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A comparison of the watershed hydrology of coastal forested wetlands and the mountainous uplands in the Southern US

G. Sun[a,*], S.G. McNulty[a], D.M. Amatya[b,c], R.W. Skaggs[b,c], L.W. Swift Jr.[d], J.P. Shepard[e], H. Riekerk[f]

[a]North Carolina State University, 920 Main Campus, Venture II, Suite 300, Raleigh, NC 27606, USA
“USDA Forest Service, Raleigh, NC 27606, USA
‘Department of Biological and Agricultural Engineering, Raleigh, NC 27695, USA
[d]Coweeta Hydrologic Laboratory, USDA Forest Service, 3160 Coweeta Lab Rd., Otto, NC 28763. USA
[e]NCASI, Southern Regional Center. Gainesville, FL 32607, USA
‘School of Forest Resources and Conservation, University of Florida, Gainesville, FL 32611, USA

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Abstract

Hydrology plays a critical roie in wetland development and ecosystem structure and functions. Hydrologic responses to forest management and climate change are diverse in the Southern United States due to topographic and climatic differences. This paper presents a comparison study on long-term hydrologic characteristics (long-term seasonal runoff patterns, water balances, storm flow patterns) of three watersheds in the southern US. These three watersheds represent three types of forest ecosystems commonly found in the lower Atlantic coastal plain and the Appalachian upland mountains. Compared to the warm, flat, and shallow groundwater dominated pine flatwoods on the coast, the inland upland watershed was found to have significantly higher water yield, Precipitation/Hamon's potential evapotranspiration ratio (1.9 for upland vs 1.4 and 0.9 for wetlands), and runoff/precipitation ratio (0.53 ± 0.092 for upland vs 0.30 ± 0.079 and 0.13 ± 0.094 for wetlands). Streamflow from flatwoods watersheds generally are discontinuous most of the years while the upland watershed showed continuous flows in most years. Stormflow peaks in a cypress-pine Aatwoods system were smaller than that in the upland watershed for most cases, but exceptions occurred under extreme wet conditions. Our study concludes that climate is the most important factor in determining the watershed water balances in the southern US. Topography effects streamflow patterns and stormflow peaks and volume, and is the key to wetland development in the southern US.

Keywords: Evapotranspiration; Forested wetlands; Pine flatwoods; Uplands; Water balance

1. Introduction

During the past few decades, management and regulation of wetlands has received increasing interest from both the public and private sector. While denigrated historically as breeding places for disease and as impediments to civilization's development, society now recognizes that wetlands provides valuable ecological services such as flood control, water quality improvement, unique wildlife habitat; while producing economically valuable agricultural crops, timber, and fisheries. Wetlands are also sinks for carbon, nitrogen and sulfur on a global scale and may be an important consideration in current concerns

* Corresponding author. Tel.: + 1-919-515-9498; fax: + 1-919-513-2978.
E-mail address: ge_sun@ncsu.edu (G. Sun).

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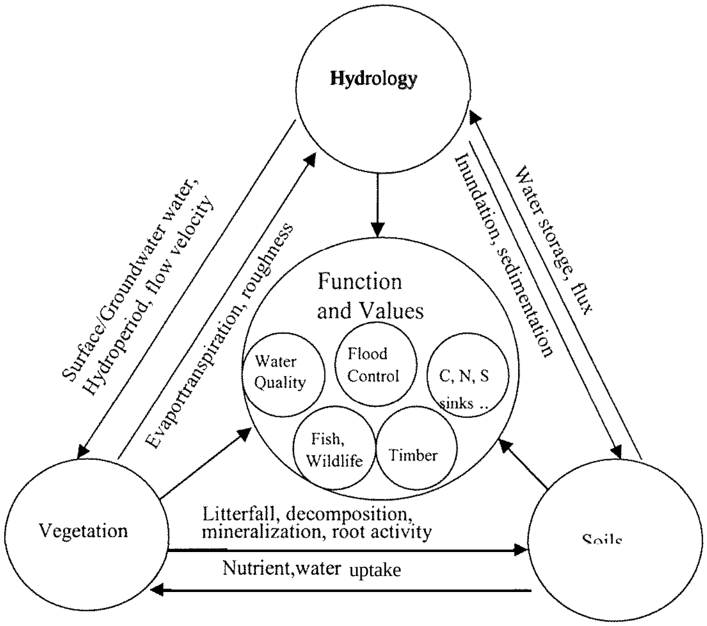

Fig. 1. Compositions and functions of a typical forested wetland

about potential climate change (Mitsch and Goselink, 1986). Ecosystems-level comparison studies between wetland and upland processes and functions are important in recognizing and protecting wetland resources.

Through interactions with vegetation and soils, hydrology plays a key role in wetland functions that eventually affect wetland societal values (Fig. 1). Basic hydrologic information such as seasonal water balance and groundwater table dynamics is needed to understand the wetland ecosystem functions, and to determine if a site is a regulatory wetland. In the past, studies on the effects of forest management on forest hydrology have been mainly focused on upland systems (Bosch and Hewlett, 1982; Whitehead and Robinson, 1993; Stednick, 1996). Literature on forested wetlands in the Southern US are lacking, but studies on this subject have increased dramatically in the 1990s (Aust and Lea, 1992; Chescheir et al., 1995; Amatya et al., 1996; Xu et al., 1999; Sun et al., 2000b). Our recent synthesis studies suggested that, compared to upland ecosystems, hydrologic responses of timber management in forested wetlands are unique, and therefore different management strategies should be adopted (Sun et al., 2001). A comparative study on the basic processes of wetland and upland hydrology across a climate and topographic gradient is helpful to understand these differential responses.

Forests play a great role in regulating the regional hydrologic patterns of the southern US where 55% of the region is covered by forests (McNulty et al., 1997). Due to the diverse climate and topography, it displays a gradient of hydrologic response to ecosystem disturbance and climate change (McNulty et al., 1997). Recent inter-disciplinary, inter-site analysis efforts to contrast the forest hydrology of small experimental watersheds across the US (Post et al., 1998) and around the world (Zhang et al., 2001) offered new insights regarding the interactions between vegetation, water storage and release, and climatic forcing. Inter-site ecohydrological comparison studies have the potential to predict the hydrologic effects of headwater forest management more accurately under different environments. Unfortunately, none of the selected sites are located in the coastal regions that have a flat topography with a large portion of forested wetlands.

This study contrasts the hydrologic characteristics of three forested watersheds: two representing forested wetland ecosystems (flatwoods) dominated

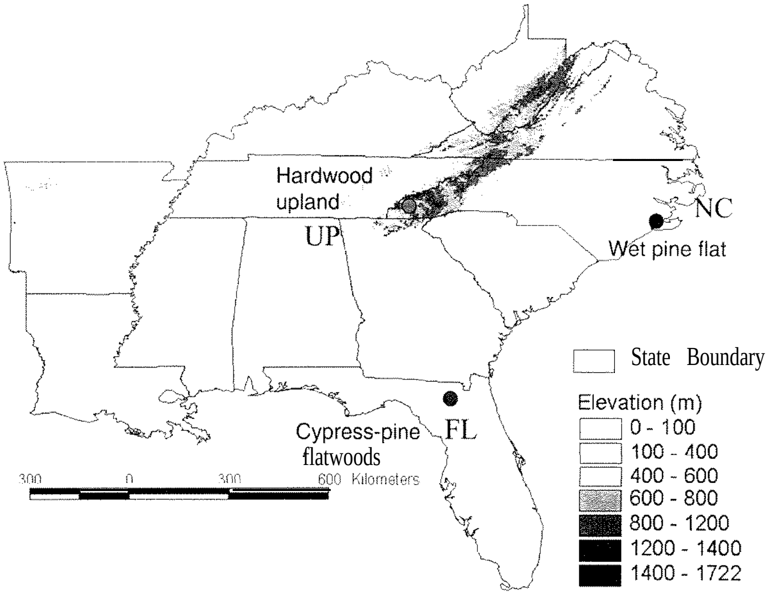

Fig. 2. Three experimental watersheds located across a climatic and topographic gradient in southern US.

by southern pines and the other one representing the southern Appalachian hilly uplands dominated by native hardwoods. These three watersheds, that are located in north-central Florida, eastern and western North Carolina, respectively, (Fig. 2), have the longest continuous records of forest hydrologic research and most extensive measurements in the southern United States.

Wetland systems have different hydrologic processes such as evapotranspiration, streamflow, and stormflow features from uplands. This paper intends to address the following three questions that are often debated by the hydrologic community or surmised by laymen and scientists alike.

I. Is actual evapotranspiration (AET) from pine flat-

Table 1
Physical parameter5 of three forested watersheds across a climatic and topographic gradient

Parameters	Bradford forest watershed #3 (FL), FL	Carteret 7 watershed #1 (NC), NC	Coweeta watershed #14 (UP), NC
Location and elevation above sea level	Latitude 29°54′; longitude 81°30′ 43-44 m	Latitude 34°48′; longitude 76°42′ 3 m	Latitude 35°03′; Longitude 82°25′ 707–992 m
Watershed size	140 ha (40% in cypress wetland)	25 ha (ditched)	61 ha (<1% in wetland)
Dominate climate	Subtropical, marine	Subtropical, marine	Subtropical, marine
Long-term annual precipitation	1400 mm, convection formation	1340 mm, convection and hurricane	1876 mm, convection and orographic formation
Mean annul air temperature (°C)	21.0	16.2	13.0
Topography (slope) (%)	< 2.0	< 0.2	49.0
Soil type	Sandy soils (<3 m)	Fine sandy loam (<3 m)	Deep sandy loam on bed rock (O-S m)
Vegetation	Unmanaged mature cypress-pine plantation	Mature loblolly pine plantation	Mature Deciduous oak, h&woods

woods close or equal to potential forest evapotranspiration (PET) in the long-term? And, is upland forest AET is far less than PET'?
2. In the long-term, what caused the hydrologic differences (streamflow/precipitation ratio) among the wetland and upland watersheds, topographical features or climate?
3. Is it true that storm flow peaks and volumes in wetlands are always lower than those in the uplands?

2. Methods

The basic physical and hydro-meteorological information of the three selected watersheds are described briefly in Table 1 and shown in Fig. 2. We intended to select three watersheds that had high quality long-term hydrologic data and covered a climatic and topographic gradient. We were not able to find watersheds that had similar sizes, however, since our comparisons were performed on a unit area basis for most hydrologic variables, watershed size should have limited effects on the hydrologic differences.

The Bradford forest watershed represents the typical forested landscape of North Florida, a mixture of two types of forest ecosystems, cypress *(Taxodium distichum)* wetlands and slash pine *(Pinus elliottii* Engelm.) uplands. The so called 'Uplands' are flat, located on relatively higher ground with < 1 m differences in elevation from the embedded wetlands. Compared to the Carteret 7 loblolly pine watershed, it is on the dry side of the soil moisture spectrum of flatwoods ecosystems, especially on the uplands that have well-drained sandy soils (Arenic Plinthic Paleudults). Cypress trees loss their leaves during the winter season (November to March) and usually start to leaf-out in early April. Cypress ponds or swamps, with sizes ranging 0.5-100 ha, are often embedded in pine plantations in Florida. Cypress wetlands are shallow depressions (<I m) commonly with an underlying impermeable clay layers at about three meters below the ground surface, surface water may present for 9 months while it rarely occurs in the pine upland in an average year. Experimental instalment and basic hydrological information for the Bradford Forest Watershed was described in detail in Riekerk (1989).

The Carteret 7 watersheds were artificially delineated using roads and parallel ditches. Surface drainage ditches are commonly used in the eastern coastal regions of North Carolina to improve soil moisture conditions for tree establishment and growth. Due to the low elevation and flat topography, this site is classified as poorly drained with hydric soils dominated by Deloss fine sandy loam (fine-loamy mixed, Thermic Typic Umbraquult). Various control drainage and forest management experiments have been conducted at this research site by using Watershed #1 as the control watershed. The loblolly pine *(Pinus taeda)* plantation has not been disturbed since 1989 after a commercial thinning during the fall of 1988 at an age of 14 year old. Due to improved drainage and fertilization, productivity, thus water use, of the forest stand is in the high end of the loblolly pine species (Sun et al., 2000a). Detailed information about the experimental design and hydro-meteorology at this site were reported in McCarthy et al. (199 1) and Amatya et al. (1996).

Watershed 14 at the Coweeta Hydrological Laboratory was chosen as an upland watershed representing another topographic extreme of the landscape in the Southern US. As one of the 2.5 active experimental watersheds at the Laboratory, it was clear-cut in 1962 and has been remained undisturbed since then. Detailed information about the hydrology of Coweeta watersheds can be found in Swank and Crossley (1988). In this paper, the Bradford Forest watershed in Florida, and the Carteret and Coweeta watersheds in North Carolina are denoted as FL, NC and UP, respectively.

To address the first two proposed questions, daily streamflow, temperature, and rainfall data were acquired from the three sites to characterize the general flow patterns and to calculate daily PET and annual water balance. PET, reflecting the atmosphere evaporative demands, was defined as the total maximum possible water loss from a forest ecosystem through the evapotranspiration processes. The actual water loss through canopy evaporation (interception) and transpiration is presumed to be less than PET under water stress conditions that may occur both in flatwoods and upland watersheds during the growing season. PET was estimated using Hamon's method as described in Federer and Lash (1978) and Vörösmarty et al. (1998) (Eq. (1)). This method uses temperature

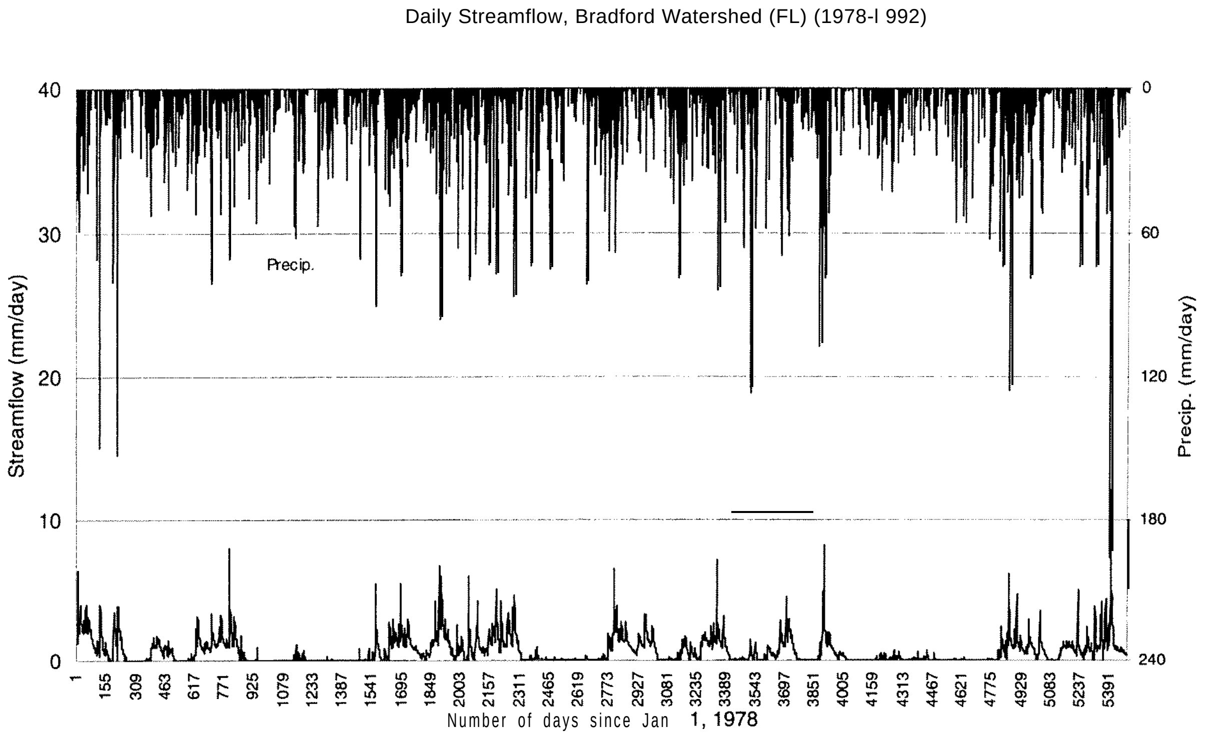

Fig. 3. Long-term daily runoff patterns for a pine flatwoods watershed (FL) in north-central Florida

as the major driving force for evapotranspiration, but also includes other variables such as daytime length and saturated vapor pressure.

$$PET = 0.165\,1 \times DAYL \times RHOSAT \times KPEC \qquad (1)$$

where PET is the forest potential evapotranspiration (mm/day); DAYL the time from sunrise to sunset in multiples of 12 h, calculated from date, latitude, slope and aspect of the watershed; RHOSAT the saturated vapor density (g/m’) at the daily mean temperature (TEMP)(°C) $= 216.7 \times ESAT/(TEMP + 273.3)$; ESAT the saturated vapor pressure (mb) $= 6.108 \times \exp[17.26939 \times TEMP/(TEMP + 237.3)]$; KPEC is the correction coefficient to adjust PET calculated using Hamon’s method to realistic values. Reported values for KPEC ranged from 1.0 (Hubbard Brook, New Hampshire) to 1.2 (Coweeta, North Carolina) (Federer and Lash, 1978). While a value of 1.3 was found in Sun et al. (1998) for the FL site, we also used 1.2 for the FL and NC watersheds to avoid uncertainty about this parameter.

A computer program is developed to calculate daily PET using the earlier method.

Advantages and disadvantages of this method in estimating forest PET are discussed in Vörösmarty et al. (1998). It was found that Hamon’s method and other more sophisticated methods gave similar results for estimating PET. Long-term (10– 15 years) water balances were constructed for each water year. We assume that changes in water storage were minimum over 10 years or longer although on an annual basis the water storage change might not be negligible, especially for wetland watersheds. Thus, annual average AET was estimated as the difference between measured average annual precipitation and streamflow for each watershed. All hydrologic fluxes are expressed in depth of water.

To address the third question proposed earlier, four rainfall events and associated storm flow hydrographs that represent the local climate patterns were selected from the UP and FL watersheds. The wetland size in FL (56 ha) is similar to the total area of UP (61 ha). The NC was believed to be inappropriate for storm

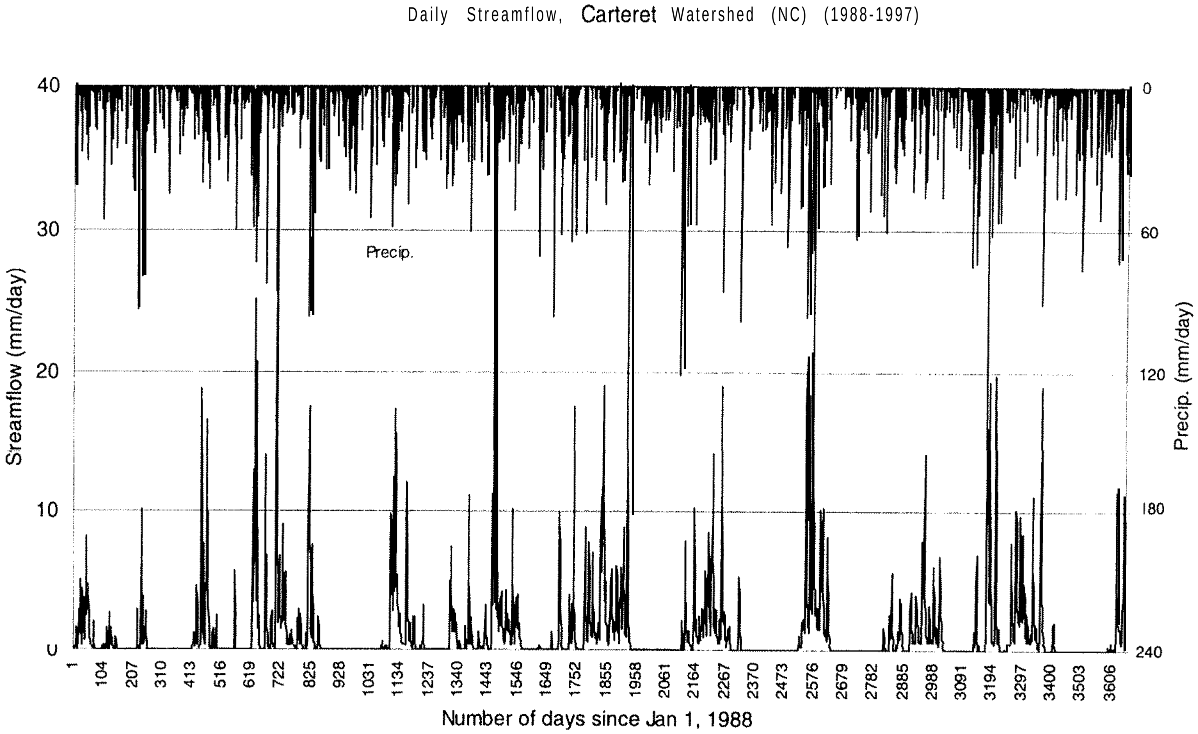

Fig. 4. Long-tenn daily runoff for a loblolly pine plantation watershed (NC) in eastern North Carolina

flow comparisons since its watershed size is too small (25 ha) and artificially ditched. Another important consideration in choosing the rainfall events was the size of the event and antecedent soil water conditions. We used baseflow rate as an indicator of antecedent soil moisture conditions. Efforts were made to ensure the rainfall events selected from the two watersheds to be comparable by choosing single events with similar total rainfall depth and duration.

3. Results and discussion

3.1. Flow patterns

The major differences in seasonal water flow patterns between UP and the flatwoods watersheds (FL and NC) were reflected in the baseflow component (Figs. 3-5). Outflow from flatwoods usually ceased during the spring and summer months when PET and AET became high (Figs. 3,4, 6 and 7). In wetlands, streamflow patterns were mainly controlled by the groundwater table or water storage that was the net results of rainfall and AET. High rainfall input and low PET at the upland watershed sustained baseflow during the non-rainfall periods (Figs. 4 and 8). The deep soils at UP offer rather large water storage that plays a significant role in regulating the upland hydrology by storing rain waters during rainy periods and releasing water continuously throughout the year (Figs. 5 and 8). In contrast, although the wetland watersheds also have large storage capacities, streamflow in Aatwoods occurred only when the entire soil profile was close to saturation in the fall and winter seasons. Stored soil water was released mainly to the atmosphere by ET (Figs. 6 and 7). Hydrology of other first-order watersheds (approximately 200 ha in area) in the South Carolina coastal plain showed similar patterns to what was found in these two small flatwoods watersheds. Over 75% of annual precipitation was returned to the atmosphere as ET, and it was not uncommon that streamflow ceased in dry seasons but flooded across the entire watershed in wet seasons (Sun et al., 2000c).

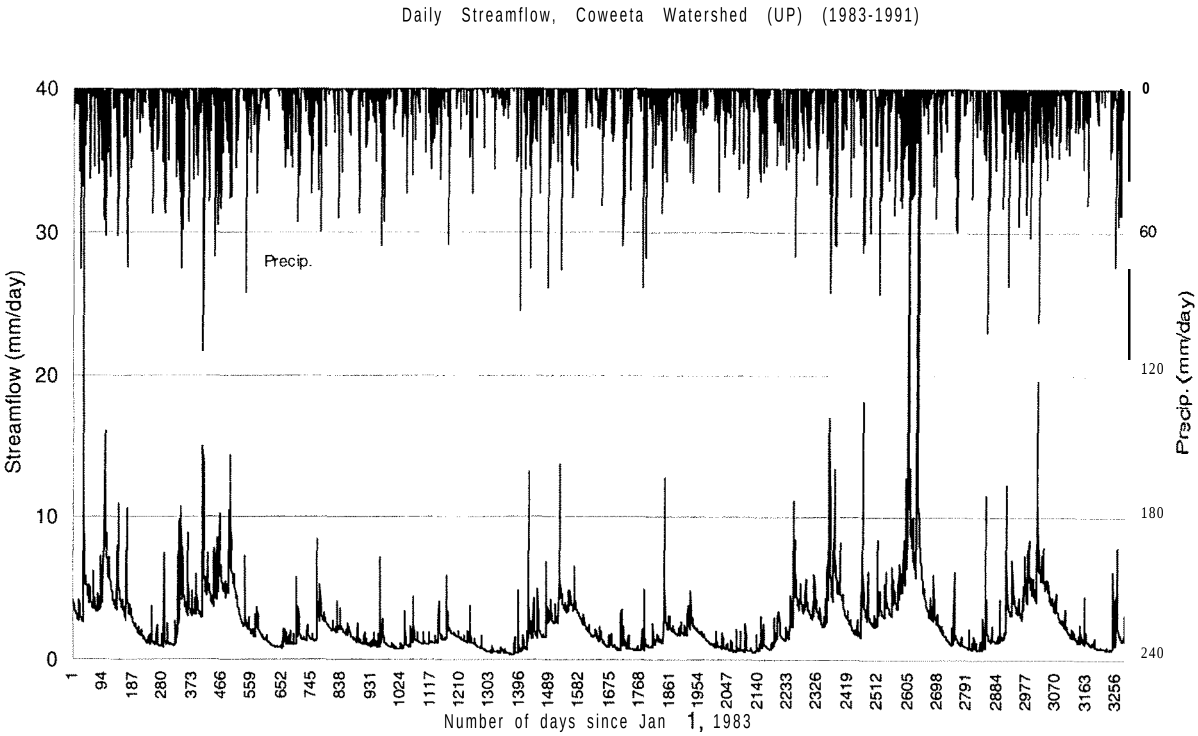

Fig. 5. Long-term daily runoff patterns for an upland watershed (UP) in western North Carolina.

3.2. Annual water balance

As expected, the UP watershed has the highest ratio (*R*/*P*) between runoff and precipitation (0.53 ± 0.092) followed by NC (0.30 ± 0.079) and FL (0.13 ± 0.094) (Table 2). We believe annual total PET, topography and soils contribute to these differences. Differences in tree species and forest management (forest productivity level) might also explain the hydrologic differences. However, as discussed in the next several paragraphs, the key-controlling factor is climate.

For the UP site, $P \gg$ PET $>$ AET, thus there is proportionally more water available for drainage than in the other two watersheds where *P* is less (FL) or close to PET (NC) (Table 2). The average AET/PET ratio for UP (0.84) is significantly higher than the wetland dominated FL watershed (0.75) but lower than that of the poorly drained, near flat NC watershed (0.93) (t-test, $P < 0.01$).

This is somewhat surprising since the FL site is a wetland site and it is often believed that actual ET from wetlands is close to potential ET such as in the NC case where AET is close to PET. The lower AET/PET ratio at the FL site might be caused by the fact that FL has higher PET values and the watershed is relatively well drained and is covered by unmanaged pine forests. The sandy soils at this site have fairly low water holding capacity, therefore, an evapotranspiration deficits occur, especially during the spring and summer months when PET $\gg P$. However, in the fall and winter month, *P* generally exceeds PET and AET. The seasonal shift of peaks of AET and *P* resulted in water excess in this relatively water-limited system (annual PET $>$ annual *P*). The water excess eventually promotes cypress wetland development in the local depressional areas on the flat landscape. Compared with other two watersheds, the low annual *P* but high PET, or low P/PET ratio, is also responsible for a low AET/PET at the FL site.

Studies at Coweeta report that, on an average, deciduous forests of the UP watershed, use 20% less water than conifers due to lower canopy interception loss (Swank and Miner, 1968). However, the AET/

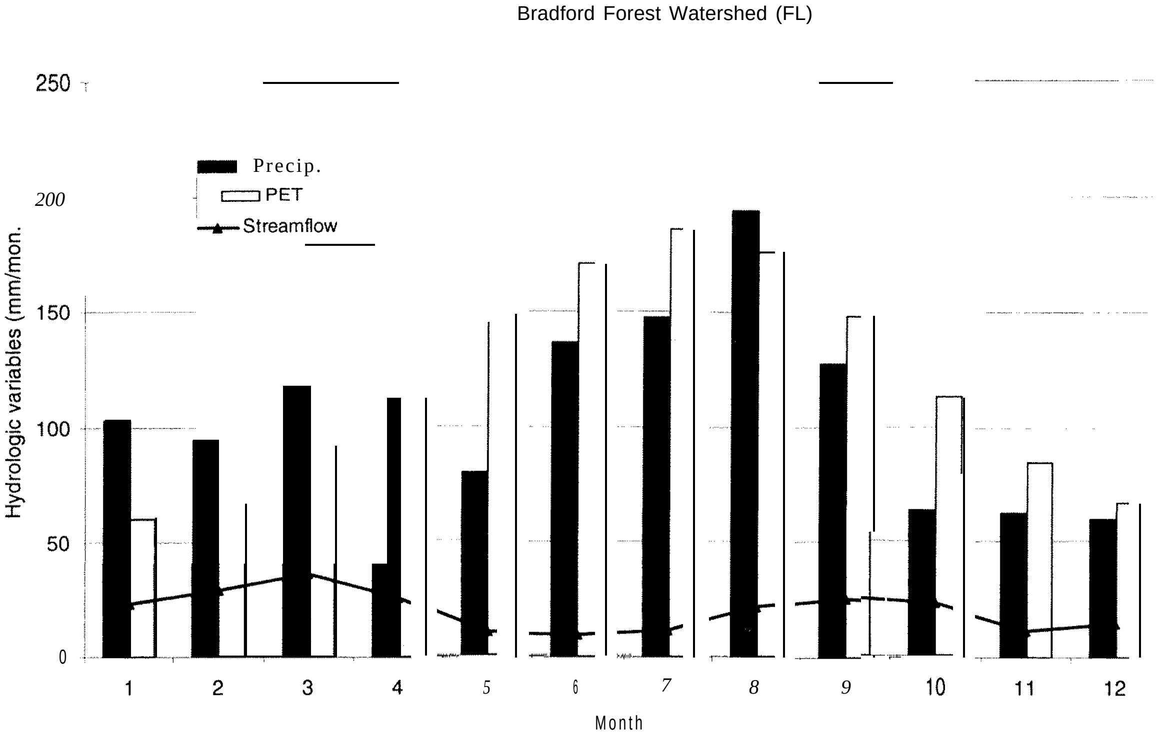

Fig. 6. Long-term averaged monthly precipitation, runoff, and calculated Hamon's PET for the Bradford Forest Watershed (FL)

PET ratio of the UP watershed was moderate because of the lower PET in the mountains with lower air temperature.

Similar to the UP site, a relationship of $P >$ PET $>$ AET exists for the NC watershed. The NC watershed has the largest AET/PET ratio (0.92) suggesting it is not a water-limited system most of the year. The leaf area index of pine in this watershed is quite high and the forest productivity appears to be in the high end of the loblolly pine species (Sun et al., 2000a), suggesting that AET at this drained site has not reached its potential. Compared to non-ditched lands, surface drainage, as a water management tool, certainly increased streamflow and thus decreased overall evapotranspiration at this site. Therefore, the highest AET/PET ratio at the NC watershed probably is a result of two facts. Firstly, the site is poorly drained due to flat topography and low hydraulic conductivity of fine sandy loam soils and thus soil moisture is available for tree use. Secondly. the productivity of loblolly pine plantation is high suggesting high water use at the site.

Earlier analysis suggests that long-term AET from wetlands at both the FL and NC sites is generally lower than PET calculated by the Hamon's method. Data also show a wetland-dominated watershed does not necessarily have a higher AET/PET ratio. This finding is contrary to general perception that ET is essentially equal to PET (Muller and Grymes, 1998). Like any other PET methods, we recognize the uncertainty that associated with PET estimated by the paper. However, it is certain that there are big differences in AET/PET ratios among the three watersheds.

The upland watershed had the highest precipitation and P/PET ratio, and a moderate AET/PET ratio. It appears that these two factors, instead of the steep terrain, are responsible for the high water yield. In other words, even if the UP site is flat, water yield would still be high simply because of $P \gg$ PET. For the two wetland watersheds, the *RIP* ratio of the FL watershed is less than half of that of the NC watershed even though the former is on a higher elevation with higher topographic relief and better drainage. Again,

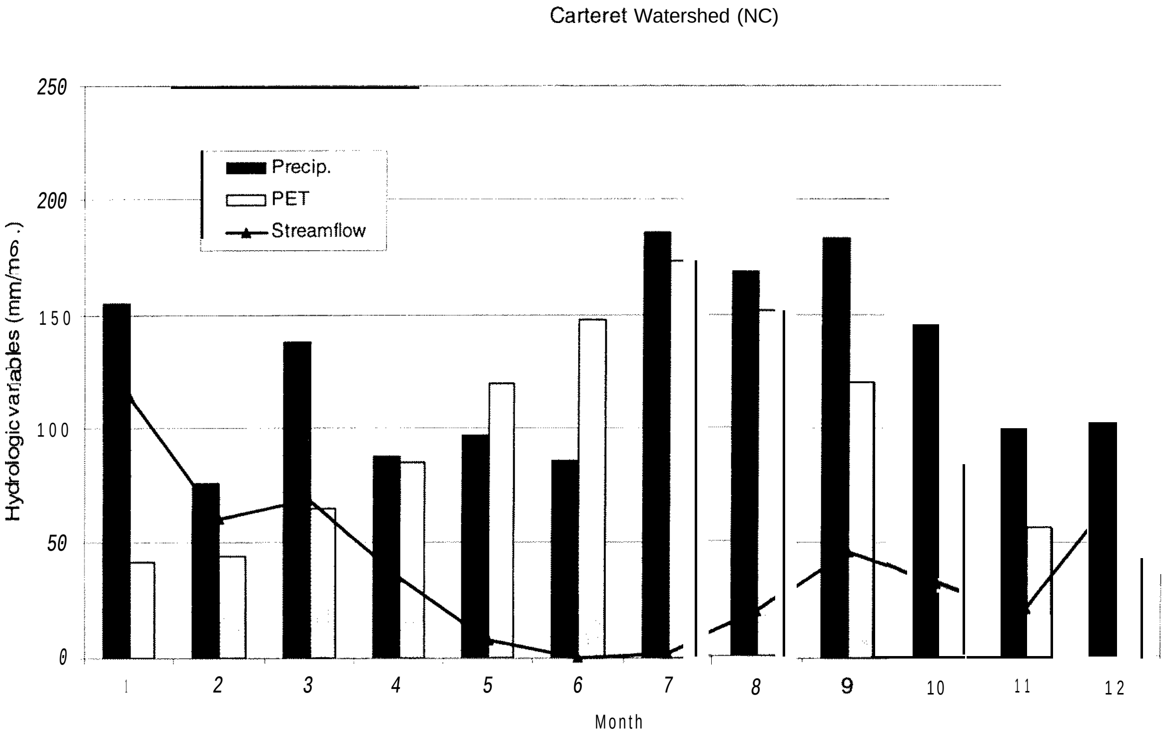

Fig. 7. Long-term averaged monthly precipitation, runoff, and calculated Hamon's PET for the Carteret 7 control watershed (NC).

the significantly higher *P*/PET ratio at the NC site is the major cause of higher flow rates. Again, it suggests topography or slopes of the landscape play secondary role in affecting the long-term hydrologic balance of the two watersheds. Therefore, this analysis suggests that climate or the Precipitation/PET ratio dictates water yield from these three watersheds. However, there is uncertainty about this speculation since it is difficult to separate the functions of topography from the roles of climate, vegetation and soils in affecting water yield. As discussed in last paragraph, there may be inaccuracy in PET estimation as well.

3.3. *Storm flow*

Four storm events selected from each of the UP and FL sites were contrasted to study the hydrologic response of two rainfall events under a dry and a wet antecedent soil water conditions. The antecedent soil water conditions are determined using streamflow records immediately prior to the rainfall events. 'Dry' or 'Wet' soil conditions are relative to the general flow conditions for each watershed. Two variables, peak flow rate and storm flow volume, were chosen as the indicators to identify how a watershed responds to a single storm event (Table 3).

The wetland watershed, FL, could absorb as high as 57 mm of rainfall under a dry condition. For small rainfall events under either a wet or a dry condition, both the peak flow rate and volume were lower in the wetland than in the upland site.

However, for the large rain storms, under a dry condition, the peakflow rate was similar to the upland but the storm flow volume is much larger. The difference in peakflow rate is partially due to higher rainfall in the wetland watershed and the larger size of wetland watershed. The stormflow volume/rainfall ratio of UP is about 0.26 while the ratio is only 0.08 in the FL watershed. Under a large storm, wet conditions, the wetland watershed had a much higher peakflow rate and storm flow volume than the upland watershed. The stormflow/rainfall ratio is 0.58 and 0.31 for FL and UP watershed, respectively. The greater response indicates the wetland has limited

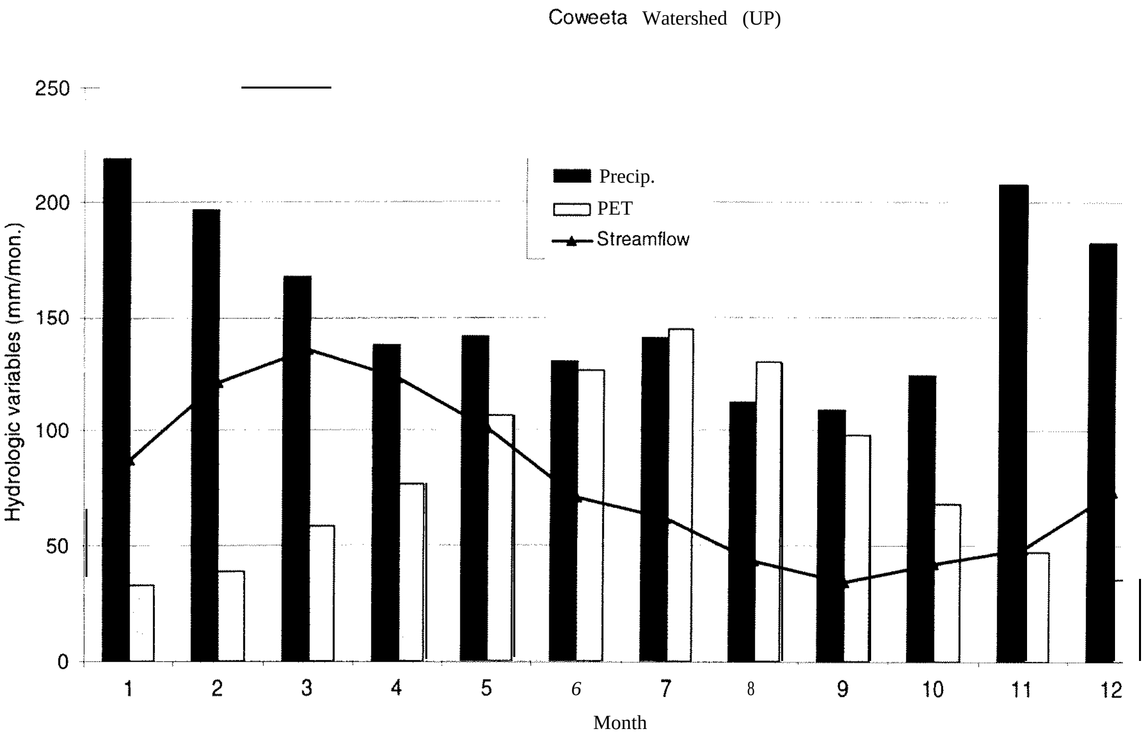

Fig. 8. Long-term averaged monthly precipitation, runoff, and calculated Hamon's PET for the Coweeta Watershed 14 (UP).

available storage to store additional rainfall. After the storage capacity, at least 57 mm, is filled, storm water can move rather quickly to the watershed outlet. Under a large rainfall event, the watershed size dominates the hydrologic patterns. Although it is safe to say the wetland watershed has a larger water storage capacity, we are not able to conclude the wetland watershed can reduce stormflow peaks and stormflow volume because of limitations in watershed size differences between the two watersheds. However, Verry (1997) suggests wetlands can reduce flood peaks even when wetlands are full, behaving similar to reservoirs or lakes. Under wet antecedent

Table 2
Average annual water balances of' three watersheds (values in parenthesis are standard deviations)

Watershed	FL'	NC"	UP
Precipitation (P) (mm)	1261 (194)	1524 (180)	1730 (391)
Runoff (R) (mm)	184 (141)	470 (156)	950 (174)
AET	1077 (98)	1054 (96)	779 (86)
PET	1431 (40)	1133 (29)	913 (22)
RIP	0.13 (0.094)	0.30 (0.079)	0.53 (0.092)
P/PET	0.88 (0.13)	I.35 (0.17)	1.87 (0.46)
AETIP	0.87 (0.094)	0.70 (0.079)	0.47 (0.09)
AET/PET	0.75 (0.064)	0.93 (0.086)	0.84 (0.086)

[a] Data from Water Year (May 1 -April 30) 1979– 1992.
[b] Data from calendar year January 1, 1988–December 3 1, 1997
. Data from Water Year (May l-April 30) 1979– 1992.

Table 3
Contrasting storm flow characteristics of four rainfall events

Watershed	Antecedent water condition	Small Storm			Large storm		
		Rainfall amount (mm)	Peak flow rate (l/s/ha)	Storm flow volume (mm)	Rainfall amount (mm)	Peak flow rate (l/s/ha)	Storm flow volume (mm)
UP	wet	30	1.1	21	157	6.8	49
	Dry	59	1.5	5	102	3.3	9
FL	wet	33	0.4	4	160	14.2	92
	Dry	57	No response		127	4.0	33

soil moisture condition, watershed size will play a critical role in determining peak flow rate and volume as well.

The Variable Source Area Concept has been accepted as the runoff generation mechanisms for forested watersheds (Hewlett and Hibbert, 1965). The theory states that storm flow or quick flow in forested watersheds occurs from direct channel interception and the saturated areas near stream channels with 'variable' dimensions during or between storm events depending on antecedent precipitation. The 'variable source area' is essentially the riparian zone or the wetland portion of a watershed. For the flatwoods sites, it may extend from none (dry period) to the entire watershed (extremely wet periods). Saturated areas in 10 experimental watersheds with sizes ranging from 2.2 to 4000 ha were found being about 2-5 1% of the total catchment area (Becker et al., 1999). Obviously, the upland watershed and the two flatwoods watersheds described in this study would be in the low and high end of the spectrum, respectively.

Apparently, the FL wetland watershed did not show lower storm flow peaks and volumes for all cases of rainfall scenarios than the UP watershed. Wetland storage capacity is finite and when the storage capacity is surpassed, wetlands could behave similarly to uplands in terms of response to rainfall events. Thus, the general perception that wetlands always have 'flooding control' functions is not accurate. One must consider the antecedent soil moisture conditions when evaluating wetland hydrologic functions.

4. Conclusions

Long-term annual water balances for three watersheds across a climatic and a topographic gradient in the southern US were constructed. The watersheds represent the three important ecosystems in the Southern US slash pine-cypress wetland, loblolly pine plantation, and southern Appalachian hardwoods. The comparison study suggests perceptions about wetland hydrology that are often surmised by wetland researchers and hydrologists may not be accurate. Although further studies are needed, our data analysis suggests that climate as affected by latitude and elevation is the most important factor that determines the long-term water balance of a forested watershed. Topography is important in affecting watershed baseflow patterns and storm flow peak and volume. Flat or depressional topography can reduce the magnitude of storm flow in most conditions, but this effect diminishes under extremely wet conditions when the system's water storage capacity is exceeded. Compared to climate (precipitation and temperature or PET), topography is the key factor controlling wetland formation, development, and functions in the southeastern US. It is important to understand that wetlands or the riparian zones are the source areas of storm flow in forested watersheds. We found long-term wetland-dominated watershed AET may be far less than PET.

The differences of the hydrologic regimes across the climatic, topographic and consequently vegetation gradients have profound implications to forest management. Compared to coastal watersheds, we would project that tree removal from deciduous hardwood uplands watershed will reduce transpiration and ET and thus increase streamflow with a larger magnitude. Higher hydrologic responses in uplands are due to higher P/PET and Streamflow/*P* ratios. For lowland wetland watersheds with shallow water tables, reduction of transpiration of trees may be compensated by an increase of soil evaporation from exposed soil surfaces. Tree removal likely has an insignificant increase in total runoff and has limited down stream impacts. Because of the low *RIP* ratio of southern wetland watersheds, the hydrologic response to forest management is expected lower compared to their upland counterparts. Favorable soil moisture and heat conditions prompt vegetation recovery and thus allow disturbed hydrology to recover to pre-disturbed conditions relatively quickly.

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