



American Society of
Agricultural and Biological Engineers

An ASABE Meeting Presentation

Paper Number: 062182

Hydrology and Water Quality of Two First Order Forested Watersheds in Coastal South Carolina

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**Written for presentation at the
2006 ASABE Annual International Meeting
Sponsored by ASABE
Oregon Convention Center
Portland, Oregon
9 - 12 July 2006**

Abstract Two first-order forested watersheds (WS 80 and WS 77) on poorly drained pine-hardwood stands in the South Carolina Coastal Plain have been monitored since mid-1960s to characterize the hydrology, water quality and vegetation dynamics. This study examines the flow and nutrient dynamics of these two watersheds using 13 years (1969-76 and 1977-81) of data prior to Hurricane Hugo (1989) and nearly 10 years (1990-1992, 1996-99, and 2003-06) immediately after Hugo. WS 80 remained as a control throughout the study period, whereas WS 77 underwent several treatments including prescribed burning, partial harvest, salvage logging and prescribed fire for red-cockaded woodpecker habitat management. Depending upon the antecedent moisture conditions, both the watersheds were highly responsive of rainfall events throughout the periods. Accordingly, annual outflows varied from 5% in 1981 to 59% in 1998 with an average of 22% of the annual precipitation for the control (WS 80) and from 9% in 2004 to 44% in 1991, with an average of 27% for the treatment watershed (WS 77). The coefficient of variation (COV) on WS 80 was higher (55%) compared to 36% for the WS 77. Annual rainfall variation was much lower (COV = 14%) than the

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variation in stream outflows. Post Hugo average outflow from WS 77 increased relative to WS 80 until 1992. By the regeneration period of 1996 reversal in outflow was noticed with the higher outflows on WS 80 than on the WS 77. While prescribed burning of WS 77 in a course of five years (1977-81) did not affect on stream outflows and chemistry, mastication in course of nine months in 2001 followed by another prescribed burning of 84% of WS 77 on May 10, 2003 seemed to have increased the outflows on WS 77 both in 2004 (64%) and 2005 (70%). Average nutrient concentrations were similar on both watersheds although there was a wide variability in $\text{NH}_4\text{-N}$ on the treatment watershed (WS 77) compared to WS 80. pH was slightly lower on the WS 77 (5.4) than on WS 80 (6.8). Both $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations were very low for both the watersheds, before and after Hugo, with organic nitrogen as the dominant factor on both watersheds. Phosphate was also very low (0.02 mg L^{-1} , on average) on both the watersheds during both the periods. Hurricane Hugo substantially increased the nutrient loads primarily due to increase in outflows. Although data presented herein may serve as baseline information for assessing impacts of both the developments and natural disturbance in the region, further studies and analysis with additional data should be conducted to verify some results such as the reversal of flow pattern after the hurricane Hugo that may have changed the dynamics of regenerated vegetation after Hugo possibly affecting stream outflows via evapotranspiration (ET) on these humid coastal plain watersheds.

Keywords. Stream outflow, Peak Flow Rate, Runoff Ratio, Water Budget, Pine Hardwood Forest

Introduction

The low-gradient, forested wetlands of the Coastal Plain of the southeastern United States represent a unique eco-hydrologic system, yet there is a very little information available on the region's hydrologic and biogeochemical processes, flooding patterns, and water and nutrient balances. Long-term hydrologic monitoring can provide the information needed to understand basic hydrologic processes and their interactions with climatic variation, land use change, and other natural and anthropogenic disturbances. It also provides researchers with baseline data for evaluating responses, generating new scientific hypotheses, and testing eco-hydrologic models. For the southeastern Coastal Plain region, with its growing population, rapidly expanding development, and intensive timber industry, this information is crucial for the sustainable management of the region's water resources.

Most of the lands in the southeastern lower coastal plain are drained by small streams, which are typically headwaters of black-water rivers or streams. They commonly begin as a minor swell or depressional area within broad wet flatwoods, pocosins, Carolina bays, or small depressional ponds, collecting excess surface water and gravitational water from the surrounding area into a channel. These streams are characterized by a low gradient streambed and side slopes, and relatively broad stream bottoms, which contribute slow surface drainage. Soils within the region often have clayey subsurface layers, which restricts internal drainage. Because of these physical features, headwater catchments in the southeastern lower coastal plain often contain forested wetlands (Harms et al., 1998). Accordingly, headwater watersheds may contain a mosaic of upland and wetland ecosystems, which enhances ecological function and values (Mitsch and Gosselink, 1993).

The ecological functions and societal values derived from forested wetlands are dependent on hydrology. Hydrology regulates the formation of hydric soils and the occurrence of wetland vegetation (Skaggs et al., 1994). Through interactions with vegetation and soils, hydrology regulates ecosystem functions that eventually affect societal values that are derived from the wetland (Sun et al., 2002). Unlike the upland watersheds dominated by hillslope processes, in their natural state, hydrology of these watersheds is characterized by shallow water tables, which respond rapidly to rainfall and evapotranspiration (ET). Since the long-term annual rainfall of this humid coastal region is generally higher than the long-term annual ET, these poorly drained sites are normally wet. The main hydrologic functions of these watersheds draining the headwater streams are considered to be: (1) near surface or shallow subsurface water table, which drives most of the stream outflows (as shallow surface runoff and drainage); (2) surface water detention that prevents flash flooding; (3) delayed discharge of surface- and subsurface-water which provides a steady water supply and improved water quality downstream. These hydrologic mechanisms control biogeochemical processes, support high biomass production, sustain diverse terrestrial, riparian- and aquatic-communities, and provide recreational opportunities.

In this paper we examine the long-term hydrology (outflow processes) of two first-order forested wetland watersheds (WS 77 and WS 80) located at the headwaters of East Cooper River, a tributary of Cooper River draining to Charleston Harbor System in Charleston, South Carolina (Fig. 1). These watersheds were established by USDA Forest Service in mid-1960's with an objective of studying water budget, rainfall-runoff processes, flooding patterns, and effects of rainfall on water table depth and soil moisture. Watershed 77 (WS 77) was initially established in November 1963 with a flow gauging station followed by the second watershed (WS 80) in October 1968. Young (1968) in his water budget study for WS 77 showed that excess water in the form of runoff could be problematic in downstream flooding, and that there was no

dependable base flow generated from this undrained watershed. The watershed (WS 80) was created as a control in the paired system with WS 77 (treatment) with an objective of studying hydrologic and water quality (soils and stream chemistry) effects of prescribed burning on the poorly drained coastal plain soils (Binstock, 1978; Richter, 1980; Richter et al., 1983). These authors reported that prescribed burning would have only an insignificant effect on soil and stream chemistry. Monitoring of both of these watersheds was discontinued in early 1982 and was not continued again until November 1989 when Category IV Hurricane Hugo caused appreciable damage to the forests in the region in September 1989 (Hook et al., 1991). Although considerable efforts have been done since then to continuously monitor both the watersheds, flow data for the watersheds were not available for some periods between 1996 to 2002. Soon after Hugo WS 77 was salvage harvested and WS 80 was not harvested. Both the watersheds now contain the vegetation that has naturally regenerated since after Hugo.

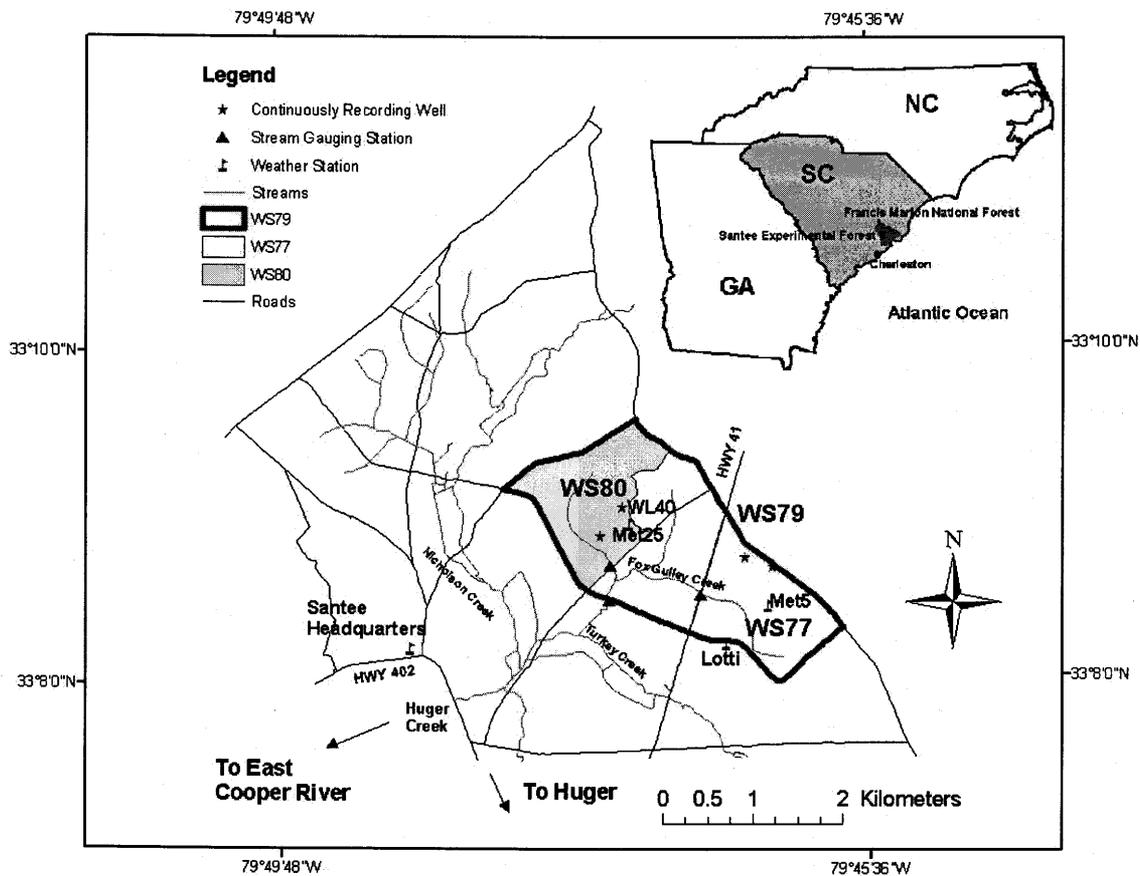


Figure 1. Location of two experimental watersheds (WS 77 and WS 80) and their monitoring stations within Santee Experimental Forest near Huger, SC (After Harder et al., 2006a).

Sun et al. (2000) analyzed the outflows from WS80 for periods from 1976-1980 and 1990 - Oct 1992 and calculated an average annual outflow to precipitation coefficient of 0.30. For the near three-year period after Hurricane Hugo in 1989, which caused appreciable damage to the watershed, their results indicated an increase in annual outflows, which may be due to reduced evapotranspiration (ET) caused by fallen and damaged trees. Using 1989 to 1999 stream flow data from WS 80 and WS 77, Miwa et al. (2003) demonstrated that headwater stream flow was

highly responsive to rain events, and that headwater stream processes are regulated by rainfall intervals, antecedent soil moisture, vegetation, soil types, topography, and surface water storage. While Amatya et al. (2003) compared the hydrology of the control watershed with that of a drained pine forest in coastal North Carolina, Harder et al. (2006a) described its short-term water budget. Recently, Wilson et al. (2006) reported the increased stream outflows and nutrient export for three years after the Hurricane Hugo from the control watershed (WS 80).

This study examines and synthesizes the results on the long-term outflow processes of these two first-order forested watersheds (WS 77 and WS 80) using data from 1964 to 1981 and 1990 to 2005 during which watershed (WS 77) has gone into several anthropogenic treatments and a natural disturbance due to Hurricane Hugo (Table 1). No data was available from 1982 until after Hugo in 1989.

Table 1. Chronology of activities that took place on the watersheds (WS 77 and WS 80),

Year(s)	Description of studies/treatments/disturbances
1963	Watershed WS77 established as a treatment watershed
1968	Watershed WS80 established as a control watershed
1976	Water quality monitoring initiated
1977	20% of the watershed WS 77 burnt using prescribed fire
1977-1979	60% of the watershed WS 77 burnt using prescribed fire in course of three years
1981	Flow and water quality monitoring discontinued on both watersheds
1983	100% of the watershed WS 77 burnt using prescribed fire at various times in a period of five years (1977-81)
1989	Hurricane Hugo damages 80% of forest in September
1989	Both flow and water quality monitoring reactivated in November on watersheds WS 77 and WS 80
1990	WS 77 was salvage harvested (entire vegetation harvested/removed); WS 80 was non-salvage harvested (all roots, stumps, branches left intact on the watershed)
2001	Secondary outlet unplugged reducing WS80 drainage area to 156 ha; Mastication (mowing) of understory vegetation occurred on WS 77 during the period of February to November.
2003	WS 77 undergoes prescribed burning on May 10;
2006	Thinning treatment of whole trees initiated in early July

Site Description

The study site is located at 33.15° N Latitude and 79.8° W Longitude within the Santee Experimental Forest, a part of the USDA Forest Service Francis Marion National Forest near the town of Huger in South Carolina (Figure 1). Both of these headwater watersheds (WS 77 and WS 80) drain the first order streams to Turkey Creek, a tributary of Huger Creek, which drains further down to East Cooper River, a major tributary of Cooper River forming the Charleston Harbor System. The monitoring of both the watersheds was discontinued in May 1982 and was restarted back in November 1989 after the Santee Experimental Forest and the surrounding area including these experimental watersheds experienced the full force of Hurricane Hugo on September 21, 1989. Over 80% of the trees and forest canopy was destroyed and nine long-term studies were prematurely terminated by this storm's passage (Hook et al., 1991).

Common soils in the area are aquic alfisols or ultisols, which typically contain argillic horizons (SCS, 1980). These topographic and soil characteristics indicate a high surface water detention capacity and slow surface water drainage. The climate is mild and wet, with an average temperature of 18.3°C, and an average annual precipitation of 1370 mm (Harder et al 2006).

The preliminary annual water budgets and hydroperiods of these two watersheds for 1976-1980 and 1990-91 have been described Sun et al. (2000), and for 1996-01 by Amatya et al. (2003).

WS 77

This first-order watershed (WS77) of 155 ha area was established first in 1963 with the installation of a flow gauging station at its outlet on Highway 41N (Fig. 2). The water balance of this watershed was first reported by Young (1968). Later this watershed served as a treatment watershed when the second watershed (WS 80) was established as a control. This watershed has received several silvicultural treatments over the past 40 years (Gilliam, 1983; Richter et al., 1983; 1982; Binstock, 1978). This low-gradient watershed with elevations ranging from 9.98 m towards the northwest to about 5.8 m at the outlet (Miwa et al., 2003) drains into Fox Gulley Creek further down to Turkey Creek (Fig. 2). Soils on the watershed are mostly poorly to moderately drained sandy loam to clayey soils with seasonally high water tables (SCS, 1980). Soon after Hurricane Hugo, this watershed underwent a salvaged-harvest where any damaged or fallen trees profitable for timber were removed. Vegetation regenerated since then is comprised of loblolly pine, longleaf pine, and some bottomland hardwoods along the stream riparian bank.

WS 80

WS 80 is a 200 ha watershed established in 1968 with a flow gauging station as a control of the paired system with WS 77 as the treatment. In November 2001, a small part of the watershed in the northeastern corner was allowed to drain separately through a culvert reducing its size to only 156 ha. This is also a low-gradient watershed with elevation range from 4 to 6 m with topography yielding 0 to 3% slopes. The watershed is characterized by somewhat poorly to poorly drained soils. The soils are composed primarily of clayey and fine sediments influenced by seasonally high water tables. Before Hurricane Hugo, the vegetation was mostly old (> 80 yr) loblolly pine (*Pinus taeda* L.). After the hurricane, the watershed remained undisturbed with no timber including the fallen trees removed. The forest vegetation since then has regenerated with loblolly pine and hardwoods predominating. Detailed description of this site and field measurements and past studies are given elsewhere (Harder et al. 2006a; Amatya et al. 2005; Amatya and Radecki-Pawlik, 2005).

Field Data Monitoring

Rainfall

Rainfall has been measured using only a weighing bucket (Gauge # 2) gauge located at Santee Experimental Forest Headquarter since 1946. Data from 1963 till 1990 were used from this gauge whenever available. Missing data were used from the nearby weighing bucket gauge at Lotti Road station (Fig. 1). There were four other manual gauges (# 2, 3, 4, and 5) in and around WS 77 and five manual gauges (# 1, 20, 21, 22, and 23) in and around WS 80 that measured rainfall on a weekly to bi-weekly basis from 1964 till 1982 for estimating the spatial variability. Spatially averaged estimate using Thiessen polygon method (Dingman, 2002) was used for the annual rainfall for 1964-82 period on both the watersheds. Data from these gauges were not available after 1989 for the post Hurricane period. In 1990 automatic tipping bucket rain gauges, Met 05 on WS 77 and Met 25 on WS 80, were installed. However, data from a single automatic gauge on each watershed was used for the post-Hurricane years beginning in 1990. An automatic tipping bucket rain gauge connected to the Campbell Scientific datalogger replaced the weighing bucket gauge at the Santee Headquarter Office in 1996. Data from this gauge was used starting in 1996. However the rain data from the study watersheds was used for the missing periods. All breakpoint data were processed to obtain daily and annual totals.

Stream Flows

Stream flow rates on watershed WS 77 have been estimated using measured stage heights upstream of a compound weir. The weir consists of a metallic 90° V-notch for a height up to 20 cm from the V-bottom to measure low flow rates, after which it expands to 120° to a height of 30 cm from the V-bottom. The weir above 30 cm is an 8 m wide, 140° concrete weir that measures large flow rates. The weir structure on the control watershed (WS 80) is similar to that on WS 77, except that the top weir is a 10 m wide, horizontal weir for accommodating large event outflows. There is a stage recorder located in a concrete blockhouse located on right bank of each of the watershed outlets. All stage data prior to Hurricane Hugo and also from 1989 to 1995 were recorded in magnetic tapes using the Analog-Digital Recorder (ADR), which were digitized at USDA Forest Service Coweeta Hydrologic Laboratory. ISCO automatic flow meters were installed in 1996. Stage data have been collected in 10-minute intervals. Stage discharge relationships were developed by measuring the stage and corresponding velocities at each of the stream outlets in late 60's. These relationships that have been recently verified are being used to compute flow rates using the measured stage heights.

Both watersheds have been continuously monitored using gauging stations (weirs and stream level recorders) since their establishment, except for the 1982-89 period. Also flow data for WS 80 for November 1992 to December 1995 period have yet to be digitized from the old tape system. Similarly, the daily flow data from July 1999 to the end of December 2002 were either not available or there were no flows for most of the days due to the drought in South Carolina (Kiuchi, 2002) and hence not included in the analysis. Data on the daily stream outflow measured between 1969-1981 and 1990-2005 were analyzed for this study. Available measured outflow rates were expressed in mean daily values, which were converted into area-based cumulative total depth. Metadata for flows for the Santee watersheds can be found at the HYDRO-DB web site at <http://www.fsl.orst.edu/climhy/hydrodb/harvest.htm.ologic>

Water Quality

Weekly stream water quality samples were collected by grab sampling method between 1976-1982, 1989-1991, and 1992-1994. The water samples were analyzed for pH, NO₃⁻, NH₄⁺, total N, PO₄²⁻, Cl⁻, K⁺, Na⁺, Ca²⁺, Mg²⁺, and SO₄²⁻. We herein briefly reported the findings from past studies and own results for post-hurricane Hugo effects (1990-94) on watershed WS 80.

Data Analysis

Rainfall data measured at the study sites were available for the entire period from 1964 till date. In this study we analyzed the rainfall from 1964 till 2005 to examine the annual and seasonal variability. Data from 1964 till 1981 were also examined for the spatial variability.

We analyzed the long-term stream outflow data from 1964 till May 2006 breaking them down for six specific periods of interest as shown in Table 2. Stream outflow data was not available from November 1981 till October 1989. Similarly, data from November 1992 to 1995 could not be analyzed, as the data were not yet available for the control watershed (WS 80). Part of beaver affected data in the summer of 2003 (Harder et al., 2006a) was also omitted in this study. Results for the first three periods (1964 to 1981) were summarized based on the past studies. Effects of the treatments were analyzed using a paired watershed approach. (Gilliam, 1983) reported that the watershed WS 77 followed an operational intensive forest management treatments during 1977 to 1981 from prescribed burning (Table 2) to clear-cut harvest in a part of the watershed including phosphorus fertilization and planting of loblolly pine seedlings.

Table 2. Periods for analysis of rainfall and stream outflow data

Period	Description of studies/treatments/disturbances
1964 -1968	Water budget of watershed WS 77; Hydrologic processes
1969 - 1976	Calibration period; Relationship of WS 77 and WS 80
1977 - 1981	Treatment period: Prescribed burning effects
1989 - 1992	Hurricane Hugo effect: Loss of 80% forest canopy
1996 - 1998	Effects of natural growth of forests after Hugo
1999 - 2001	SC Drought; Not analyzed due to little/no outflows or missing data
2002 - 2006	Effects of mastication and understory burning

Annual runoff coefficients (ROC, ratio of annual outflow and rainfall) were computed to compare rainfall normalized stream outflows for both the watersheds. We also analyzed the annual and monthly stream outflows between two watersheds to establish relationships for the calibration period (1969-76). Monthly and annual stream outflows were then compared for each of the four (1977-81, 1989-92, 1996-98, and 2002-06) disturbance and regeneration periods. Daily and cumulative outflows for both the watersheds were compared using graphical and tabular analysis for each of these periods. Effects of these four treatments were analyzed using both a double mass curve as well as regression methods. Relationship of rainfall (R) and storm outflow (Q) was examined for several storm events for these five periods. Although Q is highly influenced by R, characterizing R and Q relationship is difficult since many other factors, such as multiple storm events, complicate a storm outflow hydrograph. In order to simplify the R-Q characterization following criteria were used to identify such events for analysis:

1. A stormflow event consisted of a single peak exhibiting normal rising and falling limb trend. Therefore, a stormflow may include multiple rains as long as a rain does not disrupt normal stormflow pattern.

2. Beginning of a stormflow is sufficiently low, so that no apparent influence from previous storm event is evident. This means that a stormflow event may be excluded if significant rain occurs within 36 hours prior to the flow.
3. Outflow volume on falling limb has to drop to, at least, close to the beginning value, so that simple stormflow-baseflow separation line can be drawn. This means that stormflow events during a wet period (multiple rain and peak flows) are most likely excluded.
4. Only a rain event with an antecedent moisture condition producing a stormflow for both watersheds was selected for comparison purpose.

Results and Discussion

Annual rainfall

Annual rainfall at the study site for the years 1964 to 2005 is presented in Figure 2. Rainfall varied from as much as 1942 mm in 1994 to as low as 969 mm in 2004, with an average of 1396 mm for the 42 years period. The coefficient of variation was 16%. Rainfall was below average in the years 1999, 2000, and 2001, consistent with the drought recorded in entire State of South Carolina (Kiuchi, 2002). According to that report, 2001 was the driest year with a very little stream outflow. Although the drought was broken in late 2002 that followed 2003 with the above average rainfall, year 2004 again recorded the lowest rainfall (969 mm).

In general, months of January and March in the winter and summer months from July to September were wetter months. February, May, and November are relatively dry months.

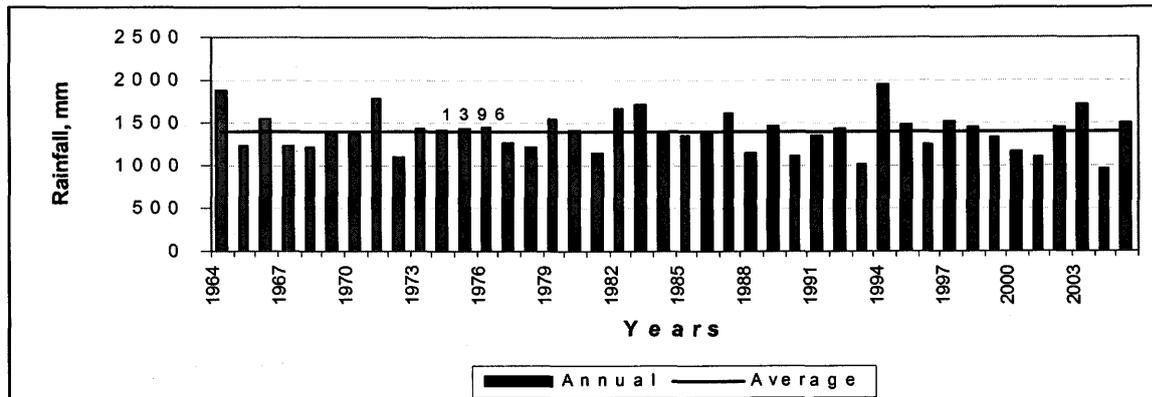


Figure 2. Measured annual rainfall at the Santee Experimental Forest Headquarters.

An example of spatial variability of rainfall on the watershed (WS 77) is presented in Table 3 with their arithmetic average and distribution for the 1967-83 period. Data in Table 4 represent a comparison of arithmetic average and Thiessen's average from all five gauges for each year. Aerial annual rainfall using arithmetic average was only slightly lower than the Thiessen average in most of the years. The variation among gauges in each year was very small with an average coefficient of variation (C.V.) of just 3% (Table 4) compared to the variation within years at each gauge with an average C.V. of 12% (Table 3). However, the difference between gauges was recorded as large as 155 mm in 1979 (Table 4). Most of the large differences between gauges exceeding 100 mm occurred for the years with above average rainfall. Although these data demonstrate that on an annual basis using data from a single gauge may introduce errors in rainfall of as much as 8% compared to using aerial average from five gauges for this relatively flat coastal watershed, larger errors may exist for temporal scales of months and events.

Table 3. Average annual rainfall and their distribution for each of the five gauges on watershed WS 80 for 1967-1983 period.

Gauge	Average Rainfall, mm	Standard Deviation, mm	Coefficient of Variation, %	Minimum Rainfall, mm	Maximum Rainfall, mm	Max-Min Difference, mm
1	1359	168	12	1115	1711	596
20	1429	170	12	1182	1795	613
21	1371	168	12	1110	1680	570
22	1384	183	13	1124	1729	605
23	1372	170	12	1133	1686	553
TOTAL AVERAGE	1383		12			

Table 4. Annual rainfall using arithmetic average and their distribution for five gauges. Average is also compared to the spatial average by Thiessen polygon method.

YEAR	Average Rainfall, mm	Standard Deviation, mm	Coefficient of Variation, %	Thiessen Average Rainfall, mm	Minimum Rainfall, mm	Maximum Rainfall, mm	Max-Min difference, mm
1967	1178	20	2	1189	1156	1202	46
1968	1238	48	4	1247	1195	1319	124
1969	1448	20	1	1450	1431	1484	52
1970	1386	47	3	1383	1347	1461	114
1971	1720	46	3	1715	1680	1795	114
1972	1189	62	5	1189	1148	1298	150
1973	1487	60	4	1491	1434	1589	154
1974	1404	34	2	1399	1369	1457	88
1975	1432	37	3	1440	1401	1495	95
1976	1493	46	3	1503	1461	1570	110
1977	1215	28	2	1217	1177	1250	74
1978	1206	32	3	1200	1168	1257	89
1979	1563	64	4	1563	1494	1649	155
1980	1350	32	2	1359	1312	1396	84
1981	1133	29	3	1138	1110	1182	72
1982	1606	61	4	1609	1538	1663	126
1983	1471	51	3	1469	1410	1541	131
TOTAL AVERAGE	1383		3				

Annual Rainfall, Annual and Monthly Stream Outflows

1964-1968 period

Based on a three-year (1964-1966) data the Young (1968) reported that the stream outflow on this poorly drained watershed is influenced quite strongly by the moisture storage capacity of the soil prior to rainfall. Two of their three years had higher than average rainfall (Fig. 2) and 20% of its annual rainfall was calculated as storm outflow. The runoff coefficient for the four-year (1965-68) period varied from 16% in 1968 with 1225 mm of rainfall to 33% in 1966 with 1554 mm of rain, with an average of 24%.

1969-1976 period

Measured annual stream outflows for the 1969 to 2005 period (except for 1982 to 1989, 1993 to 1995 and 1999 to 2002) are compared for the watersheds WS 77 and WS 80 in Figure 3. Annual precipitation and stream outflows for the 1964 to 1976 period was first analyzed and reported by (Binstock, 1978). The author reported the average annual precipitation of 1369 mm for the 1964-76 period using a Thiessen method with spatially distributed gauges around WS 77. This was about 4% lower than the average of 1424 mm obtained using a single gauge data at Santee Experimental Forest station (Fig. 2). Stream outflow averaged 380 mm during the 1964-76 for the treatment watershed WS 77 with an average annual runoff coefficient of 26.7% and 295 mm for the period of 1968-76 for the control (WS 80). The annual outflow in 1977 (Rain = 1274 mm) measured for WS 77 after 20% burning in early 1977 was 180 mm (ROC = 14%), which was 28% higher compared to 141 mm (ROC= 11%) for the control (WS 80).

For the calibration period of 1969-76, the treatment watershed (WS 77) consistently yielded higher annual outflows than the control (WS 80) with an average increase of 41%. Annual runoff coefficient (ROC) varied from 15.8% in 1972 to 27.8% in 1971 with an average of 19.8% for the control watershed (WS 80) compared to 20.8% to 41.4% with an average of 27.9% for the treatment watershed (WS 77). A strong relationship between annual outflows of these two watersheds ($Flow_{77} = 1.42 Flow_{80}$; $R^2 = 0.93$, $p < 0.001$) was obtained. Richter (1980) noted several possible reasons for this difference in outflows such as differential deep seepage, large vegetational differences affecting ET, incorrect hydrologic boundaries including flow calibration. Richter (1980) and Gilliam (1983) also found that the difference in outflows between WS 77 and WS 80 increased with outflows and WS 80 exceeded the WS 77 flow only in rare occasions.

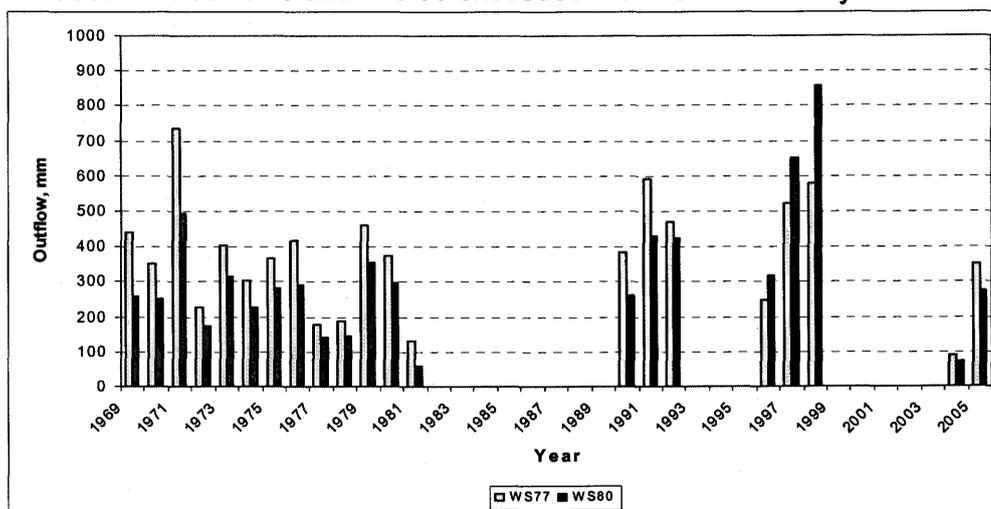


Figure 3. Measured annual stream outflow for watershed WS 77 and WS 80 for the 1969-1981, 1990-92, 1996-98, and 2003-05 periods.

Monthly outflows for both the watersheds are compared for the 1969-76 period in the top panel of Figure 4. Stream outflows were consistently higher by as much as 127 mm in August of a very wet year 1971 (rain = 1776 mm) for WS 77 than on WS 80. Data showed that the increase was larger for higher outflows than for the smaller values, possibly due to increased surface runoff on this watershed compared to the control (WS 80). This is also indicated by the regression relationship ($\text{Flow}_{77} = 1.38 \text{Flow}_{80} + 0.76$; $R^2 = 0.90$; $p < 0.001$) (Fig. 5). However, there were no outflows on both the watersheds during some months of dry season (May to October). The average monthly outflow for this period was 34 mm on WS 77 compared to 24 mm for the control (WS 80).

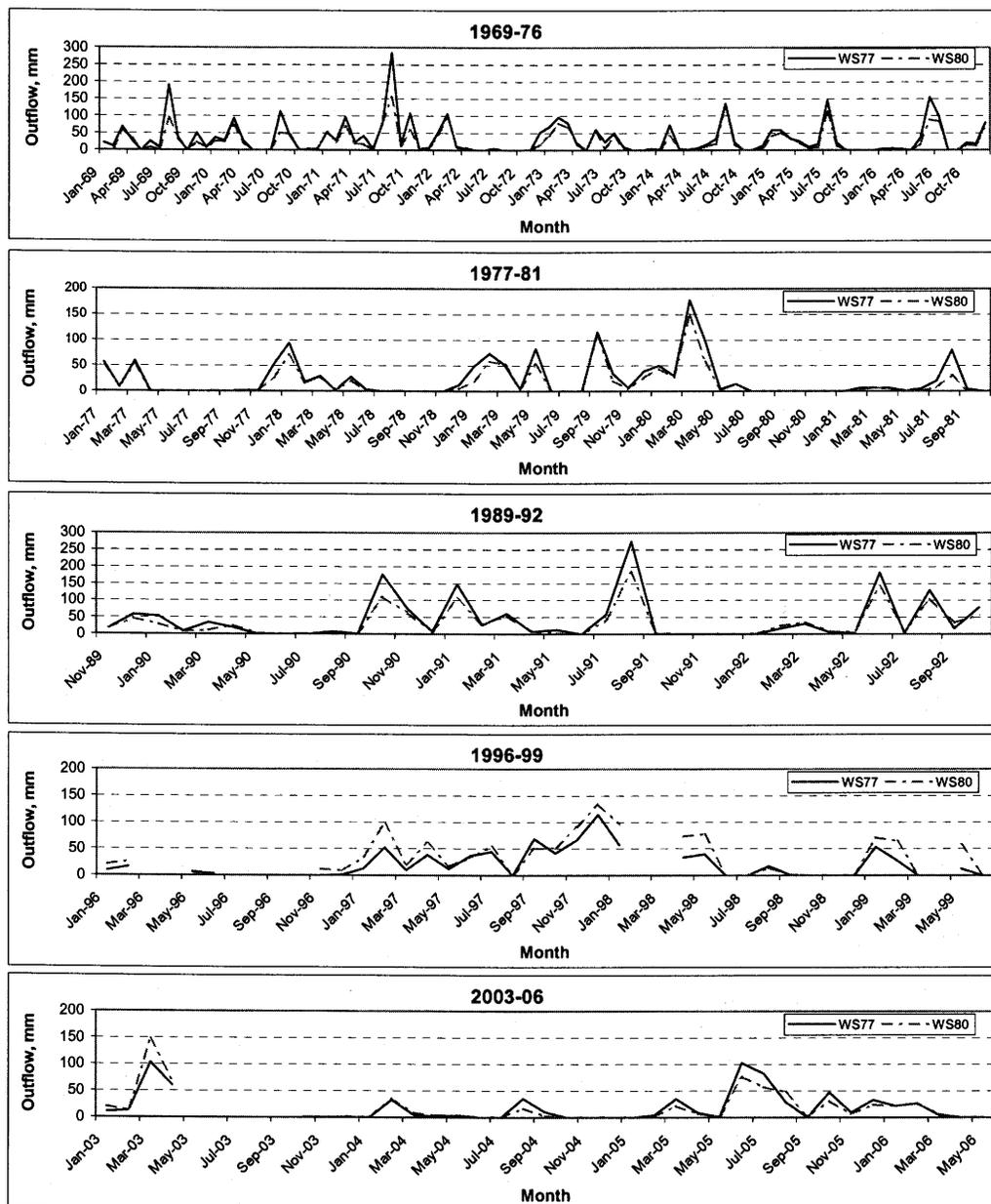


Figure 4. Measured monthly stream outflow for watershed WS 77 and WS 80 for the 1969-1981, 1990-92, 1996-98, and 2003-06 periods.

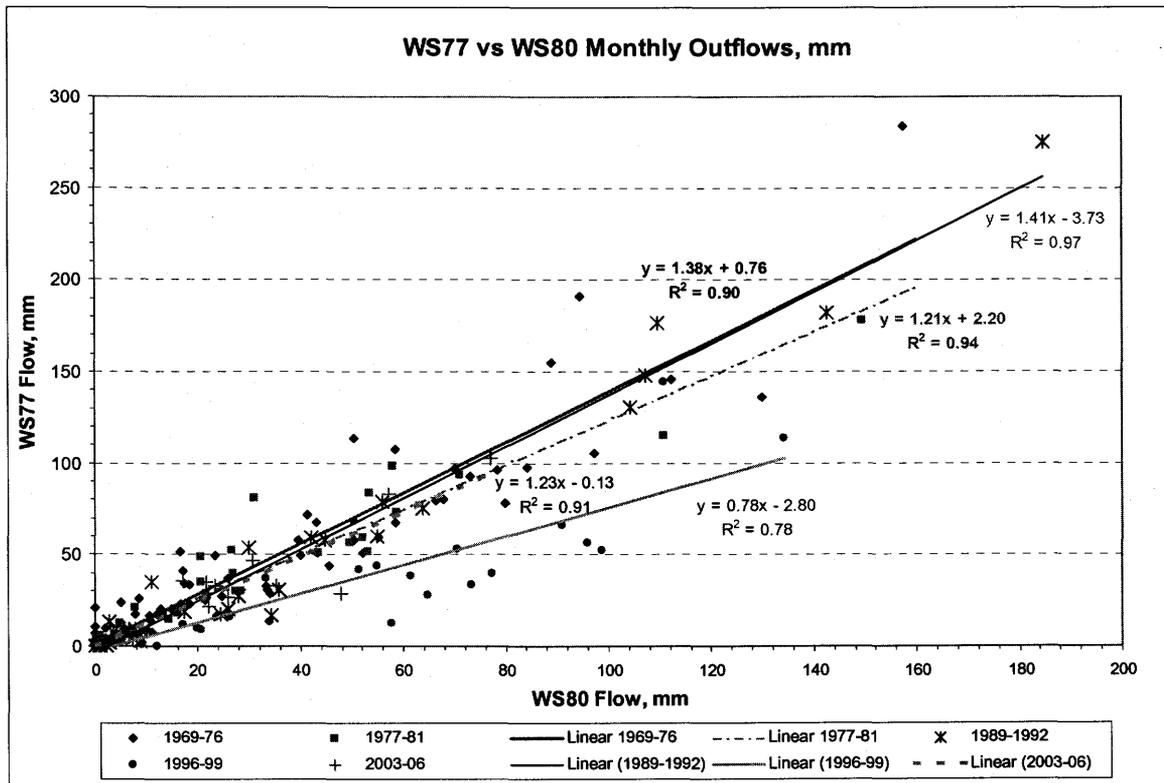


Figure 5. Measured and regression lines of monthly stream outflow for watershed WS 77 and WS 80 for the 1969-76 (calibration), 1976-1981, 1990-92, 1996-98, and 2003-06 periods.

1977-1981 period

Annual outflows for the two watersheds from 1977 to 1981 (Fig. 3) indicated a similar pattern as in the calibration years of 1969-76 with higher outflows for the watershed WS 77 that underwent various treatments of prescribed fire and harvest during this period (Table 2). But the average annual outflow of 267 mm on the treatment watershed (WS 77) was only 35% higher than 200 mm for the control (WS 80), indicating that the 28% increase in ROC for 1977 immediately after 20% burning (Binstock, 1978) had no effects on annual stream outflow. The average ROC of 19% on the treatment watershed (WS 77) was only 35% higher than that of 14% for the control (WS 80). The lower values of slopes obtained for the regression line of the annual outflows ($\text{Flow}_{77} = 1.29 \text{ Flow}_{80}$; $R^2 = 0.96$, $p < 0.001$) (not shown) as well as the monthly outflows (slope = 1.21) in this period compared to the calibration (slope = 1.38) (Fig. 5) also confirm this. These treatment effects on stream outflows were not as significant perhaps because the treatments did not occur at one time, rather occurred periodically throughout the five-year (1977-81) period. Moreover, the rainfall during this period was relatively lower (average = 1323 mm) (Fig. 2) compared to the 18-year (1964-81) average of 1396 mm. This resulted in much reduced outflows with less than 15% ROC in three (1977, 1978, and 1981) out of five years. On a monthly basis, there were many months without outflows during this five-year period (Fig. 4, 2nd panel), with an average monthly outflow of 23 mm for WS 77 compared to only 17 mm for the control (WS 80).

Gilliam (1983) reported nearly an 8% increase in water yield as a result of forest cutting in one single compartment of the watershed. The author also found nearly identical percent change (pre- to post-harvest) between WS 77 and WS 80 in low and intermediate flow classes. Their data showed 35% increase in weekly post-harvest outflows for the treatment watershed WS 77 in the 1.0 liters $\text{sec}^{-1} \text{ ha}^{-1} \text{ week}^{-1}$ class compared to only 17% increase for the control (WS 80),

indicating that tree harvesting primarily affects higher (peak flows) and not lower base flows. The outflows from WS 77 returned to pre-harvest levels within one-year after cutting, probably due to the result of rapid re-establishment of herb layer vegetation with consequent reduction in surface runoff and recovery of ET rates to near pre-harvest levels. Amatya et al. (2006) found similar results for the peak flow rates but they reported six years of time period before the hydrology of a harvested pine forest returned to base line levels in eastern North Carolina.

The daily cumulative outflows for the control (WS 80) and the treatment (WS 77) watersheds for all five treatment periods are compared using double mass curves (Figure 4). The cumulative outflow curve for the calibration (1969-76) period (thick black) has the steepest slope much above 1:1 line (dotted green) indicating a much larger rate of response from the treatment watershed (WS 77) than the control. The fact that the curve for this treatment (thin pink) during 1977-81 fell below the calibration period (blue color) but above the 1:1 line still shows higher outflows from WS 77 than WS 80 but with a reduced rate of increase than during the calibration. This clearly indicates that the treatments during this period had no effects on stream outflow.

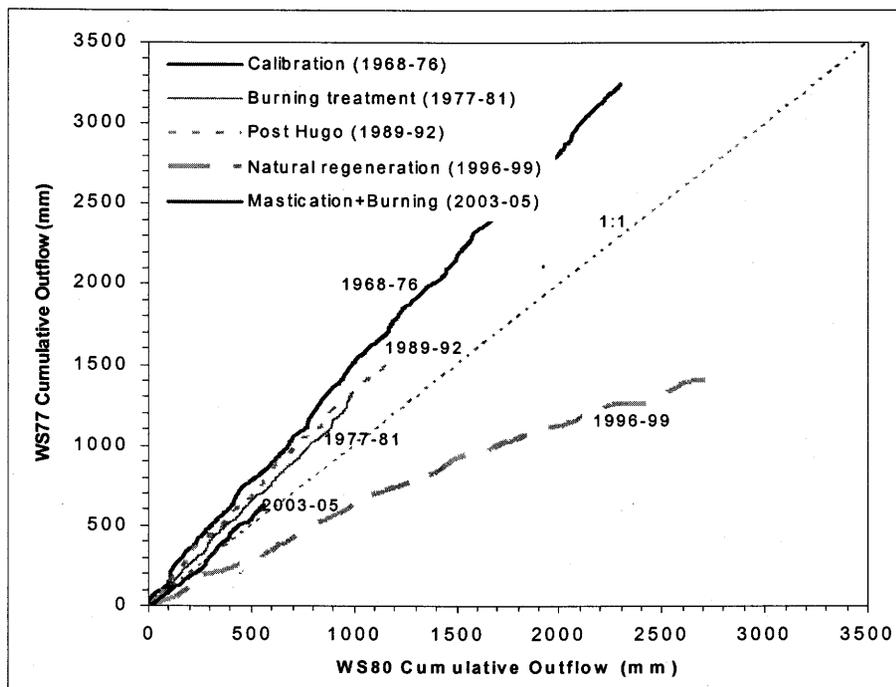


Figure 6. Double mass curves for watershed WS 77 and WS 80 for five different treatment periods (1969-76, 1977-81, 1989-92, 1996-99, and 2003-05).

1989-1992 period

The period of 1989-92 was a post Hurricane Hugo period when vegetation canopy on both watersheds were damaged badly by hurricane-force winds. The annual outflow for the treatment watershed that was salvage harvested varied from 385 mm in a relatively dry year 1990 (rain = 1122 mm) to as much as 594 mm in a relatively average year 1991 (rain = 1352 mm) with an average of 483 mm (Figs. 2 and 3). Accordingly, the annual ROC varied from 33% to 44% with an average of 37%. Similarly, the ROC for the control watershed (WS 80), which was not salvage harvested varied from 23% to 32% with an average of 28%. Compared to the calibration period (1969-76), the average annual ROC increased by 33% and 43% for the treatment (WS 77) and the control (WS 80) watersheds, respectively. Sun et al. (2000) also made similar observations. This increase in outflows was attributed to the decrease in evapotranspiration (ET) as a result of loss of about 80% forest canopy due to Hurricane Hugo.

The monthly outflow pattern was similar to the previous periods with higher outflows on WS 77 compared to the control (Fig. 4, 3rd panel). Most of the earlier months in 1990 had low or zero outflows. The fact that the post-Hugo slope of regression line (1.41) of monthly outflows between these two watersheds was only slightly higher than that (1.38) for the pre-Hugo years (Fig. 5) indicates that the increase of the flow rates on WS77 was slightly higher than that on WS 80, which may well be insignificant. The double mass curve in Figure 4 shows that the rate of increase in outflows on WS 77 compared to WS 80 for this period was lower than during the calibration. For example, the cumulative outflow of 1527 mm on WS 77 in this three-year period (1990-92) was almost the same as the total of 1524 mm for the first three-year of the 1969-76 calibration period whereas the outflows from WS 80 was 1178 mm in this period compared to 1005 mm for the first three-year of the 1969-76. This might be perhaps explained by faster rate of vegetation (pine trees) recovery on WS 77, which was salvage harvested. Miwa et al. (2003) also reported that the differences in daily peak flow between the two watersheds decreased by 1992, perhaps due to a result of vegetation recovery on WS 77. A closer look at the monthly outflows (Fig. 4) also shows this trend with higher outflows on WS 80 than on WS 77 for values below 50 mm. A recent study conducted by Wilson et al. (2006) to examine the post-hurricane effects of Hugo on the outflows and nutrient export from the control watershed (WS 80) showed similar results. Five years (1976-81) of data eight years prior to and five years (1989-94) immediately after the hurricane were used as pre- and post-disturbance data, respectively, for the evaluation. It was concluded that the post-hurricane annual increase of as much as 133 mm outflow (or 44 %) at least up to three years after the hurricane was most likely due to the loss of healthy vegetation canopy and the subsequent decrease in evapotranspiration. Data indicates that the system studied herein recovered much faster after its salvage harvesting than some upland watersheds in western North Carolina (Sun et al., 2004).

1996-1999 period

All years, except for 1996, had higher rainfall than the average in this period (Fig. 2) and especially 1997 had the highest rainfall (1512 mm). Surprisingly, annual outflows shown in Figure 3 for this period show a reverse trend from the previous periods with the control watershed (WS 80) yielding consistently higher outflows than the treatment (WS 77) for all three years. Accordingly, the annual ROC for WS 80 in 1997 and 1998 were 43% and 59%, respectively, compared to only 35% and 40% for the treatment (WS 77). However, unfortunately, data for the control watershed (WS 80) from November 1992 to 1995 have not yet been available for examining when this reversal, if any, might have occurred. Furthermore, data for 1996 was not complete with only 233 days for WS 77 and 249 days for WS 80 as seen from the monthly plots in Figure 4 (4th panel), and hence not included in annual ROC calculation. We also speculate that data for four large events that occurred on WS 80 in February and March of 1998 (*La Nina* effects) with much higher outflows than the rainfall amount might have been in error contributing to the very high ROC of 59% for that year. Monthly outflows were almost consistently higher on the control (WS 80) than the WS 77 as shown by the difference of monthly outflows between the two watersheds in Figure 7. This was also evident from the regression slope of 0.78 compared to 1.38 for the 1969-76 for the calibration and 1.40 for the post-hurricane period (Fig. 5). The cumulative mass curve in Figure 6 clearly demonstrated the reversal of flow response between these watersheds with the curve well below the 1:1 line. We speculate that the vegetation on WS80 that was not salvaged after Hugo had more hardwood stands left than on WS 77 that was salvage logged and had large areas of immature pine trees. We showed earlier that in later part of 1989-92 period outflows from the control (WS 80) was tending to be higher than from the treatment (WS 77) after the effects of Hugo perhaps due to faster recovery of pine trees with increased ET rates on the treatment watershed (WS 77). Past studies have shown that forests with pine trees have increased ET rates than those with the hardwoods (Swift et al., 1975). However, for an accurate determination of effects of

recovery of vegetation since after Hurricane Hugo on both of these watersheds, data for the 1992-95 period must be closely examined possibly together with ground water level data.

2003-2005 period

Rainfall amount of 1720 mm recorded in 2003 was well above average whereas the year 2004 recorded below average rainfall of 969 mm (Fig. 2). Year 2005 also recorded above average rainfall of 1505 mm. However, because of a prolonged period with reduced rainfall from October 2003 to early spring of 2004 (Harder et al., 2006), annual outflow in 2004 was only 89 mm from WS 77 and 73 mm on the control (WS 80) (Fig. 3). Estimated annual outflow for the control watershed (WS 80) in 2003 was 784 mm yielding a ROC of nearly 46%. But the outflow data for 2003 were not shown for both the watersheds as the data for the control were not complete for the whole year, as beavers affected flow measurements from May 15 to September 30. This was also the period with large outflows due to very wet rain events (Harder et al., 2006). The trend of outflows with higher values from the control watershed (WS 80) than the treatment watershed observed in 1996-99 period was still persisting from January to April 2003 just before the prescribed burning was conducted on May 10, 2003 (Fig. 4). No data from July 1999 to September 2002 was available either due to drought (Kiuchi, 2002) or missing data (Fig. 7). Sporadic data available from October 2002 to December 2003 also indicated higher outflows on WS 80 than on WS 77. This indicates that the effects of mastication (mowing of understory vegetation), if any, performed during the course of February to November 2001 had already diminished by late 2002 due to regrowth of the vegetation. The outflows from October to December in 2003 were very small on both the watersheds but the trend was still similar to early 2003 with higher values on WS 80 than on WS 77 (Fig. 4). However, both the monthly and annual outflow data for 2004 and 2005 (Figs. 4 and 5) showed opposite flow pattern again similar to that observed before (1969-81) and immediately after Hurricane Hugo (1989-92), indicating possible effects of burning on reduction of ET. This reversal trend is even more clearly depicted in Figure 7 with the plot of difference in monthly outflows between WS 80 and WS 77 for the 1996-06 period.

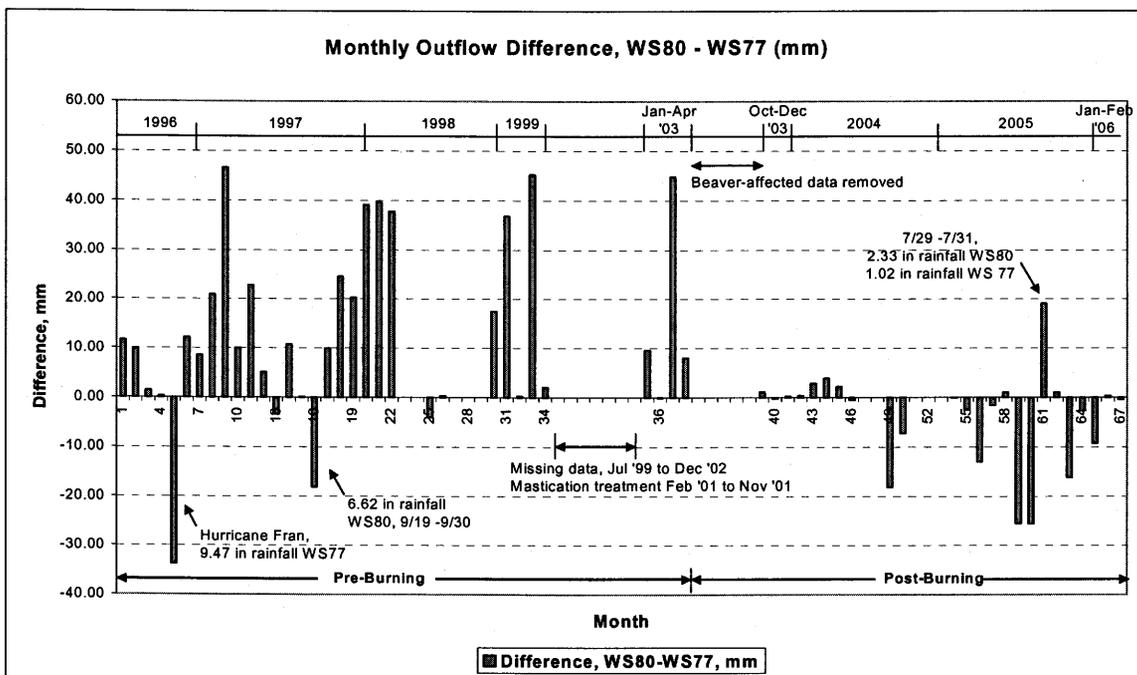


Figure 7. Double mass curves for watershed WS 77 and WS 80 for five different treatment periods.

As a result the measured annual outflows in 2004 and 2005 were 56% and 70% higher than the expected values obtained using the relationship (with zero intercept) found with data from the regeneration period (1996-99) (Fig. 5). The substantially higher regression slope of 1.23 for this period compared to 0.78 for the regeneration period (1996-99) also supports this result (Fig. 5). The double mass curve indicates a pattern of cumulative flow relationship very different from the 1996-99 period with all data lying almost along 1:1 line (Fig. 6). However, no effects of burning on annual outflows was found when compared with calibration relationship from 1969-76 period before the Hugo. This observation again depends upon the reality of the flow relationship found between these two watersheds for the 1996-99 period.

Event total rainfall and stream outflow

During the large storms Young (1968) found as much as 70% of the rainfall lost to storm outflow, and runoff values between 50% -70% of rainfall were not unusual. These stream flows occurred when the water table was near the soil surface. On the other hand rain storms as large as two inches have produced no storm-flow on the watershed when the water storage potential of the soil was high prior to rainfall. Their results also showed that excess water in the form of runoff could be problematic in downstream flooding, and that there was no dependable base-flow generated from this undrained watershed.

Two examples of storm event stream outflow and rainfall relationships using data from single peaked events and the fitted regression lines for those data for the control (WS 80) and treatment (WS 77) watersheds are presented in Figure 8 for pre- and post-Hugo periods.

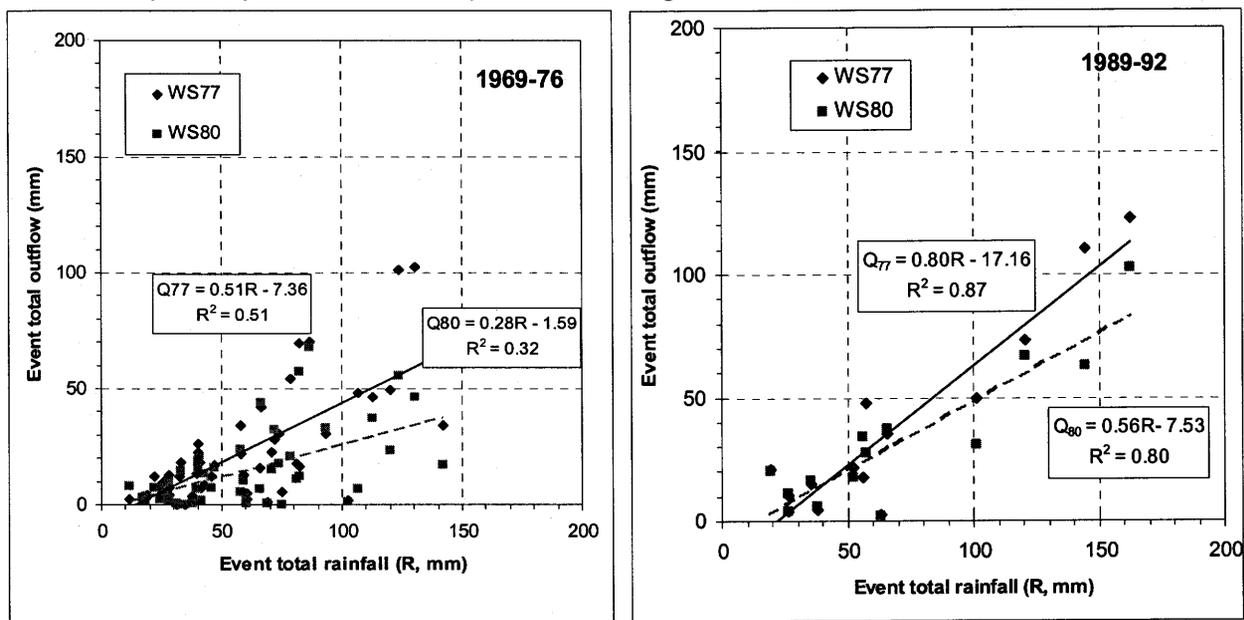


Figure 8. Event outflow versus event total precipitation for selected single peak stormflow events for watershed WS 77 and WS 80 for 1969-76 and 1989-92.

As observed in previous sections, the response of WS 77 to the rainfall was 82% higher than that for the control watershed (WS 80) for the pre-Hugo calibration period (1969-76) as shown by the regression slopes of 0.51 for WS 77 and 0.28 for WS 80. The storm response increased dramatically on both watersheds for the post-Hugo period (1989-92), especially WS 80 had its slope doubled. As a result, the response of WS 77 was only 43% higher than that for the control watershed (WS 80) as indicated by the regression slope of 0.80 for WS 77 compared to only 0.56 for WS 80. These slopes indicated that approximately, 80% and 56% of large rain

events were discharged as stream outflow for WS 77 and WS 80, respectively. The X-axis intercept was also larger for WS 77 (21.5 mm) than that of the WS80 (13.5 mm) for the post-Hugo period (1989-92). In other words, R less than 21.5 mm on average for WS 77 and 13.5 mm for WS80 may not have directly contributed to storm outflow. This characteristic, a water storage potential, might have been influenced by many physical properties of the watershed such as canopy and surface storage, soil type and depth, antecedent soil moisture, mean water table, watershed shape. These data showed that the hydrology of these low-gradient coastal plain first-order watersheds was sensitive to rain events and ET, and that stormflow generation response was rapid (Fig. 8) as the saturation spreads to large areas almost simultaneously, especially during the wet seasons with high water tables. For instance, four large events (daily outflow above 10 mm) recorded in July and August 1991 were the result of an immediate response to 89, 76, 58, and 62 mm storm events. Frequent rain events during periods with low evapotranspiration demands, such as January 1991, also caused relatively constant high stream outflow. Headwater stream outflow was also strongly affected by antecedent soil moisture, *i.e.*, preceding weather conditions. Between May and August 1990, relatively strong storm events of >20 mm size were recorded on May 10, May 27-28, June 15, July 1, July 14, and August 7. However, the outflow during the same period was less than 1 mm, and there was no flow between mid-June and mid-August. This indicated that occasional rain events during the summer do not exceed the soil water holding capacity with antecedent soil moisture content created by high ET demand, including canopy interception losses.

Miwa et al (2003) reported that the storm peak flows on these watersheds were significantly affected by vegetation type. Detailed observations of hydrograph patterns between November 1989 - April 1990 and April 1992 - September 1992 revealed that peak flow rate of WS77 were typically higher than WS80, although watershed area of WS77 was smaller than that of WS80 (160 ha and 200 ha, respectively). WS77 contained a larger portion of pine trees and had more extensive damage from Hurricane Hugo compared to WS80. Most of WS80 was covered by undisturbed, mature hardwoods, which experienced less hurricane damage compared to WS77. The differences in peak flow rates between the two watersheds decreased in 1992. This may be due to a result of vegetation recovery in WS77. However, further study would be needed to ascertain the actual effects of vegetation on peak flow rates. This could be accomplished using additional data from the 1992-95 periods of the watersheds as pointed out earlier.

Annual water budget

Young (1968) described the water budget of the first-order forested watershed using three years of measured data on WS 77, and reported an average stream flow of 38% (590 mm) of the annual rainfall and an average ET of 950 mm for the treatment watershed (WS 77). However, on a longer term basis, Richter (1980) found an average annual runoff coefficient (ROC) of only 27% (with a range of 15% to 43%) leaving the remaining 73% for ET losses for a period from 1965 to 1978 for watershed, WS77, while an average ROC of 20% (with a range of 12% to 30%) with the remaining 80% for the ET was found on the control watershed, WS80, for a period from 1970 to 1978. Similarly, Gilliam (1983) estimated the average annual stream outflow and ET for WS 77 as 350 mm and 1030 mm, and for WS 80 as 260 mm and 1133 mm, respectively, for the treatment period of 1977-81.

Sun et al. (2000) reported an average annual ET loss of 70% and 77% of total precipitation for these watersheds WS77 and WS80, respectively. Recently, Harder et al. (2006a) described a short-term water budget for the control watershed (WS 80) for a very wet year (2003 with rain = 1671 mm) and a relatively dry year (2004 with rain = 962 mm). The authors found 47% and 8% of the rainfall lost to stream outflow in 2003 and 2004, respectively. The estimated ET of 906 mm and 834 mm were 54% and 87% of the annual rainfall for 2003 and 2004, respectively.

These numbers are consistent with many other water balance studies conducted on the southeastern coastal plain forested lands that show that 60-80% of annual water loss is due to evapotranspiration (Chescheir et al., 2003; Amatya et al., 2002; Amatya et al., 1996; 1997; Sun et al., 1998; Skaggs et al., 1991). In a companion study, Harder et al. (2006b) used DRAINMOD (Skaggs, 1978) to simulate the long-term (1956-2004) water budget of the control watershed (WS80). They found the simulated annual stream outflow varying from 2% to 50% with an annual average of 21% leaving remaining 79% for ET and seepage losses.

Water Quality

Gilliam (1983) reported that the prescribed fire, a common practice in the management of these forests, was found to have no detectable effects on water quality when administered over a six-year sequence of winter and summer burns (Table 2). Based on a 4-year (1976-79) data, Richter et al (1983) found the annual deposition rates of 2.3 kg ha⁻¹ and 0.12 kg ha⁻¹ for total inorganic nitrogen (TIN) (NH₄ -N plus NO₃ -N) and PO₄, respectively, on these sites. However, using longer period of data (1976-81), Gilliam (1983) reported only 1.71 kg ha⁻¹ for TIN and about the same (0.13 kg ha⁻¹) for PO₄. Both the studies reported an insignificant change in nutrient export after the treatments on WS 77 during these years, with TIN retained more (1.68 kg ha⁻¹) in the system than the PO₄ (1.68 kg ha⁻¹).

Binkley (2001) presented results of 10 years (1976-81 and 1989-94) of data from the control watershed (WS 80) that included 5 years of post-hurricane Hugo data in the context of data from several other streams draining forested watersheds in the nation. The author reported that NO₃-N concentrations of stream water on these watersheds were very low, averaging 0.017 mg L⁻¹, with a median of 0.009 mg L⁻¹, with higher values tending to occur in winter and early spring than in summer. However, NH₄-N concentrations were more than double those of nitrate, averaging 0.045 mg L⁻¹ with a median of 0.030 mg L⁻¹. Ammonium concentrations declined with increasing stream flow although the later did not have effect on NO₃-N concentrations. Dissolved organic nitrogen (DON) concentrations were an order of higher magnitude than the dissolved inorganic nitrogen (DIN). DON averaged about 1 mg L⁻¹ with a median of 0.8 mg L⁻¹. Phosphate (PO₄) concentrations average 0.028 mg L⁻¹, with a median of 0.017 mg L⁻¹. Increase in flow slightly declined the PO₄ concentrations. No effect of the massive hurricane disturbance was apparent, except for NH₄-N, if any. The concentrations observed on this watershed were consistent (lower DIN, PO₄ and higher DON) with those from other southeastern forested watersheds dominated by conifers (Chescheir et al., 2003).

Wilson et al. (2006), in their study of post-Hurricane effects on nutrient exports on the control watershed (WS 80), concluded that the large increases in NH₄-N and TKN loadings up to two years after the hurricane were primarily due to increase in stream outflows.

Summary and Conclusion

This study summarizes long-term (1964-2006), but intermittent, rainfall, stream outflow, and nutrient data collected on two first-order forested watersheds located at USDA Forest Service's Santee Experimental Forest, which is the headwater of rapidly developing Cooper River basin draining to Charleston Harbor system. The first one (WS 77) was established in 1963 to understand the hydrologic processes and water budget of this poorly drained coastal forest system. Later the second watershed (WS 80), adjacent to WS 77, was established in 1968 as a control to study the effects of various silvicultural operations on the hydrology and water quality using a paired watershed approach. While WS 77 underwent several management treatments during the study period, both the watersheds were severely damaged by Hurricane Hugo in

1989. Thus this study analyzed the rainfall dynamics and its effects on stream outflows, which were further affected by both the management treatments and a natural disturbance.

Annual rainfall for the 42 years (1964-05) varied from 1942 mm in 1994 to 969 mm in 2004, with an average of 1396 mm. Stream outflow on these poorly drained forested watersheds was highly variable with flooding in some seasons and with or a very little flow at other times. It was very dependent upon rainfall, ET and the antecedent moisture conditions (soil storage capacity prior to rainfall). Rainfall-runoff analysis for both the annual and monthly periods showed no effects of prescribed burning and partial harvest treatments implemented during five years (1977-81) on the treatment watershed. Similarly, these treatments were shown to have no or very little effects on stream water chemistry. Data from pre- and post-hurricane Hugo showed as much as 44% increase in annual yield on the control watershed due to reduced ET as a result of substantial damage of forest canopy. Hurricane Hugo did not affect on stream nutrient concentrations, except for DIN, which was lower by an order of magnitude than the organic N for both the pre- and post-Hugo periods. The increased nutrient loadings after Hugo were attributed primarily to increase in stream outflows, which lasted for only three years in contrast with the upland watersheds with a much longer recovery period. The treatment watershed (WS 77) also yielded increased outflows after Hugo.

Interestingly, limited data for the period during 1996-99 after Hugo showed a reversal in stream outflow pattern with increased outflows as percent of annual rainfall from the control watershed (WS 80) compared to the treatment (WS 77). The fact that this trend was visible from about late 2002 continued until early 2003 shows no evidence of effects of masticating the understory vegetation that occurred during a nine-month period in 2001 on WS77. However, data for 2004 and 2005 shows the reversal of outflows back to the pattern observed during the calibration period prior to Hugo, when the treatment watershed yielded higher outflows than the control. This was possibly attributed to reduction in ET due to both the prescribed fire treatment on 84% of the watershed on May 10, 2003 and possibly some minor effects of mastication in 2001.

Synthesis of results from various phases of studies using the long-term data on these two headwater coastal forested watersheds provided some important insights on their hydrologic processes (rainfall, outflow, and ET) and nutrient exports and the effects of operational forest management (e.g. prescribed burning) as well as a natural disturbance (hurricane) affecting vegetation dynamics on poorly drained lands. However, this study clearly emphasized a need of uninterrupted long-term and good quality data for an accurate assessment of management treatments as we recognized here the complication of analysis and results the missing, bad and/or unavailability of some continuous data (e.g. 1982-89, 1992-95, and 1999-02) have created. In any case on the basis of the results observed herein, we made three important observations that may need further investigation: (a) hurricane-force winds can damage the forest and its canopy to the extent that the outflows and nutrient transport are significantly increased primarily due to reduction in ET, (b) whether the category IV hurricane Hugo in 1989 and subsequent logging after the hurricane impacted the forested watersheds to the extent that the newly regenerated vegetation on both the watersheds behaved differently than how they did prior to Hugo in 1969-76 (calibration period), and (c) operational forest management using prescribed burning, especially when such a treatment occurs at once in a scale of the watershed WS 77 (160 ha) as was done in May 2003, may increase the stream outflows for a short term. The last observation may also be further verified using measured ground water table data on these watersheds as the ground water table generally tends to rise after the removal of vegetation reducing ET and increasing storm outflows.

The results of this synthesis can be a basis for long-term reference data on poorly drained forested lands in this region. For example, flow and water quality data from WS 80 are being utilized as a baseline for calculating reference watershed loads needed for TMDL (Total

Maximum Daily Load) development for the Charleston Harbor System (Silong et al. 2005). Similarly, information from these watersheds is being used for a larger watershed-scale cumulative effects study on a near-by 5000 ha Turkey Creek watershed located mostly within Francis Marion National Forest. At the same time these results will be used for validating data being collected on a new study to examine the effects of biomass removal using commercial thinning in the first year followed by a prescribed fire in the second year both on a plot and a watershed scale on these watersheds (Trettin et al., 2005). Efforts are also underway to digitize the old data from the watersheds for the 1993-95 period that may help verify the speculations made for faster recovery of pine dominated vegetation on the treatment watershed (WS 77) compared to the control (WS 80), increasing the ET rates on the former with subsequent reductions on outflows, a pattern observed opposite prior to the hurricane Hugo on these watersheds. Similarly, the stream water quality data collected since 2003 may help explain whether the chemistry has changed due to the vegetation since its fast recovery, as data were not available after 1994.

Acknowledgements

The authors would like to acknowledge the support of the USDA Forest Service, Center for Forested Wetlands Research for this study. Thanks are also due to Bray Beltran, graduate student of College of Charleston, for helping in processing and analyzing rainfall data.

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