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Hurricane impacts on a pair of coastal forested watersheds: implications of selective hurricane damage to forest structure and streamflow dynamics

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Abstract

Hurricanes are infrequent but influential disruptors of ecosystem processes in the southeastern Atlantic and Gulf coasts. Every southeastern forested wetland has the potential to be struck by a tropical cyclone. We examined the impact of Hurricane Hugo on two paired coastal watersheds in South Carolina in terms of stream flow and vegetation dynamics, both before and after the hurricane's passage in 1989. The study objectives were to quantify the magnitude and timing of changes including a reversal in relative streamflow-difference between two paired watersheds, and to examine the selective impacts of a hurricane on the vegetative composition of the forest. We related these impacts to their potential contribution to change watershed hydrology through altered evapotranspiration processes. Using over thirty years of monthly rainfall and streamflow data we showed that there was a significant transformation in the hydrologic character of the two watersheds – a transformation that occurred soon after the hurricane's passage. We linked the change in the rainfall-runoff relationship to a catastrophic shift in forest vegetation due to selective hurricane damage. While both watersheds were located in the path of the hurricane, extant forest structure varied between the two watersheds as a function of experimental forest management techniques on the treatment watershed. We showed that the primary damage was to older pines, and to some extent larger hardwood trees. We believe that lowered vegetative water use impacted both watersheds with increased outflows on both watersheds due to loss of trees following hurricane impact. However, one watershed was able to recover to pre hurricane levels of canopy transpiration at a quicker rate due to the greater abundance of pine seedlings and saplings in that watershed.

1 Introduction

The role of vegetation in production of runoff from forested areas has been a topic of interest since Pliny the Elder wrote on the subject in the first century AD (Andreassian, 2004). Much of our understanding has come from paired watershed experiments done over the last century (Andreassian, 2004; Ice and Stednick, 2004; Ssegane et al., 2013; Zon, 1927). Yet, that technique is subject to limitation by climatic variation Peel (2009); Vogl and Lopes (2010). The technique also cannot differentiate between water loss by transpiration (controlled by vegetation) and evaporation from wet surfaces including canopy surfaces. Transpiration losses have been shown to affect soil water and thereby indirectly affecting runoff generation processes (Johnston, 1970; Klock and Helvey, 1976) and annual water yields (Megahan, 1983; Troendle and King, 1985; Watson et al., 1999; Sun et al., 2005). Using isotope effects of transpiration and evaporation from a global dataset, Jasechko et al. (2013) demonstrated that transpiration is the major component of the total evapotranspiration (ET) process in global water cycle and is very dependent upon biophysical parameters like stomatal conductance.

Runoff generation is a poorly understood phenomenon in low-gradient forested wetland watersheds found on the southeastern Gulf and Atlantic Coastal Plains, where soil saturation may occur over the entire watershed. Storm runoff varies widely, from none to over 70 % of rainfall (Epps et al., 2013), which is believed to be related soil water and depression storage. In low gradient forested watersheds, we anticipate an even greater coupling of transpirative and soil water dynamics in runoff generation processes (Amatya et al., 1996; Slattery et al., 2006; Sun et al., 2010; Amatya and Skaggs, 2011; Dai et al., 2011; Skaggs et al., 2011; Tian et al., 2012). Understanding runoff generation is, therefore, critical in these watersheds where changes in forest cover due to disruptors to forest structure can occur suddenly (hurricane impacts) or over longer time periods (climate change) (Dai et al., 2011, 2013).

Hurricanes are infrequent but influential disruptors of ecosystem processes in the southeastern Atlantic and Gulf coasts. Every southeastern forested wetland has the potential to be struck by a tropical cyclone. The ecological impact of tropical cyclones has been widely studied leading to several summaries of recent-major-hurricane impacts (E.g. (e.g., Bokaw and Walker, 1991; Haymond and Harms, 1996; Stanturf et al., 2007; Kupfer et al., 2008). Lugo's (2008) analysis of hurricane-force tropical cyclones

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presents an interesting description of hurricane effects as visible and invisible. Visible effects are the commonly described impact of high winds and heavy rainfall summarized by Everham and Brokaw (1996). Invisible effects alter the forest structure and species composition and may result in development of certain ecosystem characteristics, increases in vines, short trees, dense continuous crowns (Lugo, 2008). A notable aspect of Lugo's (2008) discussion of invisible effects was the paucity of information from temperate forests. While the effects of hurricanes on tropical forest have been examined for up to seventy years, most of the temperate knowledge a 1938 hurricane that struck Harvard Forest (Foster, 1988a, b).

The impact of a severe hurricane and subsequent re-vegetation on water yield is an example of an "invisible" effect. An apparent anomalous reversal in relative flow pattern/magnitude between two paired watersheds in the Santee Experimental Forest in coastal South Carolina was first reported in 2006 (Amatya et al., 2006). The reversal in relative flow magnitudes appear to be influenced by the impact of Hurricane Hugo on 22 September 1989; described by Hook et al. (1991). During the calibration period that followed outlet instrumentation, the control watershed consistently produced less runoff than its pair (Williams et al., 2012). A few years after Hugo, the same watershed began to produce greater runoff, a condition that persisted for over a decade. Recently however, the relationship between the two watersheds has reverted to its original state observed prior to Hugo. The three periods describing the relative flow differences between the watersheds: historical era, reversal in relative flow difference, and return to original conditions are henceforth referred to as pre, flip, and flop periods, respectively.

2 Study objectives

1. To quantify the magnitude and timing of changes including a reversal in streamflow in two paired watersheds associated with a catastrophic climatic event (Hurricane Hugo in 1989).

2. To examine selective impact of hurricane on vegetative composition and its potential contribution to altered watershed streamflow through altered evapotranspiration processes.

3 Methods

3.1 Study site

The watersheds of interest are located at 33.15° N Latitude and 79.8° W Longitude within the Santee Experimental Forest (SEF), a part of the USDA Forest Service Francis Marion National Forest (Fig. 1). Over the last half-century, the forest has been intensively studied with over 190 short and long-term vegetation studies. The forest is also the site for one of the first paired watershed studies on wetland-forested watersheds in the US (USDAFS, 1963; Amatya and Trettin, 2007). 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 (Dai et al., 2013; Harder et al., 2007). In September 1989, Hurricane Hugo with wind speeds of 60 m s^{-1} (Sparks, 1991) struck the South Carolina Coast with its eye passing through the Francis Marion National Forest. After the passage of the storm, there were less than 20 % of pines and hardwoods still left standing in the forest (Hook et al., 1991). The Santee Experimental Forest (Cordesville, SC) located 40 km from the coast and within the USDA Forest Service Francis Marion National Forest, was in close proximity to the path taken by the storm eye (Fig. 1) and received severe damage. High wind speeds were sustained as the storm progressed inland – wind speeds 139 km from the coast in Sumter, SC, were measured at 49 m s^{-1} (Brennen, 1991).

In the mid 1960's, two similar first order watersheds in SEF, watershed 77 (WS77) and watershed 80 (WS80) were selected to characterize hydrologic processes in low

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gradient forested wetland watersheds using the classical paired-watershed approach (Young and Klawitter, 1968). WS77 the treatment watershed, was instrumented in November 1963 and is 155 ha in size; WS80 the control watershed, was instrumented in November 1968 and is 206 ha in drainage area. In November 2001, a small section of WS80 was allowed to drain separately through a small culvert reducing its drainage area to 160 ha. WS77 has experienced several silvicultural treatments carried out over the past 40 yr (e.g., Gillham, 1984; Richter et al., 1983, 1982; Binstock, 1978; Amatya et al., 2006). Soon after Hurricane Hugo, WS77 underwent a salvage-harvest, where high valued damaged or fallen trees were removed from the watershed – WS80 however was left untouched. Additional descriptions of the site field measurements and past studies are detailed in Dai et al. (2013); Harder et al. (2007); Amatya et al. (2006); Amatya and Trettin (2007); Amatya and Radecki-Pawlik (2007).

3.2 Hydrologic monitoring

Continuous flow records from these watersheds were collected from 1964 through 1981 (Amatya et al., 2006; Richter et al., 1982, 1983; Binstock, 1978; Young and Klawitter, 1968; Young et al., 1972). Data collection resumed in November 1989, following Hugo, and has continued until the present (Amatya et al., 2003, 2006; Miwa et al., 2003; Sun et al., 2000; Harder et al., 2007; Dai et al., 2013).

For the period between 1946 and 1996, two weighing bucket type rain gauges located in SEF were used to calculate daily rainfall totals (Fig. 1). In 1996, automatic tipping bucket rain gauges were installed, on WS77 and WS 80. Stream flow rates on both watersheds (WS77 and WS80) were estimated using a compound weir instrumented with stage recorders. All stage data until 1995 were recorded on magnetic tapes using analog-digital recorders that were digitized at the USDA Forest Service Coweeta Hydrologic Laboratory (Amatya et al., 2006; Williams et al., 2012).

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3.3 Hydrologic analyses

The paired watershed approach has been used in forest hydrology research in the US for over 100 yr to examine impacts of silvicultural treatments and watershed disturbances on watershed outflows (Andreassian, 2004; Ice and Stednick, 2004; Ssegane et al., 2013; Zon, 1927). With this technique, flows from two closely matched watersheds are measured over several years to establish paired relationships over a range of climatic variability (Hewlett, 1982). On developing a statistically significant calibration relationship between the watersheds, an experimental treatment can then be imposed on one watershed, while the other is regarded as a control. The covariance of streamflows between the pair with variation in climate creates a powerful statistical test allowing for significance testing of even small treatment effects. WS77 and WS80 were calibrated in this way using streamflow data between 1969 and 1976, followed by a series of prescribed burning experiments on WS77 from 1977 through 1981 (Richter et al., 1982, 1983). Data on the daily stream outflow measured between 1969–1981 and 1990–2011 (http://www.srs.fs.usda.gov/charleston/santee/data.html; Dai et al., 2013) were analysed for this study. Daily data were summed on a monthly basis, as were differences in flow between the two watersheds.

3.4 Characterizing flows in WS77 and WS80

Total monthly flow differences between the two watersheds expressed as a unit depth of runoff were evaluated for the entire period of record. The flow data covered the period before (1969–1981) and after Hurricane Hugo (1991–1999) with missing data between 1981 and 1989 due to discontinuation of watershed monitoring. Missing 1995 monthly data for WS77 and WS80 were estimated using multivariate adaptive regression splines (Adamowski et al., 2012; Balshi et al., 2009; Friedman, 1991) where the monthly rainfall was the explanatory variable. Local polynomial regression fitting (LOESS) techniques (Cleveland and Grosse, 1991) were used with monthly flow difference data to create smoothed trend lines that helped to discern the deterministic

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component of data variation with time. The LOESS technique is governed solely by the distribution of the data in bivariate space. The degree to which smoothing takes place is controlled by a "bandwidth" parameter that defines the neighborhood of data points used to fit a polynomial function – the greater the bandwidth, the smoother the fitted LEOSS regression. LOESS bandwidth was chosen based on an improved Aikaike Information Criterion (Aikaike, 1973) proposed by Hurvich et al. (1998). Parameter selection for polynomial functions using the Aikaike Information Crierion (AIC) typically involve large sample numbers. The improved AIC criterion for smoothing parameter selection corrects for small sample bias and consequent model over fitting that affects standard AIC and generalized cross validation procedures Hurvich et al. (1998). We carried out all statistical analyses using the R statistical software [version 2.15.2] (RCoreTeam, 2012).

3.5 Structural changes in monthly rainfall-streamflow relationships

Changes in the long-term behavior of time series can be identified by change detection techniques such as cumulative sum of recursive residuals – CUSUM, (Brown et al., 1975). The null hypothesis tested by CUSUM is that regression coefficients of a linear model are constant over time; the alternative hypothesis is that the coefficients change over time due to influence of an external factor. CUSUM has been used for change detection in eco-hydrology (de Jong et al., 2012; Verbesselt et al., 2010; Vogl and Lopes, 2010; Webb et al., 2012), economic analysis (Caporale et al., 2011; Ghosh, 2009; Olmo et al., 2011; Tiwari et al., 2012) and quality control (Saghaei et al., 2009). However, CUSUM is considered to be less sensitive to certain changes in regression coefficients especially if the changes occur in the later dates of the period under consideration (Bauer and Hackl, 1978; Chu et al., 1995). Therefore, this study uses the moving sum of recursive residuals (MOSUM), a variant of the CUSUM, proposed by Bauer and Hackl (1978) and Chu et al. (1995) to determine changes in runoff response. We used the watershed (WS77 or WS80) whose hydrologic regime shifted due to the

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effects of Hurricane Hugo and thus changed the historical hydrologic relationship between the two paired watersheds.

The MOSUM test was implemented in R using the “strucchange” package (Zeileis et al., 2012) to determine which watershed’s (WS77 or WS80) hydrologic regime shifted due to Hurricane Hugo and thus changed the historical hydrologic relationship between the two paired watersheds. Linear regression models were independently fitted for WS77 and WS80 using monthly streamflow as the response variable, and the monthly rainfall as the explanatory variable. A window size of 12 months ($\alpha = 0.05$) was used to detect structural changes in the regression coefficients. Use of a moving window size of 6 and 24 months did not significantly ($\alpha = 0.05$) affect the estimated change point dates. The structural change point in the monthly streamflow (breakpoint or break date) and the corresponding 95 % confidence interval were estimated based on methods developed by Bai (1994, 1997); Bai and Perron (1998) and implemented by Zeileis et al. (2012). The methods assume a predefined number of structural breakpoints, which are estimated by minimizing the residual sum of squares of the regression model for a data segment. In this analysis, only a single breakpoint was assumed because Hurricane Hugo was the major climatic event that might have caused a shift in post event response of monthly flows on either WS77 or WS80.

3.6 Measuring vegetation response

Agents of the Forest Service’s Southern Research Station initiated a sampling study in the SEF to quantify the initial damage and subsequent recovery of the forest structure due to Hugo. Unfortunately, only initial plot measurements were made in 1991 and those data were lost in subsequent technology transfers. However, we were able to locate paper copies of the original field data that we used to generate digital information for 169 plots on WS80 and 119 plots on WS77. The tenth-acre (395 m^2) circular plots were laid out on approximately a 10 chain (201 m) × 6 chains (121 m) grid (Fig. 2). Every tree in a tenth-acre circular plot was tallied by species, diameter (5-cm classes), height (nearest 1.5 m), mortality, crown damage, degree of lean, and its potential to

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function as a seed tree. In addition, regeneration viability was measured in a four mil-acre (16.2 m^2) subplot within each larger plot. Regeneration was tallied by species group as either seedling if less than 2.5 cm, or sapling if 2.5–12.4 cm at ground level.

For each watershed, average number of trees per hectare (no./ha) and basal area ($m^2\,ha^{-1}$) were calculated by species group, and by mortality. Species groups were pine (*Pinus sp.* primarily *Pinus taeda*), oaks (*Quercus sp.* primarily *Q. falcate, Q.nigra, Q.laurifolia, Q. phellos*) blackgum (*Nyssa sylvatica*), sweetgum (*Liquidambar styraciflua*) and other hardwoods. Standardized *t* tests were performed to determine significant differences in tree counts on WS77 and WS80, both before and after hurricane Hugo. Every tree that was tallied was assumed to have been alive prior to the hurricane. The average number of seedlings and saplings (per hectare basis) for each species group were calculated similar to the tree data. However, in the regeneration tallies, red maple (*Acer rubra*) was tallied separately and blackgum included with other hardwoods. Standardized T-tests were applied to each species group to test differences between WS77 and WS80 for average number of seedlings and average number of saplings in each species group.

3.7 Evaluation of tree inventory data using aerial imagery

Since the inventory of WS77 (in 1991) was only conducted after salvage logging operations in late 1989, we were concerned that trees removed during salvage operations were not included in the 1991 inventory. An aerial photo appraisal was therefore conducted to estimate the possible error in tree inventory totals as a result of not accounting for the salvaged trees. A series of georeferenced aerial photos of WS77 and WS80 taken in the winter of 1983, were compared to data from the 1991 tree inventory. Plot outlines were projected onto the 1983 photos and the number of pine and hardwood trees was accounted for in each plot by visual inspection. These counts were then compared to the number of trees recorded on the plot in the 1991 inventory.

4 Results

4.1 Determining the timing of change in hydrologic character

A LOESS smoothing function with bandwidth of 0.31 (116.3 months) based on minimizing the AIC statistic for monthly flow difference data was used. The loess smoothing function then clearly illustrated the reversal in hydrologic pattern between the two watersheds (Fig. 3). The smoothing function crosses the *x* axis at two instances in time – May 1992 and December 2004. These two times demarcate the period when WS80 appeared to produce more flow than WS77 but are also very dependent on the bandwidth parameter used in the loess analysis. However, the MOSUM test detected changes in streamflow timing in the two watersheds by examining structural changes in the relationship in monthly runoff values between watersheds. The results of the MOSUM test for the two watersheds indicate three dates when structural changes occur in the linear relationship between average monthly flows measured in WS77 and WS80 (Fig. 4). The analyses were carried out on monthly data spanning the period 1969 to 2011 with several periods of missing data. Therefore, the rescaled date axes are non-linear. The break dates (and corresponding 95 % confidence interval) are March 1993 (February 1993 to April 1993), March 1994 (December 1993 to April 1994), and April 2004 (November 2003 to August 2004). The first two break dates are only a year apart and therefore may be considered the same break period if a 99 % confidence interval is considered.

Results of the MOSUM test on the individual watersheds reveal no structural change in the monthly rainfall-runoff relationship on WS77 because the moving sums of recursive residuals do not cross the 95 % confidence interval (Fig. 5a). However, a change in rainfall-runoff relationship is detected for WS80 (Fig. 5b). The structural shifts on WS80 were predicted to have occurred in June of 1990 with a 95 % confidence interval of occurrence between August 1980 and February 1991. The large confidence interval is due to the missing data. The second break date is April 2003 (June 1999 to May 2005; 95 % confidence interval).

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The difference in the two major break dates for WS77 and WS80 derived from a MOSUM analysis of the linear relationship of flows between the two watersheds, and MOSUM analyses of watershed-specific rainfall-runoff relationships is attributed to differences in the strength of the respective relationships. For example, the rainfall data used in this analysis was measured at the SEF headquarters, 2.9 km from WS80 and 3.9 km from WS77, and may not fully represent the rainfall temporal dynamics on WS77 or WS80. The above results are based on use of a moving window size of 12 months. Use of a window size of 6 months and 24 months slightly altered the reported break dates by one to three months.

Thus the change dates for the onset of the flip era range from June 1990 (MOSUM: rainfall-runoff relationships for each watershed) to March 1993 (MOSUM: runoff relationships between watersheds). The return to normal conditions, or the onset of the flop era ranges from April 2003 (MOSUM: monthly runoff relationships between watersheds) to December 2004 (LOESS). For the sake of further analyses and to ease the process estimating annual rainfall and runoff yields, the nearest January to onset range midpoints were chosen – the flip era was considered to have started in January 1992 and the flop era to have started in January 2004.

4.2 Quantifying the magnitude of streamflow change in WS77 and WS8

During the years prior to treatments applied to WS77 (1969–1976), average monthly runoff from WS77 exceeded WS80 by 9.1 ± 1.8 mm month^{-1}. During the treatment years (1977–1981), mean monthly flows in WS77 exceeded WS80 by 6.1 ± 1.7 mm month^{-1} (Fig. 6). However, no significant difference in streamflow between the watersheds after partial prescribed burning was reported by Richter et al. (1983a). For the period immediately following Hugo in 1989 to mid-1992 marking the beginning of the flip era, flows in both watersheds increase by about 45% compared to the 1977–1981 period (Table 1 and Wilson et al., 2006, for WS80). The relative difference in monthly mean flows between watersheds does not change. During the flip era (mid-1992 to end-2004) however, mean monthly flows from WS80 exceeded WS77

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by 15.7 ± 3.2 mm month^{-1}. Also during the flip era, mean monthly flows in WS77 were similar to the calibration period (1969–1976) and slightly above the 1977–1981 period. WS80 mean monthly flows in the flip era were 60 % greater than in 1989–1992 and more than double those during the calibration period. After 2005, WS77 reverts to producing over 4.2 mm per month more than WS80 and both watersheds have lower flows than recorded any time previously.

4.3 Seasonal streamflow trends in WS77 and WS80

Month-specific averages of mean monthly flows when compared across eras (Fig. 7) show that flows from the three eras are comparable for all the months of a year in WS77. The highest average flows in WS77 for six months are associated with the flip era, five months with the pre era and one month (December: 28.8 ± 18.0 mm) with the flop era. However, in WS80, monthly flows from the flip era appear to be consistently higher than the other two eras for every month of the year (Fig. 7). In WS80, the months of January to March during the flip era appear to produce the most runoff when compared to other eras. The highest flows occur in WS80 during the flip era for the month of January (78.9 ± 26.8 mm). The lowest flows also occur in WS80 during the flop era for the month of May (0.8 ± 0.4 mm). Month-specific averages of mean monthly flows when compared between watersheds (Fig. 8) show that flows between the two watersheds are most similar during the flop era and least similar during the flip era (Fig. 8). During the Pre era, mean flows in WS77 are higher than WS80 throughout the year, with the greatest differences occurring in late summer (August). Mean flows from WS80 are consistently higher than WS77 for every month of the year during the flip era with the greatest differences in flows occurring in the months of January to April.

4.4 Forest response to the hurricane hugo

4.4.1 Comparing tree inventory data with aerial image interpretation (non-salvage plots)

Counts of pine tree on 57 no-salvage plots by aerial photo interpretation counts correlated well with tree inventory data from those plots ($R = 0.70$, $p < 0.01$, $N = 57$). The differences in mean count was not significantly different with trees counted by aerial photography (6.74 trees per plot) showing fewer pine trees than those counted by tree inventory (7.60 trees per plot). Comparison of hardwood tree counts between tree inventory data and aerial photo interpretation revealed a lower but still significant correlation ($R = 0.33$, $p = 0.03$). A non-significant difference of 1.51 ($\alpha = 0.05$) more hardwood trees per plot was seen in the tree inventory data when compared to aerial photography interpretation. Overall, there was a non-significant difference of 1.88 more trees per non-salvaged plot based on using the two methods, with tree inventory data counting a few more trees than aerial photo interpretation.

4.4.2 Estimating missing trees in WS77 due to salvage (salvage plots)

Sixty-two of the plots measured in 1991 on WS77 had evidence of salvage logging, noted in the plot summaries. Counts of pine trees on 62 salvaged plots by aerial photography and by tree inventory showed significant but low correlation ($R = 0.34$, $p < 0.01$, $N = 62$). Similarly, counts of hardwood trees in salvaged plots counted by aerial photo interpretation and by tree inventory were also significant but low ($R = 0.33$, $p < 0.01$, $N = 62$). The comparison of inventory data to aerial photo interpretation in salvaged plots showed a significantly greater number of pine trees (2.32 more trees/plot, $p < 0.01$) and hardwood trees (0.86 more trees/plot) in counts made by aerial photography. Overall, there were a significantly greater number of trees (3.18 more trees/plot, $p < 0.01$) that were counted through aerial photo interpretation than counted by tree inventory. On extrapolation of these plot data to the entire watershed,

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the data suggest that 28.9 pine and 11.0 hardwood trees per hectare were salvaged in WS77 after Hugo. The average diameter (dbh) of the largest dead trees on each salvaged plot was 43.2 cm. Assuming that salvaged trees were at least as large as the remaining dead trees, the data suggest that 4.3 $mm^2\,ha^{-1}$ of pine and 1.5 $m^2\,ha^{-1}$ of hardwood basal area were removed from WS77 during the salvage operations. All subsequent presentation of tree density and basal area data include salvage count estimates based upon aerial photo interpretation.

4.4.3 Analysis of plot inventory data

Prior to Hugo, our data suggest that WS80 (186.8 trees ha^{-1}) had significantly fewer trees per unit area of watershed compared to WS77 (263.4 trees ha^{-1}). In terms of basal area however, tree density in WS80 (16.3 $m^2\,ha^{-1}$) were comparable to WS77 (18.3 $m^2\,ha^{-1}$) (Table 9). In addition, 45 % of all trees in WS80 were pine accounting for 65 % of basal area in that watershed. In WS77, pre-Hugo estimates suggest that 79 % of all trees counted were pine that accounted for 81 % of basal area. The average basal area of a pine was 0.13 m^2/tree and 0.07 $m^2\,tree^{-1}$ in WS80 and WS77, respectively. After the passage of Hurricane Hugo, 35.7 % of the trees in WS80 experienced mortality accounting for 55.4 % of basal area. In WS77, 38.5 % of the trees lost to the storm accounting for 54.5 % of basal area. It appears that mortality rates were similar in both watersheds. After Hugo, the pine trees that withstood Hugo had average basal areas of 0.10 $m^2\,tree^{-1}$ and 0.05 $m^2\,tree^{-1}$ in WS80 and WS77, respectively (Fig. 9). Overall, the average basal area per tree decreased by 30.7 % in WS80 and 26.0 % in WS77. In addition to greater basal area of trees, WS77 also had significantly ($\alpha = 0.05$) more seedling regeneration than WS80 (Table 3). WS80 showed an advantage in terms of regeneration only for oak saplings. Although the distribution of pine saplings was quite variable, WS77 averaged more than three times the number of pine saplings than WS80.

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5 Discussion

The analysis of this paired watershed data reveals a number of limitations of retrospective research and the techniques available to analyze paired watershed runoff data. Recent criticisms of the paired watershed technique (Peel, 2009; Vogl and Lopes, 2010; Alila et al., 2009)question the statistical validity of the analysis of paired watershed data. Although the distribution of runoff is not likely to be stationary or normally distributed as is required for parametric regression analysis of paired watershed data, the greatest limitation occurs when the post treatment climatic factors are outside of the range of the calibration data. The runoff data in this study show that the relationship can change drastically after a severe disturbance due to extreme climatic events possibly resulting in high flow rates.

Despite the radical changes in runoff following Hurricane Hugo, the analysis of monthly flow data by LOESS smoothing show a definitive alteration in relative monthly flows several years after the impact of Hurricane Hugo on watersheds 77 and 80. An analysis of structural change in the flow relationships between watersheds shows that the timing of this flow reversal occurred sometime between June 1990 and March 1993. The timing of the reversion back to pre-calibration conditions occurred between April 2003 and December 2004. A structural analysis of rainfall runoff relationships from each watershed revealed that changes were detected in WS80 and not in WS77, with a change in the direction of greater runoff production in WS80. Interestingly, it was WS77 that showed substantial change in regeneration with more pine seedlings based on vegetation data analysis – however this change suggests a net decrease of runoff production in WS77. These data show that Hurricane Hugo had a substantial impact on the runoff generation processes on these two watersheds. That impact changed the structure of the relationship between monthly runoff in WS77 and monthly runoff from WS80. This relationship did not return to the pre era relationship until 14 yr after the hurricane occurred. Both the runoff data in Table 1 and the MOSUM analysis suggest the main cause of the flip was due to increased flow in WS80 over the period from

1990–2003. Increased flow in WS77 occurred only until 1993 and the rainfall- runoff relation did not exceed the bounds of expected variability. Vegetation analysis suggest that rapid growth of seedlings and young pine in WS77 led to higher transpiration losses and therefore lower runoff.

The impact of Hugo on the vegetation of WS77 and WS80 is consistent with our knowledge of hurricane impact on the southern forest. The inventory of WS80 showed that mortality was greatest among large diameter pines, which were primarily loblolly pine. While pine was the predominant species in both watersheds, WS80 had fewer pine trees than WS77 but each tree was on average twice the size of pines (in terms of basal area per tree) in WS77. Since dead trees comprise about one-third of the total number of trees counted, but account for over half of the basal area lost in the hurricane the data clearly show that hurricane winds affected larger trees in both watersheds.

Large diameter loblolly pines were also found highly susceptible to breakage according to Gresham et al. (1991) as well as by Putz and Sharitz (1991) in their study of Hurricane Hugo damage. Gresham et al. (1991) also found that water oak, and laurel oak were susceptible to wind breakage as was the case for oaks on WS80. In WS80, sweetgum and blackgum received much less damage than pines or oaks, consistent with several other studies (Putz and Sharitz, 1991; Duever and McCollom, 1992; Stanturf et al., 2007). The tree inventory data from WS77 showed similar survival of smaller pines, sweetgum, and blackgum. If the estimated 4.3 $m^2\,ha^{-1}$ of salvaged pine is added to the 4.1 $m^2\,ha^{-1}$ of pine loss from the inventory data, pine tree mortality due to Hugo on WS77 (8.4 $m^2\,ha^{-1}$) and WS80 (7.8 $m^2\,ha^{-1}$) become comparable. This result agrees with work done by Hook et al. (1991) in the Francis Marion National Forest that shows uniform destruction of large pines located in proximity to the path of the hurricane center.

The analysis of monthly flow data grouped by era and watershed showed that during the Pre era, flows from WS77 exceeded WS80, with the greatest differences occurring during the summer months. WS80 had a larger hardwood basal area suggesting higher transpiration rates that would peak in summer. During the flip era, WS77 flows

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were less than WS80 and the difference was distributed throughout most of the year suggesting a higher rate of transpiration by a larger number of pines on WS77 may be the cause. During the Flop era WS77 exceed WS80 with smaller differences throughout the year.

The vegetation inventory and regeneration counts suggest an explanation of the hydrologic processes explained by flow and evapotranspiration process in the two watersheds. Throughout the calibration and early prescribed burning experiments, WS77 consistently produced more runoff than WS80. The inventory suggests WS77 had an abundance of smaller pine, more pine seedlings and more pine saplings in comparison to WS80 at the time of inventory. Many of these small pines were the result of regeneration experiments conducted on WS77 during the 1982–1989 period when no hydrological measurements were undertaken.

Pre-existing variation in forest structure was shown by Foster (1988b) to be a strong predictor of hurricane damage. Although large trees were destroyed by the hurricane on both watersheds, young pines planted on WS77 from 1982–1989 had survived and represented 6.3 $m^2\,ha^{-1}$ of basal area by 1991. In addition, WS77 had twice as many pine seedlings and therefore more pine saplings/ha than WS80. Young pines have much higher water use rates than mature pines (Irvine et al., 2004) and is related to both leaf area and high transpiration per unit leaf area (Delzon and Loustau, 2005). Song et al. (2012) analyzed the recovery of South Carolina forests after Hugo – four of their one-hectare plots are located in WS80 and were measured from 1994. Their data from WS80 show that pine tree basal area increased from 6 $m^2\,ha^{-1}$ in 1994 to 9 $m^2\,ha^{-1}$ by 2003. Water oak, the other species to show notable growth, grew from 1.4 $m^2\,ha^{-1}$ in 1994 to 1.7 $m^2\,ha^{-1}$ by 2003. Cosentino (2013) found that spectral reflectance (Normalized Difference Vegetation Index) on the entire SEF had recovered to pre-hurricane levels by 1999. These data suggest that the regeneration on WS77 allowed that watershed to resume normal transpiration by 1993 but that regeneration on WS80 did not reach that level until 2003. The MOSUM analysis also showed that a fundamental change rainfall-runoff relationship occurred between 1990–2003 in WS80 but not in WS77.

6 Summary

Flow from the paired watershed experiment has shown a stable difference in flow generation from 1969 through 1992 even after an extreme event like Hurricane Hugo in 1989. Throughout that period, flow from WS77 was consistently higher than WS80. From 1993 until 2003, flow from WS80 consistently exceeded flow from WS77. The flip in relationship represented a relative increase in WS80 or decrease in WS77 of 28 mm month^{-1}. This change was confirmed by three methods of flow analysis that all found significant change occurred in 1992. The moving sum of recursive residuals (MOSUM) method found that the rainfall-runoff relationship of WS80 was significantly changed for 1990–2003 period.

Hurricane Hugo struck these watersheds in September of 1989 and destroyed the larger pines and hardwoods (predominantly oaks) present on both watersheds. Following the hurricane, WS77 doubled its pine tree basal area, as it had twice as many pine seedlings and three times more pine saplings than WS80. Rapid regrowth of pines on WS77 appear to be responsible for near normal transpiration from 1993–2003 while delayed regrowth on WS80 limited transpiration losses that manifested as increased runoff at its watershed outlet.

7 Conclusions

The functional relationship between vegetation and hydrologic processes in southeastern coastal forests present a complex and understudied area for research. In this study, we demonstrated a fundamental shift in hydrologic character of a coastal watershed that was impacted by a hurricane. We linked the change in the rainfall-runoff relationship to a catastrophic shift in forest vegetation due to selective hurricane damage.

While both watersheds were located in the path of the hurricane, extant forest structure varied between the two watersheds as a function of experimental forest management techniques on the treatment watershed. We showed that the primary damage was to older pines, and to some extent larger hardwood trees. We believe that lowered vegetative water use impacted both watersheds with increased outflows on both watersheds due to loss of trees following hurricane impact. However, one watershed was able to recover to pre hurricane levels of canopy transpiration at a quicker rate due to the greater abundance of pine seedlings and saplings in that watershed. With the return to a dynamic equilibrium in forest structure, the subsequent growth and increased water use by trees in the impacted watershed, there appears to be a return to the original hydrologic state witnessed prior to the passage of the hurricane.

A careful study of hurricane impact can reveal information that was missed by broad scale evaluations that are typically conducted immediately after a major hurricane. Those immediate studies have done well to improve our understanding of overall impact of hurricanes to southeastern coastal forested watersheds – this study confirms those overall understandings. However, by applying those principles to varying initial stand conditions, one can expect a range of different impacts on the forest that can eventually lead to unexpected long-term impacts on ecosystem services. Furthermore, this study clearly demonstrates the significance of long-term data especially in the case of determining the impacts of catastrophic events on hydrologic processes. If flow monitoring had not been resumed soon after Hugo, we would have been unable to describe the mechanisms demonstrated in WS77 and WS80.

For future work, there is a critical need for an explicit coupling of hydrologic and vegetative growth models using directly measured transpirative losses to simulate and validate the impacts of sudden and long-term perturbations to the eco-hydrologic characteristics of a coastal forested watershed.

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Table 1. Mean monthly flows, change in flows, and rainfall by era for WS77 and WS80.

		WS77		WS80			
Era	Years	Ave. mo. flow (mm) ±SE	Change %	Ave. mo. flow (mm) ± SE	Change %	Ave. mo. flow diff. (mm) ± SE	Av. mo. rainfall (mm) ±SE
Pre	1969–1976	31.7 ± 4.5		22.6 ± 3.1		−9.1 ± 1.8	117.1 ± 7.7
	1977–1981	24.6 ± 5.5	−22.6	18.5 ± 4.4	−18.1	−6.1 ± 1.7	111.2 ± 10.1
	1989–1991	40.6 ± 12.9	65.3	29.1 ± 8.7	57.1	−11.5 ± 4.4	87.6 ± 16.0
Flip	1992–1903	30.6 ± 4.1	−24.6	47.7 ± 5.2	64.3	17.1 ± 3.4	104.5 ± 8.9
Flop	2004–1911	19.4 ± 3.2	−36.7	15.5 ± 2.8	−67.6	−3.9 ± 1.1	108.5 ± 7.2

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Table 2. Results from tree inventory data from 1991 that recorded mortality and living trees. Trees alive pre-Hugo were estimated by summing the following: alive post-Hugo + Recorded mortality + Salvage. Counts of trees salvaged from WS77 post-Hugo were inferred by aerial photo interpretation. Significance of t tests of differences in mean number of trees and mean basal area between WS77 and WS80 are shown. Standardized t test: mean WS80 $\neq$ WS 77, ** significant at $\alpha = 0.01$, * significant at $\alpha = 0.05$, NS not significant $\alpha = 0.05$.

	Alive pre-Hugo			Alive post-Hugo			Percentage loss	
	WS80	WS77	Sig.	WS80	WS77	Sig.	WS80	WS77
Number of trees per hectare								
Pine	83.5	208.8	**	28.7	119.8	**	65.7	42.6
Oaks	35.3	19.6	NS	32.1	8.2	NS	9.1	58.5
Blackgum	27.4	20.0	NS	26.9	19.5	NS	1.8	2.5
Sweetgum	19.3	10.6	NS	17.5	10.4	NS	9.0	2.3
Other HWD	21.3	4.2	NS	14.8	4.0	NS	30.2	5.9
Total	186.8	263.3	**	120.1	161.9	**	35.7	38.5
Basal Area (m^2 ha^{-1})								
Pine	10.6	14.9	**	2.8	6.5	**	73.2	56.5
Oaks	8.9	3.5	**	1.5	0.4	*	24.7	77.7
Blackgum	1.2	0.7	NS	1.2	0.7	NS	1.9	3.2
Sweetgum	1.2	0.3	**	1.1	0.3	**	13.0	0.0
Other HWD	1.2	0.4	NS	0.6	0.4	NS	48.1	5.6
Total	16.3	18.3	NS	7.3	8.3	*	55.4	54.5

Table 3. Results of regeneration counts made during inventories of WS77 and WS80 in 1991. All values represent the number of trees per hectare. Statistical significance as denoted as in Table 2.

	Seedlings			Saplings		
	WS80	WS77	Sig.	WS80	WS77	Sig.
Pine	329	792	**	34	117	NS
Oaks	132	229	*	35	13	**
Sweetgum	250	544	*	48	38	NS
Red Maple	48	56	NS	28	26	NS
Other HWD	76	53	NS	67	14	NS
Total	749	1466	*	199	163	NS

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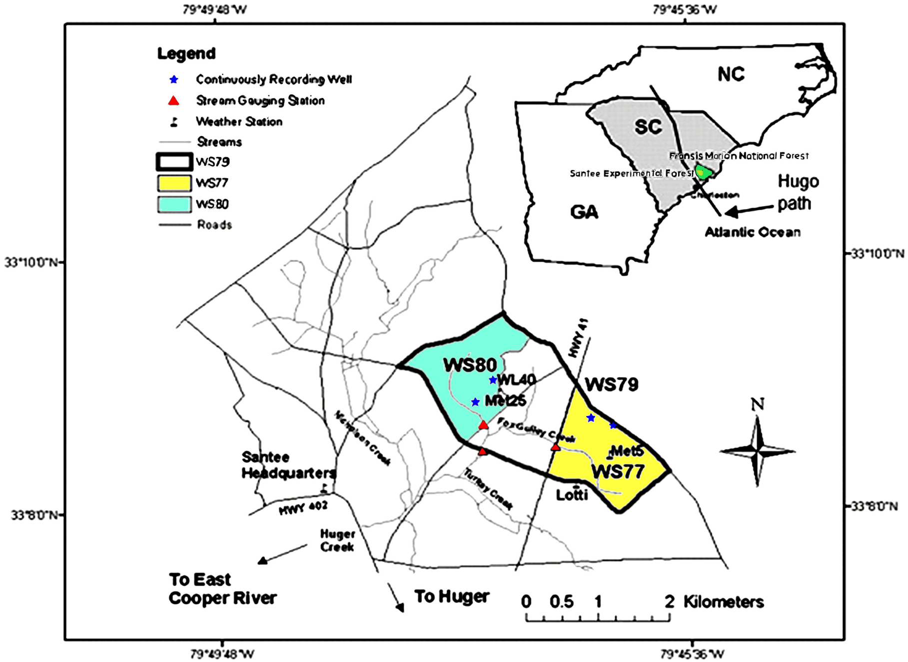

Fig. 1. Location of WS77 and WS80 on the Santee Experimental Forest in coastal South Carolina and path of the eye of Hurricane Hugo, September 1989.

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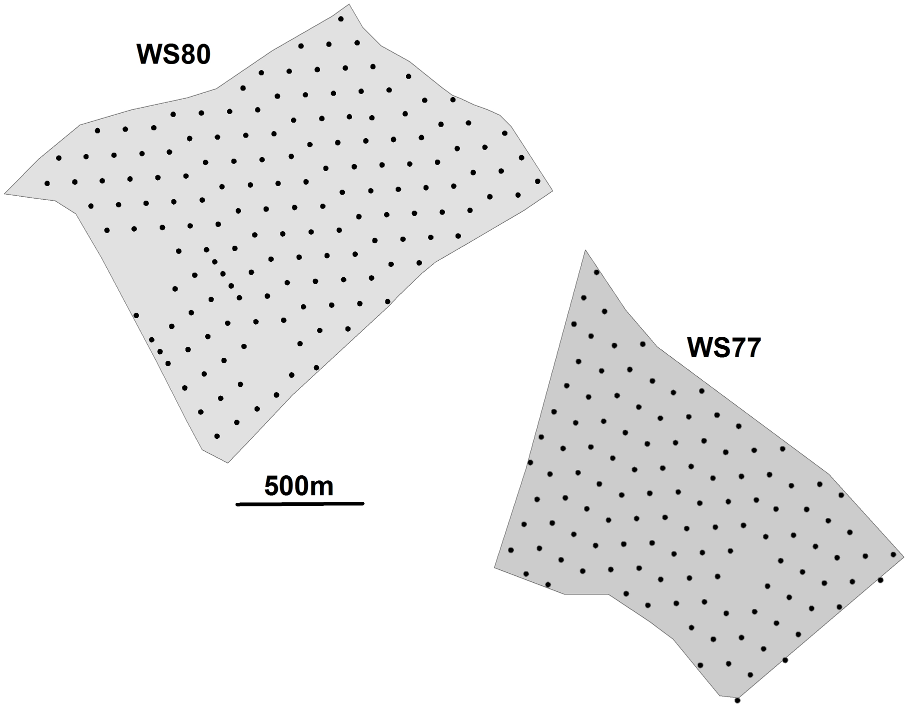

Fig. 2. Locations of vegetation sampling plots placed on watersheds 77 and 80 in 1991 and summarized in this paper.

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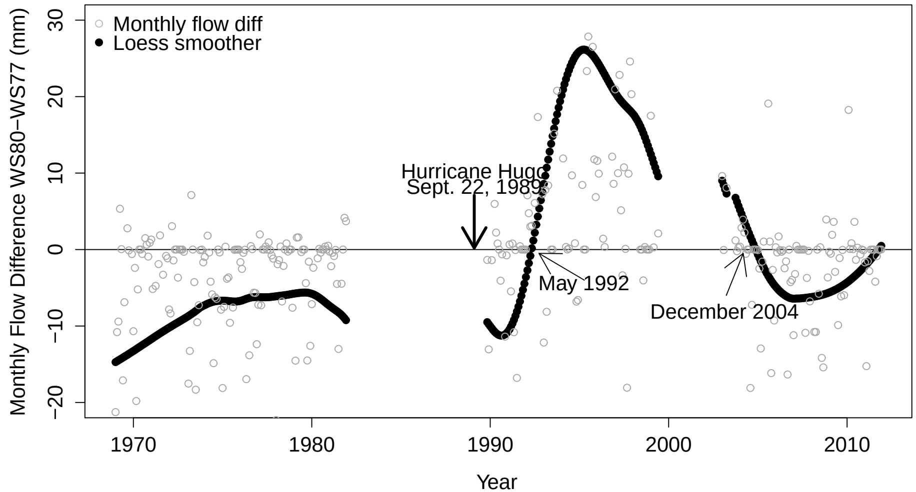

Fig. 3. A loess smoothing function (filled circles) was used to discern trends in monthly flow differences (open circles) between WS77 and WS80. Hurricane Hugo struck the study watersheds in September 1989. The loess smoothing function crosses the x axis at two points that mark the transition points between three eras: *Pre*, *Flip* and *Flop*. Periods of missing data or were 1982 to 1989 and missing data or no flow 1999 to 2002.

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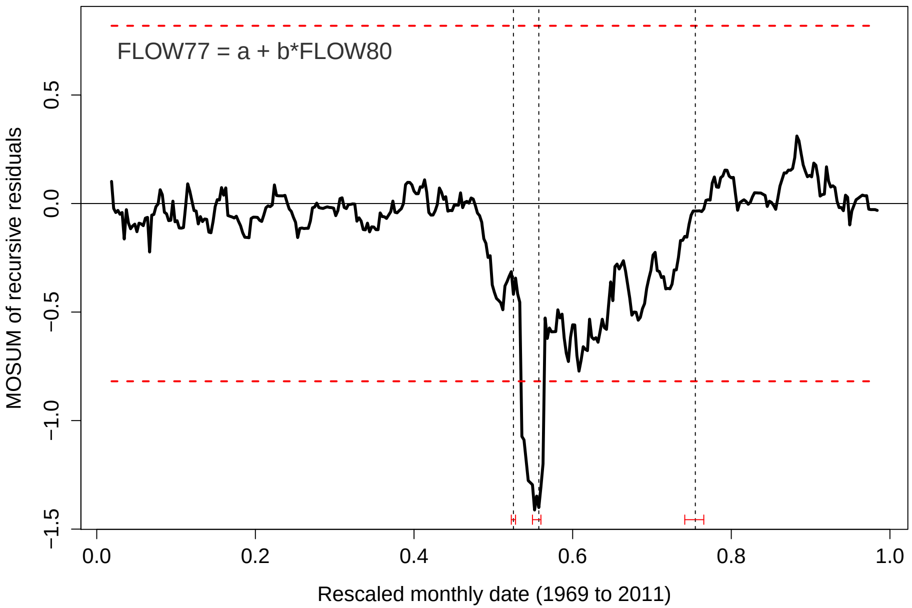

Fig. 4. Plot of moving sums of recursive residuals (MOSUM) for a linear relationship between monthly flows of watersheds WS77 and WS80. A shift of the MOSUM outside the 95 % confidence intervals (red long horizontal dotted lines) is indicative of a structural break in the linear relationship. The vertical dotted lines are estimated change dates with corresponding 95 % confidence interval (small horizontal lines that cross each break date). There are three break dates corresponding to the months of March 1993, March 1994, and April 2004. Only non-missing data is used and therefore the timescale is not linear.

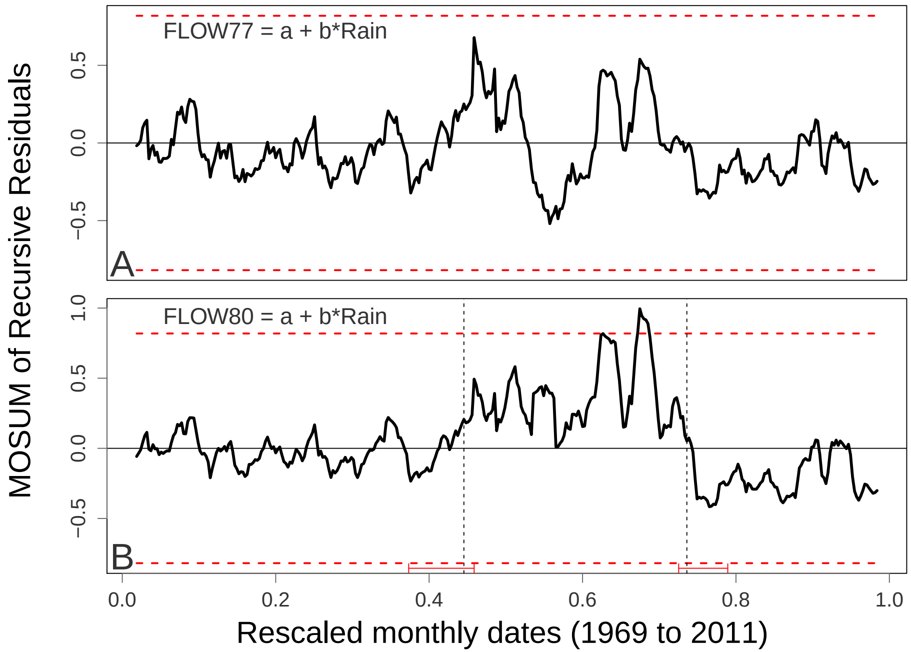

Fig. 5. Plots of moving sums of recursive residuals (MOSUM) for flows of watersheds WS77 **(A)** and WS80 **(B)** as linear functions of the monthly rainfall. **(A)** shows no structural change in the monthly flow – rainfall relationship for WS77 while **(B)** shows two dates of structural change on WS80. The first break corresponds to June 1990 while the second break corresponds to April 2003.

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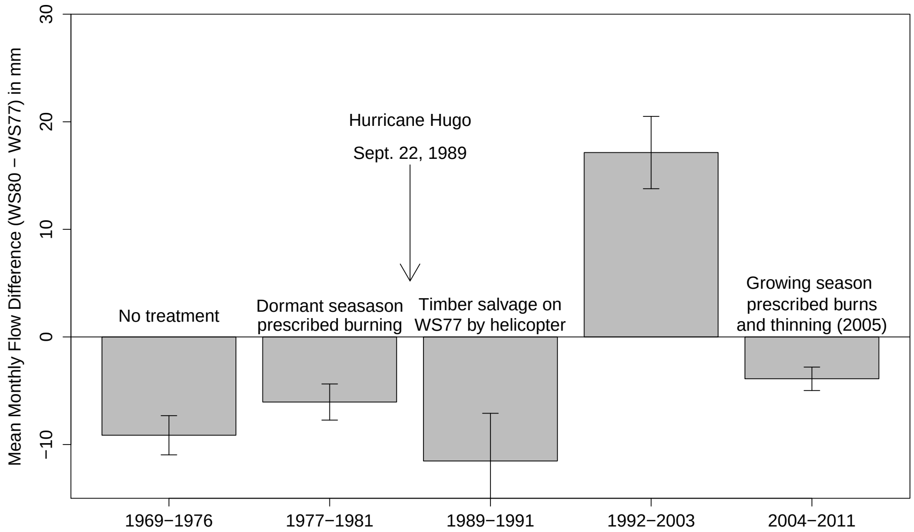

Fig. 6. Mean monthly flow differences between WS80 and WS77 from 1969–2011. No records were collected from 1982–September 1989. Treatments listed on each period were applied to WS77.

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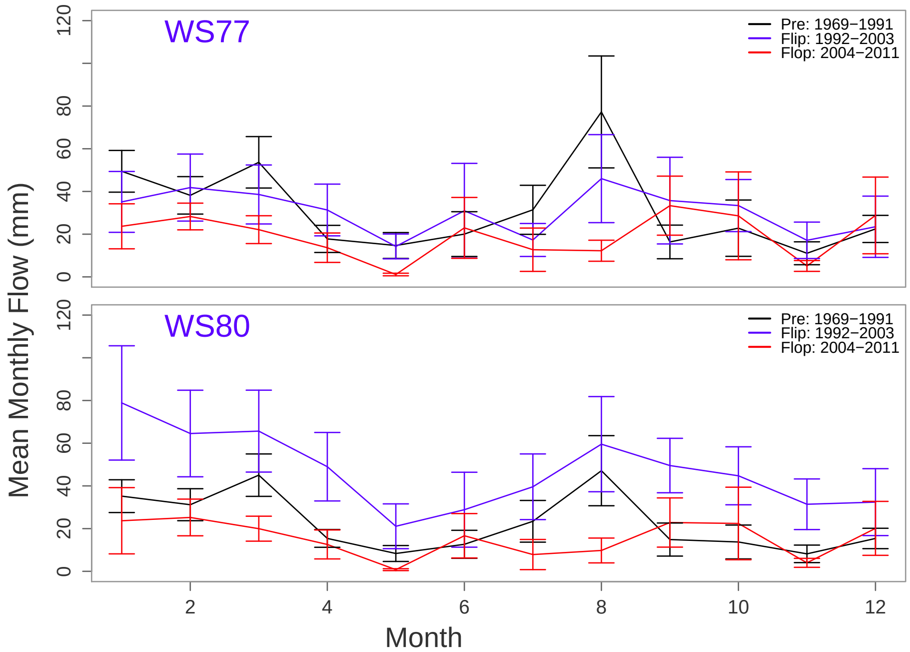

Fig. 7. Temporal variation of mean monthly flows with month of year – mean monthly stream flow data are grouped by watershed for comparison across eras. Error bars represent the one standard error.

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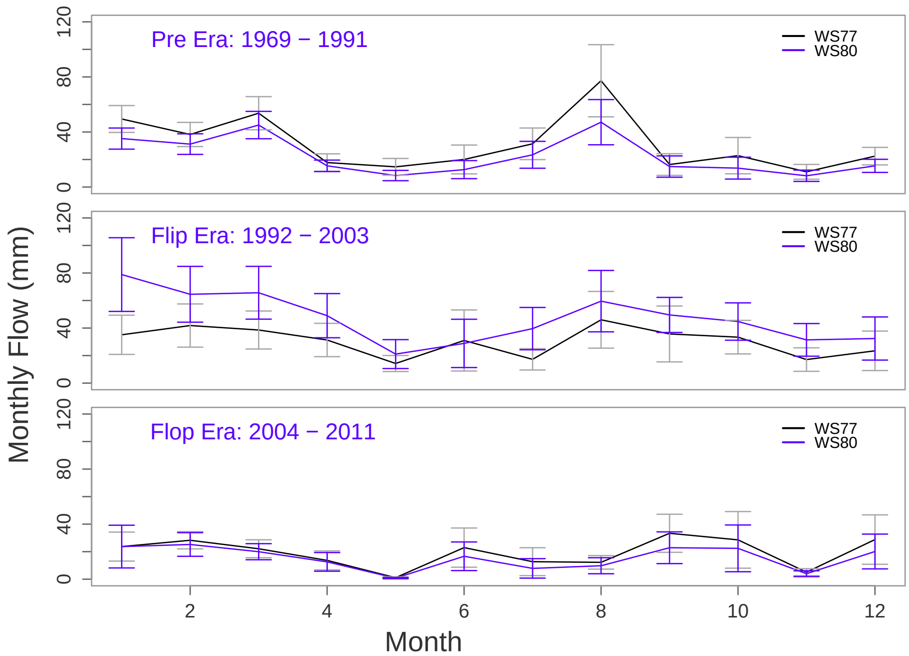

Fig. 8. Temporal variation of mean monthly flows with month of year – mean monthly stream flow data are grouped by era for comparison between watersheds. Error bars represent the one standard error.

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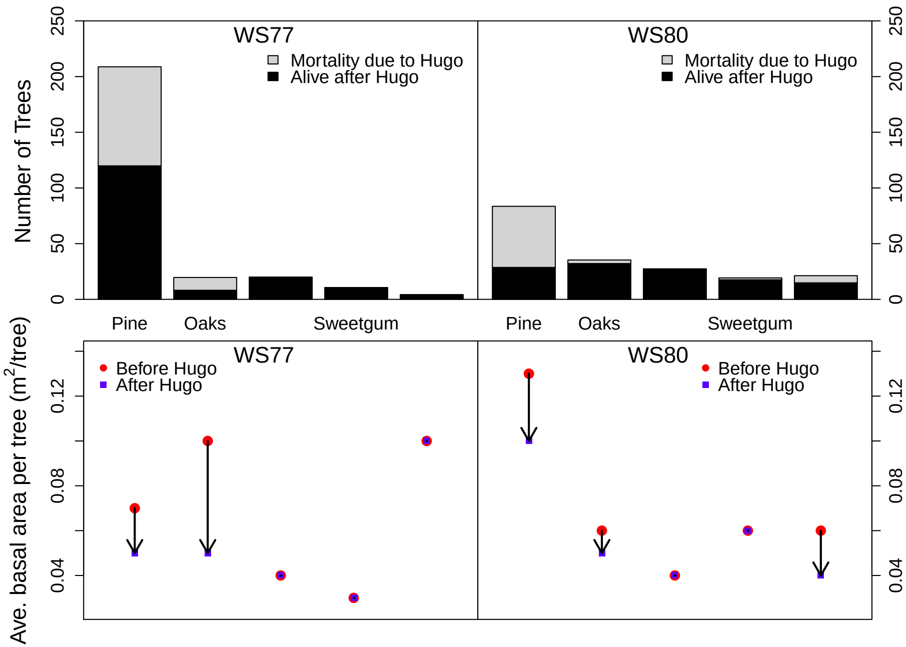

Fig. 9. Changes in forest structure in WS77 and WS80 after Hugo. The lower two panels show the effect of Hugo on different species in terms of tree numbers. The upper two panels show a change in average tree size, with length of arrows denoting a shift in average basal area per tree for several species.

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