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High-resolution characterization of a semiarid watershed: Implications on evapotranspiration estimates

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SUMMARY

The North American monsoon (NAM) contributes roughly half of the annual precipitation in the Chihuahuan Desert from July to September. Relatively frequent, intense storms increase soil moisture and lead to ephemeral runoff. Quantifying these processes, however, is difficult due to the sparse nature of existing observations. This study presents results from a dense network of rain gauges, soil probes, channel flumes, and an eddy covariance tower in a small watershed of the Jornada Experimental Range. Using this network, the temporal and spatial variability of soil moisture conditions and channel runoff were assessed from June 2010 to September 2011. In addition, tower measurements were used to quantify the seasonal, monthly and event-scale changes in land–atmosphere states and fluxes. Results from this study indicate a strong seasonality in water and energy fluxes, with a reduction in the Bowen ratio (B) from winter ($B = 14$) to summer ($B = 3.3$). This reduction was tied to higher shallow soil moisture (θ) availability during the summer ($\theta = 0.040$ m^3/m^3) as compared to winter ($\theta = 0.004$ m^3/m^3). Four consecutive rainfall–runoff events during the NAM were used to quantify the soil moisture and channel runoff responses and how water availability impacted land–atmosphere fluxes. The network also allowed comparisons of several approaches to estimate evapotranspiration (ET). Using a water balance residual approach, a more accurate ET estimate was obtained when distributed measurements were used, as opposed to single site measurements at the tower. In addition, the spatially-varied soil moisture data yielded a more reasonable daily relation between ET and θ, an important parameterization in many hydrologic models. These analyses illustrate the value of high-resolution sampling in small watersheds to characterize hydrologic processes.

1. Introduction

The North American monsoon (NAM) results in a pronounced increase in precipitation during the summer months of July, August, and September leading to elevated soil moisture and runoff generation in the southwest U.S. and northwest Mexico (e.g., Douglas et al., 1993; Gochis et al., 2006; Vivoni et al., 2008a). Soil moisture availability during the summer season induces rapid vegetation greening following the dry months in the spring (Salinas-Zavala et al., 2002; Watts et al., 2007; Forzieri et al., 2011). While the NAM has an annual recurrence, its seasonal precipitation amounts and its temporal distribution vary substantially from year to year. The convective nature of storm events also leads to significant rainfall variations in space and time (e.g., Gebremichael et al., 2007; Goodrich et al., 2008). Thus, it is important to have high-resolution observations to understand how watersheds will respond to storm events in terms of soil moisture changes, runoff generation and vegetation productivity during the NAM.

Soil moisture (θ) plays a critical role in partitioning energy and water fluxes in the arid and semiarid watersheds of the NAM region (e.g., Dugas et al., 1996; Kurc and Small, 2007; Vivoni et al., 2008a). Increases in soil water from summer storms result in a marked decrease in sensible heat flux and an increase in latent heat flux or evapotranspiration (ET). In addition to rainfall variations, soil moisture distributions are controlled by spatial patterns of soil, terrain and vegetation properties (e.g., Lawrence and Hornberger, 2007; Potts et al., 2010; Vivoni et al., 2010a). In

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regions of variable or complex terrain, redistribution processes during and after storms result in horizontal and vertical variations in soil water. These, in turn, can induce changes in how soil moisture is partitioned between evaporation from shallow soil layers and transpiration by plants from deeper layers (Scott et al., 2006; Duniway et al., 2010; Cavanaugh et al., 2011). Evapotranspiration is thus linked to the spatial distribution of soil moisture impacted by the heterogeneous landscape and its terrain, soil and vegetation characteristics.

Arid and semiarid watersheds in the NAM region are also composed of mosaics of bare soils, herbaceous plants and woody shrubs and trees. Vegetation patterns play an important role in determining infiltration, evapotranspiration losses and local runoff generation (Pierson et al., 1994; Breshears et al., 1998; Abrahams et al., 2003; Gutiérrez-Jurado et al., 2006; Mueller et al., 2007). During summer storms, overland flow is impacted by the presence of plant patches and their ability to modify soil properties, attenuate rainfall intensity and serve as runoff barriers. Thus, the spatial pattern of plant patches and bare spaces upon a heterogeneous terrain, that vary at scales on the order of meters in mixed shrubland-grassland systems (Laliberte and Rango, 2011), affects soil moisture dynamics and runoff generation (Mueller et al., 2007). These spatial features require a high-resolution characterization of terrain and vegetation properties in the hillslopes and channel reaches that compose watersheds in the NAM region (Vivoni, 2012a).

Spatiotemporal changes in vegetation distributions are also commonly observed in the arid and semiarid watersheds of the region (e.g., Huxman et al. 2005; Newman et al. (2006a)), in response to grazing, fire and climate pressures. Areas experiencing woody plant encroachment are characterized by increasing amounts of woody shrubs and trees with respect to herbaceous cover. In these settings, desertification processes promote further establishment of woody plants, an increase in bare soil and a reduction in grasses, leading to a more heterogeneous mosaic of surface properties (Gibbens et al., 2005; Okin et al., 2009; Browning et al., 2012). Vegetation changes can lead to a myriad of hydrologic consequences at individual sites that together affect local watershed dynamics as well as downstream areas. For example, Bestelmeyer et al. (2011) postulate that woody plant encroachment in upland sites has differential effects on the vegetation conditions downstream depending on the degree of hydrologic connectivity. In areas where bare soils are well connected along a terrain gradient (Mueller et al., 2007), the authors expect that vegetation changes affect downstream hydrologic conditions. Peters et al. (2010) also postulate that grass establishment is enhanced under scenarios of increased NAM rainfall at downstream sites that benefit from upland water redistribution in a heterogeneous landscape.

Clearly, a spatially-explicit approach is required to capture hydrologic connectivity in arid and semiarid watersheds in a way that allows examining the impact of vegetation changes on downstream conditions. In this study, we take a step towards developing such an approach through the establishment of high-resolution observations in a small watershed in southern New Mexico, USA. An environmental sensor network in a Chihuahuan Desert mixed shrubland was designed to capture storm event transformation into spatially-variable soil moisture and runoff responses in a watershed where terrain and vegetation gradients are observed from the use of high-resolution imagery from an Unmanned Aerial Vehicle (UAV). In particular, the UAV products allow characterizing the terrain attributes (i.e., elevation, slope, aspect, upstream area) and vegetation species distributions used to interpolate local site measurements from the environmental sensor network to the entire watershed area. Using the observations, we quantify the temporal dynamics of water and energy fluxes in the watershed at the seasonal, monthly and storm event scales and provide insight into their spatial variations and their linkage.

We also determine the role of watershed-scale soil moisture conditions on the estimation of evapotranspiration (ET) to quantify the value of high-resolution observations as compared to traditional approaches using a more limited number of soil moisture profiles (e.g., Scott, 2010). This is performed using two approaches: (1) as a residual of the monthly water balance ($ET = P - Q - \Delta S/\Delta t$, where P is precipitation, Q is runoff, and $\Delta S/\Delta t$ is the change in soil water storage over time), and (2) as a result of a piecewise linear relation between ET and θ. We postulate that a set of high-resolution observations is required to properly characterize the hydrologic dynamics in the semiarid watershed due to its variable terrain and vegetation distributions, as observed from UAV imagery. Furthermore, the observations may aid in understanding how the watershed underwent a transition from a grassland to a mixed shrubland over the last century (Gibbens et al., 2005) and how this might be related to hydrologic connectivity.

2. Methods

2.1. Study watershed and its characterization

The study area is in a shrub-dominated portion of the San Andres Mountain piedmont, along the southeastern boundary of the Jornada Experimental Range (JER) in southern New Mexico, USA (Fig. 1). A small watershed (4.67×10^4 m^2 or 4.67 ha) in the alluvial slope or bajada was first instrumented with a rain gauge and runoff flume in 1977. Using these records, Turnbull et al. (2013) analyzed the aggregate relation between event rainfall and runoff over 1977–1985 and 2003–2011, finding a change attributed to variations in precipitation intensity. Over this period, however, the topographic, vegetation and channel characteristics in the watershed also likely varied (e.g., Gibbens et al., 2005; Monger and Bestelmeyer, 2006). In addition to these long-term changes, the watershed has seasonal variations related to the NAM (July–September), which accounts for ~60% of the annual rainfall of 308 mm as obtained over the period 2005–2010 at the site rain gauge. Fig. 2 illustrates this seasonality through the monthly mean rainfall and its standard deviation (std) and the resulting vegetation response through the monthly mean (and std) Normalized Difference Vegetation Index (NDVI).

Our high-resolution observational efforts commenced in 2010 with the installation of an environmental sensor network and the characterization of the watershed through detailed field sampling and UAV-based image analysis. For example, Fig. 1 shows the location of the channel network mapped with a differential global positioning system (dGPS, Leica Geosystems GPS 1200). The watershed boundary in Fig. 1 was derived from a 1 m digital terrain model (DTM) derived from UAV images at a height of 200 m in October 2010. The BAT 3 (MLB Co.) UAV mounted with a Canon SD 900 digital camera was used to create a 6 cm orthomosaic of overlapping photos (75% forward lap and 40% side lap) shown in Fig. 1. Orthorectification and DTM generation were accomplished using the methods of Laliberte et al. (2008) and Laliberte and Rango (2011). An analysis of the DTM revealed the major terrain features in the watershed, including the distributions of elevation, slope and aspect, as shown in Fig. 3. Three major areas (north-, south- and west-facing hillslopes) with low to moderate slopes (~0–6°) are present in the watershed (mean slope of 2.6°), while the channel banks and propagating channel heads have higher slopes (~15–25°). In Fig. 3d, three sub-watersheds delineated upstream of the channel flumes are shown, with areas ranging from 0.77 ha (Flume 1) to 1.31 ha (Flume 3).