Hydrologic Effects of Global Climate Change on a Large Drained Pine Forest

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Abstract

A simulation study using a watershed scale forest hydrology model (DRAINWAT) was conducted to evaluate potential effects of climate change on the hydrology of a 3,000 ha managed pine forest in coastal North Carolina. The model was first validated with a five-year (1996-2000) data set from the study site and then run with 50-years (1951-00) of historic weather data from Plymouth, NC to determine the long-term hydrology. Later, separate simulations were conducted with 2001-2025 climate change data sets projected by two existing Global Circulation Models (GCM), Canadian Climate Change (CGC1) and the British model (HadCM2). The predicted average annual outflow of 308 mm for the 1996-00 study period (average annual rainfall (AAR) of 1232 mm) was 15% lower than the average of 362 mm for the 1951-00 period (AAR = 1288 mm). Simulation results using 2001-25 climate data projected by the CGC1 model yielded a significantly ($p<0.0001$) lower average outflow (167 mm) compared to 380 mm for the HadCM2. This indicates that the CGC1 model (AAR = 1129 mm) predicted much drier conditions (14% runoff coefficient) and the HadCM2 (AAR = 1358 mm, runoff coefficient = 27%) predicted only 5% higher ($p>0.5$) outflow than the 50 year historic data showed. Interestingly, the distribution of runoff coefficients for the HadCM2 was almost the same as that for the historic data, indicating minor potential effect of this climate change scenario on drainage. Both the GCM climate scenarios predicted significantly ($p<0.005$) higher ET than the historic. Water table depth is predicted deeper by the CGC1 model due to lower precipitation input and higher ET. However, the climate changes even under a drier and hotter scenario may not have significantly reduced tree water use although drainage may have been reduced greatly. The ET predicted by the HadCM2 (1008 mm) and CGC1 (1021 mm) were similar, indicating the increase in temperature predicted by the CGC1 model has less of an effect on the soil moisture limiting the tree growth than the increased rainfall predicted by HadCM2.

KEYWORDS. Global Circulation Model, Outflow, ET, Watershed-scale Models, DRAINWAT.

Introduction

Forests have an important role in controlling hydrologic patterns in the Southeastern US where 55% of the region is forested (Sun et al., 2002). Besides being subjected to natural disturbances (hurricanes, fires) and more recently human-induced impacts such as harvesting, fertilization, prescribed burning etc., planners and researchers are now starting to face the effects of climate change on the environment including hydrology and water quality. A recent scientific assessment analyzed how future climate variability and change may affect forests in the United States (USDA, 2001). This assessment reported that with increased temperatures, longer growing seasons and greater leaf area, vegetation may transpire more water, even with CO_2-induced increases in water use efficiency. Increased transpiration reduces runoff, affecting other uses of water. The report also stated that several climate scenarios indicate moderate increases in leaf

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area in the Southeast and Great Plains, which could greatly reduce runoff. The report cited several research needs including integrated models of land use and climate to project the interactions of these two influences on a wide range of forest goods and services including water supply, carbon storage, non-wood forest products, timber, and recreation.

The Southeast has the fastest population growth in the U.S. and this trend is expected to continue well into the 21st century (Sun et al., 2005). In addition to an increasing population base, general circulation models (GCM) predict that the Southern U.S. will experience significant increases in air temperature and variability of precipitation associated with global warming (Kittel et al., 1997). Changes in precipitation and increases in air temperature could impose additional environmental stress on both water and forest growth in the southern US during this century (Sun et al., 2000; US Global Change Program, 2000). As indicated by historical records and projected by these GCMs, the southern US is becoming wetter due to increased precipitation (Sun et al., 2005).

Loblolly pine (*Pinus taeda* L.) plantations have a great influence on wildlife habitat, water quality and water yield, and presently lead timber production in the U.S., growing on more than 13.4 million ha of forested lands (Schultz, 1997). A regional assessment of the effects of climate change on forest productivity and hydrology is currently being conducted through the National Global Change Research Program using the GIS and a forest ecosystem process model PnET-II (McNulty et al., 1997). Sun et al. (2000) applied the PnET-II model on a poorly drained 25-ha managed pine forest of 25-yr stand age located in coastal North Carolina for studying the effects of the GCM HadCM2 climate change scenario on drainage outflow, evapotranspiration (ET), leaf area index (LAI) and forest Net Primary Productivity (NPP). The study suggested that future climate change of an increase of 10% in precipitation and 2°C in air temperature would cause a significant increase of drainage (6%) and forest productivity (2.5%). This simulation study was based on the model validated mostly for the well-drained upland soils, where drainage (outflow) is driven by deep seepage and gravity due to gravity. Therefore, the authors suggested caution in the application of the PnET-II model to the coastal areas with periodic high water table, where outflow is basically driven by the shallow water table position. Furthermore, the model results were based on the hydrology of a small 25 ha watershed.

DRAINMOD (Skaggs, 1978) is a widely used hydrology model that predicts drainage outflows based on water balance at the midpoint of a shallow water table on poorly drained soils. The model that was modified to incorporate forest hydrologic processes (DRAINLOB, McCarthy et al., 1992), has been successfully tested with ten years of data on the same coastal watershed (Amatya and Skaggs, 2001). DRAINWAT (Amatya et al., 1997), an extended watershed-scale hydrologic model with its core hydrology based on DRAINLOB (McCarthy et al., 1992) 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. The availability of this model motivated the current study, as only limited studies are available on the hydrologic effects of climate change on coastal pine forests. Therefore, the main objective of this study was first to apply the DRAINWAT model to evaluate the hydrologic effects of historic (1951-2000) weather data and to use those results to evaluate the effects of widely used climate change scenarios based on the 25-year (2001-25) prediction of GCMs (HadCM2 and CGC1) on the outflows and evapotranspiration (ET).

SITE DESCRIPTION AND METHODS

Site Description

The study site (S4) is about 2950 ha in area within the Parker Tract forest owned and managed by Weyerhaeuser Company. The watershed (S4) is part of a 10,000 ha large watershed located near the town of Plymouth in Washington County, NC (Figure 1). This relatively flat site is drained by collector ditches receiving drainage from lateral ditches, which are mostly 100 m apart. Seven mineral and organic soils are present in the watershed (Table 1). The mineral soils in the northern part of the watershed are very poorly drained Portsmouth, Cape Fear and Wasda series, while organic soils, Belhaven and Pungo, are predominant in the southern half of the watershed. Surface vegetation in fields ranges from unharvested second growth mixed hardwood and pine forest to loblolly pine plantation (*Pinus taeda L.*) of various stand ages. Three automatic rain gauges backed up by manual gauges in and around the site and an on-site weather station provided the weather data for the study. The outflow at the S4 outlet was measured using a dual-span V-notch weir equipped with a datalogger. Detailed description of this and the Parker watershed site, including their instrumentation and monitoring procedures can be found elsewhere (Amatya et al 2003; Chescheir et al 1998).

DRAINWAT Model

DRAINmod (Skaggs, 1978) for WATersheds (DRAINWAT) was developed linking DRAINLOB (McCarthy et al., 1992) with the overland flow, ditch and in-stream flow routing components of the FLD&STRM model (Konyha and Skaggs, 1992). The distributed model operates as a sequenced set of simulations so that simulated outflow from each "field" (subwatershed) delineated with relatively uniform soil and stand conditions is first combined into the collector ditch of the subwatershed. The simulated combined outflow from one or more subwatersheds is then routed through the channel system to the watershed outlet. Use of the instantaneous unit hydrograph, based on time of concentration, takes into account the time that surface runoff travels across the field to the ditch and then 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 a numerical solution to the 1-D St. Venant equations to compute depth and flows at selected nodes along the stream or collector ditches. The model is also capable of taking the unsteady state flow conditions such as backwater effects, tidal surges, reservoir storages, etc (Konyha and Skaggs 1992) into account while simulating the hydrology of poorly drained lands with mixed land use and their in-stream transport hydraulics. The model has been successfully tested for predicting outflow rates in lower coastal plain watersheds with varying sizes and land uses (Konyha and Skaggs, 1992; Amatya et al., 1997; 1998).

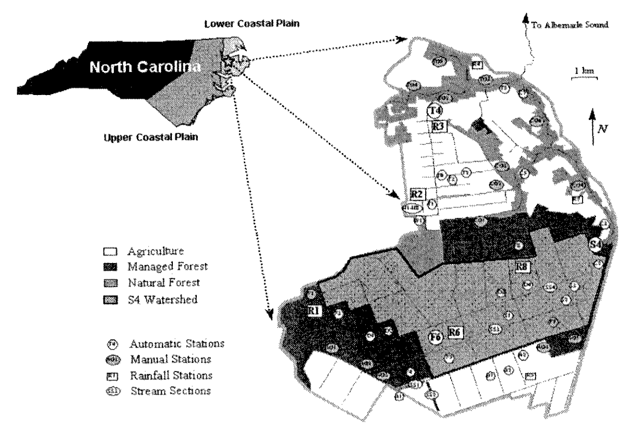

Figure 1. Location map of 2,950 ha study watershed (S4) on a managed pine forest with monitoring stations.

Recently the model has also been successfully tested with five years of data (1996-00) for predicting the outflow rates and nitrogen transport for this study watershed (S4) (Amatya et al., 2004). Precipitation measured at a gauge located at the center of the watershed (R6) was used in that study. Weather data measured at an automatic station located at the center of the watershed was used to estimate Penman-Monteith PET (Monteith, 1965) for the forest reference (Amatya et al., 2003) that was input into the model. These results are briefly described herein.

The field hydrology and ditch channel routing parameters used in that study (Tables 1 and 2) were used herein for the study of two simulation analyses. First simulation was conducted to describe the long-term hydrology using the 50-years (1951-2000) of historical weather data from the U.S. Weather Bureau station at Plymouth, North Carolina nearest to the study site. A second set of simulations was conducted to forecast the 25-year hydrology of the site using two climate change scenarios as described in the following section. Simulations with both of these scenarios used temperature-based Thornthwaite PET method in the model, as the complete weather data needed for the Penman-Monteith method were not available for the historic period and also for the future 25 year forecasts. Monthly correction factors suggested by Amatya et al. (1998) for this location were used in the model for estimating Thornthwaite-based PET in the model. Studies have shown that on a monthly to seasonal basis, outflow predictions using temperature-based Thornthwaite method with appropriate monthly correction factors may be as accurate as the Penman-Monteith based method (Amatya et al., 1997; 1998; Harder et al., 2005). The interception component in the model was not used, as leaf area index was not available for all the stands. In both the cases, tree growth was neglected and simulations were conducted using currently existing ages of vegetation throughout the watershed.

Table 1. Main soil hydraulic properties of forested watershed

Soil parameter	Soil Type				
	Belhaven	Cape Fear	Pungo	Portsmouth	Wasda
Impermeable layer depth (cm)	270	300	250	240	200
Hydraulic conductivity (cm/hr) (Depth range, cm)	20 (0-30) 1 (30-80) 0.01 (80-270)	15 (0-100) 45 (100-300)	10 (0-30) 1.7 (30-150) 5.0 (150-250)	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)	0.73	0.48	0.69	0.37	0.76
Wilting point (cm^3/cm^3)	0.45	0.22	0.40	0.13	0.45

Table 2. Characteristics of lateral and collector ditches and drainage canals.

Parameters	Lateral ditch	Collector ditch	Drainage canal
Ditch spacing, m	100 - 200	800	-
Bottom width, m	0.50 - 0.70	1.20 - 1.80	2.00 - 2.50
Ditch depth, m	0.70 - 1.00	1.80 - 2.50	2.00 - 3.00
Side slope	0.8:1	0.6:1	0.5:1
Bottom slope	0.0001	0.0001	0.0001
Manning "n"	0.025	0.035	0.04-0.05

Climate Change Scenarios

Two future climatic scenarios were acquired from predictions by the HadCM2 model developed at the UK Hadley Climate Research Center, and the CGC1 model developed by the Canadian Climate Centre (CGC1), representing warm/wet and hot/dry scenarios, respectively (Figures 2 and 3). Both are transient global climate models that give climate change predictions at low spatial resolution (about 300-400km). Those predictions were further scaled down to a gridded 0.5° by 0.5° (about 50 km * 75 km) format for the continental US by the VEMAP group (Kittel et al., 1997). In this study we used one grid cell (about 50 km * 75 km) that overlaid the Parker Tract forest containing the study watershed (S4) in coastal North Carolina to extract climate data series for the years 2001-25. Detailed information on the development of the two climate change scenarios can be found in http://www.cccma.bc.ec.gc.ca/models/cgcm1.shtml for the CGC1 model and http://www.meto.gov.uk/research/hadleycentre/models/HadCM2.html for the HadCM2 model. Model predictions have been used worldwide for assessing the impacts of climate change at the basin, continental, to global scales. As an example, Miller et al. (2003) used HadCM2 as one of the two possible climate change scenarios in their study of potential impacts of climate change on California hydrology. The GCM was then statistically downscaled and interpolated to a 10 km resolution for the study site (Zhu et al., 2005).

When compared to the average historical climate (1985-1993), the HadCM2Sul GCM suggests that the region east of the Mississippi River is projected to experience an increase in annual precipitation of up to 20% (Figure 3) with smaller increases in air temperature, but a decrease of precipitation by 10% and a large rise of air temperature (>0.5 °C) west of the Mississippi River by 2025. In contrast, the CGC1 model predicts that most of the southern U.S. will have a 10% decrease in precipitation and large increases of air temperature (1-2 °C) by 2025 (Figure 2).

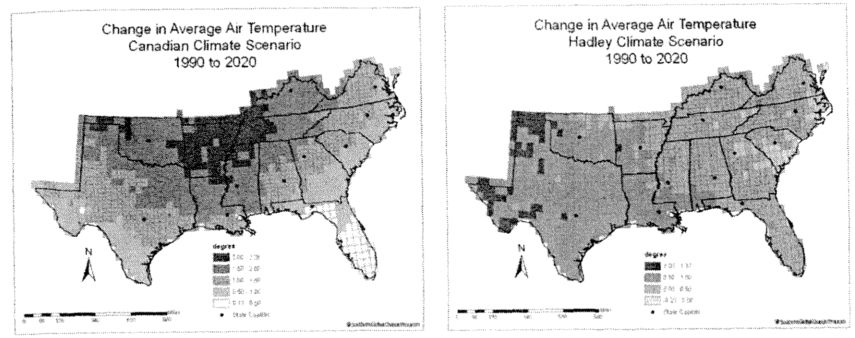

Figure 2. Change in average air temperature by Hadley and Canadian Climate Change Scenarios.

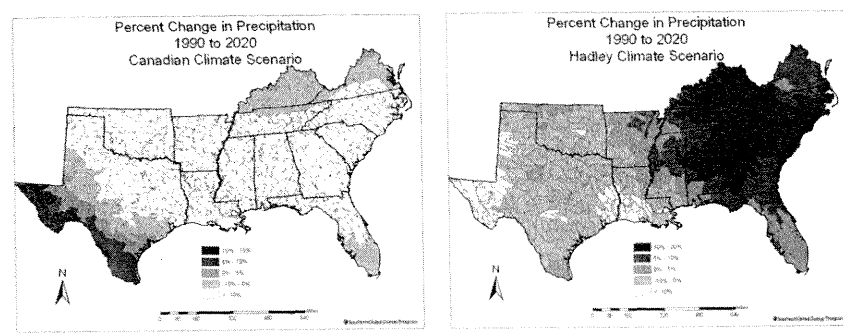

Figure 3. Percent change in precipitation by Hadley and Canadian Climate Change Scenarios.

The 25-year (2001-25) predictions given above by both the Climate Change models (HadCM2 and CGC1) for daily precipitation and air temperature in the southern US were used in DRAINWAT for simulating the hydrology of the study site for current forest stand conditions. These precipitation and air temperature data for both the models were processed to obtain the daily data sets in DRAINMOD format. An arbitrary distribution of daily rainfall into four consecutive hours from (5 AM to 8 AM) was used to obtain the hourly file in DRAINMOD format. Daily maximum and minimum daily air temperatures were also prepared in DRAINMOD formats.

Results and Discussion

Model Testing

Measured and DRAINWAT-predicted monthly and cumulative drainage outflows for the study watershed (S4) are presented in Fig. 4 (left) for each of the five years (1996-2000). Model-predicted outflows and their time distribution were in close agreement with measured data, except for winter months of 1996-97 and also the September of 1999 when the model has some overpredictions. The overprediction in 1999 was attributed to potential error in measurements during weir submergence caused by Hurricane Floyd. The predictions correlated well with the measured data ($R^2 = 0.90$, $p<0.001$). The predicted total cumulative monthly outflow of 1554 mm at the end of the five-year period was only 4 mm higher than the measured amount of 1550 mm. When considered on a year-by-year basis, the average absolute monthly deviation parameter varied from 5 mm in 1997 to 11.8 mm in 1998 (average = 8.2 mm). The yearly Nash-Sutcliffe coefficient ranged from 0.79 to 0.91 (average = 0.89), which is considered good. Some of the errors in predictions were also attributed to spatial variability in rainfall. These analyses indicate that the model can adequately describe the monthly and annual drainage outflows.

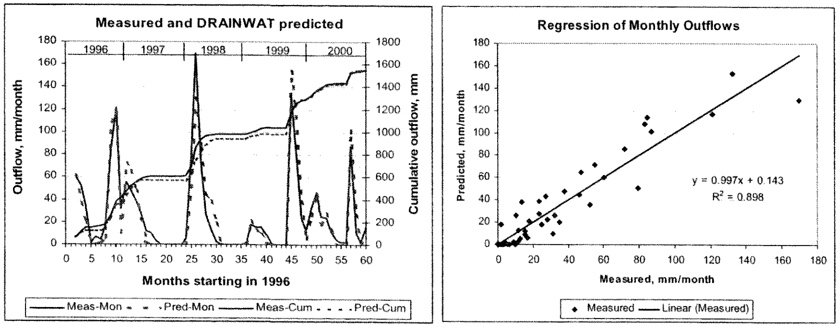

Figure 4. Measured and predicted monthly cumulative drainage outflows (left) and regression of the measured and predicted monthly outflows for the 1996-00 period.

The measured average annual runoff coefficient (ROC) varied from 0.15 for the relatively dry year 1997 (rain = 959 mm) to 0.32 for the wet year 1996 (rain = 1410 mm) with an average of 0.25, which was the same as the predicted average. The predicted annual ET using DRAINWAT varied from 887 mm in 1996 to 1006 mm in 2000 with an average of 951 mm for the average Penman-Monteith based PET of 1023 mm used in the model. The average annual evapo-transpiration for this watershed was 919 mm based on an approximate annual water balance (Rain – Outflow). This value was compared to an estimate of 910 mm by a model by Zhang et al. (2001) (Amatya et al., 2002). The difference was within 4% of the average annual rainfall (1232 mm) for that period. Although the discrepancy between the predicted and approximate methods may have been due to storage effects, this difference is considered within the acceptable error limits.

Simulations using Historic Data

The 50-year (1951-00) historical simulations yielded average annual rainfall and outflow of 1288 mm and 363 mm, respectively (Table 3). The coefficient of variation (COV) for the rain (0.14) was much less than that for the outflow (0.43), as expected. The COVs for 17-years (1988-04) of data at the Carteret site in eastern North Carolina were 0.20 for the rain and 0.53 for the outflow (Amatya et a l. this conference). The runoff coefficients (ROC) ranged from 0.43 in 1978 with 1373 mm rain to 0.08 in 1997 with 1045 mm rain (Figure 5), with an average of 0.27, which was slightly higher than the five-year validation period (0.25). Although the wettest year was 1989 with 1734 mm, the ROC was only 0.34 because of dry antecedent conditions caused by below normal rainfall in prior year 1988 (1030 mm). Similarly, the highest ROC in 1978 was caused by wet antecedent conditions caused by above normal rain (1526 mm) in the prior year 1977.

Table 3. Statistics of simulated hydrologic parameters. Historic rainfall was used for 1951-00.

Computed Statistics	Long-term 50 year (1951-00) Data					British HadCM2 GCM (2001-25)					Canadian CGC1 GCM (2001-25)				
	Rain-fall mm	Out-flow mm	ROC	ET mm	WTD cm	Rain-fall mm	Out-flow mm	ROC	ET mm	WTD cm	Rain-fall mm	Out-flow mm	ROC	ET mm	WTD cm
Average	1288	363	0.27	951	66	1358	380	0.27	1009	64	1129	167	0.14	1021	92
STDEV	185.4	154	0.09	72	27	221	200	0.10	85	34	162	90	0.06	38	28
Maximum	1760	670	0.43	1182	121	2007	870	0.43	1210	130	1445	399	0.29	1093	135
Minimum	907	85	0.08	779	15	1005	65	0.05	865	18	821	52	0.05	950	31
COV	0.14	0.43	0.33	0.08	0.42	0.16	0.53	0.39	0.08	0.53	0.14	0.54	0.44	0.04	0.31

This simulation resulted in slightly higher average ROC of 0.27 for the last five year (1996-00) period compared to the same period used in model testing, mainly due to variability of rainfall recorded at the Plymouth station compared to the gauge at the study site. The lower ROC computed in this simulation for the year 1997 was attributed to the nature of Thornthwaite method to yield higher PET during the warm years and lower PET during the cold years (Amatya et al., 1995). The predicted annual ET varied from 779 mm in 1992 (rain = 1117 mm) to 1182 mm in 1990 (rain = 1269 mm) with an average of 951 mm. Using the measured annual rainfall and predicted outflow, the calculated ET (= Rain – Outflow) yielded an average of 925 mm as in the five-year study period indicating some effects of soil water storage on ET. The poor correlation ($R^2 = 0.42$) of calculated annual ET with DRAINWAT predicted ET shows the potential errors in calculated ET when year-to-year variation in soil water storage is not taken into account. However, on the long-term basis such an error may be minimal. This analysis shows that for the same stand age of the pine forest, the hydrology in the recent five-year period has not much changed compared to the past 50 years.

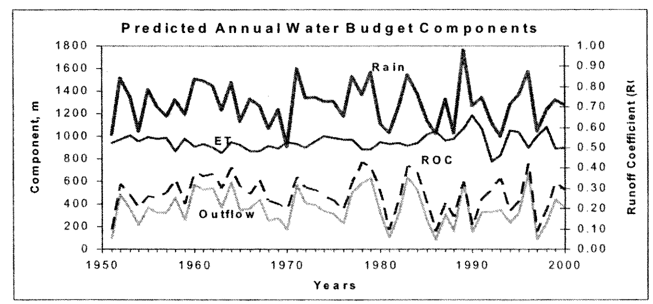

Figure 5. DRAINWAT predicted water budget components for the 1951-00 historic data.

Simulations using GCM projected data

The plots in Figure 6 illustrate the annual historical rainfall (1951-00) and rainfall forecast for 25 years (2001-25) by two GCM models (HadCM2 and CGC1). The average for the 50-year historic data was 1288 mm compared to 1358 mm for the HadCM2 model and 1129 mm for the CGC1 model. Although the HadCM2 model has about 5.5% higher average rainfall, within 0-10% range varying from season-to-season as reported by Sun et al. (2000), the annual pattern is similar to the historic data. Note that a very high rain of 2007 mm was projected for the year 2004. However, the Canadian CGC1 model yielded 12.3% lower average rain (1129 mm) compared to historic data and 16.8% lower than the HadCM2. In the following section the hydrologic effects of these two rainfall scenarios together with their forecast for change in air temperature will be explored.

Projections of annual rainfall by both the GCMs were significantly different from the actual observed ones for all years from 2001 to 2004. Year 2001 was a relatively dry year and the year 2003 was much wetter year than projected by both methods. Similarly, rainfall projected by HadCM2 in the year 2004 was almost double the observed data.

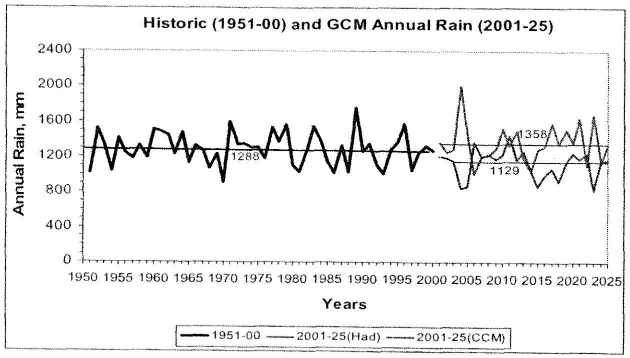

Figure 6. Historic (1951-00) annual rainfall and 25 years (2001-25) rainfall predicted by HadCM2 and CGC1.

The annual outflows predicted by DRAINWAT for 25 years (2001-25) based on the weather forecast by two GCM models (HadCM2 and CGC1) for the forested watershed (S4) is presented in Figure 7. The predicted annual outflow using weather data forecast from HadCM2 model varied from 870 mm in 2004 with the highest rainfall (2007 mm) to 65 mm in 2007 with only 1226 mm of rain, with an average of 380 mm (Figure 7 - top). This average was only 18 mm more than that obtained for the historic period (362 mm). The associated runoff coefficients (ROC) varied from 0.43 in 2004 to 0.05 in 2007, with an average of 0.27 (Figure 7 – middle), which was not statistically different ($p = 0.827$) from that obtained for the 50-year historic period.

Thus the HadCM2 climate scenario shows that the projected change of about 5% increased precipitation and slightly increased temperature in next 25 years would not have a substantial impact on drainage outflows compared to the historic data. These results suggested the changes are moderate when comparing to the predictions by Sun et al. (2000), who reported that a 10% increase in precipitation and 2 °C increase in air temperature will result in a 6 % significant increase in outflows. The COV for the forecast annual rain and the predicted outflows were 0.16 and 0.53, which were both higher than the 50-years historic data (0.14 and 0.43).

Figure 7 also presents data on DRAINWAT predicted outflows obtained by using the weather data projected by Canadian CGC1 model for the same 25 years. CGC1 GCM model consistently under projected the annual rainfall, especially in the year 2004 when it had less than half of the rainfall projected by the HadCM2 model. As a result, due to the 16.8% lower annual rainfall, on average, than the HadCM2, DRAINWAT-predicted annual outflows using the CGC1 climate data were consistently lower than those predicted using the HadCM2 data. The annual outflow varied from 52 mm in 2017 with 1076 mm of projected rain to 346 mm in 2001 (1212 mm of rain), with an average of only 167 mm compared to 380 mm for the HadCM2 model. However, the minimum (0.05) and maximum (0.43) ROC values, with an average of only 0.14, were observed in the same years (2017 and 2001), respectively (Figure 6, middle) as for the HadCM2 model. This average annual ROC was almost 46% lower than both the historic and HadCM2 scenarios (0.27). This difference, which was significantly different ($p < 0.0001$) from either of those cases, indicates the effects of this CGC1 climate change scenario on projected outflows. However, this substantial reduction in average ROC may have detrimental impacts on the water yield downstream and also stream water quality. While reduced outflows may also reduce the total export of nutrients and sediment, reduced outflows together with increased temperature may increase the concentrations of some nutrients such as NH_4-N and TKN.

The model simulations showed that the 5% increase in rainfall projected by the HadCM2 GCM model resulted in an increase of average annual evapotranspiration (ET) by 60 mm (6.3%) compared to the historic data. This difference was statistically significant ($p < 0.005$) and is consistent with the results of Sun et al. (2000). However, using the Canadian climate projection CGC1 scenario, with an average of 16.8% lower rainfall than the HadCM2 and 12.3% lower than the historic data, the predicted average annual ET of 1021 mm was only 12 mm higher, and not significantly ($p = 0.519$) different than that predicted using the HadCM2 scenario (1009 mm) (Figure 7, bottom). The difference of 70 mm higher than the historic data (951 mm) was statistically significant ($p < 0.00001$).

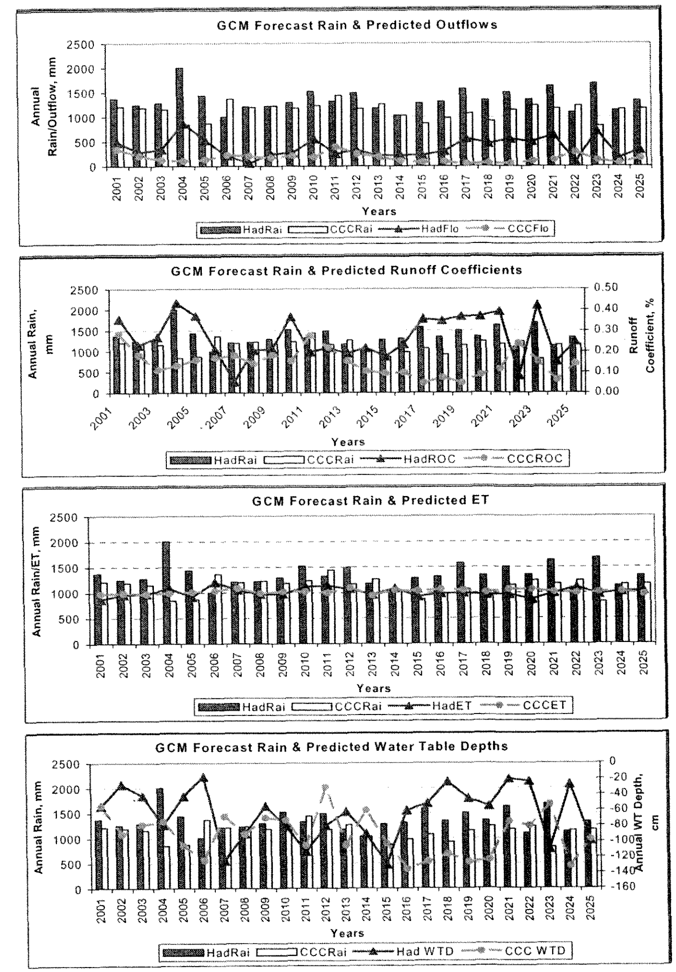

Figure 7. Annual rainfall predicted by HadCM2 and CGC1 GCMs and drainage outflows, ET and average water table depths predicted by DRAINWAT using GCMs predicted 25-years of weather data.

Thus the results of the Canadian CGC1 climate scenario indicate that drainage outflow will decrease and ET will increase significantly compared to the historic data. However, compared to the British HadCM2 scenario, use of the Canadian CGC1 model results in a decrease of outflow but no effect on ET of the pine forest at this site. The decrease in outflow was caused by reduced rain and consistently deeper predicted water table depths compared to HadCM2 (64 cm) (Figure 7, Table 3). The annual average water table depths predicted for CGC1 scenario varied from as deep as 135 cm in 2016 to 31 cm in 2012, with an average of 92 cm compared to the range of 130 cm in 2015 to only 18 cm in 2006, with an average of 64 cm for the wetter scenario of HadCM2 (Table 3). The increased ET, caused by both the increased PET due to rise in air temperature as well as unlimited soil water conditions, is generally assumed to result in greater tree growth. The CGC1 climate-based predicted annual water table depths that were deeper than that for the HadCM2, apparently did not reduce the water table depth to the extent that the ET was limited by soil water depletion in the root zone on these poorly drained high water table soils. Therefore, it was concluded that neither of the climate scenarios would have much impact on forest productivity. However, these results are to be carefully interpreted since the hydrologic model does not take into account other soil processes and their interactions with forest growth.

The results of both the climate scenarios indicate that the change in air temperature will have less significant impact than the change in precipitation on the hydrology (drainage outflows and ET) of the pine forest on these poorly drained soils. These results are consistent with the observations of Sun et al. (2002), who did not find water as a limiting factor for tree growth under the HadCM2 climate scenario for a small drained pine forest in eastern North Carolina. According to Carter (2003), if the climate change scenario with warm and moist conditions such as HadCM2 prevails there will virtually be no water stress through the 21st century, and the productivity of this region's forest will increase (http://www.usgcrp.gov/usgcrp/nacc/education/southeast/se-edu-4.htm). However, if the Canadian CGC1 model with reduced rainfall and increased temperature forecast prevails, then we will see a substantial reduction in outflows and deeper water table depths. However, the predicted water tables are not low enough for soil moisture to limit ET or productivity. The reduced water table with increased soil air volume however, may accelerate carbon and nutrient decomposition dynamics.

CONCLUSIONS

A DRAINMOD-based watershed-scale forest hydrologic model DRAINWAT was successfully tested with five years of flow data from a 2,950 ha watershed on a drained pine forest in eastern North Carolina. Compared to the current five-years of data, the DRAINWAT-predicted average annual drainage outflow and its distribution for the last fifty years (1951-2000) does not seem to have changed significantly for this managed pine forest. The predicted annual average runoff (outflow) coefficient of 0.27 and the ET of 951 mm were found to be consistent with other studies on similar forests in the region. Similarly, the average annual drainage outflow and its distribution predicted by DRAINWAT using the British HadCM2 Global Climate Model with a somewhat wetter climate were similar to that predicted using the historic data, indicating that the increase in about 5% rainfall using HadCM2 GCM would have no effect on runoff but may increase the ET of this pine forest. However, average annual predicted drainage outflows based on rainfall projected by Canadian CGC1 GCM were shown to be reduced significantly. The CGC1 model had 12.3% and 16.8% lower average annual rainfall compared to the 50 years of historic data and the HadCM2 model, respectively. The drier climate scenario did predict an increased ET compared to the historic data, but was not different compared to the wetter HadCM2 climate scenario. It was shown that the deeper annual water table depths predicted by the CGC1 GCM compared to the HadCM2 would not reduce the water availability to the extent that the ET was limited on these soils. It was concluded based on the simulation results that both the climate scenarios would have very little impact on ET and forest productivity. The results also indicate that a change in air temperature would have less significant impacts than the change in precipitation on the hydrology (drainage outflows and ET) of the pine forest on these poorly drained soils.

However, future such studies in the coastal plain should examine effects on a somewhat longer time scale of 50 years and also the interactions of soil processes including carbon and nutrient decomposition with forest growth using a physiological component in the model. Furthermore, more in-depth analysis of simulated monthly and seasonal outflows and water table may provide insights on projected effects of floods, low flows, wetland, and ET dynamics on these pine forests.

Acknowledgements

This study is supported partly by National Council of Industries for Air & Stream Improvement (NCASI), Inc and Weyerhaeuser Company. The authors would like to acknowledge the contributions of Weyerhaeuser personnel Sandra McCandless, Joe Bergman, and Cliff Tyson for providing necessary support for field data collection and processing and Scott Harder, College of Charleston for weather data processing. We would also like to thank Jennifer Moore Myers at USDA Forest Service for GCM data retrieval.

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