HYDROLOGIC PROCESSES OF FORETSED HEADWATER WATERSHEDS ACROSS A PHYSIOGRPHAIC GRADIENT IN THE SOUTHEASTERN UNITED STATES

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Abstract. Understanding the hydrologic processes is the first step in making sound watershed management decisions including designing Best Management Practices for non-point source pollution control. Over the past fifty years, various forest experimental watersheds have been instrumented across the Carolinas through collaborative studies among federal, state, and private organizations. One of the most notable theoretical hydrological advances that directly resulted from studies in this region perhaps was Variable Source Area Concept (VSAC) proposed by John Hewlett and others. VSAC offers a framework that explains the mechanisms of streamflow generation at the watershed scale and provides a basis for developing watershed management practices for minimizing negative impacts on stream water quality. Unfortunately, due to the dynamic nature of the variable source area, a zone that varies across space and time, it is rarely measured and quantified at the watershed scale. This paper presents findings from a stormflow monitoring study that spans a physiographic gradient from the mountain to the sea. This study suggests that the variable source area and stormflow flow characteristics were most influenced by antecedent soil moisture conditions, which reflect the controls of climate and topography. We found that the saturated area was rather small in the Appalachians and piedmont upland watersheds, but it could be rather large and variable in the lower coastal plain watersheds. Implications of these contrasting differences in VSA to watershed management are discussed.

Key words: forest hydrology, variable source areas, streamflow, stormflow, water table

1. INTRODUCTION

The southeastern United States has a complex topography and climate (i.e., precipitation and available energy for atmospheric demand) that result in a diverse ecohydrological conditions in headwater watersheds (Sun et al., 2004). For example, the average annual runoff/precipitation ratios in forested watersheds can vary from over 50% in the southern Appalachians mountain uplands to less than 30% in the coastal plain region (Sun et al., 2002; Lu et al., 2003; Harder et al., 2007). Runoff is mostly generated as saturation-overland flow in the costal plain region while overland flow is rare in undisturbed mountain watersheds where subsurface quick flows are the major sources of streamflow (Sun et al., 2008). The diverse physiographic conditions and associated differential water balance characteristics complicate the generalization regarding the hydrologic impacts of land management at large scales, and hamper prescribing management strategies. Our incomplete understanding of the hydrologic processes for large basins that drain from the mountain to the sea is in large part due to the complex interactions among climate, topography, geology, and vegetation at multiple scales. Past studies on small watersheds during the past century have accumulated large amount of data and resulted in the many important advances in hydrologic sciences, notably the development of the Variable Source Area Concept (Hewlett and Hibbert, 1967) and various forest hydrologic models for selected ecosystems. VSAC offers a framework that explains the mechanisms of streamflow generation at the watershed scale and provides a basis for developing watershed management practices for minimizing negative impacts on stream water quality.

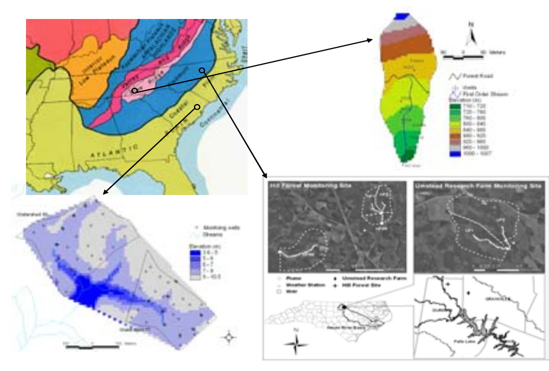

Figure 1. Installations of three watersheds (Coweeta, Hill Forest, Santee Exp. Forest) across a physiographic gradient in the Carolinas.

Table 1. Contrasting characteristics of three small forested watersheds

Watershed	Coastal Plain, WS80	Piedmont, HFW1	Mountain, WS2
Area (ha)	160	32	12
Elevation range (m)	3-10	166-195	710-1007
Mean climate: Precip Air temperature	1350 mm/yr. 19.0 °C	1120 mm/yr. 15 °C	1880 mm/yr. 13.0 °C
Vegetation	Mixed pine-hardwoods	Deciduous hardwoods	Deciduous hardwoods
Data periods	2003-2005	2007-2008	1988-1989 for PET; 1991-2005 for flow and rainfall

Unfortunately, due to the dynamic nature of the variable source area, a zone that varies across space and time, it is rarely measured and quantified at the watershed scale. Existing computer models are often site specific and are rarely transferable to other landscapes, and validations are lacking regarding internal processes such as spatial distributions of evapotranspiration and subsurface flows including groundwater table depth and soil moisture, even for small watersheds.

The objectives of this paper were to 1) contrast daily and/ storm event flow frequency distribution in three first-order watersheds in the Carolinas, and 2) discuss implications of the hydrological differences across a climatic and topographic gradient for designing Best Management Practices.

2. METHODS

Hydrometeorologic data collected from three first-order watersheds by the US Forest Service were used for this study (Table 1). These three watersheds represent three southeastern ecosystems with unique topographic and climatic regimes in the southeast.

The WS80 is located on the Santee Experimental Forest (33.15ºN, 79.8ºW), 55 km northwest of Charleston, in Berkeley county, South Carolina. This watershed has been monitored since the 1960s for water quantity and quality studies. The HFW1 is located on the North Carolina State University's Hill Forest in Durham County, a typical piedmont landscape of central North Carolina. HFW1 is one of the six watersheds that have been monitored since October 2007 to study the effectiveness of forest buffers in improving water quality (Figure 1). Treatments will be implemented in the fall of 2009. WS2 is located in the Coweeta Hydrologic Laboratory, a Long Term Ecological Research Site (LTER) in the southern Appalachians, northwestern North Carolina. WS2 is a control watershed at Coweeta that has not been disturbed for at least 80 years. WS2 has a steep slopes (>40%) and a perennial stream.

A total of 11 storm events wee selected to determine the role of antecedent soil moisture conditions on stormflow generation at the Piedmont watershed HFW1. Since we intend to compare the hydrologic response to the coastal plain, a consistent flow separation method adopted by Torres (2008, this volume) was used. This study re-examined the 51 stormflow events reported in Torres et al. (2008).

We used frequency distribution curves for daily precipitation, potential evapotranspiration (PET), and flow to illustrate the climatic and flow differences among the three small watersheds. PET was calculated using FAO grass reference PET method for the Coweeta site, Hamon's PET method (Sun et al., 2002) for the piedmont, and Penman-Monteith equations for forest lands (Dai et al., 2008).

2. RESULT AND DISCUSSION

2.1 RUNOFF RATIO AT THE STORM EVENT SCALE

At the HFW1 site, the largest rainfall event of 130.4 mm occurred on day 249 following a large storm of 100 mm on Julian day of 240 during the study period. The watershed did not respond much with a runoff/precipitation ratio (R) only about 5% due to the long period of drought in the summer months. The second storm on Julian day 249 resulted in an 18% R. This was not considered high since a rainfall of 40 mm produced a 22% of ratio during the winter season (Julian day 67, 2008).

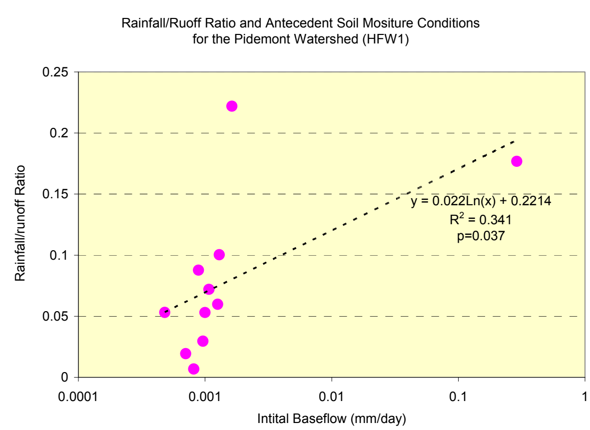

Figure 2. Runoff/Precip ratio for 11 storm events at the HFW1.

Step-wise regress analysis for the 11 storm records suggests R is significantly (R^2=0.611; p=0.022) influenced by the season (Julian date) and antecedent soil moisture condition (i.e. initial baseflow) (Figure 2). This suggests available soil water storage that reflects the balance between precipitation and evapotransiration prior to the storm events, is a major control on stormflow runoff generation in a piedmont watershed. This finding was supported by Torres et al. (2008, this volume)'s study for a large coastal watershed (7256 ha in size), the Tukey Creek in South Carolina. They report that runoff-rainfall ratios are directly proportional to the total rainfall amount during the 5 and 30 days preceding the storm event. Our analysis for the 51 storm events show that averaged runoff ratio of Turkey Creek is much higher than the piedmont site (0.27 vs 0.08), R is significantly correlated to initial flow rate (p=0.0002) and it is not influenced by season (i.e. Julian date) at this large coastal watershed. It appears that watershed size has influence in both baseflow and stormflow rates. Torres et al. (2008) suggest rainfall intensity might be important in stormflow generation for the coastal plain.

2.2 RUNOFF RATIO AT THE DAILY TIME SCALE

Daily rainfall frequency distribution shows that the mountain watershed (CW2) has a higher rainfall rate for all rainfall classes, followed by the coastal plain watershed (WS80) and the piedmont (HFW1) (Figure 3). This pattern is consistent with the annual total ranking (Table 1). In contrast, following a large energy gradient, the WS80 has the highest daily PET, followed by HFW1 and WS80 (Figure 4). The differences of PET are largest for higher classes (>5 mm/day).

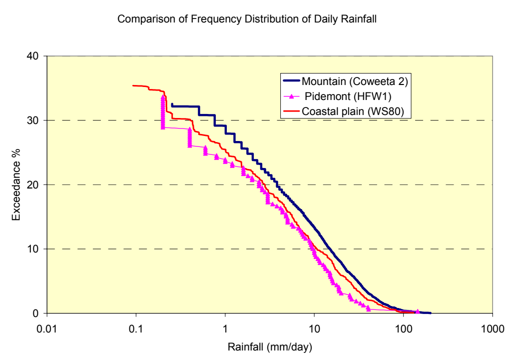

Figure 3. Daily rainfall distribution of the three sites

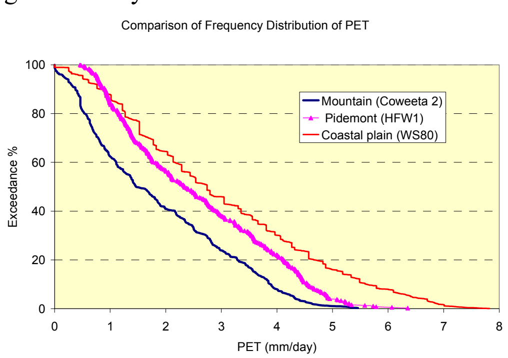

Figure 4. Daily PET distribution of the three sites.

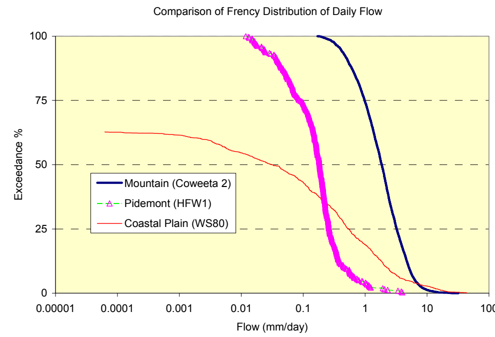

Figure 5. Daily steamflow distribution of the three sites.

The streamflow distribution has a relatively more complex pattern than rainfall and PET (Figure 5). The largest watershed (WS80) has the largest range of flow rate. It has more low flow occurrences (<0.22 mm/day) than the HWF1 and CW2, but the patterns shit for higher flow events (>0.22 mm/day). WS80 has largest number of large flow events (i.e. flow rate >7 mm/day). Based on the frequency distribution pattern of rainfall in Figure 3), the flow extremes can not be explained by rainfall adequately. We argue that this large variability of flow at WS80 reflects the flat topography and large variable source areas.

Previous landscape-level groundwater monitoring studies (Sun et al., 2002; Sun et al., 2008) show that the temporal variations of the saturated areas in the SW80 are very large (0-100% of the watershed area), and the mountain watershed (CW2) has a rather small saturated area even during extreme storm events. Consequently, during extreme storms and low available water storage (mostly in winter months), it is likely that large amount of overland flow can occur at the WS80. In contrast, soil water storage is always available to temporally intercept and store rainfall in the watershed (CW2 and HFW1), a large saturation area is not likely to develop even during wet season (winter) in the hilly watersheds (CW2 and HFW1).

CONCLUSIONS

This cross-site hydrologic comparison studies on hydrologic response to rainfall at a storm and daily scale confirm that water balances between precipitation and ecosystem evapotranspiration controls streamflow dynamics at all scales through the antecedent soil moisture conditions. This control is universally true to all landscape. Topography affects the residence time of water transport and thus the presence of the shallow groundwater table depth and the extent of watershed saturated areas. Consequently, the coastal watersheds have the highest variability in streamflow.

This study offers only exploratory explanations of the differential hydrologic response to rainfall. More monitoring data are needed for the piedmont watershed before concrete conclusions are drawn. More event based storm flow analysis is needed at the CW2 site. In spite of the limited analysis, this study can offer some implications to watershed management. First, the large variability (low and high flows) of stremeflow of costal watersheds should be given attention when designing Best Management Practices (BMPs) - perhaps the traditional design with a narrow buffer width would have limited use for fist-order streams on a flat terrain in filtering sediment; second, forest watersheds have rather large water storage capacity during the growing seasons for all sites, maintain the high evapotranpiration rate is key to realizing the stormflow reduction functions of forested watersheds. This study also suggests it takes a more time for forested watersheds to recover its hydrology from sever droughts than we normally anticipate.

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