rooting Depth

Surface vegetation ranged from unharvested second-growth mixed hardwood and pine forest to loblolly pine (LP) plantation (*Pinus taeda* L.) of various stand ages for the study period (Amatya et al. 2004). Forest growth is considered in the current model using the LAI for the biomass. Leaf area index is also a key parameter needed in estimating evapotranspiration. It was measured only for field F6 with a 5-year-old pine stand in 1996. This LAI was used to estimate daily PET across the watershed for forest reference, as discussed previously (Amatya et al. 2004), because the LAI data were not available for all types of stands on the watershed. Forest growth was not simulated, so vegetation conditions were assumed to be constant over the period of simulation.

Rooting depth affects evapotranspiration, water table depth, the soil-water balance, and, consequently, outflow. Rooting depth is used in DRAINMOD to define the zone from which water can be removed to satisfy ET demand. Skaggs et al. (1991) used 15–25 cm for the rooting depth of natural pocosin, 40 cm for pine forest, and 3.0- to 30-cm time-dependent values for agricultural crops. Diggs (2004) used 45 cm for mature pine forest; rooting depths of 37–50 cm were used in another hydrologic study of a loblolly pine plantation (Amatya and Skaggs 2001). In this study, rooting depth for forested fields and forested wetland was set to 45 cm (Table 2). For the CWS rotation on lands converted to agricultural fields, a seasonal variation from 3.0–30 cm suggested by the DRAINMOD user's guide was considered in previous work (Amatya et al. 2008). However, these values were chosen for corn only and were not appropriate for a CWS rotation. For simulating fields with a CWS crop scenario, it was assumed that half of the fields had root depths appropriate for corn (planted in April) followed by wheat (planted in November), and the other half were appropriate for wheat (harvested in June) followed by soybean (planted in late June and harvested in October). Those values were also presented in Table 3.

Potential Evapotranspiration Factors

Potential ET inputs appropriate for pine forest and for a CWS crop rotation were used to simulate the hydrologic effects of the land-use conversion. Next to rainfall, ET is the largest component of the water balance, so it is logical that differences in factors affecting ET between the two land uses should be carefully considered. Amatya et al. (2002) found approximately 9% increase, on average, in REF-ET calculated using measured LAI and maximum stomatal conductance for loblolly pine (Amatya and Skaggs 2001) with the daily measured weather data compared with the standard grass reference. The increase was primarily attributable to increase in net radiation or decrease in the albedo factor for the pine canopy. Sun et al. (2010) found approximately 17% higher REF-ET for a matured pine forest compared with a clear-cut (CC) site with

J. Hydrol. Eng. 2013.18:552-566.

Table 3. Vegetation Rooting Depth for Agricultural Cropland on Studied Watershed

Dates	January 1	March 26	April 20	April 30	May 31	June 22	September 2	September 12	September 27	October 7	October 27	November 26	December 31		
Rd1[a]	3.0	3.0	6.0	15.0	25.0	30.0	30.0	10.0	3.0	3.0	10.0	15.0	15.0		
Dates	January 1	February 9	March 1	April 1	May 10	May 11	May 26	June 5	June 19	July 4	July 20	October 27	November 16	November 21	December 31
Rd2[a]	15.0	15.0	20.0	25.0	25.0	25.0	3.0	7.0	20.0	25.0	30.0	30.0	10.0	3.0	3.0

Note: Rd1 = rooting depth 1; Rd2 = rooting depth 2.

[a] Monthly rooting depths for agricultural cropland were selected from DRAINMOD user guide (Skaggs 2013), and the values are the same regardless of soil series: Rd1 was assumed corn/wheat; Rd2 was assumed wheat/soy.

mostly grass understory for a 2005–2007 study period. The authors reported that the pine forest ET can be much higher than the grass REF-ET during the peak growing season.

Long-term simulations in this study used temperature-based Thornthwaite PET method (1948) because complete weather data for using the process-based Penman–Monteith method (Monteith 1965) were not available for the historic period. However, the monthly PET based on Thornthwaite method (TH PET) was adjusted in the model using monthly correction factors calibrated with the PET based on the Penman–Monteith method (P-M PET) from Amatya et al. (1995b, 2002) for both forested and agricultural vegetation at this location.

Long-term (1988–2004) complete weather data measured for a pine plantation forest in eastern North Carolina (Amatya et al. 2006) and data from this study site for the 1996–2001 period (Amatya et al. 2004) were used to compute daily PET for the Penman–Monteith and Thornthwaite PET methods. Daily values were used to obtain the monthly total. Then, the monthly factor was calculated as a ratio of the PET from the Penman–Monteith and the Thornthwaite methods (Amatya et al. 1995b). These monthly factors were further used to calculate the average monthly values for the pine forest. A similar procedure was followed using the long-term (1990–2001) data from the TRS site in Plymouth, North Carolina, for the agricultural crop–based P-M PET (Amatya et al. 1995b, 2002). In this case, a grass reference for the short agricultural crops was used in the P-M PET calculations.

This procedure was used because the PET rate varies depending upon the type of reference vegetation (Sun et al. 2010). Studies have shown that on a monthly to seasonal basis, outflow predictions using temperature-based Thornthwaite method with appropriately calibrated monthly correction factors may be as good as the method based on Penman–Monteith (Amatya et al. 1997, 1998; Harder et al. 2007). Interception was not simulated because leaf area index and canopy storage data were not available for various stand types on the watershed. Stand age of the current vegetation was also assumed to be constant throughout the simulation period. The monthly factors used in TH PET for both the pine forest and agricultural crop were further used to estimate the weighted average factors on the basis of weighted area of the forest and agricultural crop for each percent of computed values, as shown in Table 4.

Evaluation of Hydrologic Effects

Simulation 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 attributable to conversion to a CWS crop rotation on the percent change of mean annual and maximum outflow, maximum annual and minimum annual flow, mean daily and maximum outflow rates, and their time distribution. Average annual outflow, maximum peak flow rate, frequency and size of various flow rates, average annual ET, and water table depth were also calculated on the basis of the 50-year simulated values. Daily rainfall, simulated flow rates, and simulated WTD were analyzed to examine behavior of hydrology for a wet, dry, and normal year for the baseline forested condition compared with 100% conversion to agricultural cropland, as a worst-case scenario.

Frequency and size of daily flow and daily WTD for 50 years were also analyzed using flow frequency duration (FDC) and WTD duration curves. Flow frequency duration, the relationship between magnitude and frequency of streamflow discharges, is one of the most informative tools for showing the complete range of outflows from low flows to flood events (Smakhtin 2001). It provides a graphical summary of streamflow variability at a given location, with the shape being determined by rainfall pattern, catchment size,

Table 4. Monthly Correction Factors for Thornthwait PET Method Used in Long-Term Simulation

Months	Estimated for forest land[a]	Estimated for agricultural cropland	Estimated weighted average for various scenarios: 75% agric.+ 25% forest	50% agric.+ 50% forest	25% agric.+ 75% forest	10% agric.+ 90% forest
January	2.33	2.19	2.23	2.26	2.29	2.31
February	2.21	2.43	2.37	2.32	2.26	2.23
March	2.15	2.19	2.18	2.17	2.16	2.15
April	1.74	1.64	1.66	1.69	1.72	1.73
May	1.24	1.13	1.16	1.18	1.21	1.23
June	0.96	0.97	0.97	0.97	0.96	0.96
July	0.91	0.85	0.87	0.88	0.90	0.91
August	0.89	0.80	0.82	0.84	0.86	0.88
September	0.94	0.90	0.91	0.92	0.93	0.93
October	1.42	1.17	1.23	1.30	1.36	1.40
November	1.67	1.19	1.31	1.43	1.55	1.62
December	2.37	1.44	1.67	1.90	2.14	2.28
Average	1.57	1.41	1.45	1.49	1.53	1.55

Note: agric. = agricultural cropland.

[a] The data in column for forested land were obtained from the average of the Carteret site and Parker tract for pine forests in eastern North Carolina. The data for agricultural land were calculated by average of Amatya et al. (1995) and 6 years of data (1996–2001) of Amatya et al. (2002) for TRS, Plymouth, North Carolina.

physiographic characteristics of the catchment, and land use. Low and high flow were defined first to discuss the effects of land-use conversion on daily outflow and water table depth. Low flow was defined as "flow that is exceeded 70% of the time" (Smakhtin 2001). High flow was defined as flow that is exceeded 1–5% of the time (Brown et al. 2005). Midflow was therefore defined as flow from 6–69% of the time. Tukey's test and Student's t-test with *SAS 9.1.3* (SAS Institute 2004) and *Microsoft Excel 2007* software were used to evaluate the statistical significance of difference in simulated hydrologic variables between upstream and downstream scenario for all sizes of conversion.

Results and Discussion

Hydrologic Effects of Converting Forested Fields to Agricultural Fields

Effects of converting land use from forested to a CWS agricultural crop rotation are shown in Table 5.

Effects within Each Location of Conversion: Downstream and Upstream

Mean annual outflow increased with increase in the percent of CWS cropland, as expected, for both downstream and upstream locations (Table 5). In the DS conversion scenario, the mean annual outflow increased substantially, from 261 to 326 mm (19.9%), as the percentage of conversion increased from 0 to 100%. Runoff coefficient normalized by rainfall also increased. However, there was no substantial difference in maximum annual and daily outflow between the 10 and 75% conversion (Table 5). The frequency of zero flow rates gradually decreased from 26.9 to 14.2% for 75% conversion and then increased to 18.3% for 100% conversion to agricultural crops. In the case of the frequency of small flow rates (less than 1 mm/day), a gradual increase was found (from 49.2 to 61.8%) from baseline simulation to 75% conversion, and then a slight decrease was observed from 75 to 100% conversion of watershed area. In the case of midflow rates (1–5 mm/day), no trend was observed. However, the frequency of high flow rates (more than 5 mm/day) gradually increased from 2.1 to 5.0% as the conversion percentage increased from baseline simulation to 100%.

Results for conversion concentrated in the upstream locations of the watershed were similar to those predicted for downstream conversions (Table 5). Conversion of 50 and 75% of the forest land to cropland had a somewhat greater effect on average annual outflow for US than for DS locations, but trends in predicted runoff statistics were otherwise approximately the same (Table 5).

Effects within Each Percent Conversion

A 10% conversion to CWS agricultural land caused an increase in mean annual outflows of only 3.7% for DS and 4.8% for US cases, respectively. In the 10% conversion scenario, there were no significant differences in maximum annual and daily flow rates, and there were also no unique trends in frequency of flow rates between DS and US (Table 5).

For a 25% land-use conversion from forest to agriculture, the increases in the mean annual outflow were 9.1% for DS and 10.0% for US. Maximum annual outflow decreased 1.5% for both DS and US conversion. The maximum daily flow rate increased only 0.1% for DS and decreased only 0.1% for US. The frequency of high flow rates $>5\ \text{mm}\,\text{day}^{-1}$ increased appreciably from 2.1% for the baseline to 2.5% for DS and 3.0% for US scenarios, respectively.

When 50% of the forest cover was converted to CWS cropland, the mean annual outflow substantially increased (12.7% for DS and 16.6% for US). The maximum annual outflow did not change for DS, however, and increased 2.7% for US. Maximum daily flow decreased 0.1% for DS and increased 0.1% for US. The frequency of high flow rates $>5\ \text{mm}\,\text{day}^{-1}$ increased 3.2% for DS and 4.1% for US scenarios, respectively.

The conversion of 75% from forest to CWS cropland increased mean annual outflow by 16.4% (312 mm) for DS, and 19.4% (324 mm) for US compared with 261 mm for the baseline simulation results. In this percentage of land-use conversion, the maximum annual outflow increased 1.1% for DS but increased 5.0% for US. In addition, maximum daily outflows decreased 0.4% for DS and increased 0.2% for US. The frequency of high flow rates $>5\ \text{mm}\,\text{day}^{-1}$ increased 4.2% for DS and 4.7% for US scenarios, respectively.

However, the increase in mean annual outflow was significantly different (Tukey's test; $\alpha = 0.05$) only for 100% conversion to agricultural cropland (CWS), which yielded a 326-mm outflow (19.9% increase) compared with 261 mm for the baseline. When the entire

Table 5. Simulated Average Annual Hydrologic Variables Based on Size and Location of Land-Use Conversion from Pine Forest to Agricultural Cropland

		Annual outflows					Daily outflows		Percent days with daily flow (in 18,263 days)			
Conversion location	Forest lands converted to agricultural cropland (percent of 2,950 ha)	Mean annual flow (mm)	Increase in mean annual flow (%)	Maximum annual flow (mm)	Increase in maximum annual flow (%)	Annual runoff coefficient (%)	Maximum daily flow (mm)	Increase in maximum daily flow (%)	0 mm/day	0–1 mm/day	1–5 mm/day	>5 mm/day
Downstream	0	261	0.0	562	0.0	20.3	9.98	0.0	26.9	49.2	21.8	2.1
	10	271	3.7	564	0.4	21.0	9.98	0.0	22.2	53.5	22.0	2.3
	25	287	9.1	553	−1.5	22.3	9.99	0.1	20.7	53.8	23.0	2.5
	50	299	12.7	562	0.0	23.2	9.97	−0.1	15.4	60.2	21.2	3.2
	75	312	16.4	568	1.1	24.2	9.94	−0.4	14.2	61.8	19.8	4.2
	100	326	19.9	582	3.5	25.3	10	0.2	18.3	56.5	20.2	5.0
Upstream	0	261	0.0	562	0.0	20.3	9.98	0.0	26.9	49.2	21.8	2.1
	10	274	4.8	564	0.4	21.3	9.98	0.0	24.7	51.2	21.8	2.3
	25	290	10.0	553	−1.5	22.5	9.97	−0.1	22.2	53.9	20.9	3.0
	50	313	16.6	577	2.7	24.3	9.99	0.1	20.2	54.8	20.9	4.1
	75	324	19.4	592	5.0	25.2	10	0.2	16.4	57.5	21.4	4.7
	100	326	19.9	582	3.5	25.3	10	0.2	18.3	56.5	20.2	5.0

100% (2,950 ha) forest area was converted to CWS cropland, the simulated maximum annual outflow increased by approximately 3.5% to as much as 582 mm.

Notably, for the 10, 25, 50, and 75% land-use conversion to the CWS cropland, all outflow characteristics were somewhat greater for the upstream conversion scenario than for the downstream (Table 5 and Fig. 4). The dominant soil in the upstream area of the watershed was Cape Fear (Fig. 2, Cf). The saturated hydraulic conductivities of Cape Fear in the second (30- to 40-cm depth), third (40- to 50-cm depth), and fourth soil layer (50- to 70-cm depth) were greatly reduced from 650 to 5 cm/h for the second layer, 100 to 2 cm/h for the third layer, and 40 to 2 cm/h for the fourth layer of this soil after conversion to CWS cropland (Table 2). Belhaven soil occupies most of the area of middle and downstream, and soil hydraulic conductivity also greatly decreased after conversion to the CWS agricultural crop rotation (Table 2). This reduction of soil hydraulic conductivity resulted in a decrease of subsurface drainage but increase of surface runoff. It was concluded that differences in predicted effects of land-use conversion from forest to agricultural crops in the upstream and downstream locations in this watershed were mainly attributable to projected changes in hydraulic properties of the Cape Fear and Belhaven soils.

As presented in Fig. 4, for example, mean annual surface runoff was greater in 50% upstream conversion (120.0 mm) than in 50% downstream conversion (104.8 mm) to CWS agricultural crop [Fig. 4(a)] for all 50 years (1951–2000). On the contrary, more annual subsurface drainage was predicted for 50% downstream conversion (248.8 mm) than for the same percentage conversion upstream (236.0 mm) [Fig. 4(b)]. Bachmair et al. (2009) investigated the effects of land use and land cover (LULC) on soil structure and then preferential flow during infiltration through dye-tracer experiments from five different sites with different LULC: two grassland sites, two agricultural crop sites (tilled and untilled), and one deciduous forest site. They found that preferential flow processes significantly differed among sites of different LULC even though the soil texture from those sites was similar. Their overall conclusion was that land use affected flow processes in soils because of several controlling factors, such as soil structure, surface microtopography, surface cover, and topsoil matrix characteristics. These results are consistent with the recent finding of Skaggs et al. (2011), who reported zero surface runoff from forest lands because of high conductivity of surface layers and large surface storage. On the basis of these observations, it was assumed that the change of soil hydraulic properties caused by land-use conversion had a great influence first on the flow characteristics in soil and then, eventually, on the hydrologic processes, including surface runoff and subsurface drainage.

The effect of the percentage conversion of forest land to agricultural cropland on mean and maximum annual outflow is shown in Figs. 5(a and b) respectively, for both US and DS conversions. As expected, mean annual outflow increased as the percentage of conversion increased. Conversion of upstream locations to agricultural cropland had a greater effect on mean annual outflow than the same level of conversion at downstream locations. This indicates that the effects of percent conversion on outflow processes seem also to be affected by the soil type, their properties (especially K_s, saturated lateral hydraulic conductivity), and the location of the soil in the landscape. The greatest difference between the upstream and the downstream scenario was observed in 50% conversion for mean annual outflow and in 75% conversion for maximum annual outflow (Fig. 5). The effect of conversion observed in this study was nonlinear and was somewhat different from those analyzed by Fernandez et al. (2007), Dai et al. (2008), and Qi et al. (2009), who reported more or less linear changes in outflow responses.

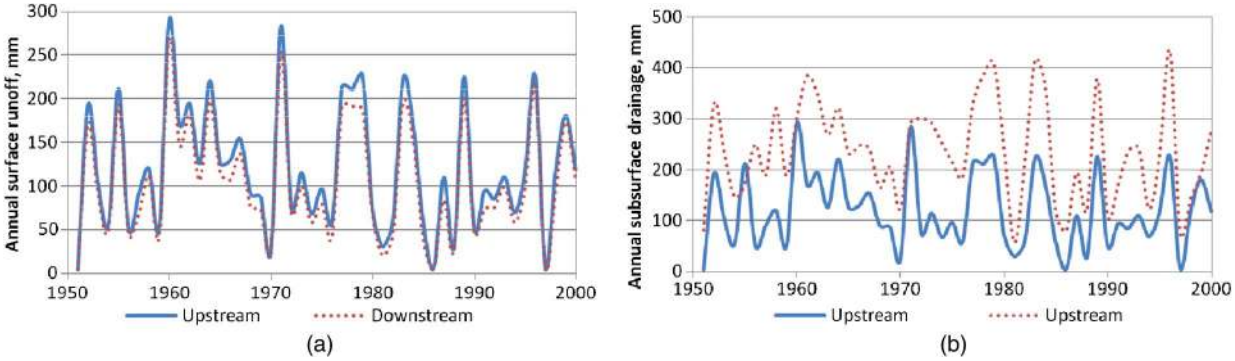

Fig. 4. (a) Surface runoff; (b) subsurface drainage: 50% US and 50% DS conversion scenario

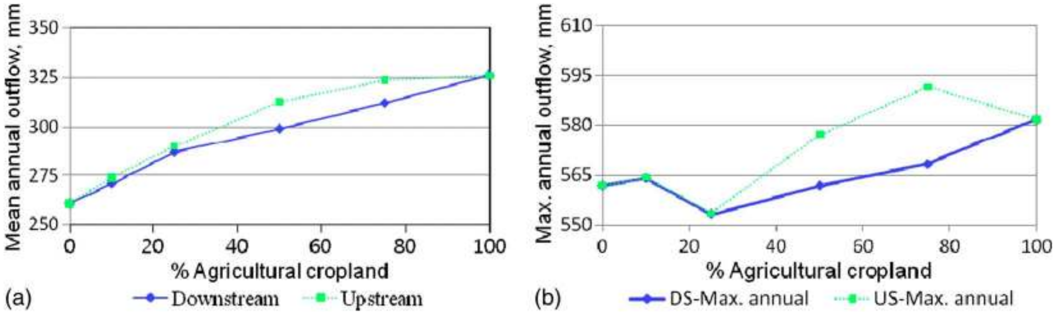

Fig. 5. Change of (a) mean annual; (b) maximum annual outflow according to land-use change and location

Effects of Full Conversion Agricultural Cropland (CWS Rotation) on Annual Water Balance

The effect of converting the forested watershed to agricultural cropland on outflow from the watershed was discussed previously. Effects on other hydrologic components and the water balance are considered in this section. Average annual values predicted in 50-year simulations for the two extreme scenarios of all forest and all cropland (CWS rotation) are given in Table 6 for rainfall, outflow (surface runoff plus subsurface drainage), ET, annual WTD, outflow/rainfall (O/R) ratio, and ET/rainfall ratio.

The average rainfall for 50 years was 1,288 mm and ranged from 907 mm in 1970 to 1,760 mm in 1989. Predicted average annual outflow increased from 261 mm for baseline simulation (100% forested lands) to 326 mm for 100% conversion to a CWS rotation. This was an increase of about 20% compared with the baseline scenario. This is greater than increases obtained by Qi et al. (2009) and Fernandez et al. (2007), with baseline forest coverages of 66 and 50%, respectively (the percent increases of runoff predicted in those studies were 14% and 16%, respectively). Dai et al. (2008) evaluated the impact of converting 100% of a wetland forest to agricultural cropland using DHI-MIKESHE and DRAINMOD. They predicted a 30 and 35% increase in average annual outflow with DHI-MIKESHE and DRAINMOD, respectively. These results are consistent with Skaggs et al. (2011), who found approximately 37% higher mean annual outflow from an agricultural site compared with all pine forest.

Conversion of 100% of the S4 watershed from forest to row-crop agriculture (CWS rotation) would increase the predicted runoff ratio from 19.6 to 24.7% (Table 5). Predicted annual outflow for the baseline scenario ranged from 9 to 562 mm. For 100% agricultural cropland, the predicted outflow value ranged from 92 to 582 mm.

Predicted average annual ET decreased from 1,013 to 902 mm because of land-use conversion. For 100% forest, annual ET ranged from 817 to 1,268 mm. Simulated annual ET decreased to a range

Table 6. Summary of Average Hydrologic Components for 50 Years

Land use	Parameters	Rainfall (mm)	Outflow (mm)	ET (mm)	WTD (cm)	O/R ratio	ET/rain (%)
All forest (baseline)	Average	1,288.0	261.0	1,013.1	94.8	19.6	80.3
	Maximum	1,759.6	561.8	1,268.0	245.7	40.9	112.1
	Minimum	907.2	8.7	817.3	41.7	0.8	60.2
	SD	185.4	142.5	79.2	41.4	9.4	13.4
	COV	0.14	0.55	0.08	0.44	0.48	0.17
All agriculture (100% conversion)	Average	1,288.0	326.2	902.4	66.3	24.7	71.2
	Maximum	1,759.6	581.9	1,161.1	112.4	37.6	93.4
	Minimum	907.2	91.9	690.8	32.0	9.0	54.8
	SD	185.4	123.5	79.4	20.4	7.0	10.3
	COV	0.14	0.38	0.09	0.31	0.28	0.14

Note: SD = standard deviation; COV = coefficient of variation.

J. Hydrol. Eng. 2013.18:552-566.

of 691 to 1,161 mm after conversion to agricultural cropland (Table 6). This was a decrease of approximately 11% with the CWS agricultural crop compared to the baseline with all-forest scenario. In another 5-year short-term study, Amatya et al. (2002) found 22.5% lower ET on the adjacent agricultural site compared with this forest site. Similarly, the ET as a percentage of rainfall decreased from 80% for all forest to 71% for a CWS rotation.

Evapotranspiration, the sum of wet canopy evaporation, dry canopy transpiration, and soil evaporation, is a significant component of the forest water balance (65% of the total rainfall) (Amatya et al. 1996; Amatya and Skaggs 2001). Decrease of ET after conversion from forest to agricultural fields would have resulted from both the reduced canopy evaporation and transpiration. Average annual WTD for 50 years decreased from 95 cm for all-forest scenarios to 66 cm for a CWS rotation. The annual average WTD ranged from 42–246 cm for baseline simulation (100% forest) and from 32–112 cm after 100% conversion to cropland.

Simulated annual water-balance components including rainfall, ET, and annual outflow are shown in Fig. 6. The differences in water-balance components between 100% forested land and 100% CWS cropland were attributed to the differences in water loss caused by ET for different land use, surface storage, and soil properties because weather, drainage design, and elevation data were identical for both simulations. Simulated annual ET substantially decreased, and annual outflow increased as forested fields were converted to all-agricultural fields. The most visible change was observed in simulated water table depth of field F5. The maximum annual average WTD was 246 cm before land-use conversion and 112 cm after conversion.

Seasonal Variation in Daily Flows of Wettest and Driest Years

The variations of the simulated daily outflows, annual rainfall, and simulated annual water table depth in the wettest and driest years are compared with those of a normal year in Fig. 7. The wettest, the driest, and the normal year were selected on the basis of total annual rainfall; seasonal patterns of rainfall for these years were not considered.

Year 1970 was the driest of the 50-year simulation period with a 377-mm rainfall deficit [Fig. 7(a)]. The rainfall amount during the first half of 1970 was only 58% of that of a normal year (1994). The simulated water table depth on June 1 was 136 cm for baseline simulation compared with 132 cm after conversion to a CWS crop rotation. After June 1, the simulated WTD dropped to more than 240 cm for baseline forested fields compared with 150 cm for agricultural cropland. This created a large soil-water deficit in both cases. As a result, the small rainfall events from May 29–December 21 did not produce predicted outflows because all the rain was stored in the dry soil profile.

Interestingly, simulated water table depth on December 22 for the baseline condition (forest) was 255 cm; the profile was so dry that the rainfall event of 24 mm on December 23 was not enough to produce outflow. Simulated water table depth for 100% agricultural cropland (after conversion) was closer to the surface, 157 cm, but the 24-mm rainfall was still not enough to produce outflow on December 23, nor for the rest of the year [Fig. 7(a)]. Similar observations were made by Amatya and Skaggs (2011) for another drained pine forest in eastern North Carolina, where the water table dropped below 250 cm. Sun et al. (2010) also found exceptionally dry soil conditions at CC and matured LP sites, with the water table depths retreating deeper than 1.5 m during a dry period in 2007.

The wettest year during the simulation period was 1989 (annual rainfall of 1,760 mm) with a surplus rainfall (difference between precipitation and potential ET) of 476 mm. As would be expected, groundwater elevations were much higher than normal owing to the consistent rainfall from February to August. Conversion from forest to a CWS crop rotation resulted in substantial increases in outflows during this wet year [Fig. 7(b)]. Not only was flow predicted during the winter for the CWS rotation when no flow was simulated for the

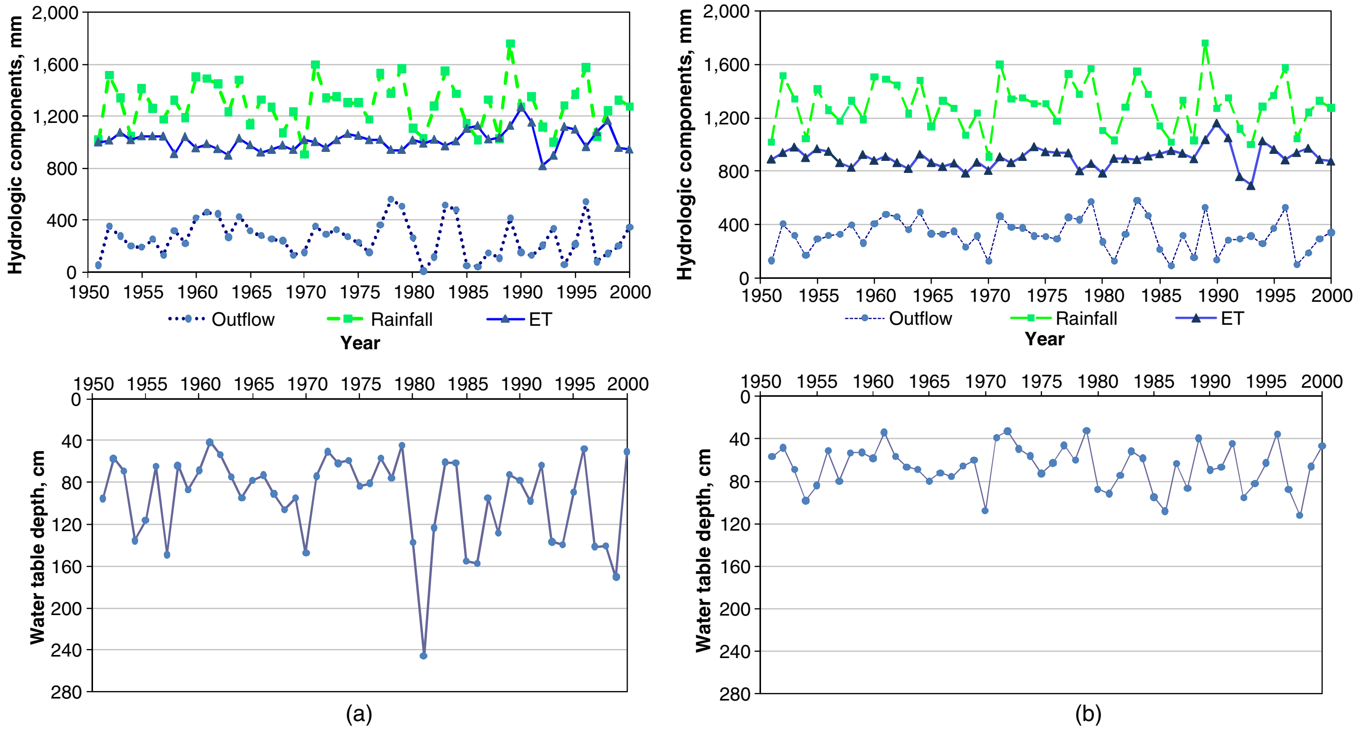

Fig. 6. Simulated water-balance components of outflow and ET with measured rainfall at the top and simulated water table depth at the bottom for (a) 100% forested area; (b) 100% agricultural cropland

forest, but the peak flow rates were approximately doubled. For the baseline simulation, only two daily flow events were more than 6 mm. However, 14 peak flow rates were more than 6 mm after conversion to CWS crop rotation [Fig. 7(b)]. The simulated maximum daily outflow of 5.0 mm before conversion increased to 9.8 mm after conversion.

Fig. 7 also shows the impact of the antecedent conditions. For the driest year (1970) [Fig. 7(a)], there was a wet antecedent (end of 1969) condition that resulted in most of the winter flow. This year was drier than other years in terms of rainfall, but wetter than other years in terms of antecedent conditions. In contrast, the antecedent conditions were very dry for the wet year (1989) [Fig. 7(b)] and the normal year (1994) [Fig. 7(c)]. As a result, there were no predicted flows in the early part of the year for either of the wettest years because of the dry antecedent conditions. The period of rewetting from these dry conditions is when the real differences in flow volumes between forest and agricultural cropland occurred. Skaggs et al. (2011) made similar observations regarding the effects of antecedent conditions on drainage flow from forest land, a wet land, and a land with an agricultural crop for eastern North Carolina.

Frequency Analysis

Flow duration curves (FDC) were used to evaluate the impact of land-use conversion on daily flow frequency regime and water table depth fluctuation. Fig. 8 shows the simulated flow duration curves of daily outflows and water table depths for both 100% forested land and 100% agricultural land. The general shape of FDC for the present study site was similar to that of pine plantations in the Glendhu experimental catchments in New Zealand (Brown et al. 2005). This response is typical of many watersheds in high-rainfall areas in which annual precipitation is greater than annual potential evapotranspiration (Brown et al. 2005). In this study, there were only very small changes in flow owing to land-use conversion from forest to an agriculture crop rotation for low and midflow regimes. There were substantial differences, however, in the high flow range, which occurred from 1–10% of the time [Fig. 8(a)]. For example, at 5% exceedance the daily flow rates on forest land were 3 mm or higher, as compared with 5 mm or higher when the entire watershed was converted to cropland. Similarly, a high flow of 8 mm/day occurred 1.3% of the time on the CWS cropland (230 out of 18,263 daily outflow events), but such flows occurred only 0.4% of the time on the forest land. Flows on forest land were zero for more than 26% of the time, compared with 18% on the agricultural land. This was primarily attributable to larger soil storage caused by higher ET and to the much larger depressional storage on the forest compared with the CWS cropland.

Simulated water table levels rose higher after the fields were converted from forest to a CWS crop rotation. This was mainly attributable to reduced total simulated ET (Table 6) reflected by lower PET value (Table 4) and smaller rooting depths (Table 3) for the CWS crop compared with the pine forest. Also, 22% of simulated daily water table depths were 150 cm or deeper, and the deepest water table depth was 270 cm before the conversion. However, only 10.7% of simulated daily water table depths were 150 cm or deeper, and the deepest water table depth was just 180 cm after land-use conversion from forest to agricultural cropland. The predicted WTD was 50 cm or less approximately 48% of the time on agricultural land compared with approximately 38% on forested land. The predicted water table remained at or near the surface approximately 20% of the time for agricultural cropland but was rarely at the surface for the forested land.

Although useful and interesting results on the hydrologic impacts of land-use conversion from pine forest to CWS crop were obtained in this study, these results should be carefully interpreted owing to some inherent limitations of the model and assumptions made during the analysis.

1. Soil hydraulic conductivities for 50-year simulation were from measured data in different periods of time (SCS 1981; Skaggs and Nassehzadeh-Tabrizi 1986; Chescheir et al. 1990; Burchell 2003; Diggs 2004), but these values were assumed to be the same during the simulation periods. No other silvicultural treatments (including harvesting) were assumed. Skaggs et al. (2006) demonstrated the effects of harvesting and regeneration on soil hydraulic properties of a drained pine forest.
2. Because of the lack of biophysical variables, including solar and net radiation, LAI, and stomatal conductance,

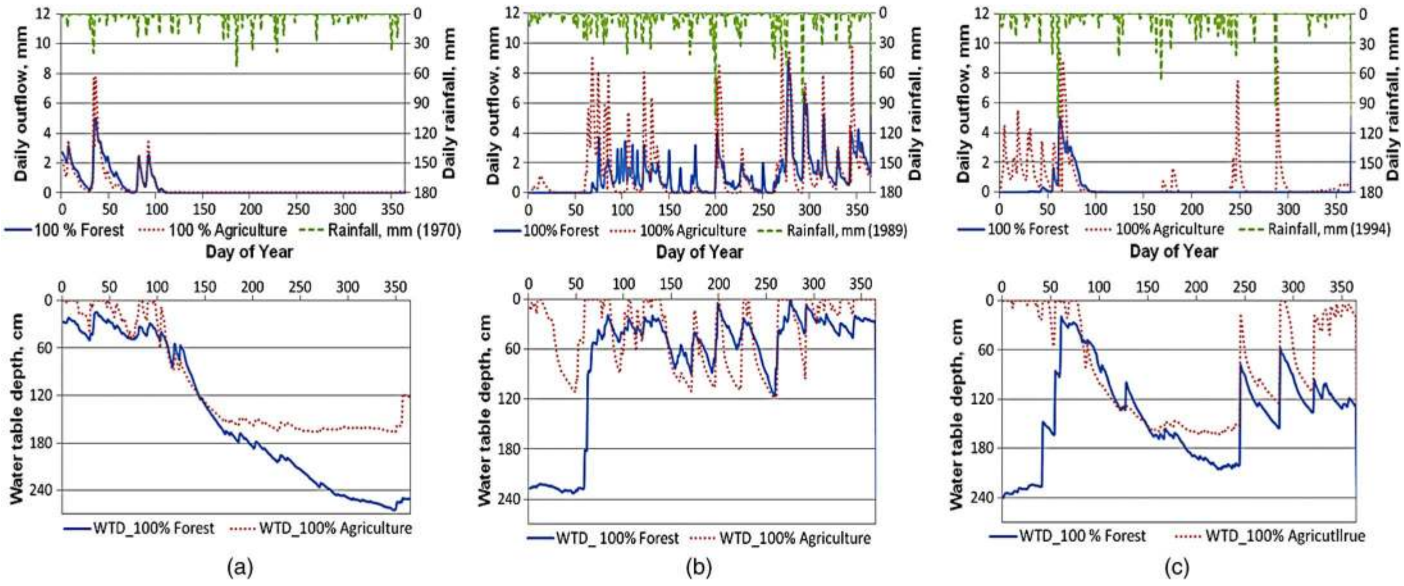

Fig. 7. Daily variation of wettest and driest years (100% forested land versus 100% agricultural land): (a) 1970 (dry); (b) 1989 (wet); (c) 1994 (normal)

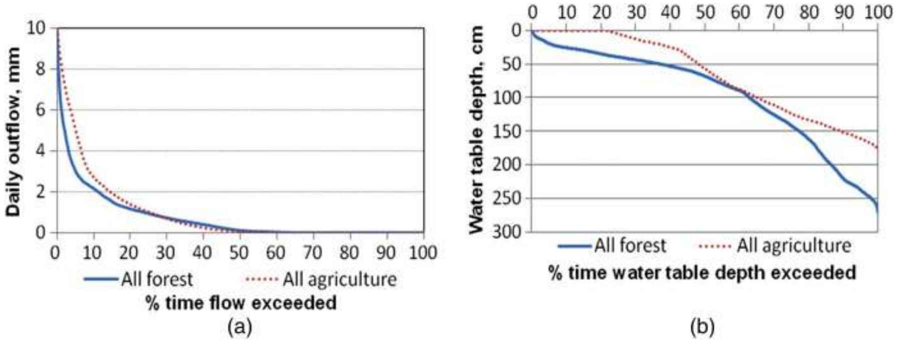

Fig. 8. (a) Simulated daily flow frequency duration curves for watershed; (b) simulated daily water table frequency duration for field F5 for all forest and all agricultural cropland

process-based Penman–Monteith PET could not be used for the long-term simulation. Instead, the temperature-based Thornthwaite method, with correction factors developed with short-term calibration with the Penman–Monteith PET (reflecting forest and ground vegetation), was used for estimating the long-term PET used in the model.

3. The same seasonal rooting depths for 50 years were used for each year, assuming a mature pine-forest stand. Actual rooting depths vary with time, especially for the younger trees.
4. Canopy evaporation attributable to interception was not simulated in this study because of the lack of LAI and canopy-coverage data. An assumption was made that the PET estimated using the correction factors based on the Penman–Monteith method would adjust for underpredictions of ET caused by ignoring interception. The net result may be an underestimation of ET for forested conditions.

Summary and Conclusions

This study was conducted to investigate the effect of the location and percentage of land-use conversion on hydrological components such as drainage outflow, water table depth, and evapotranspiration on the 2,950-ha drained pine forest in the lower coastal plain near the town of Plymouth in Washington County, North Carolina. Results indicated that converting forestland to a corn–wheat–soybean agricultural crop rotation would increase mean annual outflows and the magnitude and frequency of high flow rates for all sizes and locations of the conversion. However, conversion of up to 25% area of the $29.5-\mathrm{km}^2$ pine forest to CWS cropland was predicted to have only small hydrologic effects.

The mean annual outflow was significantly different from the baseline forest only for a 100% CWS land-use conversion. Conversion of up to 50% of the forest lands on the tract had substantial hydrologic effects, with increased maximum daily flow rates and frequencies of high flow rates $> 5\ \mathrm{mm\,day}^{-1}$. Although conversion of less than 50% in the DS location had less effect on mean annual and maximum outflows, the frequency of daily high flow rates was consistently higher for all land-use conversion in DS locations than in US locations. Stednick (1996) reported as a conservative estimate for the Eastern Coastal Plain hydrologic region that 45% of the catchment must be harvested for a measurable increase in annual water yield. These results may have important implications for land management and land-use change in terms of adverse flooding and nutrient loading effects, which have recently occurred in the southeastern Atlantic coastal plain. The effects of land-use conversion from matured pine forest to agricultural crops were primarily attributed to reduction in evapotranspiration. Similar results showing reduced ET for the agricultural crops compared with the pine forest were reported by Skaggs et al. (1991, 2011) and Fernandez et al. (2007).

Downstream land-use conversion from pine forest to CWS agricultural crop rotation is generally thought to have a greater effect on watershed hydrological components compared with upstream conversions, but in this study the results were the opposite. The writers believe that the assumed change (on the basis of previous on-site measurements) in soil-saturated hydraulic conductivity and drainable porosity during the land-use conversion from forest to agricultural crops greatly influenced the water movement and storage in the soils. The soil types in this study were not evenly distributed across the watershed; consequently, effects of the different soil types had a greater impact on the water balances than the effect of the location of conversions. Results from additional studies in various soil and climatic conditions may be required to further explain the effects of soil characteristics and the locations of land-use conversions.

Acknowledgments

This work was made possible by the support of Weyerhaeuser Company, USDA National Research Initiative (NRI, contract 98-35102-6493), National Council for Stream and Air Improvement (NCASI), the USDA Forest Service, the Center for Forested Wetlands Research, North Carolina State University, and the Post Doctoral Course Program of National Institute of Environmental Research, Republic of Korea.

References

Amatya, D. M., Chescheir, G. M., Fernandez, G. P., Skaggs, R. W., and Gilliam, J. W. (2004). “DRAINWAT-based methods for estimating nitrogen transport in poorly drained watersheds.” *Trans. ASAE*, 47(3), 677–687.

Amatya, D. M., Chescheir, G. M., and Skaggs, R. W. (1995a). “Hydrologic effects of the location and size of a natural wetland in an agricultural landscape.” *Proc., Int. Conf. on Versatility of Wetlands in the Agricultural Landscape*, American Society of Agricultural and Biological Engineers, St. Joseph, MI, 477–488.

Amatya, D. M., Chescheir, G. M., Skaggs, R. W., Fernandez, G. P., and Birgand, F. (1998). “Evaluation of a DRAINMOD based watershed scale model.” *Proc., 7th Annual Drainage Symp.: Drainage in the 21st Century*, L. C. Brown, ed., American Society of Agricultural and Biological Engineers, St. Joseph, MI, 211–219.

Amatya, D. M., Chescheir, G. M., Skaggs, R. W., and Fernandez, G. P. (2002). “Hydrology of poorly drained coastal watersheds in eastern North Carolina.” *Paper No. 022034*, American Society of Agricultural and Biological Engineers, St. Joseph, MI.

Amatya, D. M., Jha, M. K., Edwards, A. E., Williams, T. M., and Hitchcock, D. R. (2011). “SWAT-based streamflow and embayment modeling of a Karst affected watershed in SC." *Trans. ASABE*, 54(4), 1311–1323.

Amatya, D. M., Kim, H. W., Chescheir, G. M., Skaggs, R. W., and Nettles, J. E. (2008). "Hydrologic effects of size and location of harvesting on a large drained pine forest on organic soils." *Proc., 13th Int. Peat Congress*, International Peat Society, Jyväskylä, Finland, 463–467.

Amatya, D. M., and Skaggs, R. W. (2001). "Hydrologic modeling of a drained pine plantations on poorly drained soils." *Forensic Sci.*, 47(1), 103–114.

Amatya, D. M., and Skaggs, R. W. (2011). "Long-term hydrology and water quality of a drained pine plantation in North Carolina." *Trans. ASABE*, 54(6), 2087–2098.

Amatya, D. M., Skaggs, R. W., and Gregory, J. D. (1995b). "Comparison of methods for estimating REF-ET." *J. Irrig. Drain. Eng.*, 121(6), 427–435.

Amatya, D. M., Skaggs, R. W., and Gregory, J. D. (1996). "Effects of controlled drainage on the hydrology of drained pine plantations in the North Carolina coastal plain." *J. Hydrol.*, 181(1), 211–232.

Amatya, D. M., Skaggs, R. W., and Gregory, J. D. (1997). "Evaluation of a watershed scale forest hydrologic model." *Agric. Water. Manage.*, 32(3), 239–258.

Amatya, D. M., and Trettin, C. C. (2007). "Annual evapotranspiration of a forested wetland watershed, SC." *Paper No. 07-2222*, American Society of Agricultural and Biological Engineers, St. Joseph, MI.

Amoah, J. K. O. (2008). "A new methodology for estimating watershed-scale surface depression storage." Ph.D. dissertation, Florida Agricultural and Mechanical Univ., Tallahassee, FL.

Bachmair, S., Weiler, M., and Nützmann, G. (2009). "Controls of land use and soil structure on water movement: Lessons for pollutant transfer through the unsaturated zone." *J. Hydrol.*, 369(3–4), 241–252.

Brevé, M. A., Skaggs, R. W., Parsons, J. E., and Gilliam, J. W. (1997). "DRAINMOD-N, a nitrogen model for artificially drained soils." *Trans. ASAE*, 40(4), 1067–1075.

Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W., and Vertessy, R. A. (2005). "A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation." *J. Hydrol.*, 310(1–4), 28–61.

Burchell, M. R. (2003). "Practices to reduce nitrate-nitrogen losses from drained agricultural lands." Ph.D. dissertation, North Carolina State Univ., Raleigh, NC.

Chescheir, G. M., Amatya, D. M., Fernandez, G. P., Skaggs, R. W., and Gilliam, J. W. (1998). "Monitoring and modeling the hydrology and water quality of a lower coastal plain watershed." *Proc., Specialty Conf. on Watershed Management: Moving From Theory to Implementation*, Water Environment Federation, Alexandria, VA, 215–222.

Chescheir, G. M., Amatya, D. M., Giraud, F. M., Skaggs, R. W., and Gilliam, J. W. (1993). "Hydrology of a forested wetland." *Paper No. 932550*, American Society of Agricultural and Biological Engineers, St. Joseph, MI.

Chescheir, G. M., Amatya, D. M., and Skaggs, R. W. (1994). "Modeling the hydrology of natural forested wetlands." *Paper No. 942597*, American Society of Agricultural and Biological Engineers, St. Joseph, MI.

Chescheir, G. M., Skaggs, R. W., and Gilliam, J. W. (1990). "Effects of water management and land use practices on the hydrology and water quality in the Albemarle-Pamlico region." *Project No. 90-09, Albamerle-Pamlico Estuarine Study*, North Carolina State Univ., Raleigh, NC, 59.

Cho, J., Barone, V. A., and Mostaghimi, S. (2009). "Simulation of land use impacts on groundwater levels and streamflow in a Virginia watershed." *Agric. Water Manage.*, 96(1), 1–11.

Dai, Z., Amatya, D. M., Sun, G., Li, C., Trettin, C. C., and Li, H. (2008). "Modeling the effect of land use change on hydrology of a forested watershed in coastal South Carolina." *South Carolina Water Resources Conf.*, Clemson Univ. Restoration Institute, Clemson Center for Watershed Excellence, North Charleston, SC.

De Wit, M. J. M. (2001). "Nutrient fluxes at the river basin scale. I: The PolFlow model." *Hydrol. Proc.*, 15(5), 743–759.

Diggs, J. A. (2004). "Simulation of nitrogen and hydrology loading of forested fields in eastern North Carolina using DRAINMOD-N II." Master's thesis, North Carolina State Univ., Raleigh, NC.

Fernandez, G. P., Chescheir, G. M., Skaggs, R. W., and Amatya, D. M. (2007). "Application of DRAINMOD-GIS to a lower coastal plain watershed." *Trans. ASABE*, 50(2), 439–447.

Fitzpatrick, M. L., Long, D. T., and Pijanowski, B. C. (2007). "Exploring the effects of urban and agricultural land use on surface water chemistry, across a regional watershed using multivariate statistics." *Appl. Geochem.*, 22(8), 1825–1840.

Gassman, P. W., Reyes, M. R., Green, C. H., and Arnold, J. G. (2007). "The soil and water assessment tool: Historical development, applications, and future research directions." *Trans. ASABE*, 50(4), 1211–1250.

Harder, S. V., Amatya, D. M., Callahan, T. J., Trettin, C. C., and Hakkila, J. (2007). "A hydrologic budget of a first-order forested watershed, coastal South Carolina." *J. Am. Water Resour. Assoc.*, 43(3), 1–13.

Kim, H. W. (2009). "Evaluation of hydrology in an agricultural watershed and nitrogen removal by constructed wetlands." Ph.D. dissertation, North Carolina State Univ., Raleigh, NC.

Kim, H. W., Amatya, D. M., Broome, S., Hesterberg, D., and Choi, M. (2012). "Sensitivity analysis of the DRAINWAT model applied to an agricultural watershed in the lower coastal plain, North Carolina, USA." *Water Environ. J.*, 26(1), 130–145.

Konyha, K. D., and Skaggs, R. W. (1992). "A coupled, field hydrology. Open channel flow model: Theory." *Trans. ASAE*, 35(5), 1431–1440.

Li, K. Y., Coe, M. T., Ramankutty, N., and De Jong, R. (2007). "Modeling the hydrological impact of land-use change in West Africa." *J. Hydrol.*, 337(3–4), 258–268.

Li, Q., Cai, T., Yu, M., Lu, G., Xie, W., and Bai, X. (2011) "Investigation into the impacts of land-use change on runoff generation characteristics in the upper Huaihe River Basin, China." *J. Hydrol. Eng.*.

McCarthy, E. J., Flewelling, J. W., and Skaggs, R. W. (1992). "Hydrologic model for drained forested watershed." *J. Irrig. Drain Eng.*, 118(2), 242–255.

Monteith, J. L. (1965). "Evaporation and environment." *Symp. of the Society for Experimental Biology, The State and Movement of Water in Living Organisms*, G. E. Fogg, ed., Vol. 19, Academic Press, New York, 205–224.

Moriasi, D. N., Arnold, J. G., Van Leiw, M. W., Binger, R. L., Harmel, R. D., and Veith, T. L. (2007). "Model evaluation guidelines for systematic qualification of accuracy in watershed simulations." *Trans. ASABE*, 50(3), 885–900.

Nandakumar, N., and Mein, R. G. (1997). "Uncertainty in rainfall-runoff model simulations and the implications for predicting the hydrologic effects of land-use change." *J. Hydrol.*, 192(1–4), 211–232.

Qi, S., Sun, G., Wang, Y., McNulty, S. G., and Myers, J. A. M. (2009). "Streamflow response to climate and landuse changes in a coastal watershed in North Carolina." *Trans. ASABE*, 52(3), 739–749.

SAS 9.1.3 [Computer software]. Cary, NC, SAS Institute.

Shelby, J. D., Chescheir, G. M., Skaggs, R. W., and Amatya, D. M. (2005). "Hydrologic and water quality response of forested and agricultural lands during the 1999 extreme weather conditions in eastern North Carolina." *Trans. ASAE*, 48(6), 2179–2188.

Skaggs, R. W. (1978). "A water management model for shallow water table soils." *Report No. 134*, Water Resources Research Institute, North Carolina State Univ., Raleigh, NC.

Skaggs, R. W. (2013). "DRAINMOD users manual." ⟨http://www.bae.ncsu.edu/soil_water/drainmod/manuals.html⟩ (Feb. 19, 2013).

Skaggs, R. W., Amatya, D. M., Chescheir, G. M., and Blanton, C. D. (2006). "Soil property changes during loblolly pine production." *Paper No. 06-8206*, American Society of Agricultural and Biological Engineers, St. Joseph, MI.

Skaggs, R. W., Chescheir, G. M., Fernandez, G. P., Amatya, D. M., and Diggs, J. (2011). "Effects of land use on soil properties and hydrology of drained coastal plain watersheds." *Trans. ASABE*, 54(4), 1357–1365.

Skaggs, R. W., Gilliam, J. W., and Evans, R. O. (1991). "A computer simulation study of pocosin hydrology." *Wetlands*, 11(1), 399–416.

Skaggs, R. W., and Nassehzadeh-Tabrizi, A. (1986). "Design drainage rates for estimating drain spacings in North Carolina." *Trans. ASAE*, 29(6), 1631–1640.

Smakhtin, V. U. (2001). "Low flow hydrology: A review." *J. Hydrol.*, 240(3–4), 147–186.

J. Hydrol. Eng. 2013.18:552-566.

Soil Conservation Service (SCS). (1981). *Soil Survey of Washington County, North Carolina*, USDA, Washington, DC.

Stednick, J. D. (1996). "Monitoring the effects of timber harvest on annual water yield." *J. Hydrol.*, 176(1–4), 79–95.

Sun, G., et al. (2010). "Energy and water balance of two contrasting loblolly pine plantations on the lower coastal plain of North Carolina, USA." *For. Ecol. Manage.*, 259(7), 1299–1310.

Sun, G., McNulty, S. G., Lu, J., Amatya, D. M., Liang, Y., and Kolka, R. K. (2005). "Regional annual water yield from forest lands and its response to potential deforestation across the southeastern United States." *J. Hydrol.*, 308(1–4), 258–268.

Tang, Z., Engel, B. A., Pijanowski, B. C., and Lim, K. J. (2005). "Forecasting land use change and its environmental impact at a watershed scale." *J. Environ. Manage.*, 76(1), 35–45.

Thanapakpawin, P., Richey, J., Thomas, D., Rodda, S., Campbell, B., and Logsdon, M. (2007). "Effects of landuse change on the hydrologic regime of the Mae Chaem river basin, NW Thailand." *J. Hydrol.*, 334(1–2), 215–230.

Thornthwaite, C. W. (1948). "An approach toward a rational classification of climate." *Geogr. Rev.*, 38(1), 55–94.

Tong, S. T. Y., and Chen, W. (2002). "Modeling the relationship between land use and surface water quality." *J. Environ. Manage.*, 66(4), 377–393.

Weber, A., Fohrer, N., and Moller, D. (2001). "Long-term land use changes in a mesoscale watershed due to socioeconomic factors: Effects on landscape structures and functions." *Ecol. Model.*, 140(1–2), 125–140.

Wilk, J., Andersson, L., and Plermkamon, V. (2001). "Hydrological impacts of forest conversion to agriculture in a large river basin in northeast Thailand." *Hydrol. Proc.*, 15(14), 2729–2748.

Youssef, M. A., Skaggs, R. W., Chescheir, G. M., and Gilliam, J. W. (2006). "The nitrogen simulation model, DRAINMOD-N II." *Trans. ASAE*, 48(2), 611–626.