Ecohydrological response to a geomorphically significant flood event in a semiarid catchment with contrasting ecosystems

Hugo A. Gutiérrez-Jurado,[1] Enrique R. Vivoni,[1] Erkan Istanbulluoglu,[2] and Rafael L. Bras[3]

Received 23 June 2007; revised 11 August 2007; accepted 15 August 2007; published 12 December 2007.

[1] Climate and topographic conditions in a first-order semiarid catchment in central New Mexico have given rise to opposing hillslopes characterized by different soil profile, vegetation and landform characteristics. In this study, we present the differential response of these two hillslope ecosystems to a geomorphically significant (GS) flood event based upon field observations of rainfall, soil moisture and peak channel discharge. We illustrate the role played by slope position, soil properties and vegetation on soil moisture dynamics and runoff production. Furthermore, we document observed geomorphic changes in the opposing slopes. Analysis of the hillslope and channel response to this exceptional event provides insights on the terrain-soil-vegetation interactions acting on the movement of water and sediments through the semiarid system. **Citation:** Gutiérrez-Jurado, H. A., E. R. Vivoni, E. Istanbulluoglu, and R. L. Bras (2007), Ecohydrological response to a geomorphically significant flood event in a semiarid catchment with contrasting ecosystems, *Geophys. Res. Lett.*, *34*, L24S25, doi:10.1029/2007GL030994.

1. Introduction

[2] An increasing number of scientific studies stress the importance of measuring and understanding soil moisture dynamics and the controls exerted by vegetation [e.g., *Cordova and Bras*, 1981; *Rodríguez-Iturbe and Porporato*, 2004; *Newman et al.*, 2006]. Vegetation plays a significant role in the partitioning of mass and energy inputs, especially for water-limited semiarid landscapes [*Wilcox et al.*, 2003; *Kurc and Small*, 2004], and modifies hydrologic dynamics in ecosystems during storm and interstorm periods. In semiarid areas with terrain variability, close interaction also exists between hillslope and vegetation characteristics [*Istanbulluoglu and Bras*, 2005; *Gutiérrez-Jurado et al.*, 2006] which can significantly impact local water and energy fluxes. For instance, in semiarid climates, terrain aspect can lead to establishment of different plant communities and functional types on opposing hillslopes. Organization of steep hillslopes around the channel network can also induce overland or interflow which can become an additional water source for downslope sites [*Wilcox et al.*, 2003; V. Ivanov et al., Vegetation-hydrology interaction over complex terrain. II: Energy-water controls of vegetation spatio-temporal dynamics and topographic niches of favorability, submitted to *Water Resources Research*, 2007, hereinafter referred to as Ivanov et al., submitted manuscript, 2007], and hence modify soil moisture dynamics along slope positions.

[3] To our knowledge, few studies have addressed the effects of terrain aspect and slope on ecohydrological responses to a geomorphically significant (GS) event, defined here as a flood that alters landscape form. In this study, we present the different responses of opposing hillslopes with varying plant communities during a major flood event. We believe this is the first time that hillslope and channel responses, and the effects of ecosystem and soil characteristics, are documented in a first-order semiarid catchment. Observational analysis of this flood event has implications for understanding the impact of soil and vegetation properties on hillslope evolution. Our focus here is to demonstrate from a series of in-situ observations that soil properties and vegetation exert controls on soil moisture dynamics. We also compare runoff and erosion responses in the opposing ecosystems and tie this to the generation of a significant flood in the main channel.

2. Methods

2.1. Study Area

[4] The study site is located in the northwest part of the Sevilleta National Wildlife Refuge (SNWR) site in central New Mexico (Figure 1a). The site comprises a small ($\sim$0.1 km^2) first-order catchment dissected by an east-flowing ephemeral channel giving rise to opposing north and south facing slopes and an east facing headslope. The slopes sustain distinctive ecosystems: (1) a juniper-grass savanna on the north facing slope consisting of juniper (*Juniperus monosperma*) and dense black grama (*Bouteloua eriopoda*); (2) a xeric shrubland on the south facing slope dominated by creosotebush (*Larrea tridentata*) with sparse fluff grass (*Erioneuron pulchellum*); and (3) an east facing headslope comprising the ecotonal boundary between the two slopes. These ecosystems exhibit differences in plant phenology, density, structure and biomass, as well as, in rooting structure and plant water uptake. Soils in the catchment are characterized by: desert pavements on the upper flat surfaces; sandy soil matrices with a high fraction of boulders and gravels; and $CaCO_3$ horizons intersecting the hillslopes at various depths [*McMahon*, 1998]. The climate in the area is semiarid with a mean annual rainfall of $\sim$255 mm and a bimodal rainfall regime with high

[1]Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, New Mexico, USA.
[2]Department of Geosciences and Department of Biological Systems Engineering, University of Nebraska at Lincoln, Lincoln, Nebraska, USA.
[3]Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.

0094-8276/07/2007GL030994

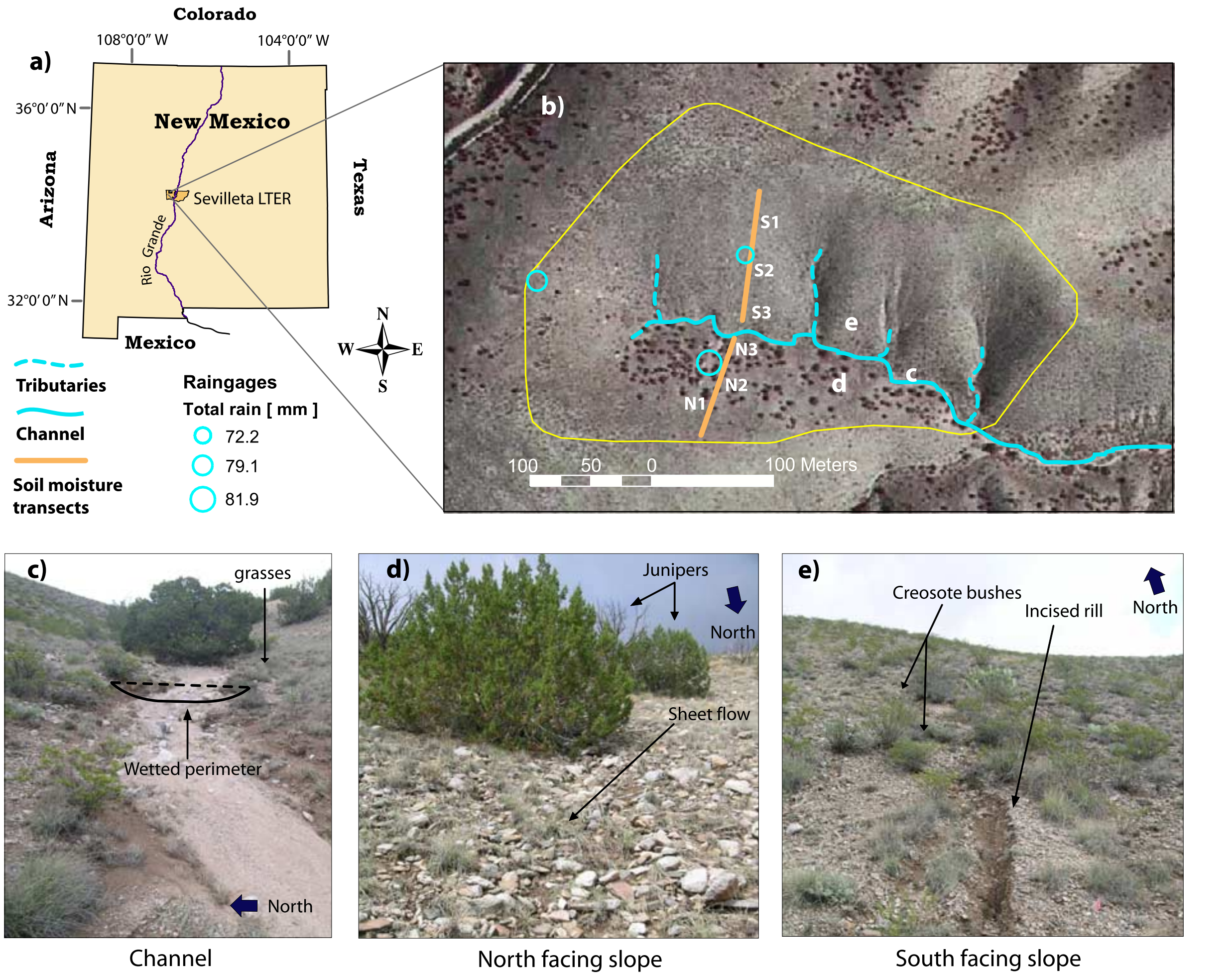

Figure 1. (a) Study site location in Sevilleta, NM. (b) 2-m aerial orthophoto of the study catchment depicting the boundary, the east flowing ephemeral channel, and the location of the soil moisture transects and three rain gauges. (c) Channel cross section one day after the flood event (wetted perimeter determined by fallen grasses). (d) North facing slope depicting the juniper trees and the observed evidence of overland sheet flow. (e) South facing slope with the creosotebush and a new incised rill (~0.5 m deep).

intensity summer storms and lower intensity winter rains. Field observations indicate that significant runoff and erosion can occur in response to convective rainfall during the North American monsoon.

2.2. Hydrologic Instrumentation and Observations

[5] An instrument network consisting of 24 water content reflectometers (WCR) and 3 tipping-bucket rain gauges was deployed along transects in the opposing north and south facing slopes (Figure 1b). WCRs were placed horizontally at: (1) 10 and 20 cm soil depths to capture the vertical movement of water pulses; and (2) at open intercanopy and within canopy sites at three positions along each slope, to assess the effect of the canopy patch. As WCRs record the electrical transmissivity of the soil as a function of water content, the signal was converted to volumetric soil moisture through in-situ calibration using gravimetric sampling across a range of conditions. During the period, three rain gauges measured the rainfall amounts in the catchment. All the instruments recorded at 30 minutes intervals. Finally, post-flood field observations allowed us to determine the major erosional effects of the event and estimate the peak channel discharge.

3. Response to GS Flood Event

3.1. Storm Rainfall and Erosional Observations

[6] A series of intense rainfall pulses were recorded in the study catchment from July 28 to 29, 2006, with a total accumulation of ~80 mm in an 18 hour period (Figures 2a and 2b). The total storm rainfall was approximately 1/3 of the annual precipitation at the site and was estimated to correspond to a return period between 150 and 200 years [*Bonnin et al.*, 2004], with maximum rainfall intensities of 25 mm in a 30-min period. The sequence of rainfall events occurred during the exceptionally wet 2006 North American monsoon season in the southwestern U.S. [e.g., *Magirl et al.*, 2007].

[7] The storm event led to a flood response, exceeding the bankfull stage at places along the main channel. The event was clearly detected via its impact on fallen grasses in the downstream direction, as well as, the movement of soil

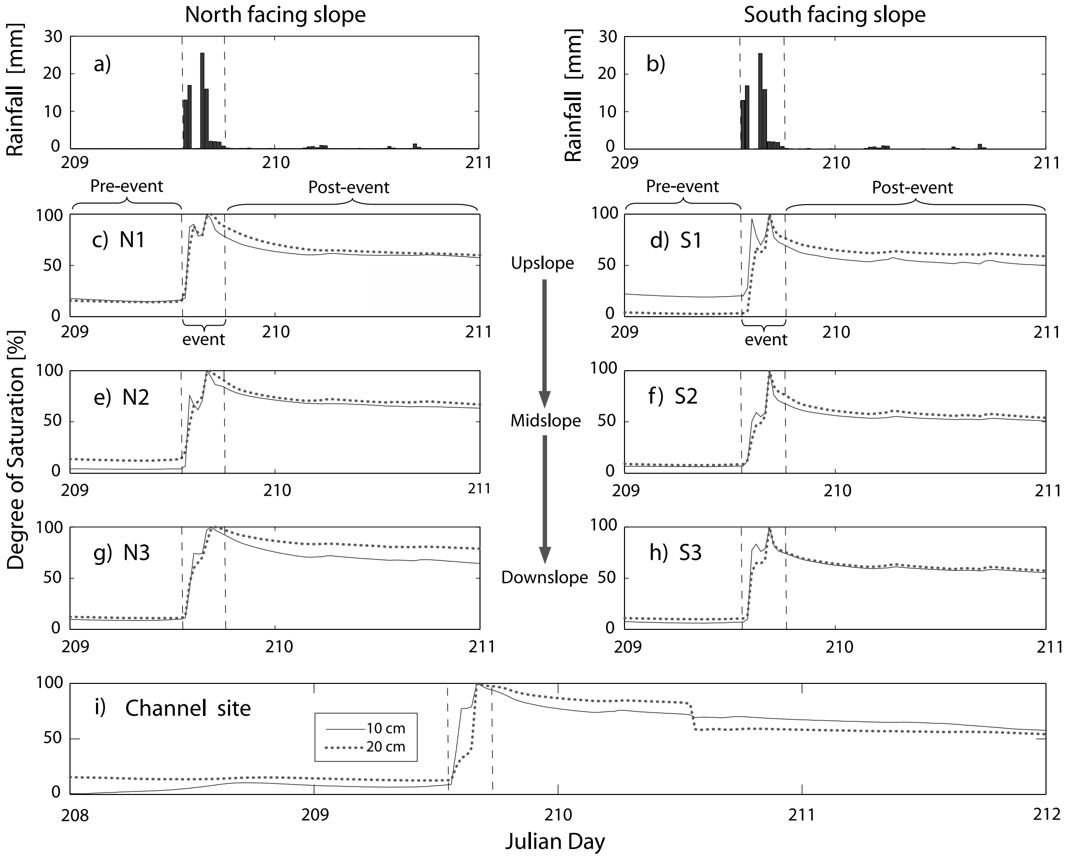

Figure 2. Rainfall and soil moisture observations at 10 cm (solid line) and 20 cm (dotted line) depths at each sampling point. Soil moisture is given as degree of saturation ($S = \theta/n$, where θ is volumetric water content and n is porosity) in percent (%). (a, b) Rainfall hyetographs at two rain gauges. (c) North facing upslope (N1), (e) midslope (N2), and (g) downslope (N3) sites. (d) South facing upslope (S1), (f) midslope (S2), and (h) downslope (S3) sites. (i) Channel site.

and large clasts. Relatively large boulders (~0.3 m in diameter) were transported in the channel (Figure 1b). Moreover, the flood event led to the development of several rills, ~0.5 m deep and several meters in length, on the toe of the south facing slope (Figure 1e), suggesting the generation of highly erosive runoff. No evidence of rill incision was found on the north facing slope, although fallen grass-cover suggested that overland sheet flow occurred in large sections (~2–3 m in width) near the slope toe (Figure 1d). Furthermore, intercanopy spaces in the north facing slope showed evidence of sediment retention behind grassy mounds (not shown).

3.2. Hillslope Hydrologic Response

[8] Volumetric soil water content observations at 10 and 20 cm depths obtained prior to, during, and after the flood event were analyzed to assess the effects of terrain aspect and slope position on soil moisture dynamics. Soil moisture time series (July 28–30, 2006) at intercanopy locations along each slope and in a channel site below the transects are shown in Figure 2. Note that soil conditions prior to the flood event were uniformly dry at the sampling depths at most sites. Two exceptions are the south facing upslope (Figure 2d) and the north facing midslope sites (Figure 2e), where the shallower (deeper) layer had higher soil moisture, respectively. Differences in antecedent conditions for these two sites may be a function of local soil properties acting to retain water from a small rainfall pulse recorded ~36 hours before the major flood event.

[9] Rainfall hyetographs show a distinct double peak with rainfall distributions of 40 and 60% of the total accumulation, respectively, and a lag time of ~1 h between storm pulses (Figures 2a and 2b). Each hillslope location exhibits a response to the two peaks with a more pronounced increase in soil moisture for the upslope sites on each hillslope (Figures 2c and 2d). This is possibly due to the proximity of these sites to the flat surface above the headslope. Note that high slopes (~20° and 17° for north and south facing slopes) can also shield these areas from an approaching storm (Ivanov et al., submitted manuscript, 2007). Position along the slope also has a strong effect on the rising and falling limbs of the soil moisture response. Upslope positions respond faster to precipitation, but also decay at a faster rate, presumably due to the redistribution of water in the downslope direction. The downslope sites, on the other hand, exhibit slower soil moisture decays, as contributions from upslope locations arrive following the end of the storm. Differences in soil moisture response between the two slopes clearly show the north facing sites remain wetter than the south facing sites, which is related to higher moisture retention due to high amounts of $CaCO_3$,

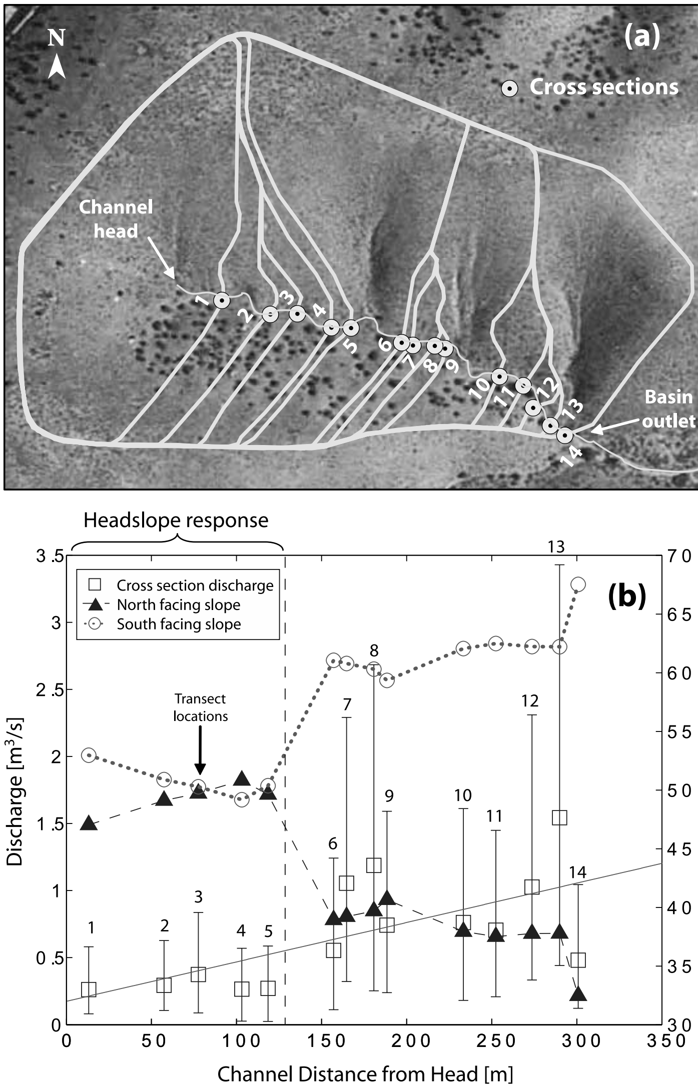

Figure 3. (a) Aerial orthophoto depicting the cross section locations (labeled 1 to 14) used to estimate peak discharge and contributing areas (outlines). (b) Variation of the channel discharge (Q_p in m^3/s) and the percentage of total contributing area from each slope (%) as a function of channel distance (m). Headslope contributing area is partitioned into north and south facing segments (not shown). Solid line represents the linear regression of Q_p with channel distance. Vertical bars on the Q_p estimates represent the uncertainty arising from estimation of Manning's n at each cross section.

silt, clay and organic matter [*McMahon*, 1998; *Gutiérrez-Jurado et al.*, 2006].

[10] Soil moisture observations in a channel site at the toe of the slopes (Figure 2i) show the dynamical response in the narrow floodplain area (~1 m width), where the sediment profile quickly became nearly saturated down to 20 cm after the second peak. Saturated conditions in the channel are sustained for a longer period as compared to the slope locations, suggesting the presence of overland and subsurface flow for up to ~2 hours, where visual evidence (i.e., fallen grasses) confirms the overland flow. Interestingly, the soil moisture dynamics in the deeper channel sediments exhibit a slow decay, indicating sustained water input, followed by a sharp decrease at the 20 cm depth. From these observations, we cannot infer the physical cause for this sudden soil moisture decrease.

3.3. Channel Hydrologic Response

[11] Inferences of peak discharge during the flood event are available from a series of post-flood observations. Maximum flood stage was determined at 14 cross sections based on fallen grasses in the wetted perimeter and sediment deposition behind grass patches on the channel banks. Cross section geometry and reach slope were obtained through a high precision, differential GPS survey (~5 cm accuracy in *x*, *y*, *z*). Peak discharge (Q_p) at each section was then determined using the Manning equation, based upon roughness values estimated using *Cowan* [1956], which accounts for irregularities of the channel geometry, channel obstructions and vegetation, and reach meandering. Given the uncertainties in Manning's n for the flood event, we computed Q_p for a range of possible roughness values. In general, high n were obtained for upstream sections with consistently lower estimation uncertainty, while the lower reach was characterized by low n with larger uncertainty. In

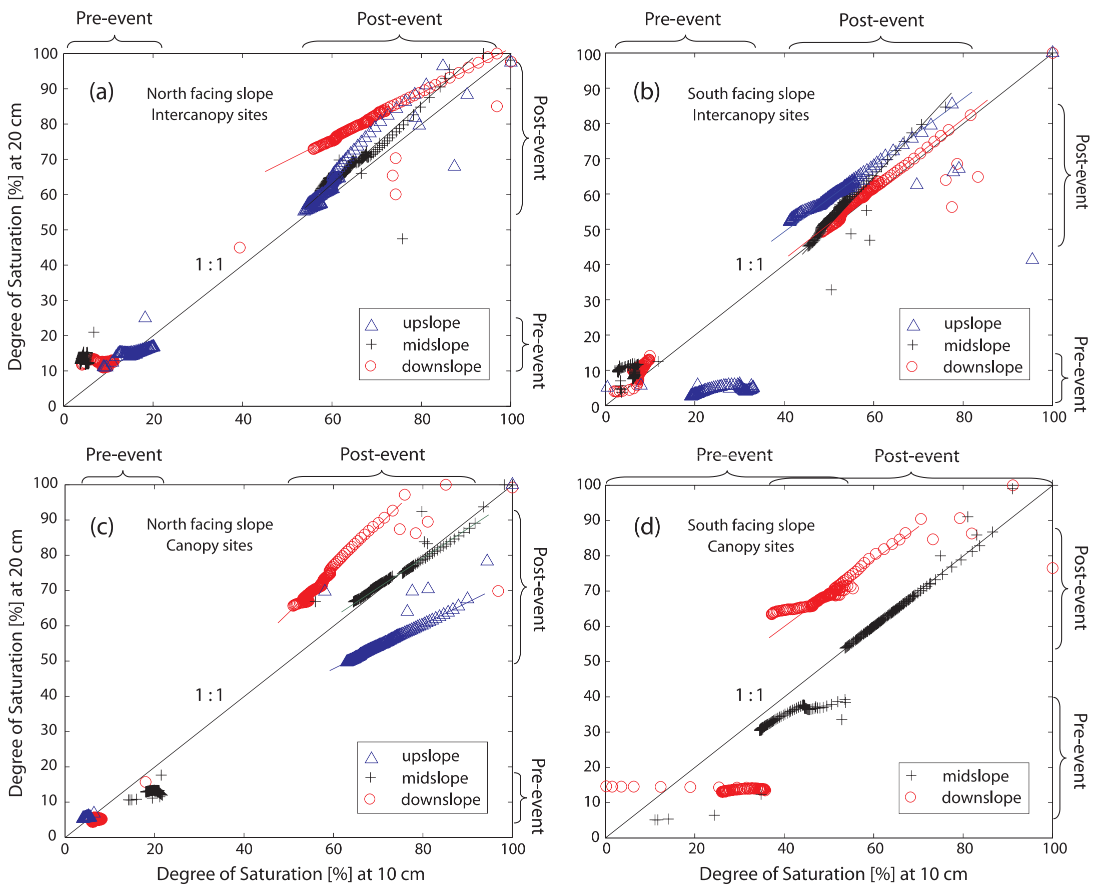

Figure 4. Observed relations between the degree of saturation (*S* in %) at 10 cm and 20 cm soil depths for the pre- and post-event conditions. (a) North facing intercanopy sites. (b) South facing intercanopy sites. (c) North facing canopy (juniper) sites. (d) South facing canopy (creosotebush) sites. The slope position effect is explored by comparing the upslope (triangles), midslope (crosses), and downslope (circles) locations.

addition, we derived the contributing area (A) at each cross section using delineations of a 10 m digital elevation model and visual corrections based on the 2 m orthophoto and site observations (Figure 3a).

[12] An estimate of Q_p as a function of distance from the channel head is presented in Figure 3b. The flood wave likely propagated through the main channel following the first rainfall pulse (see Figure 2i). Note the increasing trend in Q_p with downstream distance (linear trend of 0.3 m^3/s per 100 m, $R^2 = 0.44$), suggesting that transmission losses were minimized due to previous wetting from the first rainfall pulse. The mean and maximum Q_p over the channel length (∼300 m) were estimated at 0.68 m^3/s and 1.54 m^3/s. Based on the site contributing area (A), the peak runoff rate (R) varied from 31 to 118 mm/hr, with a mean basin R of 60.5 mm/hr (±23.7 mm/hr). This compares well with the total rainfall of 77.7 mm averaged at the rain gauges, suggesting an exceptional runoff coefficient of 0.78 for the flood event. Note the variability in Q_p among sites is quite large (±0.4 m^3/s), but can be explained by increases in A as small tributaries enter the main channel.

[13] Flood contributions from each slope may be inferred from the relative amounts of A along the channel. Figure 3b presents the percentage of A from each hillslope at the cross section sites. Relative contributions are nearly equal from the channel head to ∼125 m downstream. Along with the fairly uniform Q_p in this reach, this suggests the upper reach response is driven by the headslope with lower runoff amounts generated in the slopes. Thereafter, the south facing slope is more important in terms of the total catchment area (up to 68% of A at the outlet). Due to the incised drainages on the south facing slope (Figure 3a), the channel discharge increases downstream of the tributary confluences. In addition, minor discharge decreases along the main channel are observed due to local losses in the lower reach. This suggests the south facing slope dominates the flood response in the lower reach with minor contributions from the north facing slope. Clearly, the two slopes contribute different runoff amounts to the channel flood response.

4. Controlling Factors on the Hydrologic Response

[14] Post-field observations indicated that different runoff production modes may exist in the north and south facing slopes. Rapid development of large rills in the south facing slope are evidence of more runoff erosion, while overland sheet flow and sediment accumulation maybe an indication of less erosion in the north facing slope. This suggests that geomorphically significant flood events may be responsible

for punctuated changes in catchment morphology that differentiate landforms in the opposing slopes. Further, the different runoff modes in the opposing ecosystems seem to follow the conceptual model of *Wilcox et al.* [2003] for conserving and non-conserving slopes. With increased vegetation cover, the north facing slope retains a higher amount of runoff and sediment in the hillslope. Sparser vegetation cover on the south facing slope leads to a greater connection of intercanopy patches that facilitate downslope transport.

[15] To further study the runoff production regimes, we present an analysis of the effects of slope position, soil properties and vegetation on soil moisture dynamics in the two slopes in Figure 4. Analyses are based on the relation between degree of saturation (S) at the 10 and 20 cm depths for pre- and post-event conditions. The primary comparisons utilize the post-event relations as these depict soil drying or the recession behavior after complete surface saturation during the flood event. When the decay rate is faster at 10 cm depth relative to the 20 cm depth, the slope of the relation will be lower than the 1:1 line and vice versa. Furthermore, the position of the soil moisture relation with respect to the 1:1 line indicates if conditions are consistently wetter or drier at a soil depth.

[16] The evidence at each site suggests that slope position (upslope, midslope and downslope) has important effects on the soil moisture dynamics, despite the similar soil profile properties along the slopes [*McMahon*, 1998]. North facing intercanopy sites (Figure 4a), for example, show recession rates in the slope positions indicating downslope soil moisture redistribution. The upslope (downslope) site has a faster (slower) decay of deep water content indicating a soil moisture release (gain) along the subsurface hillslope path. Furthermore, the midslope positions in each slope (Figures 4a, 4b, 4c, and 4d) have nearly uniform soil moisture with depth and similar drying rates, suggesting these areas transmit moisture pulses downslope. While these dynamics are more typical in humid areas [*Salvucci and Entekhabi*, 1995], the nearly complete saturation of each slope results in hillslope activation potentially yielding subsurface runoff (or interflow) which may resurface downslope. Clearly, the relative position along the hillslope is an important control on soil moisture and runoff conditions experienced during major flood events.

[17] The effects of soil profile properties and the degree of connected intercanopy spaces on the runoff response can be discerned by comparing the north and south facing intercanopy sites. Note the dynamics in the south facing intercanopy site (Figure 4b) differ from the north facing counterpart (Figure 4a). The sparser plant cover on the south facing slope leads to uniform soil moisture with depth at the downslope site and similar recession rates, suggesting that surface runoff generated in the upper layer of the upslope sites is potentially transported downslope where it fills available storage. These observations support the notion that the south facing runoff regime favors surface flow through interconnected bare patches rather than subsurface transport and exfiltration as in the north facing slope. Since soil moisture recession rates are affected by hydraulic and water retention characteristics, differences in the two opposing slopes illustrate the impact of soil properties on the runoff generation.

[18] The impact of the canopy patch on the soil moisture dynamics is best seen by comparing the north facing canopy and intercanopy sites (Figures 4a and 4c). Overall, the canopy patch appears to augment the differences among the slope positions as compared to intercanopy sites. A progressive downslope shift in soil moisture conditions is observed with upslope (downslope) juniper trees having depleted (augmented) soil moisture in the lower soil layer. This behavior is possibly an indication of enhanced subsurface transport in canopy patches due to the effects of litter layers and root macropores on infiltration properties. A similar behavior is observed at the south facing canopy sites, although the upslope measurements were unavailable for comparison due to sensor malfunction.

5. Conclusions

[19] This study documents the differential responses of opposing slopes with varying ecosystems to a major flood event in a semiarid catchment. Observational analysis of the hydrologic responses provides new insights into the interaction between terrain-soil-vegetation on modifying the spatial dynamics of soil moisture. Overall, there is a strong control of slope position on soil moisture recession due to overland and subsurface runoff redistribution. Vegetation differences have been shown to enhance the slope effects on the soil moisture dynamics along both hillslopes. Furthermore, the opposing hillslopes appear to contribute varying runoff amounts to the channel flood. Responses to this event have implications on the effects of vegetation on long-term hillslope evolution.

[20] **Acknowledgments.** We acknowledge funding from NASA Grant NNG05GA17G and the useful comments from two anonymous reviewers that helped improve the manuscript.

References

Bonnin, G. M., D. Todd, B. Lin, T. Parzybok, M. Yekta, and D. Riley (2004), *Precipitation-Frequency Atlas of the United States*, vol. 1, *Semi-Arid Southwest*, *NOAA Atlas*, vol. 14, NOAA, Silver Spring, Md.

Cordova, J. R., and R. L. Bras (1981), Physically-based probabilistic models of infiltration, soil moisture, and evapotranspiration, *Water Resour. Res.*, *17*(1), 93–106.

Cowan, W. L. (1956), Estimating hydraulic roughness coefficients, *Agric. Eng.*, *37*(7), 473–475.

Gutiérrez-Jurado, H. A., E. R. Vivoni, J. B. J. Harrison, and H. Guan (2006), Ecohydrology of root zone water fluxes and soil development in complex semiarid rangelands, *Hydrol. Processes*, *20*, 3289–3316, doi:10.1002/hyp.6333.

Istanbulluoglu, E., and R. L. Bras (2005), Vegetation-modulated landscape evolution: Effects of vegetation on landscape processes, drainage density, and topography, *J. Geophys. Res.*, *110*, F02012, doi:10.1029/2004JF000249.

Kurc, S. A., and E. E. Small (2004), Dynamics of evapotranspiration in semiarid grassland and shrubland ecosystems during the summer monsoon season, central New Mexico, *Water Resour. Res.*, *40*, W09305, doi:10.1029/2004WR003068.

Magirl, C. S., et al. (2007), Impact of recent extreme Arizona storms, *Eos Trans. AGU*, *88*(17), 191.

McMahon, D. R. (1998), Soil, landscape and vegetation interactions in a small semi-arid drainage basin: Sevilleta National Wildlife Refuge, M.S. thesis, 174 pp., N. M. Inst. of Min. and Technol., Socorro.

Newman, B. D., B. P. Wilcox, S. R. Archer, D. D. Breshears, C. N. Dahm, C. J. Duffy, N. G. McDowell, F. M. Phillips, B. R. Scanlon, and E. R. Vivoni (2006), Ecohydrology of water-limited environments: A scientific vision, *Water Resour. Res.*, *42*, W06302, doi:10.1029/2005WR004141.

Rodríguez-Iturbe, I., and A. Porporato (2004), *Ecohydrology of Water-Controlled Ecosystems: Soil Moisture and Plant Dynamics*, 440 pp., Cambridge Univ. Press, New York.

Salvucci, G. D., and D. Entekhabi (1995), Hillslope and climatic controls on hydrologic fluxes, *Water Resour. Res.*, *31*(7), 1725–1739.
Wilcox, B. P., D. D. Breshears, and C. D. Allen (2003), Ecohydrology of a resource-conserving semiarid woodland: Effects of scale and disturbance, *Ecol. Monogr.*, *73*(2), 223–239.

R. L. Bras, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Room 48-211, Cambridge, MA 02139, USA.

H. A. Gutiérrez-Jurado and E. R. Vivoni, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, 801 Leroy Place, MSEC 244, Socorro, NM 87801, USA. (vivoni@nmt.edu)

E. Istanbulluoglu, Department of Geosciences and Department of Biological Systems Engineering, University of Nebraska at Lincoln, 200 Bessey Hall, Lincoln, NE 68588, USA.