

Modeling the Potential Effects of Forest Management and Climate Change on Water Yield Across the Southeastern U.S.

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Abstract

Forest ecosystems are expected to undergo dramatic structural and area changes in response to projected pressures of timber demands and global climate change in the 21st century. Associated with changes in forest structure and area distribution is forest water yield, which affects water availability for both humans and aquatic ecosystems needs. Diverse forest hydrology conditions exist in the southeastern U.S. due to great differences in climate, vegetation cover types, and land topography/elevation across the region. The objective of this study is to project the potential effects of forest management and climate change on annual water yield at a regional scale. A generalized annual actual evapotranspiration (AET) model was first calibrated with a watershed-scale database derived from 39 forest-dominated watersheds representing the diverse eco-regions of the Southeast. Then, the model was validated at a 0.5*0.5 degree spatial resolution (about 50 *75 km²) across the region using historic hydrology, climate, and landcover data. Finally, the model was applied to the region using the Hadley Centre Had2CMSul climate change scenario for the region. The simple annual time step hydrologic model adequately explained the spatial variability of water yield across the southeastern region. Modeling results suggest that water yield responses to forest removal are diverse across the physiographic gradients with the highest values occurring in the conifer-dominated regions. The model predicted water yield increases as high as 450 mm/yr as a result of complete forest removal. The Had2CMSul predicts the southeastern

region will become warmer and wetter during this century. As a result, this study projects that the majority of the region will experience a decrease (<170 mm/yr) in water yield during the first half of this century but an increase (<300 mm/yr) in the second half of this century.

Keywords: forest hydrology, climate change, Southeastern U.S., modeling, forest management

Introduction

Forest ecosystems are expected to undergo dramatic changes in response to projected pressures from timber demands, landuse change resulting from urbanization, and global climate change in the 21st century. The recently released Southern Forest Resource Assessment (<http://www.srs.fs.fed.us/sustain>) concludes that although overall the total area of forest lands did not change greatly, large areas of land have been lost to urban uses, in Florida among other states, while agricultural areas in the lower Gulf Coastal Plains, for example, have been reforested (Wear and Greis 2002). Thus, forest cover distribution patterns are projected to shift dramatically in the next 50 year due to population growth and timber price changes (Wear and Greis 2002). This landcover transformation may have significant effects on water quantity and water quality across the region. Intensive forest management practices that employ modern agriculture-type technology (i.e., short crop rotation, fertilization, ditching, irrigation) have been commonly used in the southeastern U.S. to increase timber production in a unit land area.

Water yield responses to forest management have been well studied in the southeastern U.S. and elsewhere by employing the paired small watershed approach. Studies on water-vegetation relations clearly show that forests use large amounts of water, and water yield

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from small watersheds is strongly correlated to the vegetation cover type and amount and climatic conditions (Bosh and Hewlett 1982, Stednick 1996). The most obvious and immediate watershed response to forest harvesting is increased water yield due to reduction in total ecosystem evapotranspiration, an increase in runoff, and elevated nutrient and sediment loading to streams (Swank et al. 2001). With the recovery of vegetation and ecosystem reestablishment, water quality effects diminish. Recent studies suggest that the magnitude of hydrologic response and the time required to recover to pre-disturbance levels differs greatly for various forest ecosystems (i.e., forested wetlands vs. upland mountains). The magnitude of hydrologic response is relatively higher and recovery time is longer for hilly, upland systems (Sun et al. 2001).

The recent National Assessment on Climate Change suggests that climate change and variability will have dramatic effects on both water and forests in the Southern U.S. (U.S. Global Change Program 2000). The Southern U.S. is becoming wetter (greater streamflow) due to increased precipitation) and water quality is degrading due to intensive agricultural practices, urban development, coastal processes, and mining activities. A generalized regional scale hydrologic model is needed to address the effects of climate change on water availability in forest ecosystems (U.S. Global Change Program 2000).

Watershed scale forest hydrology models have been used to simulate and explain water yield response to forest management (Swift et al. 1975, Sun et al. 1998). However, there have been few attempts to model or use historic data to explain the hydrologic responses to forest management at broad scale or to examine all the factors and interactions that affect watershed responses. Trimble and Weirich's (1987) study on large basins is the one exception. The authors found that forest recovery in the piedmont region of the southeastern U.S. has resulted in streamflow decrease from the 1920s to the 1960s. Douglass (1983) derived a general empirical equation to estimate water yield increase for the Appalachian hardwoods. The empirical model suggests that the first year hydrologic response is controlled mainly by the forest basal area removed and solar radiation received at the site. Unfortunately, the model does not include precipitation as an independent variable, thus it has limited use for similar mountain regions. The empirical WRENSS (U.S. Forest Service 1980, Huff et al. 1999) water yield methodology

derived from hydrologic models and experimental data is the first effort to model hydrologic response at a regional scale. However, this approach has not been programmed and implemented for the humid southeastern region that is dominated by high rainfall, complex climatic and topographic variability. No single conceptual or computer model can describe the hydrological processes in southeastern forest ecosystems. McNulty et al. (1996) examined the potential climate change impacts on regional forest water yield with a monthly time step, stand level forest ecosystem model PnET-IIS. This model linked forest growth and productivity and water use (evapotranspiration), and proved applicable to a variety of mature forests, but it could not simulate non-forest lands. Hence, PnET-IIS has limitations for examining the effects of forest conversions and climate change impacts on landscapes with mixed land use. Existing regional scale hydrological models for global change studies are developed on watershed hydrologic principles such as HUMUS (Brown et al. 1999) or simplified water balances (Vörösmarty et al. 1998, Hay and McCabe 2002). HUMUS, modified from the Soil Water Assessment Tool (SWAT) model, was applied to the continental U.S. (Brown et al. 1999). However, the simulation results for averaged annual water yield in large basins were not satisfactory, especially for the southeastern U.S. (Brown et al. 1999).

This paper reports applications of a generalized simple water balance model to examine annual water yield response after forest harvesting, landuse change, and climatic change across a climatic and topographic gradient in the southeastern U.S. Our objectives were to assess the potential regional impacts of silvicultural practices, projected climate change, and their combined effects on evapotranspiration and water quantity and quality across the southeastern U.S. We hypothesize that the magnitude of water yield response to disturbance from management and climate change varies across the southern U.S. We also hypothesize that the impact magnitudes from landuse change and climate change are significantly different.

Methods

Databases and spatial scales

We acquired long-term (1961-1990), fine scale (4 x 4 km²) gridded climate data for the continental U.S. (Daly 2000). We used this database for hydrologic

model validation and projection of forest management effects across the southeastern U.S.

For climate change studies, we used a spatial scale of 0.5° by 0.5° (about 50 km x 75 km) that corresponds to the grid size of the VEMAP climate database (Kittel and others 1997) (Figure 1). The historic (1895-1993) and Had2CMSul climate change scenarios (1994-2099) were used to drive the validated water balance model as described in the next paragraph. Our modeling region encompasses 13 southern states from Virginia to Texas (Figure 1). The 1992 MRLC remote sensing land-cover dataset

(<http://edc.usgs.gov/glis/hyper/guide/mrlc#mrlc4>) was used as a base regional map to display predicted hydrologic variables at a finer spatial scale, 30m, than the climate datasets (4 x 4 km² and 0.5° x 0.5°). Land cover was regrouped into five classes including evergreen forest, deciduous forest, crop, urban, and water body. In this study we examined one simple but extreme forest management scenario: clear-cut harvesting--representing the conversion of forests to urban land use.

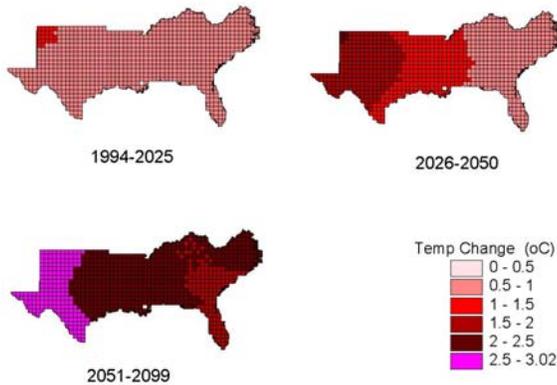


Figure 1. Had2CMSul GCM projected air temperature change (1994-2099) compared to historic climate (1895-1993) for the southeastern U.S.

Climate change scenarios

When compared to the average historical climate (1895-1993), the Had2CMSul general circulation model (GCM) suggests that the entire southeastern U.S. will have an increase in average air temperature in the range of 0.5-1.0 °C, 0.5-2.1 °C, and 0.5-1.5 °C for the time periods of 1994-2025, 2026-2050 and 2051-2099, respectively. Most of the region is projected to see an increase in annual precipitation up to 25% in the next 100 years, except southern Texas, where precipitation is predicted to decrease up to 10% (Figures 1 and 2).

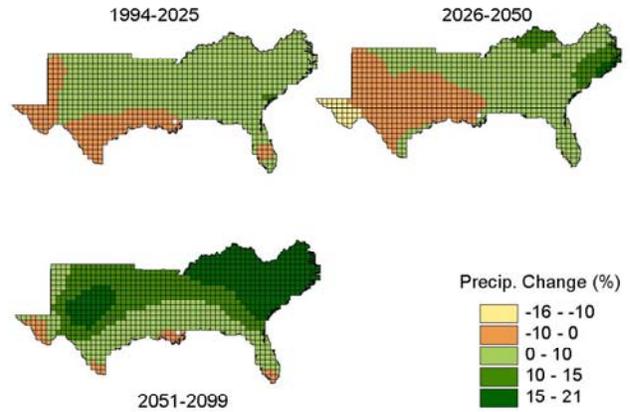


Figure 2. Had2CMSul projected annual precipitation change (1994-2099) compared to historic climate (1885-1993) for the southeastern U.S.

Hydrologic models

Annual water yield at the meso-scale (4–75 km) in this study can be estimated as the difference between precipitation received and evapotranspiration lost to the atmosphere:

$$S = P - AET \tag{1}$$

where, S = annual water yield (mm/yr), P = annual precipitation (mm/yr), AET= annual water loss from evapotranspiration (mm/yr).

The variable AET is estimated using an empirical formula (Equation 2) derived from long-term hydrologic water budget data from over 250 watersheds around the world (Zhang et al. 2001).

$$AET = \left(\frac{1 + w \frac{PET}{P}}{1 + w \frac{PET}{P} + \frac{P}{PET}} \right) \times P \tag{2}$$

where, PET is potential evapotranspiration that can be calculated from solar radiation and air temperature data; w is the plant-available water coefficient and reflects the relative differences of water use for transpiration. For a grid cell with mixed land uses:

$$AET = \sum(AET_i * f_i) \tag{3}$$

where f_i is the percentage of landuse i.

Table 1. Calibrated model parameters and modeling schemes.

Simulation Scenario		w or AET	P (mm/yr)	PET (mm/yr)
Case 1: Current climate and land cover	Evergreen	w= 2.8	Historic Data long-term average during 1961-1990; spatial resolution 4 km ²	Computed from historic air temperature databases, long-term average 1961-1990; spatial resolution 4 km ²
	Deciduous	AET reduced by 20% from evergreen AET for the upland region		
	Crop	w=0.5		
	Urban	w=0.0		
	Water	N/A AET=P		
Case 2: Forest removal under historic climate	Hilly upland region: AET reduced 20% from evergreen forest AET with w=0.0			
	Lowland region: AET computed as w=0.0 for all species			
Case 3: Climate change, current land cover	Same as Case 1		Historic climate: 1895-1993 Future climate: Projected for the period 1994-2099	

In lieu of net solar radiation data, this study calculated PET for each watershed using Hamon's temperature based method, a simple approach but comparable in prediction accuracy to more sophisticated approaches (Vörösmarty et al. 1998, Lu et al. 2003).

Since Equation 2 is sensitive to land-cover type through the w parameter and climate change through the P and AET variables, we can use Equation 1 to project the potential hydrologic responses to forest cover manipulation and climate change.

Model calibration was first conducted at the watershed scale to obtain a w parameter dataset for different land-cover types (Table 1). The database for model calibration was derived from 39 forest-dominated watersheds with long-term (6-30 years) forest hydrology data located across the southeastern U.S. (Lu et al. 2003). Model validation was carried out at the regional scale by comparing long-term (1951-1980) average regional USGS runoff values, scaled up from a 5 km resolution (Gerbert et al. 1987), and hydrology model results computed on the 0.5° by 0.5° cell by cell basis. Model validation results were considered superior when compared to results from the continental scale hydrologic model HUMUS (Brown et al. 1999). Detailed procedures and results for both model calibration and validation were reported in Sun et al. (2002).

As a result, a modeling scheme (Table 1) was developed to extrapolate Equation 1 to examine the spatial variability of water yield, and its response to forest removal and climate change at 4 x 4 km² and 0.5° x 0.5° spatial resolution respectively.

Results and Discussion

Spatial distribution of water yield across southeastern forests

We first examined the spatial distribution of water yield under current landcover and historical conditions (Case 1 in Table 1). Long term average Annual precipitation in the southeastern U.S. varies from over 1600 mm in the gulf coastal region to less 600 mm in western Texas, showing a strong south to north precipitation gradient. The highest precipitation area was found in the Appalachian Mountains near the border of NC, GA, and AL. Air temperature, and thus PET, generally follows the decreasing south-north gradient, but the pattern is modified by the land topography, such as the Appalachian Mountains. The climate of the coastal plain regions along the Atlantic Ocean and the Gulf of Mexico is characterized as hot and humid.

Affected by the combination of precipitation and evapotranspiration, the annual water yield from forest ecosystems varies greatly across the southeastern region (Figure 3). The hilly

Appalachian Mountain region produces the highest water yield, compared to the coastal plain and other low land in the piedmont region, due to lower temperature but higher precipitation. Other high water yield regions are coastal Louisiana and Alabama and the Ouachita Mountains.

Annual Water Yield across the Southern Forests

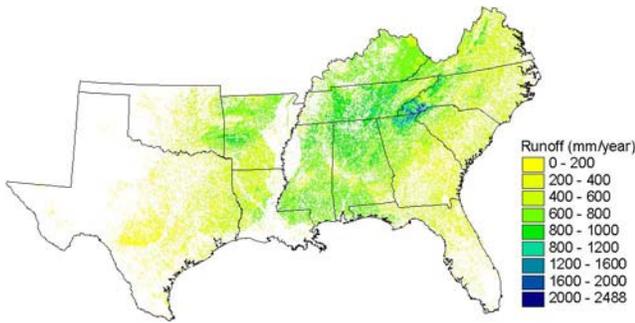


Figure 3. Simulated average annual water yield across the southeastern U.S. with a spatial resolution of 30 m scaled down from a 4 x 4 km² resolution.

Deciduous hardwoods, the dominant forest ecosystem in the hilly regions with lower AET than the conifer forests mostly covering the lowlands may also explain the high water yield in the southeastern region to some extent. As expected, the lowest water yield (0-200 mm) was found in the central Texas region which is the hottest area receiving the least precipitation. We found the runoff/precipitation ranged from less than 30% in the majority of Texas and Oklahoma and the coastal plains of Florida, Georgia, and South Carolina, to over 50% in the Appalachians and in the Gulf of Mexico coastal plain.

Spatial distribution of potential water yield response to forest removal across the region

Using the parameters and databases defined in Case 2 in Table 1, we examined the potential effects of forest removal on water yield. The magnitude of water yield response to forest removal, clear-cutting in this case, is influenced by precipitation received (Harr 1983), the forest type (Swank and Douglas 1974), the amount of solar radiation received as represented by the PET variable (Douglas 1983), and land form (upland vs. lowland) (Sun et al. 2001). Combining these factors in one single formula

(Equation 1) and using the modeling scheme described in Table 1, we predicted that water yield increase due to forest removal varies greatly across the region, ranging from 50 mm/yr to 440 mm/yr (Figure 4). This magnitude is reasonable when compared to the literature of watershed-scale experimental data (Bosch and Hewlett 1982, Douglas 1983). The high response regions to forest clear-cut were found in the in the Atlantic lower coastal plains, the high runoff region of the Louisiana and Alabama coasts, and the conifer-dominated region bordering Louisiana and Arkansas.

However, the model predicted about twice as high (>300 mm/yr) as reported value (0-150 mm/yr) in the literature for the groundwater-dominated coastal plain regions (Fisher 1981, Riekerk 1989, Wynn et al. 2000). This discrepancy may be explained by three arguments: 1) the definition of ‘water yield’ in Equation 1 is not consistent with the reported streamflow values since water yield can be recharged by groundwater storage, 2) setting the parameter *w* at 0.0 may not be appropriate for a forest harvest site, since the harvested site may experience large amounts of soil evaporation, especially when the ground water table is close to the surface. Under these conditions, AET would not change much from pre-harvest to post-harvest. Unfortunately, there are not enough data to estimate the *w* parameter for clear-cut conditions. The value of 0.0 in this study may represent the condition of an urbanized or bared landscape that was originally forested, and 3) PET values estimated for post clear-cut forests should adjusted from PET calculated for pre-harvest conditions.

Potential Water Yield Response to Forest Removal across the Southeaster US

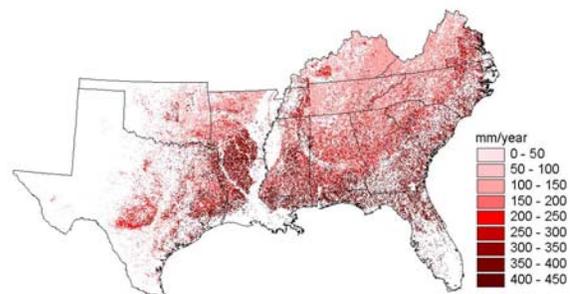


Figure 4. Simulated potential annual water yield response across the southeastern U.S. with spatial resolution of 30 m, scaled down from a 4 km resolution.

Spatial distribution of water yield response to projected climate change

Using parameters and climate database defined in Case 3 (Table 1), we examined the effects of climate change on water yield in the next 100 years. Based on the projected GCM scenario described earlier, our simulation suggested that PET would increase dramatically, especially during the last 50 years of this century and in the state of Texas (Figure 5). The variable AET, affected by the change in both PET and precipitation, is expected to increase also for the majority of the southeaster U.S., ranging from 50 to 170 mm/yr during the 2051 to 2099 period. AET is expected to decrease in southern and western portions of Texas (0-50 mm/yr).

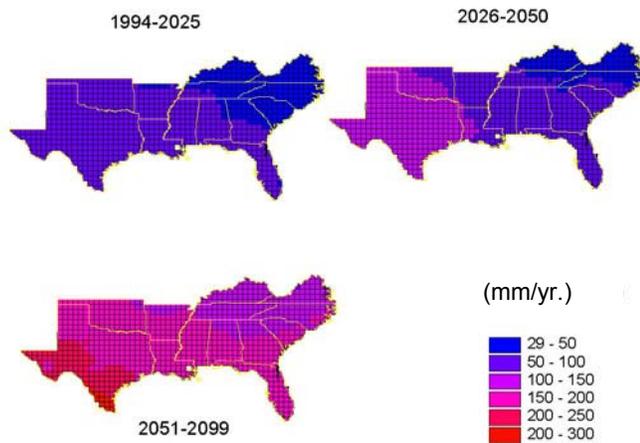


Figure 5. Predicted changes in PET across the southeastern U.S. Climate change scenarios were derived from Had2CMSul.

As a combined result from increased AET and precipitation, water yield was projected to have a rather complex pattern in space and time: an increasing trend (0-100 mm/yr) in the eastern part of the region, but a decreasing trend (0-90 mm/yr) in Texas, northwestern Oklahoma, Louisiana, and southern Mississippi during the period 1994 to 2050 (Figure 6). Water yield is predicted to increase (0-300 mm/yr) in most of the region, except the Gulf coast region and southern Florida during 2051-2099 (Figure 6).

Effects of Climate Change on Annual Water Yield

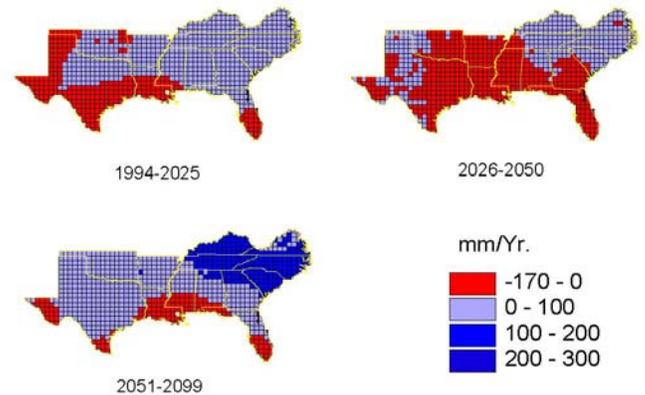


Figure 6. Predicted water yield response to climate change to across the southeastern U.S. Climate change scenarios were derived from Had2CMSul.

Summary and Conclusions

We developed a simple GIS-based modeling system to predict long-term average hydrologic response to forest harvesting and climate change at the regional scale. Regional maps of historic long-term water yield from different forest types, and water yield responses to forest harvesting and future climate change were produced. Using this model, we conclude that clear-cutting or converting forest to urban land use will increase streamflow with a large variation in magnitude across the region. The coastal plains and other conifer-dominated region that have high background runoff were identified as the regions most sensitive to forest removal. However, research is needed to reduce the uncertainty of plant water use parameters at the regional scale. Additional generalized parameters are needed to reflect the differences of hydrologic processes (changes in PET under different forest management scenarios) observed across the region.

Across the Southeast, air temperature is projected to increase up to 3.0°C while precipitation is expected to increase up to 20% for the majority of the region (Texas is exception). Consequently, annual water yield response is projected to vary both in space and time, a decrease trend in the first half the century but an increasing trend for the region.

The major concerns of climate change are decreases in local water yield for the already water-stressed region including Texas and south Florida where surface runoff is already low at present. For other

regions, increases in water yield or rainfall intensity may have negative impacts such as increased soil erosion and flooding. Forest removal or reforestation may cause water yield changes (increase or decrease) with a magnitude similar to that of climate change, given the limitations of climate change scenario accuracy. Thus, forest management can play a role in mitigating the effects of climate change on water yield across the region.

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