



## Prescribed burning effects on the hydrologic behavior of gullies in the South Carolina Piedmont

Marco A. Galang<sup>a,1</sup>, Lawrence A. Morris<sup>a</sup>, Daniel Markewitz<sup>a,\*</sup>, C. Rhett Jackson<sup>a</sup>, Emily A. Carter<sup>b</sup>

<sup>a</sup> The University of Georgia, Athens, GA 30602, USA

<sup>b</sup> USDA Forest Service, Southern Research Station, Auburn, AL, USA

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### ABSTRACT

Gullies found in the Piedmont of South Carolina are legacies of past land use and erosion. Although the majority of these gullies are now under forest vegetation and perceived as geomorphologically stable, the question of gully contribution to nonpoint source pollution remains undetermined, especially when these gullies are subjected to prescribed burning or other forest disturbance. Six prescribed burned and two reference gullies draining mature pine stands grown on former cotton fields were instrumented at the Long Cane Ranger District, Sumter National Forest, South Carolina to characterize the hydrologic behavior of these gullies and to investigate response to prescribed burning. Flow in the gullies was observed for one year of pre-burn and one year of post-burn conditions. Hydrologic behavior of these eight gullies varied greatly in the pre-treatment period. During the study, 48 rainfall events exceeding 12.7 mm were recorded, but one reference gully never produced flow and three treatment gullies flowed during three events or less and only in the pre-burn period. Although significant storm events occurred throughout the year, all gully flow events occurred between December and March. Double-mass and graphical analysis of relative stormflow production of the reference and treatment gullies in the pre- and post-treatment periods did not indicate an effect of the controlled burn on flow behavior, but the post-burn year was characterized by drought. The observed inter-annual variation in gully behavior was large. Observations of local groundwater conditions with piezometers and electrical resistivity surveys indicated that gully flows were controlled by the presence of a flow-restricting layer below the gully bed.

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### 1. Introduction

The Piedmont region of South Carolina suffered severe soil erosion from 1860 to 1920 due to deforestation and cultivation (Trimble, 1974; Richter and Markewitz, 2001). Evidence of this history is recognizable in the turbid conditions of today's rivers and streams that are unlike those of pre-European colonization described by William Bartram (Jackson et al., 2005; Harper, 1998). Remnant agricultural gullies are a ubiquitous feature of land under secondary forest vegetation growing on areas once cultivated for cotton. These gullies formed when high soil surface hydraulic conductivities of the pre-European forest were greatly reduced by the elimination of vegetative cover and organic soil horizons (forest floor) that resulted in Hortonian overland flow. After the collapse of

the cotton farming economy, much of the Piedmont reverted to forest, and these gullies have been healing (i.e., aggrading with soil and organic material, growing trees within the gully banks, increasing their surficial infiltration rates). However, studies of remnant gully hydrology are few, and little is known about the hydrologic activity of these remnant gullies or the effects of silvicultural activities, particularly prescribed fire or timber harvest, on their hydrologic activity (Hansen and Law, 2006).

Many remnant agricultural gullies become more active after timber harvest (Rivenbark and Jackson, 2004) and such gullies have been identified as significant contributors to nonpoint source pollution after timber harvest (Hewlett and Doss, 1984). The contribution of these gullies, through continued erosion, to the overall sediment production of a watershed is typically unaccounted for in erosion models (e.g. WEPP and USLE; Poesen et al., 2003) and, yet, could play a significant role in producing nonpoint source pollution.

Nonpoint source pollution associated with sediment is a key issue in the southern United States (Neary et al., 1989; Baker, 1992). In forested watersheds, best management practices are implemented to minimize sediment input to streams. These prac-

\* Corresponding author. Tel.: +1 706 542 0133.

E-mail address: [dmarke@warnell.uga.edu](mailto:dmarke@warnell.uga.edu) (D. Markewitz).

<sup>1</sup> Current address: University of the Philippines Los Baños, College, Laguna 4030, Philippines.

**Table 1**  
Morphological properties for instrumented gullies within the Sumter National Forest in the Piedmont of South Carolina. Initial measurements were taken in 2007 prior to a March 13 prescribed burn.

Gully	Treatment	Contributing area (ha)	Slope (%)	Headcut (m)		CS <sup>a</sup>	Length (m)	Average width (m)	Depth (m)	Gully bed Pre-burn cover (%) <sup>b</sup>		Contributing area Post-burn cover (%) <sup>c</sup>			
				Depth	Width					FF	CC	A	P	M	S
A	Burned	0.3	6	0.8	3.9	14	68	5.9	1.5	100	92	33	57	8	2
B	Burned	0.3	6	2.9	12.3	5	40	9.5	2.7	96	94	46	40	14	0
C	Burned	0.3	15	2.1	5.2	11	54	9.2	3.0	100	95	26	50	23	1
D	Burned	0.8	7	2.7	11.5	9	68	6.2	2.1	96	93	47	36	17	0
E	Burned	0.3	8	0.8	2.1	11	50	2.4	0.9	96	92	23	46	31	0
F	Burned	0.2	4	1.6	2.0	6	52	4.3	1.2	100	89	21	49	28	1
G	Unburned	0.7	7	1.3	4.8	17	90	7.9	2.0	96	92	na <sup>d</sup>	na	na	na
H	Unburned	0.1	16	1.3	4.4	6	36	4.3	1.4	96	92	na	na	na	na

<sup>a</sup> CS: contributing slope measured above the headcut.

<sup>b</sup> FF: forest floor; CC: canopy cover.

<sup>c</sup> A, fully consumed litter layer; P, partially consumed litter layer; M, mineral soil exposed; S, rock or stone.

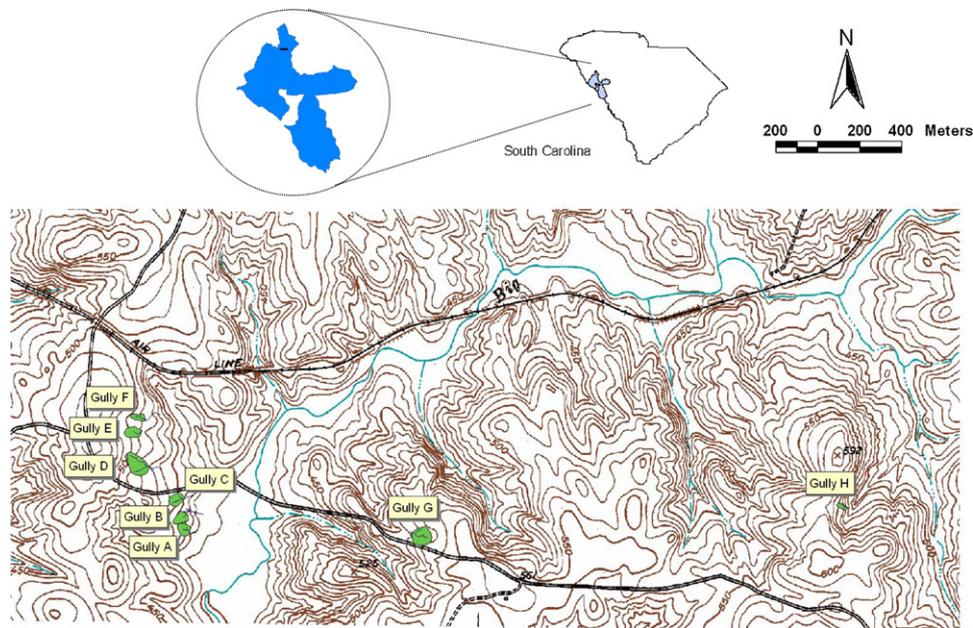
<sup>d</sup> NA, not applicable.

tices often focus on activities proximal to streams (Lynch et al., 1985) with little regard to gully networks. If gullies behave like ephemeral streams, policies pertaining to prevention of sediment movement might logically be extended to include these land features. This is especially true for gullies that connect directly to perennial streams and, thus, can readily facilitate direct transport of sediments and nutrients from upslope areas. In a survey of recently clearcut and site prepared forest management units, Rivenbark and Jackson (2004) found that for 50% of the observations where “breakthrough of sediment” occurred (i.e., areas where sediment passed the Streamside Management Zones (SMZ) and entered stream channels) there was topographical convergence associated with swales or gullies. Currently, South Carolina Best Management Practices (BMP; South Carolina Forestry Commission) defines a gully as “an eroded channel (generally at least 25 cm deep), which has deepened to the point that it cannot be removed by tillage” and recommends the maintenance of vegetation and minimal soil disturbance during forest operations.

Prescribed burning is a forest management strategy practiced in many managed pine stands in the southeastern United States for fuel reduction and wildlife management. Prescribed burning is also used to restore the fire-regime associated with longleaf pine stands long suppressed by previous policies (Youngblood et al., 2005; Wade and Lunsford, 1989). Re-introducing fire to southern hardwood forest is also under consideration (Fire and Fire Surrogates Study, 2008). Some studies have shown negative impacts of prescribed burning on sediment and nutrient movement. Wright et al. (1976) found adverse effects of prescribed burning on soil loss and water quality on moderate to steep slopes covered with Ashe juniper (*Juniperus ashei*). Townsend and Douglas (2000) observed higher total suspended sediments and volatile suspended sediments in catchments of Australia as a result of reduction in ground cover from burning. In contrast, other studies have shown that prescribed fire has little effect on soil erosion and can increase soil nutrient content. Van Lear and Danielovich (1988) recorded insignificant soil movement in a logging slash burn in the southern Appalachians. An increase in soil nutrient content occurred after the burn, and was mostly attributed to the combustion of organic materials (Carter and Foster, 2004; Certini, 2005). In the case of nitrogen (N), the influx of native herbaceous N-fixing legumes can compensate for the amount volatilized during the burn (Hendricks and Boring, 1999; Boring et al., 2004). Discrepancies between results of these studies may result partly from differences in fire intensity and severity (Neary et al., 1999).

Previous evaluations of the effect of prescribed burning on a gullied landscape are limited. Douglass and Van Lear (1983) investigated the effect of prescribed burning on watersheds with “healed” gullies and found no significant effect on storm runoff, sediment concentration, and transport. However, their investigation was conducted at a watershed level and the contribution and behavior of individual gullies were not measured. Cushwa et al. (1971) studied individual gullies in South Carolina and concluded there was no significant effect of prescribed burning on soil movement.

There is a clear need for further investigation of individual gullies, especially after a prescribed burn, to determine the role gullies play in the transport of sediment and nutrient from upslope to downslope areas. We instrumented eight remnant gullies on United States Forest Service land in the South Carolina Piedmont with flumes, stage recorders, and piezometers, and we measured gully soil profiles as well as water table dynamics to investigate three hypotheses: (1) prescribed fire increases the frequency and volume of stormflow within gullies, (2) prescribed fire increases the fluxes of nutrients and sediments from gullies, and (3) stormflow volumes within gullies increase with increasing surficial contributing area. Observations were made on two reference gullies and six treatment gullies, all of which were



**Fig. 1.** Gullies instrumented with 90° V-notch weir and stormwater sampler at the Long Cane Ranger District, Sumter National Forest, South Carolina. Gullies A–F were burned March 13, 2007 while gullies G and H served as controls.

monitored one year prior to, and one year following, prescribed fire.

## 2. Materials and methods

### 2.1. Location and description of the study site

This study was conducted in the Long Cane Ranger District, Sumter National Forest, South Carolina (34°7'55.36"N, 82°18'36.17"W). The region was subjected to deforestation and intensive cotton cultivation from the late 1800s to early 1900s, which resulted in massive gully formation (Trimble, 1974). The Long Cane District is in the Piedmont physiographic region and is dominated by the Cecil soil series (fine, kaolinitic, thermic Typic Kanhapludults), characterized as "very deep, well-drained moderately permeable soils formed in residuum weathered from felsic, igneous and high-grade metamorphic rocks" (Soil Survey Staff, Natural Resources Conservation Service, U.S. Department of Agriculture, 2007). Associated soil series include Pacolet (fine, kaolinitic, thermic Kanhapludults; shallower B horizon) and Hiwassee (fine, kaolinitic, thermic Rhodic Kanhapludults; alluvium parent material) soils. Elevation ranges from 120 to 180 m above sea level, slope varies from 2 to 12%, and average annual rainfall is 1210 mm distributed evenly throughout the year (U.S. Department of Agriculture, 1980). Vegetative cover consists of loblolly pine (*Pinus taeda*) of about 40 years old with occasional similarly aged hardwood trees established in gully beds and side slopes. The understory vegetation is mostly sweetgum (*Liquidambar styraciflua*) and briars (*Rubus* spp.). Forest floor depth ranges from 3 to 5 cm. Previous silvicultural treatments include intermediate thinning in 1997 and 1999 and prescribed burning with the last prescribed burn on February 20, 2004 (S. Wilhelm, personal communication, April 3, 2008).

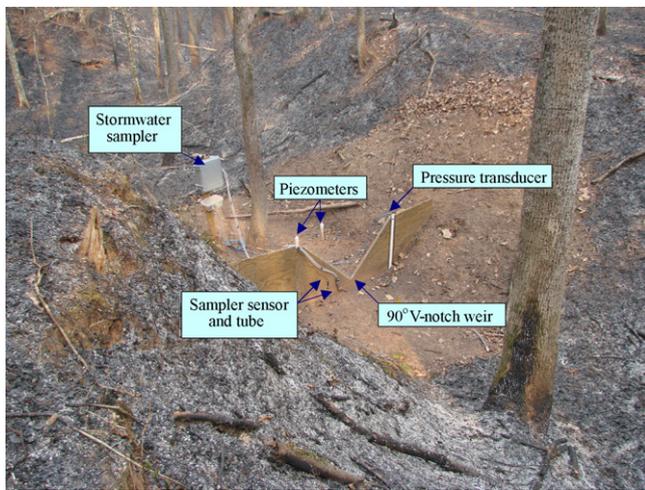
### 2.2. Gully description and instrumentation

Eight gullies ranging in size from 36 to 90 m long, 2.4 to 9.5 m wide, and 0.9 to 3.0 m deep were instrumented with 90° V-notch weirs between November and December 2005 (Table 1). Morphological properties of the individual gullies were measured following

the procedure outlined in Galang et al. (2007), with the exception of conducting the measurements between the headcut and weir instrumentation point instead of to the gully mouth. The contributing area for each gully, based on the relief and observed source of surface runoff, was mapped using a Trimble GeoExplorer 3 Global Positioning System (GPS) (Trimble Navigation Limited, Sunnyvale, California). Gully bed cover was assessed also following Galang et al. (2007), where four transects perpendicular to the gully length were established in the gully bed and surface cover at points along these transects recorded. A spherical densiometer was used to measure canopy cover at each transect location. Six treated gullies were adjacent to each other, within two management compartments, while the two reference gullies were in a separate location that was not scheduled for burning <5 km from the other six (Fig. 1).

Data-logging pressure transducers and stormwater samplers (Global Water Sampler WS750, Global Water Instrumentation, Gold River, California) were installed in each gully to measure stage height and collect runoff samples for analyses (Fig. 2). In each gully, the nadir of the weir's V-notch was set at about 15 cm above the soil surface, resulting in a dead storage space below this height. As such, below 15 cm stage height, a volume–stage relationship was developed using the gully slope and width at the point of weir instrumentation to estimate runoff volume. A positive change in stage indicated an influx of runoff (i.e., a flow event) and the flow rate was determined by dividing the change in volume by the time interval. A negative change in stage height after a flow event was considered "no flow." Stage height above 15 cm was converted to a flow rate using the Cone Equation (Water Measurement Manual, 2001). Runoff volume was calculated from the hydrograph area of each flow event, integrating flow rate by each time step (Volume at time  $i$  = Flow rate at time  $i \times 2$  min), then adding up all the volumes at each time step ( $\sum_{i=1}^n \text{Volume}_i$ ). Runoff volume for each gully was converted to depth by dividing by the contributing area of the gully.

Two HOBO® data-logging raingauges (Onset Computer Corporation, Pocasset, Massachusetts) were installed on site for local rainfall measurements. In addition, three ECH2O EC-20 soil moisture sensors (Decagon Devices Incorporated, Pullman, Washington) connected to HOBO® microstation data loggers (Onset Computer Corporation, Pocasset, Massachusetts) were installed atop the side



**Fig. 2.** Instrumented gully with a 90° V-notch weir, pressure transducer, piezometers, and stormwater sampler shortly after a prescribed burn at the Long Cane Ranger District, Sumter National Forest, South Carolina. Note: The weir was protected from fire while the gully was allowed to burn as evidenced by the ashen forest floor in the gully.

slope of three selected gullies, recording soil moisture content in the 0–20 cm depth.

### 2.3. Runoff collection and analysis

Sampling and gully observations were conducted from April 1, 2006 to March 12, 2007 for pre-burn data and from March 14, 2007 to March 12, 2008 for post-burn data. Since the majority of these gullies behave ephemerally, runoff sampling was conducted during events when the gullies flowed. During these flow events, an automatic sampler (Global Water Sampler WS750, Global Water Instrumentation, Gold River, California) collected a discrete sample of up to a maximum of 3 L per flow event. The discrete sampler was turned on when flow began and continued sampling at a maximal rate of 1 L/min under a 1.2 m head (rates are lower with less pressure head) until 3 L was collected or flow stopped. This sample rate was sufficient to collect samples over all stormflow events. The USGS precipitation gage in Greenwood, SC was monitored and sample pick-up was initiated after any rain event >1.5 cm. In general, the number of days between sample collections ranged from 2 to 10 days. In addition to event-based sampling, a biweekly visit to the site was performed to check the integrity of the instruments and the samplers at each gully. During sampling, containers with samples were taken out and replaced with newly acid-washed containers. Collected unfiltered samples were preserved frozen prior to analyses. Samples were analyzed for pH, conductivity, total suspended solids (TSS), and dissolved reactive phosphorus (DRP) following standard techniques (Clesceri et al., 1998). These same runoff samples were also analyzed for Ca, Mg, and K using ion chromatography (DX 500, Dionex Corporation, Sunnyvale, California).

### 2.4. Water table investigation

The role of the water table on gully runoff events was investigated following two techniques. First, maximum-rise piezometers were installed at 50 (shallow) and 275 cm (deep) depth in November 2006, about 1 m away from the weir on the downstream side. The rise in water line, as recorded by floating cork pieces, from each piezometer was measured every sample collection. Second, soil resistivity-transect surveys were conducted perpendicular to gullies using a SuperSting R8 IP resistivity meter (Advanced Geosciences Inc., Austin, Texas) from December to January 2006 (Winter) and in June 2007 (Summer). Soil electrical resistivity

is a technique used to investigate spatial and temporal variability in subsurface properties such as in groundwater exploration (Samouëlian et al., 2005). A resistivity survey was used in this research to determine the groundwater table depth in the area and to determine if it rose sufficiently during the wet winter season to initiate gully flow.

Field saturated hydraulic conductivity (Kfs) at the 25 and 50 cm depths were also measured at the downstream side of each weir using a Guelph Permeameter (SoilMoisture Equipment Corp., Santa Barbara, Ca). Soil samples were taken within 0–25 cm and 25–50 cm depth increments and analyzed for particle size using the hydrometer method (Day, 1965).

### 2.5. Prescribed burn treatment

Gullies designated for treatment were burned on March 13, 2007. Burning on a compartment scale was initiated using a helicopter drop of “ping-pong” balls filled with potassium permanganate and injected with glycol solution for ignition at about 10 m intervals. Drip torches were used for ignition along the compartment perimeters. Weather conditions during the burn were mostly clear skies, maximum air temperature of 80°F, relative humidity of 32% and wind speed of 11 km h<sup>-1</sup> moving to the southwest. Flame height reached 3.5 m but averaged approximately 1 m. Weirs and other instruments were protected from the burn by removal of fuels on the forest floor with a light leaf blowing. Just prior to the burn, eight HOBO® Type K thermocouples (Onset Computer Corporation, Pocasset, Massachusetts) were randomly installed on site, within the contributing areas of the six treated gullies and in between the mineral soil and forest floor.

Two weeks after the burn, ground cover of the contributing areas of each treatment gully was estimated using a point-transect method. At each side of the contributing area, two transects perpendicular to the gully were established at the 25 and 75% mark of the gully length. One transect following the orientation of the gully length was also established from the headcut to the contributing area boundary. From the gully to the boundary of the contributing area, points at 1 m intervals were assessed as covered with fully consumed dark litter layer (A), covered with partially consumed litter layer (P), exposed mineral soil (M), or exposed stone (S).

### 2.6. Soil core leaching

Soil core leaching was performed to investigate the potential of prescribed burning to mobilize nutrients. Using the same transects as for the post-burn cover estimates, which were established prior to the burn, pre-burn intact soil core samples (5 cm height × 7.5 cm diameter) were collected on the left side, moving at a direction away from the gully, of each of the transect midpoints. One week after the burn (1-week post-burn), intact soil core samples were collected on the right side of the transect midpoint. Three months after the burn (3-month post-burn), intact soil core samples were again collected on the right side of the transect midpoints, but 25 cm upslope of the position where the one-week post-burn samples were collected. Pre-burn sample cores were either mineral soil only (MS) or forest floor + mineral soil (FF + MS). Post-burn sample cores were charred organic material + mineral soil (Char + MS). Overall, 80 intact soil cores were collected in each sampling period.

Soil core leaching was performed by placing an empty core sleeve on top of the collected intact soil core sleeve to create a single larger column. The joint was secured by Parafilm® M and the bottom of the intact core was supported by a Whatman® 42 filter paper. The vertical orientation of the column was checked using a level. Deionized water equivalent to 5 cm rainfall (~1.5 pore volume) was added at the core surface and allowed to leach until the ponded water was gone and leachate loss ceased. The col-

lected leachate was analyzed for the same constituents as that of the runoff samples and using the same analytical procedures.

2.7. Data analyses

Hydrologic behavior of the gullies and inter-annual variation in storm response were examined graphically. Treatment effects of prescribed fire on gully flow production were analyzed by constructing a double-mass curve of cumulative runoff, summing the flows in all treatment gullies and both reference gullies. Change in slope of the double-mass curve following treatment was tested using a non-parametric Kruskal–Wallis test (Berryman et al., 1988; Zar, 1984). Soil core leachate data were analyzed using an Analysis of Variance (ANOVA; SAS Institute, 1999). Treatment mean comparisons using Tukey’s Honestly Significant Difference (HSD) were conducted for results that were significant ( $\alpha = 0.05$ ).

3. Results

3.1. Rainfall and soil moisture

During the second year of this study, the research site suffered from severe to extreme drought conditions (U.S. Drought Monitor). Average annual rainfall from 1971 to 2000 at the nearest weather station in Greenwood, South Carolina, 23 km from the research site, was 1176 mm [National Oceanic and Atmospheric Administration (NOAA), National Weather Service]. In 2006, the site received a total of 1020 mm, a 15% deficit (150 mm) from the 30-year average. In 2007, annual rainfall was only 660 mm, barely exceeding half of the average for the site. Although the 2006 total was near the long-term average, several winter and spring months were well below their long-term averages. In 2007, all 12 months fell below monthly averages, with the lowest comparative rainfall occurring in September,

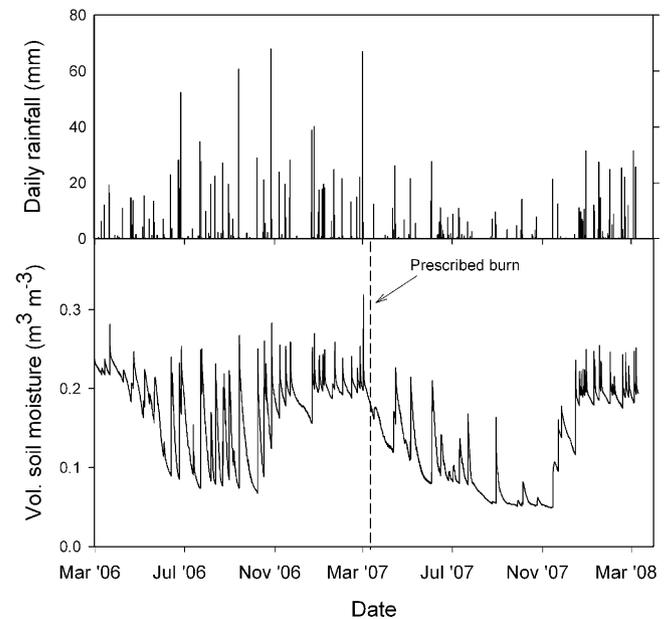


Fig. 3. Soil volumetric moisture content for the 0–20 cm depth on the bank of an instrumented gully in the Long Cane Ranger District, Sumter National Forest, South Carolina.

when a 76 mm deficit was recorded. Drought conditions continued into January 2008, with a 40 mm deficit. February 2008, on the other hand, exceeded the February monthly average. Overall, the average monthly deficit for 2006 was 13 mm while that for 2007 was 43 mm. During the pre-burn period, 34 rainfall events exceeded 12.7 mm depth, while only 14 did so in the post-burn period.

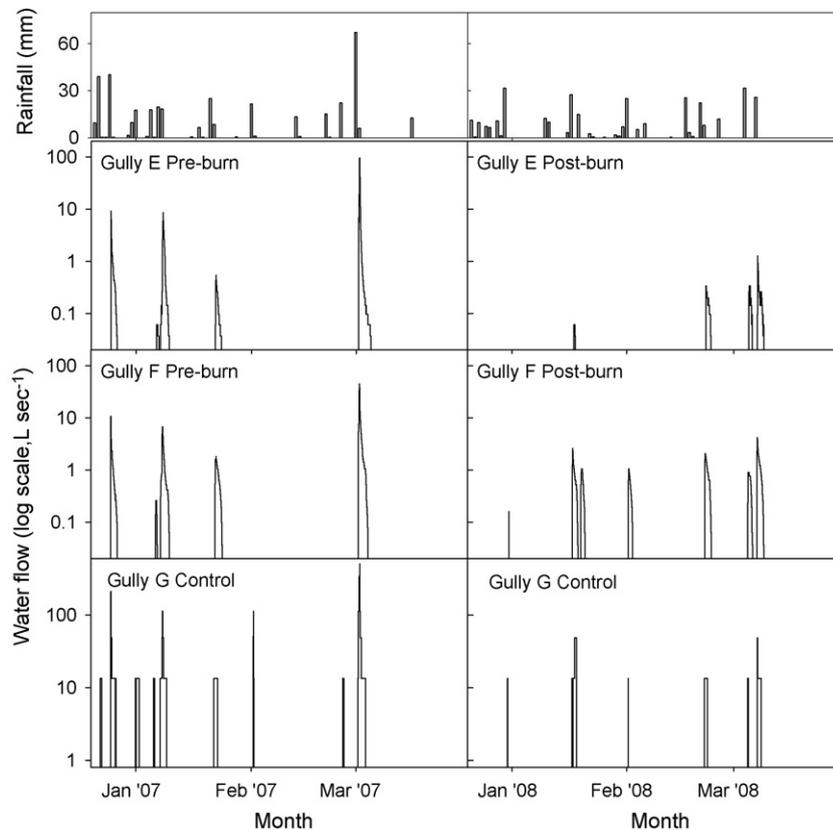


Fig. 4. Hydrographs for three flowing gullies and rainfall at the Long Cane Ranger District, Sumter National Forest, South Carolina. Runoff events occur red as pulses only between December to March.

**Table 2**  
Gully flow events for December to March before and after a March 13, 2007 prescribed burn of a 40-year-old loblolly pine stand at the Long Cane Ranger District, Sumter National Forest, South Carolina. No flow events were recorded during April to November for either period.

Gully	Number of flow events		Maximum recorded flow ( $L s^{-1}$ )	
	Pre-burn <sup>a</sup>	Post-burn <sup>b</sup>	Pre-burn	Post-burn
A	3	0	120.0	0
B	1	0	na <sup>c</sup>	0
C	2	0	na	0
D	3	6	113.3	0.03
E	6	4	95.9	1.3
F	4	7	44.7	4.2
G	10	9	511.7	48.8
H	0	0	0	0

Note: Rain events  $>12.7$  mm for pre-burn April to November and December to March is 22 and 12, respectively; rain events  $>12.7$  mm  $h^{-1}$  for pre-burn April to November and December to March is 19 and 5, respectively; rain events  $>12.7$  mm for post-burn April to November and December to March is 6 and 8, respectively; rain events  $>12.7$  mm  $h^{-1}$  for post-burn April to November and December to March is 8 and 5, respectively.

<sup>a</sup> April 2006 to March 12, 2007.

<sup>b</sup> March 14, 2007 to March 10, 2008.

<sup>c</sup> NA, not available due to instrument malfunction

The soil volumetric moisture content in the 0–20 cm depth atop the gully bank was consistent with the rainfall inputs (Fig. 3). Soil moisture content fell to below 5% during the driest month (September) of 2007.

### 3.2. Prescribed fire effectiveness

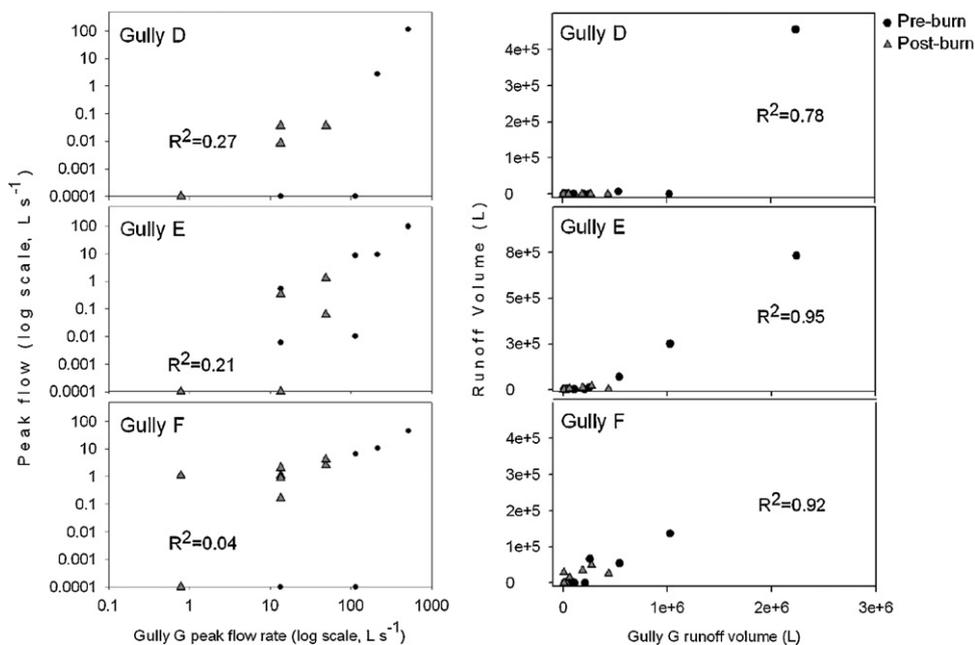
The prescribed burn succeeded in impacting nearly 100% of the existing forest floor cover (Table 1). On the average, 33 and 46% of the area post-burn was covered with fully (A) and partially (P) consumed litter layer, respectively. Mineral soil exposure (M) was observed for 20% of the area and 1% of the area was covered with rocks and stones (S). Variance across the gullies was greatest for S and M with a coefficient of variation of 118 and 42%, respectively. Fire temperature was measured in only two locations but peak temperature lasting for about 5 min varied  $>10$ -fold from 100 and 1200 °C.

### 3.3. Gully flow

Gully flow events occurred as a series of ephemeral pulses from December to March of each observation period (Fig. 4). During the

two-year study period, 48 rainfall events exceeding 12.7 mm depth were recorded (Table 2). Despite this rainfall, one of the reference gullies never produced flow, and three of the treatment gullies flowed three times or less. None of these relatively inactive gullies flowed during the post-burn period (Table 2). In the other four gullies, flow was recorded for 9–19 events, and the number of flow events was approximately equal for the pre- and post-burn periods. There were no recorded flow events from April to November during either pre-burn or post-burn sampling, although the number of rainfall events exceeding 12.7 mm was about equal for December to March and April to November (Table 2).

Although gully flows were infrequent, peak flow rates of the gullies were considerable. For the six gullies for which flow rates were recorded, these rates ranged from  $45 L s^{-1}$  to  $512 L s^{-1}$  ( $223 L s^{-1} ha^{-1}$  to  $731 L s^{-1} ha^{-1}$ ) (Tables 2 and 3). The relationships between the peak flow rate and runoff volume of the actively flowing treatment gullies (gullies D–F) and the active reference gully (G) are presented in Fig. 5. No difference in the pre- and post-fire relationships for individual storm peaks is apparent. Double-mass analysis of cumulative flow volumes in the treatment gullies (summed together) versus the active reference gully did not



**Fig. 5.** Peak flow and runoff volume comparison of three burned gullies (D–F) to one control gully (G), Long Cane Ranger District, Sumter National Forest, South Carolina. Values equal to zero were graphed at the lowest point (0.0001) in the log scale presentation for peak flow. Regression line is for pooled (pre- and post-burn) data.

**Table 3**

Summary of the 19 flow-producing events before and after the prescribed burn treatment for actively flowing gullies at the Long Cane Ranger District, Sumter National Forest, South Carolina.

	Pre-burn									
	10/27/06	11/16/06	11/22/06	12/22/06	12/25/06	01/08/07	01/24/07	02/06/07	02/13/07	03/02/07
Rainfall (mm)	67.8	19.6	28.2	38.9	40.1	18.3	24.9	21.6	13.2	67.1
Rainfall intensity (mm h <sup>-1</sup> )	22.9	9.7	6.6	8.6	13.7	13.2	7.6	7.6	13.2	14.7
Peak flow (L s <sup>-1</sup> )										
D	0	0	0	0	3	0	0	0	0	113
E	0	0	0	0	9	9	1	0	0	96
F	0	0	0	0	11	7	2	0	0	45
G	13	1	13	13	212	113	13	113	1	512
Peak flow (L s <sup>-1</sup> ha <sup>-1</sup> )										
D	0	0	0	0	3	0	0	0	0	142
E	0	0	0	0	31	29	2	0	0	320
F	0	0	0	0	54	34	9	0	0	223
G	19	1	19	19	304	162	19	162	1	731
Storm runoff volume (L)										
D	0	0	0	5	7206	0	0	0	0	455,573
E	0	0	0	197	69,165	249,065	12,330	2	0	730,952
F	0	0	0	0	54,068	137,069	66,475	0	0	632,247
G	47,831	10,127	110,508	100,604	538,246	1,024,006	255,249	206,645	39,719	2,240,345
Storm runoff depth (mm)										
D	0	0	0	0	1	0	0	0	0	57
E	0	0	0	0	23	83	4	0	0	243
F	0	0	0	0	54	69	33	0	0	316
G	7	1	16	14	77	146	36	29	6	320
	Post-burn									
	12/30/07	01/17/08	01/19/08	02/01/08	02/18/08	02/22/08	02/26/08	03/04/08	03/07/08	
Rainfall (mm)	31.5	27.4	14.7	24.9	25.4	22.1	11.9	31.5	25.7	
Rainfall intensity (mm h <sup>-1</sup> )	8.1	6.1	3.1	8.6	21.8	5.1	10.2	31.0	17.3	
Peak flow (L s <sup>-1</sup> )										
D	0	0	0	0	0	0	0	0	0	
E	0	0	0	0	0	0	0	0	1	
F	0	3	1	1	0	2	0	1	4	
G	13	49	1	13	1	13	1	13	49	
Peak flow (L s <sup>-1</sup> ha <sup>-1</sup> )										
D	0	0	0	0	0	0	0	0	0	
E	0	0	0	0	0	1	0	1	4	
F	1	13	5	5	0	10	0	4	21	
G	19	70	1	19	1	19	1	19	70	
Storm runoff volume (L)										
D	5	39	0	5	0	172	0	20	31	
E	0	1082	0	0	0	10,078	0	6599	19,439	
F	556	26,589	29,070	13,508	0	35,276	0	15,617	50,112	
G	29,052	434,795	4075	59,149	3793	184,593	7316	58,161	270,969	
Storm runoff depth (mm)										
D	0	0	0	0	0	0	0	0	0	
E	0	0	0	0	0	3	0	2	6	
F	0	13	14	7	0	17	0	8	25	
G	4	62	0	8	0	26	1	8	39	

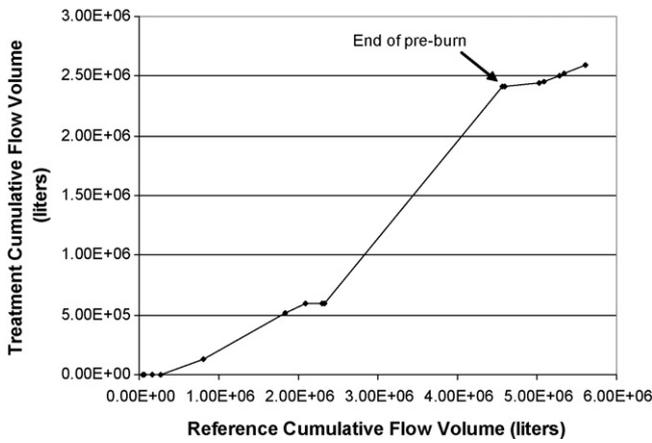
demonstrate a treatment effect (Fig. 6). In general, peak flow rate and runoff volume in the active burned gullies decreased in the post-burn period characterized by drought conditions.

### 3.4. Runoff quality

The relationship of six water quality parameters [pH, conductivity, total suspended solids, and Ca, Mg, and K concentration] is compared between one of the burned gullies and one reference gully in Fig. 7. The post-burn samples were either below or fell within the range of the pre-burn samples, with the exception of pH, which was higher, and TSS, which was lower than the pre-burn samples. Dissolved reactive phosphorus, which is of primary concern in nonpoint source pollution, was also analyzed but not

presented in the graph because most samples registered below the detection limit of 5 µg L<sup>-1</sup>. Of the 19 pre-burn samples analyzed for the burned gullies, only 9 samples (47%) contained DRP above the detection limit. For post-burn samples, 9 out of 16 samples (56%) were above the detection limit. The highest concentrations of DRP measured in pre-burn and post-burn samples from all the treated gullies were 27.3 and 30.7 µg L<sup>-1</sup>, respectively.

In comparison to the gully flow chemistry, the analysis of the soil core leachate demonstrated a significant increase in nutrient concentrations immediately after the burn, but in most cases, these elevated concentrations returned to initial concentrations three months after burning (Fig. 8). For example, in the FF+MS relative to the Ash+MS, leachate pH increased from 4.7 before the burn to 5.6 one week after the burn, but returned to pre-burn lev-



**Fig. 6.** Double-mass curve of cumulative flow volume for the active reference gully (x-axis) and the sum of all flows for the treatment gullies. Although the pre- and post-burn monitoring periods were equal in time, the drought conditions in the post-burn period produced much less gully flow.

els three months later. Similarly, leachate Ca one week after the burn was 3-fold higher, at  $1.57 \text{ mg L}^{-1}$  compared to pre-burn levels ( $0.44 \text{ mg L}^{-1}$ ), but decreased to  $0.79 \text{ mg L}^{-1}$  after three months. Magnesium followed a trend similar to that of Ca. DRP tripled (from  $4 \mu\text{g L}^{-1}$  to  $12 \mu\text{g L}^{-1}$ ) as a result of prescribed burning but three months later had also returned to the pre-burn level. The trends in conductivity and K leachate differed with conductivity increasing by  $9.4 \mu\text{S cm}^{-1}$  as a result of prescribed burning but remaining  $5.9 \mu\text{S cm}^{-1}$  higher after three months. Potassium also increased immediately after burning from  $0.79$  to  $1.93 \text{ mg L}^{-1}$  but further increased three months later to  $2.17 \text{ mg L}^{-1}$ .

3.5. Groundwater profile

Soil electrical resistivity profiles for two of the relatively active gullies (i.e., gullies E and G) show two regions of contrasting resistivity values (Fig. 9). From the surface up to about 6–8 m depth, high resistivity values ranging from about 500–3000  $\Omega \text{ m}$  are evident. Below 6–8 m depth, a low resistivity zone (<500  $\Omega \text{ m}$ ) is observed. Embedded within this low resistivity zone is an area of much lower resistivity (48–170  $\Omega \text{ m}$ ) is embedded. The resistivity image gener-

ated for summer (August) was similar to that of winter (January) although resistivity was generally lower in winter; consistent with greater soil moisture and higher groundwater.

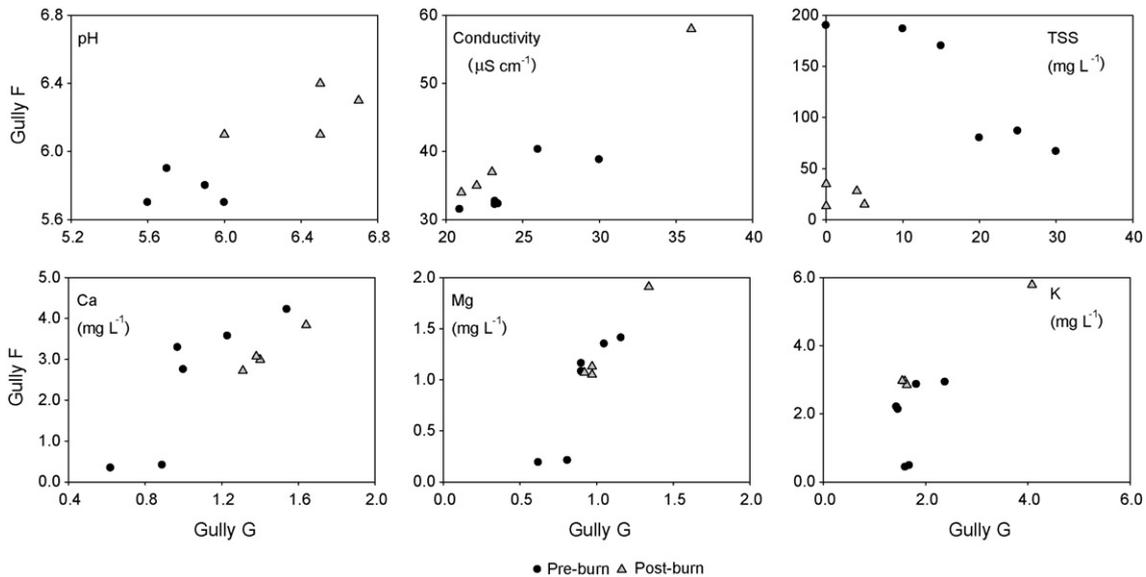
Piezometer readings indicated varying levels of water saturation in the gully beds during the seasons but also responded to rain events (Fig. 10). Of the eight gullies instrumented, four (i.e., gullies D–G) showed consistent signs of subsurface water activity in the shallow piezometer and in some instances, in the deep piezometer. A rise of the perched water table to the soil surface was also observed during some rain events (e.g., gully E in January 8 and March 2, 2007).

4. Discussion

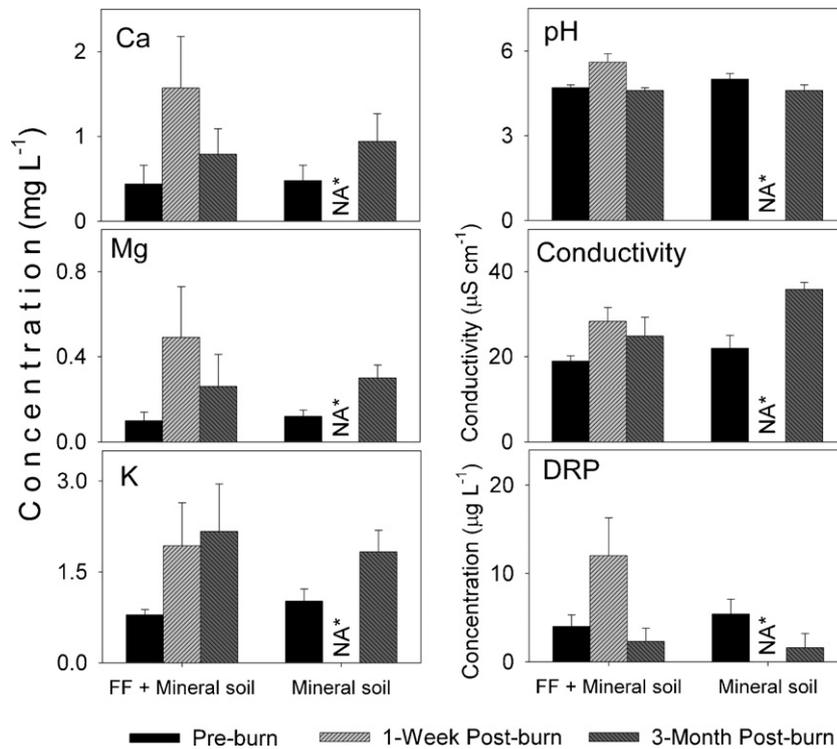
Even under mature forest cover, many southeastern Piedmont gullies, remnant of agricultural operations that ceased approximately 80 years ago, continue to flow during storms. Half of the eight gullies monitored in this study (i.e. gullies D–G) were hydrologically active, but surface morphology of neither the gullies nor their contributing areas explained the relative activity of the gullies.

Of those gullies that did flow, the relationship between the timing of flow events in the treatment gullies and reference gully did not change after the prescribed burn treatment. There were still rain events for which the active reference gully flowed and the treatment gullies did not. Both peak flow rate and runoff volume decreased during the post-burn period, although this is likely a result of the severe drought condition at the site and not of prescribed burning. The lack of larger storm events, especially during the post-burn period, greatly affected runoff production and the investigation of prescribed burn impact in this study. Nevertheless, post-burn peak flow and runoff volume relationship between the burned and reference gullies seems to fall within the range of pre-burn conditions (Fig. 5).

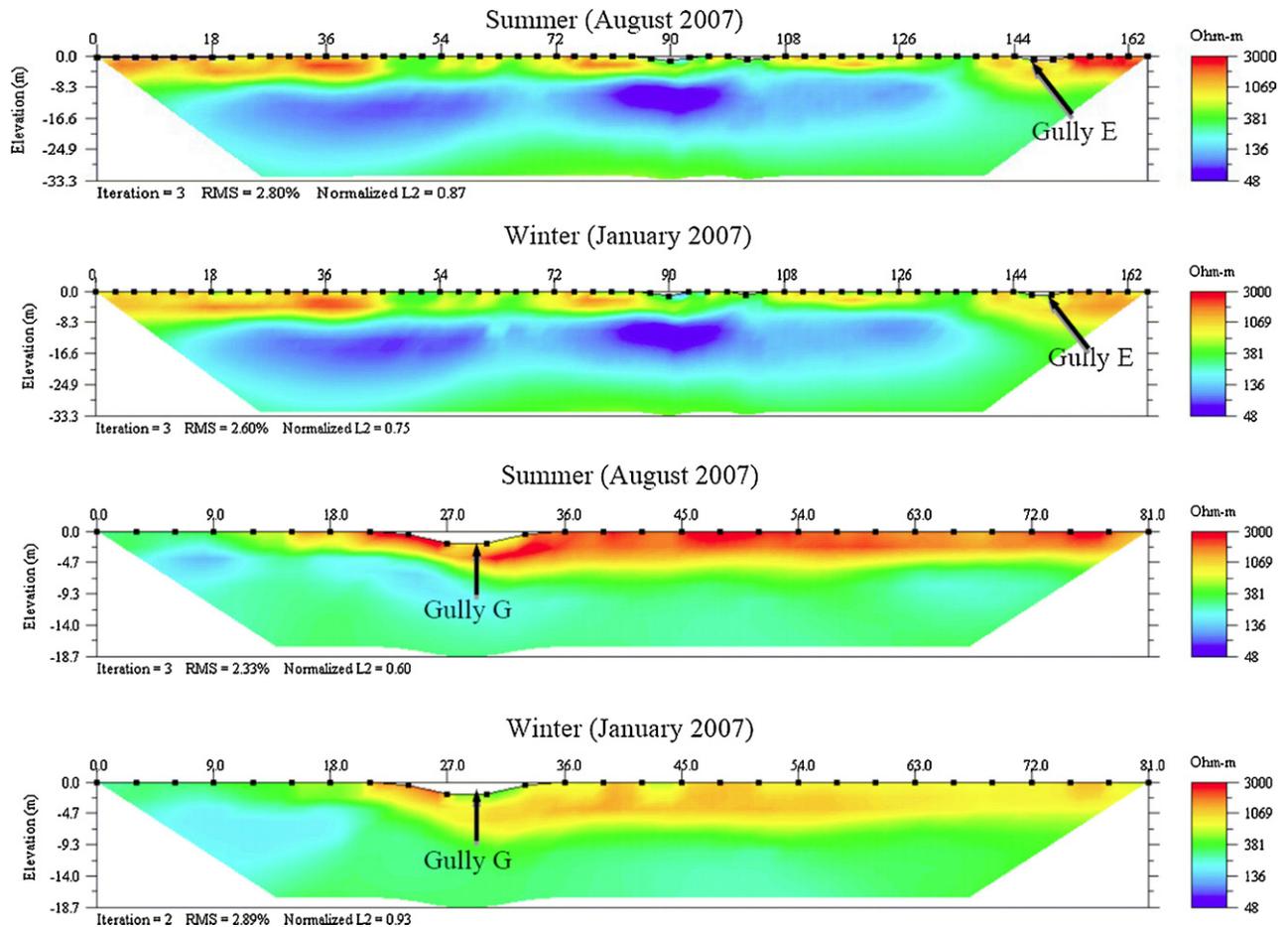
We anticipated that there would be an increase in the nutrient concentrations in gully runoff resulting from prescribed burning as has been shown in several previous studies of the same nature (e.g. Wright et al., 1976; Chorover et al., 1994; Boerner et al., 2004) but none was observed in this study. This may be a consequence of the timing of rainfall or the lack of rainfall immediately after the burn. Gully runoff quality parameters measured for post-burn samples did not deviate from that of the pre-burn samples. For



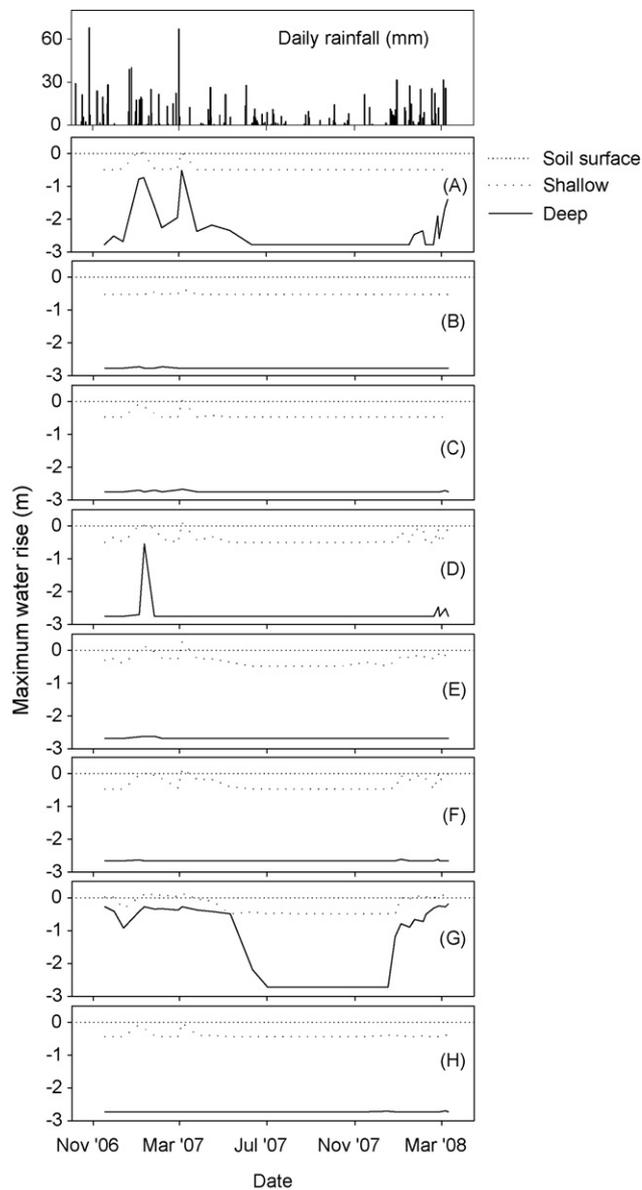
**Fig. 7.** Pre- and post-burn relationship of six runoff water quality parameters between a representative of the burned gully (F) and a control gully (G) at the Long Cane Ranger District, Sumter National Forest, South Carolina.



**Fig. 8.** Soil core leachate chemistry (mean ± 1SD) before (pre-burn), a week after (1-week post-burn), and three months after (3-month post-burn) prescribed burn treatment at Long Cane Ranger District, Sumter National Forest, South Carolina. (\*) NA indicates no data are available because it was impossible to separate ash from mineral soil.



**Fig. 9.** Cross-sectional image of soil resistivity created following a transect survey across two instrumented gullies at the Long Cane Ranger District, Sumter National Forest, South Carolina.



**Fig. 10.** Maximum water rise recorded in shallow (50-cm) and deep (275-cm) piezometers installed at the eight gullies on Long Cane Ranger District, Sumter National Forest.

DRP, all pre-burn sample concentrations were below the  $30 \mu\text{g L}^{-1}$  threshold concentration that could contribute to eutrophication of water bodies (Brady and Weilm, 2002), post-burn, only 1 out of 16 (6%) samples ( $30.7 \mu\text{g L}^{-1}$ ) exceed this threshold.

The observed increase in soil core leachate concentrations as a result of burning differed from field observations. This difference is not surprising, however, given the ability to control the timing of leaching (i.e., precipitation) events relative to the burn and the much simpler hydrologic flow paths relative to field conditions. The increase in leachate concentrations is most likely due to the mineralization of nutrients resulting from combustion of the forest floor material (Neary et al., 1999; Carter and Foster, 2004; Certini, 2005). Higher cation concentrations resulted in higher pH and conductivity (Fig. 8). The increase in leachate DRP immediately after the burn is also likely due to ash addition (Van Lear and Danielovich, 1988; Gardina et al., 2000) rather than the release of P from mineral soil (Galang et al., 2010). The subsequent decrease in P could be due to the immobilization of P by microorganisms or the binding to Ca, iron (Fe), or aluminum (Al) (DeBano and Klopatek, 1988).

Nonetheless, the magnitude of increase in DRP even in the laboratory is not significant in terms of nonpoint source pollution as it is below the critical concentration of  $30 \mu\text{g L}^{-1}$  that would contribute to pollution (Brady and Weilm, 2002).

The soil core leaching study also demonstrated the importance of the timing and intensity of rain in the transport of the nutrients in runoff following burning. Neary et al. (1999) stated that “impacts of fire on hydrology and sediment loss can be minimal in the absence of an immediate precipitation event.” All water quality parameters measured for the leachate were significantly higher one week after the burn but all, except K, were statistically indistinguishable from pre-burn levels three months later. These results suggest the significance of proper scheduling of prescribed burning in order to minimize potential nutrient loss and excessive erosion from the site. Further, it highlights the possible consequences of catastrophic wildfires if immediately followed by a torrential rain. In the Southeastern United States, prescribed burning is either conducted during late fall to early winter (dormant season burn) or spring (growing season burn) (Fairchild and Trettin, 2006). Since the observed activity of the gullies were during December to March, the dormant season burn might not be advisable on these sites as they might yield higher sediment and nutrient loss.

The seasonal occurrence of gully flow events coincided with seasonally higher groundwater table and high stream flow suggesting a contribution of groundwater to gully flow events. Estimates of the runoff depth in each flowing gully showed that in a few events (e.g., January 8 and March 2, 2007) runoff greatly exceeded rainfall. Clearly, the subsurface contributing areas to these active gullies must be larger than the surficial contributing areas for these results to occur.

A groundwater table that rises to the surface may generate event-based flow in excess of rainfall inputs (Dunne and Black, 1970). Soil electrical resistivity profiles for two of the relatively active gullies (i.e., gullies E and G), indicated that the groundwater table, identified by resistivities of  $5\text{--}100 \Omega \text{m}$  (Samouëlian et al., 2005), was approximately 6–8 m below the surface (Fig. 9). The lower resistivities in the winter (January) image relative to summer (August) also indicate soil moistening during the winter. This moistening, however, did not result in a groundwater table that reached the gully bed, although in some instances, water level rise was measured in deep piezometers. In gully G, the deep piezometer reached to within 4 m (i.e., 1.3 m gully depth plus 2.7 m piezometer depth) of the uneroded bank surface. Deep groundwater rise to this depth may have contributed to saturation of soil at shallower depths but could not be solely responsible for initiation of gully flow during the wet winter months.

In contrast, the flow of the active gullies correlated well with the water level recorded in the shallow piezometers. For gullies that flowed during wet winter months (gullies D–G), near surface water rise was recorded in all shallow piezometers indicating perched water between the 0 and 0.5 m depth. The perched water table, in some instances, rose through the soil surface with the incidence of these saturations to the surface coinciding with the flow events in the actively flowing gullies. Many studies have demonstrated the importance of subsurface flow in generating saturation overland flow (e.g. Ragan, 1967; Freeze, 1972; Dunne et al., 1975). Dunne and Black (1970) also emphasized the importance of poorly drained soils in the production of saturation overland storm runoff. Auger boreholes and measurement of saturated hydraulic conductivity (Kfs) in the gullies revealed that gullies that regularly flowed (gullies D–G) have sandy clay loam texture at the 25–50 cm depth with an average Kfs of  $0.49 \text{ cm h}^{-1}$ . Gully G has the lowest Kfs in the 0–25 cm depth, which could explain its higher activity compared to the rest of the gullies. Gullies A and C, which flowed only two to three times in the two-year observation period also have sandy clay loam texture at the 25–50 cm depth but have an average Kfs of

**Table 4**

Textural class and field saturated hydraulic conductivity (Kfs) at the 0–25 and 25–50 cm depth for eight gullies at the Long Cane Ranger District, Sumter National Forest, South Carolina.

Gully	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Kfs (cm h <sup>-1</sup> )
A	0–25	69	15	16	0.39
	25–50	59	16	25	1.56
B	0–25	52	21	28	19.01
	25–50	66	15	18	18.14
C	0–25	76	13	11	2.81
	25–50	65	15	20	0.58
D	0–25	59	20	21	1.23
	25–50	59	20	21	0.82
E	0–25	61	23	16	16.65
	25–50	51	19	30	0.03
F	0–25	54	16	30	13.20
	25–50	53	13	34	0.45
G	0–25	57	21	21	0.17
	25–50	67	11	22	0.64
H	0–25	35	30	36	29.95
	25–50	47	15	38	0.35

1.07 cm h<sup>-1</sup>. Gully B that did not record any water in either the shallow or deep piezometer had a 50-cm Kfs of 18.14 cm h<sup>-1</sup> (Table 4). One inconsistency is Gully H, this gully had a low Kfs at 50 cm depth but did not flow during the study possibly as a result of its small contributing drainage area. Otherwise, these Kfs values are consistent with the formation of perched water tables in the gully bed subsurface through water impedance; a process observed previously in investigations of interflow (Greco, 2008).

Although all gully flow during this study was observed in winter, summer rain events of high intensity and long duration could exceed subsurface Kfs values and saturate the soil sufficiently to induce gully flow. In the US Southeast this situation is possible during tropical depressions or hurricanes, which are not uncommon in the region (Hansen and Law, 2006).

As such, gully flow initiation can be summarized as follows: During summer, evapotranspiration between rain events is so high or rain intensity and duration is insufficient to saturate the gully bed (with or without the restrictive clay substrate) to induce flow; water collected in the gullies infiltrates, in which case, the gullies serve as recharge zones. During winter, rain events coupled with low evapotranspiration allow for the saturation of the gully bed with low Kfs layers, upon which, runoff collected in gullies further saturates the bed. Subsequent rain on a saturated gully bed readily yields runoff, and runoff from the contributing area draining to the saturated gully is readily transported downslope. If the gully bed is close to the groundwater table, saturation is readily facilitated and gullies flow more frequently. If a restrictive layer is absent from a gully, rain intensity and/or runoff accumulation do not exceed water infiltration and percolation rate and the gully behaves as a recharge zone. Finally, small contributing areas may limit flow occurrence in the gullies regardless of other conditions.

## 5. Conclusions

This study provides evidence of the varying nature of gullies under mature loblolly pine in the Piedmont region of Sumter National Forest, South Carolina. Hydrologic activity of these remnant agricultural gullies was highly variable. Not all of the eight gullies studied flowed during rain events, even during the wet winter months of each year, indicating that some gullies are conduits for runoff transport downslope while others are not. Surficial mor-

phology of neither the gullies nor their contributing area explained the variability in hydrologic activity of the gullies. Flow occurrence in these gullies seems to be controlled by the formation of a perched water table in the restrictive zone below the gully bed, although in some cases, there is also evidence of possible contribution of the groundwater table. Post-burn observations provided no evidence that the prescribed fire applied to the treatment watersheds affected the hydrologic behavior of gullies. Nutrient mobilization immediately after rain, as approximated by soil core leaching, was insufficient to cause significant contribution to nonpoint source pollution. Overall, the inter-annual variation in the behavior of the gullies was large while a prescribed fire treatment effect was not discernible.

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